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Geomorphology Part I

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Geography is the study of

1. the **physical features** of the earth and its atmosphere,
2. **human activity which affects and is affected by the physical features** of the earth and its atmosphere. (Definition from Oxford Dictionary)

- Human activity which affects and is affected by the physical features include the distribution of populations, distribution of resources and economic activities, and changes in the environment.

Geography, the natural science, is divided into two main branches:

1. **Physical geography:** deals with the study of processes and patterns in the natural environment like the atmosphere, hydrosphere, biosphere, and geosphere.
2. **Human geography:** deals with the environment shaped by human activity.

Physical Geography can be divided into several sub-fields, as follows:

- **Geomorphology** ('geo' meaning earth, 'morphe' meaning form and 'logos' meaning discourse) is the field concerned with understanding the surface of the Earth and the processes by which it is shaped.

- **Climatology** is the study of the climate (weather conditions averaged over a long period).
- **Meteorology** focuses on weather processes and short-term forecasting (in contrast with climatology).
- **Oceanography** is the branch of physical geography that studies the Earth's oceans and seas.
- **Hydrology** is concerned with the amounts and quality of water moving and accumulating on the land surface and in the soils and rocks near the surface and is typified by the hydrological cycle.
- **Biogeography** deals with geographic patterns of species distribution and the processes that determine these patterns.
- **Environmental geography** analyses the spatial aspects of interactions between humans and the natural environment. The branch bridges the divide between human and physical geography.
- **Geomatics** is the field of gathering, storing, processing, and delivering geographic information.

There are many other sub-branches in physical geography.

1. Interior of The Earth

- Understanding the structure of the earth's interior (crust, mantle, core) and various forces (heat, seismic waves) emanating from it is essential to understand the evolution of the earth's surface, its current shape and its future.

1.1 The study of the earth's interior is essential

- to understand the earth's surface
- to understand the geophysical phenomenon like volcanism, earthquakes, etc.
- to understand the earth's magnetic field
- to understand the internal structure of various solar system objects
- to understand the evolution and present composition of the atmosphere
- for mineral exploration

Earth's surface

- Many different geological processes shape the Earth's surface.
- The forces that cause these processes come from both above and beneath the Earth's surface.
- Processes that are caused by forces from within the Earth are **endogenous processes** (Endo meaning "in").
- By contrast, **exogenous processes** (Exo meaning "out") come from forces on or above the Earth's surface.
- The major geological features of the earth's surface like mountains, plateaus, lakes are mostly a result of endogenous processes like folding, faulting that are driven by forces from inside the earth.

Geophysical phenomenon like volcanism, earthquakes

- The forces that cause catastrophic events like earthquakes, volcanic eruptions come from deep below the earth's surface.
- For example, earthquakes occur due to the movement of the tectonic plates and the energy required for this movement is supplied by the **conventional currents in the mantle**.
- Similarly, volcanism occurs through the vents and fissures created by the tectonic movements.

Earth's magnetic field

- Earth's magnetic field is a result of **convection currents in the outer core** of the earth.
- Life on earth would not have been possible if not for the earth's magnetic field which protects the earth's atmosphere from the harmful **solar wind**.

The internal structure of various solar system objects

- The entire solar system was formed from a single nebular cloud, and the process of the formation of every solar system object is believed to be similar to that of the earth.

Evolution and present composition of the atmosphere

- For life to flourish on the surface of the earth, the atmosphere needs to have essential components like oxygen for respiration, CO_2 and other greenhouse gases to maintain the temperature on the surface, ozone to protect life from ultraviolet radiation and the right atmospheric pressure.
- All these components of the earth's atmosphere owe their existence to the **volcanic eruptions** that unlock them from the earth's interior.

Mineral exploration

- Understanding volcanic activity and the nature of rocks is essential for mineral exploration.
- Most of the minerals like **diamonds (form at a depth of 150-800 km in the mantle)** that occur on the earth's surface are formed deep below the earth's surface. They are brought to the surface by **volcanic activity**.

1.2 Direct Sources of information about the interior

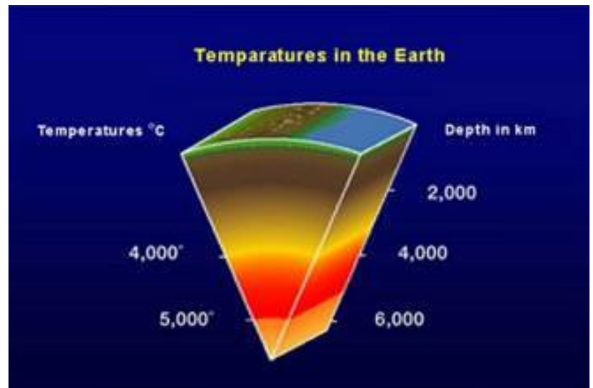
- Deep earth mining and drilling reveal the nature of rocks deep down the surface.
- But as mining and drilling are not practically possible beyond a certain depth, they don't reveal much information about the earth's interior.
- **Mponeng gold mine** (deepest mine in the world) and **TauTona gold mine** (second deepest mine in the world) in South Africa are deepest mines reaching to a depth of only 3.9 km.
- And the deepest drilling is only about 12 km deep hole bored by the Soviet Union in the 1970s over the **Kola Peninsula**.

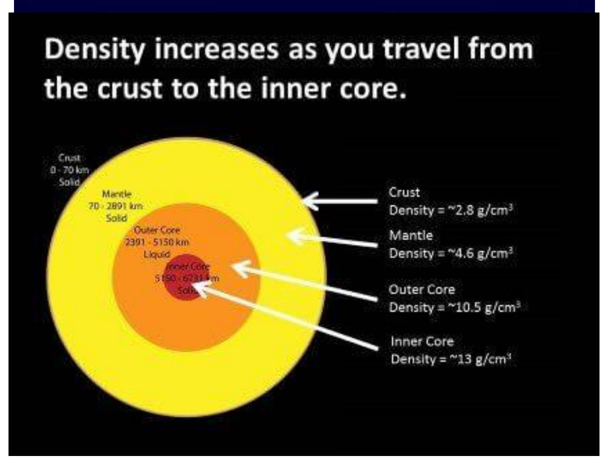
The Kola Peninsula in north-west Russia. ([TUBS, from Wikimedia Commons]())

- Volcanic eruption forms another source of obtaining direct information.

1.3 Indirect Sources of information about the interior

- Gravitation and the diameter of the earth help in estimating pressure deep inside.
- Volcanic eruptions and existence of hot springs, geysers etc. point to an interior which is very hot.





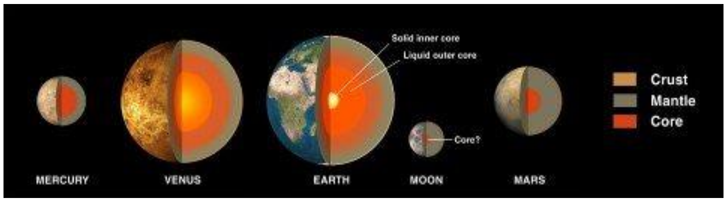
Seismic waves

- They are the most important source available to understand the layered structure of the earth.
- The velocity of seismic waves changes as they travel through materials with different **elasticity** and **density**.
- The **more elastic and denser the material is, the higher is the velocity**.
- They also undergo **refection or refraction** when they come across materials with different densities.
- Earth's internal structure can be understood by analysing the patterns of reflection, refraction

and change in velocity of the seismic waves when they travel through it.

Meteorites

- Meteorites and Earth are born from the same nebular cloud. Thus, they are likely to have a similar internal structure.
- When meteoroids they fall to earth, their outer layer is burnt during their fall due to extreme friction and the inner core is exposed.
- The heavy material composition of their cores confirms the similar composition of the inner core of the earth.



Gravitation

- The gravitation force differs according to the mass of material. The uneven distribution of mass of material within the earth influences this value. Such a difference is called **gravity anomaly**.
- Gravity anomalies give us information about the **distribution of mass** in the crust of the earth.

Magnetic field

- The geodynamo effect helps scientists understand what's happening inside the Earth's core. Shifts in the magnetic field also provide clues to the inaccessible iron core.

Sources of earth's heat

Radioactive decay

- The high temperature below the crust is attributed to the **disintegration of the radioactive substances**.
- **The nuclear decay happens primarily in the crust and the mantle**.
- Scientists believe that uranium could become sufficiently concentrated **at the base of Earth's mantle** to ignite self-sustained **nuclear fission**, as in a human-made reactor.
- The new measurements suggest **radioactive decay provides [more than half of Earth's total heat]**.

Nuclear fusion doesn't occur inside the earth. *For nuclear fusion to occur there must be far more pressure and temperature inside the earth. The earth is not massive enough to cause such conditions.*

Primordial heat

- The rest is the heat left over from Earth's formation known as the **primordial heat**.
- Primordial heat is the kinetic energy transferred to Earth by external impacts of comets and meteorites and the subsequent effects (**friction** caused by sinking of heavy elements like Fe, rising light elements like Si) and **latent heat of crystallisation released as the core solidified**.

Tidal friction

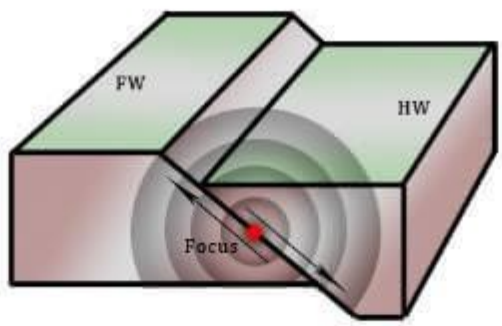
- The ocean tides are not the only effect of tidal forces (gravitational influence of the moon and the sun on earth; tides are explained in oceanography). The solid body of the Earth also bulges slightly in this way.
- The daily flexing of the Earth (both solid body and the oceans) cause loss of energy of the Earth's rotation, due to friction.
- This energy goes into heat, leading to miniscule increase in the Earth's internal temperature.
- The loss of rotational energy means that the **Earth is slowing down in its rotation rate**, currently by about 0.002 seconds per century.

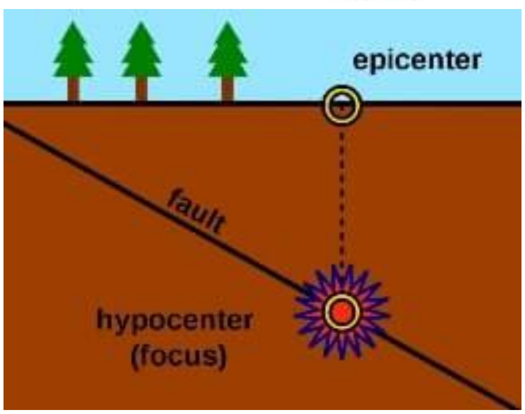
1.4 Seismic waves

- Seismic: relating to earthquakes or other vibrations of the earth and its crust.
- Seismic waves are waves of energy that travel through the Earth's layers and are a result of earthquakes, volcanic eruptions, magma movement, large landslides and large human-made explosions.
- The refraction or reflection of seismic waves is used for research into the structure of the Earth's interior.
- The terms seismic waves and earthquake waves are often used interchangeably.

How are earthquake waves produced?

- The abrupt release of energy along a fault (sharp break in the crustal layer) causes earthquake waves.
- Rock layers along a fault tend to move in opposite directions due to the force excreted on them but are held in place by counteracting frictional force exerted by the overlying rock strata.



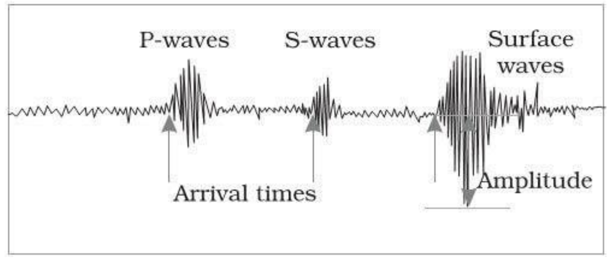


The Focus of an Earthquake ([Eround1]); Epicentre (AnsateSam, via [Wikimedia Commons])

- The pressure on the rock layers builds up over a period and overcomes the frictional force resulting in a sudden movement generating shockwaves (seismic waves) that travel in all directions.
- The point where the energy is released is called the **focus** or the **hypocentre** of an earthquake.
- The point on the surface directly above the focus is called **epicentre**.
- An instrument called 'seismograph' records the waves reaching the surface.

1.5 Types of Seismic waves or earthquake waves

- The seismic waves or earthquake waves are basically of two types — **body waves** and **surface waves**.

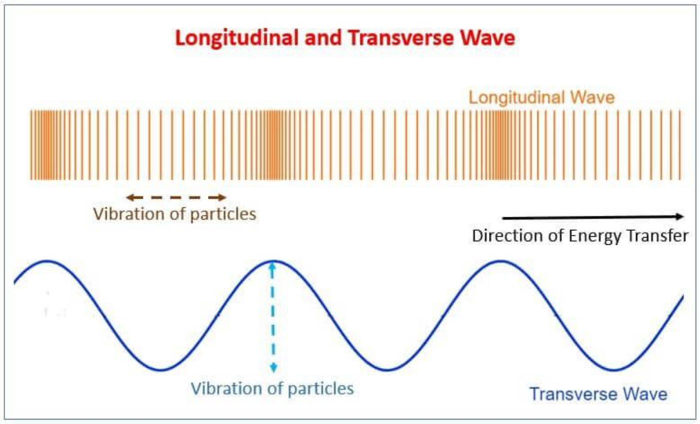


Body waves

- Body waves are generated due to the release of energy at the focus and **move in all directions** travelling through the interior of the earth. Hence, the name body waves.
- There are two types of body waves:
  1) the **P-waves or primary waves** (**longitudinal** in nature — wave propagation is similar to sound waves), and
  2) the **S-waves or secondary waves** (**transverse** in nature — wave propagation is similar to ripples on the surface of the water).

Primary Waves (P-waves)

- Primary waves are called so because they are the **fastest** among the seismic waves and hence are **recorded first on the seismograph**.
- P-waves are also called as the
  - **longitudinal waves** because the displacement of the medium is in the same direction as, or the opposite direction to, (parallel to) the direction of propagation of the wave; or
  - **compressional waves** because they produce compression and rarefaction when travelling through a medium; or
  - **pressure waves** because they produce increases and decreases in pressure in the medium.
- P-waves creates density differences in the material leading to stretching (rarefaction) and squeezing (compression) of the material.



The vibration of particles in Longitudinal wave and Transverse wave (Source)

- These waves are of relatively high frequency and are the **least destructive** among the earthquake waves.
- The trembling on the earth's surface caused due to these waves is in the **up-down direction (vertical)**.
- **They can travel in all mediums,** and their velocity depends on **shear strength (elasticity)** of the medium.
- Hence, the velocity of the P-waves in **Solids > Liquids > Gases**.
- These waves take the form of **sound waves** when they enter the atmosphere.
- P-wave velocity in earthquakes is in the range 5 to 8 km/s.
- The precise speed varies according to the region of the Earth's interior, from less than 6 km/s in the Earth's crust to 13.5 km/s in the lower mantle, and 11 km/s through the inner core.

*We usually say that the speed of sound waves depends on density. But there are few exceptions — **mercury is denser than iron**, but it is less elastic; hence the **speed of sound in iron is greater than that in mercury***

Why do P-waves travel faster than S-waves?

- **P-waves are about 1.7 times faster than the S-waves**.
- P-waves are compression waves that apply a force in the direction of propagation and hence transmit their energy quite easily through the medium and thus travel quickly.
- On the other hand, S-waves are **transverse waves** or **shear waves** (motion of the medium is perpendicular to the direction of propagation of the wave) and are hence less easily transmitted through the medium.

P-waves as an earthquake warning

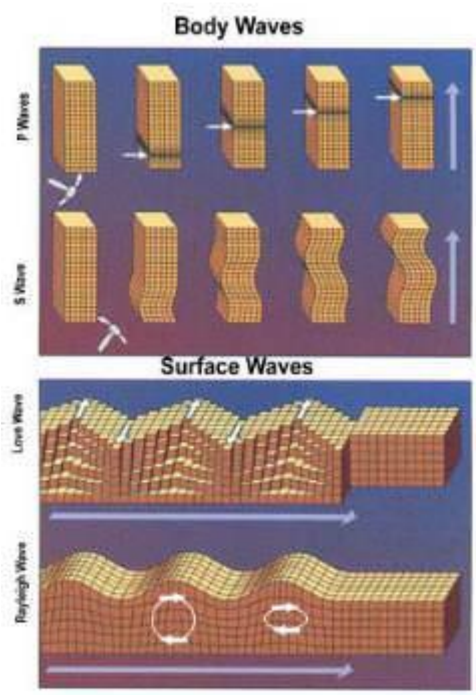
- Advance earthquake warning is possible by detecting the non-destructive primary waves that travel more quickly through the Earth's crust than do the destructive secondary and surface waves.
- Depending on the depth of focus of the earthquake, the delay between the arrival of the P-wave and other destructive waves could be up to about 60 to 90 seconds (depends of the depth of the focus).

Secondary Waves (S-waves)

- Secondary waves (secondary ➔ they are recorded second on the seismograph) or S-waves are also called as **transverse waves or shear waves or distortional waves**.
- They are analogous to water ripples or light waves.
- **Transverse waves or shear waves** mean that the direction of vibrations of the particles in the medium is perpendicular to the direction of propagation of the wave. Hence, they create **troughs** and **crests** in the material through which they pass (they distort the medium).
- S-waves arrive at the surface after the P-waves.
- These waves are of high frequency and possess **slightly higher destructive power** compared to P-waves.
- The trembling on the earth's surface caused due to these waves is from **side to side (horizontal)**.
- S-waves **cannot pass through fluids (liquids and gases)** as fluids do not support **shear stresses**.
- They travel at varying velocities (proportional to shear strength) through the solid part of the Earth.

Surface waves (L-Waves)

- The body waves **interact with the surface rocks and generate new set of waves called surface waves** (long or L-waves). **These waves move only along the surface**.
- Surface Waves are also called long period waves because of their **long wavelength**.
- They are **low-frequency transverse waves (shear waves)**.
- They develop in the **immediate neighbourhood of the epicentre** and affect only the surface of the earth and die out at smaller depth.
- **They lose energy more slowly with distance than the body waves** because they travel only across the surface unlike the body waves which travel in all directions.
- **Particle motion of surface waves (amplitude) is larger than that of body waves**, so surface waves are the **most destructive** among the earthquake waves.
- They are **slowest** among the earthquake waves and are recorded last on the seismograph.



Types of earthquake waves
https://www.youtube.com/watch?v=wDfIgoXaXis

Love waves

- It's the fastest surface wave and moves the ground from side-to-side.

Rayleigh waves

- A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean.
- Because it rolls, it moves the ground **up and down and side-to-side** in the same direction that the wave is moving.
- **Most of the shaking and damage** from an earthquake is due to the **Rayleigh wave**.

How do seismic waves help in understanding the earth's interior?

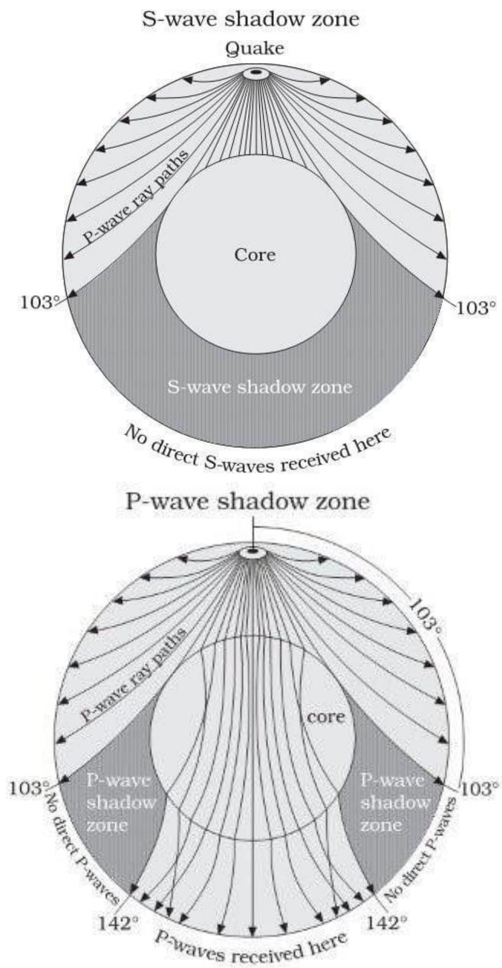
- Seismic waves get recorded in seismographs located at far off locations.
- Differences in arrival times, waves taking different paths than expected (due to refraction) and absence of the seismic waves in certain regions called as shadow zones, allow mapping of the Earth's interior.
- Discontinuities in velocity as a function of depth are indicative of changes in composition and density.
- That's is, by observing the changes in velocity, the density and composition of the earth's interior can be estimated (change in densities greatly varies the wave velocity).
- Discontinuities in wave motion as a function of depth are indicative of changes in phase.
- That is, by observing the changes in the direction of the waves, the emergence of shadow zones, different layers can be identified.

The emergence of Shadow Zone of P-waves and S-waves

- S-waves do not travel through liquids (they are **attenuated**).
- The entire zone beyond 103° does not receive S-waves, and hence this zone is identified as the shadow zone of S-waves. This observation led to the discovery of the **liquid outer core**.
- The shadow zone of P-waves appears as a band around the earth between 103° and 142° away from the epicentre.
- This is because P-waves are refracted when they pass through the transition between the semi-solid mantle and the liquid outer core.
- However, the seismographs located beyond 142° from the epicentre, record the arrival of P-

waves, but not that of S-waves. This gives clues about the **solid inner core**.

- Thus, a zone between **103° and 142°** from epicentre was identified as the **shadow zone for both the types of waves**.



Shadow Zone of P-waves and S-waves

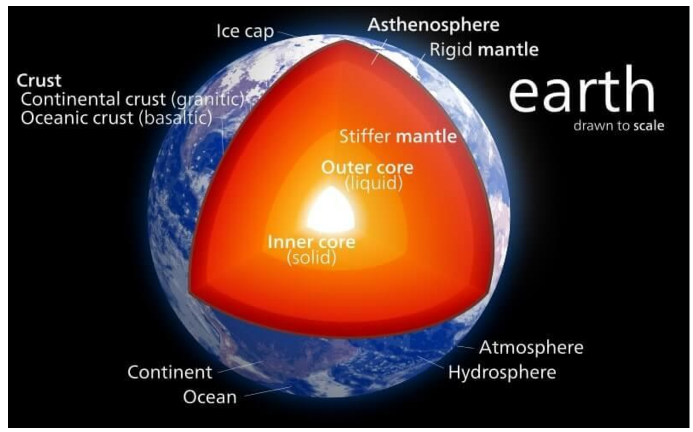
- The seismographs located at any distance within 103° from the epicentre, recorded the arrival of both P and S-waves.

Why do sound waves travel faster in a denser medium whereas light travels slower?

- The sound is a mechanical wave and travels by compression and rarefaction of the medium.
- A higher density leads to more elasticity in the medium and hence the ease by which compression and rarefaction can take place. This way the velocity of sound increases with an increase in density.
- Light, on the other hand, is a transverse electromagnetic wave.
- An increase in the density increases effective path length, and hence it leads to higher refractive index and lower velocity.

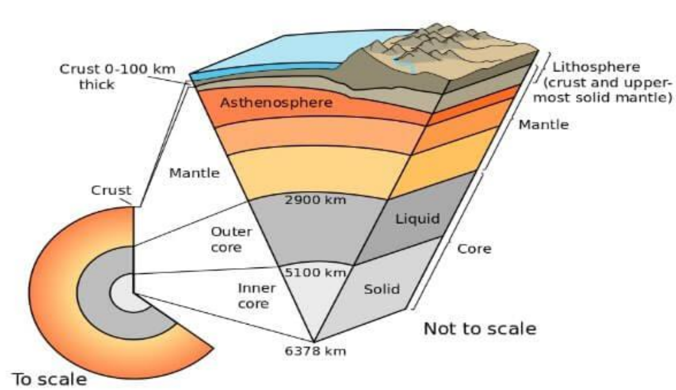
- The span of the shadow zone of the P-Waves = 78° [2 x (142° - 103°)]
- The span of the shadow zone of the S-Waves = 154° [360° – (103° + 103°)]
- The span of the shadow zone common for both the waves = 78°

1.6 The internal structure of the Earth



Earth's Layers ([Kelvinsong](), from Wikimedia Commons)

- The interior of the earth is made up of several concentric layers of which the crust, the mantle, the outer core and the inner core are significant because of their unique physical and chemical properties.
- The crust is a silicate solid, the mantle is a viscous molten rock, the outer core is a viscous liquid, and the inner core is a dense solid.



- Mechanically, the earth's layers can be divided into **lithosphere, asthenosphere, mesospheric mantle** (part of the Earth's mantle below the lithosphere and the asthenosphere), **outer core**, and **inner core**.
- Chemically, Earth can be divided into the **crust, upper mantle, lower mantle, outer core, and inner core**.

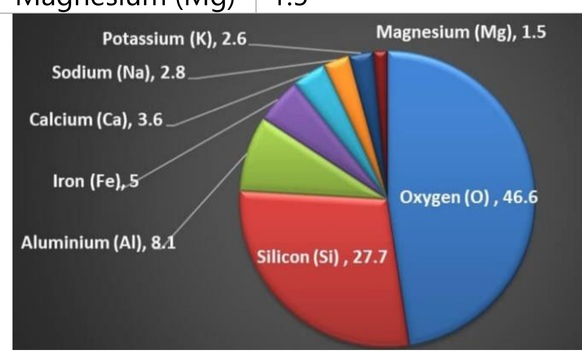
The Crust

- The crust is the outermost layer of the earth making up **0.5-1.0 per cent of the earth's volume** and **less than 1 per cent of Earth's mass**.
- Density increases with depth, and the average density is about **2.7 g/cm³** (average density of the earth is 5.51 g/cm³).
- The thickness of the crust varies in the range of range of **5-30 km in case of the oceanic crust** and as **50-70 km in case of the continental crust**.
- The continental crust can be thicker than 70 km in the areas of major mountain systems. It is as much as 70-100 km thick in the Himalayan region.
- The temperature of the crust increases with depth, reaching values typically in the range from about 200 °C to 400 °C at the boundary with the underlying mantle.
- The temperature increases by as much as 30 °C for every kilometre in the upper part of the crust.
- The outer covering of the crust is of **sedimentary material** and below that lie crystalline, igneous and metamorphic rocks which are acidic in nature.
- The lower layer of the crust consists of basaltic and ultra-basic rocks.
- The continents are composed of lighter silicates — **silica + aluminium** (also called **sial**) while the oceans have the heavier silicates — **silica + magnesium** (also called **sima**) [Suess,1831–1914 — this classification is now obsolete (out of date)].
- The continental crust is composed of lighter (**felsic**) **sodium potassium aluminium silicate** rocks, like **granite**.
- The oceanic crust, on the other hand, is composed of dense (**mafic**) **iron magnesium silicate** igneous rocks, like **basalt**.

In geology, felsic refers to igneous rocks that are relatively rich in elements that form feldspar and quartz.
It is contrasted with mafic rocks, which are relatively richer in magnesium and iron.
Felsic refers to rocks which are enriched in the lighter elements such as silicon, oxygen, aluminium, sodium, and potassium.

Most Abundant Elements of the Earth's Crust

Element	Approximate % by weight
1. Oxygen (O)	**46.6**
2. Silicon (Si)	**27.7**
3. Aluminium (Al)	**8.1**
4. Iron (Fe)	**5.0**
5. Calcium (Ca)	**3.6**
6. Sodium (Na)	2.8
7. Potassium (K)	2.6
8. Magnesium (Mg)	1.5



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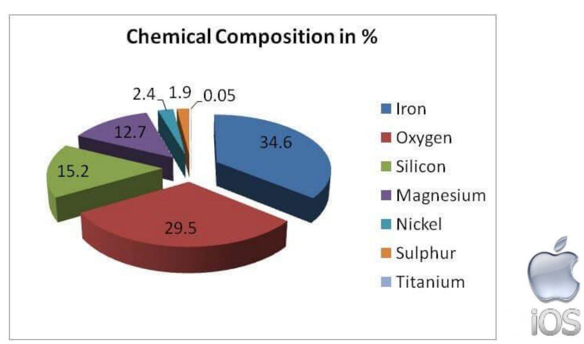
Most Abundant Elements of the Earth



Most Abundant Elements of the Earth's Crust ➔ ***OS CIA***
Most Abundant Elements of the Earth ➔ ***iOS***

The Mohorovicic (Moho) discontinuity

- Mohorovicic (Moho) discontinuity forms the boundary between the **crust** and the **asthenosphere** (upper reaches of the mantle) where there is a discontinuity in the seismic velocity.
- It occurs at an average depth of about 8 kilometres beneath the ocean basins and 30 kilometres beneath continental surfaces.
- The cause of the Moho is thought to be a change in rock composition from rocks containing **feldspar** (above) to rocks that contain no feldspars (below).

Lithosphere

- The lithosphere is the rigid outer part of the earth with thickness varying between 10-200 km.
- It is includes the **crust and the upper part of the mantle**.
- The lithosphere is broken into **tectonic plates (lithospheric plates),** and the movement of these tectonic plates cause large-scale changes in the earth's geological structure (folding, faulting).
- The source of heat that drives plate tectonics is the **primordial heat** left over from the planet's formation as well as the **radioactive decay of uranium, thorium, and potassium in Earth's crust and mantle**.

The Mantle

- It forms about **83 per cent of the earth's volume and holds 67% of the earth's mass**.
- It extends from Moho's discontinuity to a depth of 2,900 km.
- The density of the upper mantle varies between **2.9 g/cm^3 and 3.3 g/cm^3**.
- The lower mantle extends beyond the **asthenosphere**. It is in a solid state.
- The density ranges from **3.3 g/cm^3** to **5.7 g/cm^3** in the lower mantle.
- The mantle is composed of **silicate rocks that are rich in iron and magnesium** relative to the overlying crust.
- Regarding its constituent elements, the mantle is made up of **45% oxygen, 21% silicon,** and **23% magnesium (OSM)**.
- In the mantle, temperatures range from approximately 200 °C at the upper boundary with the crust to approximately 4,000 °C at the core-mantle boundary.
- Because of the temperature difference, there is a **convective material circulation** in the mantle (although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile).
- Convection of the mantle is expressed at the surface through the motions of tectonic plates.
- High-pressure conditions ought to inhibit seismicity in the mantle. However, in subduction zones, earthquakes are observed down to 670 km (420 mi).

Asthenosphere

- The upper portion of the mantle is called as asthenosphere (astheno means weak).
- It lies **just below the lithosphere** extending up to **80-200 km**.
- It is **highly viscous, mechanically weak and ductile** and its density is higher than that of the crust.
- These properties of the asthenosphere **aid in plate tectonic movement and isostatic adjustments** (the elevated part at one part of the crust area is counterbalanced by a depressed part at another).
- It is the **main source of magma** that finds its way to the surface during volcanic eruptions.

The Outer Core

- The outer core, surrounding the inner core, lies between 2900 km and 5100 km below the earth's surface.
- The outer core is composed of **iron mixed with nickel** (**nife**) and trace amounts of lighter elements.
- The outer core is **not under enough pressure to be solid**, so it is liquid even though it has a composition similar to the inner core.
- The density of the outer core ranges from **9.9 g/cm^3** to **12.2 g/cm^3**.

- The temperature of the outer core ranges from 4400 °C in the outer regions to 6000 °C near the inner core.
- Dynamo theory suggests that **convection in the outer core, combined with the Coriolis effect**, gives rise to **Earth's magnetic field**.

The Inner Core

- The inner core extends from the centre of the earth to 5100 km below the earth's surface.
- The inner core is generally believed to be composed primarily of **iron (80%) and some nickel** (**nife**).
- Since this layer can transmit shear waves (transverse seismic waves), it is solid. (When P-waves strike the outer core – inner core boundary, they give rise to S-waves)
- Earth's inner **core rotates slightly faster** relative to the rotation of the surface.
- The solid inner core is too hot to hold a permanent magnetic field.
- The density of the inner core ranges from **12.6 g/cm^3** to **13 g/cm^3**.
- The core (inner core and the outer core) accounts for just about **16 per cent of the earth's volume but 33% of earth's mass**.
- Scientists have determined the temperature near the Earth's centre to be 6000° C, 1000° C hotter than previously thought.
- At 6000°C, this iron core is as hot as the Sun's surface, but the **crushing pressure caused by gravity prevents it from becoming liquid**.

Remember: when ambient pressure increases the melting point of solid increases, and vice versa. One exception is Ice. In the case of ice increase in ambient pressure will lower its melting point.

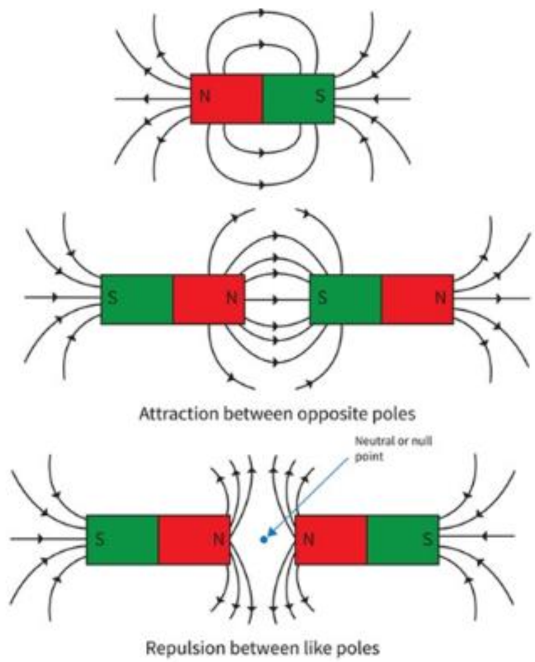
Seismic Discontinuities

- Seismic discontinuities are the regions in the earth where seismic waves behave a lot different compared to the surrounding regions due to a marked change in physical or chemical properties.

1. **Mohorovicic Discontinuity (Moho): separates the crust from the mantle.**
2. **Asthenosphere: highly viscous, mechanically weak and ductile part of mantle.**
3. **Gutenberg Discontinuity: lies between the mantle and the outer core.**

2. Earth's Magnetic Field

- A 'field' is a region in which a body experiences a force owing to the presence of other bodies.
- Gravitational fields determine how bodies with mass are attracted to each other.
- In electric fields, objects that have an electric charge are attracted or repelled from each other.
- Magnetic fields determine how electric currents that contain **moving electric charges** exert a force on other electric currents.



Field lines or magnetic flux in a simple bar magnet

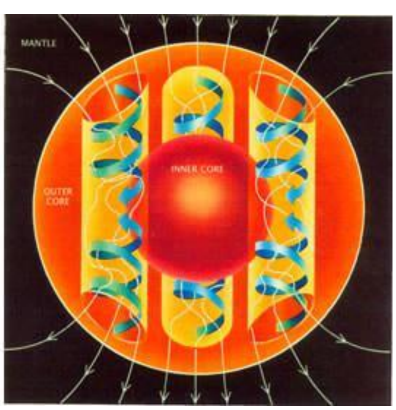
2.1 Dynamo theory: Generation of Earth's Magnetic Field and Sustaining it

- **Dynamo theory** proposes a mechanism by which a celestial body such as Earth or a star generates a magnetic field and sustains it over astronomical time scales (millions of years).
- Dynamo theory suggests that **convection in the outer core, combined with the Coriolis**

effect (caused due to the rotation of the earth), gives rise to **self-sustaining (geodynamo)** Earth's magnetic field.

Mechanism

- Earth’s magnetic field is generated in the **earth’s outer core**.
- Lower pressure than the inner core means the metal in the outer core is **fluid**.
- The temperature of the outer core ranges from 4400 °C in the outer regions to 6000 °C near the inner core.
- Heat sources include energy released by the compression of the core, energy released at the inner core boundary as it grows (latent heat of crystallisation), and radioactivity of potassium, uranium and thorium.
- The differences in temperature, pressure and composition within the outer core cause **convection currents** in the molten iron of the outer core as cool, dense matter sinks while warm, less dense matter rises.
- This **flow of liquid iron** generates **electric currents**, which in turn produce **magnetic fields**.
- Charged metals passing through these fields go on to create electric currents of their own, and so the cycle continues. This **self-sustaining loop** is known as the **geodynamo**.
- The **spiral movement** of the charged particles caused by the **Coriolis force** means that separate magnetic fields created are roughly aligned in the same direction, their combined effect adding up to produce one vast magnetic field of the planet.



Convection currents in the outer core. Spiral motion is caused due to the Coriolis Effect. (Wikipedia)

2.2 Magnetic poles

- A magnet's North pole is thought as the pole that is attracted by the Earth's North Magnetic Pole when the magnet is suspended so it can turn freely.
- Since opposite poles attract, **the North Magnetic Pole of the Earth is the south pole of its magnetic field**.
- Magnetic dipole field (simple north-south field like that of a simple bar magnet) is usually aligned fairly closely with the Earth's rotation axis; in other words, the magnetic poles are usually **fairly close to the geographic poles, which is why a compass works**.
- However, the dipole part of the field **reverses** after a few thousand years **causing the locations of the north and south magnetic poles to switch**.

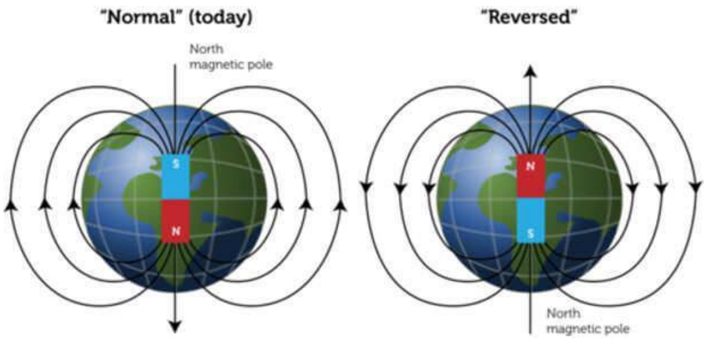
The terms magnetic north and magnetic south are not to be confused with geographic north and geographic south, and geomagnetic north and geomagnetic south.

2.3 Geomagnetic reversal

- A geomagnetic reversal or a reversal in earth’s magnetic field is a change in a planet's magnetic field such that the **positions of magnetic north and magnetic south are interchanged**.
- Based on **palaeomagnetism** (magnetism in rocks that was induced by the earth's magnetic field at the time of their formation), it is observed that over the last 20 million years, magnetic north and south have flipped roughly every 200,000 to 300,000 years.
- **The reversal is not literally 'periodic' as it is on the sun, whose magnetic field reverses every 11 years**.
- The time between magnetic reversals on the Earth is sometimes as short as 10,000 years and sometimes as long as 25 million years.
- And the time it takes to reverse could be about a few hundred or a few thousand years.
- The magnetic poles emerge at odd latitudes throughout the process of the reversal.

Normal and Reversed field

- The Earth's field has alternated between periods of **normal polarity, in which the predominant direction of the field was the same as the present direction**, and reverse polarity, in which it was the opposite.



Normal and Reversed field (The bar magnet at the centre represents earth's magnetic field)

- ***In Normal Polarity, Earth's North Magnetic Pole is the South Pole of its Magnetic Field.***
- ***In Reverse Polarity, Earth's North Magnetic Pole is the North Pole of its Magnetic Field.***

The current location of the Magnetic Poles

- The North and South Magnetic Poles wander (Polar Shift Theory) due to changes in Earth's magnetic field.
- The North Magnetic Pole (86° N, 172° W) lie to the north of Ellesmere Island in northern Canada and is rapidly drifting towards Siberia.
- The location of the South Magnetic Pole is currently off the coast of Antarctica and even outside the Antarctic Circle.
- Scientists suggest that the north magnetic pole migrates about 10 kilometres per year.
- Lately, the speed has accelerated to about 40 kilometres per year and could reach Siberia in a few decades.
- Since the Earth's magnetic field is not exactly symmetrical, the North and South Magnetic Poles are **not antipodal** (a straight line drawn from one to the other does not pass through the centre of the Earth).
- The Earth's North and South Magnetic Poles are also known as **Magnetic Dip Poles** because of the vertical "dip" of the magnetic field lines at those points.
- That is, if a magnetic compass needle is suspended freely at the magnetic poles then it will point **straight down** at the north magnetic pole (south pole of earth's magnetic field) and **straight up** at the south magnetic pole (north pole of earth's magnetic field).

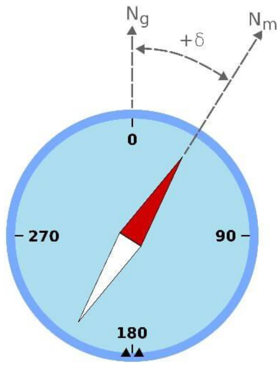
2.4 Compass

- A compass point north because all magnets have two poles, a north pole and a south pole, and the north pole of one magnet is attracted to the south pole of another magnet.
- The Earth is a magnet that can interact with other magnets in this way, so the north end of a compass magnet is drawn to align with the Earth's magnetic field.
- Because the Earth's Magnetic North Pole attracts the "north" ends of other magnets, **it is technically the "South Pole" of our planet's magnetic field**.
- While a compass is a great tool for navigation, it doesn't always point exactly north. This is because the Earth's magnetic North Pole is not the same as "true north (Earth's Geographic North Pole)."
- Although the **magnetic declination** (deviation from true north) does shift with time, this wandering is slow enough that a simple compass remains useful for navigation.

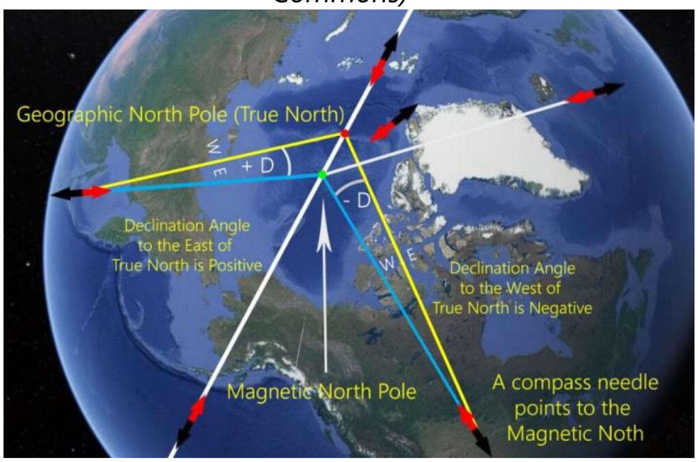
Using magnetoreception various organisms, ranging from some types of bacteria, sea turtles, some migratory birds, pigeons, etc. use the Earth's magnetic field for orientation and navigation.

Magnetic declination

- **Magnetic declination is the angle between magnetic north and true north**.
- It is positive when the angle derived is east of the true north, and it is considered negative when the angle measured is west of the true north.
- In which direction would a compass needle point if you were standing on the true North Pole?



[Magnetic Declination](#) *(Odder or GPL, via Wikimedia Commons)*



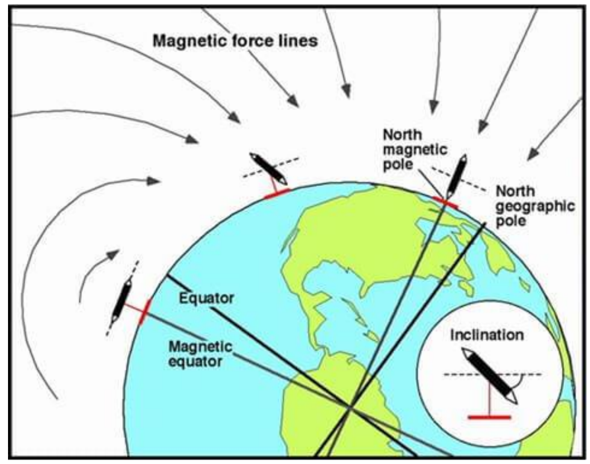
Magnetic Declination

- Importance: Ships and other long-distance means of transport that rely on the compass for navigation should do necessary corrections to account for magnetic declination at different latitudes and longitudes to stay in the right course.

***Magnetic deviation** is the error of a compass needle due to the influence of nearby metallic objects.*

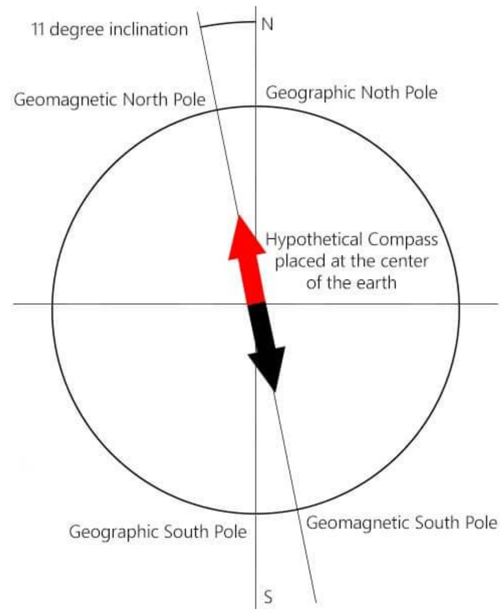
Magnetic Inclination or Magnetic Dip

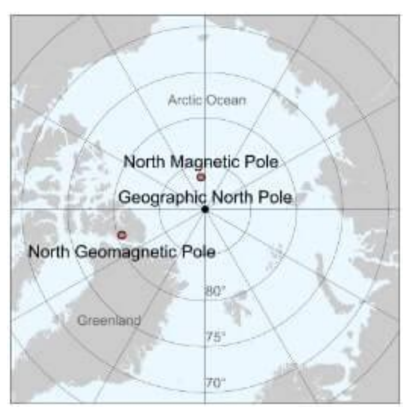
- Magnetic dip, dip angle, or magnetic inclination is the **angle made with the horizontal by the Earth's magnetic field lines**.
- In simple terms, magnetic inclination is the angle made by a compass needle when the compass is held in a **vertical** orientation.
- The magnetic equator is the irregular imaginary line, passing round the earth near the equator, on which a **magnetic needle has no dip** (because magnetic field lines are parallel to the horizontal at the equator).
- Again, the magnetic equator, like the magnetic field and poles, is **not fixed**.



From Marshak, S., 2001, Earth: Portrait of a Planet: New York, W.W. Norton. via [Rutgers.edu](#)

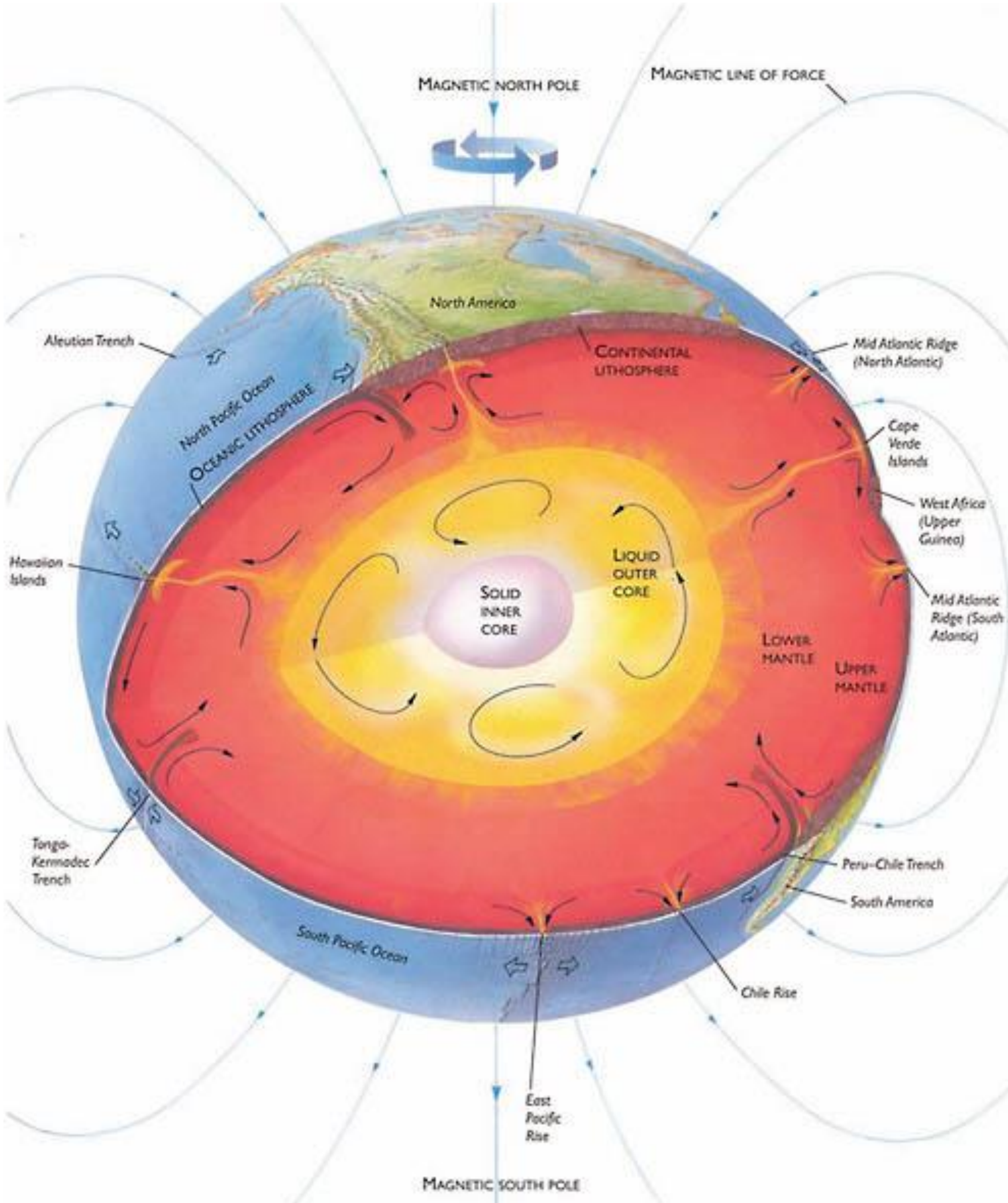
- **Magnetic dip at the magnetic equator is 0°, and at the magnetic poles, it is 90°**.
- Importance: The phenomenon of magnetic dip is important in aviation, as it causes the aeroplane's compass to give erroneous readings during banked turns and airspeed changes. Necessary corrections need to be made to the compass reading to stay in the right course.





2.5 Geomagnetic poles

- The Geomagnetic poles (dipole poles) are the **intersections of the Earth's surface and the axis of a bar magnet hypothetically placed at the centre the Earth**.
- There is such a pole in each hemisphere, and the poles are called as "the geomagnetic north pole" and "the geomagnetic south pole", respectively.
- Approximately, geomagnetic dipole is currently tilted at an angle of about **11 degrees** to Earth's rotational axis.
- On the other hand, the magnetic poles (the magnetic north pole and the magnetic south pole) are the points at which **magnetic needles become vertical**.
- The difference in the position of magnetic poles and geomagnetic poles is due to the uneven and complex distribution of the earth's magnetic field.



Earth's Magnetic field (Credits: universe-review.ca)

2.6 Magnetosphere

- The magnetosphere is the region above the ionosphere that is **defined by the extent of the Earth's magnetic field in space**.
- It extends several tens of thousands of kilometres into space, **protecting the Earth from the charged particles of the solar wind and cosmic rays** that would otherwise strip away the upper atmosphere, **including the ozone layer** that protects the Earth from harmful ultraviolet radiation.
- Many cosmic rays are kept out of the Solar system by the **Sun's magnetosphere called heliosphere**.

Magnetopause

- Earth's magnetic field, predominantly dipolar at its surface, is distorted further out by the **solar wind**.
- The solar wind exerts a pressure. However, it is kept away by the pressure of the Earth's magnetic field.
- The **magnetopause**, the **area where the pressures balance**, is the boundary of the magnetosphere.
- Despite its name, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magnetotail that extends beyond 200 Earth radii.

Magnetosheath

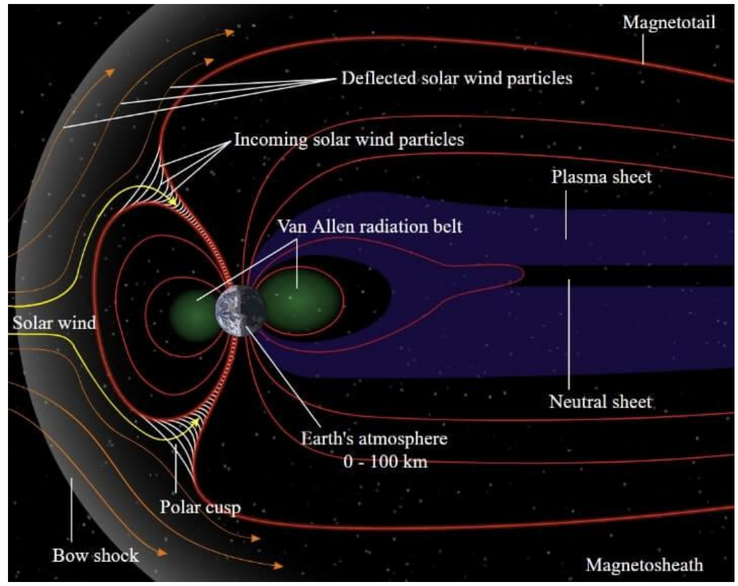
- The turbulent magnetic region just outside the magnetopause is known as the magnetosheath.

Plasmasphere

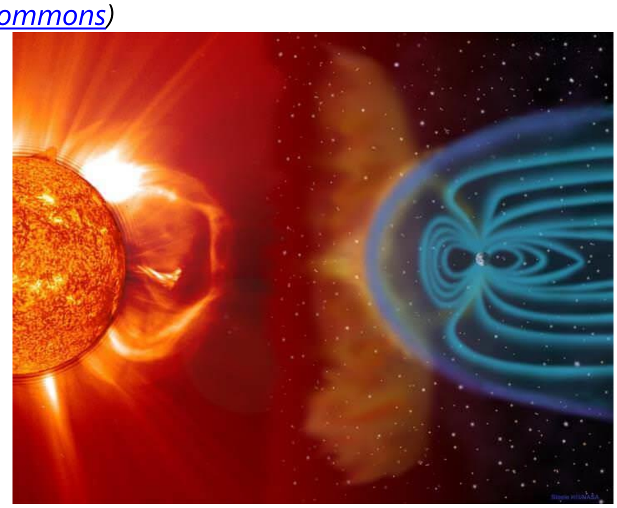
- Inside the magnetosphere is the plasmasphere, a region containing **low-energy charged particles**.
- This region begins at the height of 60 km, extends up to 3 or 4 Earth radii, and includes the **ionosphere**.
- This region rotates with the Earth.

Bow shock

- Sunward of the magnetopause is the **bow shock**, the area where the **solar wind slows abruptly**.



Earth's magnetosphere (Original bitmap from NASA. SVG rendering by Aaron Kaase, via [Wikimedia Commons])



Earth's magnetosphere (Credits: [losangeles.af.mil])

Auroras

- Aurora is the name given to the luminous glow in the upper atmosphere of the Earth which is produced by charged particles (solar wind) descending from the planet's magnetosphere.
- Positive ions slowly drift westward, and negative ions drift eastward, giving rise to a **ring current**. This current **reduces the magnetic field at the Earth's surface**.
- Some of these particles penetrate the ionosphere and collide with the atoms there.

- This results in an **excitation of the oxygen and nitrogen molecular electrons**. The molecules get back to their original state by emitting photons of light which are the aurorae.
- The charged particles follow magnetic field lines which are oriented in and out of our planet and its atmosphere near the magnetic poles. Therefore, aurorae mostly are seen to occur at **high latitudes**.

Geomagnetic storms

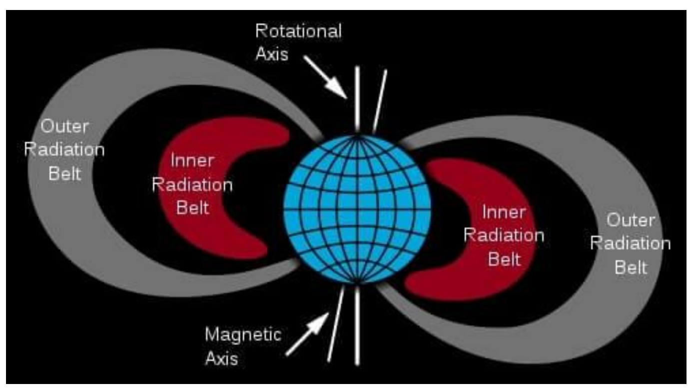
- The varying conditions in the magnetosphere, known as space weather, are largely driven by **solar activity**.
- If the solar wind is weak, the magnetosphere expands; while if it is strong, it compresses the magnetosphere and more of it gets in.
- Periods of intense activity, called geomagnetic storms, can occur when a **coronal mass ejection erupts** above the Sun and sends a shock wave through the Solar System. It takes just two days to reach the Earth.
- At the Earth's surface, a magnetic storm is seen as a **rapid drop in the Earth's magnetic field strength**.
- **Ring Current**: Ring current is the name given to the large electric current that circles the Earth above its equator during magnetic storms.

Effects

- The **ionosphere gets heated and distorted**, which means that **long-range radio communication that is dependent upon sub-ionospheric reflection can be difficult**.
- Ionospheric expansion can increase **satellite drag,** and it may become difficult to control their orbits.
- Geomagnetic storms disrupt satellite communication systems like GPS.
- Astronauts and high-altitude pilots would face high radiation levels.
- Electric power grids would see a high increase in voltage that would cause blackouts.
- Geomagnetic storms disrupt satellite communication systems like GPS.

2.7 Van Allen radiation belt

- A Van Allen radiation belt is a **zone of energetic charged particles**, most of which originate from the solar wind, that are **captured by and held around a planet by that planet's magnetic field**.
- There are two such concentric tire-shaped regions. The inner belt is 1–2 Earth radii out while the outer belt is at 4–7 Earth radii.
- By trapping the solar wind, the belts deflect the energetic particles and **protect the atmosphere**.
- The **belts endanger satellites**, which must have their sensitive components protected with adequate shielding if they spend significant time near that zone.
- Spacecraft travelling beyond low Earth orbit enter the zone of radiation of the Van Allen belts. Beyond the belts, they face additional hazards from cosmic rays and solar particle events.



Van Allen Belts (Booyabazooka, via Wikimedia Commons)

2.8 Magnetic field of other solar system objects

Moon

- The magnetic field of the Moon is very weak in comparison to that of the Earth and doesn't have a magnetic dipole. It is not strong enough to prevent atmospheric stripping by the solar wind.

Mercury

- Mercury's magnetic field is approximately a magnetic dipole (meaning the field has two poles) and is just 1.1% that of Earth's magnetic field.
- It's proximity to the sun makes it next to impossible to sustain an atmosphere.

Mars

- Mars does not have an intrinsic global magnetic field, but the solar wind directly interacts with the atmosphere of Mars, leading to the formation of a magnetosphere.
- The **lack of a significant magnetosphere** is thought to be one reason for Mars's thin atmosphere.

Venus

- Venus **lacks a magnetic field**.
- Its ionosphere separates the atmosphere from outer space and the solar wind.
- In spite of the absence of a magnetic field, **Venus's atmosphere is one of the densest among the terrestrial planets**.

Jupiter

- Jupiter has the **largest magnetic field and a thick atmosphere**.

Saturn

- Saturn's magnetosphere is the second largest of any planet in the Solar System after Jupiter.

Uranus and Neptune too have a significant and similar magnetic field.

3. Geomorphic Movements

- Earth's crust and its surface are constantly evolving (changing) due to various forces emanating from below (**endogenic forces**) as well as above the surface of the earth (**exogenic forces**).
- These forces cause physical and chemical changes to the geomorphic structure (earth's surface).
- Some of these changes are imperceptibly slow (e.g. weathering, folding), some others are gradual (e.g. erosion) while the remaining are quite sudden (earthquakes, volcanic eruptions).
- **Geomorphic:** relating to the form of the landscape and other natural features of the earth's surface.
- **Geomorphic agents:** mobile medium (like running water, moving ice masses or glaciers, wind, waves, currents etc.) which removes, transports and deposits earth materials.
- **Geomorphic processes:** physical and chemical processes that take place on the earth's surface (folding, faulting, weathering, erosion, etc.) due to endogenic and exogenic forces.
- **Geomorphic movements:** large scale physical and chemical changes that take place on the earth's surface due to geomorphic processes.

3.1 Endogenic Geomorphic Movements

- The large-scale movements on the earth's crust or its surface brought down by the forces emanating from deep below the earth's surface are called as endogenic geomorphic movements or simply endogenic movements (endo: internal; genic: origin; geo: earth; morphic: form).
- The geomorphic processes that are driven by the forces emanating from deep below the earth's surface are called endogenic geomorphic processes (folding, faulting, etc.).

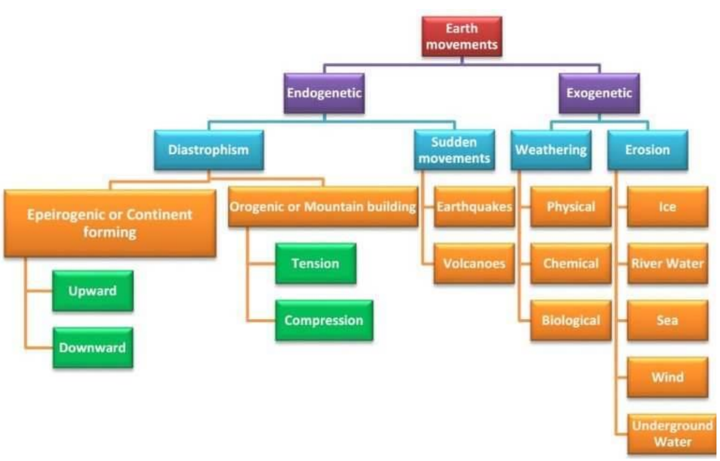
The force behind Endogenic Movements

- The ultimate source of energy behind forces that drive endogenic movements is **earth's internal heat**.
- Earth's internal heat is a result of mainly radioactive decay (50% of the earth's internal heat) and gravitation (causes pressure gradients).

- Differences in temperature and pressure (temperature gradients or geothermal gradients and pressure gradients) among various layers of the earth give rise to **density differences** and these density differences give rise to **conventional currents**.
- Convectional currents in the mantle drive the **lithospheric plates** (crust and upper mantle) and the **movement of the lithospheric plates** (**tectonics**) is the cause behind endogenic movements.
- The Earth's rotation (**Coriolis effect**) can influence where convection currents travel.
- The destination of convection currents determines the nature and location of the endogenic movements.

Classification of Endogenic movements

- Endogenic movements are divided into **diastrophic movements** and **sudden movements**.
- Diastrophism refers to **deformation** of the Earth's crust.
- Diastrophic movements are gradual and might stretch for thousands of years.
- On the other hand, sudden movements like earthquakes and volcanic eruptions occur in a very short period.
- Diastrophic movements are further classified into **epeirogenic movements (continent forming — subsidence, upliftment)** and **orogenic movements (mountain building — folding, faulting)**.



Diastrophism

- Diastrophism refers to deformation of the Earth's crust due to diastrophic movements (deforming movements) such as **folding, faulting, warping (bending or twisting of a large area) and fracturing**.
- All processes that move, elevate or build up portions of the earth's crust come under diastrophism. They include:
  1. **orogenic processes** involving mountain building through severe folding (crust is severely deformed into folds) and affecting long and narrow belts of the earth's crust;
  2. **epeirogenic processes** involving uplift or warping of large parts of the earth's crust (simple deformation);
  3. **earthquakes and volcanism** involving local relatively minor movements;
  4. **plate tectonics** involving horizontal movements of crustal plates.
- The most obvious evidence of diastrophic movement can be seen where sedimentary rocks have been bent, broken or tilted.

Epeirogenic or continent forming movements

- Epeirogenic or **continent forming** movements are **radial** movements (act **along the radius of the earth)**.
- Their direction may be **towards (subsidence)** or **away (uplift)** from the centre.
- They cause upheavals or depressions of land exhibiting **undulations** (wavy surface) of **long wavelengths** and little folding.
- The broad central parts of continents are called **cratons** and are subject to epeirogeny, hence the name continent forming movements.

Uplift

- Raised beaches, elevated wave-cut terraces, sea caves and fossiliferous beds above sea level are evidence of upliftment.

Uplifted landforms

- In India, raised beaches occur at several places along the **Kathiawar, Nellore, and Tirunelveli coasts**.
- Several places which were on the sea some centuries ago are now a few miles inland due to upliftment.
- For example, **Coringa near the mouth of the Godavari, Kaveripattinam in the Kaveri delta** and **Korkai on the coast of Tirunelveli**, were all flourishing seaports about 1,000 to 2,000 years ago.

Subsidence

- Submerged forests and valleys, as well as buildings, are evidence of subsidence.
- In 1819, a part of the **Rann of Kachchh** was submerged as a result of an earthquake.
- Presence of peat and lignite beds below the sea level in **Tirunelveli** and the **Sundarbans** is an example of subsidence.
- The **Andamans and Nicobars** have been isolated from the **Arakan coast** by **submergence** of the intervening land.

Arakan coast (Highlighted part)

- On the east side of **Bombay island**, trees have been found embedded in the mud about 4 m below low water mark. A similar submerged forest has also been noticed on the Tirunelveli coast in Tamil Nadu.
- A large part of the **Gulf of Mannar** and **Palk Strait** is very shallow and has been submerged in geologically recent times. A part of the former town of **Mahabalipuram** near Chennai is submerged in the sea.

Orogenic or the mountain-forming movements

- In contrast to epeirogenic movement, the orogenic movement is a **more complicated deformation** of the Earth's crust, associated with **crustal thickening** (due to the convergence of tectonic plates).
- Such plate convergence forms orogenic belts that are characterised by "the folding and faulting of layers of rock, by the intrusion of magma, and by volcanism.
- Orogenic or the mountain-forming movements **act tangentially to the earth surface,** as in plate tectonics.
- **Tension** produces **fissures** (since this type of force acts away from a point in two directions), and **compression** produces **folds** (because this type of force acts towards a point from two or more directions).

Fissure and Fold

Sudden Movements

- Sudden geomorphic movements occur mostly at the **lithospheric plate margins** (tectonic plate margins).
- The plate margins are highly unstable regions due to pressure created by pushing and pulling of magma in the mantle (**convectional currents**).

- These movements cause considerable deformation over a short period.

Earthquakes

- Earthquakes occur when the surplus accumulated stress in rocks in the earth's interior due to folding, faulting or other physical changes is relieved through the weak zones over the earth's surface in the form of **kinetic energy** (seismic waves).
- Such movements may result in uplift or subsidence in coastal areas.
- An earthquake in Chile (1822) caused a one-metre uplift in coastal areas.
- An earthquake in New Zealand (1885) caused an uplift of up to 3 metres.
- An earthquake in Japan (1891) caused subsidence of up to 6 metres.
- Earthquakes may cause a change in contours, change in river courses, shoreline changes, glacial surges (as in Alaska), landslides, soil creeps, mass wasting etc.

Volcanoes

- Volcanism includes the movement of molten rock (magma) onto or towards the earth's surface through narrow volcanic vents or fissures.
- A volcano is formed when the molten magma in the earth's interior escapes through the crust by vents and fissures in the crust, accompanied by steam, gases **(hydrogen sulphide, sulphur dioxide, hydrogen chloride, carbon dioxide** etc.) and pyroclastic material (cloud of ash, lava fragments carried through the air, and vapour).
- Depending on the chemical composition and viscosity of the lava, a volcano may take various forms.

3.2 Exogenic Geomorphic Movements

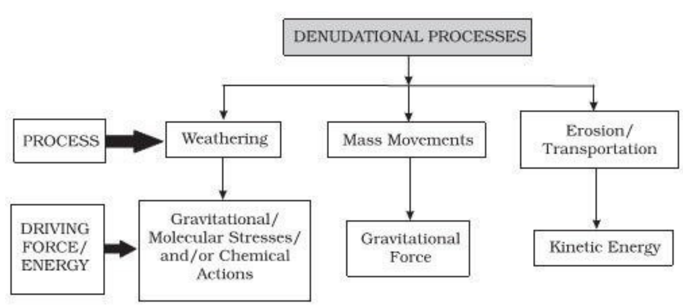
- The geomorphic processes on the earth's crust or its surface brought down by the **forces emanating from above the earth's surface** (wind, water) are called exogenic geomorphic process.
- Exogenic geomorphic process gives rise to exogenic geomorphic movements or simply exogenic movements such as **weathering** and **erosion**.
- The effects of most of the exogenic geomorphic processes are small and slow but will, in the long run, affect the rocks severely due to continued fatigue.

The force behind Exogenic Movements

- Exogenic processes are a direct result of the sun's heat.
- Sun's energy dictates the weather patterns like winds, precipitation, etc.
- Sun's heat along with weather patterns are responsible for stress induced in earth materials giving rise to exogenic movements (weathering and erosion).
- Earth materials become subjected to **molecular stresses** caused due to temperature changes.
- Chemical processes normally lead to **loosening of bonds** between grains.
- Stress is produced in a solid by pushing or pulling (**shear stresses** — separating forces) forces.

Denudation

- All the exogenic processes (weathering and erosion) are covered under a general term, denudation.
- The word 'denude' means to strip off or to uncover.
- Denudation depends on physical (folds, faults, orientation and inclination of beds, presence or absence of joints, bedding planes, hardness or softness of constituent minerals, permeability) and chemical (chemical susceptibility of mineral constituents to corrosion) properties of the rocks.



Weathering

- Weathering is the **disintegration** of rocks, soil, and minerals under the influence of physical (heat, pressure) and chemical (leaching, oxidation and reduction, hydration) agents.
- As very little or no motion of materials takes place in weathering, it is an **in-situ or on-site process**.
- The weathered material is carried farther away by **erosion**.
- There are three major groups of weathering processes: **1) chemical; 2) physical or mechanical; 3) biological weathering processes.** All the types of weathering often go hand in hand.

Physical Weathering Processes

- Physical weathering involves **mechanical disintegration** of rocks due to temperature changes, freeze-thaw cycles, wet-dry cycles, crystallisation of salts, animal and plant activity, etc.
- Various mechanisms of physical weathering are explained below.

Exfoliation due to pressure release or unloading

- Intrusive igneous rocks formed deep beneath the Earth's surface are under tremendous pressure due to overlying load.
- Removal of the overlying load because of continued erosion causes vertical pressure release with the result that the upper layers of the rock expand and fracture parallel to the surface.
- Over time, sheets of rock break away from the exposed rocks along the fractures, a process known as **exfoliation**.
- Exfoliation due to pressure release is also known as "**sheeting**".

Exfoliation due to thermal stress weathering

- Thermal stress weathering results from the subsequent expansion and contraction of rocks caused by diurnal and seasonal variations in the temperatures.
- The surface layers of the rocks tend to expand more than the rock at depth, and this leads to peeling off of the surface layers (exfoliation).
- This process is most effective in **dry climates** and **high elevations** where **diurnal temperature changes are drastic**.
- Although temperature changes are the principal driver, moisture can enhance thermal expansion in rock.

Granular Disintegration

- Granular disintegration happens in rocks composed of different types of coarse-grained minerals.
- Dark-coloured minerals absorb more heat than the light-coloured minerals.
- This leads to differential expansion and contraction of mineral grains resulting in grain by grain separation from the rock.

Frost weathering

- During the warm season, the water penetrates the pore spaces or fractures in rocks.
- During the cold season, the water freezes into ice, and its volume expands as a result.
- This exerts tremendous pressure on rock walls to tear apart even where the rocks are massive.
- Frost weathering occurs due to the growth of ice within pores and cracks of rocks during repeated cycles of freezing and melting.
- Frost weathering is the collective name for several processes where ice is present.
- These processes include **frost shattering, frost-wedging** and **freeze-thaw weathering**.

Frost wedging

- Freeze wedging is caused by the repeated freeze-thaw cycle.
- Cracks filled with water are forced further apart with subsequent freezing and thawing.

Shattering

- Severe frost can disintegrate rocks along weak zones to produce **highly angular pieces** with sharp corners and edges through the process of shattering.
- Shattering piles up rock fragments called **scree** at the foot of mountain areas or along slopes.

Block Separation (freeze-thaw weathering)

- Repeated freeze-thaw cycles weaken the rocks which, over time, break up along the joints into angular pieces. The splitting of rocks along the joints into blocks is called block disintegration.

Salt Weathering

- Salt weathering occurs when saline solutions seep into cracks and joints in the rocks and evaporate, leaving salt crystals behind.
- Salt crystals expand during the crystallization process and also when they are subjected to above normal temperatures.
- The expansion in near-surface pores causes splitting of individual grains within rocks, which eventually fall off (granular disintegration or granular foliation).
- Salt weathering is normally associated with **arid climates** where strong heating causes strong evaporation and crystallisation.

Mass Wasting

- Mass wasting is the mass movement of unconsolidated soil, sand, rocks, regolith (the layer of unconsolidated solid material covering the bedrock of a planet), etc. along a slope under the influence of gravity.
- Mass wasting occurs when the gravitational force acting on a slope exceeds its resisting force leading to **slope failure** (mass wasting).
- Timescales of the mass wasting process may be a few seconds (debris flows and mudflows) or hundreds of years (mass wasting along the slopes of stable mountains leaving behind alluvial fan like structures).

Chemical Weathering

- Chemical weathering involves **chemical decomposition** of rocks and soil.
- Chemical weathering processes include **dissolution, solution, carbonation, hydration, oxidation and reduction** that act on the rocks to decompose, dissolve or reduce them to a fine state.
- These weathering processes are interrelated and go hand in hand and hasten the weathering process.

- Acids produced by microbial and plant-root metabolism, water and air (oxygen and carbon dioxide) along with heat speed up all chemical reactions.

Natural dissolution

- Dissolution: a process where a solute in gaseous, liquid, or solid phase dissolves in a solvent to form a solution.
- Some minerals, due to their natural solubility (like nitrates, sulphates, and potassium), oxidation potential (iron-rich minerals) will weather through dissolution naturally (rains).
- These minerals are easily **leached** out without leaving any residue and accumulate in dry regions.

Solution weathering

- Solution weathering occurs **when the solvent is an acidic solution** rather than simple water.
- A solution is a liquid mixture in which the minor component (the solute) is uniformly distributed within the major component (the solvent).
- **Acidic solutions** are any solution that has a higher concentration of hydrogen ions than water; solutions that have a lower concentration of hydrogen ions than water is called **basic or alkaline solutions**.

Carbonation – Natural solution weathering

- Carbonation refers to reactions of carbon dioxide to give **carbonates, bicarbonates, and carbonic acid**.
- Carbonation weathering is a process in which atmospheric carbon dioxide leads to **solution weathering**.
- As rain falls, it dissolves small amounts of carbon dioxide from the air, forming a weak acid that can dissolve some minerals like **limestone (calcium carbonate)** (solution weathering).
- When carbonic acid reacts with limestone, it produces calcium bicarbonate, which is partially soluble in water (dissolution weathering).
- Caves are formed when underground water containing carbonic acid travels through blocks of limestone, dissolves out the limestone, and leaves empty pockets (caves) behind (E.g. **Karst topography**).
- Carbonation process speeds up with a decrease in temperature because **colder water holds more dissolved carbon dioxide gas**. Carbonation is, therefore, a large feature of **glacial weathering**.

Anthropogenic solution weathering

- **Rainfall is naturally acidic** — pH of ~5.6 (CO_2 dissolves in the rainwater producing **weak carbonic acid**).
- Acid rain occurs when gases such as **sulphur dioxide** and **nitrogen oxides** are present in the atmosphere.
- These oxides react in the rainwater to produce stronger acids and can lower the pH to less than 4.
- These acids are capable of attacking certain kinds of rocks in much the way that carbonic acid does.

*Sulphur dioxide, SO2, comes from **volcanic eruptions or fossil fuels**.*
The conversion of metallic ores to the pure metals often results in the formation of sulphur dioxide.

Hydration

- Hydration is the **chemical addition of water** that involves the rigid attachment of H+ and OH- ions to the atoms and molecules of a mineral.
- When rock minerals take up water, the increased volume creates physical stresses within the rock. For example, iron oxides are converted to iron hydroxides which are larger in volume.
- Hydration is reversible, and continued repetition of this process causes fatigue in the rocks and may lead to their disintegration.
- The volume changes in minerals due to hydration will also help in physical weathering through **exfoliation** and **granular disintegration**.

Hydrolysis

- In biological hydrolysis, a **water molecule is consumed** to affect the **separation of a larger molecule into component parts**.

- In biological hydrolysis pure water reacts with **silicate** or **carbonate minerals** resulting in the complete dissolution of the original mineral (dissolution weathering).
- Biological hydrolysis is an important reaction in **controlling the amount of CO_2 in the atmosphere** and can affect climate.

Oxidation and Reduction

- In weathering, oxidation means **a combination of a mineral with oxygen to form oxides** (rusting in case of iron) or hydroxides. **Red soils** appear red due to the presence of iron oxides.
- Oxidation occurs where there is ready access to the atmosphere and water.
- The minerals most commonly involved in this process are iron, manganese, sulphur etc.
- When oxidised minerals are placed in an environment where oxygen is absent, **reduction** takes place.
- Such conditions usually exist below the water table, in areas of stagnant water and waterlogged ground.
- The red colour of iron upon reduction turns to greenish or bluish grey.

Biological activity and weathering

- Biological weathering is the removal of minerals from the environment due to growth or movement of organisms.
- Living organisms contribute to both mechanical and chemical weathering.
- Lichens and mosses grow on essentially bare rock surfaces and create a more humid chemical microenvironment.
- On a larger scale, seedlings sprouting in a crevice and plant roots exert physical pressure as well as providing a pathway for water and chemical infiltration.
- Burrowing and wedging by organisms like earthworms, rodents etc., help in exposing the new surfaces to chemical attack and assists in the penetration of moisture and air.
- Decaying plant and animal matter help in the production of **humic, carbonic and other acids** which enhance decay and solubility of some elements.
- Algae utilise mineral nutrients for growth and help in the concentration of iron and manganese oxides.

Significance of weathering

- Weathering is the **first step in the formation of soil** from rocks.
- Weathering weakens soil and rocks and makes it easy to exploit natural resources.
- Weathering leads to **natural soil enrichment**.
- Weathering leads to **mineral enrichment** of certain ores by leaching unwanted minerals leaving behind the valuable ones.

Soil Erosion, another exogenic movement, is covered in the subsequent chapters.

4. Tectonics

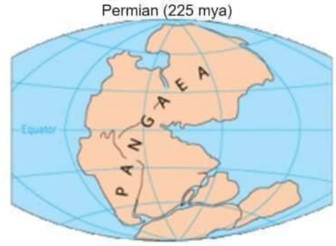
- During WW II, it was discovered that the ocean floor had some unique relief features like ridges, trenches, seamounts, shoals etc.
- Ridges and trenches gave insights into natural boundaries between various lithospheric plates (tectonic plates). These important discoveries led to the field of tectonics in geology.
- Tectonics is the scientific study of forces (convection currents in the mantle) and processes (collisions of the lithospheric plates, folding, faulting, volcanism) that control the structure of the Earth's crust and its evolution through time.
- It is basically about understanding the large-scale deformation of the lithosphere (crust and upper mantle above asthenosphere) and the forces that produce such deformation.
- It deals with the folding and faulting associated with mountain building; the large-scale, gradual upward and downward movements of the crust (epeirogenic movements); the growth and behaviour of old cores of continents known as cratons; and sudden horizontal displacements along faults.

4.1 Important concepts that tried to explain the tectonic processes

Geologic Time Scale
Tectonics (By Pmfias.com)

- Prechambrian Supereon (4.5 bya – 541 mya)
  - Hadean Eon (4.5 bya – 4.0 bya)
  - Archean Eon (4.0 bya – 2.5 bya)
  - Proterozoic Eon (2.5 bya – 541 mya)
- Unnamed Supereon (541 mya – present)
  - Phanerozoic Eon (541 mya – present)
    - Paleozoic Era (541 mya – 250 mya)
      - Cambrian Period (541 – 485 mya)
      - Ordovician Period (485 – 440 mya)
      - Silurian Period (440 – 415 mya)
      - Devonian Period (415 – 360 mya)
      - Carboniferous Period (360 – 300 mya)
      - Permian Period (300 – 250 mya)
    - Mesozoic Era (250 mya – 66 mya)
      - Triassic Period (250 – 200 mya)
        - Early Triassic Epoch (250 – 247 mya)
        - Middle Triassic Epoch (247 – 237 mya)
        - Late Triassic Epoch (237 – 200 mya)
      - Jurassic Period (200 – 145 mya)
        - Early Jurassic Epoch (200 – 175 mya)
        - Middle Jurassic Epoch (175 – 163 mya)
        - Late Jurassic Epoch (163 – 145 mya)
      - Cretaceous Period (145 – 66 mya)
        - Early Cretaceous Epoch (145 – 100 mya)
        - Late Cretaceous Epoch (100 – 65 mya)
    - Cenozoic Era (66 mya – present)
      - Paleogene Period (65 – 23 mya)
        - Paleocene Epoch (65 – 56 mya)
        - Eocene Epoch (56 – 33 mya)
        - Oligocene Epoch (33 mya – 23 mya)
      - Neogene Period (23 – 2.58 mya)
        - Miocene Epoch (23 mya – 5.3 mya)
        - Pliocene Epoch (5.3 mya – 2.58 mya)
      - Quaternary Period (2.58 mya – present)
        - Pleistocene Epoch (2.58 mya – 11,700 ya)
        - Halocene Epoch (11,700 ya – present)

Permian (225 mya)

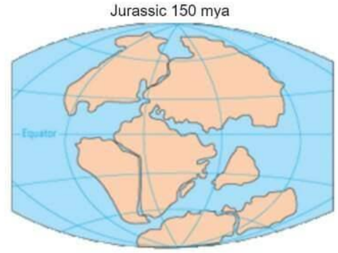


- Pangea Intact
- Pangea was covered by a mighty ocean called as Panthalassa

- Pangaea broke up into Laurentia (Laurasia) to the north and Gondwanaland to the south
- The Tethys sea seperated Laurentia and Gondwanaland
- Rifts formed splitting West Gondwana from east Gondwana.
- India separated from Antarctica.
- Laurasia split from South America and Africa.

Triassic 200 mya

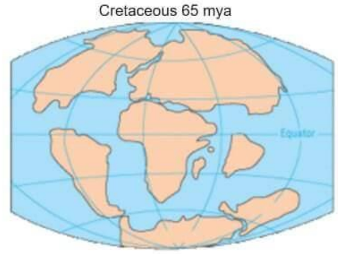
Jurassic 150 mya

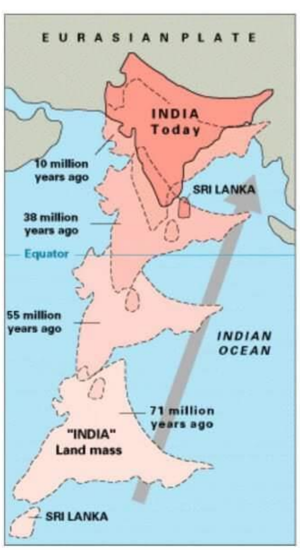


- Seafloor spreading further opened the central North Atlantic and Indian oceans.
- At the end of the period, a new rift split South America from Africa.

- Madagascar drifted away from Africa, which continued its move north.
- The northward drift of India continued, and Australia split from Antarctica.
- Zealandia, a microcontinent nearly half the size of Australia, broke away from the Gondwanan supercontinent about 83 million years ago.

Cretaceous 65 mya





Tertiary is the former term for the geologic period from 66 million to 2.58million years ago. The term is now obsolete.

Continental Drift Theory (CDT)

- Continental drift refers to the movement of the continents relative to each other.

Polar wandering (similar to Continental Drift Theory)

- Polar wandering is the relative movement of the earth's crust and upper mantle with respect to the rotational poles of the earth.

Seafloor Spreading Theory (SFST)

- Seafloor spreading describes the movement of oceanic plates relative to one another.

Plate Tectonics (PT)

- Plate tectonics is the movement of lithospheric plates relative to each other.

Convection Current Theory (CCT)

- Convection current theory forms the basis of SFST and PT. It explains the force behind plate movements.

4.2 Continental Drift Theory (Alfred Wegener, 1922)

- Alfred Wegener suggested continental Drift Theory in the 1920's.
- According to Continental Drift Theory there existed one big landmass which he called **Pangaea** which was covered by one big ocean called **Panthalassa**.
- A sea called **Tethys** divided the Pangaea into two huge landmasses: **Laurentia (Laurasia)** to the north and **Gondwanaland** to the south of Tethys.
- Drift started around 200 million years ago (Mesozoic Era, Triassic Period, Late Triassic Epoch), and the continents began to break up and drift away from one another.

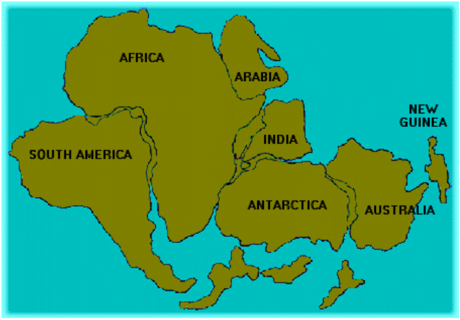
Forces behind the drifting of continents, according to Wegener

- According to Wegener, the drift was in two directions:
  - equator wards due to the interaction of forces of gravity, pole-fleeing force (due to centrifugal force caused by earth's rotation) and buoyancy (*ship floats in water due to buoyant force offered by water*), and
  - westwards due to tidal currents because of the earth's motion (earth rotates from west to east, so tidal currents act from east to west, according to Wegener).
  - Wegener suggested that tidal force (gravitational pull of the moon and to a lesser extent, the sun) also played a major role.
- The polar-fleeing force relates to the rotation of the earth. Earth is not a perfect sphere; it has a bulge at the equator. This bulge is due to the rotation of the earth (greater centrifugal force at the equator).
- Centrifugal force increases as we move from poles towards the equator. This increase in centrifugal force has led to pole fleeing, according to Wegener.
- Tidal force is due to the attraction of the moon and the sun that develops tides in oceanic waters (tides explained in detail in oceanography).
- According to Wegener, these forces would become effective when applied over many million years, and the drift is continuing.

Evidence in support of Continental Drift

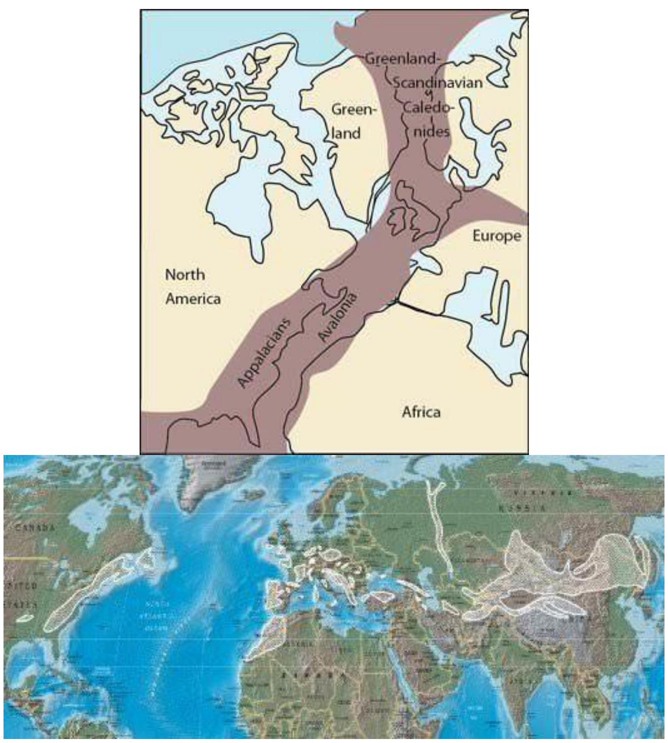
Evidence for CDT

Apparent Affinity of Physical Features



Apparent Affinity of Physical Features

- The bulge of Brazil (South America) seems to fit into the Gulf of Guinea (Africa).
- Greenland seems to fit in well with Ellesmere and Baffin islands of Canada.
- The west coast of India, Madagascar and Africa seem to have been joined.
- North and South America on one side and Africa and Europe on the other fit along the mid-Atlantic ridge.
- The Caledonian and Hercynian mountains of Europe and the Appalachians of USA seem to be one continuous series.



Continuous Very Old Fold Mountain Chain

Criticism

- Coastlines are a temporary feature and are liable to change.
- Several other combinations of fitting in of unrelated landforms could be attempted.

- Continental Drift Theory shifts India's position too much to the south, distorting its relationship with the Mediterranean Sea and the Alps.
- The mountains do not always exhibit geological affinity.

Causes of Drift

- The gravity of the earth, the buoyancy of the seas and the tidal currents were given as the main factors causing the drift, by Wegener.

Criticism

- This is illogical because for these factors to be able to cause a drift of such a magnitude, they will have to be millions of times stronger.

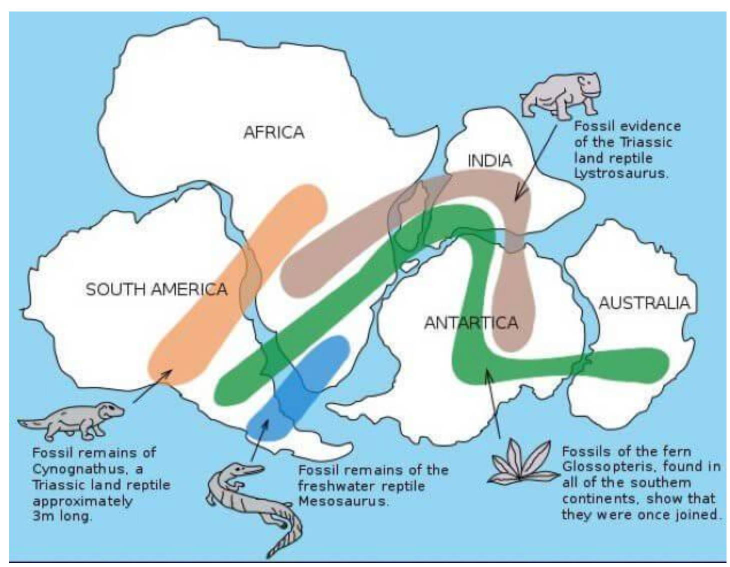
Polar wandering (Shifting of Poles)

- The position of the poles constantly drifted (due to plate tectonics).

Criticism

- Poles may have shifted, not necessarily the continents.

Botanical Evidence



Distribution of Fossils across the Gondwanaland

- Presence of glossopteris vegetation in Carboniferous rocks of India, Australia, South Africa, Falkland Islands (Overseas territory of UK), Antarctica, etc. (all split from the same landmass called Gondwana) can be explained from the fact that parts were linked in the past.

Criticism

- Similar vegetation is found in unrelated parts of the world like Afghanistan, Iran and Siberia.

Distribution of Fossils

- The observations that Lemurs occur in India, Madagascar and Africa led some to consider a contiguous landmass "Lemuria" linking these three landmasses.
- Mesosaurus was a small reptile adapted to shallow brackish water. The skeletons of these are found only in South Africa and Brazil. The two localities presently are 4,800 km apart with an ocean in between them.

Rocks of Same Age Across the Oceans

- The belt of ancient rocks of 2,000 million years from Brazil coast matches with those from western Africa.

Criticism

- Rocks of the same age and similar characteristics are found in other parts of the world too.

Tillite deposits

- **Tillite deposits** are **sedimentary rocks formed out of deposits of glaciers**.
- The Gondwana system of sediments are found in India, Africa, Falkland Island, Madagascar, Antarctica and Australia (all were previously part of Gondwana).
- Overall resemblance demonstrates that these landmasses had remarkably similar histories.

Placer Deposits

- Rich **placer deposits of gold** are found on the Ghana coast (West Africa) but the source (gold-bearing veins) are in Brazil, and it is obvious that the gold deposits of Ghana are derived from the Brazil plateau when the two continents lay side by side.

Drawbacks of Continental Drift Theory

- Wegener failed to explain why the drift began only in Mesozoic era and not before.
- The theory doesn't consider oceans.
- Proofs heavily depend on assumptions that are generalistic.
- Forces like buoyancy, tidal currents and gravity are too weak to be able to move continents.
- Modern theories (Plate Tectonics) accept the existence of Pangaea and related landmasses but give a very different explanation to the causes of drift.

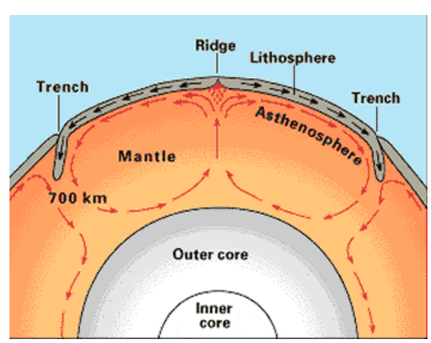
Though scientifically unsound on various grounds, Wegener's theory is a significant milestone in the study of tectonics, and it laid a strong foundation for future the theories like seafloor spreading and plate tectonics.

4.3 Seafloor Spreading

- To understand the concept of Seafloor Spreading, we must first understand some basic concepts that form the cornerstones for the concept of Seafloor Spreading.
- These cornerstones are **Convectional Current Theory** and **Paleomagnetism**.

Convection Current Theory

- Convection Current Theory is the soul of Seafloor Spreading Theory.
- **Arthur Holmes** in 1930s discussed the possibility of **convection currents in the mantle**.
- These currents are generated due to **radioactive elements causing thermal differences** in the mantle.



Convection currents in the mantle

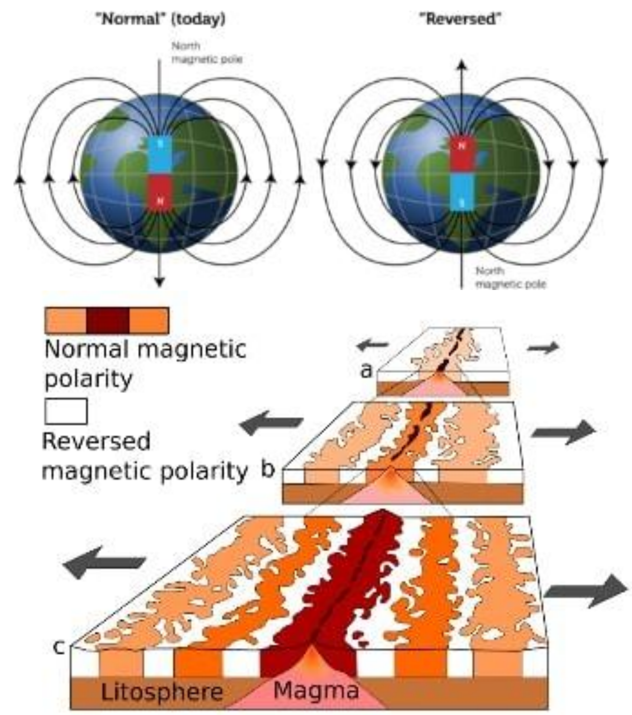
- According to this theory, the intense heat generated by radioactive substances in the mantle (100-2900 km below the earth surface) seeks a path to escape and gives rise to the formation of convection currents in the mantle.
- Wherever **rising limbs of these currents meet, oceanic ridges are formed** on the seafloor due to the **divergence** of the lithospheric plates (tectonic plates), and wherever the **failing limbs meet, trenches are formed** due to the **convergence** of the lithospheric plates (tectonic plates).
- **The movement of the lithospheric plates is caused by the movement of the magma in the mantle**.

Paleomagnetism

- Paleomagnetism is the study of the **record of earth's magnetic field** with the help of **magnetic fields recorded in rocks, sediment**, or archaeological materials.
- Rocks formed from underwater volcanic activity are mainly **basaltic** (low silica, iron-rich) that makes up most of the ocean floor.
- Basalt contains magnetic minerals, and as the rock is solidifying, these minerals **align themselves in the direction of the magnetic field.**
- This locks in a record of which way the magnetic field was positioned at the time.
- Paleomagnetic studies of rocks have demonstrated that the orientation of the earth's magnetic field has **frequently alternated (geomagnetic reversal)** over geologic time.
- The polarity of the Earth's magnetic field and magnetic field reversals are thus detectable by studying the rocks of different ages.

Paleomagnetism: Strong evidence of Seafloor Spreading and Plate Tectonics

- **Paleomagnetism** led the revival of the continental drift hypothesis and its transformation into theories of Sea Floor Spreading and Plate Tectonics.
- The regions that hold the unique record of earth's magnetic field lie along the **mid-ocean ridges** where the sea floor is spreading.
- On studying the **paleomagnetic rocks** on either side of the oceanic ridges, it is found that **alternate magnetic rock stripes were flipped** so that one stripe would be of normal polarity and the next, reversed.
- Hence, paleomagnetic rocks (paleo: denoting rocks) on either side of the mid-ocean or submarine ridges provide the **most important evidence to the concept of Sea Floor Spreading**.
- Magnetic field records also provide information on the **past location of tectonic plates**.



The alternating pattern of magnetic striping on the seafloor

Explanation

- These oceanic ridges are boundaries where tectonic plates are **diverging** (moving apart).
- The fissure or vent (in between the ridge) between the plates allowed the magma to rise and harden into a long narrow band of rock on either side of the vent.
- Rising magma **assumes the polarity of Earth's geomagnetic field at the time** before it solidifies on the oceanic crust.
- As the conventional currents pull the oceanic plates apart, the solidified band of rock moves away from the vent (or ridge), and a new band

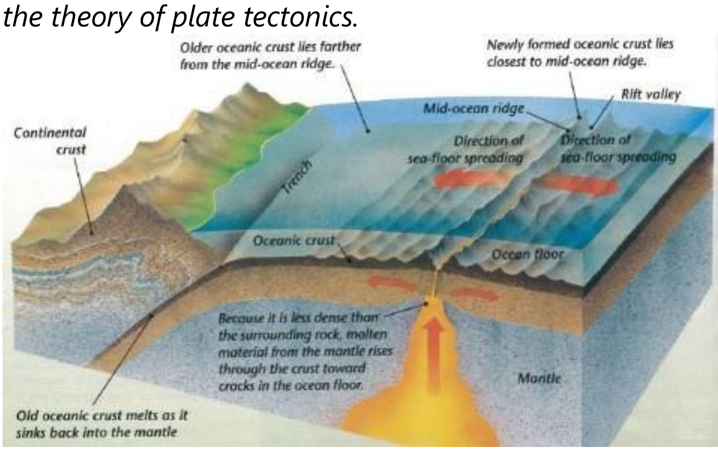
of rock takes its place a few million years later when the magnetic field was reversed. This results in this **magnetic striping** where the **adjacent rock bands have opposite polarities**.

- This process repeats over and over giving rise to a series of narrow parallel rock bands on either side of the ridge and **alternating pattern of magnetic striping on the seafloor.**

The concept of Sea Floor Spreading

- Harry Hess proposed the idea of See Floor Spreading**.**
- When oceanic plates diverge, tensional stress causes fractures to occur in the lithosphere.
- **Basaltic magma** rises from the fractures and cools on the ocean floor to form **new seafloor**.
- The newly formed seafloor (oceanic crust) then **gradually moves away** from the ridge, and its place is taken by an even newer seafloor and the cycle repeats.
- With time, **older rocks are spread farther away from the spreading zone** while **younger rocks will be found nearer to the spreading zone**.

Seafloor spreading helps explain continental drift in the theory of plate tectonics.



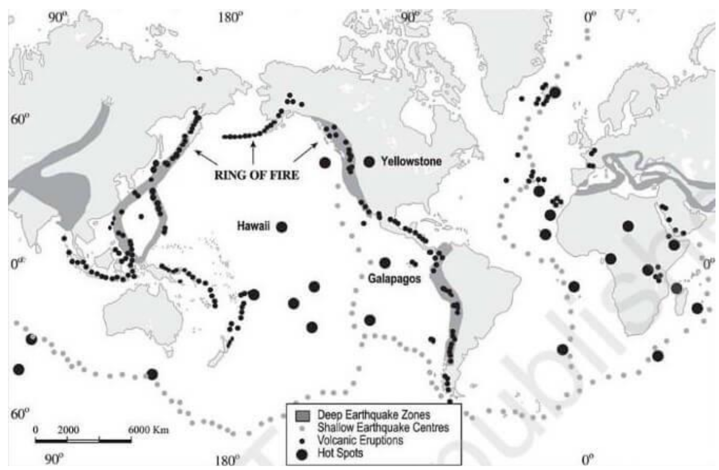
Seafloor Spreading

Evidence for Seafloor Spreading

Nature of oceanic rocks around mid-ocean ridges

- Rocks on either side of the crest of oceanic ridges having equidistant locations from the crest were found to have similarities both in terms of their constituents, their age and magnetic orientation.
- Rocks closer to the mid-oceanic ridges have normal polarity and are the youngest and the age of the rocks increases as one moves away from the crest (ridge).
- The **rocks of the oceanic crust near the oceanic ridges are much younger than the rocks of the continental crust**.

Distribution of Earthquakes and Volcanoes along the mid-ocean ridges

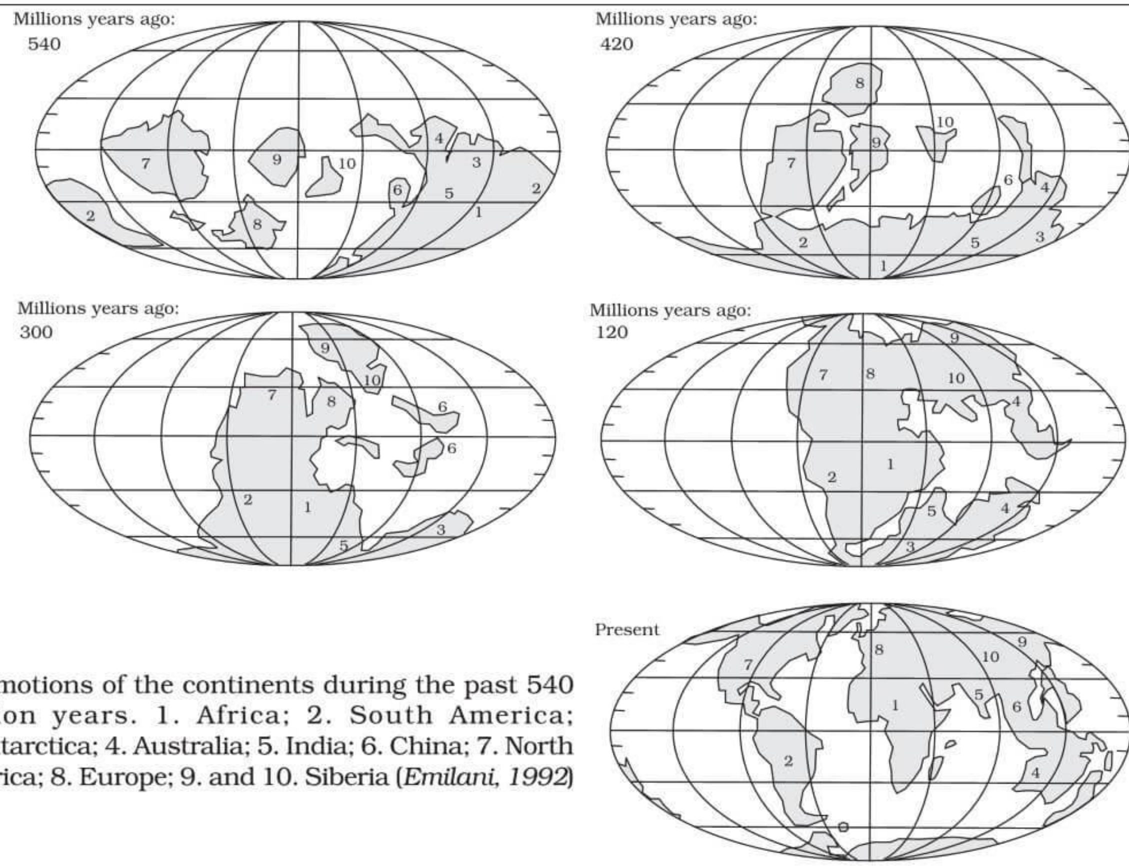


- The normal temperature gradient on the sea floor is 9.4° C/300 m, but near the ridges it becomes higher, indicating an upwelling of magmatic material from the mantle.
- Dots in the central parts of the Atlantic Ocean and other oceans are almost parallel to the coastlines. This indicates that the seafloor has widened with time.
- In general, the foci of the earthquake in the areas of mid-oceanic ridges are at shallow depths whereas, along the Alpine-Himalayan belt as well as the rim of the Pacific, the earthquakes are deep-seated ones.

4.4 Plate Tectonics

- It was from the continental drift theory, convection current theory and the theory of seafloor spreading, the theory of **Plate Tectonics** was formulated.
- In 1967, **McKenzie and Parker** suggested the theory of plate tectonics. Morgan later outlined the theory in 1968.

- According to the theory of plate tectonics, the **earth's lithosphere is broken into distinct plates** which are floating on a **ductile layer called asthenosphere** (upper part of the mantle).
- Plates move horizontally over the **asthenosphere** as rigid units.
- The lithosphere includes the **crust** and **top mantle** with its thickness range varying between **5-100 km in oceanic parts and about 200 km in the continental areas**.
- The oceanic plates contain mainly the **Simatic crust** and are relatively thinner, while the continental plates contain **Sialic material** and are relatively thicker.
- Lithospheric plates (**tectonic plates**) vary from **minor plates** to **major plates**, **continental plates** (Arabian plate) to **oceanic plates** (Pacific plate), sometimes a **combination** of both continental and oceanic plates (Indo-Australian plate).
- The movement of these crustal plates (due to convection currents in the mantle) causes the formation of various landforms and is the principal cause of all earth movements.



The motions of the continents during the past 540 million years. 1. Africa; 2. South America; 3. Antarctica; 4. Australia; 5. India; 6. China; 7. North America; 8. Europe; 9. and 10. Siberia (*Emilani, 1992*)

The position of the continents through geologic past

Force for plate movement

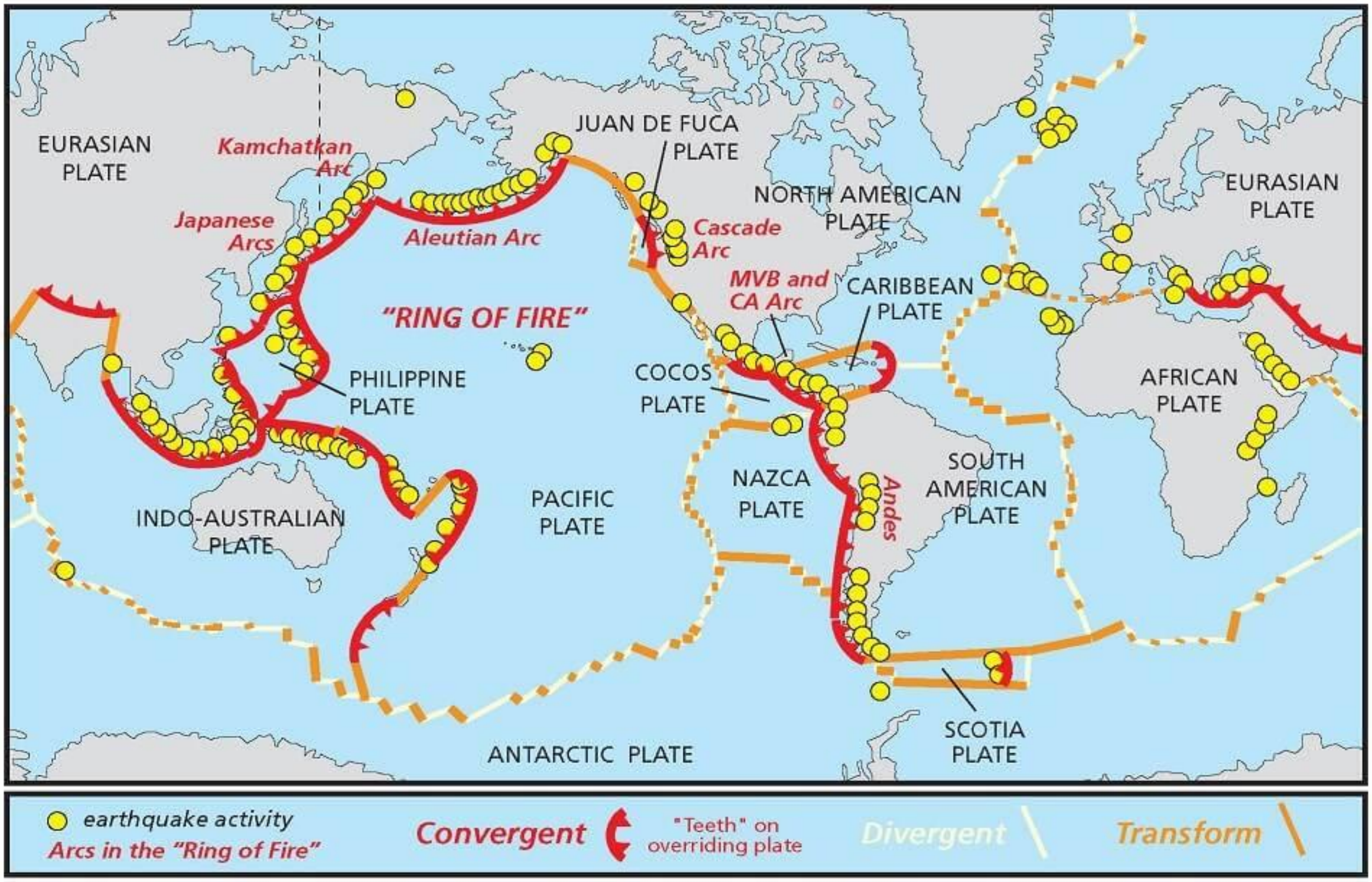
- Convection currents in the mantle that are generated due to thermal gradients.

Rates of Plate Movement

- The Arctic Ridge has the slowest rate (less than 2.5 cm/year), and the East Pacific Rise in the South Pacific (about 3,400 km west of Chile), has the fastest rate (more than 15 cm/year).

Major tectonic plates

1. Antarctica and the surrounding oceanic plate
2. North American plate
3. South American plate
4. Pacific plate
5. India-Australia-New Zealand plate
6. Africa with the eastern Atlantic floor plate
7. Eurasia and the adjacent oceanic plate



Divergent, Convergent and Transform Boundaries ([nps.gov](https://www.nps.gov) R.J. Lillie. 2005. Parks and Plates)

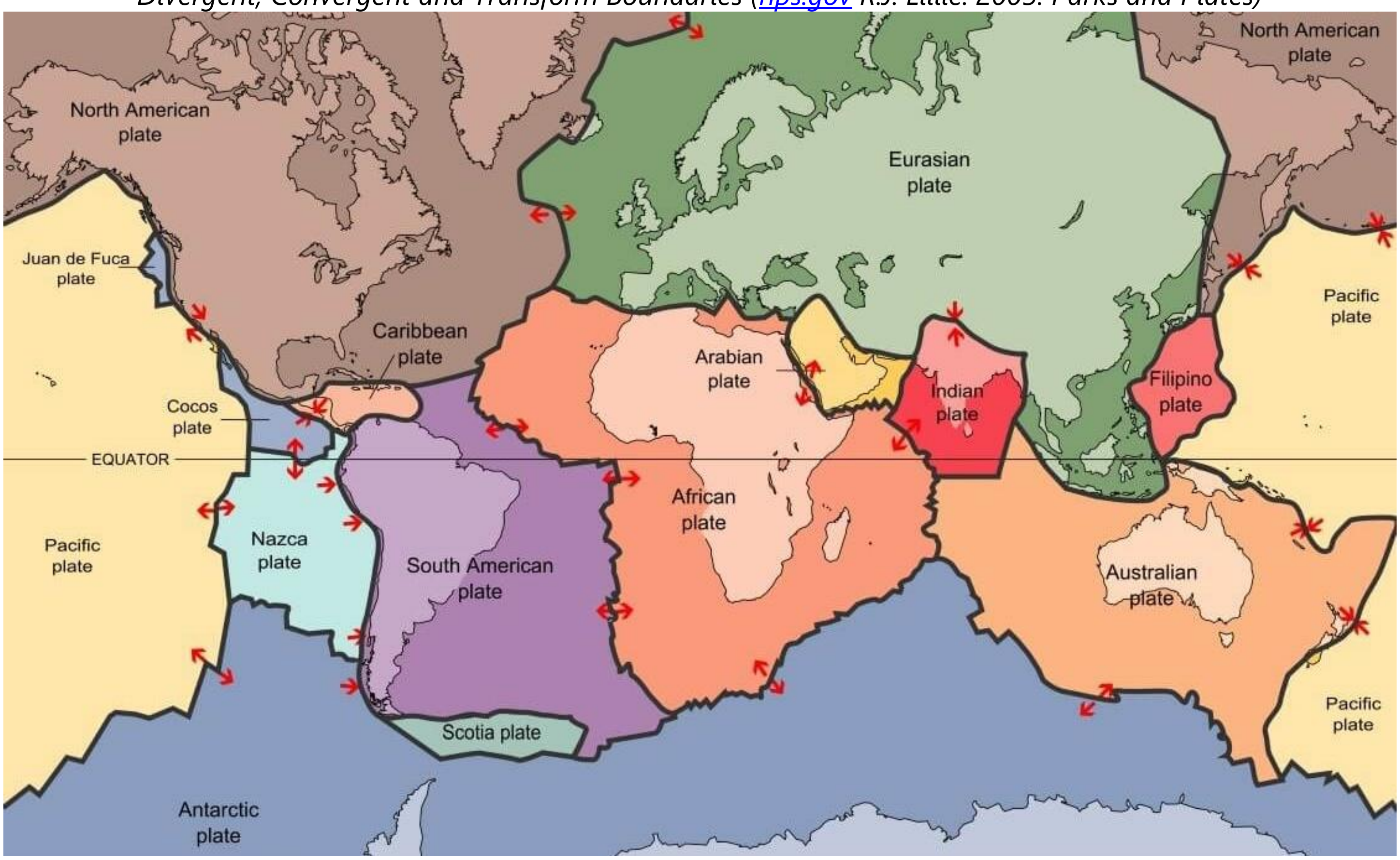


Plate Boundaries

Minor tectonic plates

1. Cocos plate: Between Central America and Pacific plate
2. Nazca plate: Between South America and Pacific plate
3. Arabian plate: Mostly the Saudi Arabian landmass
4. Philippine plate: Between the Asiatic and Pacific plate
5. Caroline plate: Between the Philippine and Indian plate (North of New Guinea)
6. Fuji plate: North-east of Australia
7. Turkish plate
8. Aegean plate (Mediterranean region)
9. Caribbean plate
10. Juan de Fuca plate (between Pacific and North American plates)
11. Iranian plate.

- There are many more minor plates other than the ones mentioned above.
- Most of these minor plates were formed due to **stress created by converging major plates**.
- Example: the Mediterranean Sea is divided into numerous minor plates due to the compressive force exerted by Eurasian and African plates.

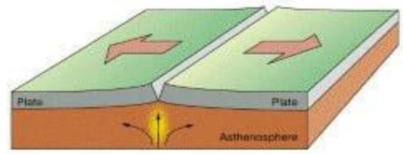
The figure below shows the changes in landform with time due to the interaction of various plates.

Interaction of Plates

- Major geomorphological features such as fold and block mountains, mid-oceanic ridges, trenches, volcanism, earthquakes etc. are a direct consequence of the interaction between various lithospheric plates.
- There are three ways in which the plates interact with each other.

Divergence forming Divergent Edge or the Constructive Edge

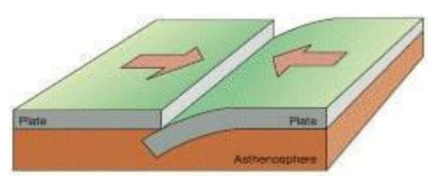
- In this kind of interaction, the plates diverge (**move away** from each other).
- **Mid-ocean ridges** (e.g. Mid-Atlantic Ridge) are formed due to this kind of interaction.
- Here, the basaltic magma erupts and moves apart (seafloor spreading).
- On continents, **East African Rift Valley** is the most important geomorphological feature formed due to the divergence of **African and Somali plates**.
- Divergent edges are sites of earth **crust formation** (hence the name **constructive edge**), and volcanic earth forms are common along such edges.
- Earthquakes (shallow focus) are common along divergent edges.



Divergent Boundary

Convergence forming Convergent Edge or Destructive Edge

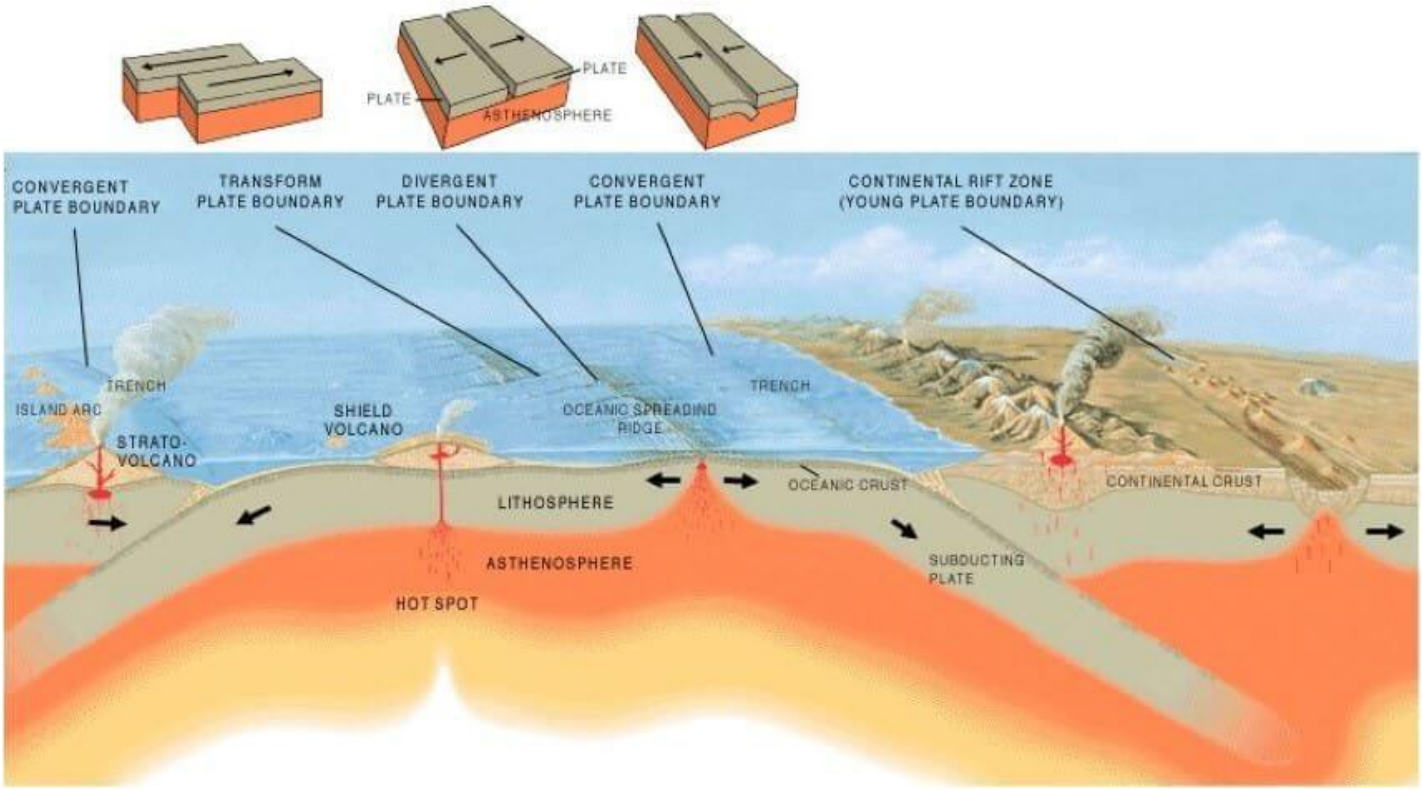
- In this kind of interaction, two lithospheric plates **collide** against each other.
- The zone of collision may undergo crumpling and folding, and folded mountains may emerge (**orogenic collision**). **Himalayan Boundary Fault** is one such example.
- When one of the plates is an oceanic plate, it gets embedded in the **softer asthenosphere** of the continental plate, and as a result, **trenches** are formed at the **zone of subduction.**
- Near the convergent edge a part of the crust is destroyed, hence the name **Destructive Edge**.
- The subducted material gets heated, up and is thrown out forming **volcanic island arc and continental arc systems** and a dynamic equilibrium is achieved.



Convergent Boundary

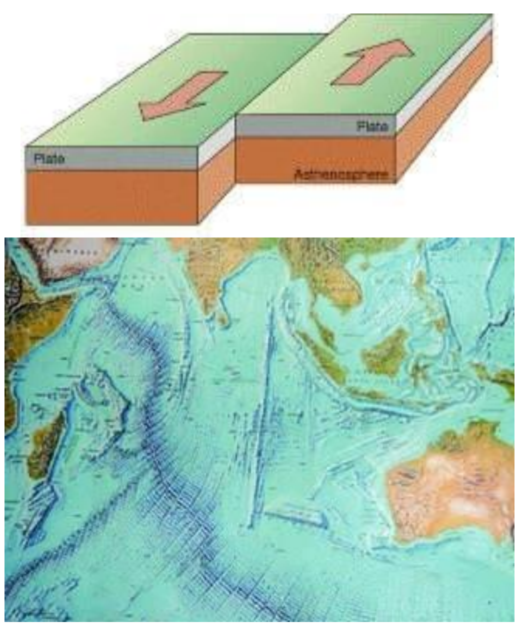
Transcurrent Edge or Conservative Edge or Transform Edge

- In this kind of interaction, two plates slide past against each other, and there is **no creation or destruction of landform** but **only deformation** of the existing landform.



Types of Plate Boundaries (Jose F. Vigil. USGS, via [Wikimedia Commons](https://commons.wikimedia.org))

- In oceans, **transform faults** are the planes of separation generally perpendicular to the mid-oceanic ridges.
- **San Andreas Fault** (Silicon Valley lies dangerously close to the faultline) along the western coast of USA is the best example for a transcurrent edge on continents.



Transform Edge

Evidence in Support of Plate Tectonics

- Evidence for both See Floor Spreading and Plate tectonics are **complimentary** (almost same evidences).

Paleomagnetism

- **Paleomagnetic rocks** are the most important evidence. The orientation of iron grains on older rocks shows an orientation which points to the existence of the South Pole, once upon a time, somewhere between present-day Africa and Antarctica (polar wandering).

Older rocks form the continents while younger rocks are present on the ocean floor

- On continents, rocks of up to 3.5 billion years old can be found while the oldest rock found on the ocean floor is not more than 75 million years old (western part of Pacific floor).
- As we move, towards ridges, still younger rocks appear. This points to an effective spread of seafloor (See floor spreading is almost similar to plate tectonics except that it examines the interaction between oceanic plates only) along oceanic ridges which are also the plate margins.

Gravitational anomalies

- In trenches, where subduction has taken place (convergent edge), the value of gravitational constant 'g' is less. This indicates a loss of material.
- For instance, gravity measurements around the Indonesian islands have indicated that large gravity anomalies are associated with the oceanic trench bordering Indonesia.

Earthquakes and Volcanoes

- The fact that all plate boundary regions are areas of earthquake and volcanic disturbances goes to prove the theory of plate tectonics.

The significance of Plate Tectonics

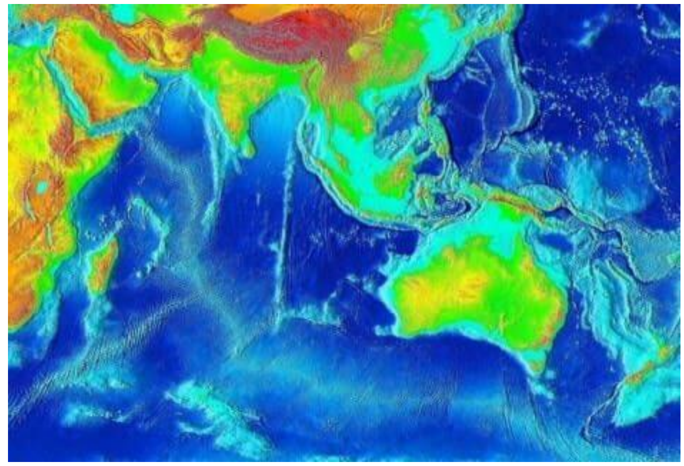
- Almost all major landforms formed are due to plate tectonics.
- New minerals are thrown up from the core with the magmatic eruptions.
- Economically valuable minerals like copper and uranium are found near the plate boundaries.
- From present knowledge of crustal plate movement, the shape of landmasses in future can be predicted.
- For instance, if the present trends continue, North and South America will separate. A piece of land will separate from the east coast of Africa. Australia will move closer to Asia.

Movement of The Indian Plate

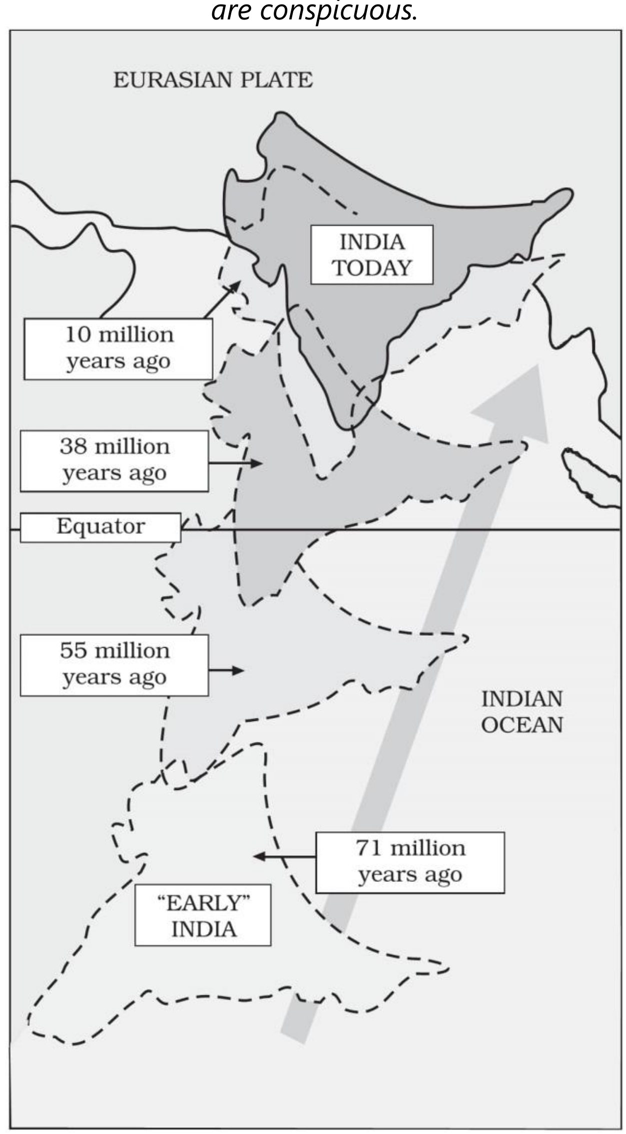
- The Indian plate includes Peninsular India and the Australian continental portions.

Indian Plate Boundaries

- The subduction zone along the **Himalayas** forms the northern plate boundary in the form of continent-continent convergence.
- In the east, it extends through Rakinyoma Mountains (Arakan Yoma) of Myanmar towards the island arc along the Java Trench.
- The eastern margin is a spreading site lying to the east of Australia in the form of an oceanic ridge in SW Pacific.
- The Western margin follows **Kirthar Mountain** of Pakistan. It further extends along the **Makrana coast** (Pakistan and Iranian coasts) and joins the spreading site from the **Red Sea rift (Red Sea rift is formed due to the divergence of Somali plate and Arabian plate)** south-eastward along the **Chagos Archipelago (Formed due to hotspot volcanism)**.



Topography of Indo-Australian Plate. The boundaries are conspicuous.



- The boundary between India and the Antarctic plate is also marked by an oceanic ridge (divergent boundary) running in roughly W-E direction and merging into the spreading site, a little south of New Zealand.

Movement

- India was a large island situated off the Australian coast. The **Tethys Sea** separated it from the Asian continent till about 225 million years ago.
- India is supposed to have started her northward journey about 200 million years (**Pangaea** broke).
- About 140 million years ago, the subcontinent was located as south as 50° S latitude.
- The Tethys Sea separated the Indian plate and the Eurasian plate.
- The Tibetan block was a part of the Asiatic landmass.
- India collided with Asia about **40-50 million years ago** causing rapid uplift of the Himalayas (the Indian plate and the Eurasian plate were close to the equator back then).
- It's thought that India's coastline was denser and more firmly attached to the seabed, which is why Asia's softer soil was pushed up rather than the other way around.
- The process is continuing, and the **height of the Himalayas is rising** even to this date.
- The northward movement of the Indian tectonic plate pushing slowly against the Asiatic plate is evident by the **frequent earthquakes** in the region.
- During the movement of the Indian plate towards the Asiatic plate, a major event that occurred was the outpouring of lava and formation of the **Deccan Traps (shield volcano)**.
- The shield volcanism started somewhere around **60 million years ago** and continued for a long period.

4.5 Comparison: Continental Drift – See Floor Spreading – Plate Tectonics

	Continental Drift	**See Floor Spreading**	**Plate Tectonics**
Explained by	Put forward by **Alfred Wegener** in 1920s	**Arthur Holmes** explained Convectional Current Theory in the 1930s. Based on convection current theory, **Harry Hess** explained See Floor Spreading in the 1940s	In 1967, McKenzie and Parker suggested the theory of plate tectonics. Morgan later outlined the theory in 1968
Theory	Explains the Movement of Continents only	Explains the Movement of Oceanic Plates only	Explains the Movement of Lithospheric plates that include both continents and oceans.
Forces for movement	Buoyancy, gravity, pole-fleeing force, tidal currents, tides,	Convection currents in the mantle drag crustal plates	Convection currents in the mantle drag crustal plates
Evidence	Apparent affinity of physical features, botanical evidence, fossil evidence, Tillite deposits, placer deposits, rocks of same age across different continents etc.	Ocean bottom relief, Paleomagnetic rocks, distribution of earthquakes and volcanoes etc.	Ocean bottom relief, Paleomagnetic rocks, distribution of earthquakes and volcanoes, gravitational anomalies at trenches, etc.
Drawbacks	Too general with silly and sometimes illogical evidence.	Doesn't explain the movement of continental plates	---------------------
Acceptance	Discarded	Not complete	Most widely accepted
Usefulness	Helped in the evolution of	Helped in the evolution of	Helped us understand various

	convection current theory and seafloor spreading theory	plate tectonics theory	geographical features.

Multiple choice questions

1. Polar fleeing force relates to:
   a) Revolution of the Earth
   b) Rotation of the earth
   c) Gravitation
   d) Tides
2. Which one of the following is not a minor plate?
   a) Nazca
   b) Philippines
   c) Arabia
   d) Antarctica
3. Which one of the following facts was not considered by those while discussing the concept of sea floor spreading?
   a) Volcanic activity along the mid-oceanic ridges.
   b) Stripes of normal and reverse magnetic field observed in rocks of ocean floor.
   c) Distribution of fossils in different continents.
   d) Age of rocks from the ocean floor.
4. Which one of the following is the type of plate boundary of the Indian plate along the Himalayan mountains?
   a) Ocean-continent convergence
   b) Divergent boundary
   c) Transform boundary
   d) Continent-continent convergence

Answers: 1: b); 2: d); 3: c) & 4: d)

Answer in about 30 words.

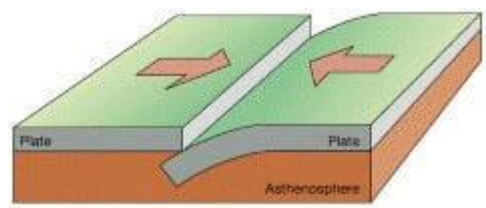
1. What were the forces suggested by Wegener for the movement of the continents?
2. How are the convectional currents in the mantle initiated and maintained?
3. What is the major difference between the transform boundary and the convergent or divergent boundaries of plates?
4. What was the location of the Indian landmass during the formation of the Deccan Traps?

Answer in about 150 words

1. What are the evidences in support of the continental drift theory?
2. Bring about the basic difference between the drift theory and Plate tectonics.
3. What were the major post-drift discoveries that rejuvenated the interest of scientists in the study of distribution of oceans and continents?

5. Convergent Boundary

- Along a convergent boundary two lithospheric plates **collide** against each other.
- When one of the plates is an oceanic plate, it gets embedded in the **softer asthenosphere** of the continental plate, and as a result, **trenches** are formed at the **zone of subduction.**



Convergent Boundary

In convergence there are subtypes namely:

1. **Collision of oceanic plates or ocean-ocean convergence** (formation of **volcanic island arcs**).
2. **Collision of continental and oceanic plates or ocean-continent convergence** (formation of **continental arcs and fold mountains**).
3. **Collision of continental plates or continent-continent convergence** (formation of **fold mountains**)
4. **Collision of continent and arc, or continent-arc convergence.**

The above concepts are explained in the next chapters.

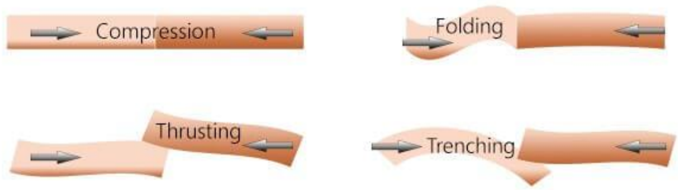
5.1 Ocean-Ocean Convergence or The Island-Arc Convergence

- The concept of Ocean-Ocean Convergence helps us understand the **formation of Japa-**

nese Island Arc, Indonesian Archipelago, Philippine Island Arc and Caribbean Islands.

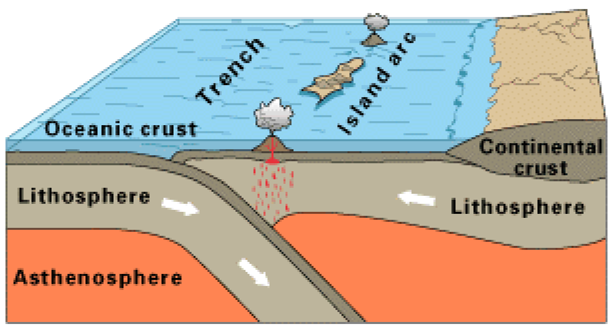
- **Archipelago:** an extensive group of islands.
- **Island arc:** narrow chain of islands which are volcanic in origin. An island arc is usually curved.

Basics



*In all types of convergence, the **denser plate subducts,** and the less dense plate is either **up thrust or folded or both** (upthrust and folded).*

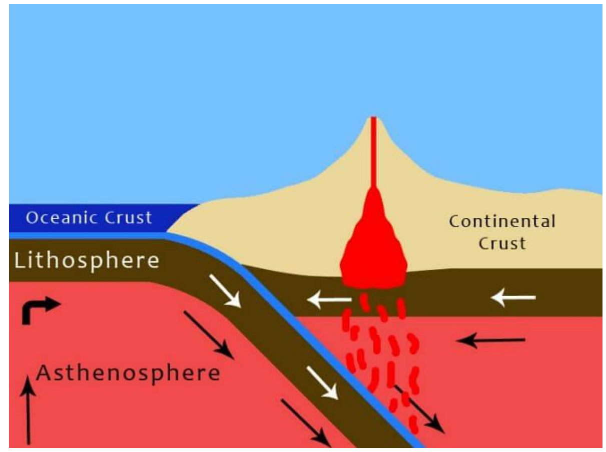
- In Ocean-Ocean Convergence, a **denser oceanic plate** subducts below a **less dense oceanic plate** forming a **trench** along the boundary.



Oceanic-oceanic convergence

Ocean – Ocean Convergence (via [Wikimedia Commons](#))

- As the ocean floor crust (oceanic plate) loaded with sediments **subducts** into the softer **asthenosphere**, the rocks in the subduction zone become **metamorphosed (alteration of the composition or structure of a rock)** under high pressure and temperature.
- After reaching a depth of about 100 km, the plates melt. Magma (**metamorphosed sediments and the melted part of the subducting plate**) has lower density and is at high pressure.
- It rises upwards due to the **buoyant force** offered by surrounding denser medium.
- The magma flows out to the surface. A continuous upward movement of magma creates constant volcanic eruptions at the ocean floor.



Subduction Zone Illustration (Eround1, via [Wikimedia Commons](#))

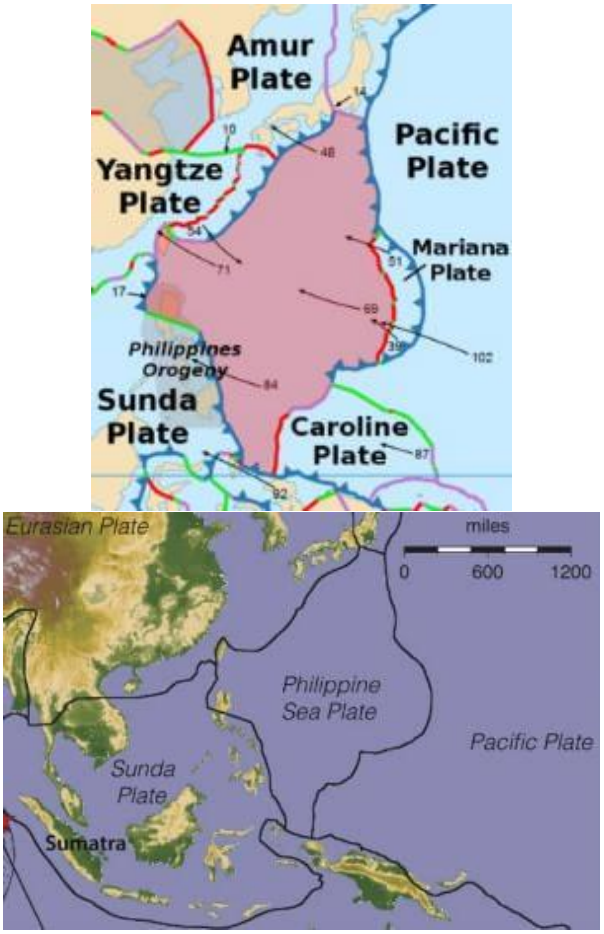
- Constant volcanism above the subduction zone creates layers of rocks. As this process continues for millions of years, a volcanic landform is created which in some cases rises above the ocean waters.
- Such volcanic landforms all along the boundary form a **chain of volcanic islands** which are collectively called as **Island Arcs** (Indonesian Island Arc or Indonesian Archipelago, Philippine Island Arc, Japanese Island Arc etc.).
- Orogenesis (mountain building) sets in motion the process of **building continental crust by replacing the oceanic crust** (this happens at a much later stage. For example, new islands are born around Japan in every few years. After some million years, Japan will be a single landmass because continental crust formation is constantly replacing the oceanic crust).

This explanation is common for all the island arc formations (ocean-ocean convergence). We only need to know the plates involved with respect to each island formation.

Formation of the Philippine Island Arc System

- Philippine Island Arc system is formed due to subduction of **Philippine Sea plate** under the **Sunda Plate** (major continental shelf of the **Eurasian plate**). The trench formed here is called **Philippine Trench**.
- **Sunda Shelf:** The extreme south-eastern portion of the Eurasian plate, which is a part of Southeast Asia, is a **continental shelf**. The re-

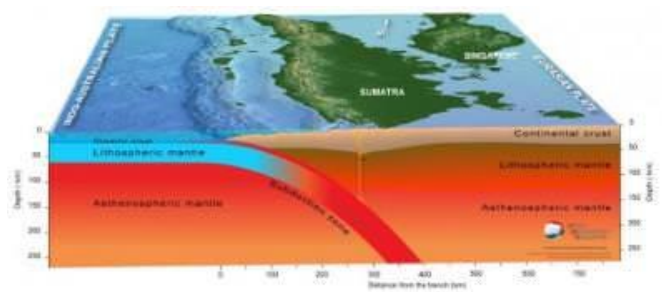
gion is called the **Sunda Shelf**. The Sunda Shelf and its islands is known as the **Sundaland block of the Eurasian plate**.



Minor plates in the Southeast Asia

Formation of the Indonesian Archipelago

- In the case of Indonesian Archipelago, the **Indo-Australian plate** is subducting below **Sunda Plate (part of Eurasian Plate)**. The trench formed here is called **Sunda trench** (**Java Trench** is a major section of Sunda trench).



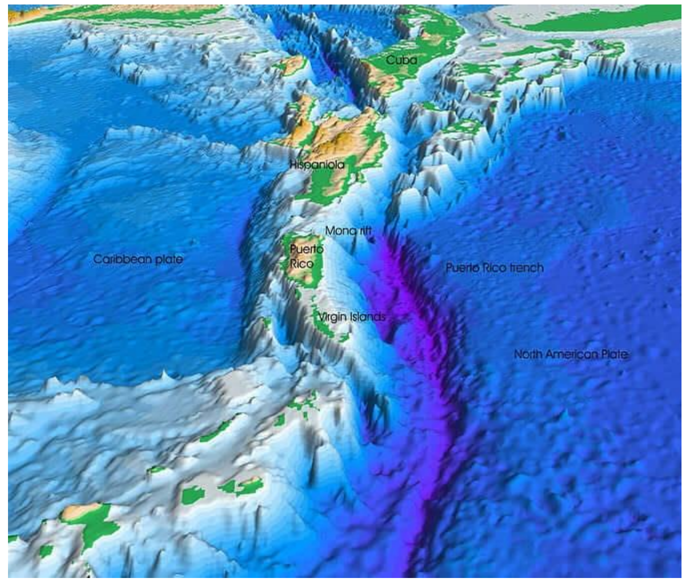
- **Anak Krakatau (child of Krakatau)** volcano lies close to the Java Trench. It is situated in the **Sunda Strait** between the Indonesians Islands of **Java** and **Sumatra**.
- Underwater land shifting on the Anak Krakatau volcano in December 2018 triggered a Tsunami that killed more than 400 people.

Anak Krakatau volcano situated between the Indonesians Islands of Java and Sumatra (Google Maps)

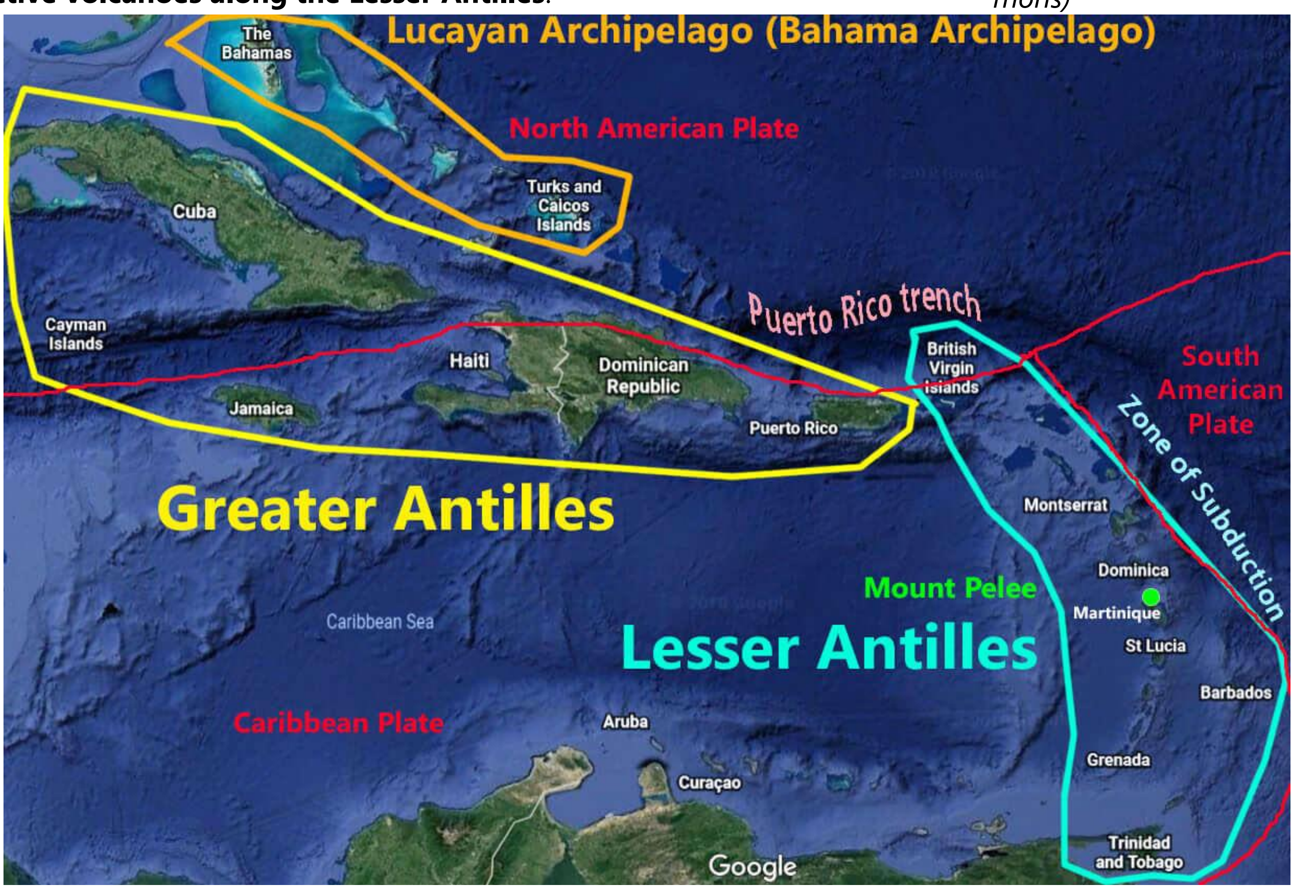
Formation of the Caribbean Islands

- The Caribbean Plate is a mostly oceanic tectonic plate. The northern boundary with the North American plate is a **transform or strike-slip boundary** (more about this in the subsequent chapters).
- The Caribbean Plate is moving to the east while the North American Plate is moving to the west.
- The **Puerto Rico Trench** is located at a boundary between the two plates that pass each other along a **transform boundary with only a small component of subduction**.
- The boundary between the two plates in the past has been convergent, and most of the **Greater Antilles** group of islands are formed due to the complex interaction between the two plates.
- The eastern boundary of the Caribbean Plate is a subduction zone, the **Lesser Antilles subduction zone**, where oceanic crust of the South American Plate is being subducted under the Caribbean Plate.
- This subduction zone explains the presence of **active volcanoes along the Lesser Antilles**.

- **Mount Pelée** is an active volcano at the northern end of Martinique Island (French overseas department) in the Lesser Antilles island arc of the Caribbean.
- The volcano is famous for its eruption in 1902. The eruption killed about 30,000 people. Most deaths were caused by pyroclastic flows which destroyed the city of Saint-Pierre.



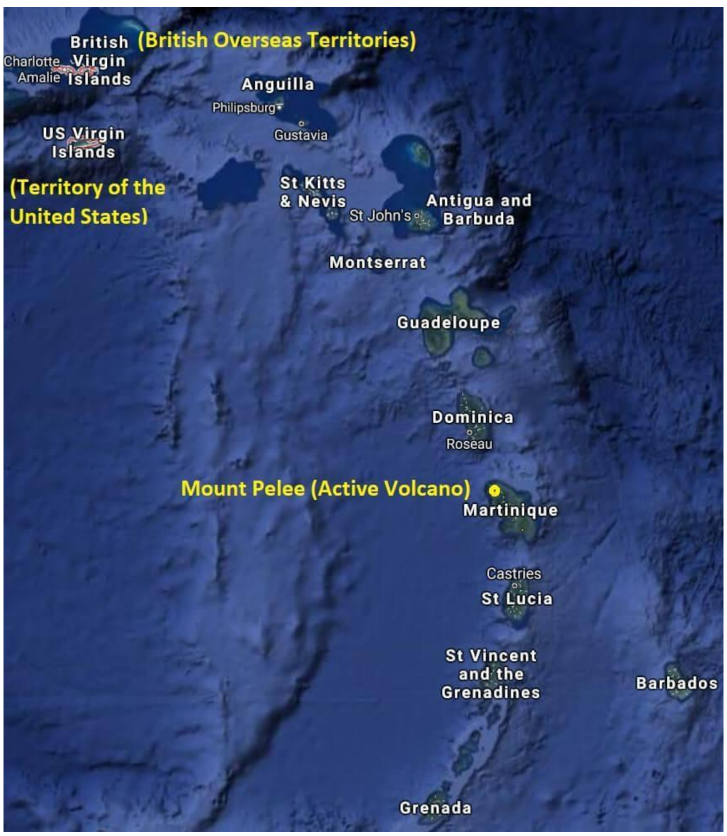
3D view of the Caribbean Islands (Wikipedia Commons)



The Greater Antilles and Lesser Antilles Island Arcs (Map from Google Earth)

The island groups in the Caribbean Sea

- The Greater Antilles is a grouping of the **larger islands** in the Caribbean Sea: Cuba, Hispaniola (containing Haiti and the Dominican Republic), Puerto Rico, Jamaica, and the Cayman Islands.
- Together, the **Lesser Antilles** and the **Greater Antilles** compose the Antilles (or the **Caribbean islands**).
- When combined with the **Lucayan Archipelago (Bahama Archipelago)**, all three are known as the **West Indies**.
- Lucayan Archipelago is an island group comprising the Commonwealth of The Bahamas and the British Overseas Territory of the Turks and Caicos Islands.



Islands in the Lesser Antilles Island Arcs (Map from Google Earth)

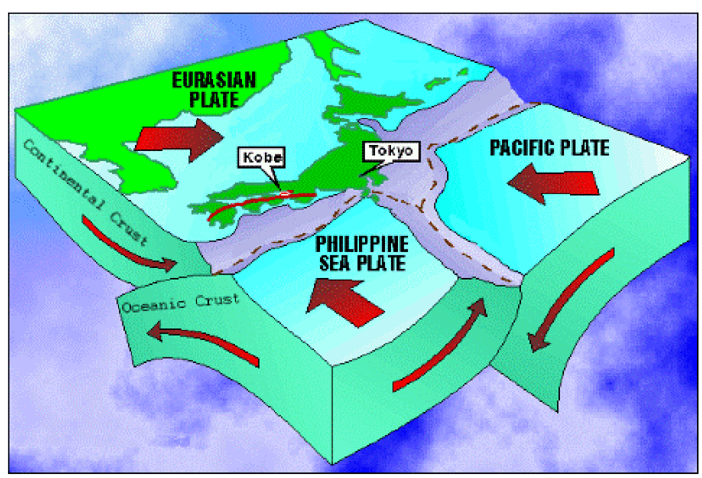
Formation of Isthmus of Panama

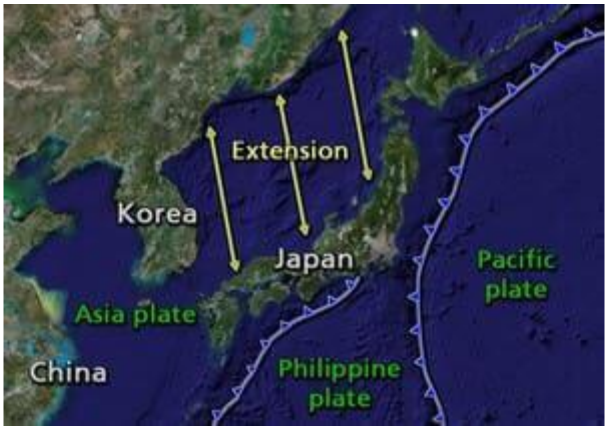
- Formation of the Isthmus of Panama involved subduction of the **Pacific-Farallon Plate** beneath the **Caribbean and South American plates**, forming a volcanic arc on the edge of the Caribbean Plate.
- The remains of the ancient Farallon Oceanic Plate are the Juan de Fuca Plate, parts of the North American Plate and the South American Plate, the Cocos Plate and the Nazca Plate.
- This initial Panama Arc began to form as the Caribbean Plate moved eastward.
- The North and South American plates continued to move westward past the Caribbean Plate.
- In addition to their east-west (strike-slip) motion, the plates also acquired a north-south component of convergence, leading to the collision of the Panama Arc with South America.
- This collision drove uplift in both the Northern Andes and the Panama Arc, forming the Isthmus of Panama.

Plates in the region of Isthmus of Panama

Formation of the Japanese Island Arc

- Japan's volcanoes are part of three volcanic arcs.





Triple Junction of the plates

- The arcs meet at a triple junction on the island of Honshu.
- Northern arc is formed due to the subduction of the **Pacific Plate** under the **Eurasian Plate**. The trench formed is **Japan Trench.**
- Central arc is formed due to the subduction of the **Pacific Plate** under the **Philippine Plate** (island formation is not significant along this arc). The trench formed is **Izu Trench.**
- Southern Arc is formed due to the subduction of the **Philippine Plate** under the **Eurasian Plate.** The trench formed is **Ryukyu Trench.**
- Japanese island arc was very close to the mainland.
- The force exerted by the Pacific plate and the Philippine plate tilted the arc towards its east giving rise to the **Sea of Japan.**

The Mariana Trench or Marianas Trench

- The Mariana Trench or Marianas Trench, the **deepest trench**, is located in the western Pacific Ocean.
- The Mariana Trench is formed due to the subduction of the **Pacific Plate** below the **Mariana Plate**.
- The maximum known depth is between 10,994 & 11,034 metres in its floor known as the **Challenger Deep**.

The Mariana trench is not the part of the seafloor closest to the centre of the Earth. This is because the Earth is not a perfect sphere (its Geoid); its radius is about 25 kilometres smaller at the poles than at the equator.

*As a result, parts of the **Arctic Ocean seabed** are at least 13 kilometres closer to the Earth's centre than the Challenger Deep seafloor.*

Explain the formation of thousands of islands in Indonesian and Philippines archipelagos (20 marks – Mains 2014)

20 marks = 200 words

- Indonesian archipelago and Philippine archipelago are located along the **plate margins**. Both the archipelagos were formed due to **ocean-ocean convergence**.
- Indonesian archipelago was formed due to convergence between Sunda oceanic plate (part of the Eurasian plate) and Indo-Australian plate whereas Philippine archipelago was formed due to convergence between Sunda oceanic plate and Philippine Sea plate.
- In ocean-ocean convergence, two oceanic plates converge or collide. The denser plate subducts into the **asthenosphere** below the convergence zone and forms a **trench** at the surface. This region below the convergence zone is called the **zone of subduction**.
- In the zone of subduction, due to high temperature and pressure, the rocks undergo **metamorphosis** and the **sediments** in the oceanic plate melt to form **magma**.
- The magma being lighter moves upwards due to the buoyant force offered by the surrounding **denser medium**. At the surface magma at high pressure escapes in the form of volcanic eruptions.
- The magma solidifies creating a volcanic layer. **Subsequent volcanism** builds a layer over layer and a volcanic mountain if formed. Such mountains are formed all along the converging edge above the less dense plate.
- Over time the mountains merge, and the oceanic crust **gets transformed** into continental crust.
- This is how Indonesian archipelago and Philippine archipelago were formed.

If asked for 10 marks = 100 words

- Indonesian and Philippine archipelagos are formed due to **ocean-ocean convergence**.

- In ocean-ocean convergence, the denser plate subducts into the **asthenosphere**. This region below the convergence zone is called the **zone of subduction**.
- In the zone of subduction, the rocks undergo **metamorphosis** and the **sediments** in the oceanic plate melt to form **magma**.
- At the surface magma escapes in the form of volcanic eruptions.
- Constant **volcanism** builds a layer over layer and a volcanic mountain if formed.
- Such mountains are formed all along the converging edge.
- Over time the mountains merge, and the oceanic crust **gets transformed** into continental crust.
- This is how Indonesian archipelago and Philippine archipelago were formed.

Related question

In spite of extensive volcanism, there is no island formation along the divergent boundary (mid-ocean ridge)

- **Basaltic magma** flows out along the divergent edge (fissure type or shield type volcano).
- Basaltic magma has **less silica,** and hence it is less viscous. It flows over a long-distance causing seafloor spreading but not volcanic islands.
- On the other hand, along the convergent boundary, **andesitic or acidic magma** flows out.
- **Andesitic or acidic magma** has **more silica** content, and hence it has higher viscosity. It doesn't move quickly and also solidifies faster. This helps in building a layer over layer on a confined region giving rise to a volcanic mountain.

5.2 Continent-Ocean Convergence or The Cordilleran Convergence

- The concept of Continent-Ocean Convergence is important to understand the formation of **the Rockies**, **the Andes** and other similar **fold mountain systems**.
- Continent-Ocean Convergence is also called **Cordilleran Convergence** because this kind of convergence gives rise to extensive mountain systems.
- A cordillera is an extensive chain of mountains or mountain ranges. Some mountain chains in North America and South America are called cordilleras.
- Continent-Ocean Convergence is similar to ocean-ocean convergence. One important difference is that in continent-ocean convergence **mountains are formed instead of islands**.
- When oceanic and continental plates collide or converge, the oceanic plate (denser plate) subducts or plunges below the continental plate (less dense plate) forming a **trench** along the boundary.
- The **trenches formed here are not as deep as those formed in ocean-ocean convergence**.
- As the ocean floor crust (oceanic plate) loaded with sediments subducts into the softer asthenosphere, the rocks on the continental side in the subduction zone become **metamorphosed** under high pressure and temperature (metamorphism: alteration of the composition or structure of rock by heat, pressure).

Formation of Continental Arcs

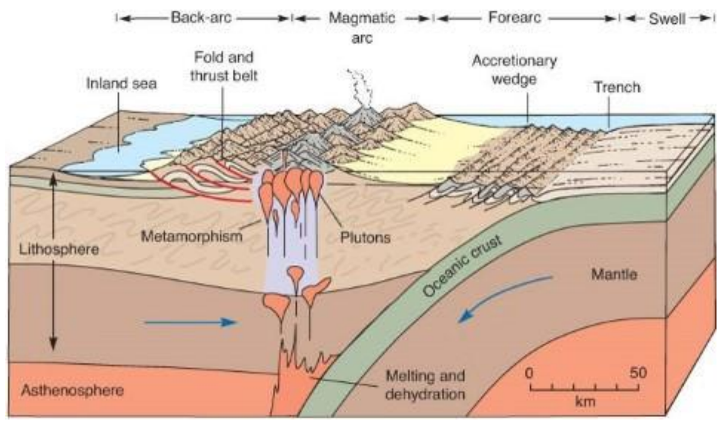
- After reaching a certain depth, plates melt. Magma (metamorphosed sediments and the melted part of the subducting plate) has lower density and is at high pressure.
- It rises due to the **buoyant force** offered by surrounding denser medium. The magma flows out, sometimes violently to the surface.
- A continuous upward movement of magma creates constant volcanic eruptions at the surface of the continental plate along the margin.
- Such volcanic eruptions all along the boundary form a chain of volcanic mountains which are collectively called as a **continental arc**. E.g. the **Cascade Range (parallel to the Rockies), the Western Chile range (parallel to the Andes)**
  - ✓ ***Arc:*** *narrow chain of volcanic islands or mountains.*
  - ✓ ***Island arc:*** *A narrow chain of volcanic islands (Japanese Islands).*

- ✓ ***Continental arc:*** *A narrow chain of volcanic mountains on continents (Cascade Range).*
- ✓ ***Accretionary wedge:*** *As the oceanic plate subducts, the sediments brought by it accumulates in the trench region. These accumulated sediments are called as **accretionary wedge**.*
- ✓ *The accretionary wedge is compressed into the continental margin leading to **crustal shortening**.*
- ✓ ***Convergence ➔ Crustal Shortening***
- ✓ ***Divergence ➔ Crustal Widening***
- ✓ ***Crustal Shortening at one place is compensated by Crustal Widening in some other place.***

Formation of Fold Mountains (Orogeny)

Orogeny (Geology) *is a process in which a section of the earth's crust is **folded** and deformed by **lateral compression** (force acting sideways) to form a mountain range.*
*Orogenic movements are 'Tectonic movements' of the earth involve the **folding of sediments**, **faulting** and **metamorphism** (rocks that have transformed by heat, pressure).*

- Continental margins are filled with **thick sediments** brought by the rivers.
- As a result of convergence, the buoyant granite of the continental crust overrides (is placed above) the oceanic crust (continental crust in **upthrust** by the oceanic crust).
- As a result, the edge of the deformed continental margin is thrust above sea level.
- The advancing oceanic plate adds more compressive stress on the upthrust continental margin and leads to its **folding** creating a **fold mountain system (orogenic belt)**.
- In some cases, the advancing oceanic plate compresses the **orogenic belt** leading to its folding **(Rockies and Andes).**
- With the formation of the orogenic belt (fold mountain belt), resistance builds up which effectively stops convergence. Thus, the subduction zone progresses seaward.
- With the culmination of compression, erosion continues to denude mountains. This results in **isostatic adjustment** (denser regions sink, and less denser regions rise) which causes the ultimate exposure of the roots of mountains.
- Examples are found in the **Rockies**, deformed in the late Mesozoic and early Tertiary period, and the **Andes**, where the deformation began in the Tertiary Period is still going on.



Continent-Ocean Convergence

Formation of the Andes

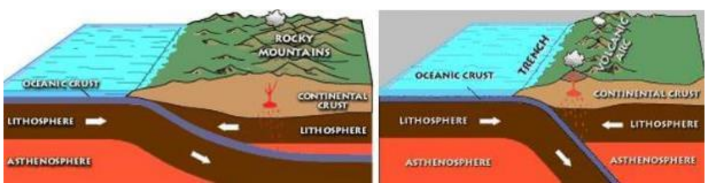
- The Andes are formed due to convergence between **Nazca plate** (oceanic plate) and the **South American plate** (continental plate). **Peru-Chile trench** is formed due to subduction of Nazca plate.
- The Andes are a continental arc (narrow, continental volcanic chain) formed due to the volcanism above the subduction zone.
- The pressure offered by the **accretionary wedge** folded the volcanic mountain, raising the mountains significantly.
- The folding process is continuing, and the mountains are constantly rising. Volcanism is still active.
- **Ojos del Salado active volcano** on the Argentina-Chile border is the **highest active volcano** on earth at 6,893 m. (**Olympus Mons** on Mars is the highest volcano in the solar system. It is 26 – 27 km high)
- **Mount Aconcagua** (6,960 m, Argentina) in the Andes is the highest peak outside the Himalayas and the highest peak in the western hemisphere. It is an **extinct volcano**.

Western Chile Range (Chilean Coast Range)

- The range was separated from the Andes during the Tertiary rise of the Andes due to the subsidence of the Intermediate Depression.

5.3 Formation of the Rockies

- The **North American plate** (continental plate) moved westwards while the **Juan de Fuca plate** (minor oceanic plate) and the **Pacific plate** (major oceanic plate) moved eastwards.
- The convergence gave rise to a series of parallel mountain ranges.
- Unlike the Andes, the Rockies are formed at a distance from the continental margin due to the **less steep subduction by the oceanic plates**.
- **Trenching is less conspicuous** as the boundary is filled with accretionary wedge and there are a series of fault zones (San Andreas Fault) that make the landform different from the Andes.



Left: Formation of the Rockies (less steep subduction); Right: Formation of the Andes

5.4 Continent-Continent Convergence or The Himalayan Convergence

Understanding Continent-Continent Convergence is important to understand the Formation of the Himalayas, the Alps, the Urals and the Atlas Mountains.

- In ocean-ocean convergence and continent-ocean convergence, **at least one of the plates is denser** and hence the subduction zone is **quite deep** (few hundred kilometres).
- At continent-continent convergent margins, due to **lower density**, both of the continental crustal plates are too light (buoyant) to be carried downward (subduct) into a trench.
- In most cases, neither plate subducts or even if one of the plates subducts, the **subduction zone will not go deeper than 40 – 50 km**. The two plates converge, buckle up (**suture zone**), fold, and fault.
- As the continental plates converge, the ocean basic or a sedimentary basin (geoclinal or geosynclinal sediments found along the continental margins) is squeezed between the two converging plates.
- Huge slivers of rock, many kilometres wide are thrust on top of one another, forming a towering mountain range.
- With the building up of resistance, convergence comes to an end. The mountain belt erodes, and this is followed by **isostatic adjustment**.
- As two massive continents weld, a single large continental mass joined by a mountain range is produced.
- Examples: **The Himalayas, Alps, Urals, Appalachians** and **the Atlas Mountains**.

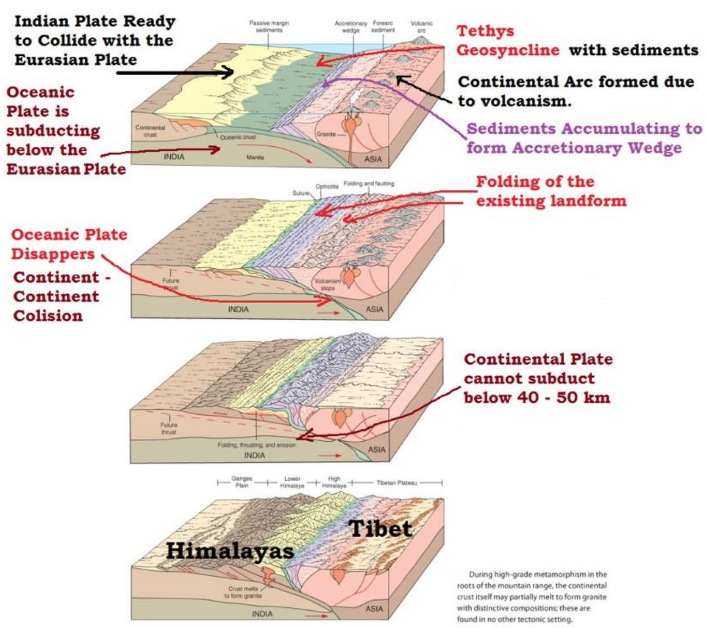
Suture zone: *The subduction of the continental crust is not possible beyond 40 km because of the normal buoyancy of the continental crust. Thus, the fragments of oceanic crust are plastered against the plates causing welding of two plates known as* ***suture zone****. Example: The Indus-Tsangpo suture zone.*

Formation of the Himalayans and the Tibetan Plateau

- The Himalayas are the **youngest mountain chain** in the world.
- Himalayan mountains have come out of a **great geosyncline** called the **Tethys Sea** and that the uplift has taken place in different phases.
- During **Permian Period (250) million years ago**, there was a supercontinent known as **Pangaea.**
- Its northern part consisted of the present-day North America and Eurasia (Europe and Asia) which is called as **Laurasia or Angaraland or Laurentia**.
- The southern part of Pangaea consisted of present-day South America, Africa, South India, Australia and Antarctica. This landmass was called **Gondwanaland.**
- In between Laurasia and Gondwanaland, there was a long, narrow and shallow sea known as the **Tethys Sea** (all this was explained earlier in Continental Drift Theory).
- There were many rivers which were flowing into the Tethys Sea (**some of the Himalayan rivers**

were older than the Himalayas themselves. We will study this in Antecedent and Subsequent Drainage).

- Sediments were brought by these rivers and were deposited on the floor of the Tethys Sea.
- These sediments were subjected to powerful compression due to the northward movement of the Indian Plate. This resulted in the folding of sediments.
- An often-cited fact used to illustrate this process is that the **summit of Mount Everest is made of marine limestone** from this ancient ocean.



- Once the Indian plate started plunging below the Eurasian plate, these sediments were further folded and raised. This process is still continuing (India is moving northwards at the rate of about **five cm per year** and crashing into rest of Asia).
- And the folded sediments, after a lot of erosional activity, appear as the present-day Himalayas.
- Tibetan plateau was formed due to **upthrusting** of the southern block of the Eurasian Plate.
- The Indo-Gangetic plain was formed due to the consolidation of alluvium brought down by the rivers flowing from the Himalayas.
- The curved shape of the Himalayas convex to the south is attributed to the maximum push offered at two ends of the Indian Peninsula during its northward drift.

Phases of formation

- The Himalayas do not comprise a single range but a series of at least three ranges running more or less parallel to one another.
- Therefore, the Himalayas are supposed to have emerged out of the Himalayan Geosyncline, i.e. the Tethys Sea in **three different phases** following one after the other.
- The first phase commenced about **50-40 million years ago** when the **Great Himalayas** were formed. The formation of the Great Himalayas was completed about 30 million years ago.
- The second phase took place about **25 to 30 million years ago** when the **Middle Himalayas** were formed.
- The **Shiwaliks** were formed in the last phase of the Himalayan orogeny — say about **two million to twenty million years ago**.
- Some of the fossil formations found in the Shiwalik hills are also available in the Tibet plateau. It indicates that the past climate of the Tibet plateau was somewhat similar to the climate of the Shiwalik hills.

*Recent studies have shown that convergence of the Indian plate and the Asian plate has caused a **crustal shortening** of about 500 km in the Himalayan region. This shortening has been compensated by seafloor spreading along the oceanic ridge in the Indian Ocean.*

Evidence for the rising Himalayas

- Today's satellites that use high precision atomic clocks that can measure accurately even a small rise of one cm. The heights of various places as determined by satellites indicate that the Himalayas rise by few centimetres every year. The present rate of uplift of the Himalayas has been calculated at 5 to 10 cm per year.
- Due to uplifting, lakes in Tibet are desiccated (lose water) keeping the gravel terraces at much higher levels above the present water level. This could be possible only in the event of uplift of the region.
- The frequent tectonic activity (occurrence of earthquakes) in the Himalayan region shows that the Indian plate is moving further northwards and plunging into the Eurasian plate.

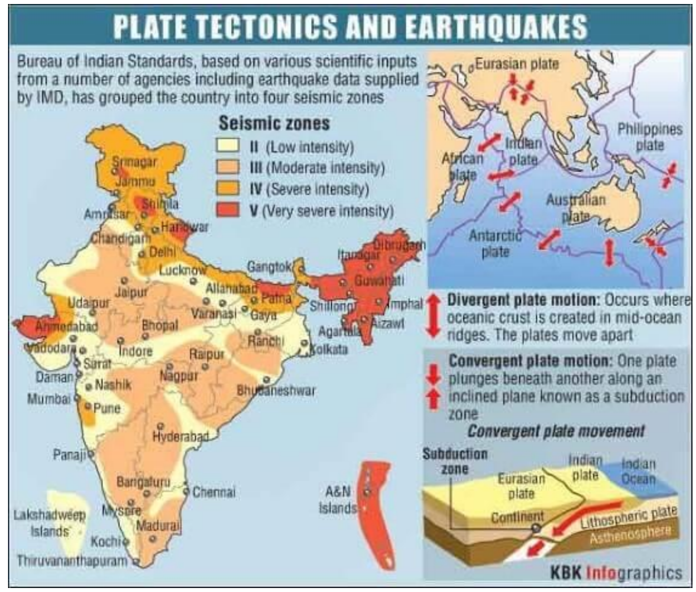
- This means that the Himalayas are still being raised due to compression and have **not yet attained isostatic equilibrium**.
- The Himalayan rivers are in their youthful stage and have been rejuvenated (make or cause to appear younger) in recent times. This shows that the Himalayan Landmass is rising, keeping the rivers in youth stage since a long time.

Formation of Alps, Urals, Appalachians and the Atlas Mountains

- The formation of each of these mountains is similar to the formation of the Himalayas.
- **The Alps** are **young fold mountains** which were formed due to the collision between **African Plate** and the **Eurasian Plate**.
- **The Atlas Mountains** are also **young folded mountains** which are still in the process of formation. They are also formed due to the collision between **African Plate** and the **Eurasian Plate**.
- **The Urals** are **very old fold mountains** which were formed even before the breakup of Pangaea. They were formed due to the collision between Europe and Asia.
- **The Appalachians** are also **very old fold mountains** which were formed even before the breakup of Pangaea. They were formed due to the collision between North America and Europe.

Volcanism and Earthquakes in Continent-Continent Convergence

- Oceanic crust is only 5 – 30 km thick. But the continental crust is 50 – 70 km thick. Magma cannot penetrate this thick crust, so there are **no volcanoes**, although the magma stays in the crust.
- **Metamorphic rocks** are common because of the stress the continental crust experiences.
- With enormous slabs of crust smashing together, continent-continent collisions bring on numerous and **large earthquakes** (Earthquakes in Himalayan and North Indian Region, Kachchh region).



Mains Question on Fold Mountains.

Why are the world's fold mountain systems located along the margins of continents? Bring out the association between the global distribution of Fold Mountains and the earthquakes and volcanoes.

Why fold mountains at the continental margin?

- Fold mountains are formed due to convergence between two continental plates (Himalayas, Alps) or between an oceanic and a continental plate (the Rockies, Andes).
- In Continent-Continent (C-C) convergence, oceanic sediments are squeezed and up thrust between the plates and these squeezed sediments appear as fold mountains along the plate margins.
- In Continent-Ocean (C-O) convergence, the continental volcanic arc formed along the continental plate margin is compressed and is uplifted by the colliding oceanic plate giving rise to fold mountains along the continental plate margin.

Earthquakes

- In both C-C convergence and C-O convergence, there is the formation of **fold mountains and frequent occurrence of earthquakes**.

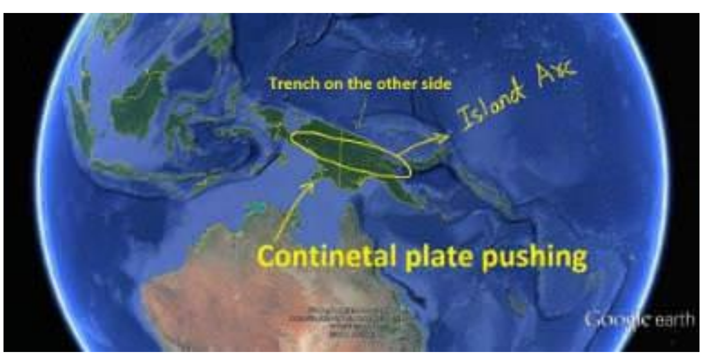
- This is because of the sudden release of friction between the subducting plate and up thrust plate.
- In C-C convergence, the denser plate pushes into the less dense plate creating a fault zone along the margin.
- Further collision leads to the sudden release of energy along this fault zone generating disastrous **earthquakes (shallow-focus earthquakes)**.
- In C-O regions the subducting oceanic plate grinds against the surrounding denser medium producing **mostly shallow-focus earthquakes**, and **deep in the subduction zone deep-focus earthquakes occur**.
- Volcanism is observed only in C-O convergence and is **almost absent in C-C convergence**.

Volcanism

- This is because of the thick continental crust in C-C convergence which prevents the outflow of magma. Magma here lies stocked within the crust.
- In C-O convergence, metamorphosed sediments and melting of the subducting plate form magma which escapes to the surface through the less thick continental crust.

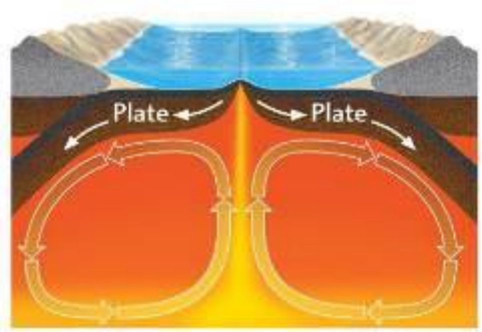
5.5 Continent-Arc Convergence or New Guinea Convergence

- New Guinea came into being about 20 million years ago as a result of continent-arc collision.
- The continental plate pushes the island arc towards the oceanic crust. The oceanic plate plunges under the island arc.
- A trench occurs on the ocean side of the island arc and, ultimately, the continental margin is firmly welded against the island arc.



6. Divergent boundary

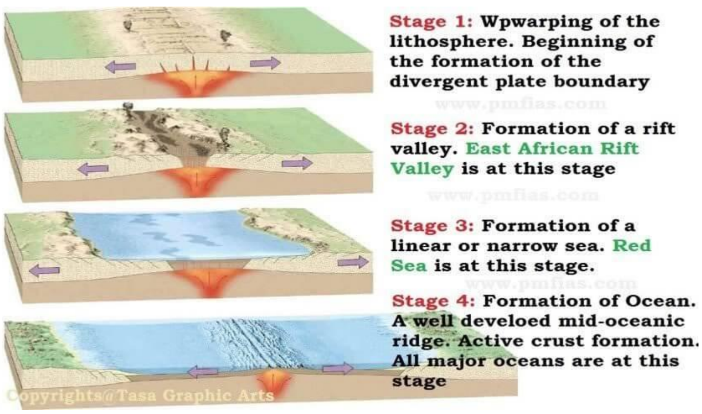
- In the Seafloor Spreading Theory, we have studied how divergent boundaries below the oceans are responsible for the spreading of the seafloor.
- In Plate Tectonics, we have learnt about the major and minor lithospheric plates and how these plates moved through the geological past.
- We have studied about **convection currents** in the mantle which are the primary reason behind plate movements — divergence and convergence of the lithospheric plates.
- The horizontal limbs of the convection currents, just below the lithosphere, drag the plates horizontally.
- The falling limbs of the convection currents create a negative pressure on the lithosphere, and this negative pressure (pulling force) is responsible for the formation of the convergent boundary.
- The **rising limbs**, on the other hand, create positive pressure on the lithosphere, and this positive pressure (pushing force) creates a divergent boundary.
- Divergence (divergent boundary) is responsible for the **evolution and creation of new seas and oceans** just like convergent boundaries are responsible for the formation of **fold mountains, volcanic arcs**.



6.1 Evolution – Formation of Rift Valleys, Rift Lakes, Seas and Oceans

- The formation of atmosphere and the oceans took millions of years. They were formed due to continuous 'degassing' of the Earth's interior.

- After the Earth's surface temperature came down below the boiling point of water, rain began to fall.
- Water began to accumulate in the hollows and basins, and the primeval (earliest) water bodies were formed.
- The primeval water bodies evolved to form seas and oceans.
- The process of formation of a new sea **begins with the formation of a divergent boundary**.
- **New lithosphere is created at the divergent boundary and old lithosphere is destroyed somewhere else at the convergent boundary**.



Basic Terms

- **Upwarp:** a broad elevated area of the earth's surface.
- **Plume:** a column of magma rising by convection in the earth's mantle.
- **Rift Valley:** a linear-shaped lowland (graben) between several highlands (horst) or mountain ranges created by the action of a geologic rift or fault.

Stage 1: Upwarping, fault zones

- Rising limbs of the convection currents create a **plume** that tries to escape to the surface by upwarping the lithosphere (doming the lithosphere upwards).
- During upwarping, a series of faults are created. Both normal and thrust faults (reverse fault) occur during upwarping. The divergence of plates begin.

Stage 2: Rift Valley Formation

- Faulting due to divergence creates extensive rift system (fault zones, rift valleys).
- The lithosphere is subject to a horizontal extensional force, and it will stretch, **becoming thinner (E.g. The crust above Yellowstone hotspot is thinning because of mantle plume)**.
  Eventually, it will rupture, leading to the formation of a rift valley.
- This process is accompanied by surface manifestations along the rift valley in the form of volcanism and seismic activity.
- Rifts are the initial stage of a continental break-up and, if successful, can lead to the formation of a new ocean basin.
- An example of a place on Earth where this has happened is the South Atlantic Ocean, which resulted from the breakup of South America and Africa around 138m years ago.
- The East African Rift is described as an active type of rift. Beneath this rift, the **rise of a large mantle plume** is doming the lithosphere upwards (Ethiopian Highlands), causing it to weaken.
- The rifting started in the **Afar region** in northern Ethiopia at around 30 million years ago and propagating southwards towards Zimbabwe. (It's unzipping Africa!)
- Rifting is followed by **flood basalt volcanism** in some places that spread around the rift creating plateaus and highlands (Ethiopian Highlands, Kenya Dome).

Mains 2018: What is a mantle plume and what role it plays in plate tectonics?

Backdrop: In early 2018, a large crack made a sudden appearance in south-western Kenya adding fuel to the debate on the breakup of Africa.

***Narmada and Tapti Rift Valleys** (fault zones) are formed from a mechanism different from the one explained above. They are formed due to the bending of the northern part of the Indian plate during the formation of Himalayas.*

Stage 3: Formation of Linear Sea or Rift Lakes

- Rift valley deepens due to further divergence and makes way for ocean waters.

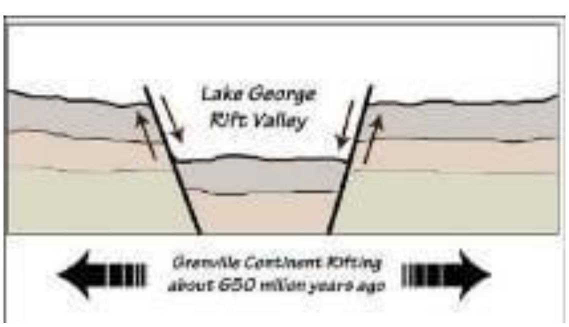
- If the rift valleys are formed deeper within the continents, rains waters accumulate forming rift lakes.
- Rift lakes form **some of the largest freshwater lakes** on earth.
- Rift valleys evolve into a volcanic vent. Block mountains on either side of the rift evolve into oceanic ridges.
- Successive volcanism and seafloor spreading create spreading sites where new crust is formed (divergent boundary is also called a **constructive edge**).
- Oceanic crust starts to replace continental crust. This stage is the formation of linear seas. Example: **Red Sea**.

Stage 4: Linear Sea transforms into Ocean

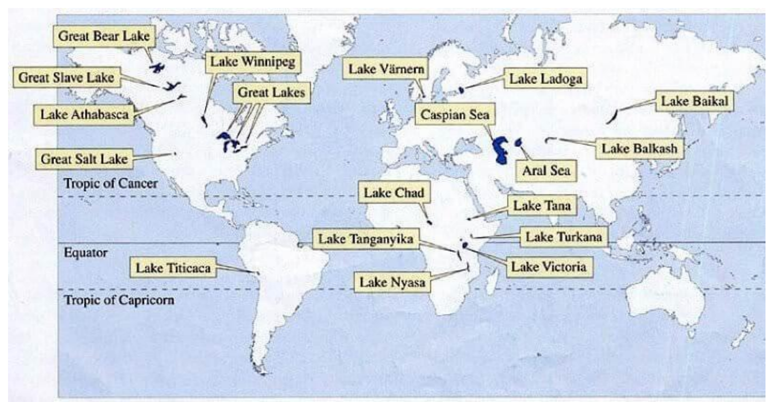
- The intense outpouring of basaltic magma accentuates **see floor spreading** and **oceanic crust formation**.
- Oceanic crust replaces the continental crust, and a mighty ocean is formed.
- Crust formation along the mid-oceanic ridge (divergent boundary) is compensated by crust destruction (crustal shortening) along the convergent boundary (destructive Edge). This is how the continents and oceans get transformed.

6.2 Rift valley lakes

- A rift lake is a lake formed as a result of subsidence related to movement on faults within a rift zone, an area of extensional tectonics in the continental crust.
- They are often found within rift valleys and may be very deep. The rift lakes are bound by large steep cliffs along the fault margins.



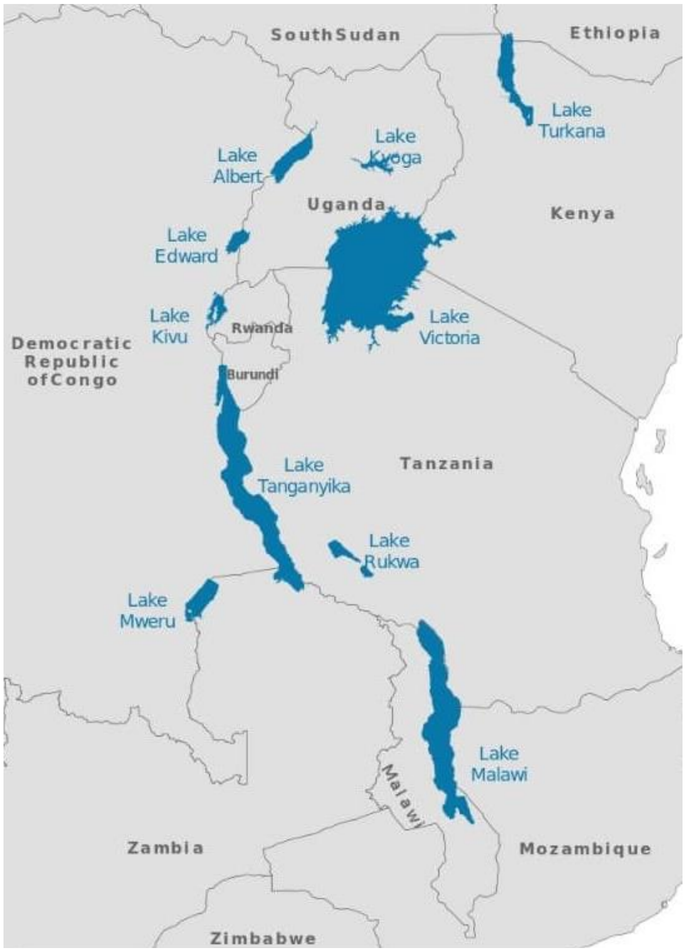
- Many of the **world's largest lakes are located in rift valleys**.
- **Lake Baikal** in Siberia lies in an active rift valley. It is the **deepest lake in the world** (the deepest point is 1642 meters below the surface).
- It is also the **largest (by volume) freshwater lake in the world**, containing roughly 20% of the world's unfrozen surface fresh water.
- **Lake Tanganyika**, **second largest freshwater lake by volume**, is in the **Albertine Rift**, the westernmost arm of the active East African Rift.
- **Lake Tanganyika** is also the **world's longest freshwater lake** and the **second deepest lake in the world** (the deepest point is 1470 meters below the surface).
- **Lake Superior** in North America, the **largest freshwater lake by area**, lies in the ancient and dormant Midcontinent Rift.
- **Lake Victoria** is the world's **second largest freshwater lake by surface area**.



Major Lakes of the World

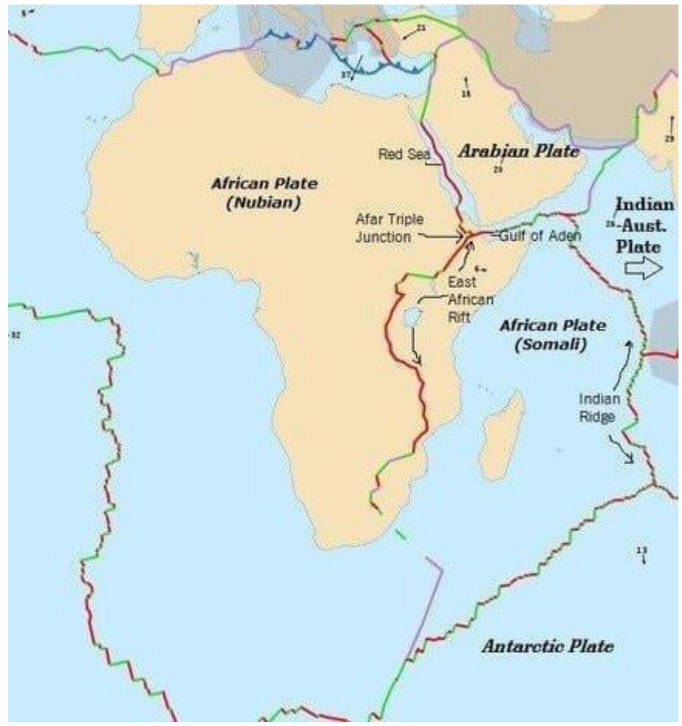
Great Lakes of North America (Phizzy, via [Wikimedia Commons](#))

6.3 Great Rift Valley



African Great Lakes (MellonDor, from Wikimedia Commons)

- The Great Rift Valley is a geographical feature running north to south for around 6,400 kilometres from northern Syria to central Mozambique in East Africa.
- The northernmost part of the Rift forms the Beqaa Valley in **Lebanon**.
- Farther south, the valley is the home of the **Jordan River** which continues south through the Jordan Valley into the **Dead Sea** on the Israeli-Jordanian border.
- From the Dead Sea southward, the Rift is occupied by the **Gulf of Aqaba** and the **Red Sea**.
- The **Afar Triangle of Ethiopia and Eritrea** is the location of a triple junction.
- The Gulf of Aden is an eastward continuation of the rift, and from this point, the rift extends south-eastward as part of the mid-oceanic ridge of the Indian Ocean.
- In a southwest direction, the fault continues as the Great Rift Valley, which split the older **Ethiopian highlands** into two halves.
- In eastern Africa, the valley divides into the Eastern Rift and the Western Rift. The Western Rift, also called the **Albertine Rift** contains **some of the deepest lakes in the world**.

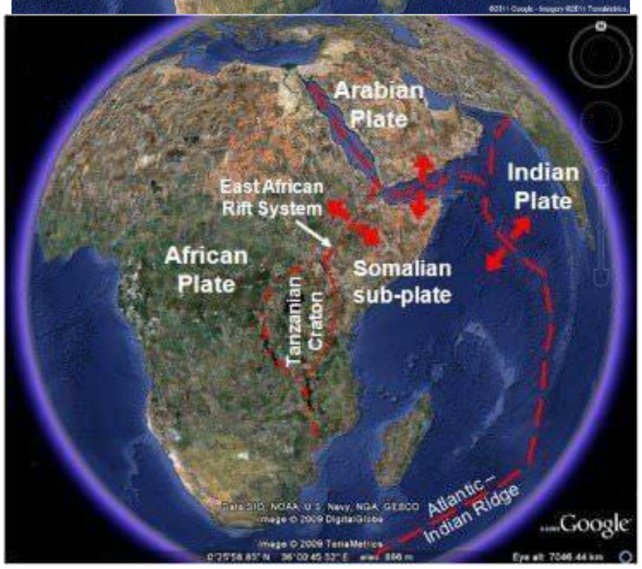


East African Rift Valley

- The Eastern Rift Valley (also known as **Gregory Rift**) includes the main **Ethiopian Rift**, running eastward from the **Afar Triple Junction**, which continues south as the **Kenyan Rift Valley**.
- The Western Rift Valley includes the **Albertine Rift**, and farther south, the valley of **Lake Malawi**.
- To the north of the **Afar Triple Junction**, the rift follows one of two paths: west to the **Red Sea Rift** or east to the **Aden Ridge in the Gulf of Aden**.
- The EAR transects through Ethiopia, Kenya, Uganda, Rwanda, Burundi, Zambia, Tanzania, Malawi and Mozambique.
- Before rifting, enormous continental flood basalts erupted on the surface and uplift of the **Ethiopian, Somalian, and East African plateaus** occurred.

Breaking up of Africa

- The East African Rift (EAR) is an **active continental rift zone** in East Africa.
- The EAR began developing around the onset of the Miocene, **22-25 million years ago**.
- In the past, it was considered to be part of a larger Great Rift Valley.
- The EAR is subjected to different stages of rifting along its length. To the **south, where the rift is young**, extension rates are low, and faulting occurs over a wide area. Volcanism and seismicity are limited.
- Towards the **Afar region**, however, the entire rift valley floor is covered with volcanic rocks.
- This suggests that, in this area, the **lithosphere has thinned almost to the point of complete break-up**.



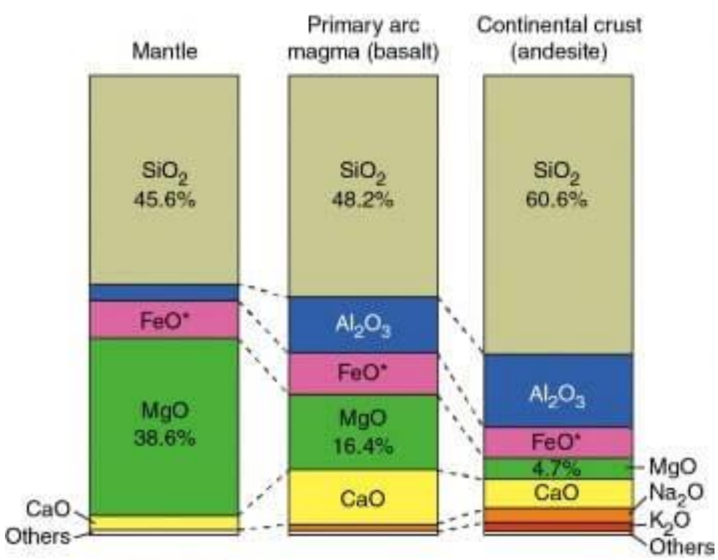
- The rift is a narrow zone that is a developing divergent tectonic plate boundary, in which the African Plate is in the process of splitting into two tectonic plates, called the **Somali Plate** and the **Nubian Plate (African Plate)**, at a rate of 6–7 mm annually.
- As extension continues, **lithospheric rupture** will occur within 10 million years, the Somalian plate will break off, and a new ocean basin will form.

Volcanism and seismicity along East African Rift Valley

- The East African Rift Zone includes many active as well as dormant volcanoes.
- **Mount Kilimanjaro** (it has three volcanic cones), is a **dormant** stratovolcano in Tanzania, **Mount Kenya** is an extinct stratovolcano.
- Although most of these mountains lie outside of the rift valley, the EAR created them.
- The EAR is the **largest seismically active rift system** on Earth today.
- The majority of earthquakes occur near the Afar Depression, with the largest earthquakes typically occurring along or near major border faults.

How come Mount Kilimanjaro and Mount Kenya that formed close to the divergent boundary are stratovolcanoes when the magma that flows out at the divergent boundary is basaltic?

- The formation of stratovolcano and shield volcano depends on the silica content of the magma.
- **Shield volcanoes** are formed from magma that contains a low proportion of silicates (**magma coming from the mantle, like in divergent boundary**).
- Stratovolcanoes are formed from magma that contains a high proportion of silicates (**magma formed due to the melting of crustal plates, like in convergent boundary**).
- Mt Kilimanjaro is a stratovolcano. It was formed during the process of formation of the African rift valley.
- During the formation of the African rift valley, there was a lot of faulting. The stress caused in the crustal plates led to the melting of the subsurface layer into magma, and the volcanism around Kilimanjaro occurred due to this magma (high proportion of silicates).
- Take a look at the picture below to know the proportion of silicon content in mantle and crust.



Silicon content in the mantle, oceanic crust (mafic) and the continental crust (felsic)

- Majority of the stratovolcanoes occur along the convergent boundary, but there is no fixed rule that they should occur only along convergent boundaries. It all depends on the nature of magma that flows out.

7. Classification of Mountains

Classification of mountains on the basis of location

Continental mountains

Coastal mountains

- the Rockies,
- the Appalachians,
- the Alpine mountain chains,
- the Western Ghats and
- the Eastern Ghats (India);

Inland mountains

- the Vosges and the Black Forest (Europe),
- the Kunlun, Tienshan, Altai mountains of Asia,
- the Urals of Russia, the Aravallis,
- the Himalayas, the Satpura, and the Maikal of India.

Oceanic mountains

- Oceanic mountains are found on continental shelves and ocean floors.
- If the height of the mountains is considered from the ocean floor, **Mauna Kea (9140 m)**, would be the highest mountain. It is a dormant volcanic mountain in the Hawaii hotspot volcanic chain.

Mauna Kea, a dormant volcano in the island of Hawaii

Classification of mountains on the basis of the period of origin

- A total of nine orogenic or mountain building movements have taken place so far.

- Some of them occurred in Pre-Cambrian times between 600-3,500 million years ago.
- The three more recent orogenies are the **Caledonian, Hercynian and Alpine**.

Precambrian mountains

- They belong to the Pre-Cambrian period, a period that extended for more than 4 billion years.
- The rocks have been subjected to upheaval, denudation and metamorphosis.
- So, the remnants appear as **residual mountains.**
- Some of the examples are Laurentian mountains, Algoman mountains etc.

Caledonian mountains

- They originated due to the great mountain-building movements and associated tectonic movements of the late Silurian and early Devonian periods (approximately 430 million years and 380 million years ago).
- Examples are the **Appalachians, Aravallis, Mahadeo** etc.

Hercynian mountains

- These mountains originated during the upper Carboniferous to Permian Period in Europe (approximately 340 million years and 225 million years ago).
- Some examples are the mountains of **Vosges and the Black Forest, Altai, Tien Shan mountains of Asia, Ural Mountains etc**.

Alpine system

- Has its origin in the **Tertiary Period** (**65 million years to 7 million years ago)**.

Examples are

- **the Rockies of North America, the Alpine mountains of Europe,**
- **the Atlas Mountains of north-western Africa,**
- **the Himalayas of the Indian subcontinent**
- **the mountains radiating from Pamir knot like Pontic, Taurus, Elburz, Zagros and Kunlun etc**.
- Being the most recently formed, these ranges, such as the Alps, Himalayas, Andes and Rockies are the **loftiest with rugged terrain**.

Classification of mountains on the basis of mode of origin

Original or Tectonic mountains

- Original or Tectonic mountains are the product of tectonic forces.
- The tectonic mountains may be categorized into
  1. **fold mountains (the Himalayas, the Rockies, the Andes),**
  2. **block mountains (Vosges mountains in France, the Black Forest in Germany, Vindhya and Satpura in India) and**
  3. **volcanic mountains (Cascade Range in the USA, Mount Kenya, Mount Kilimanjaro, Mount Fujiyama)**.

Circum-erosional or Relict or Residual mountains

- Circum-erosional or Relict or Residual mountains (**Aravallis in India, Urals in Russia**) are the remnants of old fold mountains derived as a result of **denudation** (strip of covering).
- Residual mountains may also evolve from plateaus which have been dissected by rivers into hills and valleys.
- Examples of **dissected plateaux**, where the down-cutting streams have eroded the uplands into mountains of denudation, are the Highlands of Scotland, Scandinavia and the **Deccan Plateau**.

7.2 Fold Mountains

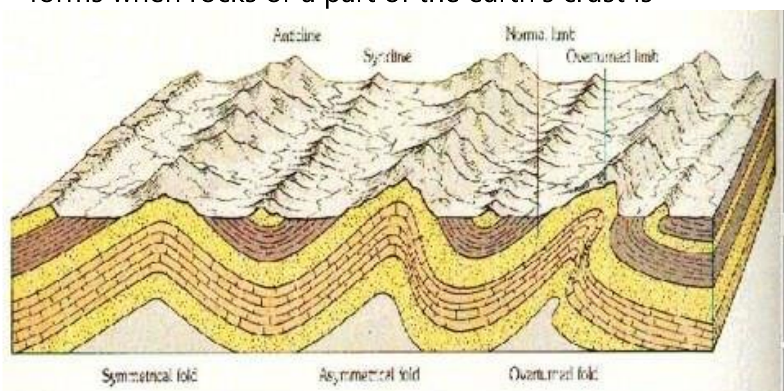
- Fold mountains are formed when sedimentary rock strata in **geosynclines** are subjected to compressive forces.

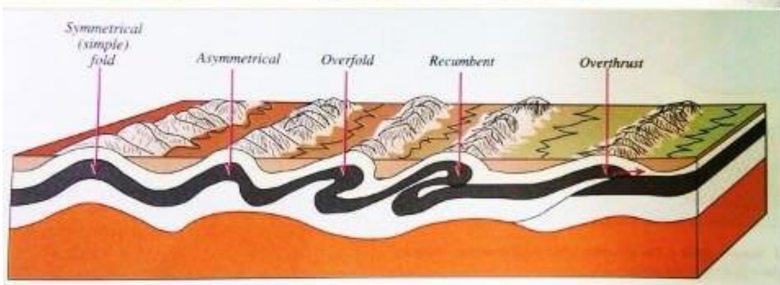
- They are the **loftiest** mountains, and they are generally concentrated along continental margins.

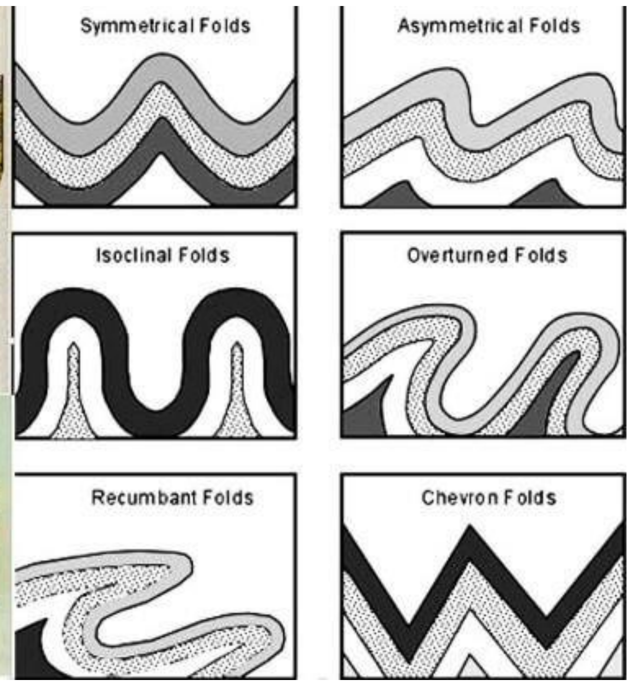
***Geosyncline**: a large-scale depression in the earth's crust containing very thick deposits. E.g. Tethys geosyncline.*

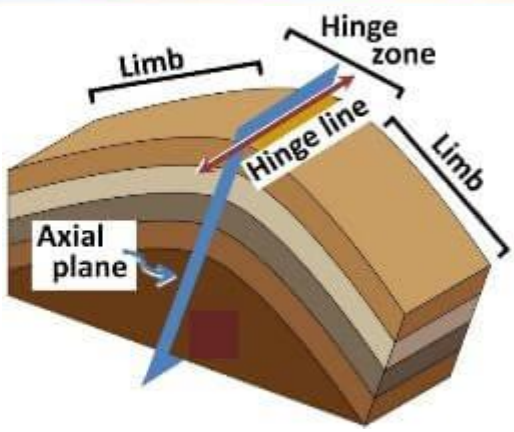
'Fold' in geology

- A fold is an undulating structure (wave-like) that forms when rocks or a part of the earth's crust is folded (deformed by bending) under compressional stress. The folds are made up of **multiple strata** (rock layers).
- The folds that are upwardly convex are called as **anticlines**. The core (centre) of an anticline fold consists of the older strata, and the strata are progressively younger outwards.
- In contrast, the folds that are downwardly convex are called **synclines**. The core of a syncline fold consists of the younger strata, and the strata are progressively older outwards.









- **Limbs:** The limbs are the flanks of the fold.
- **Hinge line:** the where the flanks join together (the line of maximum curvature).
- **Axial plane:** plane defined by connecting all the hinge lines of stacked folding surfaces (the plane in which hinge lines of various strata lie).

Types of folds

- A **symmetrical fold** is one in which the axial plane is vertical.
- An **asymmetrical fold** is one in which the axial plane is inclined.
- An **isoclinal fold** has limbs that are essentially parallel to each other and thus approximately parallel to the axial plane.
- An **overturned fold** has a highly inclined axial plane such that the strata on one limb are overturned.
- A **recumbent fold** has an essentially horizontal axial plane.

Classification of fold mountains

On the basis of period of origin

- On the basis of the period of origin, fold mountains are divided into very old fold mountains, old fold mountains and Alpine fold mountains.

Very Old Fold Mountains

- They are more than 500 million years old.
- They have rounded features (due to denudation).
- They are of low elevation.
- The **Appalachians** in North America and the **Ural Mountains** in Russia are the examples.

Old Fold Mountains

- Old fold mountains had their origin before the Tertiary period (tertiary period started 66 million years ago).
- The fold mountain systems belonging to **Caledonian** and **Hercynian** mountain-building periods fall in this category.
- They are also called **thickening relict fold mountains** because of lightly rounded features and medium elevation.
- Top layers are worn out due to erosional activity. Example: **Aravalli Range** in India.
- The **Aravalli Range** in India is the **oldest fold mountain systems in India**.
- The range rose in post-Precambrian event called the **Aravalli-Delhi orogeny.**

Alpine or young fold mountains

- Alpine fold mountains belonging to the Tertiary period (66 million years ago to present) can be grouped under the new fold mountains category since they originated in the Tertiary period.
- Examples are the **Rockies, the Andes, the Alps, the Himalayas**, etc.

Characteristics

- Rugged relief.
- Imposing height (lofty).
- High conical peaks.

On the basis of the nature of folds

Simple fold mountains

- Simple fold mountains with open folds in which **well-developed systems of synclines and anticlines** are found, and folds are of wavy patterns.

Complex fold mountains

- Complex fold mountains in which the rock strata are intensely compressed to produce a complex structure of folds.
- In the Himalayas, over folds and recumbent folds are often found detached from their roots and carried a few hundred kilometres away by the tectonic forces. These detached folds are called '**nappe**.'

Characteristics of Fold Mountains

- Fold mountains belong to the group of **youngest mountains of the earth**.
- The presence of fossils suggests that the **sedimentary rocks** of these folded mountains were formed after accumulation and consolidation of silts and sediments in a marine environment.
- Fold mountains extend for **great lengths** whereas their **width is considerably small**.
- Generally, fold mountains have a concave slope on one side and a convex slope on the other.
- Fold mountains are mostly found along continental margins facing oceans (C-O Convergence).
- Fold mountains are characterized by **granite intrusions** (formed when magma crystallises

and solidifies underground to form intrusions) on a massive scale.

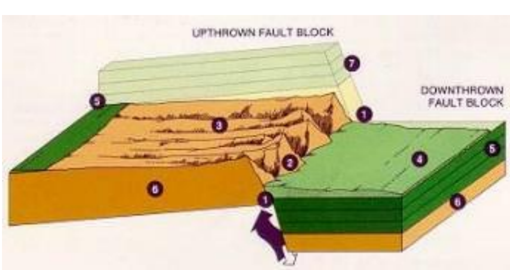
- **Recurrent seismicity** is a common feature in folded mountain belts.
- High heat flow often finds expression in **volcanic activity** (Himalayas is an exception, because of C-C convergence).
- These mountains are by far the most widespread and also the most important.
- They also contain rich mineral resources such as **tin, copper, gold** etc.

7.3 Block Mountains

- Block mountains are created because of faulting on a large scale (when large areas or blocks of earth are broken and **displaced vertically or horizontally**).
- The uplifted blocks are termed as **horsts,** and the lowered blocks are called **graben**.
- The **Great African Rift Valley (valley floor is graben)**, The **Rhine Valley (graben)** and the **Vosges mountain (horst)** in Europe are examples.
- Block mountains are also called **fault block mountains** since they are formed due to faulting as a result of tensile and compressive forces.

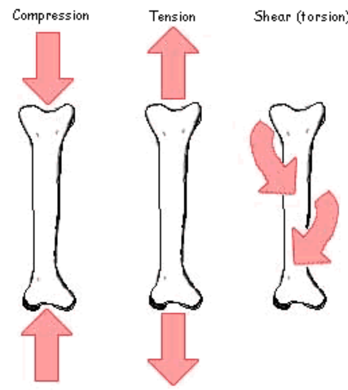
There are two basic types of block mountains:

1. **Tilted block** mountains have one steep side contrasted by a gentle slope on the other side.
2. **Lifted block mountains** have a flat top and extremely steep slopes.



'Fault' in Geology

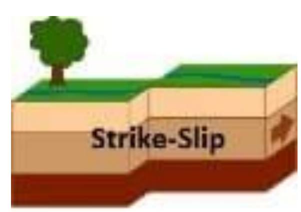
- When the earth's crust bends folding occurs, but when it cracks, faulting takes place.
- A fault is a planar fracture (crack) in a volume of earth's crust, across which there has been significant displacement of a block/blocks of crust.
- The **faulted edges are usually very steep**, e.g. the Vosges and the Black Forest of the Rhineland.
- Faults occur due to tensile and compressive forces acting on the parts of the crust.



- Large faults within the Earth's crust result from the action of plate tectonic forces, such as subduction zones or **transform faults**.
- Energy release associated with rapid movement on active faults is the cause of most **earthquakes**.
- In an active fault, the pieces of the Earth's crust along a fault move over time.
- Inactive faults had movement along them at one time, but no longer move.
- The type of motion along a fault depends on the type of fault.

Types of faults

Strike-slip fault



- In a strike-slip fault (also known **transcurrent fault**), the plane of the fault is usually **near ver-**

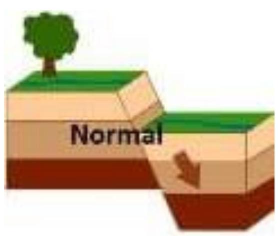
tical, and the blocks move laterally either **left or right** with very little vertical motion (the displacement of the block is **horizontal**).

Transform fault

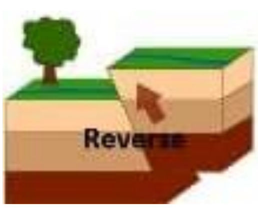
- A special class of strike-slip fault is the transform fault or transform boundary **when it forms a plate boundary**.
- **A transform fault is the only type of strike-slip fault that is classified as a plate boundary**.
- Most of these faults are hidden in the deep ocean, where they offset divergent boundaries in short zigzags resulting from seafloor spreading.
- They are less common within the continental lithosphere. The best example is the **Dead Sea transform fault**.
- The transform boundary ends abruptly and is connected to another transform, a spreading ridge, or a subduction zone.

Dip-slip faults

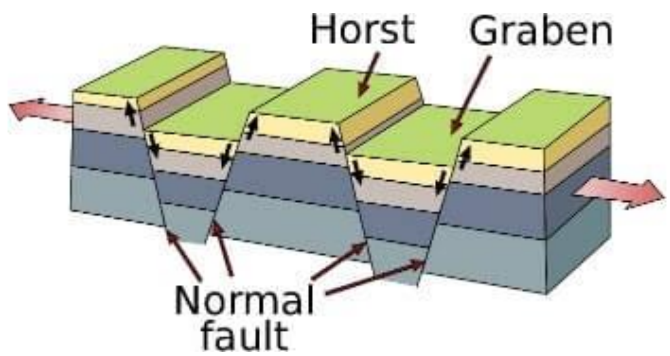
- Dip-slip faults can be either **normal or reverse**.
- In a normal fault, the hanging wall (displaced block of crust) moves **downward**, relative to the footwall (stationary block).



- In a **reverse fault (thrust fault)** the hanging wall moves **upwards**.



- Reverse faults occur due to compressive forces whereas normal faults occur due to tensile forces.
- A downthrown block between two normal faults is a **graben**.
- An upthrown block between two normal faults is a **horst**.
- Normal faults occur mainly in areas where the crust is being extended such as a **divergent boundary**.
- **Reverse faults** occur in areas where the crust is being shortened such as at a **convergent boundary**.



Rift Valley system

- Tension causes the central portion to be let down between two adjacent fault blocks forming a graben or rift valley, which will have steep walls.
- The East African Rift Valley system is the best example.
- In general, large-scale block mountains and rift valleys are due to tension rather than compression.

Block Mountains

- Block mountains may originate when the middle block moves downward and becomes a rift valley while the surrounding blocks stand higher as block mountains.

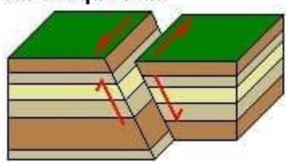
Plateaus

- Sometimes, the surrounding blocks subside leaving the middle block stationary. Such cases are found in high plateau regions.

Oblique-slip faults

- A fault which has a component of **dip-slip** and a component of **strike-slip** is termed an oblique-slip fault.
- Nearly all faults have some component of both dip-slip and strike-slip.

- **Many disastrous earthquakes** are caused along the oblique slip.



7.4 Volcanic mountains

- Volcanic mountains are formed due to volcanic activity.
- Mount Aconcagua, Mount Kilimanjaro, Mount Mauna Kea and Mount Fujiyama are examples of such mountains.
- These are, in fact, volcanoes which are built up from material ejected from fissures in the earth's crust.
- The materials include molten lava, volcanic bombs, cinders, ashes, dust and liquid mud.
- They fall around the vent in successive layers, building up a characteristic volcanic cone.
- Volcanic mountains are often called **mountains of accumulation**.
- They are common in the Circum-Pacific belt.

7.5 Significant mountains and mountain ranges

Basics

Ridge

- Mountain ridges refer to mountains which originate as a result of local folding and faulting.
- Generally, the slope of one side of the ridge is steep in contrast to the moderate slope on the other side (**in case of Himalayas, the southern slope is steeper compared to the northern slope**).
- In some cases, a ridge may have a symmetrical slope on both sides.

Mountain range

- It refers to a series of ridges which originated in the same age and underwent the same processes.
- The most prominent or characteristic feature of mountain ranges is their long and narrow extension.
- Example: the Himalayas is a mountain range with Himadri ridge, Himachal ridge and Shiwalik ridge.

Mountain System

- A group of mountain ranges formed in a single period, similar in their form, structure and extension, is termed a mountain system.
- Examples are the Basin Range of Nevada (USA), the Rocky mountain system of North America and the Appalachian.

Mountain Chain

- It consists of mountain ranges which differ in size and period of formation.

Cordillera

- Cordillera is a community of mountains which includes ridges, ranges, mountain chains and mountain systems.
- The best example is the Western Cordillera in the western part of North America.

Longest Mountain Ranges

1. The Andes - 7,000 km
2. The Rockies - 4,830 km
3. The Great Dividing Range - 3,500 km
4. The Transantarctic Mountains - 3,500 km
5. The Ural Mountains - 2,500 km
6. The Atlas Mountains - 2,500 km
7. The Appalachian Mountains - 2,414 km
8. The Himalayas - 2,400 km
9. The Altai Mountains - 2,000 km (1,243 mi)
10. The Western Ghats - 1,600 km
11. The Alps - 1,200 km
12. Drakensberg - 1,125 km
13. The Aravalli Range - 800 km

The Andes

- The Andes is the **longest** continental mountain range in the world.
- The Andes is the world's highest mountain range outside of Asia with an **average height of 4000 m**.
- The highest peak is **Mount Aconcagua (6,962 m)** (volcanic origin, but now it's dormant).
- **World's highest volcanoes are in the Andes**.
- **Ojos del Salado (6,893 m)** (active volcano) on the **Chile-Argentina** border is the highest volcano on earth.

The Rockies

- Rocky Mountain range forms a part of the American Cordillera

American Cordillera

- The American Cordillera is a chain of mountain ranges (cordilleras) that consists of an almost continuous sequence of mountain ranges that form the western backbone of the Americas and Antarctica.
- It is also the backbone of the volcanic arc that forms the **eastern half of the Pacific Ring of Fire**.

North Cordillera

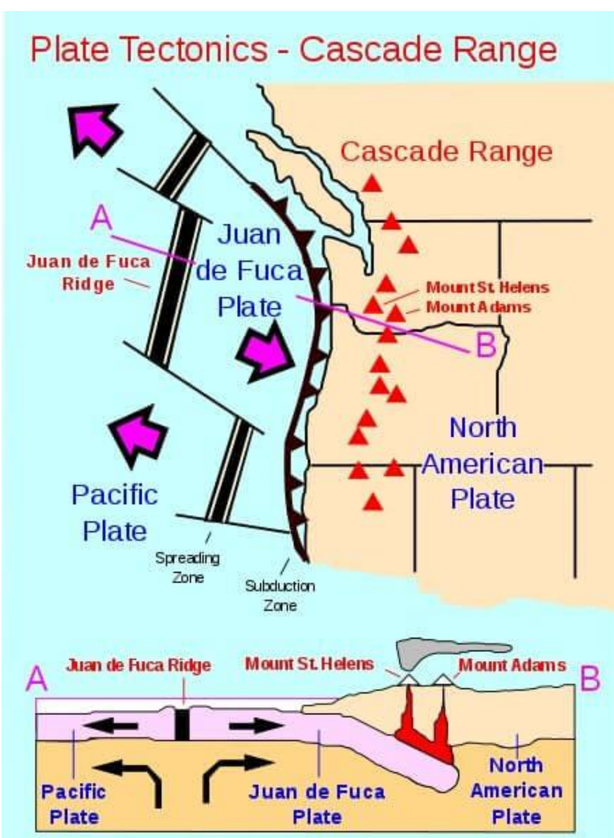
- The ranges of the Cordillera from Mexico northwards are collectively called the North American Cordillera.
- They include the Alaska Range and the Brooks Range in Alaska, main belt of the Rocky Mountains along with the parallel Columbia Mountains, the Sierra Nevada, the Cascades, and various small Pacific coastal ranges.
- In Mexico, the Cordillera continues through the Sierra Madre Occidental and the Sierra Madre Oriental.

South Cordillera

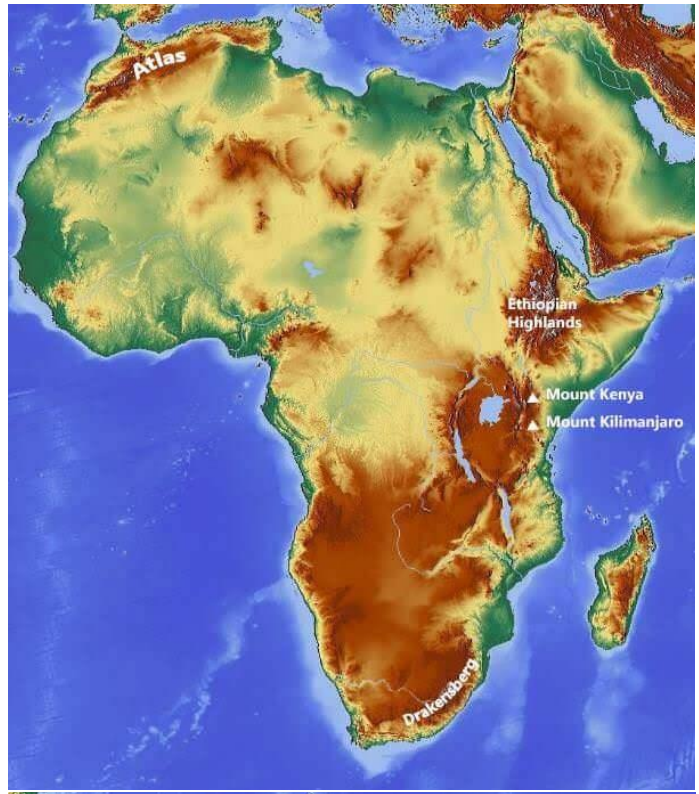
- The Cordillera continues through the mountain ranges of Central America in Guatemala, Honduras, Nicaragua, Costa Rica, and Panama, and becomes the Andes Mountains of South America.
- The Andes with their parallel chains continue to the very tip of South America at **Tierra del Fuego**.
- The Cordillera continues along the Scotia Arc before reaching the mountains of the Antarctic Peninsula.

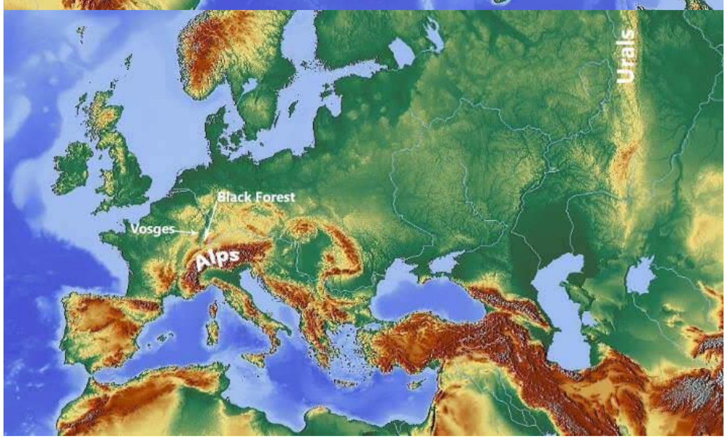
Cascade Range

- The Cascade Range or the Cascades is a major mountain range of western North America.
- The Cascades (Cascade volcanoes) are part of the Pacific Ocean's Ring of Fire.
- They are made up of a band of thousands of **very small, short-lived volcanoes**.
- The Cascade Range has few strikingly large volcanoes, like **Mount St. Helens**.
- The volcanoes and earthquakes in the Cascades arise from a common source: subduction, where the dense **Juan de Fuca oceanic plate** plunges beneath the **North American Plate**.



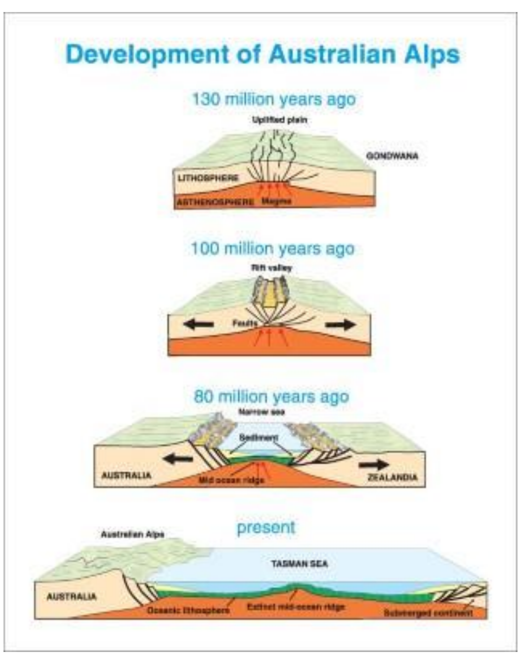
Cascade Volcanism (Wikipedia Commons)





The Great Dividing Range

- The Great Dividing Range, or the Eastern Highlands, is Australia's most substantial mountain.
- It is also known as the **Australian Alps** and was formed due to rifting.



Transantarctic Mountains

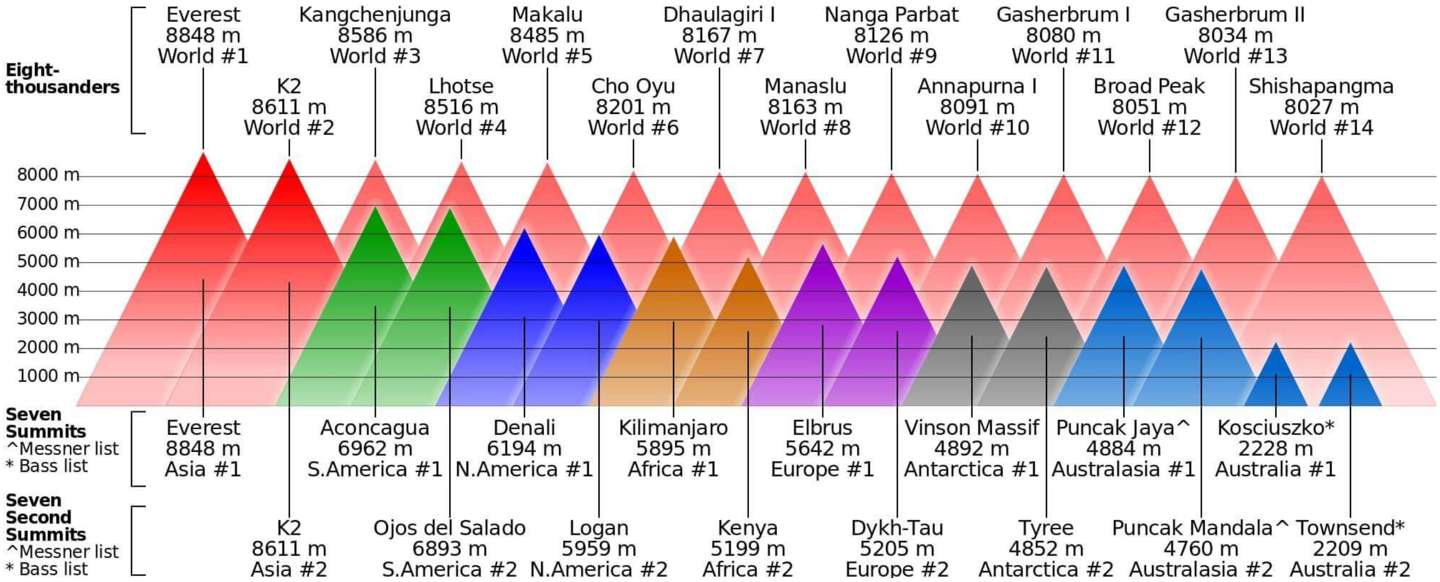
Transantarctic Mountains (krill oil [CC0], via [Wikimedia Commons](#))

The Ural Mountains

- Mountain range that runs approximately from north to south through western Russia, from the coast of the Arctic Ocean to the **Ural River** and northwestern Kazakhstan.
- They are formed due to **Continent-Continent collision of** supercontinent **Laurussia** with the young and weak continent of **Kazakhstania**.
- Their eastern side is usually considered the natural boundary between Europe and Asia.
- Since the 18th century, the mountains have been a **major mineral base of Russia**.

Atlas Mountains

- Mountain range across the north-western stretch of Africa extending about 2,500 km (1,600 mi) through **Algeria, Morocco and Tunisia.**
- The highest peak is **Toubkal** (4,165 metres) in southwestern Morocco.
- These mountains were formed when Africa and Europe collided.



Highest Mountains on Earth

The Himalayas

- The Himalayan range is home to the planet's highest peaks, including the highest, **Mount Everest.**
- Its western anchor, **Nanga Parbat**, lies just south of the northernmost bend of Indus river, its eastern anchor, **Namcha Barwa**, just west of the great bend of the Brahmaputra river (Tsangpo river).
- The range varies in width from 400 kilometres in the west to 150 kilometres in the east.

Geology

- The Himalaya are among the **youngest mountain ranges** on the planet and consist mostly of **uplifted sedimentary and metamorphic rock**.
- According to the modern theory of plate tectonics, their formation is a result of a continental collision or orogeny along the convergent boundary between the Indo-Australian Plate and the Eurasian Plate.
- The Arakan Yoma highlands in Myanmar and the Andaman and Nicobar Islands in the Bay of Bengal were also formed as a result of this collision.

Impact on climate

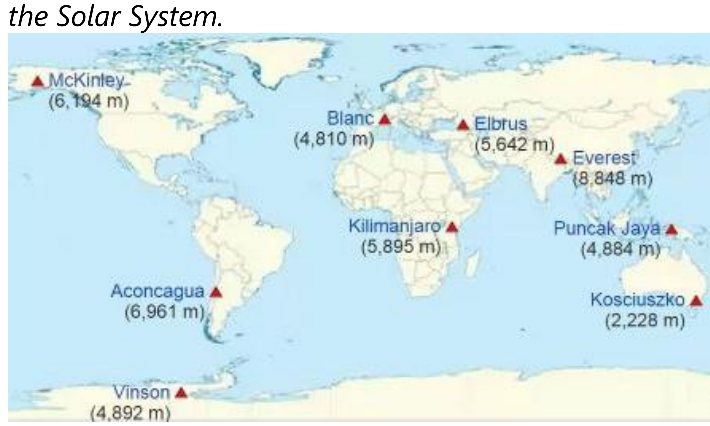
- The Himalayas are believed to play an important part in the formation of Central Asian deserts, such as the **Taklamakan and Gobi**.

The Alps

- The mountains were formed as the African and Eurasian tectonic plates collided.
- Extreme folding caused by the event resulted in marine sedimentary rocks rising by thrusting and folding into high mountain peaks such as **Mont Blanc** (4,810 m) (French–Italian border).
- The Alpine region area contains about a hundred peaks higher than 4,000 m, known as the **four-thousanders.**

Highest mountain peaks

*The highest known mountain on any planet in the Solar System is **Olympus Mons** on Mars (~26 km in elevation). It is also the **highest active volcano** in the Solar System.*



*Highest Mountain of each continents (The other name of Mount McKinley is **Mount Denali**.)*

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Geomorphology Part II

Print Friendly PDF

1. Volcanism

- A volcano is a vent or a fissure in the crust from which lava (molten rock), ash, gases, rock fragments erupt from a magma chamber below the surface.
- Volcanism is the phenomenon of eruption of molten rock, pyroclastics and volcanic gases to the surface through a vent.

1.1 Causes of Volcanism

- There is a **huge temperature difference** between the inner layers and the outer layers of the earth due to the differential amount of radioactivity.
- This temperature difference gives rise to **convectional currents** in the mantle.
- The convection currents in the mantle create convergent and divergent boundaries (weak zones).
- At the divergent boundary, molten, semi-molten and sometimes gaseous material appears on earth at the first available opportunity.
- The earthquakes here may expose fault zones through which magma may escape (**fissure type volcano**).
- At the convergent boundary, the subduction of denser plate creates magma at high pressure which will escape to the surface in the form of violent eruptions.

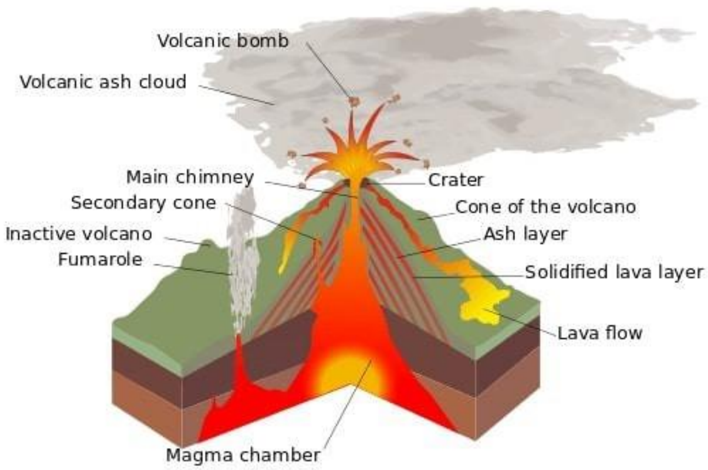
1.2 Lava types

- Magma is composed of molten rock and is stored in the Earth's crust. Lava is magma that reaches the surface through a volcano vent.

Andesitic or Acidic or Composite or Stratovolcanic lava

- These lavas are **highly viscous** with a high melting point.
- They are **light-coloured, of low density, and have a high percentage of silica**.
- They **flow slowly and seldom travel far** before solidifying.
- The resultant volcanic cone is therefore stratified (hence the name **stratovolcano**) and steep-sided.
- The **rapid solidifying of lava** in the vent obstructs the flow of the out-pouring lava, result-

ing in **loud explosions**, throwing out many volcanic **bombs or pyroclasts**.



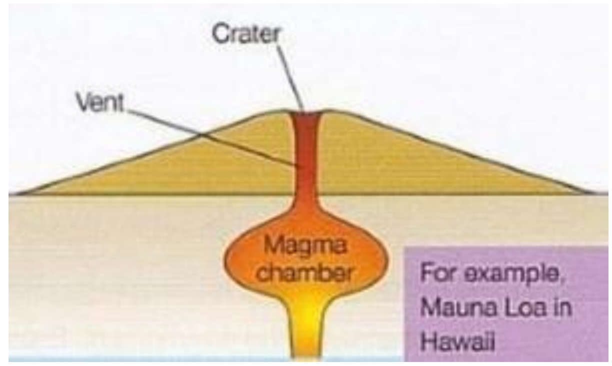
Volcano (Medium69.Cette William Crochot, via Wikimedia Commons)

- Sometimes the lavas are so viscous that they form a **lava plug** at the crater like that of **Mt. Pelée** in Martinique (an island in the Lesser Antilles, Caribbean Islands).
- Andesitic lava flow occurs mostly along the **destructive boundaries** (convergent boundaries).

Lava Plug at the crater

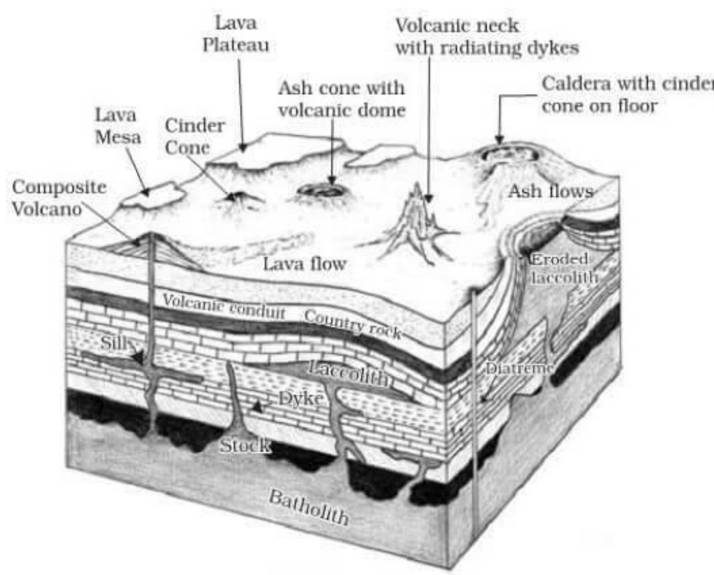
Basic or Basaltic or Shield lava

- These are the **hottest lavas**, about 1,000 °C and are **highly fluid**.
- They are **dark coloured basalt, rich in iron and magnesium but poor in silica**.
- They flow out of volcanic vent **quietly** and are **not very explosive**.
- Due to their **high fluidity**, they flow readily with a speed of 10 to 30 miles per hour.
- They affect extensive areas, spreading out as **thin sheets** over **great distances** before they solidify.
- The resultant volcano is **gently sloping** with a wide diameter and forms a flattened shield or dome.
- Shield type lava flow is common along the **constructive boundaries** (divergent boundary).



1.3 Volcanic Landforms

- Volcanic landforms are divided into **extrusive and intrusive landforms** based on whether magma cools within the crust or above the crust.
- Rocks formed by cooling of magma within the crust are called **Plutonic rocks.**
- Rocks formed by cooling of lava above the surface are called **Igneous rocks**.
- In general, the term 'Igneous rocks' is used to refer all rocks of volcanic origin.



Extrusive and Intrusive volcanic landforms

Extrusive Volcanic Landforms

- Extrusive landforms are formed from material thrown out to the surface during volcanic activity.
- The materials thrown out include lava flows, pyroclastic debris, volcanic bombs, ash, dust and gases such as **nitrogen compounds, sulphur compounds** and minor amounts of **chlorine, hydrogen** and **argon**.

Conical Vent and Fissure Vent

Fissure vent

- A fissure vent (volcanic fissure) is a narrow, linear volcanic vent through which lava erupts, **usually without any explosive activity**.
- The vent is often a few meters wide and may be many kilometres long.
- Fissure vents are common in **basaltic volcanism** (**shield type volcanoes**).

Conical vent

- A conical vent is a narrow cylindrical vent through which magma flows out violently.
- Conical vents are common in **andesitic volcanism** (**composite or stratovolcano**).

Mid-Ocean Ridges

- The system of mid-ocean ridges stretches for more than 70,000 km across all the ocean basins.
- The central portion of the mid-ocean ridges experiences frequent eruptions.
- The lava is **basaltic** (less silica and hence less viscous) and causes the **spreading of the seafloor**.

Composite Type Volcanic Landforms

- They are conical or central type volcanic landforms.
- Along with andesitic lava, large quantities of pyroclastic material and ashes find their way to the surface.
- **Andesitic lava** along with pyroclastic material accumulates in the vicinity of the vent openings leading to the formation of layers, and this makes the mounts appear as a **composite volcano or a stratovolcano** (divided into layers).

- The highest and most common volcanoes have composite cones.
- **Mount Stromboli (the Lighthouse of the Mediterranean)**, Mount Vesuvius, Mount Fuji are examples.

Shield Type Volcanic Landforms

- The **Hawaiian volcanoes** are the most familiar examples.
- These volcanoes are mostly made up of **basaltic lava** (very fluid).
- These volcanoes are not steep.
- They become explosive if somehow water gets into the vent; otherwise, they are less explosive.
- Example: Hawaiian volcanoes **Mauna Loa** (active shield volcano) and **Mauna Kea** (dormant shield volcano).

Fissure Type Flood Basalt Landforms (Lava Plateaus)

- Sometimes, a very thin magma escapes through cracks and fissures in the earth's surface and flows after intervals for a **long time**, **spreading over a vast area**, finally producing a **layered, undulating (wave-like), flat surface**.

- Example: **Siberian Traps**, **Deccan Traps**, **Snake Basin, Icelandic Shield, Canadian Shield**.

Crater

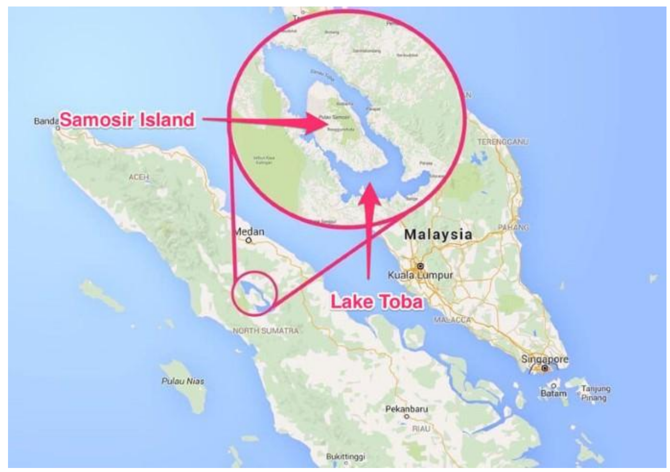
- A crater is an inverted cone-shaped vent through which the magma flows out. When the volcano is not active the crater appears as a bowl-shaped depression.

The crater of Mount Fuji, Japan

- When water from rain or melted snow gets accumulated in the crater, it becomes a **crater lake**.

Caldera

- In some volcanoes, the magma chamber below the surface may be emptied after volcanic eruptions.
- The volcanic material above the chamber **collapses** into the empty magma chamber, and the collapsed surface appears like a large cauldron-like hollow (tub shaped) called the caldera.
- When water from rain or melted snow gets accumulated in the caldera, it becomes a **caldera lake** (in general, the caldera lakes are also called crater lakes).
- Due to their unstable environments, some crater lakes exist only intermittently. Caldera lakes, in contrast, can be quite **large and long-lasting**.
- For example, **Lake Toba (Indonesia)** formed after its supervolcanic eruption around 75,000 years ago. It is the **largest crater lake in the world**.



- Mount Mazama (Cascade Volcanic Arc, USA) collapsed into a caldera, which was filled with water to form Crater Lake (the literal name of the lake formed by the collapse of Mount Mazama is 'Crater Lake'!).

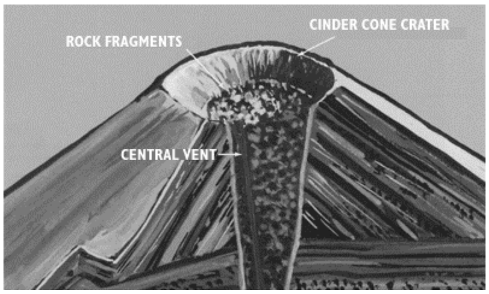
Caldera lake of Mount Mazama

A crater lake, in general, could be of volcanic origin (volcanic crater lake, volcanic caldera lake) or due to a meteorite impact (meteor

crater or impact crater), or in the crater left by an artificial explosion caused by humans. Lonar Lake, also known as Lonar crater (Lonar, Buldhana district, Maharashtra) was created by a meteor impact during the Pleistocene Epoch.

Cinder cone

- A cinder cone is a **steep circular or oval-shaped hill of loose pyroclastic fragments** that have been built around a volcanic vent.



Lava Dome

- A lava dome (volcanic dome) is a mound-shaped protrusion (a structure that extends outside the surface) resulting from the slow extrusion (coming out) of viscous lava from a volcano.
- In Lava domes, viscous **magma piles up** around the vent.
- The magma does not have enough gas or pressure to escape, although sometime later after sufficient pressure builds up, it may erupt explosively.

Lava dome protruding from a volcanic vent

Pseudo volcanic features

- Pseudo volcanic features are certain topographic features that resemble volcanic forms but are of non-volcanic origin. They include **meteorite crater, salt plugs, and mud-volcanoes**.

Meteorite Craters

- Meteorite craters are impact craters that are formed when a meteorite strikes the surface of the earth creating a huge depression.

Salt plug or salt dome

- A salt plug is formed when underground salt deposits at high pressure become ductile and pierce through the overlying sediments to create a diapir (a dome-like intrusion forced into brittle overlying rocks.
- Salt extrusions may take the form of salt hills which exhibit volcanic crater like features.
- Salt structures are impermeable and can lead to the formation of a **stratigraphic trap** (an impermeable layer capable of retaining hydrocarbons. **Structural traps**, in contrast, are cracks in faults and folds that can retain hydrocarbons).

Mud-volcanoes

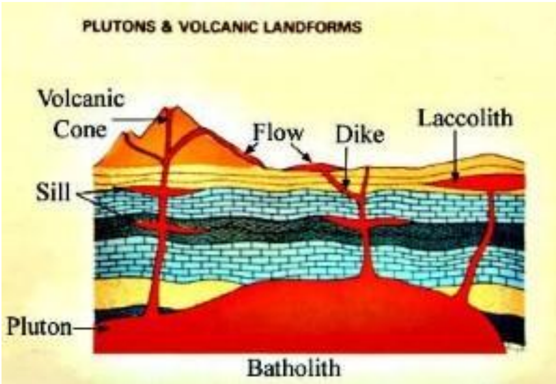
- A mud volcano or mud dome is a landform created by the eruption of mud, water and gases.
- Mud-volcanoes have a similar shape to other types of volcanoes and contains several cones.
- They are usually found near the subduction zones and hot springs.
- Other mud volcanoes, entirely of a **non-volcanic origin**, occur near oil-fields where **methane and other volatile hydrocarbon gases** mixed with mud force their way upward.

Intrusive Volcanic Landforms

- Intrusive landforms are formed when magma cools within the crust.

Batholiths

- These are large **granitic** rock bodies formed due to solidification of hot magma **inside the earth**.
- They appear on the surface only after the denudation processes remove the overlying materials.
- Batholiths **form the core of huge mountains** and may be exposed on the surface after erosion.



Laccoliths

- These are large dome-shaped intrusive bodies connected by a pipe-like conduit from below.
- These are intrusive counterparts of an exposed domelike batholith.
- The **Karnataka plateau** is spotted with dome hills of granite rocks. Most of these, now exfoliated, are examples of laccoliths or batholiths.

Lapolith

- As and when the lava moves upwards, a portion of the same may tend to move in a **horizontal** direction wherever it finds a weak plane. It may get rested in different forms.
- In case it develops into a saucer shape, concave to the sky body, it is called Lapolith.

Phacolith

- A wavy mass of intrusive rocks, at times, is found at the base of synclines or the top of the anticline in folded igneous strata.
- Such wavy materials have a definite conduit to source beneath in the form of magma chambers (subsequently developed as batholiths). These are called the Phacoliths.

Sills

- The near horizontal bodies of the intrusive igneous rocks are called sill. The thinner ones are called sheets.

Dykes

- When the lava makes its way through cracks and the fissures developed in the land, it solidifies almost **perpendicular** to the ground.
- It gets cooled in the same position to develop a **wall-like structure**. Such structures are called dykes.
- These are the most commonly found intrusive forms in the western Maharashtra area.
- These are considered the **feeders for the eruptions** that led to the development of the **Deccan traps**.

1.4 Volcanism Types

- Four types of volcanism can be identified.
  1. **Exhalative (vapour or fumes)**
  2. **Effusive (lava outpouring)**
  3. **Explosive (violent ejection solid material)**
  4. **Subaqueous Volcanism**

Exhalative (vapour or fumes)

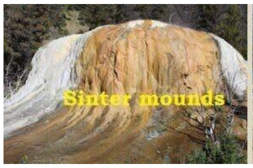
This includes the discharge of material in **gaseous forms**, such as

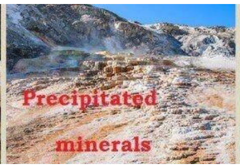
- ✓ **steam, fumes and**
- ✓ **Hydrochloric acid**
- ✓ **Ammonium chloride**
- ✓ **Sulphur dioxide**
- ✓ **Carbon dioxide**
- ✓ **Carbon monoxide.**
- ✓ **Hydrogen sulphide**
- ✓ **Hydrogen**
- ✓ **Nitrogen**

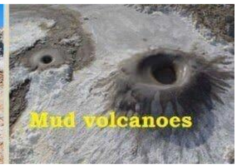
Fumaroles and Solfataras

- These gases may escape through vents which are in the form of **hot springs, geysers, fumaroles and solfataras.**
- This kind of volcanism indicates the volcano is reaching its **extinction**.

- Associated landforms are called sinter mounds, cones of precipitated minerals and mud volcanoes.



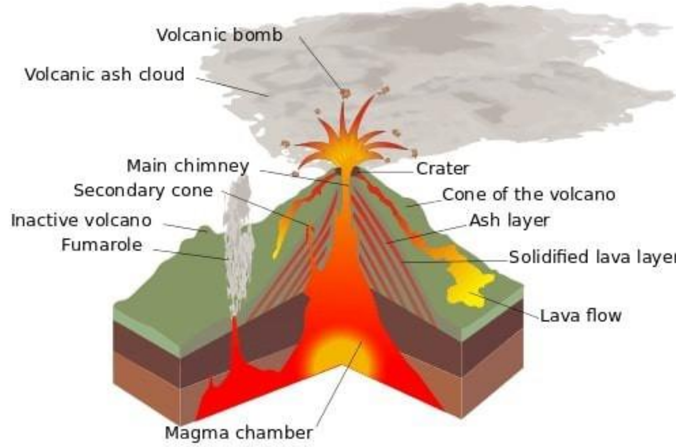




Effusive (Lava outpouring)

- Effusive: relating to or denoting igneous rocks poured out as lava and later solidified.
- This type of activity refers to **abundant outpourings of basaltic lava from a vent or fissure**.
- The **Deccan traps**, which are composed of such lavas today, cover an area of 5,00,000 square km. The original extent of the formation must have been at least 14 lakh square km.
- **Columnar structure** is sometimes developed in fine-grained plateau basalts (Deccan Traps near Mumbai).

Explosive (Violent ejection of solid material)



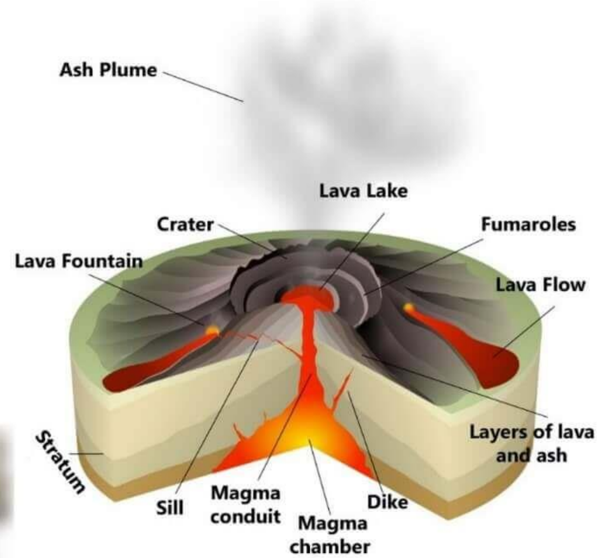
Volcano (William Crochot, via Wikimedia Commons)

- This type of activity results in fragmentation and ejection of solid material through vents.
- Volcanic eject that settles out of air or water is sometimes called pyroclastic sediments.
- **Tephra:** all fragmented ejects from the volcanoes.
- **Ash:** The finest sand-sized tephra
- **Lapilli:** These are gravel-sized particles either in the molten or solid state.
- **Blocks:** Cobble or boulder-sized solid ejecta.
- **Bombs:** a lump of lava thrown out by a volcano.
- **Tuff:** Layers of volcanic dust and ashes.
- Smaller particles like lapilli and ash travel through air for many kilometres.
- The heavier particles like bombs and blocks fall in the vicinity of the vent.

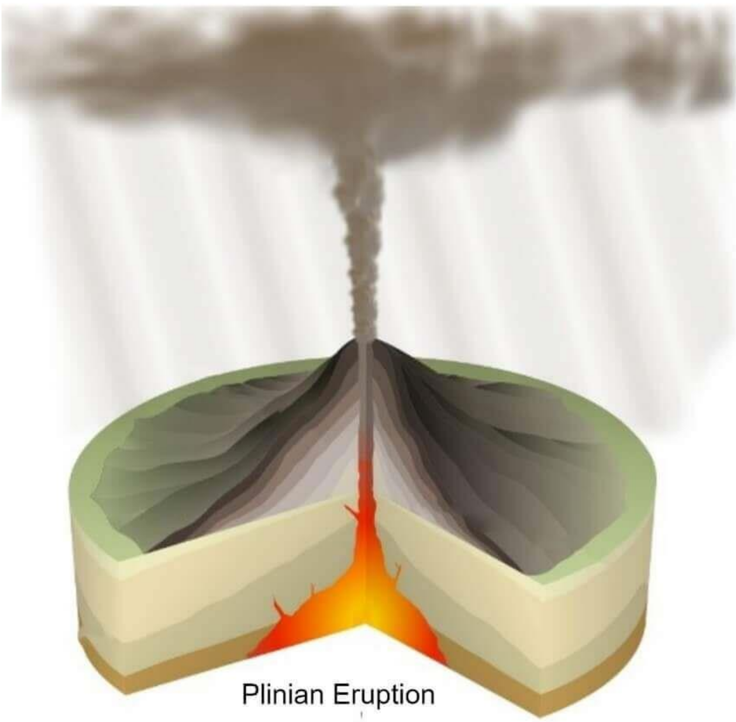
Subaqueous Volcanism

- This type of volcanic activity takes places **below the surface of the water**.
- When lava is in contact with water, it consolidates to produce a structure like that of a heap of pillows.

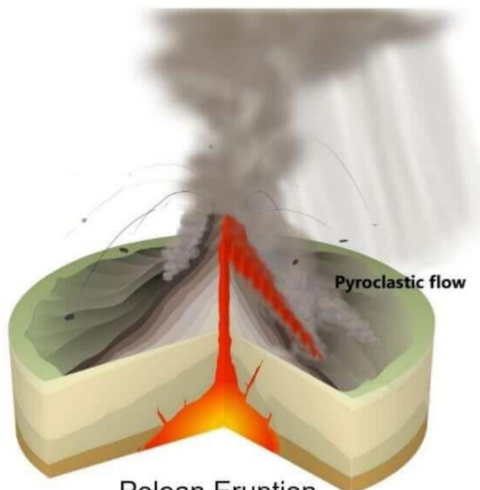
Icelandic Eruption



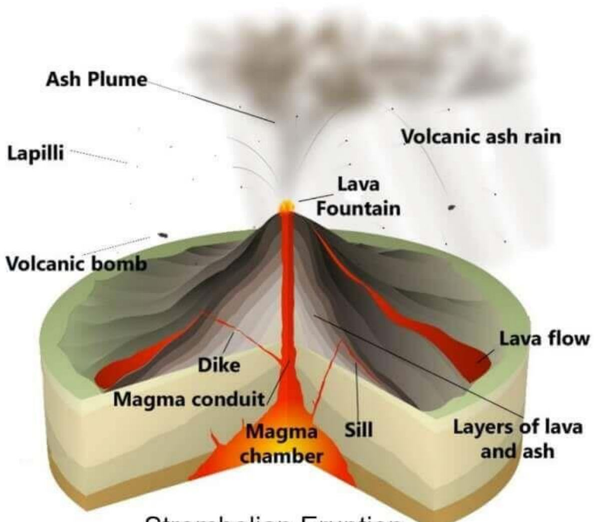
Hawaiian Eruption



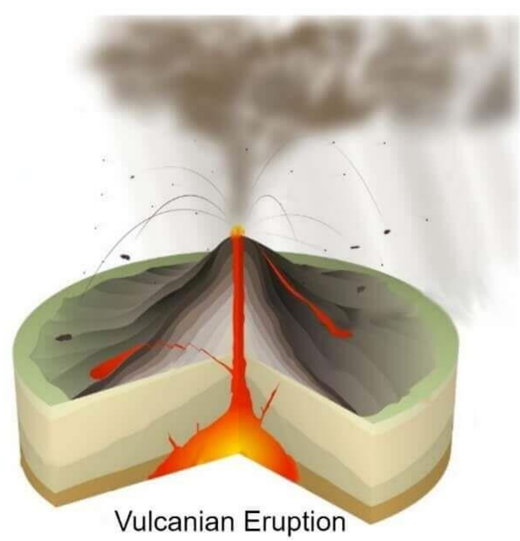
Plinian Eruption



Pelean Eruption



Strombolian Eruption



Vulcanian Eruption

- Highly viscous lavas erupted at lesser depths develop glassy margins on pillows. The related volcanic product is **hyaloclastite**. Most hyaloclastites identified are in Iceland.

1.5 Eruptive Volcanism Types

Hawaiian Eruption

- Hawaiian eruptions are a type of volcanic eruption, named after the Hawaiian volcanoes.
- They are the **calmest types** characterised by the **effusive eruption** of very fluid **basalt-type lavas** from craters, lava lakes, fissures with **little-ejected material** (**low gaseous content)**.
- A single flow spreads widely over open slopes or flows down the valleys as lava rivers.

- Steady production of small amounts of lava builds up the large, broad form of a **shield volcano**.

- Eruptions **are not centralised** at the main summit as with other volcanic types and often occur at vents around the summit and from fissure vents radiating out of the centre.

Icelandic Eruptions

- The Icelandic type is characterized by effusions of molten basaltic lava that flow from long, parallel fissures.
- Such outpourings often build lava plateaus. E.g. **Deccan Traps, Siberian Traps**.

Strombolian Eruption

- Strombolian eruptions are a type of volcanic eruption, named after Stromboli (Lipari Islands, Italy).
- Stromboli Volcano (**lighthouse of the Mediterranean**) has been erupting continuously for centuries.
- Strombolian eruptions are driven by the **continuous formation of large gas bubbles** within the magma.
- Upon reaching the surface, the bubbles burst with a loud pop, throwing magma in the air.
- Because of the high gas pressures associated with the magma, **episodic explosive eruptions** occur (erupts once in every few minutes – fountain like eruption).

Anak Krakatoa

- The greatest volcanic explosion known to humans is perhaps that of Krakatoa (**Plinian**) eruption in 1883.
- The explosion could be heard in Perth, Australia, almost 3,000 miles away.
- More than 36,000 people died, mostly from the tsunamis that followed the explosion.
- At present, Krakatoa (Krakatau or Krakatoa Archipelago) is a group of four small volcanic islands in the **Sunda Strait**, **between Java and Sumatra**.
- Three of the four islands are the remnants of the previous volcanic structure destroyed in 1883 eruption.

- The fourth island, **Anak Krakatau** (meaning Child of Krakatoa) emerged in the 1920s from the caldera formed in 1883. It is the current location of eruptive activity.
- In recent times, Anak Krakatau has become increasingly active with [Strombolian type eruptions]().

2018 Sunda Strait tsunami

- The eruption of Anak Krakatoa in December 2018 and subsequent collapse of the southwest sector of the volcano, including the summit, triggered the tsunami that has killed more than 400 people.
- While Indonesia possessed a tsunami warning system for tsunamis caused by earthquakes, there were none in place for volcanic tsunamis, and hence there were no early warnings.

Vulcanian Eruption

- In Vulcanian eruptions, intermediate viscous magma within the volcano makes it difficult for gases to escape.
- This leads to the **build-up of high gas pressure**, eventually resulting in an **explosive eruption**.
- They are also more explosive than their Strombolian counterparts, with eruptive columns often reaching between 5 and 10 km high.
- The molten lava is explosively ejected as a great cauliflower cloud of dark tephra. Bombs, blocks, lapilli and other ejecta fall in the surrounding area.
- After each eruption cycle, **the volcano is dormant for decades or centuries**.

Plinian Eruption

- Plinian eruptions (or **Vesuvian**) are a type of volcanic eruption, named after the historical eruption of **Mount Vesuvius** in 79 AD that buried the Roman town of Pompeii.
- In Plinian eruptions, dissolved volatile gases stored in the magma are channelled to the top through a narrow conduit (pipe-like structure).
- The gases erupt into a **massive column** of the gas plume that reaches up **2 to 45 km into the atmosphere**.
- As it reaches higher the plume expands and becomes less dense and convection and thermal expansion of volcanic ash drive it even further up into the stratosphere.
- At the top of the plume, powerful prevailing winds drive the plume in a direction away from the volcano.

Mount Vesuvius

- Mount Vesuvius is a stratovolcano in Bay of Naples, Italy.
- It is best known for its **Plinian type** eruption in AD 79 that led to the destruction of the Roman cities of Pompeii, Herculaneum and others. More than 1,000 people died in the eruption.
- The eruption ejected a cloud of stones, ashes and volcanic gases to a height of more than 30 km.
- Vesuvius has erupted many times since. Today, it is regarded as **one of the most dangerous volcanoes** in the world because of the population of 3,000,000 people living nearby.
- The eruptions alternated between Plinian and Peléan with most of them being Plinian type.

Mount St. Helens

- Mount St. Helens is an **active** volcano located in the Cascade Volcanic Arc.

- Mount St. Helens is most notorious for its major 1980 Plinian type eruption that killed more than 50 people.

Mount Tambora

- Mount Tambora is an active volcano located in Lesser Sunda Islands of Indonesia.

Mount Tambora (Google Maps)

- Tambora is known for its major Plinian type eruption in 1815.
- The 1815 eruption was one of the most powerful in recorded history, with a Volcanic Explosivity Index (VEI) of 7.
- The ash from the eruption column dispersed around the world and **lowered global temperatures**, in an event sometimes known as the **Year Without a Summer** in 1816.
- More than 71,000 people died due to **famines** caused in Europe and America.

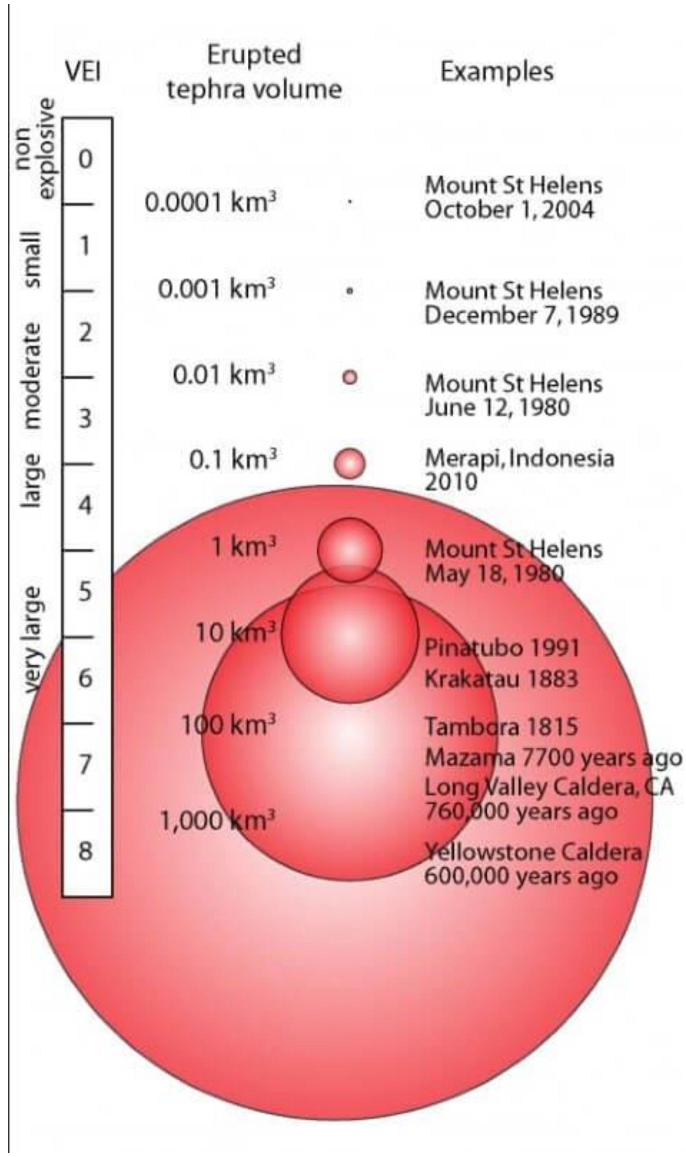
Nevado del Ruiz

- Nevado del Ruiz is a volcano located in Colombia.
- The volcano usually generates Vulcanian to Plinian eruptions, which produce **destructive lahars**.
- In 1985, a small eruption produced an enormous lahar that buried and destroyed the towns causing an estimated 25,000 deaths.

Lahar

- A lahar is a **violent type of mudflow or debris flow** composed of a slurry of pyroclastic material, rocky debris and water. The material flows down from a volcano, typically along a river valley.
- Lahars are extremely destructive as they flow fast and can engulf entire settlements in a matter of minutes.

Lahar



Volcanic Explosivity Index (USGS)

Mount Pinatubo

- Mount Pinatubo is an active volcano located in the Luzon island of the Philippines.

- Pinatubo Plinian type eruption in 1991 brought about **dramatic changes in the global environment**.
- The amount of sulfuric ash it sent into the **stratosphere** cooled global ground temperatures by 1°C for the next two years, and **ozone depletion** temporarily increased substantially.
- The eruption resulted in more than 700 deaths.

Pelean Eruption

- Peléan eruptions are a type of volcanic eruption, named after the volcano **Mount Pelée in Martinique**.
- In Peléan eruptions, a large amount of gas, dust, ash, and lava fragments are blown out **laterally** by the **collapse of the cinder cone**. The sudden burst of lava dome causes the collapse of the cinder cone.
- This type of eruption results in very viscous, gas-rich, acidic lava **breaking out laterally and flowing out violently** at high speed causing massive destruction on its path.
- Hot gas and lava mixture are not carried skyward to become cold tephra but spreads downslope as a **nuce ardente**, continuing to **cushion** the flowing fragments.

Pelean Eruption

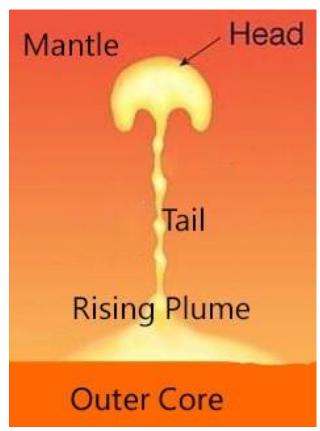
Mount Pelée

- Mount Pelée is a volcano at the northern end of Martinique Island (French overseas department in the Lesser Antilles island arc of the Caribbean).
- The volcano is famous for its Pelean type eruption in 1902 that killed about 30,000 people.
- Most deaths were caused by pyroclastic flows which destroyed the city of Saint-Pierre.

1.6 Hotspot Volcanism

- Hotspot volcanism is a type of volcanism that typically occurs at the **interior parts of the lithospheric plates** rather than at the zones of convergence and divergence (plate margins).
- The **Iceland Hotspot** and **Afar Hotspot** which are situated at the divergent boundary are exceptions.
- Hotspot volcanism explains the so-called **anomalous volcanism** — the type that occurs far from plate boundaries, like in Hawaii and Yellowstone, or in excessive amounts along mid-ocean ridges, as in Iceland.
- Well known hotspots include the **Hawaiian Hotspot, the Yellowstone Hotspot, the Reunion Hotspot**.
- Hotspot volcanism occurs due to abnormally hot centres in the mantle known as **mantle plumes**.
- Most of the mantle plumes lie far from tectonic plate boundaries (e.g. Hawaiian Hotspot), while others represent unusually large-volume volcanism near plate boundaries (e.g. Iceland Hotspot).

Mantle Plumes

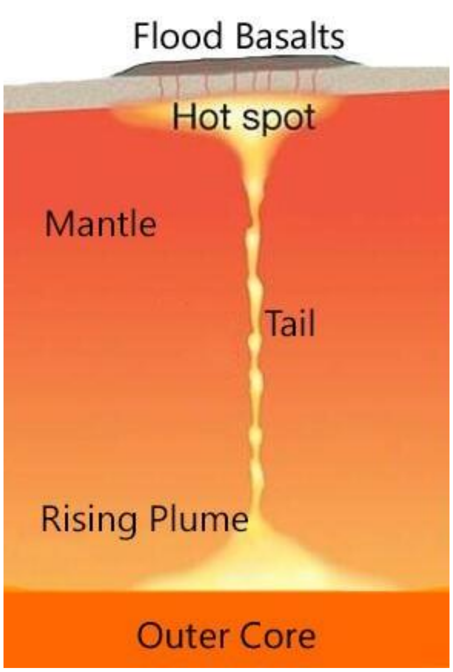


- A mantle plume is **convection of abnormally hot rock** (magma) within the Earth's mantle.
- Unlike the larger convection cells in the mantle which change their position over geological timescales, the position of the mantle plumes seems to be relatively **fixed**.

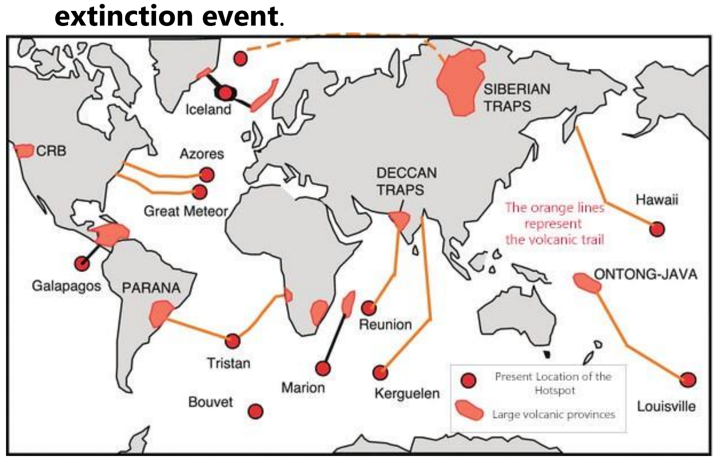
- Mantle plumes are theorised to form at the **core-mantle boundary** where an abnormally hot plume of rock accumulates.
- The mantle plume is shaped like a mushroom with a long conduit (tail) connecting the bulbous head to its base. The head expands in size as the plume rises.
- The plume rises through the Earth's mantle becoming a diapir (dome-like intrusion forced into brittle overlying rocks) in the upper mantle (lower parts of the lithosphere).

Mantle plumes and flood basalt volcanism (large igneous provinces)

- On the continents, mantle plumes have been responsible for **extensive accumulations of flood basalts**.
- Mantle plumes (few hundred kilometres in diameter) and rise slowly towards the upper mantle.
- When a plume head encounters the base of the lithosphere, it flattens out and undergoes widespread decompression melting to form **large volumes of basalt magma**.
- The basaltic magma may then erupt onto the surface through a series of fissures giving rise to **large igneous provinces**. When created, these regions often occupy several thousand square kilometres.



- Large igneous provinces, such as **Iceland, Siberian Traps, Deccan Traps, and Ontong Java Plateau**, are extensive regions of basalts on a continental scale resulting from flood basalt eruptions.
- Very large amounts of volcanic material in large igneous provinces can cover huge areas with lava and volcanic ash, causing **long-lasting climate change** (such as the triggering of a small ice age).
- The **Réunion hotspot** (produced the **Deccan Traps about 66 million years ago**) coincides with the Cretaceous–Paleogene extinction event (also known as Cretaceous-Tertiary (K-T) extinction or — fifth and the most recent mass extinction).
- Though a meteor impact (**Chicxulub Crater**) was the cause of the extinction event, the volcanic activity may have caused environmental stresses.
- Additionally, the largest flood basalt event (the **Siberian Traps**) occurred around 250 million years ago and was coincident with the largest mass extinction in history, the **Permian–Triassic extinction event**.

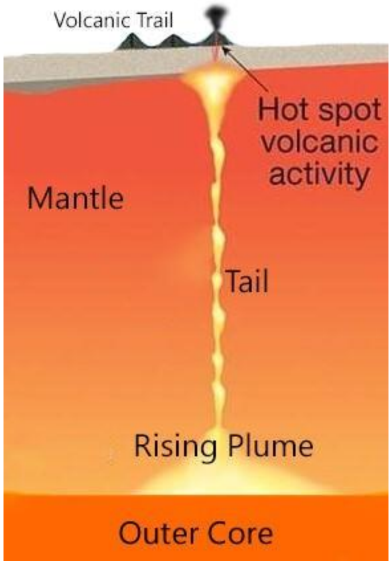


Large Igneous Provinces (Credits: Gautam Sen)

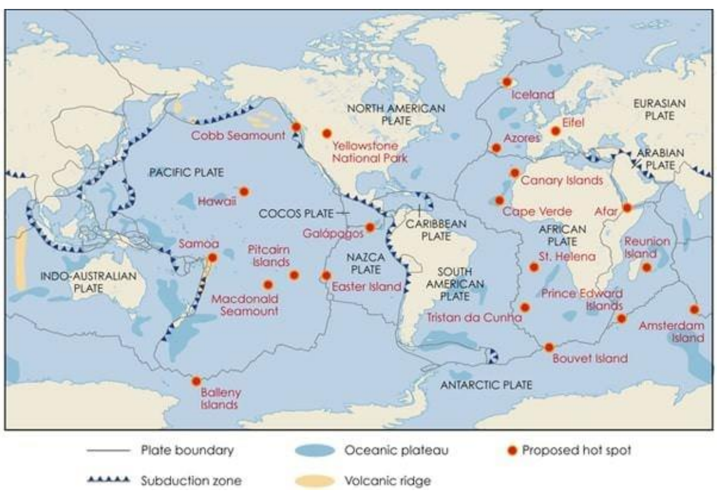
Mantle plumes and volcanic hotspots

- The mantle plume provides a continuous supply of **abnormally hot magma** to a **fixed location** in the mantle referred to as a **hotspot**.
- The abnormally high heat of the hotspot facilitates the **melting of rock at the base of the lithosphere**.
- The melted rock, known as magma, which is at high pressure, often pushes through cracks in

the crust to form hotspot volcanoes (e.g. Mount Mauna Kea).



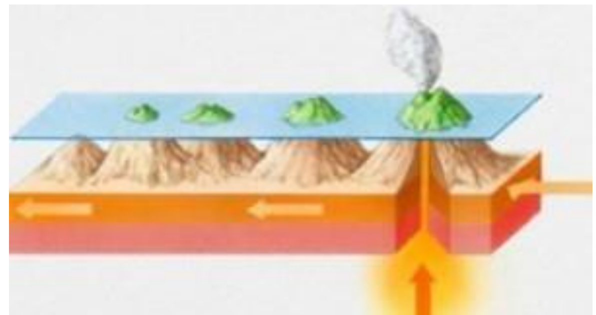
Distribution of hotspots

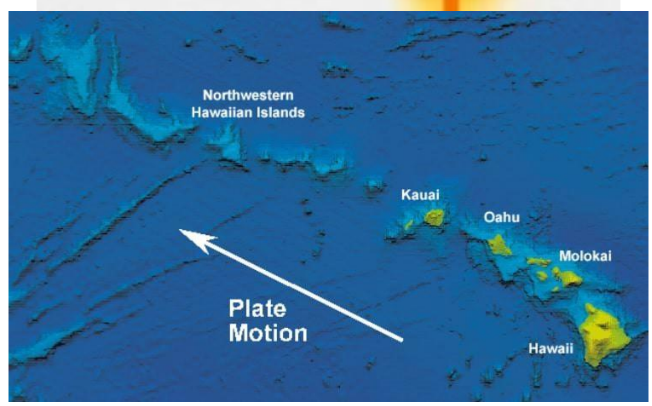


Distribution of hotspots (Credits: K. Cantner, Earth Magazine)

Hotspot volcano chain

- A volcano above a hotspot does not erupt forever. Attached to the tectonic plate below, the volcano moves and is eventually cut off from the hotspot (**plate moves overhead relative to the fixed plume source**).
- Without any source of heat, the volcano becomes extinct and cools. This cooling causes the rock of the volcano and the tectonic plate to become denser. Over time, the dense rock **sinks and erodes**.
- A new and active volcano develops over the hotspot creating a continuous cycle of volcanism, forming a **volcanic arc** that parallels plate motion.
- The Hawaiian Islands chain in the Pacific Ocean is the best example. The islands and seamounts (submarine mountains) exhibit **age progression**, with the youngest near present-day Hawaii and the oldest near the **Aleutian Trench**.



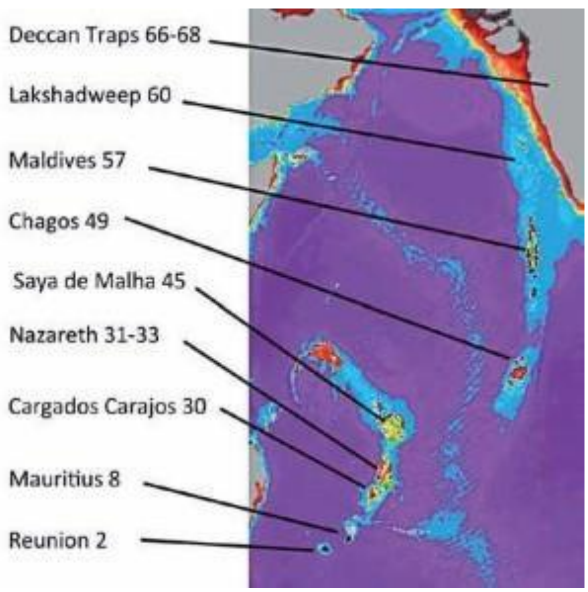


- Other hotspots with time-progressive volcanic chains behind them include **Réunion, the Chagos-Laccadive Ridge, the Louisville Ridge, the Yellowstone**.
- Some hotspots lack time-progressive volcanic trails, e.g., **Iceland, the Galapagos, the Azores, the Canaries**.

Reunion Hotspot

- The Reunion hotspot is a volcanic hotspot which currently lies under the **Island of Reunion in the Indian Ocean**. The hotspot is believed to have been active for over 66 million years.
- A huge eruption of this hotspot 66 million years ago is thought to have laid down the **Deccan Traps** and opened a rift which separated India from the Seychelles Plateau.
- As the Indian plate drifted north, the hotspot continued to punch through the plate, creating a string of volcanic islands and undersea plateaus.

- The **Chagos-Laccadive Ridge (Lakshadweep is a part of this ridge)** and the southern part of the **Mascarene Plateau** are volcanic traces of the Reunion hotspot.
- The **Laccadive Islands, the Maldives, and the Chagos Archipelago** are **atolls** resting on former volcanoes created 60-45 million years ago that subsequently submerged below sea level.
- About 45 million years ago the mid-ocean rift crossed over the hotspot, and the hotspot passed under the African Plate.
- The hotspot appears to have been relatively quiet from 45-10 million years ago, when activity resumed, creating the **Mascarene Islands, which include Mauritius, Reunion, and Rodrigues**.



Mantle plumes and divergence (plate tectonics)

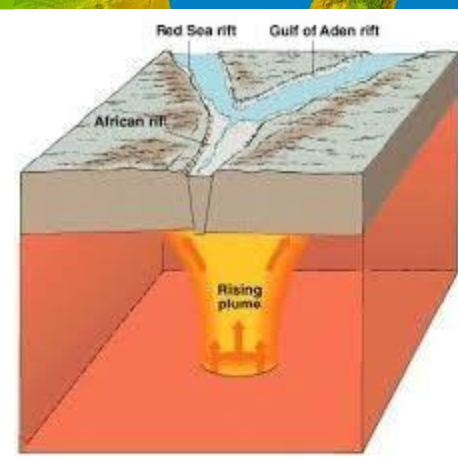
Mains 2018: What is a mantle plume and what role it plays in plate tectonics?

Backdrop: In early 2018, a large crack made a sudden appearance in south-western Kenya adding fuel to the debate on the breakup of Africa.

Also, the Yellowstone supervolcano has evoked a lot of interest in recent times ([The Yellowstone supervolcano is a disaster waiting to happen]()).

- Mantle plumes are convection currents on a small scale (in comparison to major convection currents in the mantle).
- The plume rises through the centre and diverges in all directions just below the lithospheric plates.
- The divergence of the plume exerts extensional stress (tensile stress) on the lithospheric plate above and causes the plate to stretch and rupture and then diverge to form a **rift** in between.
- **Afar hotspot** in Africa got ruptured due to the mantle plume below. At the **Afar triple junction**, the Arabian, African, and Somali plates are moving away from the centre.

Afar Triple Junction: The Afar Triple Junction is located along a divergent plate boundary dividing the Nubian, Somalian, and Arabian plates. Here, the Red Sea Rift meets the Aden Ridge and the East African Rift.



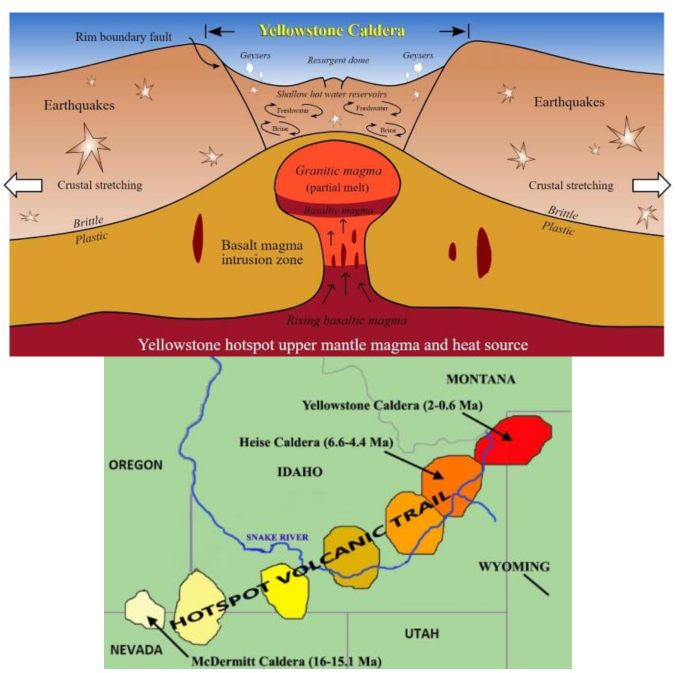
Mantle plumes and uplifted landforms (epeirogenic movements)

- As the plume reaches the lithosphere, it spreads out laterally doming zones of the Earth. E.g. The Ethiopian Highlands.
- The **Ethiopian Highlands** began before the beginning of the Tertiary Period (66 mya), as the mantle plume below uplifted a broad dome of the ancient rocks of the Arabian-Nubian Shield.
- Around 30 million years ago, a flood basalt plateau began to form, piling layers upon layers of voluminous fissure-fed basaltic lava flows.
- The opening of the Great Rift Valley split the dome of the Ethiopian Highlands into three parts — two parts to the east and west of the rift and the third part consist of the mountains of the southern Arabian Peninsula (geologically a part of the ancient Ethiopian Highlands, now separated by the rifting).

Mantle plumes and thinning of the continental crust

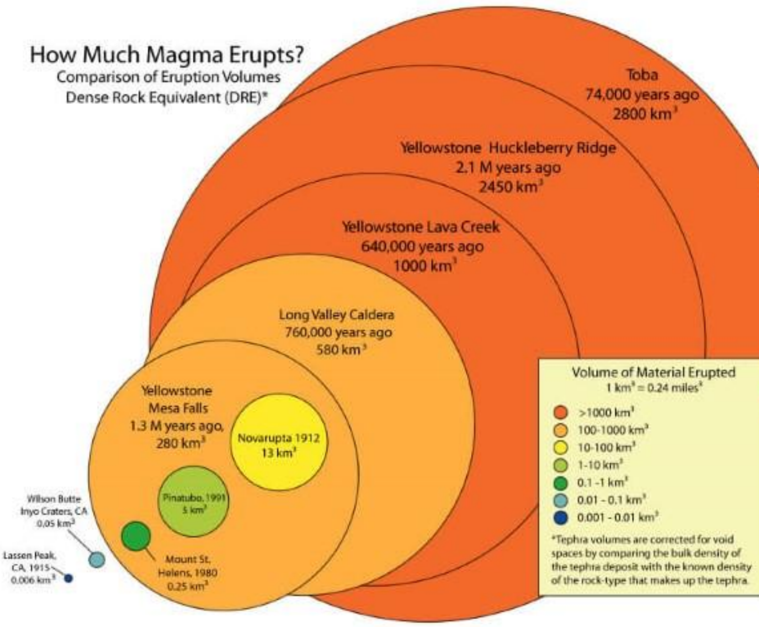
- The Yellowstone hotspot is an example for a **hotspot developed beneath a continent**.
- Here the mantle plume has been **thinning the part of America's crust** (divergence of the plume exerts extensional stress on the lithospheric plate) above and is likely to thin the whole of the surface opening the door for the underlying **supervolcano**.

Mantle plumes and Supervolcanoes



Yellowstone hotspot volcanic trail

- A supervolcano is a large volcano in which the volume of magma deposits that can erupt to the surface is greater than 1,000 cubic kilometres.
- Supervolcanoes occur when a large volume of magma accumulates under the lithospheric plate but is unable to break through it.
- Over time (thousands of years), the pressure keeps building up until the plate can no longer contain the pressure, resulting in an eruption.
- This can occur at **hotspots (for example, Yellowstone Caldera)** or **subduction zones (for example, Toba Caldera Lake**, Sumatra Island, Indonesia).



- A supervolcanic super-eruption can cause a **small-scale or regional extinction event**.
- The ash from such a volcano can engulf the entire counties and major portions of the continent in which they occur.
- The gas and dust ejected from the volcano can blanket the earth's troposphere for months or years to come causing **severe climate change**.
- There were more than 40 super-eruptions in earth's history, and the most recent occurred in New Zealand's **Lake Taupo** (Taupo supervolcano) some 26,000 years ago.
- The Oruanui eruption of the Taupo Volcano was the world's largest known eruption in the past

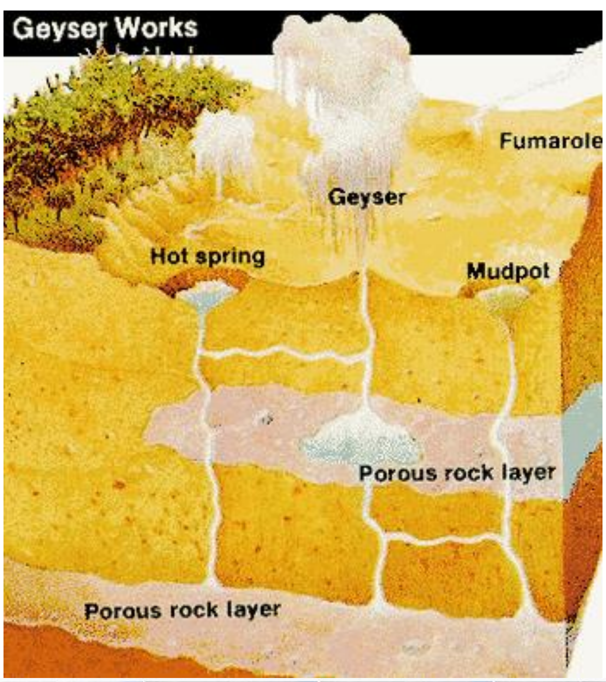
70,000 years, with a Volcanic Explosivity Index of 8.

- The Toba eruption (Indonesia) 74,000 years ago, caused by shifting tectonic plates triggered a dramatic global winter.

1.7 Geysers and Hot Springs

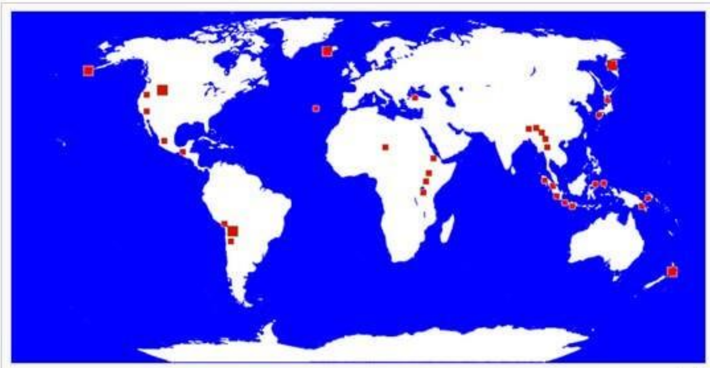
- Water that percolated into the porous rock is subjected to intense heat by the underlying hard rock which is in contact with hot magma in the mantle or the lower part of the crust.
- Under the influence of intense heat, the water in the capillaries and narrow roots in the porous rock undergoes intense expansion and gets converted to steam resulting in high pressure.
- When this steam or water at high pressure finds a path to the surface through narrow vents and weak zones, appear at the surface as geysers and hot water springs.

Geyser	Hot water spring
Steam or water at high pressure, along its path, gets accumulated in small reservoirs, fissures and fractures. Once the pressure exceeds the threshold limit, the steam bursts out to the surface disrupting the water at the mouth. Hence the name geyser.	Steam or water at high pressure smoothly flows to the top through the vent and condense at the surface giving rise to a spring.
Silicate deposits at mouth give them their distinct colours.	Some springs are very colourful because of the presence of **cyanobacteria** of different colours.
Generally, geysers are located near active volcanic areas. **Iceland** is famous for its geysers.	Found all across the world
Usually, a carter like structure is created at the mouth.	



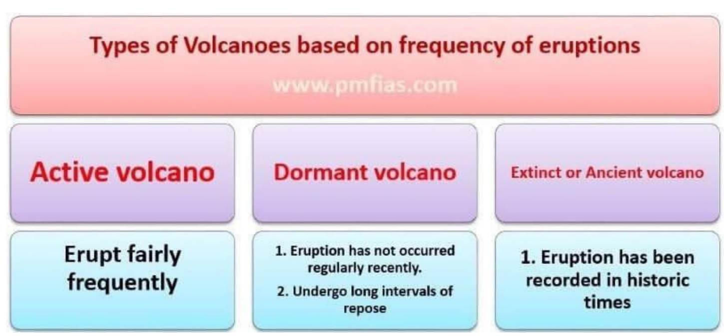
1. Steam rises from heated water
2. Pulses of water swell upward
3. Surface is broken
4. Ejected water spouts upward and falls back down into the pipe

- Almost all the world's geysers are confined to three major areas: **Iceland, New Zealand and Yellowstone Park of U.S.A**.



Distribution of major geysers in the world.

1.8 Extinct, Dormant and Active volcanoes

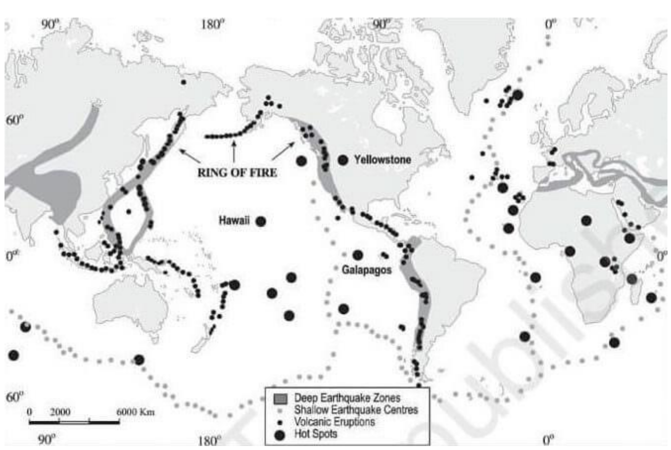


- **Barren Island in the Andaman and Nicobar Islands**, Anak Krakatoa are active volcanoes

- **Mount Kilimanjaro** (it has three volcanic cones), is a **dormant** stratovolcano in Tanzania.
- **Mount Kenya** is an extinct stratovolcano.
- The **Barren Island in the Andaman and Nicobar Islands** of India which was thought to be extinct erupted recently.
- Before a volcano becomes extinct, it passes through a **waning stage** during which steam and other hot gases and vapours are exhaled. These are known as **fumaroles or solfataras.**

1.9 Distribution of Earthquakes and Volcanoes across the World

- Most known volcanic activity and the earthquakes occur **along converging plate margins and mid-oceanic ridges**.
- It is said that nearly 70 per cent of earthquakes occur in the Circum-Pacific belt.
- Another 20 per cent of earthquakes take place in the Mediterranean-Himalayan belt including Asia Minor, the Himalayas and parts of northwest China.
- Since the 16th century, around 480 volcanoes have been reported to be active.
- Of these, nearly 400 are located in and around the Pacific Ocean, and 80 are in the mid-world belt across the Mediterranean Sea, Alpine-Himalayan belt and in the Atlantic and Indian Oceans.
- The belts of highest concentration are **Aleutian-Kurile islands** arc, **Melanesia** and **New Zealand-Tonga belt**.
- Only 10 per cent to 20 per cent of all volcanic activity is above the sea, and terrestrial volcanic mountains are small when compared to their submarine counterparts.



Pacific Ring of Fire

- Circum-Pacific region popularly termed the **'Pacific Ring of Fire'**, has the greatest concentration of active volcanoes. Volcanic belt and earthquake belt closely overlap along the 'Pacific Ring of Fire'.

Regions with active volcanism along 'Pacific Ring of Fire'

- The Aleutian Islands into Kamchatka, Japan,
- the Philippines, and Indonesia (Java and Sumatra in particular),
- Pacific islands of Solomon, New Hebrides, Tonga and North Island, New Zealand.
- Andes to Central America (particularly Guatemala, Costa Rica and Nicaragua), Mexico and right up to Alaska.

The 5 countries with the most volcanoes (Source)

1. United States – 173 (most of them are in Alaska)
2. Russia - 166
3. Indonesia - 139
4. Iceland - 130
5. Japan – 112

Other regions

Along the Atlantic coast

- In contrast, the Atlantic coasts have comparatively few active volcanoes but many dormant or extinct volcanoes, e.g. St. Helena, Cape Verde Islands and the Canary Islands etc.
- But the volcanoes of **Iceland** and the **Azores** are active.

Great Rift region

- In Africa, some volcanoes are found along the East African Rift Valley, e.g. **Mt. Kilimanjaro** and **Mt. Kenya**.

The West Indian islands

- The Lesser Antilles (Part of West Indies Islands) are made up mainly of volcanic islands, and some of them still bear signs of volcanic liveliness.

Mediterranean volcanism

- Volcanoes of the Mediterranean region are mainly associated with the Alpine folds, e.g. **Vesuvius**, **Stromboli (Light House of the Mediterranean)** and those of the Aegean islands.
- A few continue into Asia Minor (Mt. Ararat, Mt. Elbruz).
- The volcanism of this broad region is largely the result of convergence between the Eurasian Plate and the northward-moving African Plate.
- This type of volcanism is mainly due to **breaking up of the Mediterranean plate** into multiple plates due to the interaction of African and Eurasian plate

Volcanos in India

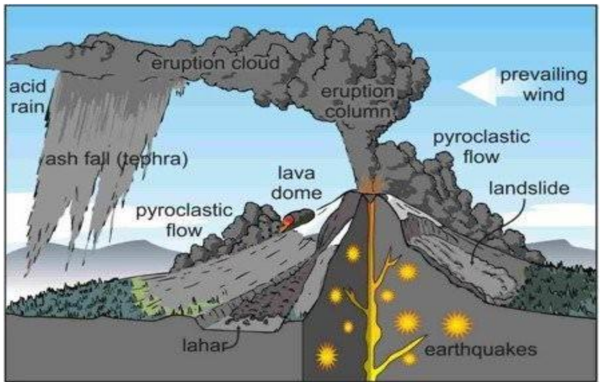
- There are **no volcanoes in the Himalayan region** or the Indian peninsula.
- **Barren Island** (**only active volcano in India**) in the Andaman and Nicobar Islands became active in the 1990s.
- It is now considered an active volcano after it spewed lava and ash in 2017.
- The other volcanic island in Indian territory is **Narcondam**, about 150 km north-east of Barren Island; it is **probably extinct**. Its crater wall has been destroyed.

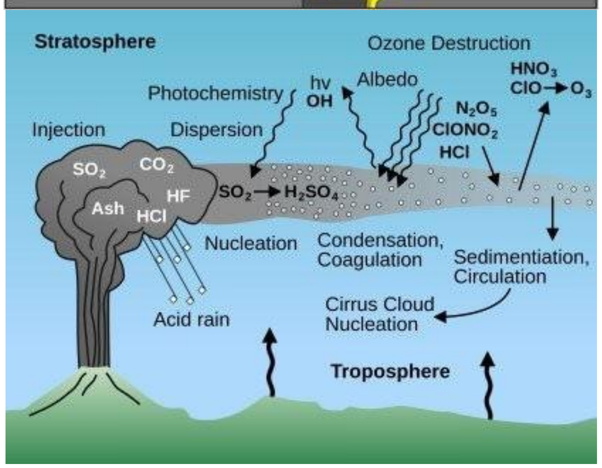
1.10 Destructive Effects of Volcanoes

- Showers of cinders and bombs can cause damage to life. E.g. the eruption of **Mount Vesuvius** in 79 AD.
- Tsunamis can be generated in large water bodies due to violent eruptions. E.g. 1883 Krakatoa eruption.
- The collapse of the volcanic landforms in seas and oceans cause tsunamis. E.g. 2018 Sunda Strait tsunami.
- The ash from a larger eruption dispersing over a large area can lower temperatures at a regional or global scale. This could trigger famines on a large scale. E.g. 1815 eruption of Mount Tambora.
- In Hawaiian type eruption, a single flow spreads widely over open slopes or down the valleys as lava rivers engulfing entire cities.
- Lahars (a violent type of mudflow or debris flow) can bury entire cities in a matter of minutes causing a high number of causalities. E.g. 1985 eruption of Nevado del Ruiz volcano.
- The sudden collapse of lava domes can cause violent volcanic flows that destroy everything on their path. E.g. the 1902 eruption of Mount Pelée.
- Powerful winds drive the gas plume higher into the atmosphere and carry it to a greater distance disrupting air travel (this happened in 2010 when a stratovolcano in Iceland erupted and disrupted air travel over entire Europe for weeks).
- A supervolcanic super-eruption can cause a small-scale extinction event. E.g. The Toba eruption (Indonesia) triggered a dramatic global winter 74,000 years ago.

Volcanism – Acid Rain, Ozone Destruction

- The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are **sulphur dioxide, carbon dioxide, and hydrogen fluoride**.
- Locally, sulphur dioxide gas can lead to acid rain and air pollution downwind from a volcano.
- Globally, large explosive eruptions that inject a tremendous volume of sulphur aerosols into the stratosphere can lead to lower surface temperatures and **promote depletion of the Earth's ozone layer**.





1.11 Positive Effects of Volcanoes

- Volcanism creates new fertile landforms like islands, plateaus, volcanic mountains etc. E.g. Deccan traps.
- The volcanic ash and dust are **very fertile** for farms and orchards.
- Volcanic rocks yield very fertile soil upon weathering and decomposition.
- Although steep volcano slopes prevent extensive agriculture, forestry operations on them provide valuable timber resources.
- Mineral resources, particularly metallic ores are brought to the surface by volcanoes. Sometimes copper and other ores fill the gas-bubble cavities.
- The famed Kimberlite rock of South Africa, the source of diamonds, is the pipe of an ancient volcano.
- In the vicinity of active volcanoes, waters in depth are heated from contact with hot magma giving rise to **springs and geysers**.
- The heat from the earth's interior in areas of volcanic activity is used to generate **geothermal electricity**. Countries producing geothermal power include USA, Russia, Japan, Italy, New Zealand and Mexico.
- The **Puga valley in Ladakh** region and **Manikaran (Himachal Pradesh)** are promising spots in India for the generation of geothermal electricity.
- Geothermal potential can also be used for space heating.
- As scenic features of great beauty, attracting a heavy tourist trade, few landforms outrank volcanoes.
- At several places, national parks have been set up, centred around volcanoes. E.g. Yellowstone National Park.
- As a source of crushed rock for concrete aggregate or railroad ballast and other engineering purposes, lava rock is often extensively used.

1.12 Rocks

- Rock is an aggregate of one or more minerals held together by chemical bonds.
- **Feldspar** and **quartz** are the most common minerals found in rocks.
- The scientific study of rocks is called **petrology**.
- Based on the mode of formation three major groups of rocks are defined: igneous, sedimentary, and metamorphic.
- **Igneous Rocks** — solidified from magma and lava.
- **Sedimentary Rocks** — the result of deposition of fragments of rocks.
- **Metamorphic Rocks** — formed out of existing rocks undergoing recrystallisation.

Igneous Rocks or Primary rocks

- The solidification of magma formed the first rocks on earth.
- Rocks formed out of solidification of magma (molten rock below the surface) and lava (molten rock above the surface) and are known as **igneous or primary rocks**.
- Having their origin under conditions of high temperatures the igneous rocks are **unfossiliferous**.
- **Granite, gabbro, basalt,** are some of the examples of igneous rocks.

- There are three types of igneous rocks based on place and time taken in cooling of the molten matter, **plutonic rocks, volcanic rocks** and **intermediate rocks**.
- There are two types of rocks based on the presence of acid-forming radical, silicon, **acidic rocks** and **basic rocks.**

Intrusive igneous rocks (Plutonic rocks)

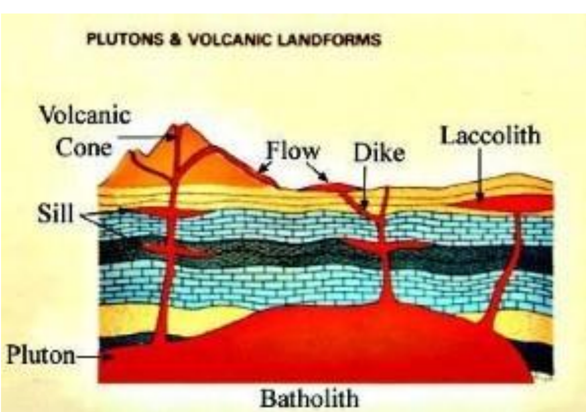
- If magma cools slowly at great depths, mineral grains formed in the rocks may be **very large**.
- Such rocks are called **intrusive rocks or plutonic rocks (e.g. Granite).**
- These rocks appear on the surface only after being uplifted and denuded.

Extrusive igneous rocks (Lava or Volcanic rocks

- Sudden cooling of magma just below the surface or lava above the surface results in small and smooth grains in rocks as rapid cooling prevents crystallisation, as a result, such rocks are fine-grained.
- Such rocks are called **extrusive rocks or volcanic rocks (e.g. Basalt)**.
- The Deccan traps in the Indian peninsular region is of basaltic origin.
- Basic rocks contain a greater proportion of **basic oxides**, e.g. of iron, aluminium or magnesium, and are thus **denser and darker in colour**.

Hypabyssal or Dyke Rocks or Intermediate rocks

- These rocks occupy an intermediate position between the deep-seated plutonic bodies and the surface lava flows.
- Dyke rocks are semi-crystalline in structure.



Acid Rocks

- Acidic rocks are characterised by high content of silica (quartz and feldspar) — up to 80 per cent.
- The rest is divided among aluminium, alkalis, magnesium, iron oxide, lime etc.
- These rocks have a lesser content of heavier minerals like iron and magnesium. Hence, they are less dense and are lighter in colour than basic rocks.
- These rocks constitute the sial portion of the crust.
- Due to the excess of silicon, **acidic magma cools fast,** and it does not flow and spread far away.
- **High mountains** are formed of this type of rock.
- Add rocks are hard, compact, massive and resistant to weathering.
- **Granite, quartz** and **feldspar** are typical examples.

Basic Rocks

- These rocks are poor in silica (about 40 per cent); magnesia content is up to 40 per cent, and the remaining is spread over iron oxide, lime, aluminium, alkalis, potassium etc.
- Due to low silica content, the parent material of such rocks **cools slowly and thus, flows and spreads far away**. This flow and cooling give rise to plateaus.
- Presence of heavy elements imparts to these rocks a dark colour. **Not being very hard, these rocks are weathered relatively easily**.
- **Basalt**, **gabbro** and **dolerite** are typical examples.

Economic Significance of Igneous Rocks

- Since magma is the chief source of metal ores, many of them are associated with igneous rocks.
- The minerals of great economic value found in igneous rocks are magnetic iron, nickel, copper, lead, zinc, chromite, manganese, gold, diamond and platinum.

- Amygdales are almond-shaped bubbles formed in basalt due to escape of gases and are filled with minerals.
- The old rocks of the great Indian peninsula are rich in these crystallised minerals or metals.
- Many igneous rocks like granite are used as building materials as they come in beautiful shades.

Sedimentary Rocks or detrital rocks

- Sedimentary rocks are formed by **lithification** — consolidation and compaction of sediments.
- Hence, they are layered or stratified of varying thickness. Example: **sandstone, shale** etc.
- Sediments are a result of denudation (weathering and erosion) of all types of rocks.
- These types of rocks cover 75 per cent of the earth's crust but volumetrically occupy only 5 per cent (because they are available only in the upper part of the crust).
- Ice deposited sedimentary rocks are called **till or tillite**. Wind-deposited sediments are called **loess**.

Depending upon the mode of formation, sedimentary rocks are classified into:

1. mechanically formed — **sandstone, conglomerate, limestone, shale, loess**.
2. organically formed — **geyserite, chalk, limestone, coal**.
3. chemically formed — **limestone, halite, potash**.

Mechanically Formed Sedimentary Rocks

- They are formed by mechanical agents like running water, wind, ocean currents, ice, etc.
- Arenaceous sedimentary rocks have more sand and bigger sized particles and are hard and **porous**. They form the **best reservoirs for liquids like groundwater and petroleum**. E.g. sandstone.
- Argillaceous rocks have more clay and are fine-grained, softer, **mostly impermeable** (mostly non-porous or have very tiny pores). E.g. claystone and shales are predominantly argillaceous.

Chemically Formed Sedimentary Rocks

- Water containing minerals evaporate at the mouth of springs or salt lakes and give rise to Stalactites and stalagmites (deposits of lime left over by the lime-mixed water as it evaporates in the underground caves).

Organically Formed Sedimentary Rocks

- The remains of plants and animals are buried under sediments, and due to heat and pressure from overlying layers, their composition changes. **Coal and limestone** are well-known examples.
- Depending on the predominance of calcium content or the carbon content, sedimentary rocks may be calcareous **(limestone, chalk, dolomite)** or **carbonaceous (coal)**.

Chief Characteristics of Sedimentary Rocks

- They are **stratified** — consist of many layers or strata.
- They hold the most informative geological records due to the marks left behind by various geophysical (weather patterns, wind and water flow) and biological activities (fossils).
- They are **fossiliferous** — have fossils of plants and animals.
- These rocks are **generally porous and allow water to percolate** through them.

The spread of Sedimentary Rocks in India

- Alluvial deposits in the Indo-Gangetic plain and coastal plains is of sedimentary accumulation. These deposits contain loam and clay.
- Different varieties of sandstone are spread over Madhya Pradesh, eastern Rajasthan, parts of Himalayas, Andhra Pradesh, Bihar and Orissa.
- The great Vindhyan highland in central India consists of sandstones, shales, limestones.

- Coal deposits occur in river basins of the Damodar, Mahanadi, the Godavari in the Gondwana sedimentary deposits.

Economic Significance of Sedimentary Rocks

- Sedimentary rocks are not as rich in minerals of economic value as the igneous rocks.
- But important minerals such as hematite iron ore, phosphates, building stones, coals, petroleum and material used in the cement industry are found.
- The decay of tiny marine organisms yields petroleum. Petroleum occurs in suitable structures only.
- Important minerals like bauxite, manganese, tin, are derived from other rocks but are found in gravels and sands carried by water.
- Sedimentary rocks also yield some of the richest soils.

Metamorphic Rocks

- The word metamorphic means '**change of form**'.
- Metamorphism is a process by which **recrystallisation and reorganisation of minerals** occur within a rock. This occurs due to pressure, volume and temperature changes.
- When rocks are forced down to lower levels by tectonic processes or when molten magma rising through the crust comes in contact with the crustal rocks, metamorphosis occurs.
- In the process of metamorphism in some rocks grains or **minerals get arranged in layers or lines**. Such an arrangement is called **foliation or lineation**.
- Sometimes minerals or materials of different groups are arranged into alternating thin to thick layers. Such a structure in is called **banding**.
- **Gneissoid, slate, schist, marble, quartzite** etc. are some examples of metamorphic rocks.

Causes of Metamorphism

- **Orogenic (Mountain Building) Movements:** Such movements often take place with an interplay of folding, warping and high temperatures. These processes give existing rocks a new appearance.
- **Lava Inflow:** The molten magmatic material inside the earth's crust brings the surrounding rocks under the influence of intense temperature pressure and causes changes in them.
- **Geodynamic Forces:** The omnipresent geodynamic forces such as plate tectonics also play an important role in metamorphism.

On the basis of the agency of metamorphism, metamorphic rocks can be of two types

Thermal Metamorphism

- The change of form or re-crystallisation of minerals of sedimentary and igneous rocks under the influence of high temperatures is known as thermal metamorphism.
- A magmatic intrusion causing thermal metamorphism is responsible for the **peak of Mount Everest** consisting of **metamorphosed limestone**.
- As a result of thermal metamorphism, **sandstone changes into quartzite and limestone into marble**.

Dynamic Metamorphism

- This refers to the formation of metamorphic rocks under high pressure.
- Sometimes high pressure is accompanied by high temperatures and the action of chemically charged water.
- The combination of directed pressure and heat is very powerful in producing metamorphism because it leads to more or less complete recrystallisation of rocks and the production of new structures. This is known as dynamo thermal metamorphism.
- Under high pressure, **granite is converted into gneiss; clay and shale are transformed into schist**.

Metamorphic Rocks in India

- The gneisses and schists are commonly found in the Himalayas, Assam, West Bengal, Bihar, Orissa, Madhya Pradesh and Rajasthan.

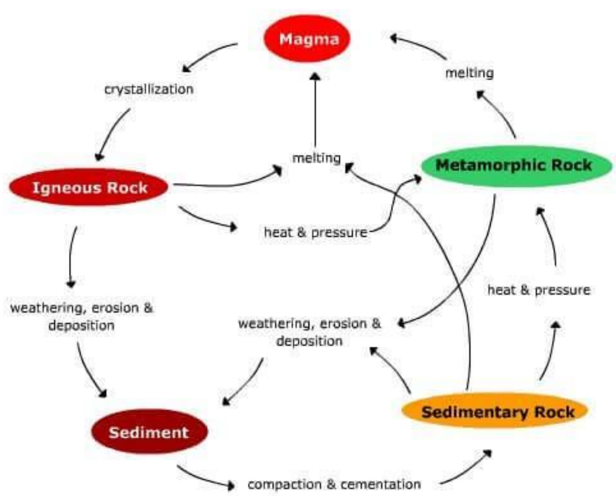
- Quartzite is a hard rock found over Rajasthan, Bihar, Madhya Pradesh, Tamil Nadu and areas surrounding Delhi.
- Marble occurs near Alwar, Ajmer, Jaipur, Jodhpur in Rajasthan and parts of Narmada Valley in Madhya Pradesh.
- Slate, which is used as a roofing material and for writing in schools, is found over Rewari (Haryana), Kangra (Himachal Pradesh) and parts of Bihar.
- Graphite is found in Orissa and Andhra Pradesh.

Some examples of Metamorphosis

Igneous or Sedimentary rock	Influence	Metamorphosed rock
Granite	**Pressure**	**Gneiss**
Clay, Shale	**Pressure**	**Schist**
Sandstone	**Heat**	**Quartzite**
Clay, Shale	**Heat**	**Slate ➔ Phyllite**
Coal	**Heat**	**Anthracite ➔ Graphite**
Limestone	**Heat**	**Marble**

Rock cycle

- Rock cycle is a continuous process through which old rocks are transformed into new ones.
- **Igneous rocks are primary rocks**, and other rocks form from these rocks.
- Igneous rocks can be changed into **sedimentary or metamorphic rocks**.
- The fragments derived out of igneous and metamorphic rocks form into sedimentary rocks.
- **Sedimentary and igneous rocks themselves can turn into metamorphic rocks**.
- The crustal rocks (igneous, metamorphic and sedimentary) may be carried down into the mantle (interior of the earth) through subduction process and the same meltdown and turn into molten magma, the source for igneous rocks



Some Rock-Forming Minerals

- **Feldspar:** Half the crust is composed of feldspar. It has a light colour, and its main constituents are silicon, oxygen, sodium, potassium, calcium, aluminium. It is used for **ceramics and gloss making**.
- **Quartz:** It has two elements, silicon and oxygen. It has a hexagonal crystalline structure. It is uncleaved, white or colourless. It cracks like glass and is present in sand and granite. It is used in the manufacture of **radio and radar**.
- **Bauxite:** A hydrous oxide of aluminium, it is the **ore of aluminium**. It is non-crystalline and occurs in small pellets.
- **Cinnabar (mercury sulphide):** Mercury is derived from it. It has a brownish colour.
- **Dolomite:** A double carbonate of calcium and magnesium. It is used in cement and iron and steel industries. It is white.
- **Gypsum:** It is hydrous calcium sulphate and is used in cement, fertiliser and chemical industries.
- **Haematite:** It is a red ore of iron.
- **Magnetite:** It is the black ore (or iron oxide) of iron.
- **Amphibole:** It forms about 7 per cent of the earth's crust and consists mainly of aluminium, calcium, silica, iron, magnesium, etc. It is used in the **asbestos industry**.
- **Mica:** It consists of potassium, aluminium, magnesium, iron, silica, etc., and forms 4 % of the earth's crust. It is generally found in igneous

and metamorphic rocks and is mainly used in **electrical instruments**.

- **Olivine:** The main elements of olivine are magnesium, iron and silica. It is normally a greenish crystal.
- **Pyroxene:** It consists of calcium, aluminium, magnesium, iron and silica. It is of green or black colour.
- Other minerals like chlorite, calcite, magnetite, hematite, bauxite, barite, etc., are also present in rocks.

Multiple choice questions.

1. Which one of the following are the two main constituents of granite? (a) Iron and nickel (c) Silica and aluminium (b) Iron and silver (d) Iron Oxide and potassium
2. Which one of the following is the salient feature of metamorphic rocks? (a) Changeable (c) Crystalline (b) Quite (d) Foliation
3. Which one of the following is not a single element mineral? (a) Gold (c) Mica (b) Silver (d) Graphite
4. Which one of the following is the hardest mineral? (a) Topaz (c) Quartz (b) Diamond (d) Feldspar
5. Which one of the following is not a sedimentary rock? (a) Tillite (c) Breccia (b) Borax (d) Marble

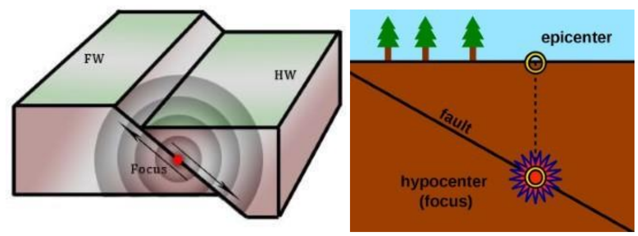
Answers:
1) C. Silica and aluminium (Granite is an acidic igneous rock).
2) D. Foliation (E.g. Marble)
3) C. Mica is a group of silicate minerals; Graphite is a naturally-occurring form of crystalline carbon
4) B. Diamond is the hardest
5) D. Marble is a metamorphic rock

2. Earthquakes

- An earthquake is shaking or trembling of the earth's surface, caused by the seismic waves or earthquake waves that are generated due to a sudden movement (sudden release of energy) in the earth's crust (shallow-focus earthquakes) or upper mantle (some shallow-focus and all intermediate and deep-focus earthquakes).
- A seismograph, or seismometer, is an instrument used to detect and record earthquakes.

Focus and epicentre

- The point where the energy is released is called the **focus** or the **hypocentre** of an earthquake.
- The point on the surface directly above the focus is called **epicentre** (first surface point to experience the earthquake waves).
- A line connecting all points on the surface where the intensity is the same is called an **isoseismic line**.



The focus of an Earthquake

Foreshocks and aftershocks

- Usually, a major or even moderate earthquake of shallow focus is followed by many lesser-size earthquakes known as aftershocks.
- A mild earthquake preceding the violent shaking movement of an earthquake is known as a foreshock.

Swarms

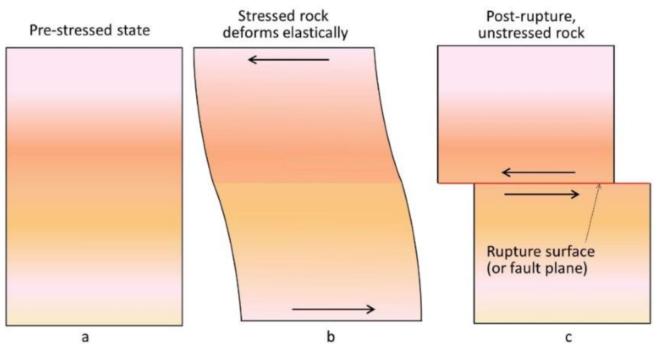
- Large numbers of small earthquakes may occur in a region for months without a major earthquake.
- Such series of earthquakes are called earthquake swarms.
- Earthquakes associated with volcanic activity often occur in swarms.
- Earthquake swarms can serve as markers for the location of the flowing magma throughout the volcanoes.

2.2 Causes of Earthquakes

Fault Zones

- The immediate cause of most shallow earthquakes is the sudden release of stress along a fault rupture (crack) in the earth's crust.

- Sudden slipping of rock formations along fault rupture in the earth's crust happens due to the constant change in volume and density of rocks due to intense temperature and pressure in the earth's interior.



Deformation and Rupturing ([Steven Earle])

- The longer the length and the wider the width of the faulted area, the larger the resulting magnitude.
- The **longest earthquake ruptures along thrust faults (convergent boundary)** are approximately 1,000 km.
- The longest earthquake ruptures on strike-slip faults (transform fault) are about half to one third as long as the lengths along the thrust fault.
- The fault ruptures along normal faults (divergent boundary) are **shorter**.

Plate tectonics

- Slipping of land along the faultline along convergent, divergent and transform boundaries cause earthquakes.
- **Reverse faults (convergent boundary) are associated with the most powerful earthquakes**, **megathrust earthquakes**, including almost **all of those of magnitude 8 or more**.
- **Megathrust earthquakes** occur at subduction zones, where one tectonic plate is forced underneath another. E.g. 2004 Indian Ocean earthquake.
- Strike-slip faults, particularly **continental transforms**, can produce major earthquakes **up to about magnitude 8**.
- **San Andreas Fault** is a transform fault where Pacific plate and North American plate move horizontally relative to each other causing earthquakes along the fault lines.
- Earthquakes associated with normal faults (divergent boundary) are generally less than magnitude 7.

Volcanic activity

- Volcanic activity also can cause an earthquake, but **the earthquakes of volcanic origin are generally less severe and more limited in extent** than those caused by fracturing of the earth's crust.
- Earthquakes in volcanic regions are caused by the consequent release of elastic strain energy both by tectonic faults and the movement of magma in volcanoes.
- Such earthquakes can serve as an **early warning of volcanic eruptions**, as during the 1980 eruption of Mount St. Helens
- There is a clear correspondence between the geographic distribution of volcanoes and major earthquakes, particularly in the Circum-Pacific Belt and along oceanic ridges.
- Volcanic vents, however, are generally several hundred kilometres from the epicentres of most major shallow earthquakes, and many earthquake sources occur nowhere near active volcanoes.

Human Induced Earthquakes

- Human Induced Earthquakes refers to typically minor earthquakes and tremors that are caused by human activity like mining, large scale petroleum extraction, artificial lakes (reservoirs), nuclear tests etc.

Reservoir-induced seismicity

- The pressure offered by a column of water in a large and **deep** artificial lake alter stresses along an existing fault or fracture. Also, the percolation of water weakens the soil structure and lubricates the faults.
- Loading and unloading of water can significantly change the stress. This significant change in stress can lead to a sudden movement along the fault or fracture, resulting in an earthquake.
- The 6.3 magnitude 1967 **Koynanagar earthquake** occurred near the Koyna Dam reservoir in Maharashtra and claimed more than 150

lives. There have been several earthquakes of smaller magnitude since then.

- Some geologists believe that the earthquake was due to reservoir-triggered seismic activity.
- The **2008 Sichuan earthquake**, which caused approximately 68,000 deaths, is another possible example. It is believed that the construction and filling of the Zipingpu Dam may have triggered the earthquake.

2.3 Earthquakes based on the depth of focus

- Earthquakes can occur anywhere between the Earth's surface and about 700 kilometres below the surface.
- For scientific purposes, this earthquake depth range of 0 – 700 km is divided into three zones: **shallow, intermediate, and deep**.
- Shallow focus earthquakes are found within the earth's outer crustal layer, while deep focus earthquakes occur within the deeper subduction zones of the earth.
- **Shallow earthquakes are 0 – 70 km deep.**
- **Intermediate earthquakes are 70 – 300 km deep.**
- **Deep earthquakes are 300 – 700 km deep**.
- Of the total energy released in earthquakes, about **12-15 per cent comes from intermediate earthquakes**, about **3-5 per cent from deeper earthquakes** and about **70-85 per cent from the shallow earthquakes**.
- A quake's destructive force depends not only on the energy released but also on location, distance from the epicentre and depth.
- On 24 August 2016, a 6.2 earthquake rocked Central Italy killing about 300 people. An even bigger 6.8 hit Myanmar the same day killing just a few people.
- Italy's quake was very shallow, originating within 10 kilometres underground. By contrast, the quake in Myanmar was deeper — 84 kilometres.

Shallow-focus earthquake

- The great majority of earthquakes have shallow-focus. Hence, they are also called as '**crustal earthquakes**.'
- Majority of the shallow focus earthquakes are of smaller magnitudes (usual range of 1 to 5). But a few can be of a higher magnitude and can cause a great deal of destruction.
- They occur quite frequently and at random. However, as most of them are either of smaller magnitudes or occur along submarine ridges, they are often not felt.
- **Though comparatively of low magnitude, shallow focus earthquakes can cause relatively greater damage at the surface (as the whole energy is directed towards a small area) compared to their deep-focus counterparts**.

Deep-focus earthquake

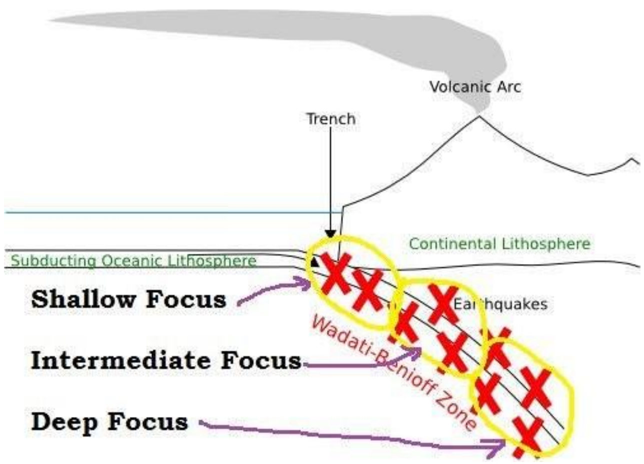
- In general, the term "deep-focus earthquakes" is applied to earthquakes deeper than 70 km.
- The deeper-focus earthquakes commonly occur in patterns called **Benioff zones** that dip into the Earth, indicating the presence of a **subducting slab (zone of subduction)**.
- Hence, they are also are known as **intraplate earthquakes** (triggered by the collision between plates).
- They happen as **huge quakes with larger magnitudes** (usual range of 6 to 8), as a great deal of energy is released with the forceful collision of the plates.
- **But the earthquakes alone may not cause much destruction as the foci of the quakes lie at great depths and the energy of the quakes dissipates over a wide area**.
- The strongest deep-focus earthquake in seismic record was the magnitude 8.3 Okhotsk Sea earthquake that occurred at a depth of 609 km in 2013.
- The deepest earthquake ever recorded was a 4.2 earthquake in Vanuatu at a depth of 735.8 km in 2004.

Wadati–Benioff zone: Earthquakes along the Convergent boundary

- Wadati Benioff zone is a zone of subduction along which earthquakes are common. **The most powerful earthquakes occur along this**

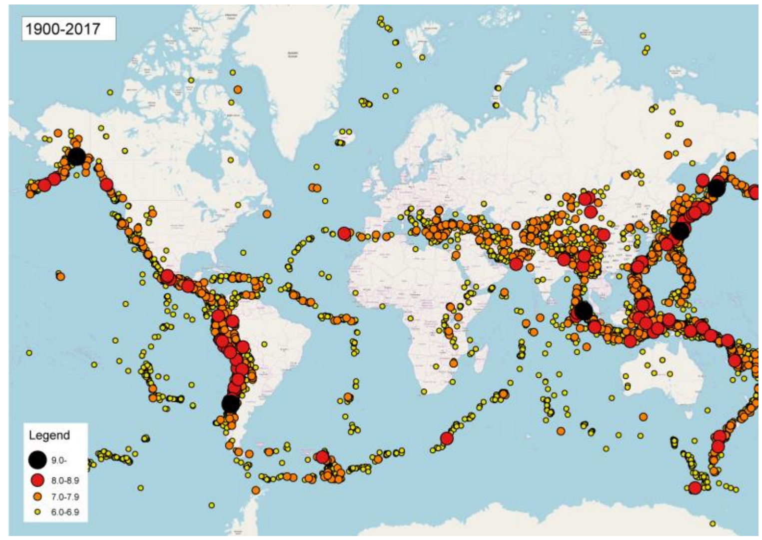
zone (most powerful earthquakes occur along the convergent boundary).

- Differential motion along the zone produces numerous earthquakes, the foci of which may be as deep as about 700 kilometres.
- **Wadati–Benioff zones** can be produced by slip along the **subduction thrust fault (Himalayan Region – C-C convergent boundary)** or **slip on faults within the downgoing plate (O-O and C-O convergent boundary)**.



2.4 Distribution of Earthquakes

- Earth's major earthquakes occur mainly in belts coinciding with the margins of tectonic plates.
- The most important earthquake belt is the **Circum-Pacific Belt**, which affects many populated coastal regions around the Pacific Ocean—for example, those of New Zealand, New Guinea, Japan, the Aleutian Islands, Alaska, and the western coasts of North and South America.
- The seismic activity is by no means uniform throughout the belt, and there are many branches at various points.
- Because at many places the Circum-Pacific Belt is associated with volcanic activity, it has been popularly dubbed the "Pacific Ring of Fire."
- **The Pacific Ring of Fire accounts for about 68 per cent of all earthquakes**.
- A second belt, known as the **Alpine Belt (Himalayas and Alps)**. The energy released in earthquakes from this belt is about 15 per cent of the world total.
- The mid-world mountain belt (Alpine Belt) extends parallel to the equator from Mexico across the Atlantic Ocean, the Mediterranean Sea from Alpine-Caucasus ranges to the Caspian, Himalayan mountains and the adjoining lands.
- There also are striking connected belts of seismic activity, mainly along oceanic ridges—including those in the Arctic Ocean, the Atlantic Ocean, and the western Indian Ocean—and along the **rift valleys of East Africa**.



Distribution of Earthquakes

2.5 Richter magnitude scale

- Charles F. Richter developed the Richter magnitude scale (M_L) for measuring the strength (amount of energy released) of earthquakes in 1930s.
- Because of the various shortcomings of the M_L scale, seismologists now use moment magnitude scale (M_w).
- Both the scales are logarithmic and are scaled to have **roughly comparable numeric values**.
- Moment magnitude scale M_w scale is now generally referred to as the Richter scale.
- Under the Richter magnitude scale, an **increase of one step corresponds to about 32 times increase in the amount of energy released**, and **an increase of two steps corresponds to 1,000 times increase in energy**.
- Thus, **an earthquake of M_w of 7.0 releases about 32 times as much energy as one of 6.0 and nearly 1,000 times (~ 32 X 32) one of 5.0**.

- Richter scale is only effective for regional earthquakes no greater than M_5. Moment magnitude scale is more effective for large earthquakes.

Magnitude	Description	Average earthquake effects	Frequency of occurrence
1.0–1.9	Micro	• Microearthquakes, not felt, or felt rarely. • They are recorded by seismographs.	Several million per year
2.0–2.9	Minor	• Felt slightly by some people. • No damage to buildings.	Over one million per year
3.0–3.9		• Often felt by people, but very rarely causes damage. • Shaking of indoor objects can be noticeable.	Over 100,000 per year
4.0–4.9	Light	• Noticeable shaking of indoor objects. • They are felt by most people in the affected area. • Slightly felt outside. • Generally, causes none to minimal damage. • Some objects may fall off shelves or be knocked over.	10,000 to 15,000 per year
5.0–5.9	Moderate	• Can cause damage of varying severity to poorly constructed buildings. • At most, none to slight damage to all other buildings. • Felt by everyone.	1,000 to 1,500 per year
6.0–6.9	**Strong**	• Damage to a moderate number of well-built structures in populated areas. • Earthquake-resistant structures survive with slight to moderate damage. • Poorly designed structures receive moderate to severe damage. • Felt in wider areas; up to hundreds of kilometres from the epicentre. • Strong to violent shaking in the epicentral area.	100 to 150 per year • 2011 Christchurch earthquake (6.2)
7.0–7.9	**Major**	• Causes damage to most buildings, some to partially or completely collapse or receive severe damage. Well-designed structures are likely to receive damage. Felt across great distances with major damage mostly limited to 250 km from epicentre.	10 to 20 per year • **1819 Rann of Kutch earthquake (7.7–8.2)** • **2001 Gujarat earthquake (7.7)**
8.0–8.9	**Great**	• Major damage to buildings, structures likely to be destroyed. • Will cause moderate to heavy damage to sturdy or earthquake-resistant buildings. • Damaging in large areas. • Felt in extremely large regions.	One per year • 1556 Shaanxi earthquake (8.0) • 1950 Assam–Tibet earthquake (8.6) • 2008 Sichuan earthquake (8.0) • 2010 Chile earthquake (8.8)
9.0 and		• At or near total destruction – severe	One per 10 to 50 years

greater		damage or collapse to all buildings. • Heavy damage and shaking extends to distant locations. • Permanent changes in ground topography.	• **1960 Valdivia earthquake, Chile (9.4–9.6)** • **1964 Alaska earthquake (9.2)** • **2004 Indian Ocean earthquake (9.1–9.3)** • **2011 Tōhoku earthquake, Japan (9.1)**

Based on U.S. Geological Survey documents

Most powerful earthquakes ever recorded

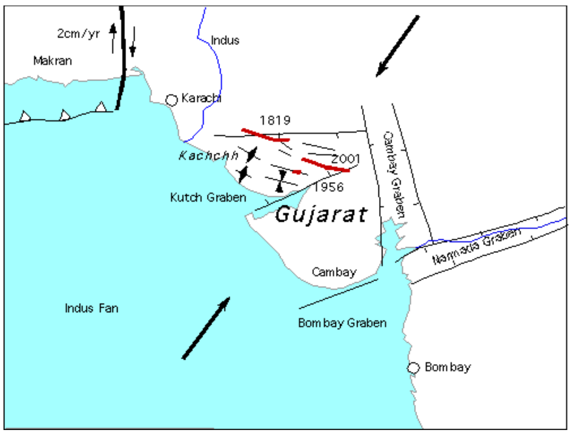
	Event	M_w	Focus	
1	1960 Valdivia earthquake	9.4–9.6	33 km	• Undersea megathrust earthquake • **Most powerful earthquake ever recorded** • The resulting tsunami affected the entire Pacific Rim killing 1,000–7,000 people.
2	1964 Alaska earthquake	9.2	25 km	• Collapsing structures and tsunamis resulted in 100+ deaths.
3	2004 Indian Ocean earthquake	9.1–9.3	30 km	• Undersea megathrust earthquake • Caused by a rupture along the fault between the **Burma Plate** and **the Indian Plate**. • A series of large tsunamis up to 30 metres high were created. • The earthquake and the resulting tsunami caused the 6th deadliest natural disaster in recorded history with more than 227,000 causalities in 14 countries. • The shift of mass and the massive release of energy slightly altered the Earth's rotation.
4	2011 Tōhoku earthquake	9.1	30 km	• Undersea megathrust earthquake • Most powerful earthquake ever recorded in Japan • The earthquake triggered powerful tsunami waves • 15,896 causalities • Caused **Fukushima Daiichi nuclear disaster**

Notable earthquakes

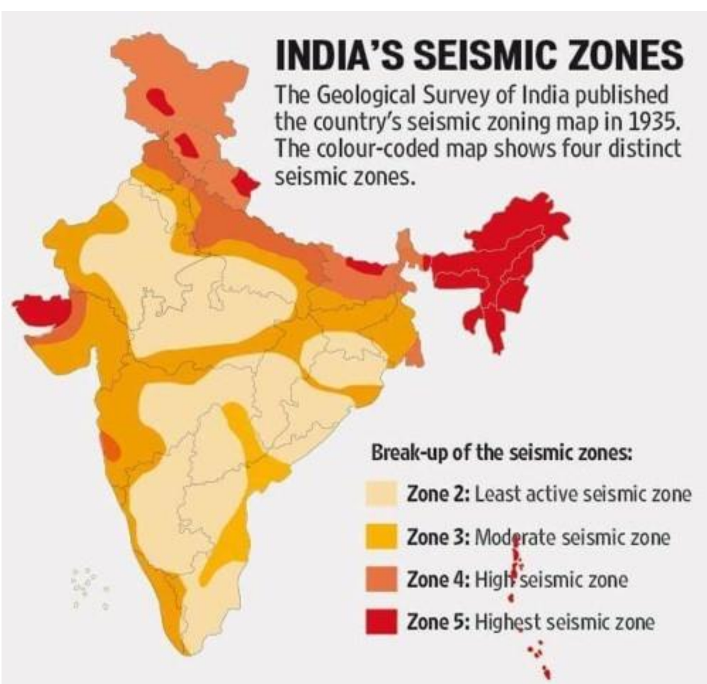
Event	Magnitude	Notes
1556 Shaanxi earthquake	8.0	**Deadliest earthquake** with 8,00,000+ fatalities Most of the deaths were caused due to the collapse of artificial caves carved into the loess cliffs
2011 Tōhoku earthquake and tsunami	9.1	**Costliest earthquake** that caused damage to property worth $250 billion
1819 Rann of Kutch earthquake	7.7 to 8.2	It triggered a tsunami and caused more than 1000 deaths The earthquake caused an area of subsidence that formed the **Sindri Lake** and a local zone of uplift to the north about 80 km long, 6 km wide and 6 m high that dammed the several rivers. This natural dam was known as the **Al-**

		lah Bund (Dam of God).
2001 Gujarat earthquake (Focus: 24 km)	7.7	The earthquake killed between 13000 and 20000 people

- The Gujarat quake occurred 400 km to the south-east of the tectonic boundary separating Indian Plate and the Eurasian Plate.
- The current tectonics is governed by the effects of the continuing continental collision along this boundary.
- The collision has reactivated the original rift faults and development of new thrust faults in the region.
- The pattern of uplift and subsidence associated with the 1819 Rann of Kutch earthquake is consistent with reactivation of such faults.
- The area saw many minor earthquakes in the 20th Century including the 2001 earthquake.



Earthquake zones of India



Earthquake zones of India (Source)

- The latest seismic zone map prepared by the National Disaster Management Authority reveals that **nearly 59% of India's land area is prone to moderate or severe earthquakes**.
- This earthquake zoning map divides India into five different zones of earthquake intensity and highlights the location that falls under them.

2.6 Effects of Earthquakes

Shaking and ground rupture

- Shaking and ground rupture result in severe damage to buildings and other rigid structures.
- Ground rupture (crack along the fault) is a major risk for large engineering structures such as dams, bridges and nuclear power stations.

Landslides and avalanches

- Earthquakes, along with severe storms, volcanic activity, coastal wave attack, and wildfires, can produce slope instability leading to landslides, a major geological hazard.

Fires

- Earthquakes can cause fires by damaging electrical power or gas lines.
- More deaths in the 1906 San Francisco earthquake were caused by fire than by the earthquake itself.

Soil liquefaction

- Soil liquefaction occurs when water-saturated soil temporarily loses its strength and transforms from a solid to a liquid. Soil liquefaction may cause rigid structures, like buildings and bridges, to tilt or sink.

Tsunami

- Megathrust earthquakes can produce long-wavelength, long-period sea waves due to abrupt movement of large volumes of water.

Floods

- Floods may be secondary effects of earthquakes if dams are damaged.
- Earthquakes may cause landslips to dam rivers, which collapse and cause floods.

3. Tsunami

- Tsunami is a Japanese word for "**Harbour wave**". A tsunami is a series of **very long-wavelength** waves in large water bodies like seas or large lakes caused by a major disturbance above or below the water surface or due to the displacement of a large volume of water.
- They are sometimes referred to as tidal waves because of **long wavelengths**, although the attractions of the Moon and Sun play no role in their formation.
- Earthquakes (e.g. 2004 Indian Ocean Tsunami), volcanic eruptions (e.g. tsunami caused by the violent eruption of Krakatoa in 1883), landslides (tsunami caused by the collapse of a section of Anak Krakatoa in 2018), underwater explosions, meteorite impacts, etc. have the potential to generate a tsunami.
- Subduction zones off Chile, Nicaragua, Mexico and Indonesia have created killer tsunamis.
- The Pacific among the oceans has witnessed the most number of tsunamis (over 790 since 1990).

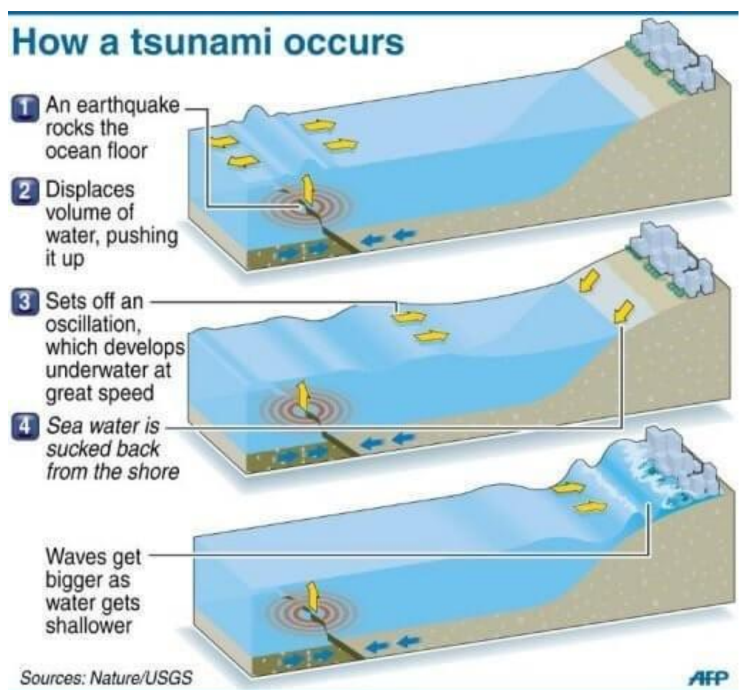
3.1 Mechanism of tsunami waves

Disturbance

- Megathrust earthquakes cause a sudden displacement in a seabed sufficient to cause the sudden raising of a large body of water.
- As the subducting plate plunges beneath the less dense plate, stresses build up, the locked zone between the plates give way abruptly, and the parts of the oceanic crust is then upthrust resulting in the displacement of a large column of water vertically.
- The tsunami on December 26, 2004, was caused after an earthquake displaced the seabed off the coast of Sumatra, Indonesia.
- A marine volcanic eruption can generate an impulsive force that displaces the water column and gives birth to a tsunami.
- During a submarine landslide, the equilibrium sea-level is altered by sediment moving along the floor of the sea. Gravitational forces then propagate a tsunami.
- Most destructive tsunamis can be caused due to the fall of extra-terrestrial objects on to the earth.

Propagation of the waves

- Gravity acts to return the sea surface to its original shape.
- The ripples then race outward, and a tsunami is caused.
- As a tsunami leaves deep waters and propagates into the shallow waters, it transforms. This is because as the depth of the water decreases, the speed of the tsunami reduces. But the change of total energy of the tsunami remains constant.
- With the decrease in speed, the height of the tsunami wave grows. A tsunami which was imperceptible in deep water may grow to many metres high, and this is called the **'shoaling' effect**.



- Sometimes, the sea seems to at first draw a breath, but then this withdrawal is followed by the arrival of the crest of a tsunami wave. Tsunamis have been known to occur suddenly without warning.

- In some cases, there are several great waves separated by intervals of several minutes or more.
- The first of these waves is often preceded by an extraordinary recession of water from the shore, which may commence several minutes or even half an hour beforehand.

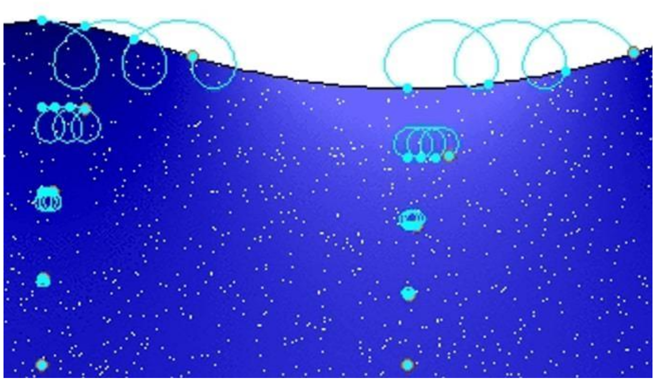
3.2 Properties of Tsunami Waves

Basics

- Wave crest and trough: The highest and lowest points of a wave are called the crest and trough respectively.
- Wave height: It is the vertical distance from the bottom of a trough to the top of a crest of a wave.
- Wave amplitude: It is one-half of the wave height.
- Wave period: It is the time interval between two successive wave crests or troughs.
- Wavelength: It is the horizontal distance between two successive crests.
- Wave frequency: It is the number of waves passing a given point during a one second time interval.

Normal waves

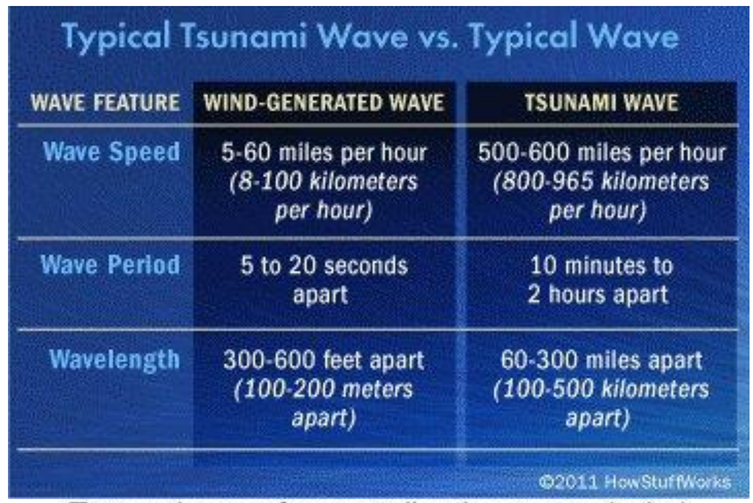
- The horizontal and vertical motions are common in ocean water bodies.
- The **horizontal motion** refers to the **ocean currents and waves**. The **vertical motion** refers to **tides**.



Wind generated wave motion

- Water moves ahead from one place to another through ocean currents while the water in the normal wind-generated waves do not move, but the **wave trains move ahead**.
- The motion of normal waves seldom affects the stagnant deep bottom water of the oceans.
- The actual motion of the water beneath the waves is **circular**. It indicates that things are carried up and forward as the wave approaches, and down and back as it passes.
- As a wave approaches the beach, it slows down. And, when the depth of water is less than half the wavelength of the wave, the wave breaks (dies).

Normal waves vs Tsunami waves



Typical Tsunami Wave vs. Typical Wave

WAVE FEATURE	WIND-GENERATED WAVE	TSUNAMI WAVE
Wave Speed	5-60 miles per hour (8-100 kilometers per hour)	500-600 miles per hour (800-965 kilometers per hour)
Wave Period	5 to 20 seconds apart	10 minutes to 2 hours apart
Wavelength	300-600 feet apart (100-200 meters apart)	60-300 miles apart (100-500 kilometers apart)

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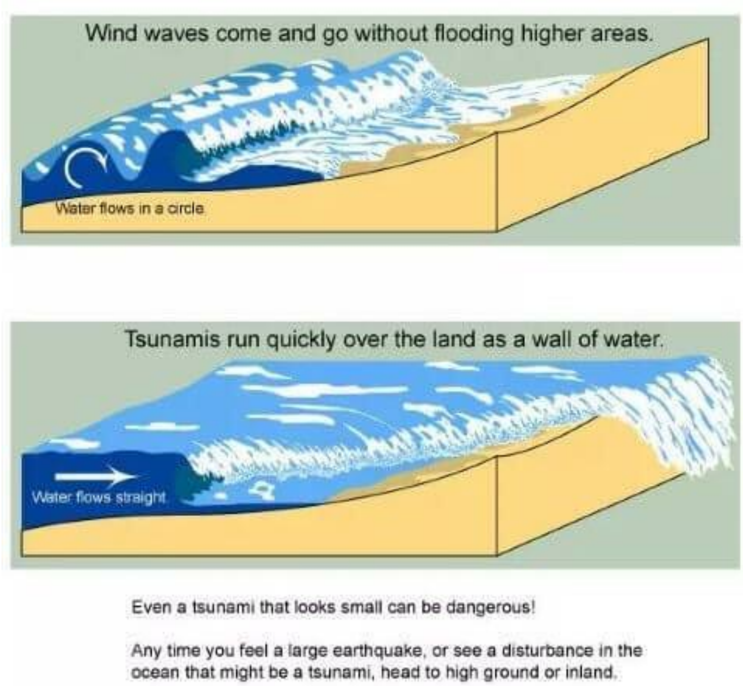
Tsunamis are often no taller than normal wind waves, but they are much more dangerous.



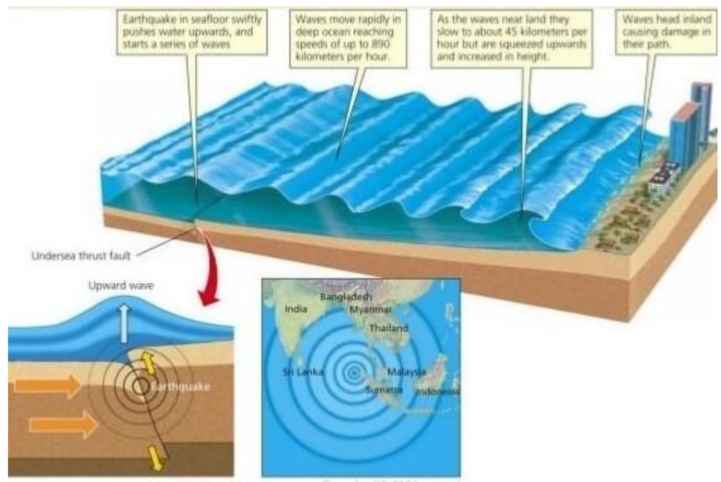
- Tsunamis are a series of waves of very, very long wavelengths and period.
- Tsunamis are different from the wind-generated waves (period of five to twenty seconds).
- Tsunamis behave as **shallow-water waves** because of their long wavelengths. They have a period in the range of ten minutes to two hours and a wavelength exceeding 500 km.
- The rate of energy loss of a wave is inversely related to its wavelength. So, tsunamis lose little energy as they propagate because of their very large wavelength.
- **They travel at high speeds in deep waters, and their speed falls when they hit shallow waters**.
- A tsunami that occurs 1000 metres deep in water has a speed of more about 350 km per hour. At 6000 m, it can travel at speeds about 850 km per hour.
- **Tsunami waves are not noticed by ships far out at sea**.
- Their amplitude is negligible when compared with their wavelength, and hence the waves go unnoticed in deep oceans.
- **When tsunamis approach shallow water, however, the wave amplitude increases (conservation of energy)**.
- The waves may occasionally reach a height of 20 to 30 metres above mean sea level in closed harbours and inlets (funnelling effect).

3.3 2004 Indian Ocean Tsunami

- Tsunami or the Harbour wave struck havoc in the Indian Ocean on the 26th of December 2004.
- The wave was the result of an earthquake that had its epicentre near the western boundary of Sumatra.
- The magnitude of the earthquake was 9.0 on the Richter scale.

Plate tectonics

- **Indian plate** went under the **Burma plate**, there was a sudden movement of the sea floor, causing the earthquake.
- The ocean floor was displaced by about 10 – 20m and tilted in a downward direction.
- A huge mass of ocean water flowed to fill in the gap that was being created by the displacement.
- This marked the withdrawal of the water mass from the coastlines of the landmasses in the south and Southeast Asia.
- After thrusting of the Indian plate below the Burma plate, the water mass rushed back towards the coastline as a tsunami.



Tsunami waves

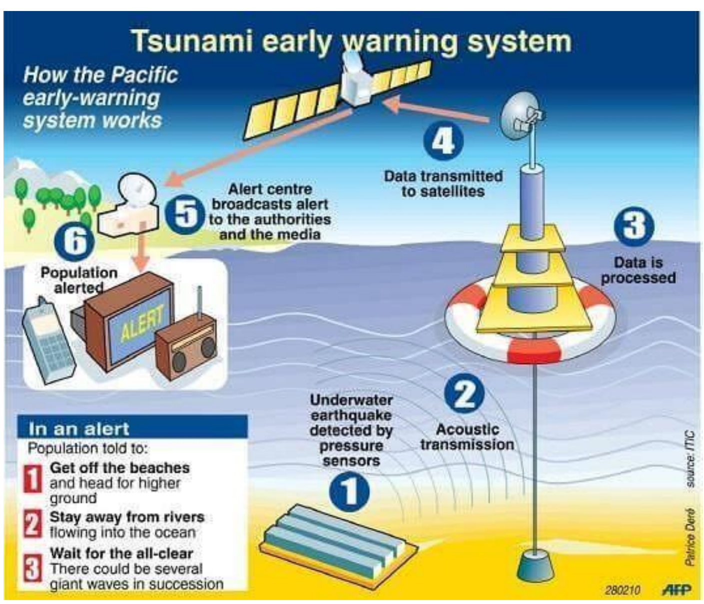
- Tsunami travelled at a speed of about 800 km. per hour, comparable to speed of commercial aircraft and completely washed away some of the islands in the Indian ocean.
- The Indira point in the Andaman and Nicobar Islands that marked the southernmost point of India got completely submerged.
- As the wave moved from earthquake epicentre from Sumatra towards the Andaman Islands and Sri Lanka, the **wavelength decreased with decreasing depth of water**.
- The travel speed also declined from 700-900 km per hour to less than 70 km per hour.
- Tsunami waves travelled up to a depth of 3 km from the coast killing more than 10,000 people and affected more than lakh of houses.
- In India, the worst affected were the coastal areas of Andhra Pradesh, Tamil Nadu, Kerala, Pondicherry and the Andaman and Nicobar Islands.

Shifts in Geography

- Tsunamis and earthquakes can cause changes in geography.
- The December 26 earthquake and tsunami shifted the North Pole by 2.5 cm in the direction of 145 degrees East longitude and reduced the length of the day by 2.68 microseconds.
- This, in turn, affected the velocity of earth's rotation and the Coriolis force which plays a strong role in weather patterns.
- The Andaman and Nicobar Islands may have (moved by about 1.25 m owing to the impact of the colossal earthquake and the tsunami.

3.4 Warning Systems

- While the earthquake cannot be predicted in advance, it is possible to give a three-hour notice of a potential tsunami.
- Such early warning systems are in place across the Pacific Ocean. Post-2004, they were installed in the Indian Ocean as well.
- In 1965, early warning system was started by the National Oceanic and Atmospheric Administration (NOAA). The member states of the NOAA include the major Pacific Rim countries.
- NOAA has developed the **'Deep Ocean Assessment and Reporting of Tsunamis' (DART) gauge.**



- Each gauge has a very sensitive pressure recorder on the sea floor. Data is generated whenever changes in water pressure occur.
- The data is transmitted to a surface **buoy** which then relays it over satellite.
- Computer systems at the **Pacific Tsunami Warning Centre (PTWC) in Hawaii** monitor data.
- Based on the data, warnings are issued.

India's preparedness

- The Deep Ocean Assessment and Reporting System (DOARS) was set up in the Indian Ocean post-2004.
- The Indian government plans to set up a network with Indonesia, Myanmar and Thailand etc.
- A **National Tsunami Early Warning Centre**, which can detect earthquakes of more than 6 magnitude in the Indian Ocean, was inaugurated in 2007 in India.
- Set up by the **Ministry of Earth Sciences** in the **Indian National Centre for Ocean Information Services (INCOIS), Hyderabad**, the tsunami warning system would take 10-30 minutes to analyse the seismic data following an earthquake.

4. Soil erosion and Landforms

- Soil erosion is the loosening and displacement of topsoil from the land due to the action of agents like wind and water.
- Soil erosion in nature may be a slow process (geological erosion) or a fast process promoted by human activities like overgrazing, deforestation.
- Weathering and erosion lead to the simultaneous process of 'degradation' and 'aggradation'.
- Erosion is a mobile process while weathering is a static process (there is no motion of disintegrated material except the falling down under the force of gravity).

4.1 Water Erosion

- Running water is one of the main agents, which carries away soil particles.

- Soil erosion by water occurs by means of raindrops, waves or ice.
- Erosion by water is termed differently according to the intensity and nature of erosion: **raindrop erosion, sheet erosion, rill and gully erosion, stream bank erosion, landslides, coastal erosion, glacial erosion**.

Raindrop erosion or splash erosion

- A raindrop is approximately 5 mm in diameter and hits the soil at a velocity of 32 km/hr. Larger raindrops and gusts of wind hit the soil surface even at higher velocities.
- Raindrops behave like tiny bombs when falling on exposed soil, displace soil particles and destroy soil structure.
- Presence of vegetation on land prevents raindrops from falling directly on the soil thus erosion of soil in areas covered by vegetation is prevented.

Sheet erosion

- With continued rainfall the displaced soil particles fill in the spaces between soil particles and prevent water from seeping into the soil. This results in surface runoff and even more erosion.
- The detachment and transportation of soil particles by flowing rainwater is called sheet or wash off erosion.

- Weathering and erosion tend to level down the irregularities of landforms and create a **peneplane**.

Rill and gully erosion

- In rill erosion finger like rills appear on the cultivated land after it has undergone sheet erosion.
- These rills are usually smoothened out every year while forming.
- Each year the rills slowly increase in number become wider and deeper.

- Gully erosion is the removal of soil along drainage lines by surface water runoff.
- When rills increase in size, they become gullies. Once started, gullies will continue to move by headward erosion or by slumping of the side walls.
- Gullies formed over a large area gives rise to **badland topography (Chambal Ravines)**.
- When a gully bed is eroded further due to headward erosion, the bed gradually deepens and flattens out, and a **ravine** is formed. The depth of a ravine may extend to 30 metres or more.
- Further erosion of ravine beds gives rise to **canyons.** Canyons are few hundred meters deep and wide. (Grand Canyon on Colorado River).

Streambank erosion

- The erosion of soil from the banks (shores) of the streams or rivers due to the flowing water is called bank erosion.

- In certain areas where the river changes its course, the river banks get eroded at a rapid rate.
- Streambank erosion damages the adjoining agricultural lands, highways and bridges.

Landslide

- The sudden mass movement of soil is called a landslide.
- Landslides occur due to instability or loss of balance of land mass with respect to gravity.
- The loss in balance occurred mainly due to excessive water or moisture in the earth mass.
- Gravity acts on such an unstable landmass and causes the large chunks of surface materials such as soil and rocks to slide down rapidly.

Coastal erosion

- In the coastal areas, waves dash along the coast and cause heavy damage to the soil.
- During the landfall of cyclones, storm surges destroy beaches and wash away the top layer.
- In estuaries, tidal bores cause extensive damage to the surrounding banks.

Glacial erosion

- In the polar regions and high mountainous regions like the Himalayas, soil erosion is caused by sowing moving glaciers. This is called glacial erosion.

4.2 Wind Erosion

- Wind erosion or **aeolian erosion** is quite significant in arid and semi-arid regions.
- Winds usually blow at high speeds in deserts due to the absence of physical obstruction.
- These winds remove the fertile, arable, loose soils leaving behind a depression devoid of topsoil.
- The depression formation in deserts is the first step in Oasis formation. Oasis forms in depressions when there is underground water that gets accumulated above rocks.
- Very fine and medium sands are moved by wind in a succession of bounds and leaps, known as **saltation**.
- Small sand and dust particles are transported over long distances through the air by a process known as **suspension**.
- Coarse sand is not usually airborne but rather is rolled along the soil surface. This type of erosion is called **surface creep.**
- Very coarse sand and gravels are too large to be rolled by wind, so wind-eroded soils have surfaces covered with coarse fragments. This kind of arid soil surface is known as **desert pavement**.

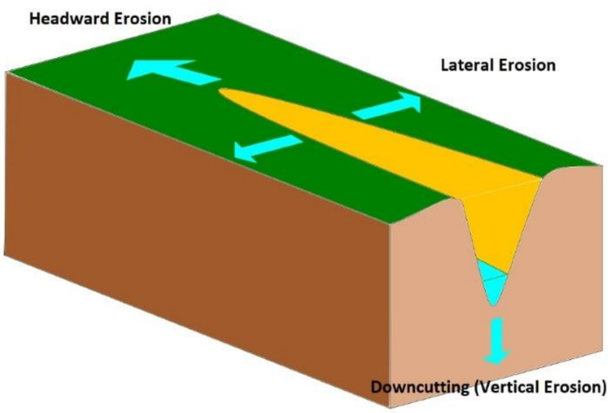
4.3 Fluvial Landforms and Cycle of Erosion

- The landforms created as a result of **degradational action (erosion and transportation)** or **aggradational work (deposition)** of running water are called fluvial landforms.

Fluvial Erosional Landforms

- Fluvial Erosional Landforms are landforms created by the erosional activity of rivers.
- Various aspects of fluvial erosive action include:
- ✓ **Hydration:** the force of running water wearing down rocks.
- ✓ **Corrosion:** chemical action that leads to weathering.
- ✓ **Attrition:** river load particles striking, colliding against each other and breaking down in the process.
- ✓ **Corrasion or abrasion:** solid river load striking against rocks and wearing them down.
- ✓ **Downcutting (vertical erosion):** the erosion of the base of a stream (downcutting leads to valley deepening).

- ✓ **Lateral erosion:** the erosion of the walls of a stream (leads to valley widening).
- ✓ **Headward erosion:** erosion at the origin of a stream channel, which causes the origin to move back away from the direction of the stream flow, and so causes the stream channel to lengthen.

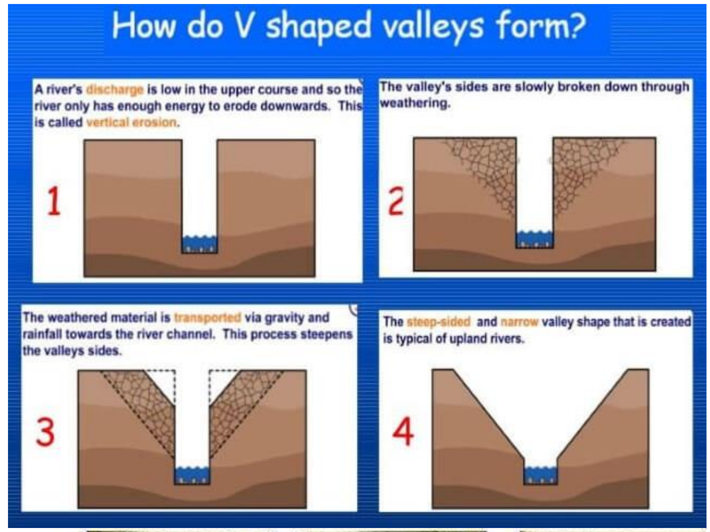


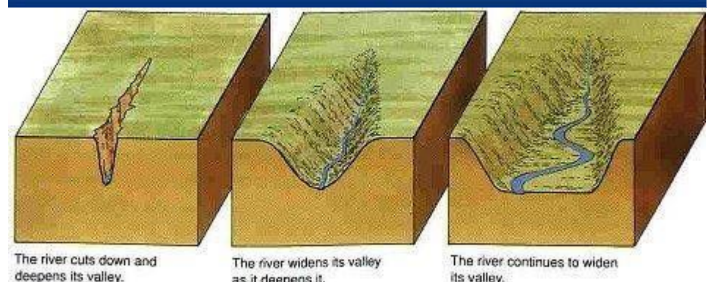
Vertical, Lateral and Headward Erosion (Kayau, from Wikimedia Commons)

- ✓ **Braiding:** the main water channel splitting into multiple, narrower channel. A braided river, or braided channel, consists of a network of river channels separated by small, and often temporary, islands called braid bars. Braided streams occur in rivers with low slope and/or large sediment load.

River Valley Formation

- The extended depression on the ground through which a stream flows is called a river valley.
- At different stages of the erosional cycle, the valley acquires different profiles.
- At a young stage, the valley is deep, narrow with steep wall-like sides and a convex slope.
- The erosional action here is characterized by predominantly **vertical downcutting** nature.

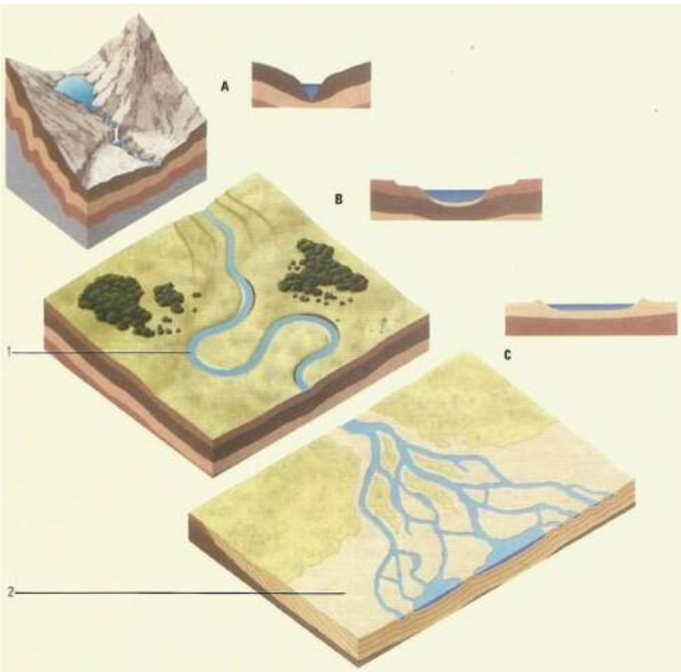




- The profile of valley here is typically 'V' shaped.
- A deep and narrow 'V' shaped valley is also referred to as **gorge** and may result due to downcutting erosion or because of the recession of a waterfall (the position of the waterfall receding due to erosive action).
- Most Himalayan rivers pass through deep gorges (at times more than 500 metres deep) before they descend to the plains.
- An extended form of the gorge is called a **canyon.** The Grand Canyon of the Colorado River in Arizona (USA) runs for 483 km and has a depth of 2.88 km.
- A tributary valley lies above the main valley and is separated from it by a steep slope down which the stream may flow as a waterfall or a series of rapids.
- As the cycle attains maturity, the **lateral erosion** (erosion of the walls of a stream) becomes

prominent and the valley floor flattens out (attains a ‘V’ to ‘U’ shape).
- The valley profile now becomes typically ‘U’ shaped with a broad base and a concave slope.

River course



Youth

- Young rivers (A) close to their source tend to be fast-flowing, high-energy environments with rapid headward erosion, despite the hardness of the rock over which they may flow.
- Steep-sided **"V-shaped' valleys, waterfalls, and rapids** are characteristic features.
- E.g. Rivers flowing in the Himalayas.

Maturity

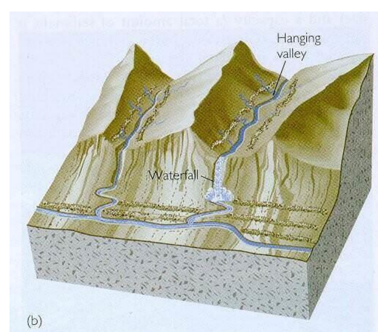
- Mature rivers (B) are lower-energy systems.
- Erosion takes place on the outside of bends, creating looping meanders in the soft alluvium of the river plain.
- Deposition occurs on the inside of bends and on the river bed.
- E.g. Rivers flowing in the Indo-Gangetic-Brahmaputra plain.

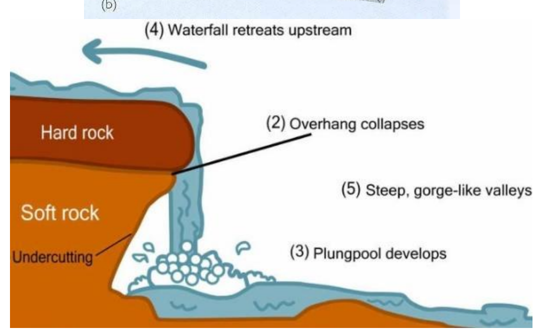
Old Age

- At a river's mouth (C), sediment is deposited as the velocity of the river slows.
- As the river becomes shallower more deposition occurs, forming **temporary islands (Majuli, a river island in the Brahmaputra River, Assam is currently the world's largest river island)** and **braiding** (e.g. braided channels of Brahmaputra river flood plain in Assam) the main channel into multiple, narrower channels.
- As the sediment is laid down, the actual mouth of the river moves away from the source into the sea or lake, forming a **delta**.
- E.g. Ganga-Brahmaputra delta.

Waterfalls

- A waterfall is simply the fall of an enormous volume of water from a great height.
- They are **mostly seen in** the **youth stage** of the river.
- Relative resistance of rocks, the relative difference in topographic reliefs, fall in the sea level and related rejuvenation, earth movements etc. are responsible for the formation of waterfalls.





- **Kunchikal Falls** (it is a cascade falls — falls with many steps) formed by Varahi river in Shimoga district, Karnataka is the highest waterfall in India (455 m).
- **Nohkalikai Falls (340 m)** is the tallest plunge waterfall in India. The waterfall is located near Cherrapunji.
- **Jog or Gersoppa falls (253 m)** on Sharavati river (a tributary of Cauvery), Karnataka is the second-highest plunge waterfall in India.
- **Angel Falls** in Venezuela is the world's highest waterfall, with a height of 979 metres and a plunge of 807 metres.
- **Tugela Falls** (948 m) in the Drakensberg mountains, South Africa is the world's second highest waterfall.

Potholes

- The small cylindrical depressions in the rocky beds of the river valleys are called potholes.
- Potholing or pothole-drilling is the mechanism through which the fragments of rocks when caught in the water eddies or swirling water start dancing circularly and grind and drill the rock beds.
- They thus form small holes which are gradually enlarged by the repetition of the said mechanism.

Terraces

- Stepped benches along the river course in a flood plain are called terraces.
- Terraces represent the level of former valley floors and remnants of former (older) floodplains.

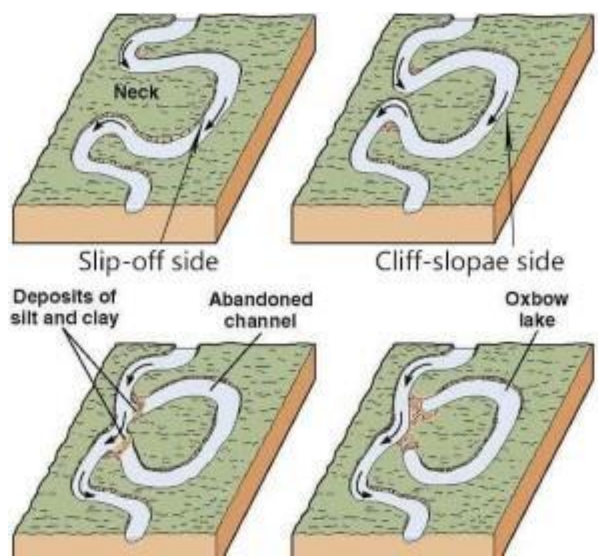
Gulleys/Rills

- Gulley is a water-worn channel, which is particularly common in semi-arid areas.
- It is formed when water from overland-flows down a slope, especially following heavy rainfall, is concentrated into rills, which merge and enlarge into a gulley.
- The **ravines of Chambal Valley** in Central India and the **Chos of Hoshiarpur** in Punjab are examples of gulleys.

Ravines of Chambal Valley in Madhya Pradesh

Meanders

- A meander is defined as a pronounced curve or loop in the course of a river channel.
- The outer bend of the loop in a meander is characterized by intensive erosion and vertical cliffs and is called the **cliff-slope side**. This side has a concave slope.
- The inner side of the loop is characterized by deposition, a gentle convex slope, and is called the **slip-off side.**
- The meanders may be wavy, horse-shoe type or oxbow type.



Oxbow Lake

- Sometimes, because of intensive erosion action, the outer curve of a meander gets accentuated to such an extent that the inner ends of the loop come close enough to get disconnected from the main channel and exist as independent water bodies called as oxbow lakes.
- These water bodies are converted into swamps in due course of time.

- In the Indo-Gangetic plains, southwards shifting of Ganga has left many oxbow lakes to the north of the present course of the Ganga.

Peneplane (Or peneplain)

- This refers to an undulating featureless plain punctuated with low-lying residual hills of resistant rocks. It is considered to be an **end product of an erosional cycle**.

Uluru or Ayers Rock in central Australia standing on a peneplane

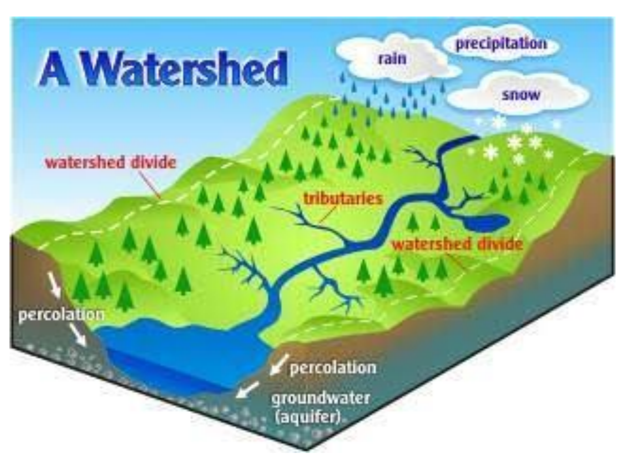
- Fluvial erosion, in the course of geologic time, reduces the land almost to base level (sea level), leaving so little gradient that essentially **no more erosion could occur**.

Drainage basin

- Other terms that are used to describe drainage basins are **catchment, catchment area, catchment basin, drainage area, river basin, and water basin.**
- The drainage basin includes both the streams and rivers and the land surface.
- The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channelling it to a single point.
- In **closed (endorheic) drainage** basins the water converges to a single point inside the basin, known as a **sink**, which may be a permanent lake (e.g. Lake Aral, also known Aral Sea, Dead Sea), dry lake (some desert lakes like Lake Chad, Africa), or a point where surface water is lost underground (sinkholes in Karst landforms).

Drainage Divide

- Adjacent drainage basins are separated from one another by a drainage divide.
- Drainage divide is usually a ridge or a high platform.
- Drainage divide is conspicuous in case of youthful topography (Himalayas), and it is not well marked in plains and senile topography (old featureless landforms — rolling plateaus of Peninsular region).



Difference between a River Basin and a Watershed

- Both river basins and watersheds are areas of land that drain to a particular water body, such as a lake, stream, river or estuary.
- In a river basin, all the water drains to a large river. The term watershed is used to describe a smaller area of land that drains to a smaller stream, lake or wetland.
- There are many smaller watersheds within a river basin.
- Example: watershed of Yamuna + watershed of Chambal + watershed of Gandak + …. = Drainage basin of Ganga.

Some important drainage basins across the world

Basin	Continent	Drains to	Basin Area km^2
Amazon River	**South America**	**Atlantic Ocean**	**6,144,727**
Hudson Bay	North America	Atlantic Ocean	3,861,400
Congo River	Africa	Atlantic Ocean	3,730,474
Caspian Sea	Asia/Europe	**Endorheic basin**	3,626,000
Nile River	Africa	Mediterranean Sea	3,254,555
Mississippi-Missouri River	North America	Gulf of Mexico	3,202,230
Lake Chad	Africa	**Endorheic basin**	2,497,918
Black Sea	multiple	Mediterranean Sea	2,400,000
Niger River	Africa	Atlantic Ocean	2,261,763
Yangtze River (Chang Jiang)	Asia	Pacific Ocean	1,722,155
Baltic Sea	Europe	Atlantic Ocean	1,700,000
Ganges–Brahmaputra	**Asia**	**Bay of Bengal**	**1,621,000**
Indus River	**Asia**	**Arabian Sea**	**1,081,733**

Drainage systems (drainage patterns)

- Drainage systems, also known as river systems, are the patterns formed by the streams, rivers, and lakes in a particular drainage basin.
- They are governed by tectonic irregularity, nature of underlying rock strata, and the gradient of the land.
- Based on the correlation between the topology and the direction of flow, drainage patterns are classified into concordant drainage and discordant or insequent drainage.

Concordant drainage

- A drainage pattern is described as concordant if it **correlates to the topology** and **geology** of the area.
- In simple words, in a concordant drainage pattern, the path of the river is highly dependent on the slope of the river and topography.
- Concordant drainage patterns are the most commonly found drainage patterns and are classified into many consequent, subsequent, obsequent and resequent.

Consequent Rivers

- The rivers which follow the **general direction of the slope** are known as the consequent rivers.
- Most of the rivers of peninsular India are consequent rivers.
- For example, rivers like the **Godavari, Krishna and Cauvery,** descending from the Western Ghats and flowing into the Bay of Bengal, are some of the consequent rivers of Peninsular India.

Subsequent Rivers

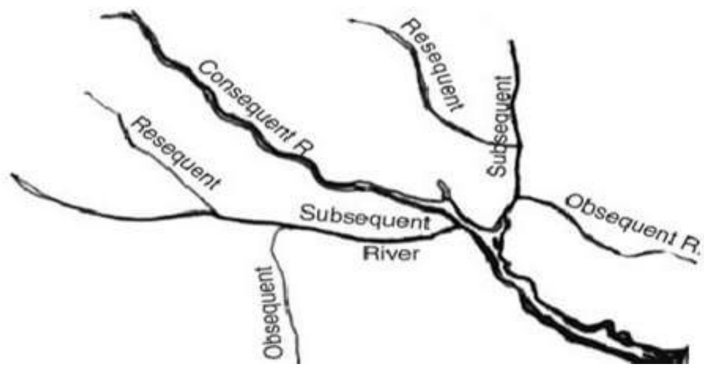
- A tributary stream that is formed by headward erosion **along** an underlying rock after the main drainage pattern (consequent river) has been established is known as a subsequent river.
- The **Chambal, Sind, Ken, Betwa, Tons and Son** meet the Yamuna and the Ganga at right angles. They are the subsequent drainage of the Ganga drainage system.

Obsequent Rivers

- After the valley development of consequent and subsequent rivers, obsequent rivers may form at right angles to the subsequent rivers and flow **opposite** to the direction of flow of the original consequent river.

Resequent Rivers

- A resequent river flows in the same direction as that of the initial consequent drainage.
- Resequent rivers originate at a much later stage (hence they are called resequent) in comparison to the master consequent rivers.



Discordant or Insequent drainage patterns

- A drainage pattern is described as discordant if it **does not correlate to the topology (surface relief features)** and **geology** of the area.
- In simple words, in a discordant drainage pattern, the river follows its initial path irrespective of the changes in topography.
- Discordant drainage patterns are classified into two main types: **antecedent** and **superimposed**.
- Usually, rivers in both these drainage types flow through a **highly sloping surface**.

Antecedent Drainage or Inconsequent Drainage

- A part of a river slope and the surrounding area gets uplifted, and the river **sticks to its original slope**, cutting through the uplifted portion like a saw (vertical erosion) and forming deep gorges. This type of drainage is called **antecedent drainage.**
- Example: **Indus, Sutlej, Brahmaputra and other Himalayan rivers that are older than the Himalayas themselves**. There are usually called **antecedent rivers (rivers older than the existing land itself)**.

Superimposed or Epigenetic (Discordant) or Superinduced Drainage

- When a river flowing over a softer rock stratum reaches the harder basal rocks but continues to follow the initial slope, it seems to have no relation with the harder rock bed. This type of drainage is called superimposed drainage.

Explanation

- Usually, the drainage patterns (dendritic, trellis, etc.) are strongly influenced by the hardness and softness of the rock and patterns of faults or fractures.
- Sometimes, however, the land rises rapidly relative to the base level of the stream. This increases the gradient of the stream and therefore, gives the stream more erosive power.
- The stream has enough erosive power that it cuts its way through any bedrock, **maintaining its former drainage pattern**.
- You get a situation, then, where the drainage pattern does not correspond to the hardness or softness of the bedrock or the locations of faults and fractures.
- In other words, it is a drainage pattern which exhibits discordance with the underlying rock structure because it originally developed on a cover of rocks that has now disappeared due to denudation.
- Consequently, river directions relate to the former cover rocks and, as the latter was being eroded, the rivers have been able to retain their courses unaffected by the newly exposed structures.
- The stream pattern is thus superposed on or placed on structural features that were previously buried.
- The **Damodar**, the **Subarnarekha**, the **Chambal**, the **Banas** and the rivers flowing at the **Rewa Plateau** present some good examples of superimposed drainage.
- [In simple words, the river flow becomes independent of present Topography. It flows in its initial paths without being influenced by changing topography].

Antecedent Drainage: *cuts through the newly formed landform and maintains the same path. E.g. Himalayan Rivers.*

Superimposed Drainage: *cuts deeper through the existing landform and maintains the same path. E.g. some medium scale rivers of the Northern and Eastern peninsular India.*

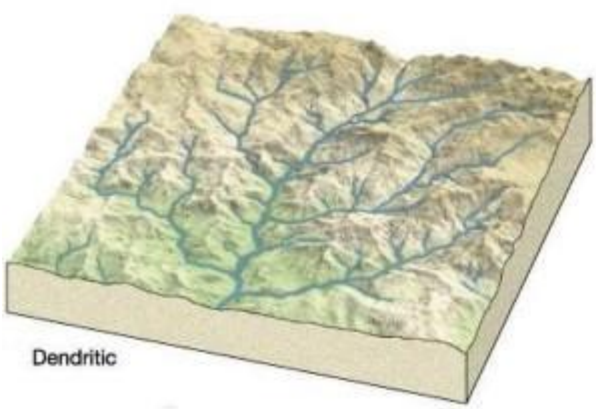
Antecedent Drainage: *The soil formed is weak (mostly weak sediments), and the rivers easily erode it.*

Superimposed Drainage: *The rivers have high erosive power so that they can cut through the underlying strata.*

Other Drainage Patterns

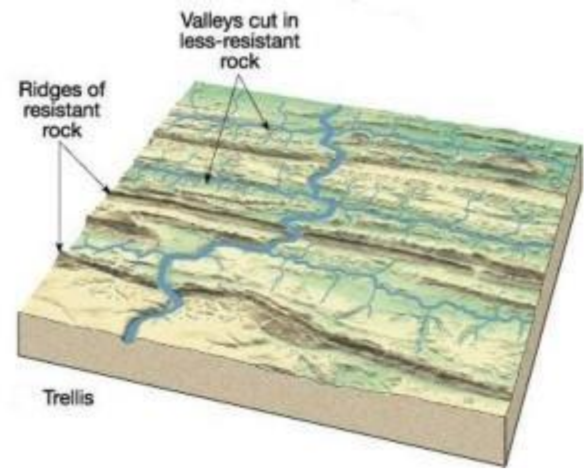
Dendritic or Pinnate Drainage Pattern

- This is an irregular tree branch shaped pattern that develops in a terrain which has uniform lithology (uniform rock structure), and where faulting and jointing are insignificant.
- Examples**: Indus, Godavari, Mahanadi, Cauvery, Krishna.**



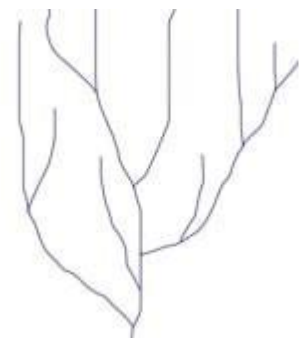
Trellis Drainage Pattern

- In this type of pattern, the short subsequent streams meet the main stream at **right angles**, and differential erosion through soft rocks paves the way for tributaries.
- Examples: The old folded mountains of the **Singhbhum (Chotanagpur Plateau)** and **Seine and its tributaries in Paris basin (France)** have drainage of trellis pattern.



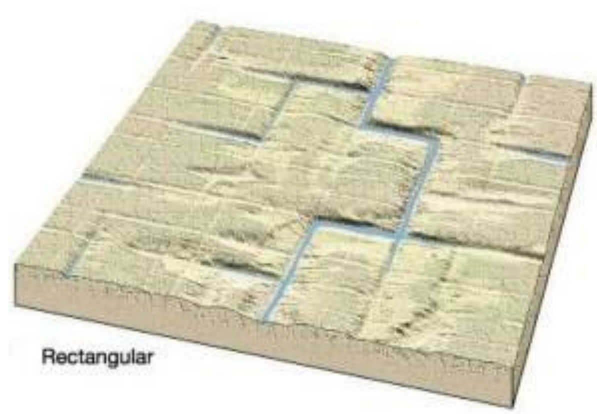
Angular Drainage Pattern

- The tributaries join the main stream at acute angles.
- This pattern is common in **Himalayan foothill regions.**



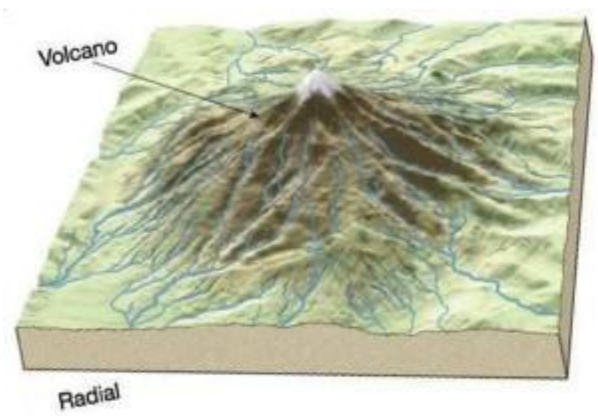
Rectangular Drainage Pattern

- The main stream bends at right angles and the tributaries join at **right angles** creating rectangular patterns.
- This pattern has a subsequent origin. Example: Colorado River (USA), streams found is the Vindhyan Mountains of India.



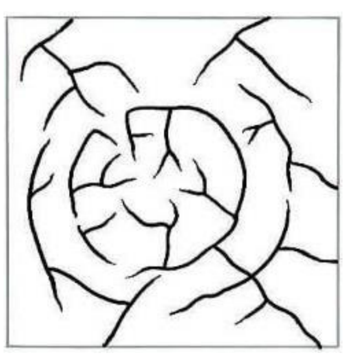
Radial Drainage Pattern

- The tributaries from a summit follow the slope downwards and drain down in all directions.
- Examples: **Streams of Saurashtra region,** the **rivers originating from the Amarkantak Mountain, Central French Plateau, Mt. Kilimanjaro**.
- The Narmada, Son and Mahanadi originate from Amarkantak Hills and flow in different directions.



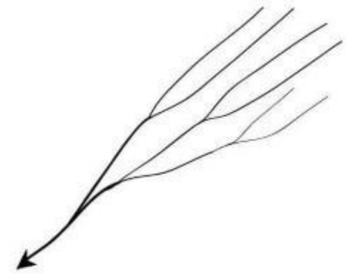
Annular Drainage Pattern

- When the upland has a soft outer stratum, the radial streams develop subsequent tributaries which try to follow circular drainage around the summit.
- Example: Black Hill streams of South Dakota.
- This is not a very common drainage pattern in India. Some examples of this are however found in **Pithoragarh (Uttarakhand), Nilgiri Hills in Tamil Nadu and Kerala**.



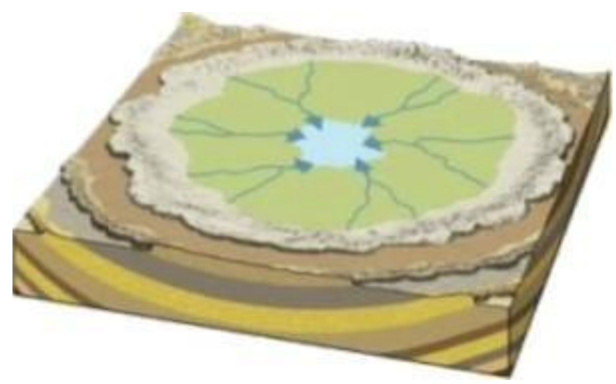
Parallel Drainage Pattern

- The tributaries seem to be running parallel to each other in a uniformly sloping region.
- Example: **Rivers of lesser Himalayas** and The **small and swift rivers originating in the Western Ghats** that flow into Arabian Sea.



Centripetal Drainage Pattern

- In a low-lying basin, the streams converge from all sides.
- Examples: **streams of Ladakh, Tibet**, and the **Baghmati** and its tributaries in Nepal.



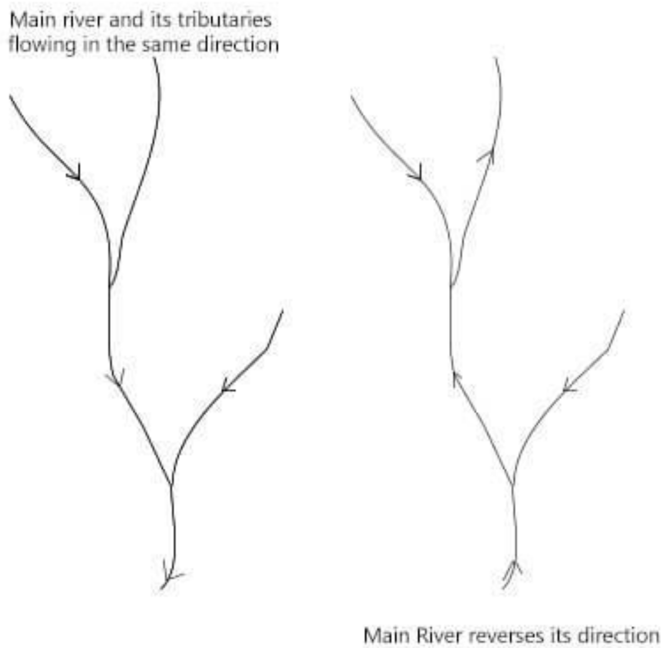
Deranged Drainage Pattern

- This is an uncoordinated pattern of drainage characteristic of a region recently vacated by an ice-sheet.
- The picture is one of the numerous watercourses, lakes and marshes; some inter-connected and some in local drainage basins of their own.
- This type of drainage is found in the glaciated valleys of Karakoram.

Barbed Drainage Pattern

- A pattern of drainage in which the confluence of a tributary with the main river is characterized by a discordant junction — as if the tributary intends to flow upstream and not downstream.

- This pattern is the result of the capture of the main river which completely reverses its direction of flow, while the tributaries continue to point in the direction of former flow.
- The Arun River (Nepal), a tributary of the Kosi is an interesting example of barbed drainage pattern.



Fluvial Depositional Landforms

- Fluvial Depositional Landforms are landforms created by the depositional activity of rivers.
- The depositional action of a stream is influenced by stream velocity and the volume of river load.
- The decrease in stream velocity reduces the transporting power of the streams which are forced to leave some load to settle down.
- Various landforms resulting from fluvial deposition are as follows:

Alluvial Fans and Cones

- When a stream leaves the mountains and comes down to the plains, its velocity decreases due to a lower gradient.
- As a result, it sheds a lot of material, which it had been carrying from the mountains, at the foothills.
- This deposited material acquires a conical shape and appears as a series of continuous fans. These are called alluvial fans.
- Such fans appear throughout the **Himalayan foothills** in the north Indian plains.

Natural Levees

- These are narrow ridges of low height on both sides of a river, formed due to deposition action of the stream, appearing as natural embankments.
- These act as natural protection against floods but a breach in a levee causes sudden floods in adjoining areas, as it happens in the case of the **Hwang Ho river of China**.

Delta

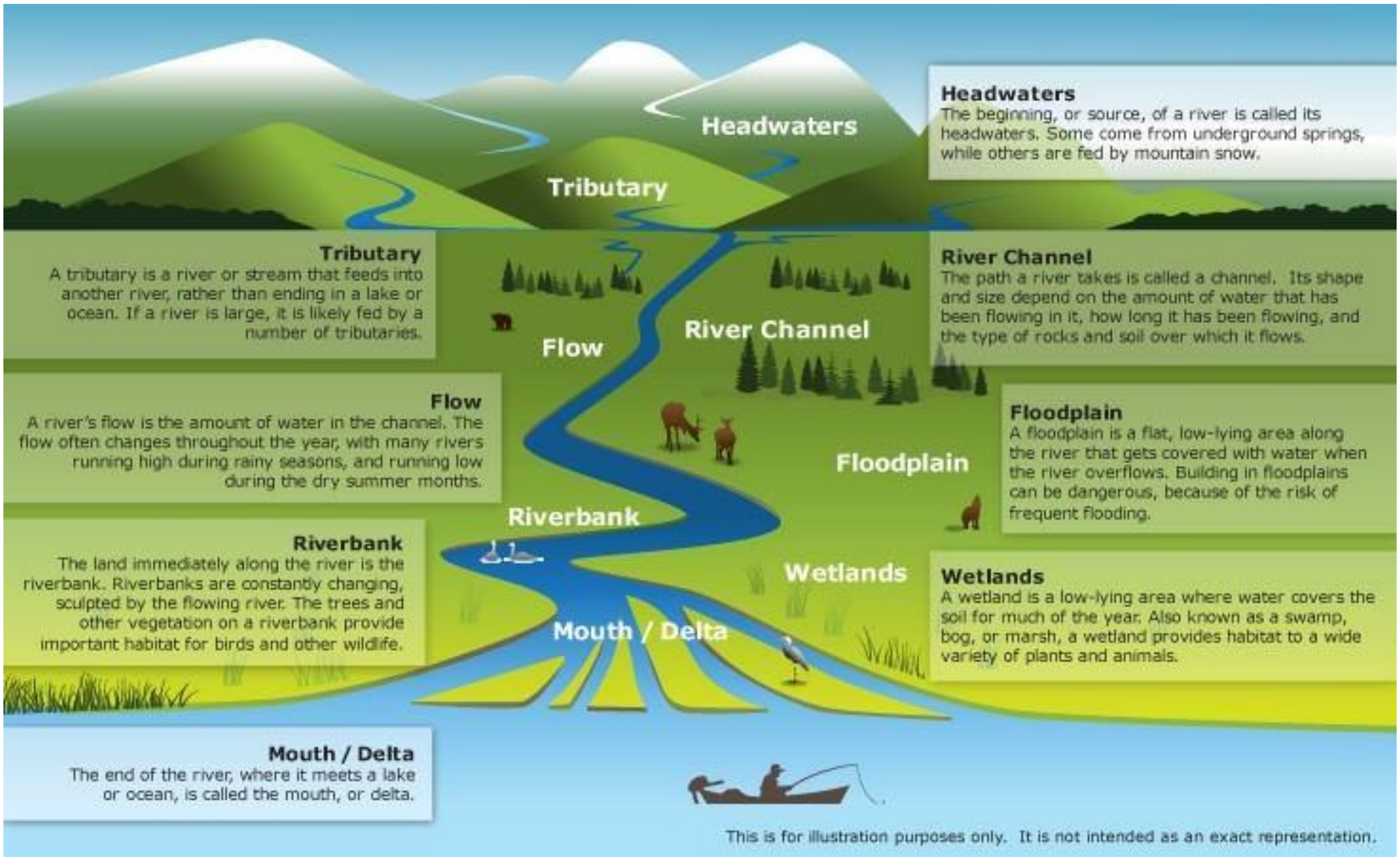
- A delta is a tract of alluvium at the mouth of a river where it deposits more material than that can be carried away.
- The river gets divided into distributaries which may further divide and rejoin to form a network of channels.

A combination of two processes forms a delta:

1. the load-bearing capacity of a river is reduced as a result of the check to its speed as it enters a sea or lake, and

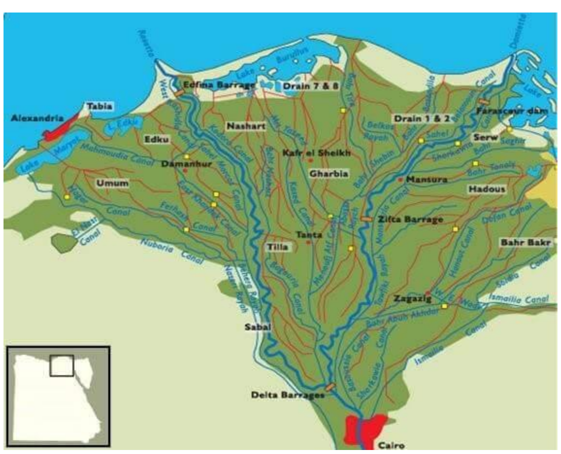
2. clay particles carried in suspension in the river **coagulate** in the presence of salt water and are deposited.

- The finest particles are carried farthest to accumulate as bottom-set beds. Depending on the conditions under which they are formed, deltas can be of many types.



Arcuate or Fan-shaped (Curved)

- This type of delta results when light depositions give rise to shallow, shifting distributaries and a general fan-shaped profile. Examples: **Nile, Ganga, Indus.**



Bird's Foot Delta (Elongated)

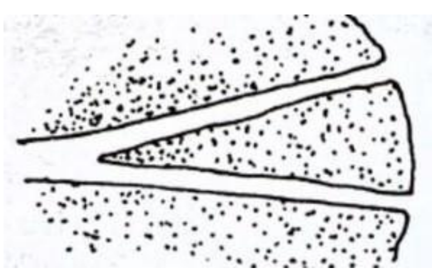
- This type of delta emerges when limestone sediment deposits do not allow downward seepage of water.
- The distributaries seem to be flowing over projections of these deposits which appear as a bird's foot.
- The currents and tides are weak in such areas and the number of distributaries lesser as compared to an arcuate delta. Example: **Mississippi River**.

Estuaries

- Sometimes the mouth of the river appears to be submerged. This may be due to a drowned valley because of a rise in sea level.
- Here fresh water and the saline water get mixed. When the river starts 'filling its mouth' with sediments, mud bars, marshes and plains seem to be developing in it.
- These are **ideal sites for fisheries, ports and industries** because estuaries provide access to deep water, especially if protected from currents and tides. Example: **Hudson estuary**.

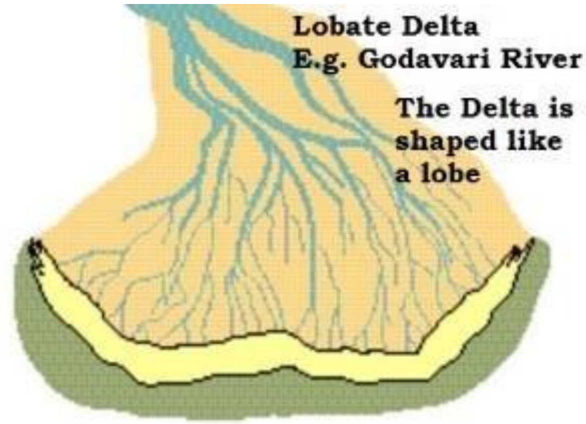
Cuspate Delta

- This is a pointed delta generally formed along strong coasts and is subjected to strong wave action. There are very few or no distributaries in a cuspate delta.
- Example: Tiber river on the west coast of Italy.



High-constructive deltas – Elongate and Lobate Delta

- Develops when fluvial action and depositional process dominate the system.
- Elongate delta is represented by the **bird-foot delta of the Mississippi River**.
- The Godavari River represents lobate delta.



Lobate: Shaped like a lobe

Godavari – Lobate
Krishna – Arcuate
Kaveri – Quadrilateral
Nile, Indus, Ganga-Brahmaputra – Arcuate
All the above are more or less the same kind (arcuate) of deltas

- Both of these types have a large sediment supply that tends to disperse sediment along the shoreline.
- A lobate delta (a subtype of fan-shaped delta) is formed if the river water is as dense as the seawater (precipitation or coagulation of river sediments occur immediately, and hence the delta is not elongated).
- A bird-boot delta (elongated delta) is formed when the river water is lighter than seawater (precipitation or coagulation of river sediments can occur at a distance from shore, and hence the delta is elongated).

High-destructive deltas

- Shoreline energy is high and much of the sediment delivered by the river is reworked by wave action or currents before it is finally deposited. .
- Deltas formed by rivers such as the Nile and the Rhône have been classified as wave-dominated.
- In this class of high-destructive delta, sediment is finally deposited as arcuate sand barriers near the mouth of the river.

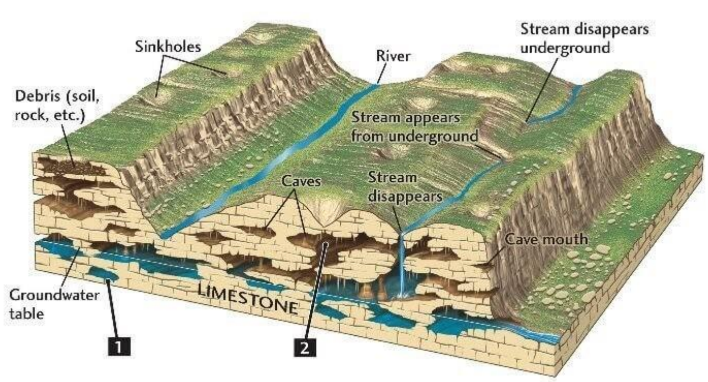
4.4 Karst Landforms and Cycle of Erosion

- Karst landforms are characterized by **underground** drainage systems with sinkholes, fissures, caves formed from the dissolution (chemical weathering) and erosion of soluble rocks such as limestone, dolomite.

- There is the general absence of surface drainage as the water flow is mostly subsurface (underground).
- In its pure state, limestone is made up of calcium carbonate, but where magnesium is also present, it is termed as dolomite.
- Limestone is an organically formed sedimentary rock (formed by the decomposition of calcareous shells) and is soluble in rainwater.
- The carbonic acid that causes karstic features is formed as rain passes through the atmosphere picking up carbon dioxide (CO_2).
- Once the rain reaches the ground, it may pass through soil that can provide much more CO_2 to form a weak carbonic acid solution, which dissolves calcium carbonate (limestone).
- Karsts are so named after a province of **Yugoslavia** (in Balkans) **on the Adriatic Sea** coast where such formations are most noticeable.

Conditions for the formation of karst topography

- Surface or subsurface strata made up of porous water-soluble rocks such as limestone.
- Thinly bedded and highly jointed and cracked rock strata that make it easy for the water to seep in.
- Moderate to abundant rainfall for chemical weathering of limestone.
- A perennial source of water and a low water table to erode the weathered rock.



Sinkhole/Swallow Hole

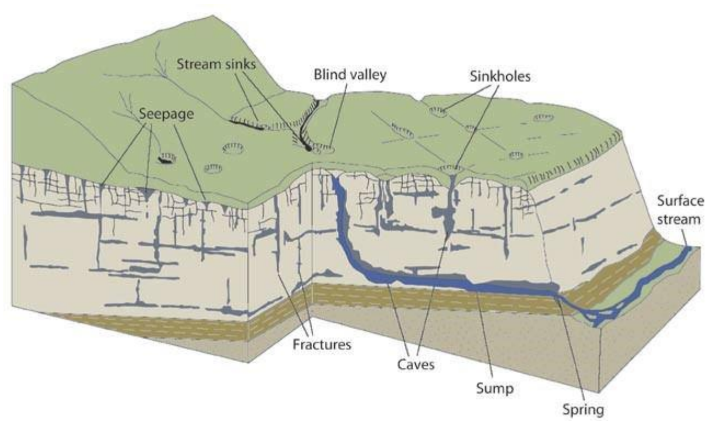
- Sinkholes are funnel-shaped depressions developed by enlargement of the cracks found in porous water-soluble rocks, as a result of continuous solvent action (chemical weathering) of the rainwater.
- The surface streams disappear underground through swallow holes.
- There is a great variation in size and depth of sinkholes.

Karst Window

- When some adjoining sinkholes collapse, they form an open, broad area called a karst window.

Polje/Blind Valley

- Dolines are small depressions dotting a karst landscape. They are less common than sinkholes
- Some adjoining dolines may come together to form a long, narrow trench called uvala.
- Some uvalas may coalesce to create a ‘U’ shaped valley called polje.
- If the streams lose themselves in these valleys, then these are called blind valleys.



Cavern

- This is an underground cave formed by water action by various methods in a limestone stratum.
- Mechanical action by rock debris and pebbles and solution action of water may be responsible for cavern formation.
- In India, such caves can be seen in Bastar, Dehradun, Shillong plateau.

Arch/Natural Bridge

- When a part of the cavern collapses the portion, which keeps standing forms an arch.

Sinking Creeks/Bogas

- In a karst valley, the water often gets lost through cracks and fissures in the bed. These are called sinking creeks, and if their tops are open, they are called bogas.

Stalactite and Stalagmite

- When water containing limestone seeps through the roof in the form of a continuous chain of drops a small deposit of limestone is left behind due to evaporation of water contributing to the formation of a lean inverted cone-like structure growing downwards from the roof called stalactite.
- The remaining portion of the drop falls to the floor. This also evaporates, leaving behind a small deposit of limestone aiding the formation of a stalagmite, thicker and flatter, rising upwards from the floor.
- Sometimes, stalactite and stalagmite join together to form a complete pillar known as the column.

Dry Valley/Hanging Valley/Bourne

- Sometimes, a stream erodes so much that it goes very deep. The water table is also lowered. Now the tributaries start serving the subterranean drainage and get dried up. These are dry valleys or bournes.
- Lack of adequate quantities of water and reduced erosion leaves them hanging at a height from the main valley. Thus, they are also referred to as hanging valleys.

The Karst Cycle of Erosion

Youth

- Youth begins with the surface drainage on an initial limestone surface.
- Gradually, the upper impervious layer is eroded.
- Dolines, sinkholes and swallow holes are formed.

- No large caverns exist, and underground drainage has not yet completed its course.

Maturity

- There is maximum underground drainage.
- Surface drainage is limited to short-sinking cracks ending in swallow holes or blind valleys.
- Cavern networks are characteristic of this stage.
- Late maturity marks the beginning of the decline of karst features.
- The portions of cavern streams are exposed through karst windows. These expand to form large uvalas, and detached areas of original limestone upland begin to stand out as hums.

Old Age

- Large-scale removal of limestone mass leaves behind a karst plain.
- There is a reappearance of surface drainage with only a few isolated hums as remnants of the original limestone terrain.

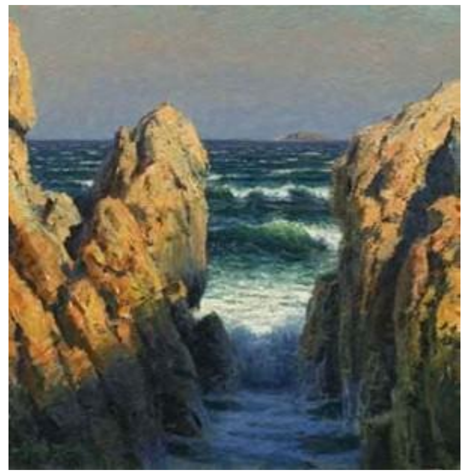
4.5 Marine Landforms and Cycle of Erosion

- Sea waves, aided by winds, currents, tides and storms carry on the erosional and depositional processes.
- The erosive work of the sea depends upon size and strength of waves, slope, the height of the shore between low and high tides, the shape of the coast, the composition of rocks, depth of water, human activity etc.
- The wave pressure compresses the air trapped inside rock fissures, joints, faults, etc. forcing it to expand and rupture the rocks along weak points. This is how rocks undergo weathering under wave action.
- Waves also use rock debris as instruments of erosion (glaciers are quite good at this). These rock fragments carried by waves themselves get worn down by striking against the coast or one another.
- The solvent or chemical action of waves is another mode of erosion, but it is pronounced only in case of soluble rocks like limestone and chalk.

Marine Erosional Landforms

Chasms

- These are narrow, deep indentations (a deep recess or notch on the edge or surface of something) carved due to headward erosion (downcutting) through vertical planes of weakness in the rocks by wave action.
- With time, further headward erosion is hindered by lateral erosion of chasm mouth, which itself keeps widening till a bay is formed.



Wave-Cut Platform

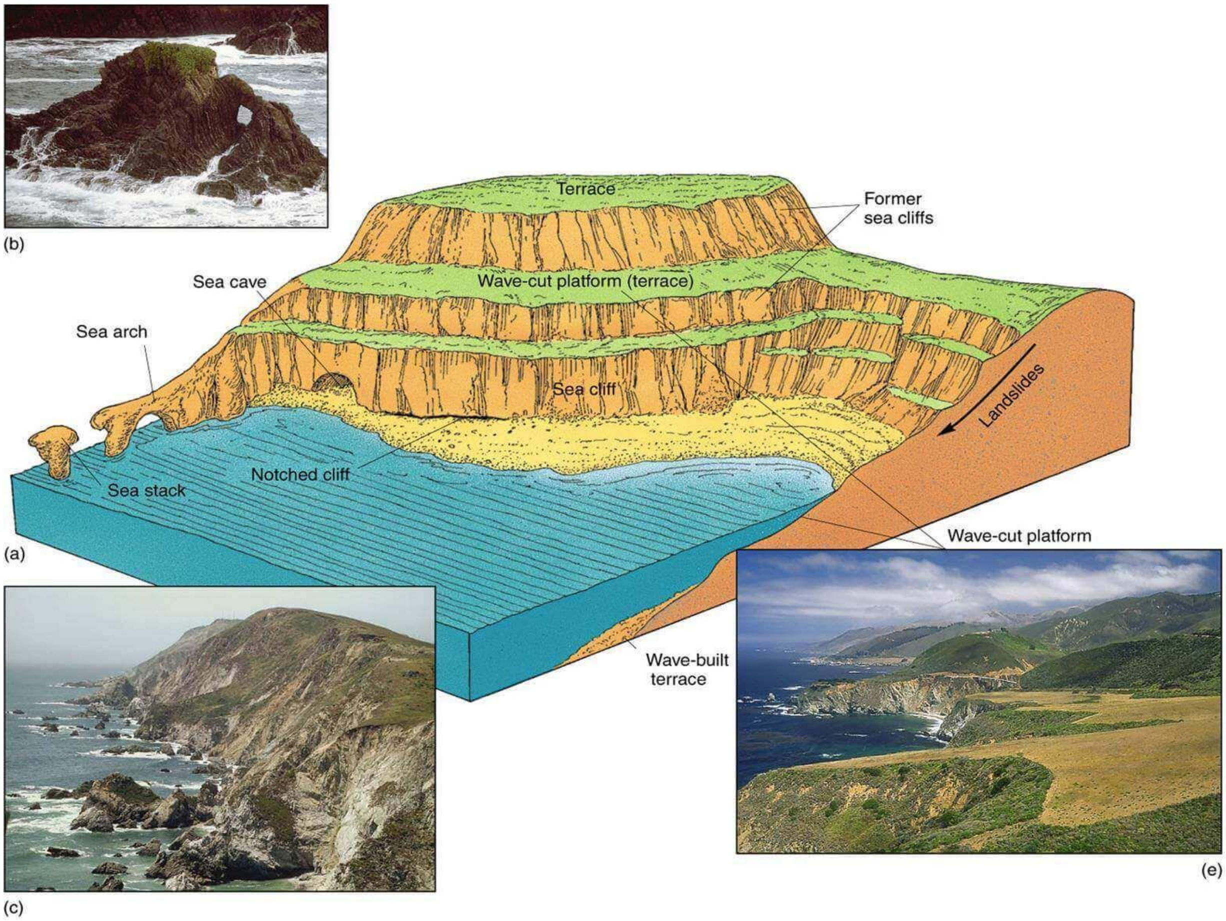
- When the sea waves strike against a cliff, the cliff gets eroded (lateral erosion) gradually and retreats.
- The waves level out the shore region to carve out a horizontal plane or a wave-cut platform.
- The bottom of the cliff suffers the maximum intensive erosion by waves and, as a result, a notch appears at this position.

Sea Cliff

- Shoreline marked by a steep bank (escarpment, scarp).

Sea Caves

- Differential erosion by sea waves through rock with varying resistance across its structure produces arched caves in rocks called sea caves.



Sea Arches

- When waves from opposite directions strike a narrow wall of rock, differential erosion of the rock leaves a **bridge like structure** called Sea arch.

Stacks/Skarries/Chimney Rock

- When a portion of the sea arch collapses, the remaining column-like structure is called a stack, skarry or chimney rock.

Hanging Valleys

- If the fluvial erosion of a stream at the shore doesn't match the retreat of the sea, the rivers appear to be hanging over the sea. These river valleys are called hanging valleys.

Blow Holes or Spouting Horns

- The burst of water through a small hole on a sea cave due to the compression of air in the cave by strong waves. They make a peculiar noise.

Plain of Marine Erosion/Peneplain

- The eroded plain left behind by marine action is called a plain of marine erosion. If the level difference between this plain and the sea level is not much, the agents of weathering convert it into a peneplain.

Marine Depositional Landforms

Beach

- This is the temporary covering of rock debris on or along a wave-cut platform.

Bar

- Currents and tidal currents deposit rock debris and sand along the coast at a distance from the shoreline.
- The resultant landforms which remain sub-merged are called bars.
- The enclosed water body so created is called a **lagoon.**

Barrier

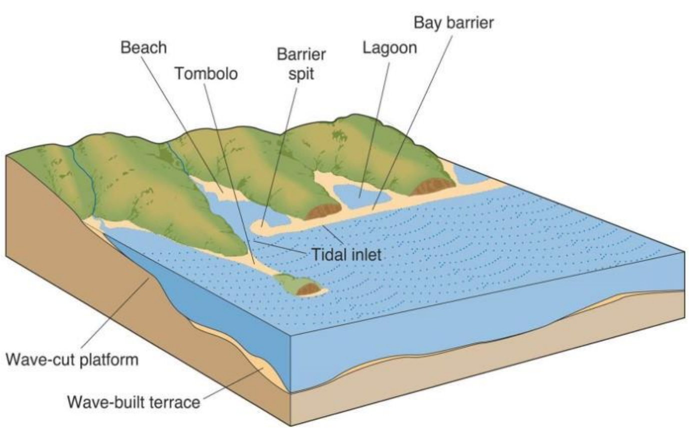
- It is the overwater counterpart of a bar.

Spit and Hook

- A spit is a projected deposition joined at one end to the headland, with the other end free in the sea.
- The mode of formation is similar to a bar or barrier.
- A shorter spit with one end curved towards the land is called a **hook.**

Tombolos

- Sometimes, islands are connected to each other by a bar called tombolo.



Coastlines

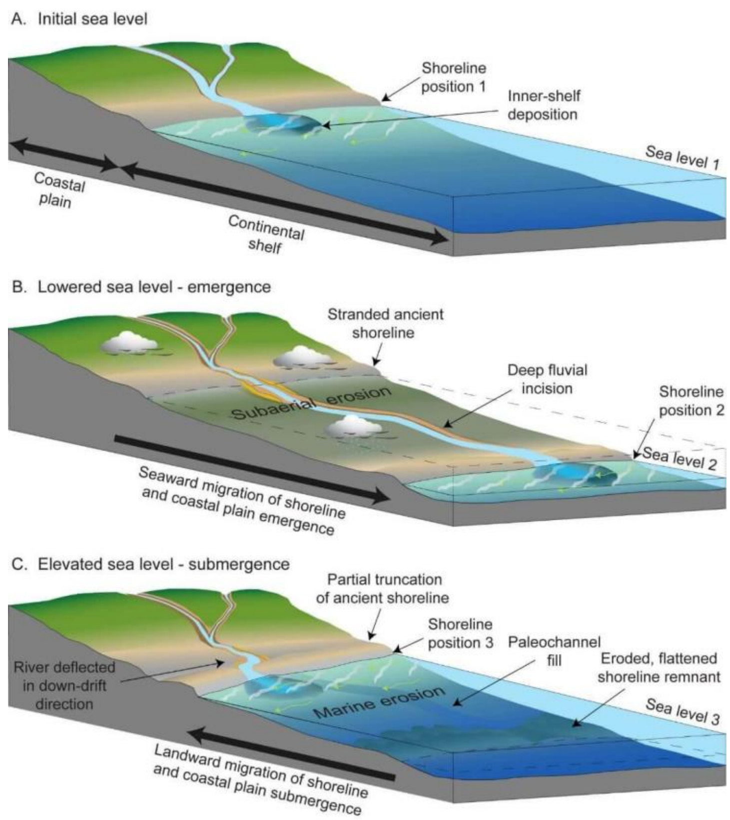
- The boundary between the coast (the part of the land adjoining or near the sea) and the shore (the land along the edge of a sea) is known as the coastline.

Coastlines can be divided into the following classes:

1. Coastline of Emergence
2. Coastline of Submergence
3. Neutral coastline
4. Compound coastline
5. Fault coastline

- Coastline is modified either due to rise or fall in sea levels or upliftment or subsidence of land, or both.

Coastlines of Emergence



- These are formed either by an uplift of the land or by the lowering of the sea level.
- Bars, spits, lagoons, salt marshes, beaches, sea cliffs and arches are the typical features.
- The **east coast of India**, especially its south-eastern part **(Tamil Nadu coast)**, appears to be a **coast of emergence**.
- The **west coast of India**, on the other hand, is **both emergent and submergent**. The **northern portion of the coast is submerged** as a result of faulting and the southern portion, that is the **Kerala coast, is an example of an emergent coast**.

- **Coramandal coast → Tamil Nadu Coast → Coastline of emergence**
- **Malabar coast → Kerala Coast → Coastline of emergence**
- **Konkan coast → Maharashtra and Goa Coast → Coastline of submergence**

Coastlines of Submergence

- A submerged coast is produced either by subsidence of land or by a rise in sea level.
- Ria, fjord, Dalmatian and drowned lowlands are its typical features.

Ria

- When streams dissect a region into a system of valleys and divides, submergence produces a highly irregular shoreline called ria coastline.
- The coast of south-west Ireland is a typical example of ria coastline.

Fjord

- Some coastal regions have been heavily eroded by glacial action, and the valley glacier troughs have been excavated below sea level.
- After the glaciers have disappeared, a fjord coastline emerges.
- These coasts have long and narrow inlets with very steep sides.
- The fjord coasts of Norway are a typical example.

Dalmatian

- The Dalmatian coasts result by submergence of mountain ridges with alternating crests and troughs which run parallel to the sea coast.
- The Dalmatian coast of Yugoslavia is a typical example.

Drowned lowland

- A drowned lowland coast is low and free from indentations, as the submergence of a low-lying area forms it.
- It is characterized by a series of bars running parallel to the coast, enclosing lagoons.
- The Baltic coast of eastern Germany is an example of this type of coastline.

Neutral Coastlines

- These are coastlines formed as a result of new materials being built out into the water.
- The word 'neutral' implies that there need be no relative change between the level of the sea and the coastal region of the continent.
- Neutral coastlines include the alluvial fan-shaped coastline, delta coastline, volcano coastline and the coral reef coastline.

Compound Coastlines

- Such coastlines show the forms of two of the previous classes combined, for example, submergence followed by emergence or vice versa.
- The coastlines of Norway and Sweden are examples of compound coastlines.

Fault Coastlines

- Such coastlines are unusual features and result from the submergence of a downthrown block along a fault, such that the uplifted block has its steep side (or the faultline) standing against the sea forming a fault coastline.

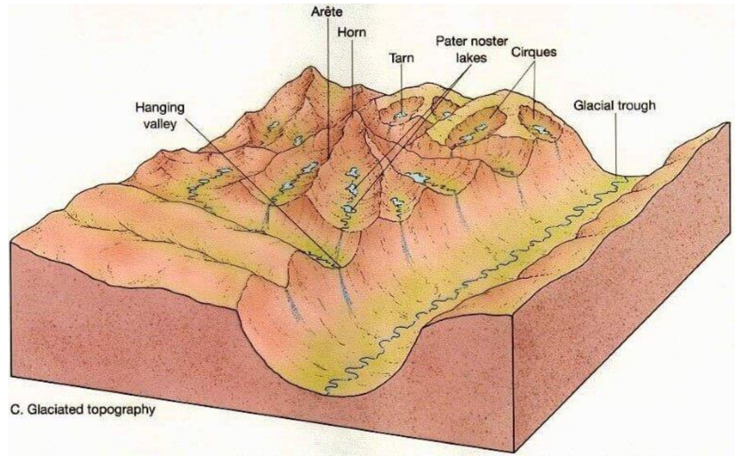
4.6 Glacial Landforms and Cycle of Erosion

- A glacier is a moving mass of ice at speeds averaging a few meters a day.
- Types of Glaciers: **continental glaciers, ice caps, piedmont glaciers and valley glaciers**.
- The continental glaciers are found in Antarctica and Greenland. The biggest continental ice sheet in **Iceland.**
- Ice caps are the covers of snow and ice on mountains from which the valley or mountain glaciers originate.
- The piedmont glaciers form a continuous ice sheet at the base of mountains as in southern Alaska.
- The valley glaciers, also known as Alpine glaciers, are found in higher regions of the Himalayas in our country and all such high mountain ranges of the world.
- The largest of Indian glaciers occur in the Karakoram range, viz. **Siachen (72 km),** while Gangotri in Uttar Pradesh (Himalayas) is 25.5 km long.
- A glacier is charged with rock debris which are used for erosional activity by moving ice.
- A glacier during its lifetime creates various landforms which may be classified into erosional and depositional landforms.

Glacial Erosional Landforms

Cirque/Corrie

- Hollow basin cut into a mountain ridge.
- It has a steep sided slope on three sides, an open end on one side and a flat bottom.
- When the ice melts, the cirque may develop into a **tarn lake.**



Glacial Trough

- Original stream-cut valley further modified by glacial action.
- It is a 'U' Shaped Valley. It is at a mature stage of valley formation.
- Since glacial mass is heavy and slow-moving, erosional activity is uniform – horizontally as well as vertically.
- A steep-sided and flat bottomed valley results, which has a 'U' shaped profile.

Hanging Valley

- Formed when smaller tributaries are unable to cut as deeply as bigger ones and remain 'hanging' at higher levels than the main valley as **discordant tributaries**.
- A valley carved out by a small tributary glacier that joins with a valley carved out by a much larger glacier.

Arete

- Steep-sided, sharp-tipped summit with the glacial activity cutting into it from **two** sides.

Horn

- The ridge that acquires a 'horn' shape when the glacial activity cuts it from **more than two sides.**

D-Fjord

- Steep-sided narrow entrance-like feature at the coast where the stream meets the coast.
- Fjords are common in **Norway, Greenland and New Zealand**.

Why are the world's highest mountains at the equator?

- Ice and glacier coverage at lower altitudes in cold climates is more important than the collision of tectonic plates. (Glacial erosion is very strong because of the huge boulders of rocks carried by the glacial ice that graze the surface. Though ice moves only a few meters a day, it can take along it huge rocks that can peel the outer layers.)
- Scientists have solved the mystery of why the world's highest mountains sit near the equator.
- Colder climates are better at eroding peaks. In colder climates, the snowline on mountains starts lower down, and erosion takes place at lower altitudes.
- In general, mountains only rise to around 1,500m above their snow lines, so it is the altitude of these lines — which depends on climate and latitude — which ultimately decides their height.
- At low latitudes, the atmosphere is warm, and the snowline is high. Around the equator, the snowline is about 5,500m at its highest, so mountains get up to 7,000m.
- There are a few exceptions (that are higher), such as Everest, but extremely few.
- When you then go to Canada or Chile, the snowline altitude is around 1,000 m, so the mountains are around 2.5km.

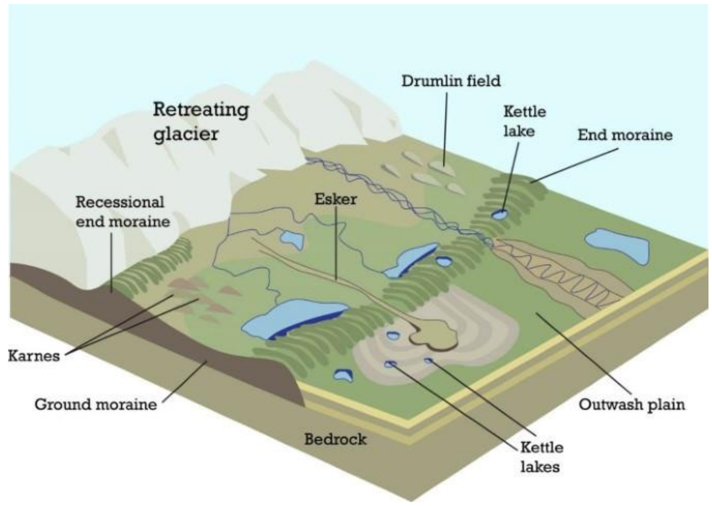
Glacial Depositional Landforms

Outwash Plain

- When the glacier reaches its lowest point and melts, it leaves behind a stratified deposition material, consisting of rock debris, clay, sand, gravel etc. This layered surface is called till plain or an outwash plain.

Esker

- Winding ridge of un-assorted depositions of rock, gravel, clay etc. running along a glacier in a till plain.
- The eskers resemble the features of an embankment and are often used for making roads.



Kame Terraces

- Kame terraces form when sediment accumulates in ponds and lakes trapped between lobes of glacier ice or between a glacier and the valley side.

Drumlin

- Inverted boat-shaped deposition in a till plain caused by deposition.

Kettle Holes

- Formed when the deposited material in a till plain gets depressed locally and forms a basin.

Moraine

- The general term applied to rock fragments, gravel, sand, etc. carried by a glacier.
- Depending on its position, the moraine can be ground moraine and end moraine.

Glacial Cycle of Erosion

Youth

- The stage is marked by the inward cutting activity of ice in a cirque.
- Aretes and horns are emerging. The hanging valleys are not prominent at this stage.

Maturity

- Hanging valleys start emerging. The opposite cirques come closer, and the glacial trough acquires a stepped profile which is regular and graded.

Old Age

- The emergence of a ‘U’-shaped valley marks the beginning of old age.
- An outwash plain with features such as eskers, kame terraces, drumlins, kettle holes etc. is a prominent development.

4.7 Arid Landforms and Cycle of Erosion

- Arid regions are regions with scanty rainfall. Deserts and Semi-arid regions fall under arid landforms.

Erosional Arid Landforms

Water Eroded Arid Landforms

Rill

- A rill is a narrow and shallow channel cut into the soil by the erosive action of flowing water.

Gully

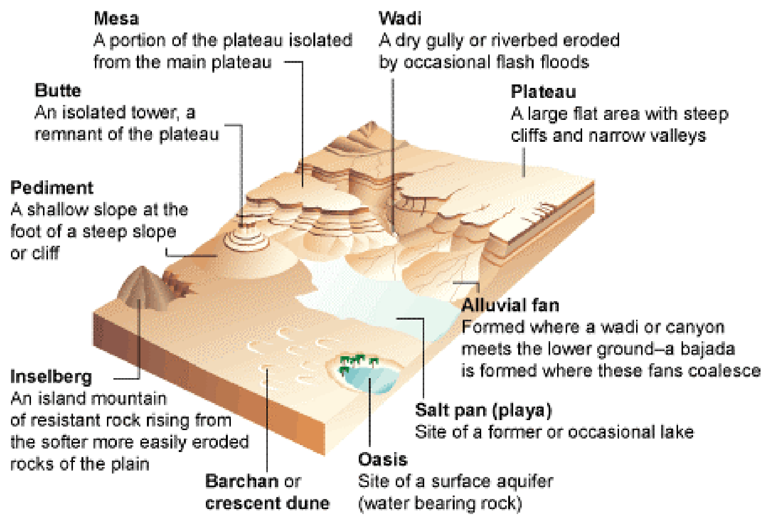
- A gully is a landform created by running water. Gullies resemble large ditches or small valleys but are metres to tens of metres in depth and width.

Ravine

- A ravine is a landform narrower than a canyon and is often the product of stream cutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys.

Badland Topography

- In arid regions, occasional rainstorms produce numerous rills and channels which extensively erode weak sedimentary formations.
- Ravines and gullies are developed by linear fluvial erosion leading to the formation of badland topography.
- Example: **Chambal Ravines.**



Bolsons

- The intermontane basins in dry regions are generally known as bolsons.

Playas

- Three unique landforms viz. pediments, bajadas and playas are typically found in bolsons.
- Small streams flow into bolsons, where water is accumulated. These **temporary lakes are called playas.**
- After the evaporation of water, salt-covered playas are called **salinas**.

Pediments

- In form and function there is no difference between a pediment and an alluvial fan; however, pediment is an erosional landform while a fan is a constructional one.

- A true pediment is a rock cut surface at the foot of mountains.

Bajada

- Bajadas are **moderately sloping depositional plains** located between pediments and playa.
- Several alluvial fans coalesce to form a bajada.

Wind Eroded Arid Landforms

- The wind or **Aeolian erosion** takes place in the following ways, viz. deflation, abrasion, and attrition.
- Deflation == removing, lifting and carrying away dry, unsorted dust particles by winds. It causes depressions known as blowouts.
- Abrasion == When wind loaded with sand grains erodes the rock by grinding against its walls is called abrasion or sandblasting.
- Attrition == Attrition refers to wear and tear of the sand particles while they are being transported.

Following are the major landforms produced by wind erosion.

Deflation basins

- Deflation basins, called blowouts, are hollows formed by the removal of particles by wind. Blowouts are generally small but may be up to several kilometres in diameter.

Mushroom rocks

- A mushroom rock also called **rock pedestal or a pedestal rock**, is a naturally occurring rock whose shape, as its name implies, resembles a mushroom.
- The rocks are deformed in many different ways: by erosion and weathering, glacial action, or from a sudden disturbance. Mushroom rocks are related to, but different from, yardang.

Inselbergs

- A **monadnock or inselberg** is an isolated hill, knob, ridge, outcrop, or small mountain that rises abruptly from a gently sloping or virtually level surrounding plain.

Demoiselles

- These are rock pillars which stand as resistant rocks above soft rocks as a result of differential erosion of hard and soft rocks.

Zeugen

- A table-shaped area of rock found in arid and semi-arid areas formed when the more resistant rock is reduced at a slower rate than softer rocks around it.

Yardangs

- Ridge of rock, formed by the action of the wind, usually parallel to the prevailing wind direction.

Wind bridges and windows

- Powerful wind continuously abrades stone lattices, creating holes. Sometimes the holes are gradually widened to reach the other end of the rocks to create the effect of a window—thus forming a wind window. Window bridges are formed when the holes are further widened to form an arch-like feature.

Arid Depositional Landforms

- The depositional force of wind also creates landforms. These are as follows.

Ripple Marks

- These are depositional features on a small scale formed by saltation (the transport of hard particles over an uneven surface in a turbulent flow of air or water).

Sand Dunes

- Sand dunes are heaps or mounds of sand found in deserts. Generally, their heights vary from a few metres to 20 metres, but in some cases, dunes are several hundred metres high and 5 to 6 km long.

Some of the forms are discussed below:

Longitudinal dunes

- Formed parallel to the wind movement. The windward slope of the dune is gentle whereas the leeward side is steep. These dunes are commonly found at the heart of trade-wind deserts like the Sahara, Australian, Libyan, South African and Thar deserts.

Transverse dunes

- Dunes deposited perpendicular (transverse) to the prevailing wind direction.

Barchans

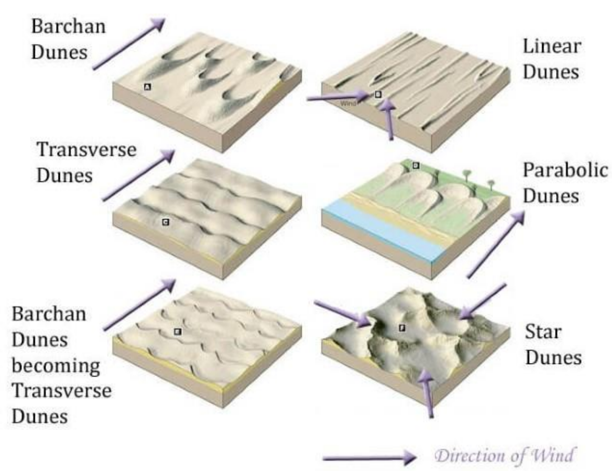
- Crescent-shaped dunes. The windward side is convex whereas the leeward side is concave and steep.

Parabolic dunes

- They are U-shaped and are much longer and narrower than barchans.

Star dunes

- Have a high central peak, radically extending three or more arms.

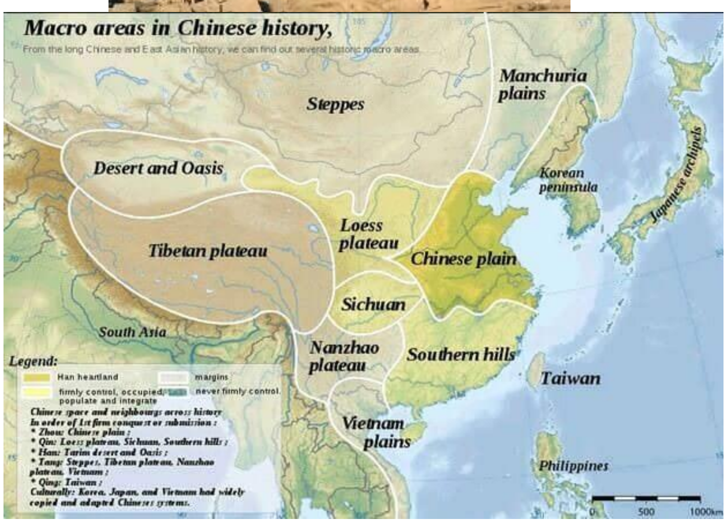


Loess

- In some parts of the world, windblown dust and silt blanket the land. This layer of fine, **mineral-rich** material is called loess.
- Extensive loess deposits are found in **northern China, the Great Plains of North America, central Europe, and parts of Russia and Kazakhstan**.
- The thickest loess deposits are near the **Missouri River** in the U.S. state of Iowa and along the **Yellow River in China**.
- Loess accumulates, or builds up, at the edges of deserts. For example, as the wind blows across the Gobi, a desert in Asia, it picks up and carries fine particles. These particles include sand crys-

tals made of quartz or mica. It may also contain organic material, such as the dusty remains of skeletons from desert animals.

- Loess often develops into **extremely fertile agricultural soil**. It is full of minerals and drains water very well. It is easily tilled, or broken up, for planting seeds.
- Loess usually erodes very slowly – Chinese farmers have been working the loess around the Yellow River for more than a thousand years.



5. Lakes

- A lake is a body of water of considerable size, localised in a basin, that is surrounded by land apart from a river or other outlet that serves to feed or drain the lake.
- Lakes lie on land and are not part of the ocean, and therefore are distinct from lagoons, and are also larger and deeper than ponds.
- Natural lakes are generally found in mountainous areas, rift zones, and areas with ongoing glaciation.
- Most lakes have at least one natural outflow (**exorheic lake**) in the form of a river or stream, which maintain a lake's average level by allowing the drainage of excess water
- Other lakes are found in **endorheic basins**. Some lakes do not have a natural outflow and lose water solely by evaporation or underground seepage or both. They are termed **endorheic lakes**.
- The majority of lakes on Earth are fresh water, and most lie in the Northern Hemisphere at higher latitudes.
- Canada, Finland and Siberia contain most of the freshwater lakes.
- Lakes are temporary features of the earth's crust; they will eventually be eliminated by the double process of draining and silting up.

5.1 Classification of Lakes

Temporary lakes

- Lakes may exist temporarily filling up the small depressions of undulating ground after a heavy shower.
- In this kind of lakes, evaporation is greater than precipitation.
- Example: Small lakes of deserts.

Permanent lakes

- In this kind of lakes, Evaporation is lesser than Precipitation.
- These lakes are deep and carry more water than could ever be evaporated.
- Example: **Great Lakes of North America, East African Rift Lakes**.

Freshwater lakes

- Most of the lakes in the world are fresh-water lakes fed by rivers and without-flowing streams e.g. Great Lakes of North America.

Saline lakes

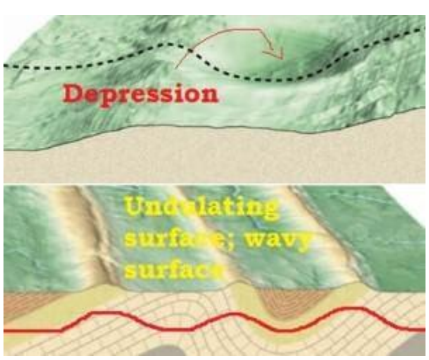
- Salt lakes (saline lakes) can form where there is **no natural outlet** or where the water evaporates rapidly, and the drainage surface of the water table has a higher-than-normal salt content.

- Because of the intense evaporation (negative freshwater balance, i.e., more water is lost in evaporation than gained from rivers) these lakes are saline.
- For example, the **Dead Sea** has a salinity (salt content) of 250 parts per thousand, and the **Great Salt Lake of Utah, U.S.A**. has a salinity of 220 parts per thousand.
- Examples of salt lakes include the **Great Salt Lake**, the **Aral Sea** and the **Dead Sea**.
- **Playas or salt lakes** are a common feature of deserts (arid landforms).

Lakes Formed by Earth Movement:

Tectonic lakes

- Due to the warping (simple deformation), subsidence (sliding downwards), bending and fracturing (splitting) of the earth's crust, tectonic depressions occur.
- Such depressions give rise to **lakes of immense sizes and depths**.
- They include **Lake Titicaca** and the **Caspian Sea.**



Rift valley lakes

- A rift valley is formed when two blocks of earth move apart letting the 'in-between' block slide downwards. Or, it's a sunken land between two parallel faults.
- Rift valleys are deep, narrow and elongated. Hence the lakes formed along rift valleys are also deep, narrow and very long.
- Water collects in troughs (valley in the rift), and their floors are often below sea level.
- The best-known example is the **East African Rift Valley** which runs through Zambia, Malawi, Tanzania, Kenya and Ethiopia, and extends along the Red Sea to Israel and Jordan over a total distance of 3,000 miles.
- It includes such lakes as **Lakes Tanganyika**, **Malawi, Rudolf, Edward, Albert**, as well as the **Dead Sea** 1,286 feet below mean sea level, the **world's lowest lake**.

Lakes Formed by Glaciation:

Cirque lakes or tarns

- Cirque is a hollow basin cut into a mountain ridge.
- It has a steep-sided slope on three sides, an open end on one side and a flat bottom.
- When the ice melts, the cirque may develop into a tarn lake.

Rock-hollow lakes

- The advance and retreat of glaciers can scrape depressions in the surface where water accumulates; such lakes are common in Scandinavia, Patagonia, Siberia and Canada.
- These are formed by ice-scouring (eroding) when ice sheets scoop out (dig) hollows on the surface.
- Such lakes of glacial origin are abundant in **Finland (Land of Lakes)**. It is said that there are over 35,000 glacial lakes in Finland.

Lakes due to morainic damming of valleys

- Valley glaciers often deposit morainic debris across a valley so that lakes are formed when water accumulates behind the barrier.

Lakes Formed by Volcanic Activity:

Crater and caldera lakes

- During a volcanic explosion, the top of the cone may be blown off leaving behind a natural hollow called a crater. This may be enlarged by subsidence into a caldera.
- In dormant or extinct volcanoes, rain falls straight into the crater or caldera which has no superficial outlet and forms a crater or caldera lake. E.g. **Lake Toba (Indonesia)**.
- When water accumulates in an **impact crater** a crater lake is formed. Example: **Lonar in Maharashtra**.

Lakes Formed by Erosion:

Karst lakes

- The solvent action of rain-water on limestone carves out solution hollows. When these become clogged with debris lakes may form in them.
- The collapse of limestone roofs of underground caverns may result in the exposure of long, narrow- lakes that were once underground.

Wind-deflated lakes

- The winds in deserts create hollows. These may reach groundwater which seeps out forming small, shallow lakes. Excessive evaporation causes these to become **salt lakes and playas**.
- Example: **Great Basin of Utah, U.S.A.**

Lakes Formed by Deposition:

Lakes due to river deposits

- Ox-bow lake, e.g. those that occur on the flood-plains of Lower Mississippi, Lower Ganges etc.

Lakes due to Marine deposits

- Also called as Lagoons. Example: Lake Chilka.

Lakes due to damming of water

- Lakes formed by these processes are also known as barrier lakes. Landslides, avalanches may block valleys so that rivers are dammed. Such lakes are short-lived.
- Example: Lakes that are formed in Shiwaliks (Outer Himalayas). Dehradun (all Duns) were lakes few centuries ago.

Man-made lakes

- Besides the natural lakes, man has now created artificial lakes by erecting a concrete dam across a river valley so that the river water can be kept back to form reservoirs.
- Example: Lake Mead above the Hoover Dam on the Colorado River, U.S.A.
- Man's mining activities, e.g. tin mining in West Malaysia, have created numerous lakes. Inland fish culture has necessitated the creation of many fishing lakes.

5.2 Lakes and Man

- In countries where they are found in abundance, such as Finland, Canada, U.S.A., Sweden and the East African states, lakes are used as inland waterways.

Means of communication

- Large lakes like the Great Lakes of North America provide a cheap and convenient form of transport for heavy and bulky goods such as coal, iron, machinery, grains and timber.
- **The Great Lakes-St. Lawrence waterways** penetrate more than 1,700 miles into the interior. They are thus used as the chief arteries of commerce.

Economic and industrial development

- The Great Lakes-St. Lawrence waterways were responsible for the development of the interior wheat farms and lakeside industries.

Water storage

- E.g. Kolleru lake in Andhra Pradesh.

Hydro-electric power generation

- E.g. Artificial lakes like Hirakud.

Agricultural purposes

- Many dams are built across artificial lakes. E.g. Bhakra Nangal Dam (Himachal Pradesh; its reservoir is known as the **Gobind Sagar Lake**) and Hirakud Dam (Odisha) on the Mahanadi in India.

Regulating river flows

- E.g. **Hoover Dam on the River Colorado** and the **Bhakra and Nangal Dams on the Sutlej** in India.
- The Hirakud dam was originally conceived as a flood control measure. But the project is criticised for doing more damage than good.

Moderation of climate

- Land and sea breeze.

Source of food

- Many large lakes have important supplies of protein food in the form of freshwater fish. Sturgeon is commercially caught in the Caspian Sea, salmon and sea trout in the Great Lakes.

Source of minerals

- Salt lakes provide valuable rock salts. In the Dead Sea, the highly saline water is being evaporated and produces common salt. **Borax** is mined in the salt lakes of the Mojave Desert.

Tourist attraction and health resorts

- E.g. Lake Chilka, Leh, Dead Sea etc.

5.3 Important Lakes on Earth

- **Note 1:** ***Black Sea is not a lake*** *since* ***Bosporus*** *and* ***Dardanelles Straits*** *connect it to the Mediterranean Sea. Many big rivers fall into the Black Sea, making the salinity of its surface water half that of the ocean: 17 per cent.*
- **Note 2:** *the* ***Caspian Sea and the Dead Sea are lakes****.* ***The surface and shores of the Dead Sea are 423 metres below sea level, making it Earth's lowest elevation on land.***
- **Note 3:** *While writing facts about lakes, people ignore the Caspian Sea because for them it is too big to be considered a lake. But it is still a lake (closed body).*

World's Highest and Lowest Lakes

- The world's highest lake, if size is not a criterion, maybe the **crater lake of Ojos del Salado**, at 6,390 metres. It is in the Andes.

- The **highest large lake** in the world is the **Pumoyong Tso (Pumuoyong Tso**; 5018 metres above sea level) in the Tibet Autonomous Region of China.
- The **world's highest commercially navigable lake** is **Lake Titicaca** in Peru and Bolivia border at 3,812 m. It is also the **largest lake in South America**.
- The world's **lowest lake is the Dead Sea**, bordering Israel and Jordan at 418 metres below sea level. It is also one of the lakes with the highest salt concentration.

The largest lakes (surface area) by continent

- **Australia – Lake Eyre** (salt lake)
- **Africa – Lake Victoria**, also the third-largest freshwater lake on Earth. It is one of the Great Lakes of Africa.
- **Antarctica – Lake Vostok** (subglacial)
- **Asia – Lake Baikal** (if the Caspian Sea is considered a lake, it is the largest in Eurasia, but is divided between the two geographic continents)
- **Europe – Lake Ladoga**, followed by Lake Onega, both located in northwestern Russia.
- **North America – Lake Superior**.
- **South America – Lake Titicaca**, which is also the highest navigable body of water on Earth at 3,812 metres above sea level. The much larger Lake Maracaibo is a contiguous body of water with the sea, so it is ignored.

Largest Lakes by Surface Area

1. **Caspian Sea (saline lake) – Asia**
2. **Lake Superior (freshwater lake) – North America**
3. **Lake Victoria (freshwater lake) – Africa**
4. **Lake Huron (freshwater lake) – North America**
5. **Lake Michigan (freshwater lake) – North America**

Largest Lakes by Volume

1. **Caspian Sea (saline lake)**
1. **Lake Baikal (fresh water lake)**
2. **Lake Tanganyika (freshwater lake)**
3. **Lake Superior (freshwater lake)**

Deepest Lakes in the World

1. **Lake Baikal**
2. **Lake Tanganyika**
3. **Caspian Sea**

Lake Baikal (Deepest)

- Located in Siberia, Russia.
- It is the **deepest lake in the world** (1,600+ metres deep).
- It is the world's second largest lake by volume (the Caspian Sea is the largest lake) and the world's largest freshwater lake by volume.
- It is the second longest freshwater lake.

Lake Tanganyika (Longest)

- The **longest freshwater lake in the world**.
- It is also the second largest freshwater lake by volume.
- It is the second deepest lake in the world, after Lake Baikal.

Great Lakes

- Great Lakes of North America are a series of interconnected freshwater lakes which connect to the Atlantic Ocean through the **Saint Lawrence Seaway**.
- **Lake Michigan is the largest lake that is entirely within one country**.

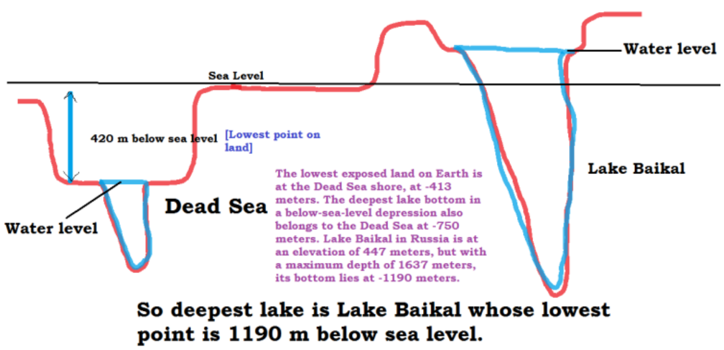
Superior, Michigan, Huron, Erie, and Ontario (in the order of west to east)
Superior, Huron, Michigan, Erie, and Ontario (In the order of largest to smallest)

Dead Sea

- Also called the Salt Sea.

- Lake bordering Jordan to the east, and Palestine and Israel to the west.
- It Earth's lowest elevation on land.

- Lake Baikal is the deepest lake. Its depth is 1,642 m. Considering that the lake surface is at 455.5 m above sea level, the deepest point of Lake Baikal is at 1186.5 m below sea level.
- The lowest point on land is the Dead Sea. It's **420 meters below sea level**. Its depth is 306 m. The lowest point of dead sea is 420+306 = 726 meters below sea level.
- There is a fundamental difference between the lowest point on land and the deepest lake.



Aral Sea

- It was a lake lying between Kazakhstan in the north and Uzbekistan, in the south.
- The Aral Sea has been steadily shrinking since the 1960s after the rivers that fed the lake were diverted to feed Soviet irrigation projects.
- The Aral Sea in 1989 (left) and 2008 (right).

6. Plateau

- A plateau is a flat-topped tableland.
- Plateaus occur in every continent and take up a **third of the Earths land**.
- They are one of the four major landforms, along with mountains, plains, and hills.
- Plateaus, like mountains, may be young or old. The Deccan plateau in India is one of the oldest plateaus.
- Valleys form when river water cuts through the plateau. The Columbia Plateau, between the Cascade and the Rocky Mountains in the north-western United States, is cut through by the Columbia River.
- Sometimes, a plateau is so eroded that it is broken up into smaller raised sections called **outliers.**
- Many outlier plateaus are composed of very old, dense rock formations.
- Iron ore and coal often are found in plateau outliers.
- Plateaus are very useful because they are rich in mineral deposits. As a result, many of the mining areas in the world are located in the plateau areas.

6.1 Economic significance of plateaus

Plateaus are of great economic significance. Comment with reference to India And World.

- The plateau of France (Massif Central), the Deccan plateau of India, Katanga plateau of Congo (Copper mines), Western Australian plateau or Kimberly Plateau (diamond mines) and Brazilian plateau or Brazilian Highlands are very good sources of minerals.
- Iron, copper, gold, diamonds, Manganese, coal, etc., are found in these plateaus.

- East African plateau is famous for gold and diamond mining.
- In India, huge reserves of iron, coal and manganese are found in the Chotanagpur plateau.
- In the plateau areas, there may be several waterfalls as the river falls from a great height. In India, the **Hundru Falls** in the **Chotanagpur plateau** on the river **Subarnarekha** and the **Jog Falls in Karnataka** are examples of such waterfalls.
- These sites are ideal for hydro-electric power generation.
- **Angel falls** in Venezuela is also a waterfall that descends a plateau.
- Plateaus are not as useful as plains from agriculture perspective.
- It is difficult to dig wells and canals in plateaus due to the presence of hard rocks. This hampers irrigation.
- The hard rocks on plateaus cannot form fertile soil, but agricultural activities are promoted where lava soils have developed.
- The lava plateaus like **Deccan traps** are rich in **black soil** that is fertile and good for cultivation. Example: Maharashtra has good **cotton growing soils** called **regurs**.
- **Loess Plateau** in China has very fertile soils that are good for many kinds of crops.
- Many plateaus have scenic spots and are of great attraction to tourists (e.g. Jog Falls in Karnataka, Grand Canyon, USA, many waterfalls)

6.2 Plateau Formation

- Tectonic plateaus are formed from processes that create mountain ranges, **volcanism (Deccan Plateau),** crustal shortening (**Tibetan Plateau —** thrusting of one block of crust over another, and folding occurs. Example:), and thermal expansion **(Ethiopian Highlands)**.

Thermal expansion

- Plateaus caused by thermal expansion of the lithosphere are usually associated with hot spots.
- Thermal expansion of the lithosphere means the replacement of cold mantle lithosphere by hot asthenosphere (magma).
- When the lithosphere underlying a broad area is heated rapidly by an upwelling of hot material (mantle plume) in the underlying asthenosphere, the consequent warming and thermal expansion of the uppermost mantle causes uplift of the overlying surface.
- The **Yellowstone Plateau in the United States**, the **Massif Central in France**, and the **Ethiopian Plateau in Africa** are prominent examples.

Crustal shortening

- The great heights of some plateaus, such as the Plateau of Tibet is due to **crustal shortening.**
- Crustal shortening, which thickens the crust as described above, has created high mountains along what are now the margins of such plateaus.
- Plateaus that were formed by crustal shortening and internal drainage lie within major mountain belts and generally in arid climates.
- They can be found in North Africa, Turkey, Iran, and Tibet, where the African, Arabian, and Indian continental masses have collided with the Eurasian continent.

Volcanic flood basalts

- Plateaus can form where extensive lava flows and volcanic ash bury pre-existing terrain giving rise to **flood basalts or traps**.
- The volcanism involved in such situations is commonly associated with **hot spots**.
- For example, the basalts of the Deccan Traps, which cover the Deccan plateau in India, were erupted 60–65 million years ago over the same hot spot that presently underlies the volcanic island of **Reunion**.
- In North America, the Columbia River basalts may have been ejected over the same hot spot that underlies the **Yellowstone** area today.
- The lavas and ash are generally carried long distances from their sources and the **topography is not dominated by volcanoes or volcanic centres**.
- The thickness of the volcanic rock can be tens to even hundreds of metres, and the top surface of flood basalts is typically very flat but often with sharply incised canyons and valleys.

- Volcanic plateaus are commonly associated with massive eruptions that occurred during the Cenozoic or Mesozoic eras. Eruptions of that scale are rare, and none seems to have taken place in recent time.
- Volcanic plateaus include the **Columbia Plateau** in the north-western USA, **Deccan Traps** of peninsular India, **Laurentian plateau or The Canadian Shield** and the **Siberian Traps of Russia**.

Others

- Some plateaus, like the Colorado Plateau, the Ordos Plateau in northern China, or the East African Highlands (e.g. Kenya Dome), do not seem to be related to hot spots or to vigorous upwelling in the asthenosphere but appear to be underlain by unusually hot material.
- The reason for localised heating beneath such areas is poorly understood, and thus an explanation for the distribution of plateaus of that type is not known.
- There are some plateaus whose origin is not known. Those of the Iberian Peninsula and north-central Mexico exhibit a topography that is largely high and relatively flat.

6.3 Plateau Types

- There are two kinds of plateaus: **dissected plateaus** and **volcanic plateaus**.

Dissected plateau

- A dissected plateau forms as a result of upward movement in the Earth's crust.
- The slow collision of tectonic plates causes the uplift.
- The **Colorado Plateau**, in the western United States, Tibetan plateau etc. are examples.

Volcanic plateau

- A volcanic plateau is formed by numerous small volcanic eruptions that slowly build up over time, forming a plateau from the resulting lava flows.
- The **Columbia Plateau** in the north-western United States of America and **Deccan Traps** are two such plateaus.

Others

- **Intermontane plateaus** are the highest in the world, bordered by mountains. The **Tibetan Plateau** is one such plateau.
- **Continental plateaus** are bordered on all sides by the plains or seas, forming away from mountains.

6.4 Major plateaus of the World

Tibetan Plateau

- It is the **Highest and largest plateau** in the world and hence called the **'roof of the world'.**
- It is formed due to the collision of the Indo-Australian and Eurasian tectonic plates.
- The plateau is sufficiently high enough to reverse the Hadley cell convection cycles and to drive the monsoons of India towards the south.
- It covers most of the Autonomous Tibetan Region, Qinghai Province of Western China, and a part of Ladakh in Jammu and Kashmir.
- It is surrounded by mountains to the south by the Himalayan Range, to the northeast by the **Kunlun Range**, and to the west by the **Karakoram Range**.

Columbia – Snake Plateau

- River Columbia and its tributary Snake meet in this plateau.
- It is bordered by the **Cascade Range** and the **Rocky Mountains** and divided by the **Columbia River.**
- This plateau has been formed as the result of volcanic eruptions with a consequent coating of **basalt lava (flood basalt plateau).**

Colorado Plateau

- It lies in the western part of U.S.A. It is the largest plateau in America.
- It is divided by the **Colorado River** and the **Grand Canyon**.
- This plateau is an example of the intermontane plateau. Mesas and buttes are found here at many places (arid Landforms).
- The plateau is known for the groundwater which is under positive pressure and causes the emergence of springs called **Artesian wells**.

Deccan Plateau

- Deccan Plateau is a large plateau which forms most of the southern part of India.
- It is bordered by two mountain ranges, the Western Ghats and the Eastern Ghats.
- The plateau includes the Deccan Traps which is one of the largest volcanic features on Earth.
- Made of multiple basalt layers or lava flows, the Deccan Traps covers 500,000 square kilometres in area.
- The Deccan Traps are known for containing some unique fossils.
- The Deccan is rich in minerals. Primary mineral ores found in this region are **mica and iron** ore in the **Chotanagpur region**, and **diamonds, gold** and other metals in the **Golconda region**.

Kimberley Plateau

- It lies in the northern part of Australia.
- This plateau is made of volcanic eruption.
- Many minerals like iron, gold, lead, zinc, silver and **diamonds** are found here.

Katanga Plateau

- It lies in the Congo.
- It is famous for **copper production**.
- Other minerals like Cobalt, Uranium, Zinc, Silver, Gold and Tin are also mined here.

Mascarene Plateau

- Plateaus also form in the ocean, such as the Mascarene Plateau in the Indian Ocean.
- It extends between the Seychelles and Mauritius Islands.

Laurentian Plateau

- Lying in the eastern part of Canada, it is a part of Canadian Shield.
- Fine quality of iron-ore is found here.

Mexican Plateau

- It is called as 'Mineral Store'. Different types of metallic minerals like silver, copper etc. are obtained from here.
- World's biggest silver mine Chihuahua is situated in the plateau.

Patagonian Plateau

- It is a Piedmont plateau (arid landforms) lying in southern part of Argentina.
- It is a **rain shadow desert plateau**.
- It is an important region for sheep rearing.

Altiplano Plateau or Bolivian Plateau

- It is an intermontane plateau which is located between two ranges of Andes Mountain.
- It is a major area of Tin reserves.

Massif Central

- This plateau lies in central France.
- It is famous for Grape cultivation.

Anatolian Plateau

- Also known as **Asia Minor**, most of Turkey lies on this plateau.
- It is an intermontane plateau lying between **Pontiac** and **Taurus Mountain ranges**.

- **Tigris – Euphrates Rivers** flow through this plateau.
- Precious wool producing **Angora goats** are found here.

Others

- **Piedmont Plateau:** it is located in the Eastern United States. It sits between the Atlantic coastal plain and the main Appalachian Mountains
- **Spanish Plateau or Iberian Plateau:** It is situated in the middle of Spain. It is a lava plateau. It is rich in minerals like Iron.
- **Loess Plateau**: It is in China. The soil here is made of fine particles brought by the wind. This fine loamy soil is extremely productive. Crops grown in this soil along the **Yellow River** give great yields.
- **Potwar Plateau:** It is situated in the northern plateau (Punjab) region of Pakistan. The **Salt Range** is located to the south-west of the plateau.
- **Bavarian Plateau:** Southern part of Germany.
- **Ahaggar Plateau:** A small plateau located in Algeria, Sahara.
-

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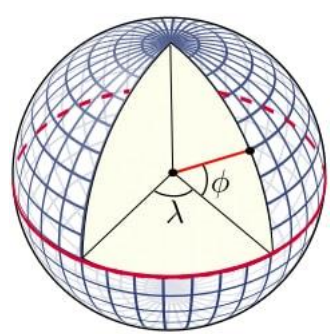
Climatology Part I

Print Friendly PDF

1. Latitudes and Longitudes

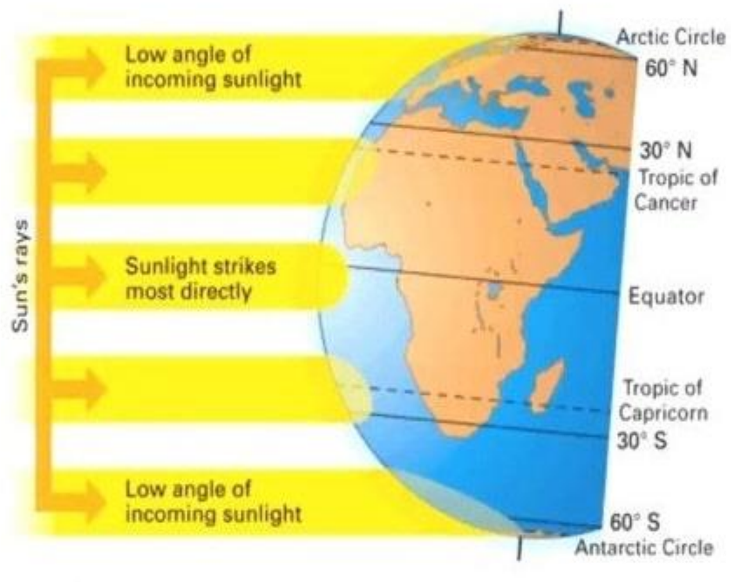
- Latitudes and Longitudes (coordinate system) are imaginary lines used to determine the location of a place on earth.
- Example: The location of New Delhi is 28° N Latitude, 77° E Longitude.



Latitude (ϕ) and longitude (λ) are defined on a perspective spherical modal (Wikipedia)

1.1 Latitude or Parallel

- Latitude is the angular distance of a place north or south of the equator measured in degrees from the centre of the earth.
- As the earth is **slightly flattened at the poles**, the **linear distance of a degree of latitude at the pole is a little longer than that at the equator**.
- For example, at the equator linear distance of a degree of latitude is 110.57 km (68.7 miles), at 45° it is 111.13 km (69 miles), and at the poles, it is 111.7 km (69.4 miles). The average is taken as **111 km (69 miles)**.



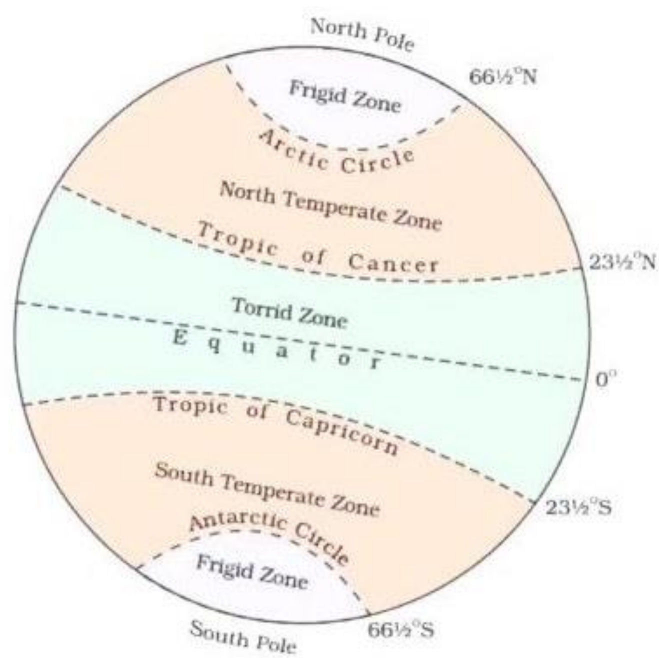
Latitudinal Heat zones of the earth

- The mid-day sun is exactly overhead at least once a year on all latitudes in between the Tropic of Cancer and the Tropic of Capricorn. This area, therefore, receives the maximum heat and is called the **torrid zone**.
- The mid-day sun never shines overhead on any latitude beyond the Tropic of Cancer and the Tropic of Capricorn. The angle of the sun's rays goes on decreasing towards the poles.
- As such, the areas bounded by the Tropic of Cancer and the Arctic circle, and the Tropic of Capricorn and the Antarctic circle, have moderate temperatures. These are, therefore, called **temperate zones**.
- Areas lying beyond the Arctic circle and the Antarctic circle are very cold. Here the sun does not rise much above the horizon. Therefore, its rays are always slanting. These are, therefore, called **frigid zones**.

Important parallels of latitudes

- Besides the **equator (0°)**, the **north pole (90° N)** and the **south pole (90° S)**, there are four important parallels of latitudes:
  1. The **Tropic of Cancer (23½° N)** in the northern hemisphere.
  2. The **Tropic of Capricorn (23½° S)** in the southern hemisphere.
  3. The **Arctic circle (66½° N)** in the northern hemisphere.
  4. The **Antarctic circle is (66½° S)** in the southern hemisphere.

Latitudinal Heat zones of the earth



1.2 Longitude or Meridian

- Longitude is an angular distance of a place east or west of the **Prime (First) Meridian** measured in degrees from the centre of the earth.

- On the globe, longitude is shown as a series of semi-circles that run from pole to pole passing through the equator. Such lines are also called **meridians**.
- It was decided in 1884 to choose the meridian which passes through the Royal Astronomical Observatory at **Greenwich, near London**, as the **zero meridian or prime meridian**.
- All other meridians radiate eastwards and westwards of the prime meridian up to 180°.
- Unlike the parallels of latitude, the meridians of longitude are of **equal length**.
- The meridians of longitude have one very important function; they determine local time in relation to **Greenwich Mean Time (GMT)**, which is sometimes referred to as **World Time**.

Longitude and Time

- Since the earth makes one complete rotation of 360° in one day or 24 hours, it passes through **15° in one hour** or **1° in 4 minutes**.
- The earth rotates from west to east, so **every 15° we go eastwards, local time is advanced by 1 hour**.
- Conversely, **if we go westwards by 15°, local time is retarded by 1 hour**.
- Thus, the **places east of Greenwich gain time**, whereas **places west of Greenwich lose time**.
- A traveller going eastwards gains time from Greenwich until he reaches the meridian 180° E when he will be 12 hours ahead of GMT (GMT+12).
- Similarly, in going westwards, he loses 12 hours when he reaches 180° W. There is thus a total difference of 24 hours or a whole day between the two sides of the 180° meridian.

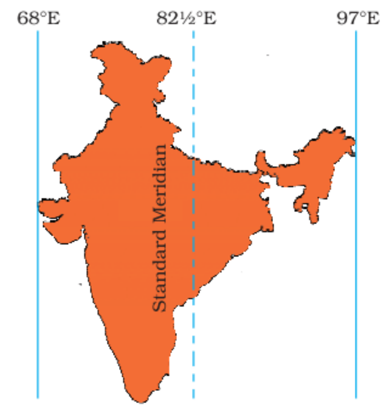
180° E and 180° W correspond to the same longitude. The difference is the direction of travel.

Standard Time and Time Zones

- Standard Time is the time corresponding to a certain longitude or longitudes as chosen by a country.
- Most countries adopt their standard time from the central meridian of their countries. E.g. **IST corresponds to the time at 82.5° E longitude**.
- In countries that have a very **large longitudinal extent** (**large east-west span**), such as Canada, USA, Russia, it would be inconvenient to have a single time zone. So, such countries have multiple time zones.
- For example, Russia has nine time zones, and Canada and USA have six time zones each.

Indian Standard Time

- Indian Standard Time (IST) is taken as the time at **82.5° E longitude** (passing close to the east of **Prayagraj or Allahabad**). Which means, **IST is 5 hours 30 mins ahead of GMT** (**IST = GMT+5:30**).



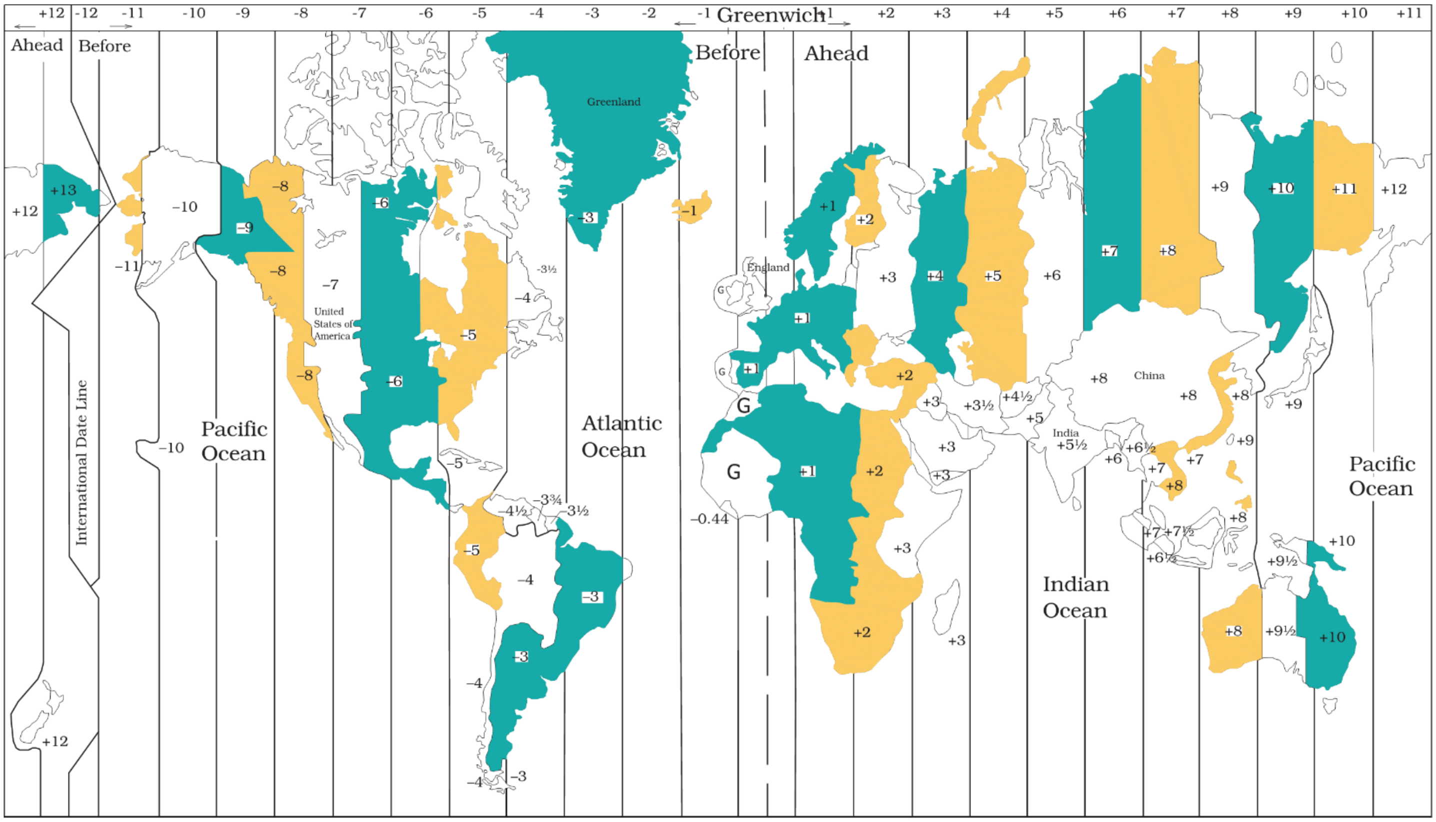
Longitudinal extent of India

Chaibagaan Time

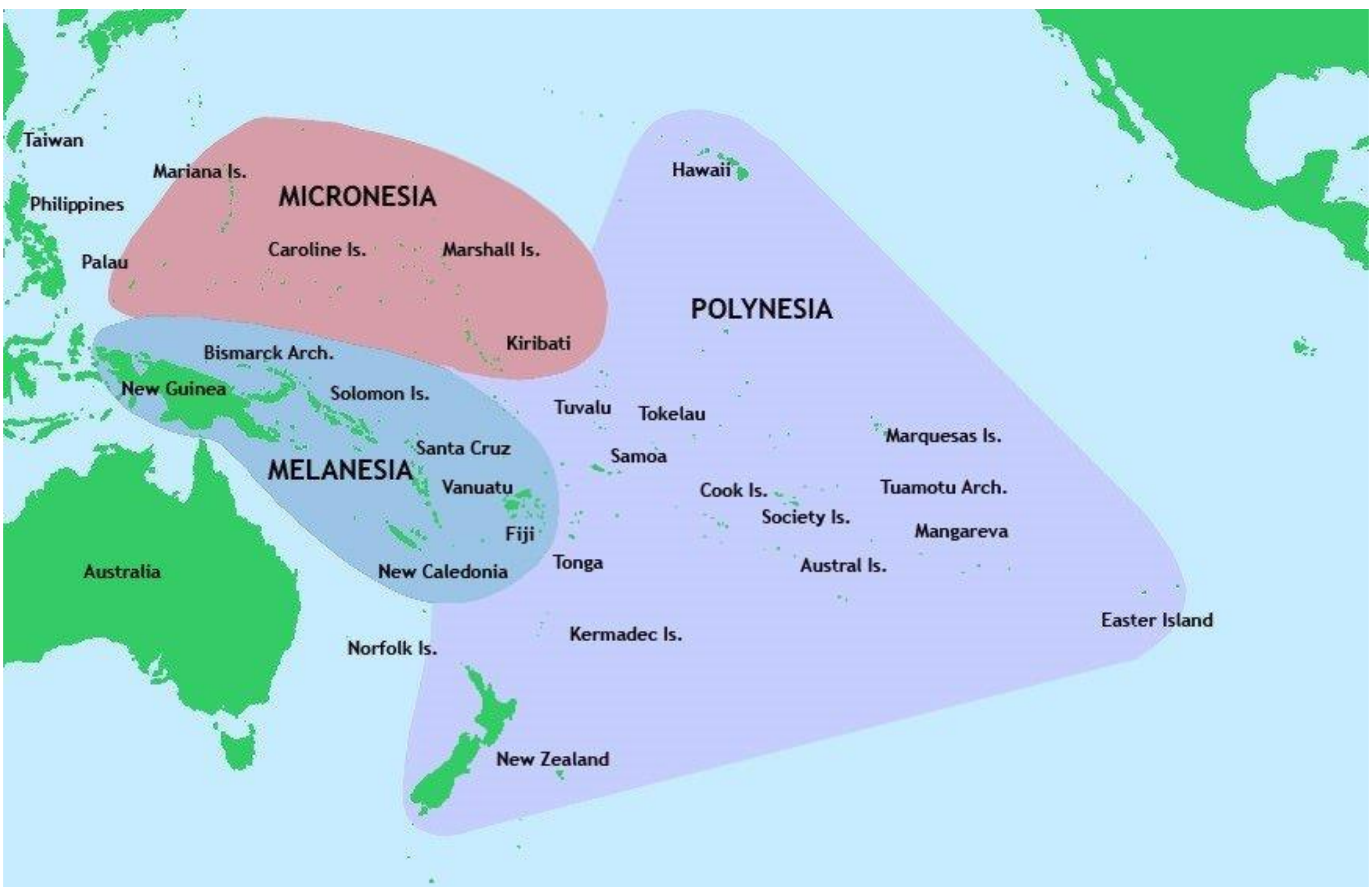
- One hundred fifty years ago, British colonialists introduced “Chaibagaan time” or “Bagaan time”, a schedule observed by tea planters, which was **one hour ahead of IST**.
- This was done to improve productivity by optimising the usage of daytime.
- After Independence, Assam, along with the rest of India, has been following IST.
- The administration of the Indian state of Assam put forward a proposal to change its time zone back to Chaibagaan time to conserve energy and improve productivity.
- Indian government refused to accept such a proposal.

The International Date Line

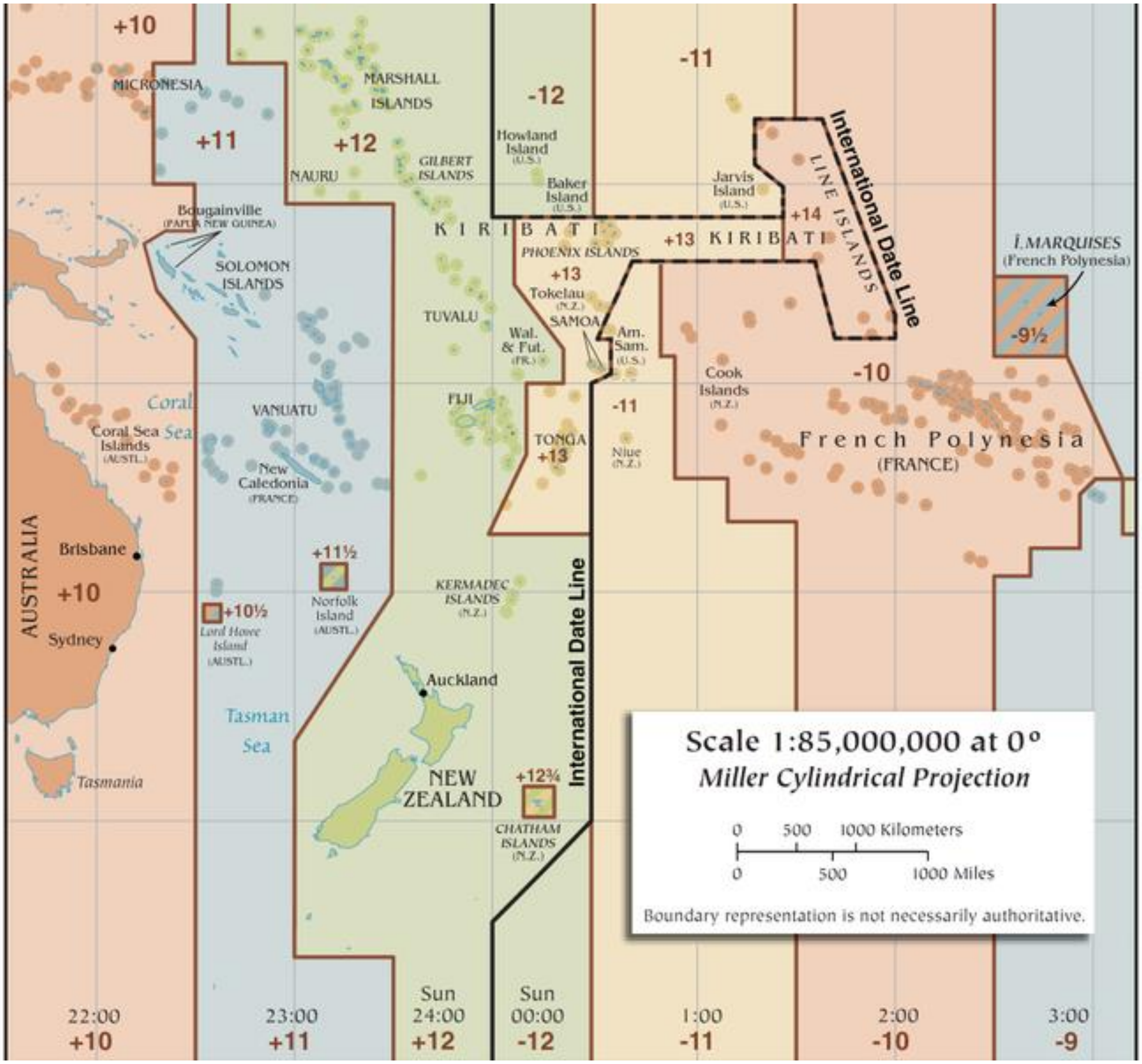
- The International Date Line (IDL) an imaginary line that passes through the Pacific Ocean.



Time Zones and International Date Line



The Island Groups of Australia, Polynesia, Melanesia and Micronesia



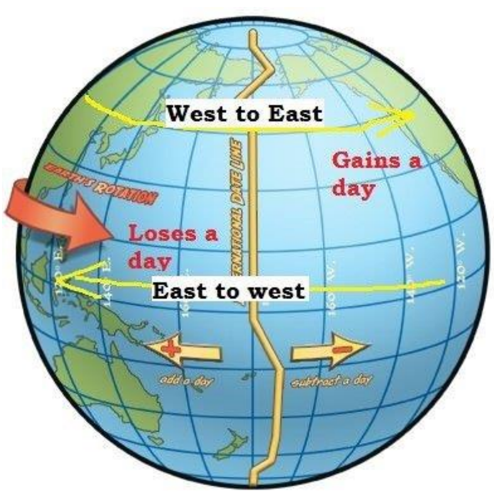
IDL cutting across Oceania (Australia, Melanesia, Micronesia and Polynesia) (Jailbird, via Wikimedia Commons)

Samoa, Christmas Island (Kiribati) and Tonga are the first places that welcome a New Year. Baker Island (USA) and Howland Island (USA) are the last to celebrate a new year.

- **Along the International Date Line, the date changes by exactly one day when it is crossed**.
- A traveller crossing the date line from east to west loses a day, and while crossing the dateline from west to east, he gains a day.

Explanation:

- 180° E is GMT+12 and 180° W is GMT-12, hence the difference between 180° E and 180° W is 24 hours.
- That is, time difference on either side of IDL is 24 hours. So, the date changes as soon as one crosses IDL.



International Date Line

Why is the international dateline drawn in a zig-zag manner?

- The International Date Line curves from the normal 180° meridian at the **Bering Strait**, and at the island groups of **Polynesia, Melanesia and Micronesia**.
- If the dateline was straight, then two regions of the same Island Country or Island group would fall under different date zones. Thus, to avoid any confusion of date, this line is drawn in a zig-zag manner.

Some of regions along the dateline keep Asiatic, or New Zealand standard time, others follow the American date and time.

1.3 Comparison: Latitude vs Longitude

Latitude	Longitude
• Angular distance of a point measured along the north or south of the equator	• Angular distance measured along the equator
• Latitudes are named south and north of Equator	• Longitudes are named east or west of Prime Meridian
• Also called as Parallels	• Also called as Meridian
• Equator = 0° Latitude	• Prime meridian = 0° Longitude
• Equator has the maximum length	• All longitudes are equal in length
• Equator, Tropic of Cancer 23.5° N, Tropic of Capricorn 23.5° S, Arctic circle 66.5° N, Antarctic circle 66.5° S, North Pole 90° N and South Pole 90° S are important latitudes	• Prime meridian 0° and International Date Line 180° E or 180° W are important longitudes
Both are used to determine the location of a point on earth. The location is identified with Co-ordinates	

Prelims Mock: Statements

1) A person travelling from Japan to Alaska across International Date Line will gain a day.
2) A person travelling from Hawaii to New Zealand across International Date Line will lose a day.
3) It is inconvenient for a country of greater latitudinal extent but smaller longitudinal extent (Chile for example) to have multiple time zones.
4) On a 24-hour clock, the time is 00:00 in London. Then the time in Mumbai on a 12-hour clock will be 05:30 AM.

Which of the above statements are false?

a) None
b) 1 and 2 only
c) 1, 2 and 3 only
d) 3 only

Explanation:

- If the time and date in Japan is 12:00 AM 01/01/2019, then the date in Alaska (USA) will be 31/12/2018. Thus, a person travelling from Japan to Alaska across the International Date Line will gain a day (Japan is more than 18 hours ahead of Alaska).
- IST is GMT+5:30. So, if it is 00:00 in London, then the time in India is 05:30 AM. If it is 23:00 GMT, 31/12/2018, then the time and date in India is 4:30 AM 01/01/2019.
- On a 24-hour clock, the time is 00:00 in London. Then the time in Mumbai on a 12-hour clock will be 05:30 AM.

Answer: a) None

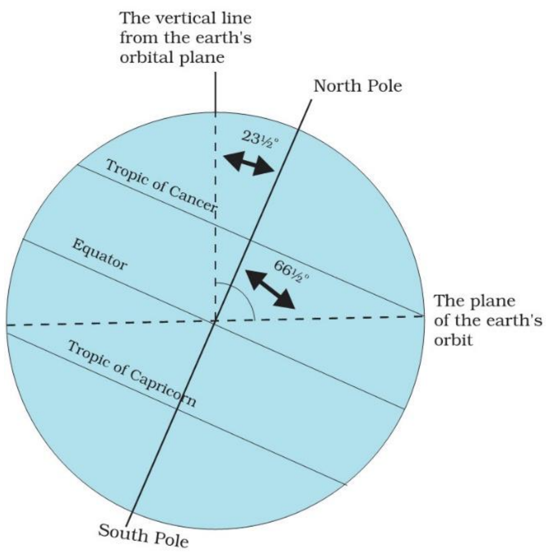
2. Motions of the earth

- Rotation and revolution are the most important motions of the earth.

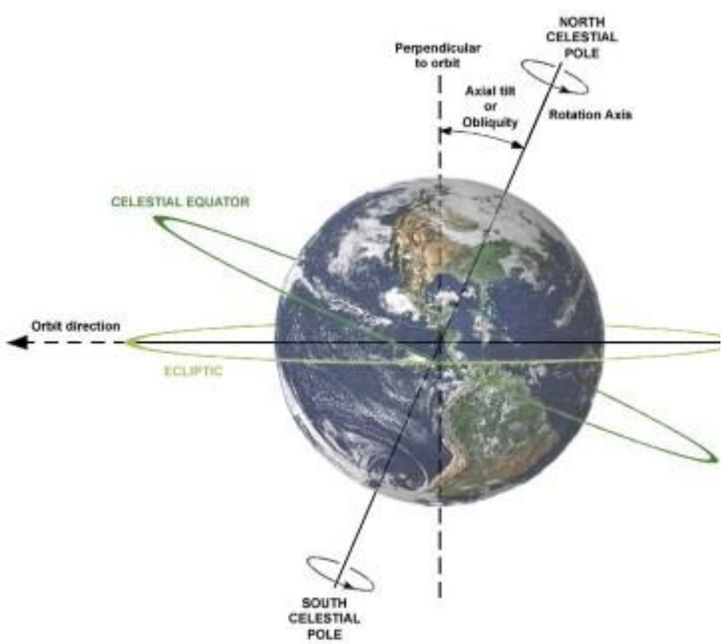
2.1 Rotation of Earth

- The spinning movement of the earth is called rotation.
- The Earth rotates around its axis in **west to east** direction.
- Earth's axis is the imaginary line that passes through the North Pole, earth's centre and the South Pole.

- Earth's axis is **antipodal** — meaning it passes through the centre of the earth connecting two exactly opposite ends.
- It takes approximately 24 hrs (**23 hours, 56 minutes, and 4 seconds**) to complete one rotation.
- **Days and nights occur due to rotation of the earth**.
- The circle that divides the day from night on the globe is called the **circle of illumination**.
- Earth rotates on a **tilted axis**. Earth's rotational axis makes an angle of **23.5°** with the normal, i.e. it makes an angle of **66.5° with the orbital plane of the earth (ecliptic plane)**.



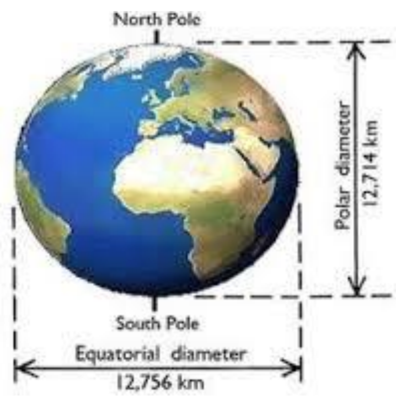
Inclination of the Earth's Axis



Inclination of the Earth's Axis

Shape of the earth

- The shape of the earth is **Geoid** (some sources mention is as **oblate spheroid**). That is, the earth is **slightly flattened at the poles and bulged at the equatorial region**.
- The radius at the equator is larger than at the poles due to the long-term effects of the **earth's rotation** (the **speed of rotation**, and hence the **centrifugal force**, is greater at the equator than at the poles).



Geoid

- The gravitation force is not the same at different latitudes on the surface. It is **greater near the poles and less at the equator**.
- This is because of
  a) The poles are closer to the centre due to the equatorial bulge and thus have a stronger gravitational field.
  b) The speed of rotation of the earth is greater at the equator than at the poles. Thus, the centrifugal force is greater at the equator. As the centrifugal force and the gravitational force are counteracting forces (acting in the opposite direction), the latter is slightly less at the equator compared to the poles.

Que: Shouldn't the gravity at the equator be greater as there is more mass at the equator?
Ans: The density of earth along the poles is greater than along the equator (because of the difference is speed of rotation). As a denser object of a given mass is smaller, you get closer to its centre of mass and experience a stronger gravitational force.

Temperature falls as we move from equator towards poles

- Temperature falls at the surface of the earth as one moves away from the equator towards poles.
- This is because of the **spherical (geoid)** shape of the earth and the position of the sun relative to earth.
- The **energy received per unit area decreases from equator to poles** as the equator receives direct sunlight and the sun's rays becomes **slant or oblique** as we move poleward.

Prelims mock: Statements

1. The shape of the Earth is Geoid.
2. The region that lies between Tropic of Cancer and Tropic of Capricorn is called Torrid Zone.
3. The temperature decreases from equator to poles because of the shape of the earth.
4. The North Pole is a latitude.

Which of the above statements are true?

a) 1 and 2 only
b) 1, 3 and 4 only
c) 1, 2 and 3 only
d) All

Answer: None are false, d) all

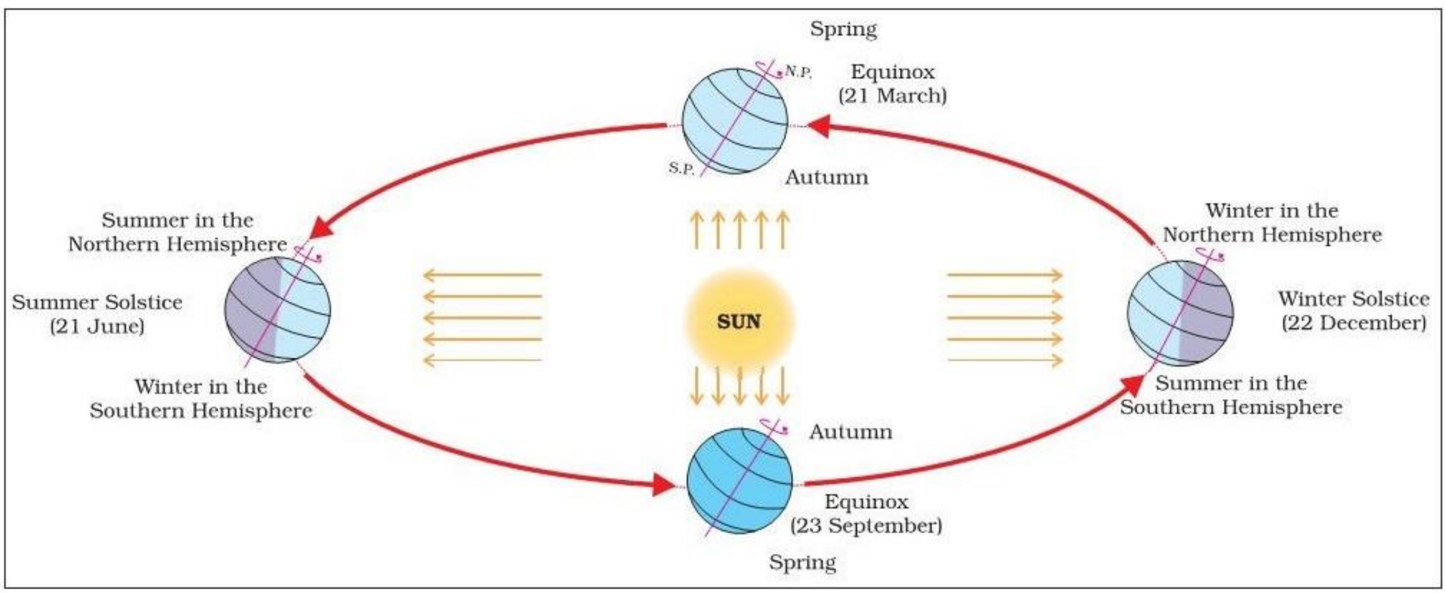
2.2 Revolution

- At the same time that the Earth spins on its axis, it also orbits or revolves around the Sun. This movement is called revolution.
- The plane in which the earth revolves around the sun is called as **orbital plane** or the **ecliptic**.

Most large objects in orbit around the Sun lie ***near the plane of Earth's orbit, known as the ecliptic****. The planets are very close to the ecliptic, whereas comets and Kuiper belt objects are at significantly greater angles to it.*

- It takes **365¼ days** (one year) for the earth to complete one revolution around the sun.
- Six surplus hours saved every year are added to make one day over a span of four years.
- This surplus day is added to the month of February. Thus, every fourth year, February is of 29 days instead of 28 days. Such a year with 366 days is called a **leap year**.

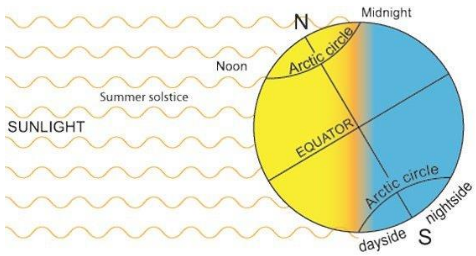
Solstice



Summer solstice

- On **21st June**, the northern hemisphere is tilted towards the sun, and the rays of the sun fall directly on the **Tropic of Cancer**. As a result, these areas receive more heat.
- Since a large portion of the northern hemisphere is getting light from the sun, it is **summer** in the regions north of the equator.
- The **longest day and the shortest night** all across the northern hemisphere occur on **21st June**.

- At this time in the southern hemisphere, all these conditions are reversed. It is winter season there. The nights are longer than the days.
- This position of the earth is called the **summer solstice**. *(For southern hemisphere 21st June is winter solstice)*
- During summer solstice the whole of Arctic region falls within the 'zone of illumination' all day long.



Winter solstice

- On **22nd December**, the **Tropic of Capricorn** receives direct rays of the sun.
- The **longest night and the shortest day** all across the northern hemisphere occur on **22nd December**.
- It is summer in the southern hemisphere with longer days and shorter nights. The reverse happens in the northern hemisphere.
- This position of the earth is called the **winter solstice**. *(For southern hemisphere 22nd December is summer solstice)*

Midnight sun

- Because of the axial tilt of the Earth, the Sun does not set at high latitudes in local summer.
- The number of days per year with potential midnight sun increases as one goes closer towards the poles.
- The Sun remains continuously visible for one day during the summer solstice (21st June in the Northern Hemisphere and 22nd December in the Southern Hemisphere) at the polar circle, for several weeks only 100 km closer to the pole, and for **six months at the pole**.
- At extreme latitudes, the midnight sun is usually referred to as **polar day**.
- At the poles themselves, the Sun rises and sets only once each year on the equinox.
- The opposite phenomenon, polar night, occurs in winter when the Sun stays below the horizon throughout the day.

The Sun sets and rises very close to the horizon at the higher latitudes

Daylight saving in temperate regions

- Daylight saving time (DST) or summer time is the practice of advancing clocks during summer months by one hour or more.
- In DST, evening time is increased by sacrificing the morning hours.

Normal days = Start office at 10 AM and close at 5 PM.
DST = Start office at 9 AM and Close at 4 PM

- Typically, users in regions with summer time (countries in extreme north and south) adjust clocks forward one hour close to the start of spring and adjust them backwards in the autumn to standard time.
- Advantages: benefits retailing, sports, and other activities that exploit sunlight after working hours. Reduces evening use of incandescent lighting, which was formerly a primary use of electricity.
- Disadvantages: DST clock shifts sometimes complicate timekeeping and can disrupt travel and sleep patterns.

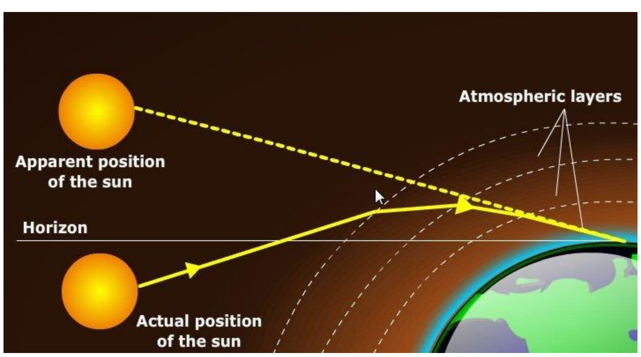
Equinox

- On **21st March** and **September 23rd**, direct rays of the sun fall on the equator.
- At this position, neither of the poles are tilted towards the sun; so, the whole earth experiences **equal days and equal nights**. This is called an equinox.

- On 23rd September, it is **autumn season** (season after summer and before the beginning of winter) in the northern hemisphere and **spring season** (season after winter and before the beginning of summer) in the southern hemisphere.
- The opposite is the case on 21st March when it is spring in the northern hemisphere and autumn in the southern hemisphere.

Days are always longer than nights at the equator

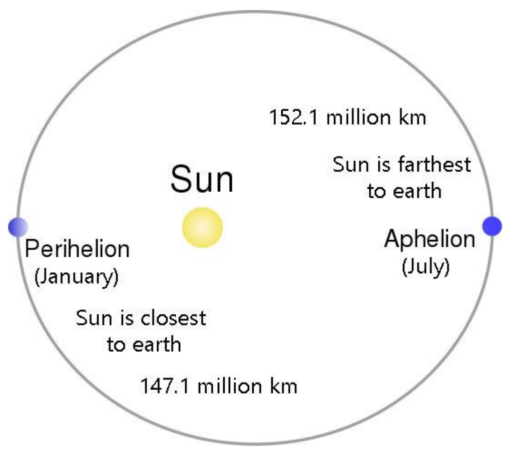
- If there was no atmosphere, there would be no refraction, and the daytime and night-time would be near equal at the equator, at least during equinoxes.
- But due to atmosphere, the sun's rays get refracted (bending of light due to change in density of the medium).
- Refraction is particularly stronger during the morning and the evening time when the sun's rays are slant.
- Even though the actual sun is below the horizon, its **apparent image** would appear above the horizon due to **refraction**. This makes the days longer than nights at the equator.



Apparent position of the Sun due to Refraction of Light

Perihelion and Aphelion

- The earth revolves around the sun in an **elliptical orbit** with the sun at one of the foci.
- Approximately every 100,000 years, Earth's orbital path changes from being nearly circular to elliptical due to gravitational influences of other planetary objects, particularly the Moon.
- The Earth is closest to the Sun at its **perihelion** which occurs about **two weeks after the December Solstice**.
- At perihelion position, the earth is about **147.1 million km away** from the sun.
- It is farthest from the Sun at its **aphelion** which occurs about **two weeks after the June Solstice**.
- At aphelion position, the earth is about **152.1 million km** away from the sun.
- The dates when Earth reaches the extreme points on its orbit are not fixed.



Perihelion and Aphelion

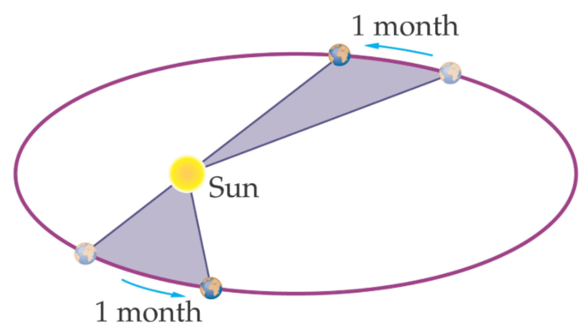
How much does the elliptical orbit affect the weather on earth?

Amount of energy received from the sun

- The difference in the amount of the sun's energy that the earth receives (called the solar constant) doesn't vary considerably between perihelion and aphelion.
- Throughout the year, the solar constant varies by very little due to the very small eccentricity of the earth's orbit (eccentricity of an ellipse varies between 0 and 1. A circle is an ellipse with eccentricity 0).
- After all, the distance difference between perihelion and aphelion is only a small fraction of Earth's average distance to the sun.
- In the southern hemisphere, the meagre solar constant increase is offset by the higher water to land ratio.

Duration of seasons

- The elliptical orbit does affect our weather by affecting the duration of the seasons, although this effect is not significant.
- Earth is farther away from the Sun in summer. Therefore, its orbital velocity is at its lowest, and it requires more time to travel from the summer solstice point to the autumnal equinox (September 23rd) than it needs to move between the winter solstice and vernal equinox (21st March).



The varying orbital speed of the earth (in the figure, the orbit of the earth is exaggerated)

- Thus, the winter is about 89 days, and the summer is approximately 92 days long.
- That is, **in the northern hemisphere the summer is slightly longer than the winter**.

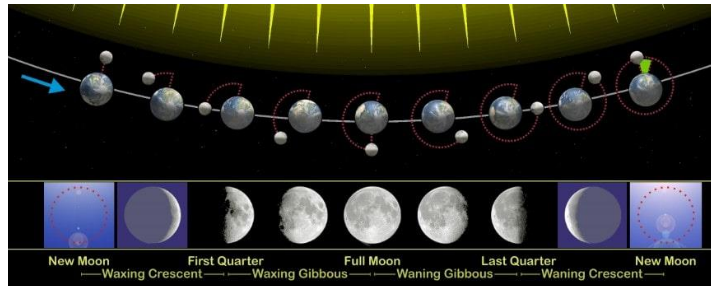
Kepler's second law of planetary motion *states that a line between the sun and the planet sweeps equal areas in equal times. Thus, the speed of the planet increases as it nears the sun and decreases as it recedes from the sun.*
The earth achieves its fastest orbital speed at the perigee and slowest orbital speed at the apogee.

Eclipse

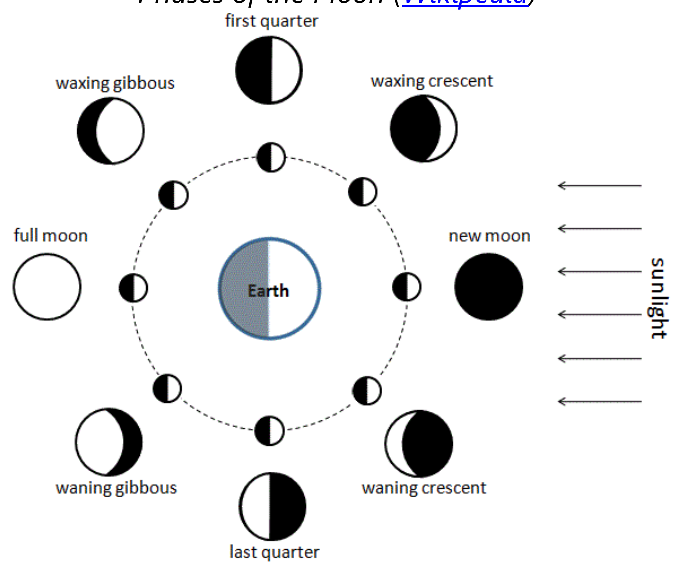
- An eclipse happens when a planet or a moon gets in the way of the sun's light.
- On earth, we experience two kinds of eclipses: 1) **solar eclipses that occur only on a new moon day** and **lunar eclipses that occur only on a full moon day**.
- Revolution of the moon around the earth close to the earth's ecliptic plane, proximity between the moon and the earth, and the relative apparent size of the sun and the moon, are all together responsible for the occurrence of solar and lunar eclipses.

The Sun's distance from Earth is about 400 times the Moon's distance, and the Sun's diameter is about 400 times the Moon's diameter. Because these ratios are approximately the same, the Sun and the Moon as seen from Earth appear to be approximately the same size.

Phases of the moon



Phases of the Moon (Wikipedia)



Phases of the Moon (Wikipedia)

- The lunar phase or phase of the Moon is the shape of the sunlit portion of the Moon as viewed from Earth.
- The Moon's rotation is **tidally locked** by Earth's gravity; therefore, most of the same lunar side always faces Earth. This near side is variously sunlit, depending on the position of the Moon in its orbit.

Tidal locking *is the situation when an object's orbital period matches its rotational period. E.g. the Moon's rotation time is* ***27.3 days****, just the same as its orbital time,* ***27.3 days****.*

- During the New moon phase, the Sun and the Moon are aligned on the same side of the Earth, and the side of the Moon facing Earth is under darkness.

- As the Moon waxes (the amount of illuminated surface as seen from Earth is increasing), the lunar phases progress through **new moon, crescent moon, first-quarter moon, gibbous moon, and full moon**.
- The Moon is then said to wane as it passes through the **gibbous moon, third-quarter moon, crescent moon, and back to new moon**.
- The lunar phases gradually and cyclically change over the period of a **synodic month** (about **29.53 days**), as the **orbital positions** of the Moon around Earth and Earth around the Sun **shift**.

Perigee and Apogee

- Like the Earth's orbit around the Sun, the Moon's path around the Earth is elliptical.
- The point in the Moon's orbit that is closest to the Earth is called the **perigee** and the point farthest from the Earth is known as the **apogee**.
- The terms are also sometimes used interchangeably with the Earth's Perihelion and Aphelion.
- In January 2019 perigee was ~3,57,000 km and apogee was ~4,06,000 km.
- The distance of perigee and apogee positions change from time to time.
- On average, the distance is taken as **382,900 kilometres** from the Moon's centre to the centre of Earth.

Sidereal period

- The orbit of a planet around the Sun measured with respect to the **fixed stars** is used to determine the sidereal period.
- The sidereal period of the Earth is **365.25 days** (Gregorian calendar month is about 30.44 days).
- The Moon's sidereal orbital period (the **sidereal month**) is **~27.3 days** — the time interval that the Moon takes to orbit 360° around the Earth relative to the **fixed stars**.

Synodic period

- Synodic period is the time required for a body within the solar system, such as a planet, the Moon, to return to the same position **relative to the Sun** as seen by an observer on the Earth.
- The Moon's synodic period is the time between successive recurrences of the same phase; e.g., between full moon and full moon.

The Moon completes one revolution

- ✓ ***relative to the fixed stars*** *in about* ***27.32 days*** *(a* ***sidereal month****) and*
- ✓ ***relative to the Sun*** *in about* ***29.53 days*** *(a* ***synodic month****).*

Thus, one Georgian year = 12 Georgian months = ~ 13.37 sidereal months =~ 12.37 synodic months

- The time difference in sidereal and synodic months is due to the **constantly shifting orbital positions of the Moon around Earth and of Earth around the Sun**.

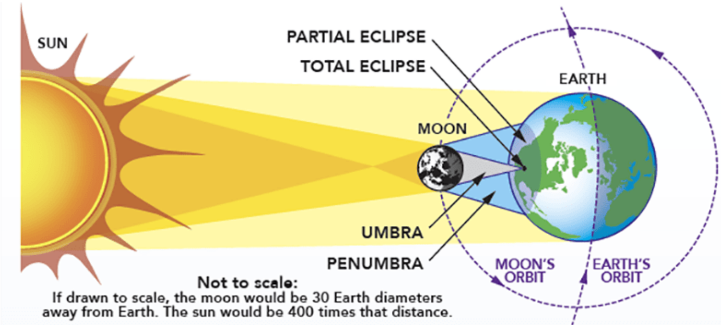
Supermoons & Micromoons

- The Moon's phase and the date of its approach to its perigee or apogee are not synced.
- When a Full Moon or New Moon occurs close to the **Moon's perigee**, it is known as a **Supermoon**.
- On the other hand, when a Full Moon or New Moon occurs close to the **Moon's apogee**, it is known as a **Micromoon**.

Supermoon and Micromoon

Solar Eclipse

- A solar eclipse happens when the moon gets in the way of the sun's light and casts its shadow on Earth.



Solar Eclipse (NASA illustration)

- The type of solar eclipse that happens during each season (whether total, annular or partial) depends on **apparent sizes of the Sun and Moon**.

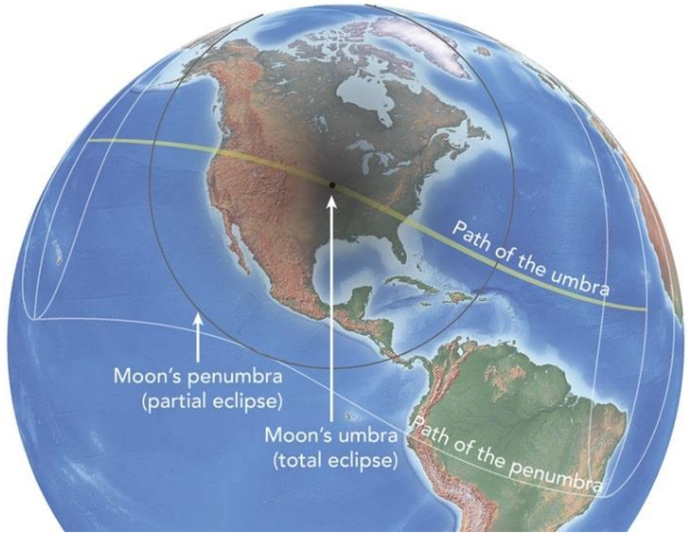
Total Solar Eclipse (Umbra)

- A total solar eclipse occurs when the sun and the moon are **exactly in line** with the Earth and the moon completely obscures the sun.
- During a total solar eclipse, the sun's **corona** is visible to the naked eye as a bright ring around the obscured sun.
- **A total solar eclipse happens about every year and a half somewhere on Earth**.
- The moon's shadow on Earth isn't very big, so only a small portion of places on Earth will see it.
- On average, the same spot on Earth only gets to see a solar eclipse for a few minutes about every 375 years!

Sun's Corona during a total solar eclipse

Umbra

- Umbra is the region of the shadow of the moon in which all light from the sun is completely excluded.
- Thus, in an eclipse of the Sun, the **regions within the umbra experience a total solar eclipse**.
- During any one eclipse, totality (total solar eclipse or umbra) occurs at best only in a narrow track on the surface of Earth. This narrow track is called the **path of totality**.



Path of totality (umbra) (Credits)

Annular Solar Eclipse

- An annular eclipse occurs when the Sun and Moon are exactly in line with the Earth, but the **apparent size of the Moon is smaller (when the moon is at its apogee) than that of the Sun**.
- Hence the Sun appears as a very **bright ring** surrounding the dark disk of the Moon.

Annular Solar Eclipse

Partial Solar Eclipse (Penumbra)

- A partial eclipse occurs when the sun and the moon are **not exactly in line** with the earth and the moon only partially obscures the sun.
- This phenomenon can usually be seen from a large part of the Earth outside of the track of an annular or total eclipse.

- However, some eclipses can only be seen as a partial eclipse, because the umbra passes above the Earth's polar regions and never intersects the Earth's surface.
- Partial eclipses are virtually unnoticeable in terms of the sun's brightness as it takes well over 90% coverage to notice any darkening at all.
- A partial solar eclipse happens **at least twice a year** somewhere on Earth.

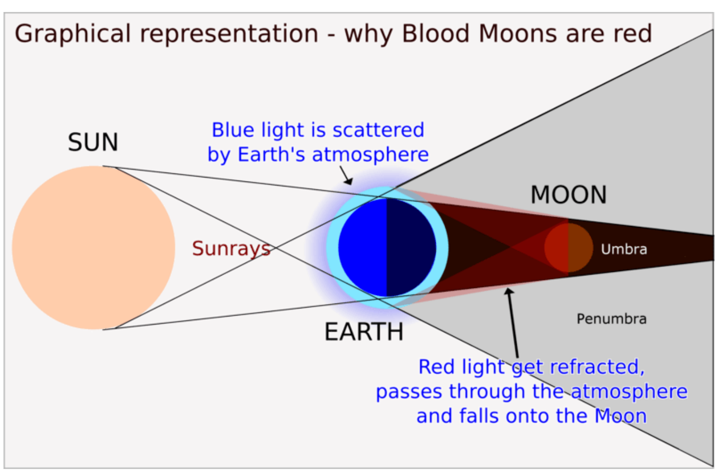
Penumbra

- Penumbra is the region of the shadow of the moon outside the umbra where the light from the Sun is partially blocked.
- Thus, in an eclipse of the Sun, the **regions within the penumbra experience partial solar eclipse**.

Lunar Eclipse

- During a lunar eclipse, Earth gets in the way of the sun's light hitting the moon. That means that during the night, a full moon fades away as Earth's shadow covers it up.
- If the moon passes through the lighter part of Earth's shadow, a **penumbral eclipse (partial eclipse)** occurs.
- If the moon passes through the darker part of Earth's shadow, an **umbral eclipse (total eclipse)** occurs.

Blood moon



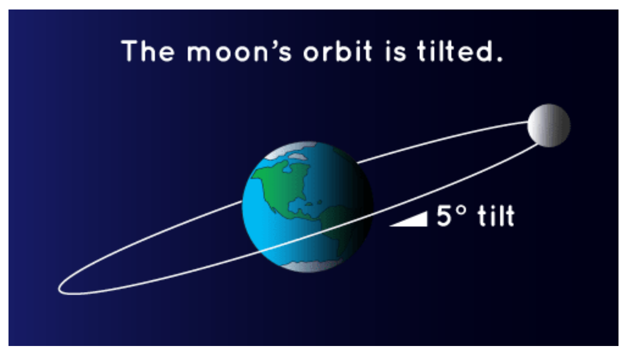
Lunar Eclipse and Blood Moon (Eggishorn, from Wikimedia Commons)

- During a total lunar eclipse, a little bit of light from Earth's sunrises and sunsets (on the disk of the planet) falls on the surface of the moon.
- The moon can look reddish because of the Earth's atmosphere that absorbs the other colours while it bends (**refraction**) some sun-light toward the moon
- How red the moon appears can depend on how much pollution, cloud cover or debris there is in the atmosphere.

Why don't we have a lunar eclipse or a solar eclipse every month?

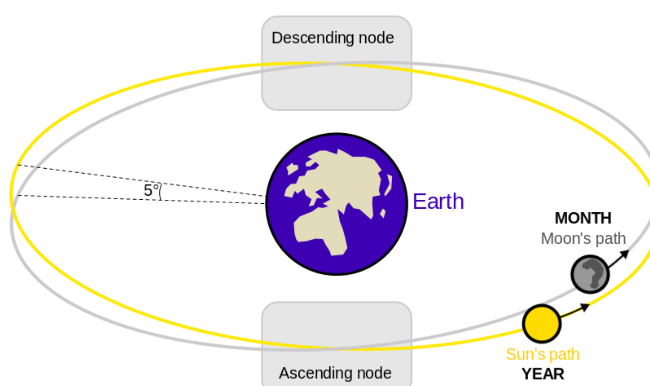
Why not every full moon day a lunar eclipse? Why not every new moon day a solar eclipse?

- Not every new moon causes a solar eclipse and not every full moon sees a lunar eclipse.
- This is because of the of **moon's tilted orbit around Earth** with respect to the earth's orbital plane (ecliptic).



Moons orbital plane is tilted to the earth's ecliptic (Earth's orbital plane) by about 5.1° (NASA)

- Solar and lunar eclipses happen only during an eclipse season **when the plane of the Earth's orbit around the Sun crosses with the plane of the Moon's orbit around the Earth**.



Eclipse season occurs at the descending and the ascending nodes (SuperManu, Wikipedia)

- It is because of the non-planar and non-circular differences that eclipses are not a common event.
- If the orbit of the Earth around the Sun and the Moon's orbit around the Earth were both in the same plane, then **there would be a lunar eclipse at every full moon, and a solar eclipse at every new moon**.
- And if both orbits were perfectly circular, then each solar eclipse would be the **same type** every month.

Prelims Question: Variations in the length of daytime and nighttime from season to season are due to

In simple words, seasons are caused due to?

a) the earth's rotation on its axis [causes day and night]
b) the earth's revolution around the sun in an elliptical manner
c) latitudinal position of the place
d) revolution of the earth on a tilted axis

- The earth's rotation on its axis causes day and night.
- The earth's revolution around the sun in an elliptical manner causes **perihelion** (closest position of earth to sun) and **aphelion** (farthest position of earth to sun).
- Latitudinal position of the place determines the amount of sunlight received.
- Revolution of the earth on a tilted axis **causes seasons** or variations in the length of daytime and nighttime from season to season.

Answer: d) revolution of the earth on a tilted axis
Rotation of earth ➔ Days and Nights
Revolution of earth on a tilted axis ➔ Seasons (Variations in the length of daytime and nighttime from season to season)
Revolution of the earth around the sun in an elliptical manner ➔ Perihelion and Aphelion
Revolution of the moon around the earth ➔ Phases of the Moon (New Moon, Full Moon)
Revolution of the moon around the earth in an elliptical manner ➔ Perigee and Apogee
Revolution of the moon on a tilted orbital plane around the earth ➔ Solar Eclipse and Lunar Eclipse
Revolution of the moon on a tilted orbital plane around the earth in an elliptical manner ➔ Moons apparent size is different for various Solar Eclipses (not all solar eclipses are similar)

3. Atmosphere

- Our planet earth is enveloped by a deep blanket of gases extending several thousands of kilometres above its surface. This gaseous cover of the earth is known as the atmosphere.
- Like land (lithosphere) and water (hydrosphere), the atmosphere is also an integral part of the earth and it is held in place by the gravitational influence of earth.

3.1 Evolution of Earth's atmosphere

- The first atmosphere consisted of gases in the solar nebula, primarily hydrogen.

Hadean eon (4,540 – 4,000 mya): The primordial atmosphere

- **Volcanic outgassing** created the primordial atmosphere.
- Outgassing from volcanism, supplemented by gases produced during the late heavy bombardment of Earth, produced the next atmosphere.

*During the **Late Heavy Bombardment** (4 billion years ago), a disproportionately large number of asteroids have collided with the early terrestrial planets including earth.*

- Over time, the Earth's surface solidified leaving behind hot volatiles which resulted in a **heavy CO_2 atmosphere** with hydrogen, nitrogen, inert gases and water vapour.
- After the formation of oceans, **dissolving in ocean water removed most CO_2 from the atmosphere**.
- Some CO_2 reacted with metals to form carbonates that were deposited as sediments.

- The early atmosphere contained almost **no oxygen**.
- Most of the lighter gases like the hydrogen and helium escaped into space and are continually escaping even to the present day due to **atmospheric escape** (outer layers stripped by solar wind).

Archean eon (4000 mya – 2500 mya)

- The atmosphere was **without oxygen,** and the atmospheric pressure was around **10 to 100 atmospheres**.
- Nitrogen formed the major part of the then stable "second atmosphere".
- Most of the nitrogen in the air was carried out from deep inside the earth by volcanoes.
- In the late Archean Eon, an oxygen-containing atmosphere began to develop, apparently produced by photosynthesising cyanobacteria.
- The constant re-arrangement of continents influenced the long-term evolution of the atmosphere by transferring carbon dioxide to and from large continental carbonate stores.

Proterozoic Eon (2500 mya – 541 mya): Oxygen in atmosphere

- Free oxygen did not exist in the atmosphere until about 2.4 billion years ago.
- O_2 showed major variations until reaching a steady state of more than 15% by the end of the Proterozoic.

Phanerozoic Eon (541 mya to present): The present atmosphere

- The amount of oxygen reached a peak of about 30% around 280 million years ago.
- Two main processes govern changes in the oxygen levels in the atmosphere:
  1. Plants use carbon dioxide from the atmosphere, releasing oxygen.
  2. Breakdown of **pyrite (iron sulphide)** and **volcanic eruptions** release **sulphur** into the atmosphere, which oxidises and hence **reduces the amount of oxygen in the atmosphere**. However, volcanic eruptions also release carbon dioxide, which plants can convert to oxygen.
- Periods with much oxygen in the atmosphere are associated with rapid development of animals.
- Today's atmosphere contains 21% oxygen, which is great enough for this rapid development of animals.

3.2 Composition of Atmosphere

- The composition of Earth's atmosphere is largely governed by the by-products of the life that it sustains.
- Dry air from Earth's atmosphere contains **78.08% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide**, and traces of hydrogen, helium, and other noble gases.
- The remaining gases are often referred to as trace gases, among which are the greenhouse gases, principally **carbon dioxide, methane, nitrous oxide**, and **ozone**.
- Various industrial pollutants also may be present as gases or **aerosols**, such as chlorine, fluorine compounds and elemental mercury vapor.
- Sulphur compounds such as hydrogen sulphide and sulphur dioxide (SO_2) may be derived from natural sources or industrial air pollution.

Permanent Gases of the Atmosphere

Name	Percentage by Volume
Nitrogen (N_2)	**78.08**
Oxygen (O_2)	**20.95**
Argon (Ar)	**0.93**
Carbon dioxide (CO_2)	**0.036**
Neon (Ne)	0.002
Helium (He)	0.0005
Krypto (Kr)	0.001
Methane (CH_4)	**0.000179**
Xenon (Xe)	0.00009
Hydrogen (H_2)	0.00005

NO AC NH KM

- Permanent atmospheric gases remain in fixed proportion to the total gas volume.
- Other constituents vary in quantity from place to place and from time to time.
- Heavier gases like nitrogen and oxygen tend to stick at the bottom of the atmosphere.

- The proportion of gases changes in the higher layers of the atmosphere in such a way that oxygen will be almost in negligible quantity at the height of 120 km.
- Similarly, carbon dioxide and water vapour are found only up to 90 km from the surface of the earth.

Important constituents of the atmosphere

Oxygen

- All living organisms inhale oxygen.
- Besides, oxygen can combine with other elements to form important compounds, such as, oxides.
- Also, **normal combustion is not possible without oxygen**.

Nitrogen

- It is a relatively inert gas and is an important constituent of all organic compounds.
- The main function of nitrogen is to control combustion by diluting oxygen, i.e., it prevents spontaneous combustion of oxygen in the atmosphere.
- It also indirectly helps in oxidation of different kinds.

Carbon Dioxide

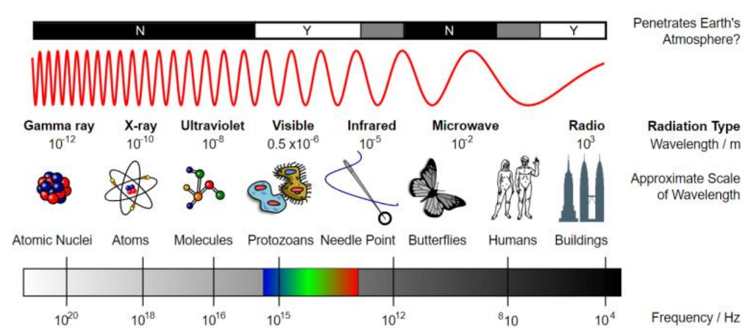
- Green plants, through photosynthesis, absorb carbon dioxide from the atmosphere.
- Being an **efficient absorber of heat**, carbon dioxide is a very important factor in the **heat energy budget**.
- With increased burning of fossil fuels – oil, coal and natural gas – the carbon dioxide percentage in the atmosphere has been increasing at an alarming rate.
- More carbon dioxide in the atmosphere means more heat absorption. This could significantly raise the temperature at lower levels of the atmosphere thus inducing drastic climatic changes.

Ozone (O_3)

- Ozone (O_3) is a type of oxygen molecule consisting of three oxygen atoms.
- It forms less than 0.00005% by volume of the atmosphere and is **unevenly distributed**.
- It is between 20 km and 30 km altitude (**stratosphere**) that the greatest concentrations of ozone are found.
- It is **formed at higher altitudes (due to interaction between O_2 and UV light)** and transported downwards.
- Ozone plays a crucial role in **blocking the harmful ultraviolet radiation** from the sun.

Water Vapour

- Water Vapour is one of the most variable gaseous substances present in atmosphere – constituting between **0.02% and 4%** of the total volume (in cold dry and humid tropical climates respectively).
- 90% of moisture content in the atmosphere exists within 6 km of the surface of the earth.
- Like carbon dioxide, water vapour plays a significant role in the insulating action, of the atmosphere.
- It absorbs not only the **long-wave terrestrial radiation** (**infrared or heat emitted by earth** during nights), but also a part of the **incoming short-wave solar radiation (visible and UV radiation)**.



Electromagnetic Spectrum (Inductiveload, via Wikimedia Commons)

- Water vapour is the source of precipitation and clouds.
- On condensation, it releases **latent heat of condensation** — the ultimate driving force behind all storms.

Solid Particles

- The Solid Particles present in the atmosphere consist of sand particles (from weathered rocks and also derived from volcanic ash), pollen grains, small organisms, soot, ocean salts; the upper layers of the atmosphere may even have fragments of meteors which got burnt up in the atmosphere.
- These solid particles perform the function of **absorbing, reflecting and scattering the radiation**.
- The solid particles are, consequently, responsible for the **orange and red colours at sunset and sunrise** and for the **length of dawn** (the first appearance of light in the sky before sunrise) and **Twilight** (the soft glowing light from the sky when the sun is below the horizon, caused by the **refraction** of the sun's rays by the atmosphere. Dusk: the darker stage of twilight.).
- The blue colour of the sky is also due to **selective scattering by dust particles**.
- Some of the dust particles are **hygroscopic** (i.e. readily absorbing moisture from air) in character, and as such, act as **nuclei of condensation**.
- Thus, dust particles are an **important contributory factor in the formation of clouds and different forms of precipitation, fog and hailstones**, etc.

Mains 2015: How far do you agree that the behaviour of the Indian monsoon has been changing due to humanising landscapes? Discuss.

- Humanising landscapes refers to the large-scale interaction of humans with the natural environment and the consequent changes brought upon due to such interactions.
- Examples of such interactions include urbanisation, industrialisation, deforestation and desertification, depletion of water resources, etc.
- Consequences of such interactions include rapid increase in concentration of greenhouse gases and aerosols in the atmosphere, global climate change, changes in sea surface temperature, alarming rate of depletion of natural resource, imbalances in the ecosystems, etc.

Impact on Monsoons

- The increasing incidence of El Nino, La Nina, El Nino Modoki, IOD, due to climate change post-industrial revolution has an overarching effect on the overall mechanism of the Indian Monsoons.
- Localised pollution (condensation nuclei), deforestation, on the other hand, cause a change in regional monsoon patterns.
- The impact of El Nino, La Nina, El Nino Modoki, etc. will be discussed in the chapter on 'Indian Monsoons'.
- Here let us focus on the impact of condensation nuclei on the behaviour of the Indian monsoons.

High concentration of condensation nuclei disrupts regional patterns of Indian monsoons

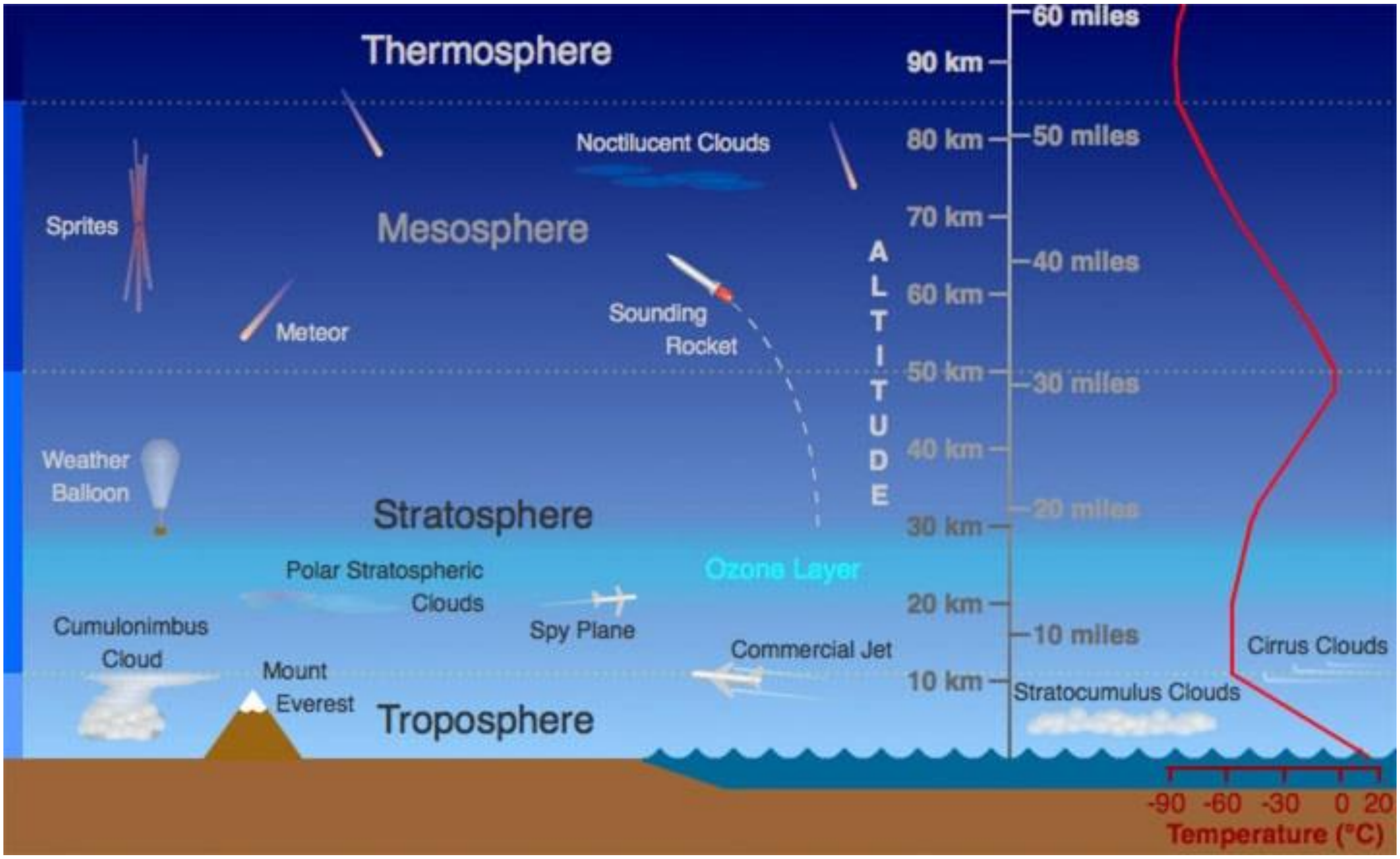
- Increase in the number of condensation nuclei due to increased availability of pollutants and dust particles will increase condensation of water vapour.
- As the urban atmosphere tends to have greater concentration of condensation nuclei due to vehicular pollution and construction activity, the monsoonal rainfall is disproportionately high in the urban areas.
- As a consequence, the agriculture-dependent rural areas tend to receive disproportionately low rainfall.

3.3 Structure of Atmosphere

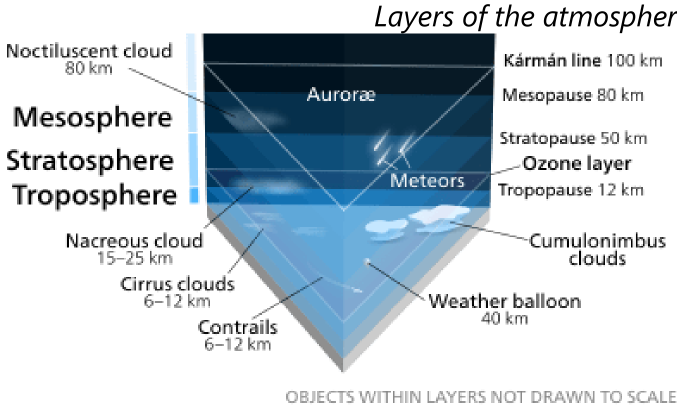
- The atmosphere can be studied as a layered entity – each layer having its peculiar characteristics. These layers are systematically discussed below.
  1. **Troposphere: 0 to 12 km**
  2. **Stratosphere: 12 to 50 km**
  3. **Mesosphere: 50 to 80 km**
  4. **Thermosphere: 80 to 700 km**
  5. **Exosphere: 700 to 10,000 km**

Troposphere

- Its altitude is 8 km at the poles and 18 km at the equator.



Layers of the atmosphere (*[Wikimedia Commons](#)*)



Layers of the atmosphere (Kelvinsong, [Wikimedia Commons](#))

- The **thickness is greater at the equator because of the heated air that rises to greater heights**.
- The troposphere ends with the Tropopause.
- The temperature in this layer, as one goes upwards, **falls** (positive lapse rate) at the rate of **6.5 °C per kilometre**.
- It is -45 °C at the poles and -80 °C over the equator at Tropopause (**greater fall in temperature above equator is because of the greater thickness of troposphere – 18 km**).
- The troposphere is marked by temperature inversion, turbulence and eddies.
- It is also meteorologically the most significant zone in the entire atmosphere (all weather phenomena like cyclones, rainfall, fog and hailstorm etc. are confined to this layer).
- It is also called the convective region since **all convection stops at Tropopause**.

Tropopause

- Topmost layer of troposphere.
- It acts as a boundary between troposphere and stratosphere.
- This layer is marked by constant temperatures.

Stratosphere

- It lies beyond tropopause, up to an altitude of 50 km from the earth's surface.
- The temperature in this layer remains constant for some distance but then rises (negative lapse rate) to reach a level of 0 °C at 50 km altitude.
- **This rise is due to the presence of ozone** (harmful ultraviolet radiation is absorbed by ozone).

- This layer is **almost free from clouds** and associated weather phenomenon, making conditions **most ideal for flying aeroplanes**.
- So, the aeroplanes fly in lower stratosphere, sometimes in upper troposphere where weather is calm.
- Sometimes, **cirrus clouds** are present at lower levels in this layer.

Ozonosphere

- It lies at an altitude between 20 km and 55 km from the earth's surface and spans the stratosphere and lower mesosphere. But the **highest concentration occurs between 20 km and 30 km**.
- Because of the presence of ozone molecules, **this layer absorbs and reflects the harmful ultraviolet radiation**.
- The **temperature rises** (negative lapse rate) at a rate of 5° C per kilometre through the ozonosphere.
- The ozonosphere is also called **chemosphere** because of a lot of chemical activity taking place.
- Ultraviolet light splits O_2 into individual oxygen atoms (atomic oxygen); the atomic oxygen then combines with unbroken O_2 to create ozone, O_3.
- The ozone molecule is unstable (although, in the stratosphere, long-lived) and when ultraviolet light hits ozone it splits into a molecule of O_2 and an individual atom of oxygen (**ozone-oxygen cycle**).
- Stratospheric ozone depletion is caused by chlorofluorocarbons, bromofluorocarbons and other ozone-depleting substances that increase the concentrations of **chlorine** and **bromine radicals**.
- Each of these radicals initiate and catalyse a chain reaction capable of breaking down over 100,000 ozone molecules.

Mesosphere

- Most of the **meteors burn up in this layer** on entering from the space.
- Temperatures drop with increasing altitude to the mesopause.
- **Mesopause is the coldest place on Earth** and has an average temperature around −85 °C.
- Just below the mesopause, the air is so cold that even the very scarce water vapour at this altitude can be sublimated into **polar-mesospheric noctilucent clouds**.
- These are the highest clouds and may be visible to the naked eye during sunset and sunrise.

Thermosphere

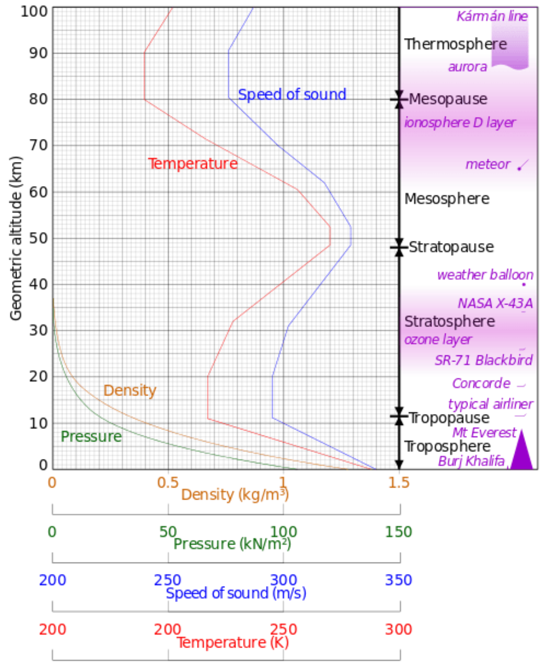
- In thermosphere temperature rises (negative lapse rate) very rapidly with increasing height **because of radiation from the sun**.
- **Ionosphere** is a part of this layer. It extends between 80-400 km.
- Though temperature is high, the atmosphere is **extremely rarefied** – gas molecules are spaced hundreds of kilometres apart. Hence a person or an object in this layer doesn't feel the heat.
- **The International Space Station and satellites orbit in this layer**.
- **Aurora's** are observed in lower parts of this layer.
- The **Kármán line**, located within the thermosphere at an altitude of 100 km, is commonly used to define the boundary between Earth's atmosphere and outer space.
- By international convention, this marks the beginning of space where human travellers are considered astronauts.

The mass of Earth's atmosphere is distributed approximately as follows:

- ✓ ***50% is below 5.6 km.***
- ✓ ***90% is below 16 km.***
- ✓ ***99.99997% is below 100 km, the Kármán line.***

Speed of sound follows temperature profile

- *This is because speed of sound is directly proportional to temperature as we move away from earth.*
- *Because in an ideal gas of constant composition the speed of sound depends only on temperature and not on the gas pressure or density.*



Speed of sound follows temperature profile

Exosphere

- This is the uppermost layer of the atmosphere extending beyond the ionosphere above a height of about 400 km.
- The air is extremely rarefied, and the temperature gradually increases through the layer.
- Light gases like helium and hydrogen float into the space from here.
- Temperature gradually increases through the layer (as it is exposed to direct sunlight).
- This layer coincides with space.

Atmospheric escape

- Certain light gases like hydrogen are constantly lost into space from exosphere due to atmospheric escape.
- Atmospheric escape of gases (**atmospheric stripping**) happens when gas molecules achieve escape velocity due to **low gravity** or due to energy received from the sun (heat, solar wind).
- Jovian planets retain gases with low molecular masses because of low temperatures and higher gravity.
- Titan, a moon of Saturn, and Triton, a moon of Neptune, possess significant nitrogen-rich atmospheres.
- **Earth's magnetic field** reduces atmospheric escape by protecting the atmosphere from solar wind that would otherwise greatly enhance the escape of hydrogen.

3.4 Importance of Earth's Atmosphere

- Earth is unique among plants as it has life and life on earth would not have been possible if not for the present state of atmosphere.

Life-giving gases

- Plants require carbon dioxide to survive while animals and many other organisms need oxygen for their survival.
- Nitrogen is fixed by bacteria and lightning to produce ammonia used in the construction of nucleotides and amino acids.

Regulates the entry of solar radiation

- All life forms need a particular range of temperature and a specific range of frequencies of solar radiation to carry out their biophysical processes.
- The atmosphere absorbs certain frequencies and lets through some other frequencies of solar radiation. In other words, the atmosphere regulates the entry of solar radiation.

Temperature balance

- The atmosphere also keeps the temperature over the earth's surface within certain limits.
- In the absence of the atmosphere extremes of temperature would exist between day and night.

Blocks harmful radiation

- The atmosphere helps to protect living organisms from genetic damage by solar ultraviolet radiation, solar wind and cosmic rays.

Shields the earth from impact objects

- The atmosphere also takes care of extra-terrestrial objects like meteors which get burnt up while passing through the atmosphere (**mesosphere** to be precise) due to friction.

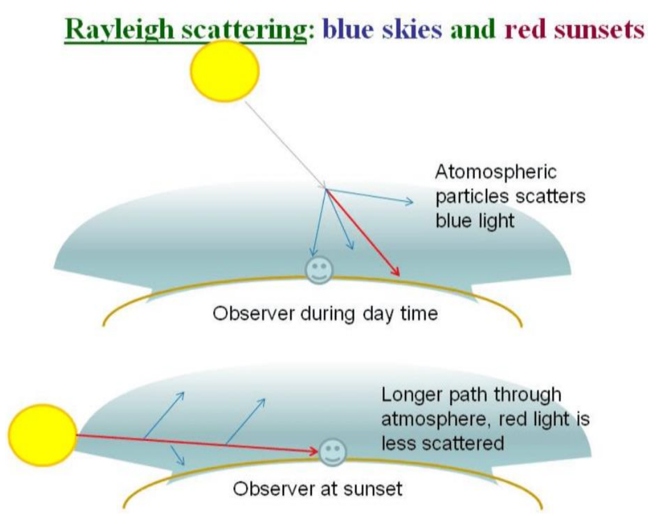
Weather and climate

- Weather is another important phenomenon which dictates the direction of many natural and human-made processes like plant growth, agriculture, soil-formation (weathering and erosion), human settlements, etc. Various climatic factors join together to create weather.

Water on earth exists in liquid state due to Atmosphere

- Since **liquids cannot exist without pressure**, an atmosphere allows liquid to be present at the surface, resulting in lakes, rivers and oceans.
- Earth and **Titan** are known to have liquids at their surface and terrain on the planet suggests that Mars had liquid on its surface in the past.

Scattering of light



Scattering by atmosphere (Credits)

- When light passes through Earth's atmosphere, photons interact with it through scattering.
- On an overcast, there is no direct radiation as it has all been scattered by the clouds.
- Due to a phenomenon called **Rayleigh scattering, shorter (blue) wavelengths scatter more easily than longer (red) wavelengths**. This is why the sky looks blue; you are seeing scattered blue light.
- This is also why sunsets are red. Because the Sun is close to the horizon, the Sun's rays pass through more atmosphere than normal to reach your eye. Much of the blue light has been scattered out, leaving the red light in a sunset.

4. Temperature Distribution on Earth

- The **differential amount of sun's energy received** by various latitudinal zones on earth is the primary reason behind the occurrence of seasonal patterns of weather and climate.
- Thus, understanding the patterns of distribution of temperature in different seasons is important for understanding various climatic features like wind systems, pressure systems, precipitation etc.

4.1 Ways of Transfer of Heat Energy

Radiation

- Radiation **doesn't** require a medium for heat transfer.
- Heat is transferred from one body to another **without actual contact or movement in the medium**.
- E.g. Heat transfer from sun to earth through space.

Insolation

- **Insolation** is the amount of sun's energy received in the form of radiation by the earth.
- It is measured as the amount of solar energy received per square centimetre per minute.
- Earth intercepts less than a billionth of solar radiation.
- Earth receives sun's radiation in the form of **short waves (visible light or wavelengths below visible light – most of it is ultraviolet radiation)** which are electromagnetic.
- The earth absorbs short wave radiation during daytime and reflects the **heat** received into space as **long-wave radiation (mostly infrared radiation which is nothing but heat)** during night.

Conduction

- The heat transfer through conduction happens due to **molecular activity** in a conducting medium. There is no actual movement of the medium itself.
- Generally, denser materials like iron, water are good conductors, and lighter medium like air are bad conductors of heat.

Convection

- Convection is the transfer of heat energy by **actual transfer of matter** or substance from one place to another. E.g. heat transfer by convection cells in a boiling pot of water, atmosphere or oceans.

Heat from the interior

- Some heat from within the earth's interior is transferred to the surface through volcanoes, springs and geysers. But this heat received at the surface is negligible compared to that received from sun.
- However, the heat received from the interior at the ocean bottom is key to the survival of deep ocean lifeforms that depend on bacteria that grow near the volcanic vents.
- At ocean depths, as sunlight is non-existent, photosynthesis is impossible. The bacteria rely on **chemosynthesis**, a process in which microbes use **chemicals** in the vent fluid to produce energy.

4.2 Factors Affecting Temperature Distribution

- The Angle of Incidence or the Inclination of the Sun's Rays
- Duration of Sunshine
- Transparency of Atmosphere
- **Albedo**
- Land-Sea Differential
- Prevailing Winds
- Ocean Currents
- Altitude
- Aspects of Slope
- Earth's Distance from Sun

The Angle of Incidence or the Inclination of the Sun's Rays

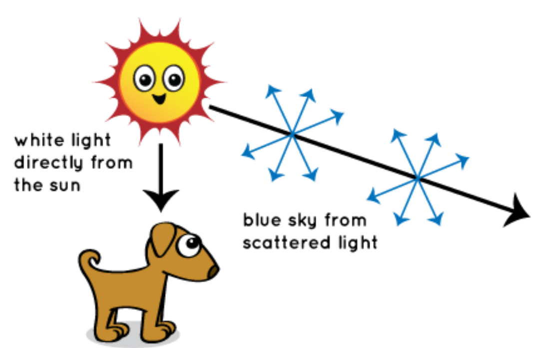
- The area lying close to the equator receive the maximum heat due to near vertical rays of the sun.
- The sun's rays get progressively slanting as one moves away from the equator towards poles.
- As a result, the heat received from the sun decrease as the distance increases from the equator.
- Areas lying close to the poles receive the least of sun's energy as the sun's rays are near horizontal.

Duration of Sunshine

- Heat received depends on day or night; clear sky or overcast, summer or winter etc.
- Earth's atmosphere plays an important role in moderating the temperatures between seasons and between days and nights.

Transparency of Atmosphere

- Aerosols (smoke, sooth, pollen), dust, water vapour, clouds etc. effect transparency.
- **If the wavelength of the radiation is more than the radius of the obstructing particle (such as a gas)**, then **scattering** of radiation takes place.



Scattering of Sun's light (NASA)

- If the wavelength is less than the obstructing particle (such as a dust particle), then **reflection** takes place.

- **Absorption** of solar radiation takes place if the obstructing particles happen to be **water vapour, ozone molecules, carbon dioxide molecules or clouds** (**Greenhouse effect**).
- Most of the light received by earth is **scattered light**.

Albedo

- **Albedo** of a surface is the proportion of sunlight that the surface can reflect back into space.
- Albedo of land is much greater than albedo of oceans and water bodies.
- Snow-covered areas reflect up to 70-90% of insolation.

Land-Sea Differential

- The **specific heat of water is 2.5 times higher than landmass**; therefore water takes longer to get heated up and to cool down.
- Average penetration of sunlight is more in water – up to 20 metres than in land – where it is up to 1 metre or less. Therefore, land cools or becomes hot more rapidly compared to oceans.
- In oceans, continuous convection cycle helps in heat exchange between layers **keeping diurnal and annual temperature ranges low**.

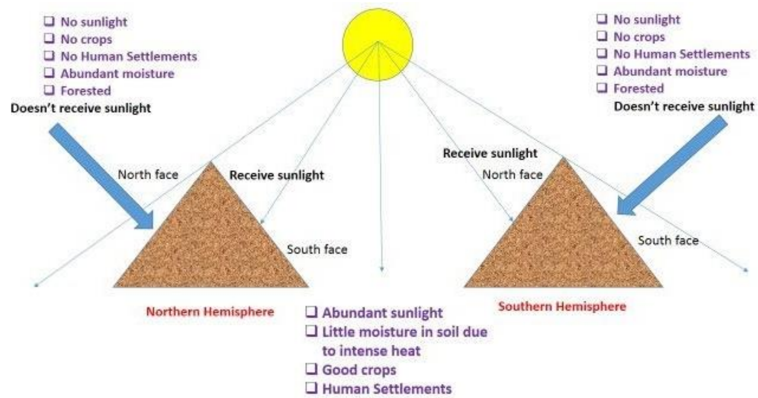
Temperature Anomaly

- The difference between the mean temperature of a place and the mean temperature of its parallel (latitude) is called the **temperature anomaly or thermal anomaly**.
- The **largest anomalies occur in the northern hemisphere and the smallest in the southern hemisphere.**

Prevailing Winds

- Winds transfer heat from one latitude to another. E.g. Poles would have been much colder if it is not for the moderating effect by the atmospheric circulation.
- Winds also help in exchange of heat between land and water bodies. E.g. **Land breeze and sea breeze**.

Aspects of Slope



Insolation along a sloping surface

- The direction and the steepness of the slope control the amount of solar radiation received locally.
- Slopes more exposed to the sun receive more solar radiation than those away from the sun's direct rays.
- Slopes that receive direct Sun's rays are dry due to **loss of moisture** through excess evaporation. These slopes remain barren if irrigational facilities are absent.
- But slopes with good irrigational facilities are good for agriculture due to abundant sunlight available. They are occupied by **dense human settlements**.
- Slopes that are devoid of direct sunlight are usually well forested.

Ocean Currents

- Ocean currents influence the temperature of adjacent land areas considerably.
- For example, U.K., considering its latitudinal location, has a relatively moderate climate due to the **warm North Atlantic Drift**.

Altitude

- With increase in height, pressure falls, the effect of greenhouse gases decreases and hence temperature decreases (applicable only to troposphere).
- The normal **lapse rate is roughly 1 °C for every 150-155 metres** of ascent (in troposphere).

Earth's Distance form Sun

- During its revolution around the sun, the earth is farthest from the sun **(~152 million km)** near **4th July**. This position of the earth is called **aphelion.**
- Near **3rd January**, the earth is the nearest to the sun **(~147 million km).** This position is called **perihelion.**
- Therefore, the annual insolation received by the earth on 3rd January is slightly more than the amount received on 4th July.
- However, the effect of this variation in the solar output is masked by other factors like the **distribution of land and sea and the atmospheric circulation**.
- Hence, this variation in the solar output does not have great effect on daily weather changes on the surface of the earth.

4.3 The Mean Annual Temperature Distribution

- The horizontal or latitudinal distribution of temperature is shown with the help of a map with isotherms.
- The Isotherms are imaginary lines joining places having equal temperature.
- Effects of altitude is not considered while drawing an isotherm (temperatures are reduced to sea levels).

General characteristics of isotherms

Generally, follow the parallels

- Isotherms have close correspondence with the latitude parallels mainly because the same amount of insolation received by all the points located on the same latitude.
- The isotherms are irregular over the northern hemisphere due to an **enhanced land-sea contrast**.
- The thermal equator (ITCZ) generally lies to the north of geographical equator.

Sudden bends at ocean-continent boundaries

- Due to differential heating of land and water and due to ocean currents, temperatures above the oceans and landmasses vary even on the same latitude.

Spacing between isotherms

- Narrow spacing between isotherms indicate high thermal gradient (rapid change in temperature).
- Wide spacing between isotherms indicate low thermal gradient (small or slow change in temperatures).

General Temperature Distribution

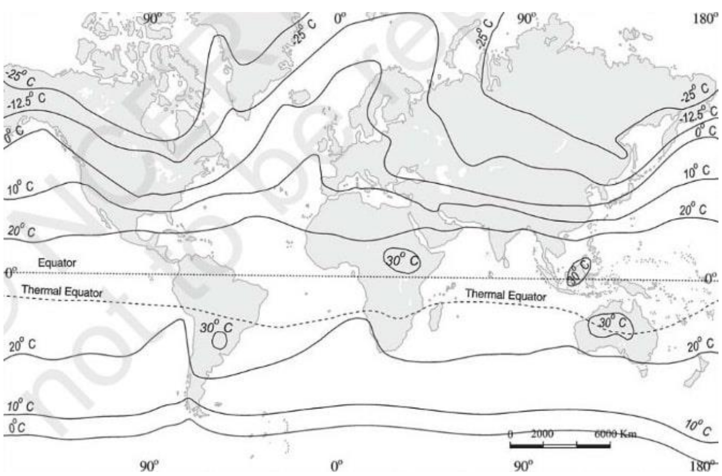
- The highest temperatures occur over tropics and subtropics.
- The lowest temperatures occur in polar and sub-polar regions and the interiors of large continental subpolar regions due to the effect of **continentality** (far from the moderating effect of the seas).
- Diurnal (daily) and annual range of temperatures are highest in the interiors of continents due to **continentality**.
- Diurnal and annual range of temperatures are least in oceans because of **high specific heat and mixing**.
- The **northern hemisphere is warmer** because of the **predominance of land over water** in the north.
- Low-temperature gradients are observed over tropics (sun is almost overhead the entire year).
- High-temperature gradients are observed over middle and higher latitudes (sun's apparent path varies significantly from season to season).
- Temperature gradients are usually low over the eastern margins of continents because of **warm ocean currents**.
- While passing through an area with warm ocean currents, the isotherms show a **poleward shift**.
- E.g. North Atlantic Drift and Gulf Stream in Northern Atlantic; Kurishino Current and North Pacific current combined in Northern Pacific.
- Temperature gradients are usually high over the western margins of continents because of **cold ocean currents**.

- Mountains also affect the horizontal distribution of temperature. For example, the Himalayas insulate India from the cold winds of Siberia, the Rockies and the Andes block the oceanic influence from going inwards into North and South America.

Seasonal Temperature Distribution

- In general, the effect of the latitude on temperature is well pronounced on the map, as the isotherms are generally parallel to the latitude.
- The deviation from this general trend is more pronounced in January than in July, especially in the northern hemisphere **because of the land surface area** which is much larger than in the southern hemisphere.

Seasonal Temperature Distribution – January



Isotherm map for the month of January

- During January, it is winter in the northern hemisphere and summer in the southern hemisphere.

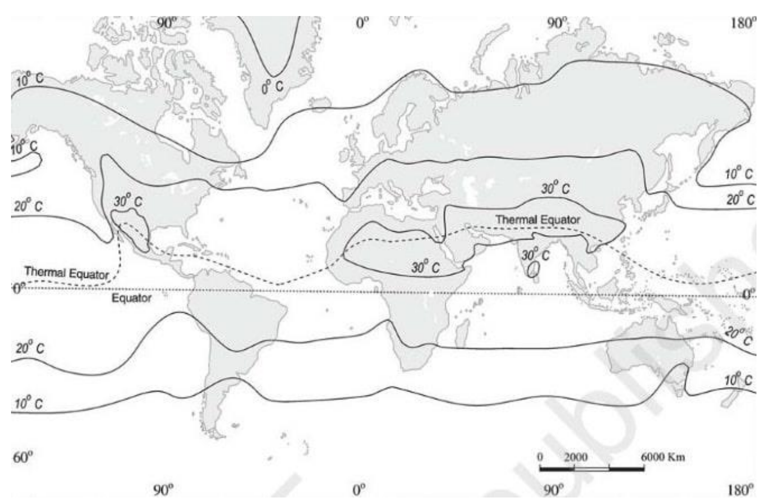
Northern Hemisphere

- The western margins of continents are warmer than their eastern counterparts since the **Westerlies** are able to carry high temperature (from the oceans) into the landmasses.
- The isotherms are closer on the eastern margins as temperature gradient is high because of the **less moderating effect of the oceans** (westerlies flow from west to east).
- The isotherms deviate to the north over the ocean.
- For example, the presence of **warm Gulf Stream and North Atlantic drift** make the Northern Atlantic warmer and the isotherms show a poleward shift indicating that the currents are able to carry high temperatures poleward.
- The isotherms deviate to the south over the continents (**due to continentality**) as the cold polar winds are able to penetrate southwards into the interiors.
- Lowest temperatures are recorded over northern Siberia and Greenland.

Southern Hemisphere

- The effect of the ocean is well pronounced in, and the isotherms exhibit a more regular behaviour.
- The isotherms are more or less parallel to the latitudes, and the variation in temperature is gradual.
- The high-temperature belt runs in the southern hemisphere, somewhere along 30° S latitude (**subtropics are devoid of cloud cover due to anticyclonic circulation at the surface**).
- The thermal equator lies to the south of geographical equator (because the Intertropical Convergence Zone or ITCZ has shifted southwards with the apparent southward movement of the sun).

Seasonal Temperature Distribution – July



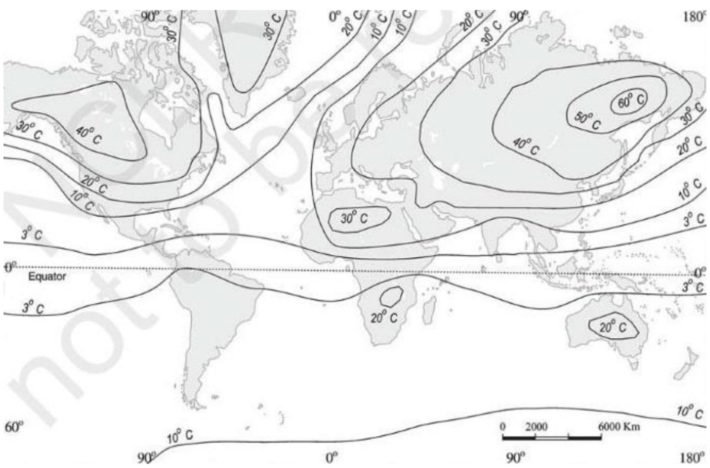
Isotherm map for the month of July

- During July, it is summer in the northern hemisphere and winter in the southern hemisphere.

- The isotherms generally run parallel to the latitudes.
- Thermal equator lies to the north of the geographical equator.
- The equatorial oceans record warmer temperature, more than 27 °C.
- Over the land more than 30 °C is noticed in the subtropical continental region of Asia, along the 30° N latitude.

Northern Hemisphere

- The highest annual range of temperature is more than 60° C over the Siberian region (**continentality**).
- The least range of temperature, 3° C, is found between 20° S and 15° N.



The range of temperature between January and July. It is highest in the Siberian region

- Over the northern continents, a poleward bend of the isotherms indicates that the landmasses are overheated, and the hot tropical winds are able to go far into the northern interiors.
- The isotherms over the northern oceans show an equatorward shift indicating that the **oceans are cooler** and are able to **carry the moderating effect into tropical interiors**.
- The lowest temperatures are experienced over Greenland.
- The highest temperature belt runs through northern Africa, West Asia, north-west India arid south-eastern USA.
- The temperature gradient is irregular and follows a zig-zag path over the northern hemisphere.

Prelims Practise: The main reason that the earth experiences highest temperatures in the subtropics in the northern hemisphere rather than at the equator is:

a) Subtropical areas tend to have less cloud cover than equatorial areas.
b) Subtropical areas have longer day hours in the summer than the equatorial.
c) Subtropical areas have an enhanced "greenhouse effect" compared to equatorial areas.
d) Subtropical areas are nearer to the oceanic areas than the equatorial locations.

Explanation:

- There is no cloud cover in the subtropics because of the subsiding air and the consequent divergence (anticyclonic circulation) at the surface.
- Subtropical areas have longer day hours in the summer than the equatorial, but the difference is not substantial.
- Moreover, the weather in the equatorial region is turbulent with dense overcast skies and most of the heat is lost in the form of **latent heat of vaporisation**.

Answer: a) Subtropical areas tend to have less cloud cover than equatorial areas.

Southern Hemisphere

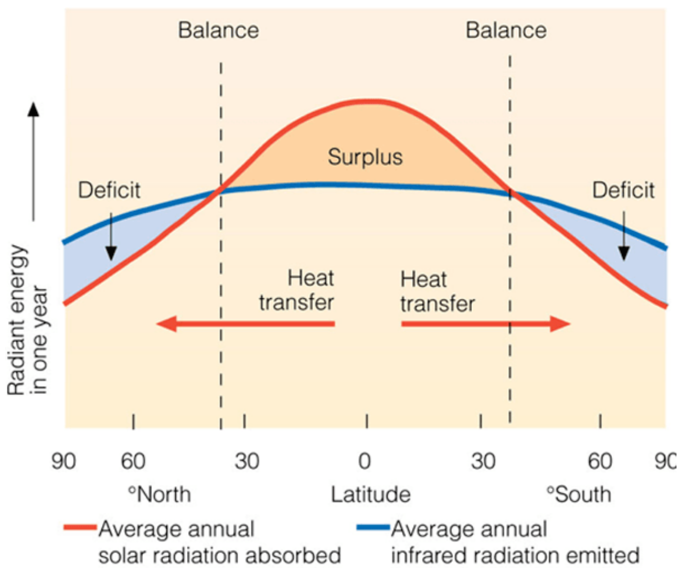
- The gradient becomes regular over the southern hemisphere but shows a slight bend towards the equator at the edges of continents.

4.4 Latitudinal Heat Balance

- Regions within the equator and 40° N and S latitudes receive abundant sunlight and hence more heat will be gained than lost. Hence, they are **energy surplus regions.**
- Regions beyond 40° N and S latitudes lose more heat than that gained from sunlight. Hence, they are **energy deficit regions** (because of **slant sunlight and high albedo of polar regions**).
- Going by this logic, the tropics should have been getting progressively hotter and the poles

progressively cooler. And the planet would have been inhospitable except for few regions near mid-latitudes.

- But this is not the case as the atmosphere and the oceans transfer excess heat from the tropics (energy surplus region) towards the poles (energy deficit regions) making up for heat loss at higher latitudes.
- And **most of the heat transfer takes place across the mid-latitudes (30° to 50)**, and hence much of the **stormy weather (jet stream and temperate cyclones)** is associated with this region.
- Thus, the transfer of surplus energy from the lower latitudes to the deficit energy zone of the higher latitudes maintains an overall balance over the earth's surface.



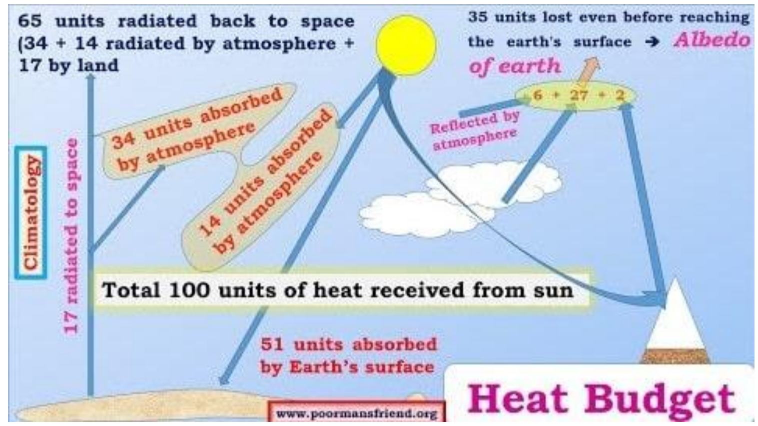
Latitudinal Heat Balance (Credit: [NASA])

4.5 Heat Budget

- The earth receives a certain amount of Insolation **(short waves – UV and visible part of the electromagnetic spectrum)** and gives back **heat** into space by terrestrial radiation **(longwave or infrared radiation).**
- Through this give and take, or the heat budget, the earth maintains a constant temperature.

Prelims Practise: The atmosphere is mainly heated by the:

a) Short wave solar radiation
b) Long wave terrestrial radiation
c) Reflected solar radiation
d) Scattered solar radiation



Explanation:

- 51 units of the incoming shortwave (daytime) radiation is directly absorbed by the earth's surface.
- **35 units are lost even before reaching the surface** due to albedo (2 units), reflection by atmosphere (6 units) and reflection by the clouds (27 units).
- The remaining 14 units of the incoming shortwave (daytime) radiation is absorbed by the atmosphere.
- Hence, the incoming shortwave radiation is responsible for only 14 units out of the **total 48 units absorbed by the atmosphere**.
- The remaining **34 units are received from the outgoing longwave (infrared) terrestrial radiation**.

Answer: d) Long wave terrestrial radiation

Answer in 30 words

1) How does the unequal distribution of heat over the planet earth in space and time cause variations in weather and climate?
2) What are the factors that control temperature distribution on the surface of the earth?
3) In India, why is the day temperature maximum in May and why not after the summer solstice? (Hint: **By June 21st Monsoons cover more than half of India**)
4) Why is the annual range of temperature high in the Siberian plains? (Hint: **Continentality**)

Answer in 150 words

1) How do the latitude and the tilt in the axis of rotation of the earth affect the amount of radiation received at the earth's surface?
2) Discuss the processes through which the earth-atmosphere system maintains heat balance.
3) Compare the global distribution of temperature in January over the northern and the southern hemisphere of the earth.

4.6 Vertical Distribution of Temperature

To understand the vertical distribution of temperature we need to know about latent heat, lapse rate and adiabatic lapse rate
The terms 'Adiabatic Lapse Rate' and 'Latent Heat of Condensation' frequently occur in climatology. Understanding these terms once for all will help immensely in understanding the subsequent topics of climatology.

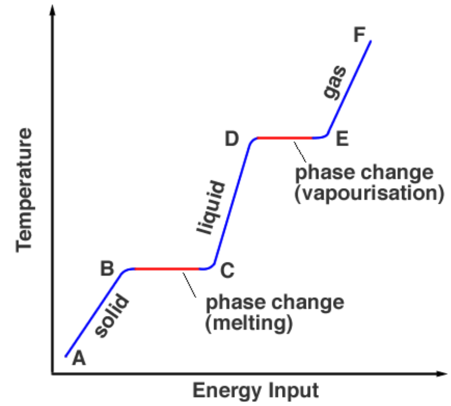
Latent Heat of Condensation

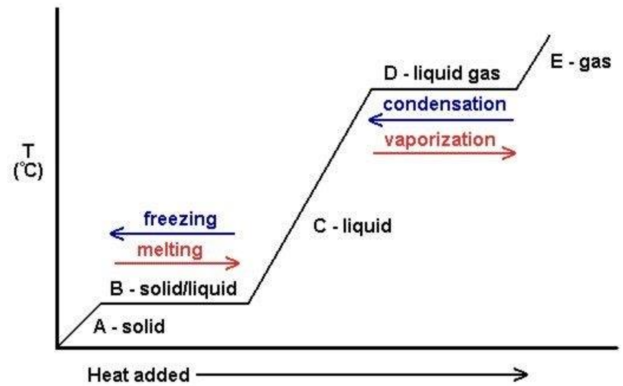
- Adiabatic lapse rate determines the **rate of condensation** in the atmosphere which in turn determines the amount of **latent heat of condensation** released.
- The heat released in the form of **latent heat of condensation** supplies the energy necessary for the formation of towering cumulonimbus thunderstorm cloud and the formation of tropical cyclones.

Latent Heat

- Latent heat is the amount of energy absorbed or released by a substance during a change in its physical state (phase change) that occurs **without changing its temperature**.
- For example, when a pot of water is kept boiling, the temperature remains at 100 °C until the last drop evaporates because all the heat being added to the liquid is absorbed as **latent heat of vaporisation** and carried away by the escaping vapour molecules.
- Similarly, while ice melts, it remains at 0 °C, and the liquid water that is formed with the **latent heat of fusion** is also at 0 °C.

Explanation





Graph: On X – axis: Heat supplied to the system; On Y – Axis: Temperature change in the system

- From the above graph, we can observe that there is no change in temperature in the system during change of state or phase change. Then where did the heat supplied go?
- Initially, the heat supplied is used to raise the temperature of the system (A-B and then C-D)
- During phase change, the heat supplied is consumed to turn solid into liquid (B-C: **latent heat of fusion – heat absorbed**) and then liquid into gas (D-E: **latent heat of vaporisation – heat absorbed**).
- Thus, the heat supplied in used in phase change. Hence temperature of the system remains constant during phase change process. (B-C & D-E)
- But when gas turns into liquid (**latent heat of condensation – heat released**) or liquid into solid (**latent heat of fusion – heat released**), heat is released (this heat is the heat that was used during the phase change process).
- **Thus, latent heat of condensation is the heat released when gases turn into liquid**.

When water vapour in atmosphere condenses into raindrops latent heat of condensation is released. Water evaporates from the ocean surface by absorbing latent heat of vaporisation.

Lapse Rate

- Lapse rate (**Temperature Lapse** or **Temperature Lapse Rate**) is the rate of change in temperature of the atmosphere with altitude (elevation).
- The lapse rate is considered **positive** when the temperature decreases with elevation, **zero** when the temperature is constant with elevation, and **negative** when the temperature increases with elevation **(temperature inversion)**.
- Hence, the lapse rate of troposphere below tropopause is positive, the lapse rate of tropopause is zero, and the lapse rate of stratosphere is negative.
- The fall in temperature with altitude is primarily due to the following reason:
  - ✓ Atmosphere is mostly transparent to in the incoming shortwave radiation but actively absorbs the outgoing terrestrial (longwave) radiation.
  - ✓ Greenhouse house gases like CO_2, water vapor, are the primary absorbers of the terrestrial radiation and their concentration is highest at the earth's surface and goes on decreasing with altitude. Hence, temperature falls with altitude.
- The lapse rate of **non-rising air (environmental lapse rate)** is highly variable, being affected by **radiation, convection, condensation and concentration of greenhouse gases**.
- It averages about **6-6.5 °C per kilometre (1 °C for every 153-165 metres)** in the lower atmosphere (troposphere).

Adiabatic Lapse Rate (ALR)

- Lapse rate is the rate of fall in temperature of atmosphere with elevation.
- Adiabatic Lapse Rate is the rate of fall in temperature of a **rising or a falling** air parcel adiabatically.
- Adiabatic change refers to the **change in temperature with pressure**.
- Adiabatic Lapse rate is governed by **Gas law.**

Adiabatic or adiabatically: *Heat* ***doesn't*** *enter or leave the system. All temperature changes are internal.*
Gas law*: According to gas law Pressure 'P' is directly proportional to Temperature 'T' when Volume 'V' is a constant.*

Relation between pressure, temperature and volume

Example 1: A balloon

- When we blow air into a balloon, pressure increases but temperature doesn't increase due to proportionate increase in volume (here V is not constant).
- When excess air is blown, balloon bursts as it cannot withstand the pressure.

Example 2: Vehicle tube

- In a vehicle tube, volume remains constant. When air is blown, pressure increases and hence the temperature.
- We are usually advised not to have full-blown tubes because when vehicle travels on a road, the friction between the tire and the road increases the temperature of the air in the tube.
- As temperature is directly proportional to pressure, increase in temperature leads to increase in pressure and at certain pressure threshold, the tire bursts.

The above examples explain the relation between Pressure, Temperature and Volume.
But the processes are **non-adiabatic** as there is (will be) heat exchange between the system and the external environment.

Adiabatic Process: Temperature changes in a parcel of rising or falling air

- An air bubble rises in water whereas stone sinks. This is obvious. The stone is denser (heavier than water), and it sinks whereas the air bubble is less dense (lighter than water) and it rises.

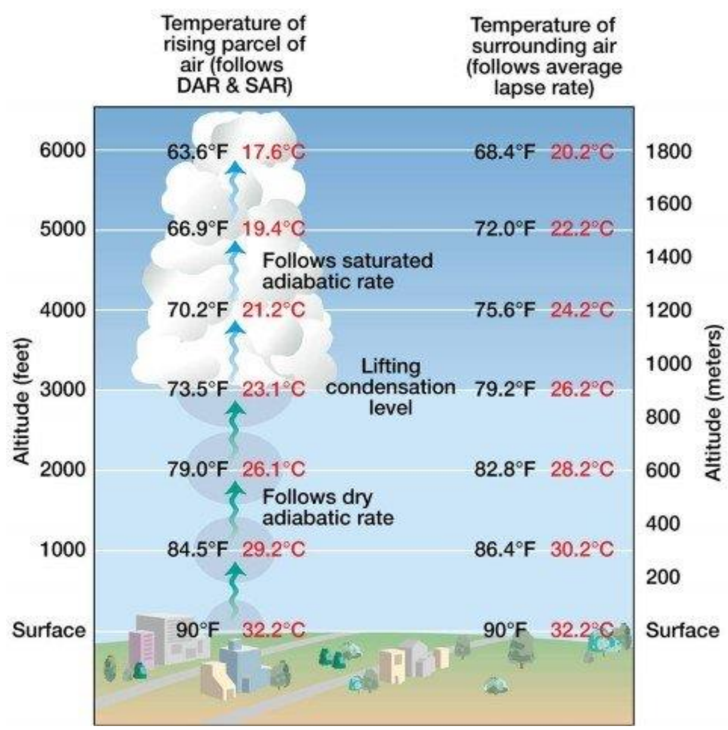
- Similarly, a parcel of air rises when it is less dense than the surrounding environment, and it falls when its density becomes greater than the surrounding environment.
- When an air parcel is subjected to differential heating compared to the surrounding air, it becomes lighter (less dense) or heavier (denser) depending on whether the air parcel is heated or cooled.

A parcel of rising or falling air

- When an air parcel receives more heat than the surrounding air, its temperature increases leading to an increase in volume (increase in volume implies the air parcel is getting less dense).
- The air parcel becomes lighter than the surrounding air, and it starts to rise. This process is **non-adiabatic** (there is heat exchange between the air parcel and the external environment).
- But when the air parcel starts to rise, the ambient pressure on it starts to fall (the atmospheric pressure decreases with height, so the pressure on the air parcel decreases with height).
- With the fall in ambient pressure, the volume of the air parcel increases and the hence the temperature of the air parcel falls (gas law).
- This is an **adiabatic** process as there is no heat exchange between the air parcel and the external environment. Temperature changes are only due to change in pressure or volume or both.
- This fall in temperature with the rising of the air parcel is called **adiabatic temperature lapse.**
- And the rate at which it happens is called **adiabatic lapse rate** (this is **positive** adiabatic lapse rate as the temperature is falling).
- The fall in temperature aids condensation of water vapour. Condensation of water vapour releases **latent heat of condensation** in the process.
- The latent heat of condensation is the **major driving force behind tropical cyclones, convectional rain.**
- Rising of a parcel of air (and associated positive adiabatic lapse rate) is the first step in the formation of thunderstorms, tornadoes and cyclones.

A parcel of falling air

- When an air parcel is in the upper levels, it gets cooled due to lower temperatures (because of lapse Rate).
- Its volume falls, and its density increases. When it becomes denser than the surroundings, it starts to fall.
- This also happens when an air parcel is in contact with cooler surfaces like mountain slopes.
- The beginning of fall is a non-adiabatic process as there is an exchange of heat between the air parcel and the surrounding environment.
- When an air parcel is falling, the atmospheric pressure acting on it will increase, and its internal temperature will increase adiabatically (this is negative adiabatic lapse rate as the temperature is rising).



Adiabatic Lapse Rate and Lapse Rate

- ***Lapse Rate*** ➔ *change in temperature with height.*
- ***Adiabatic Lapse Rate*** ➔ *change in temperature of a rising parcel of air without either losing heat to the external environment or gaining heat from the external environment.*
- ***Rising parcel of air*** ➔ *On ascent, the air expands as pressure decreases. This expansion reduces the temperature and aids condensation of water vapour. Condensation of water vapour releases the* ***latent heat of condensation*** *in the process.*

- ***Falling parcel of air*** ➔ *On descent through atmosphere, the lower layers are compressed under atmospheric pressure. As a result, the temperature increases.*
- ***Katabatic Wind*** ➔ *a hot dry wind that blows down a mountain slope. It is an example for a falling parcel of air in which the temperature changes happening adiabatically.*

Dry Adiabatic Lapse rate (DALR)

- The Dry Adiabatic Lapse Rate (DALR) is the rate of fall in temperature with altitude for a parcel of **dry or unsaturated air** (air with less moisture) rising under adiabatic conditions.
- Unsaturated air has less than 100% relative humidity.

Saturated air ➔ *The air cannot hold any more moisture. Its stomach is full.*
Unsaturated air ➔ *Its stomach is not full. It can accommodate some more moisture.*

- When a rising air parcel has little moisture (below normal), condensation during upliftment is low, the latent heat of condensation released is low (less additional heat from inside).
- As a result, the fall in temperature with height is greater compared to the adiabatic lapse rate of a normal parcel of air.
- The dry adiabatic lapse rate for the Earth's atmosphere is around **9.8 °C per kilometre**.
- Dry Adiabatic Lapse rate is mainly associated with **stable conditions (because it has less moisture).**

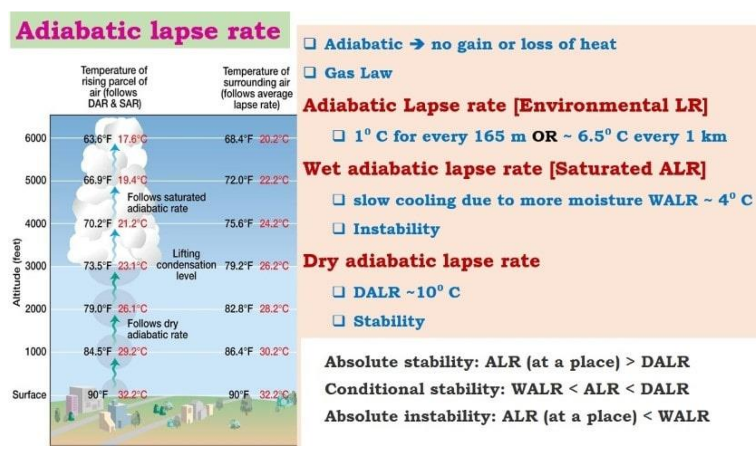
Wet Adiabatic Lapse Rate (WALR)

- When an air parcel that is saturated (stomach full) with water vapour rises, some of the vapour will condense and release latent heat (additional heat from inside).
- This process causes the parcel to cool more slowly than it would if it were not saturated.
- The moist adiabatic lapse rate varies considerably because the amount of water vapour in the air is highly variable.
- The greater the amount of vapour, the smaller the adiabatic lapse rate (because the condensation process keeps on adding more latent heat of condensation). On an average, it is taken as **4 °C per kilometre**.
- Wet Adiabatic Lapse rate is mainly associated with **unstable conditions (because it has more moisture).**
- As an air parcel rises and cools, it may eventually lose its moisture through condensation; its lapse rate then increases and approaches the dry adiabatic value.

Significance in meteorology (weather forecasting)

- The difference between the normal lapse rate in the atmosphere and the dry and moist adiabatic lapse rates determines the vertical stability of the atmosphere.
- For this reason, the lapse rate is of prime importance to meteorologists in forecasting certain types of cloud formations, the incidence of thunderstorms, and the intensity of atmospheric turbulence.

Weather conditions at different adiabatic lapse rates



Weather conditions at different adiabatic lapse rates

- **LR = 6 °C/km**
- **DALR ➔ ALR > 6 °C/km**
- **WALR ➔ ALR < 6 °C/km**

- ***Absolute stability: ALR (at a place) > DALR ➔ Little moisture in the air parcel (it won't rain)***
- ***Conditional stability: WALR < ALR < DALR ➔ Normal moisture conditions (it may or may not rain)***
- ***Absolute instability: ALR (at a place) < WALR ➔ Excess moisture in the air parcel (it will rain)***

Absolute stability: ALR (at a place) > DALR

- The above condition means that there is little moisture in air.
- When there is little moisture, condensation of water vapour is low, so latent of condensation released will be low, and the rising parcel of air gets cold quickly, and it falls to the ground once it becomes denser.
- So, there will be no cloud formation, and hence there will be no rain (thunderstorms).
- This simply means that the condition is stable.

Conditional stability: WALR < ALR < DALR

- The above condition means that there is enough moisture in air and there are chances of thunderstorms.
- When there is considerable moisture in the air parcel, condensation of water vapour will be reasonably high, so latent of condensation released will be adequate to drive a thunderstorm.
- The occurrence of thunderstorm depends on external factors.
- So, the weather will be associated with conditional stability (it may rain, or it may not rain)

Absolute instability: ALR (at a place) < WALR

- The above condition means that there is more moisture in air and there will be thunderstorms.
- When there is unusually high moisture in the air parcel, condensation of water vapour will be very high, so latent of condensation released will be great enough to drive a violent thunderstorm.
- So, the weather will be associated with absolute instability.

Temperature Inversion

UPSC mains 2013: What do you understand by phenomenon of "temperature inversion" in meteorology? How does it affect weather and habitants of the place?

- **Under normal conditions, temperature usually decreases with altitude (positive lapse rate)**.
- Temperature inversion is a reversal of the normal behaviour of temperature in the troposphere, in which a layer of cool air at the surface is overlain by a layer of warmer air (temperature increases with altitude — negative lapse rate).
- In other words, the vertical temperature gets inverted during temperature inversion.

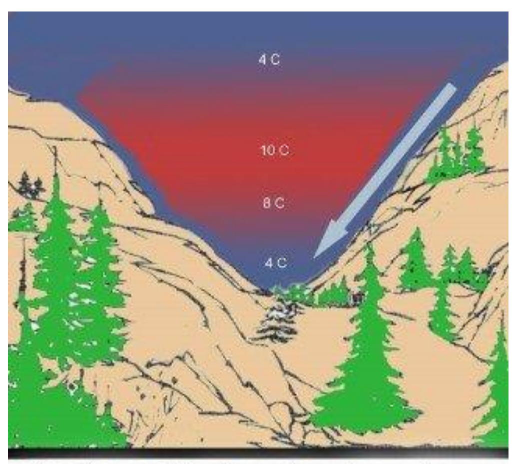
Temperature Inversion

Ideal Conditions for Temperature Inversion

1. **Long nights**, so that the outgoing radiation is greater than the incoming radiation.
2. **Clear skies**, which allow unobstructed escape of radiation.
3. **Calm and stable air**, so that there is no vertical mixing at lower levels.

Types of Temperature Inversion

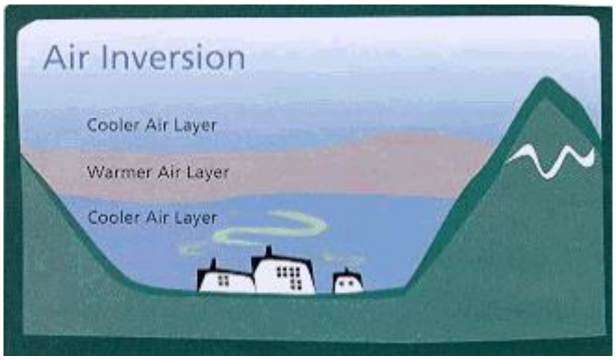
Temperature Inversion in Intermontane Valley (Air Drainage Type of Inversion)



Zone of warm nighttime temperatures above a valley temperature inversion. (From Schroeder and Buck, 1970)

- Sometimes, the temperature **along a sloping surface** increases instead of decreasing with elevation.

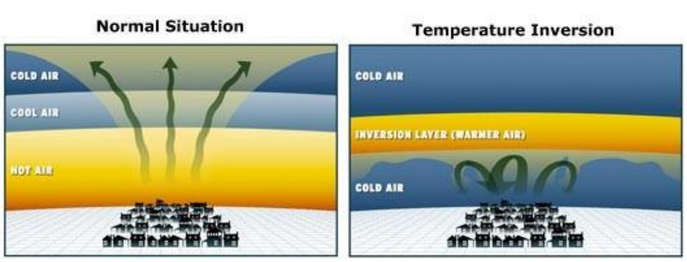
- Here, the top part of the sloping surface radiates heat back to space rapidly and cools the surrounding air making it denser.
- The cold air sinks towards the bottom along the slope and settles as a zone of low temperature at the bottom while the upper layers are relatively warmer.
- This kind of temperature inversion is very strong in the middle and higher latitudes and regions with high mountains or deep valleys.



Temperature Inversion in Intermontane Valley (Air Drainage Type of Inversion)

Ground Inversion (Surface Temperature Inversion)

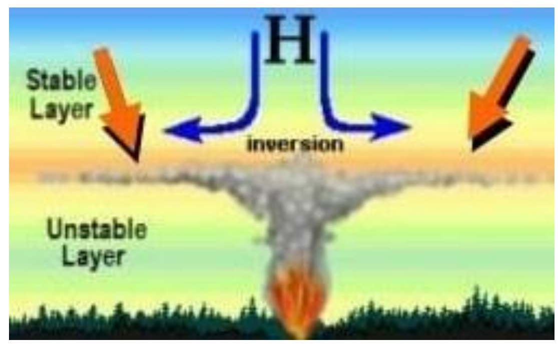
- This type of inversion occurs when air in contact with a colder surface becomes cooler than the overlying atmosphere.
- This occurs most often on clear nights when the ground cools off rapidly by radiation.
- If the temperature of surface air drops below its dew point, **fog** may result.
- This kind of temperature inversion is very common in the **higher latitudes**.
- In the lower and middle latitudes, this kind of inversion gets destroyed easily during daytime.



Ground Inversion (Surface Temperature Inversion)

Subsidence Inversion (Upper Surface Temperature Inversion)

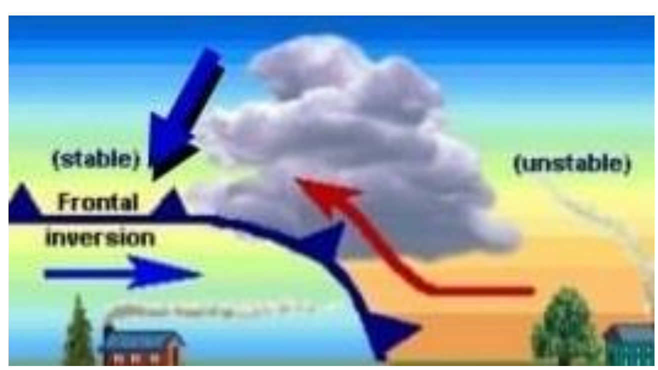
- A subsidence inversion develops when a widespread layer of air descends.
- As it descends, the ambient atmospheric pressure increases and the layer is compressed and heated.
- If the air mass sinks low enough, it forms a warm intermediate layer which is at a higher temperature compare to the layers below, producing a temperature inversion.
- Subsidence inversions are common over areas located under large **high-pressure centres**.
- Such conditions occur in the northern continents in winter and over the subtropical oceans.
- This temperature inversion is also called upper surface temperature inversion because it takes place in the upper parts of the atmosphere.



Subsidence Inversion (Upper Surface Temperature Inversion)

Frontal Inversion (Advectional type of Temperature Inversion)

- A frontal inversion occurs when a cold air mass undercuts a warm air mass and lifts it aloft.
- This kind of inversion has considerable slope, whereas other inversions are nearly horizontal.
- Also, humidity may be high, and clouds may be present immediately above it.
- This type of inversion is **unstable** and is **destroyed as the weather changes**.



Frontal Inversion (Advectional type of Temperature Inversion)

Effects of Temperature Inversion

- **Convection is inhibited**: An inversion acts as a cap on the upward movement of air from the layers below.
- Convection is limited to levels below the inversion, and the rainfall is below normal.
- In regions where a pronounced low-level inversion is present, **convective clouds cannot grow high enough** to produce rain.
- **Pollution is exacerbated**: diffusion of dust, smoke, and other pollutants is limited due to stable conditions.
- Visibility may be greatly reduced below the inversion due to the accumulation of dust and smoke particles.
- Because air near the base of an inversion tends to be cool, **fog** is frequently present there. Fog lowers visibility affecting vegetation and human settlements.
- Inversions also affect diurnal variations in temperature. Diurnal variations tend to be very **small**.

Effect on intermontane valley regions

- The temperature of the air at the valley bottom can go below freezing whereas the air at higher altitude remains comparatively warm.
- The trees along the lower slopes are bitten by frost, whereas those at higher levels are free from it.
- Houses and farms in intermontane valleys are usually situated along the upper slopes, avoiding the cold and foggy valley bottoms.
- For instance, **coffee growers of Brazil and apple growers and hoteliers of mountain states of Himalayas** in India avoid lower slopes.
- Air pollutants such as dust particles and smoke do not disperse in the valley bottoms.

5. Pressure Systems and Wind Systems

5.1 Atmospheric pressure

- The weight of a column of air contained in a unit area from the mean sea level to the top of the atmosphere is called the atmospheric pressure.
- The atmospheric pressure at sea level is **1034 gm per square centimetre**.
- Atmosphere (atm) is an internationally recognised unit for measuring atmospheric pressure at a place.
- The units used by meteorologists are **millibars (mb)** and **Pascal (Pa)**.
- One millibar is equal to the force of one gram on a square centimetre.
- A pressure of 1000 millibars is equal to the weight of 1.053 kilograms per square centimetre.
- The normal pressure at sea level is taken to be about **1013.25 millibars** (equal to the weight of a column of mercury 75 cm high).

1 atm = 1013.25 millibars (mb) = 101325 pascals (Pa) = 101.325 kilopascals (kPa)

- Atmospheric pressure varies from place to place due to differences in topography, sun's insolation and related weather and climatic factors.

5.2 Atmospheric pressure cells

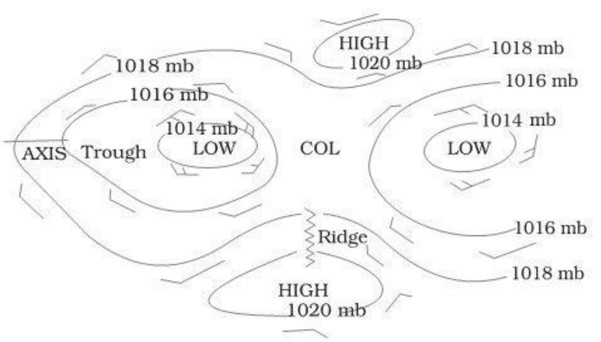
- When heated, the volume of a parcel of air increases (air expands) and hence the pressure within the air parcel falls creating a **low-pressure cell** (low-pressure centre).
- When cooled, the volume of the air parcel decreases (air is compressed) and hence the pressure within the air parcel increases creating a **high-pressure cell** (high-pressure centre).
- A combination of atmospheric pressure cells give rise to distinct pressure systems within the atmosphere.
- Distribution of continents and oceans have a marked influence over the distribution of pressure.
- In **winter, the continents are cooler than the oceans and tend to develop high-pressure centres, whereas, in summer, they are relatively warmer and develop low pressure**. It is just the reverse with the oceans.

5.3 Isobars

- **Isobars** are lines connecting places having equal pressure.
- The spacing of isobars expresses the rate of pressure changes and is referred to as **pressure gradient.**
- Close spacing of isobars indicates a steep or strong pressure gradient, while wide spacing suggests weak gradient.
- The pressure gradient may thus be defined as the decrease in pressure per unit distance in the direction in which the pressure decreases most rapidly.

Closed Isobars or Closed Pressure centres

- Low-pressure system (low-pressure cell) is enclosed by one or more isobars with the lowest pressure in the centre.
- High-pressure system (high-pressure cell) is also enclosed by one or more isobars with the highest pressure in the centre.



Closed Isobars

5.4 Vertical Variation of Pressure

- In the lower atmosphere, the pressure decreases rapidly with height.
- The decrease in pressure with altitude, however, is not constant because of the factors that control air density (temperature and amount of water vapour) are highly variable.
- Since air pressure is proportional to **density as well as temperature**, it follows that a change in either temperature or density will cause a corresponding change in the pressure.
- In general, the atmospheric pressure decreases on an average at the rate of about 34 millibars every 300 metres of height.
- The vertical pressure gradient force is much larger than that of the horizontal pressure gradient. However, it is generally balanced by a nearly equal but opposite **gravitational force**. Hence, we do not experience strong upward winds.

Standard Pressure and Temperature

Level	Pressure in mb	Temperature °C
Sea Level	1,013.25	15.2
1 km	898.76	8.7
5 km	540.48	-17. 3
10 km	265.00	-49.7

- At the height of Mt. Everest, the air pressure is about two-thirds less than what it is at the sea level.

5.5 Factors affecting Wind Movement

Wind: horizontal movement of air
Currents: vertical movement of air.

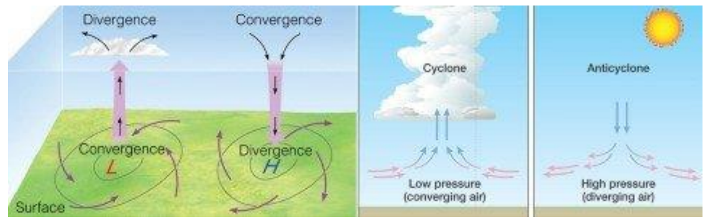
- The factors that affect wind movement are **pressure gradient force, buoyant force, friction, Coriolis force, gravitational force and centripetal acceleration**.

Pressure Gradient Force

- The pressure gradient (difference in pressure) between atmospheric pressure cells and the surroundings causes the movement of air from relatively high-pressure centres to relatively low-pressure centres.
- This movement (motion) of air is called as wind. Greater the pressure difference, greater is the wind speed.
- Small differences in pressure are highly significant in terms of the wind direction and velocity.
- The pressure gradient is strong where the isobars are close to each other and is weak where the isobars are apart.
- The wind direction follows the direction of pressure gradient, i.e. **perpendicular to the isobars.**

Buoyant force

- The atmospheric pressure cells also determine whether the air sinks or rises at a place.
- The surrounding atmosphere exerts buoyant force on low-pressure cells and hence the air within a low-pressure cell rises.
- On the other hand, the air within a high-pressure cell sinks as it is denser than the surrounding atmosphere.
- Rising air is associated with convergence and unstable weather (cyclonic conditions) whereas the sinking (subsiding) air is associated with divergence and stable conditions (anticyclonic conditions).
- A rising pressure indicates increasing stability, while a falling pressure indicates the weather becoming more unstable.
- The converging wind movement around a low is called **cyclonic circulation**.
- Around a high, the wind diverges, and the movement is called **anti-cyclonic circulation**.
- The wind circulation at the earth's surface is associated with an exactly opposite wind circulation above in the upper troposphere.
- Apart from convergence, convection currents, orographic uplift and uplift along fronts cause the rising of air, which is essential for the formation of clouds and precipitation.



Divergence and Convergence. Cyclonic and Anticyclonic conditions

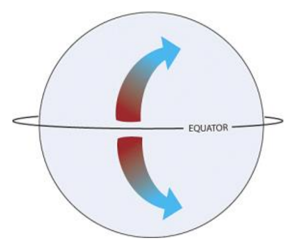
Pressure System	Pressure Condition	Pattern of Wind Direction	
		Northern Hemisphere	**Southern Hemisphere**
Cyclone	Low	Anticlockwise	Clockwise
Anticyclone	High	Clockwise	Anticlockwise

Frictional Force

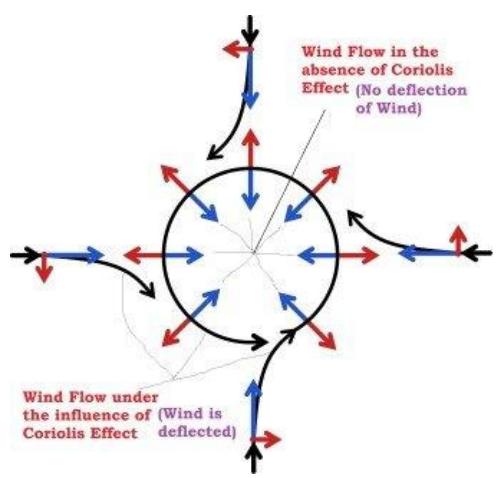
- The irregularities of the earth's surface resist the wind movement in the form of friction.
- The influence of friction generally extends up to an elevation of 1-3 km.
- Over the sea surface, the friction is minimal.
- At the surface, due to high friction, the wind direction makes high angles with isobars.

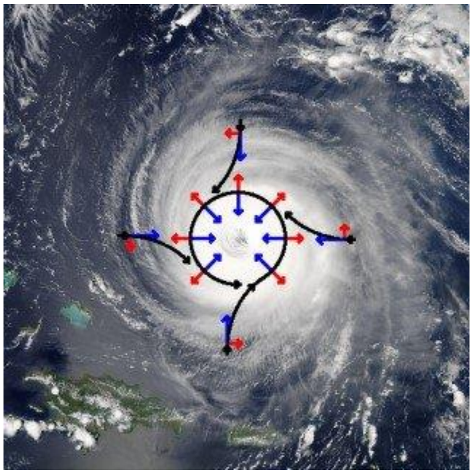
Coriolis force

- Due to the earth's rotation, winds do not cross the isobars at right angles as the pressure gradient force directs but get deflected from their original path.
- This deviation is the result of the earth's rotation and is called the Coriolis effect.
- Due to this effect, **winds in the northern hemisphere get deflected to the right** of their path and those in the **southern hemisphere to their left (Farrell's Law)**.
- This deflection force does not seem to exist until the air is set in motion and increases with **wind velocity** and an **increase in latitude**.



Farrell's Law: winds in the northern hemisphere get deflected to the right





Cyclones in the northern hemisphere rotate anti-clockwise due to Coriolis force

Coriolis effect

- The Coriolis effect is the **apparent deflection of objects** (such as aeroplanes, wind, missiles, sniper bullets and ocean currents) moving in a straight path **relative** to the earth's surface.

Causes of the Coriolis Effect

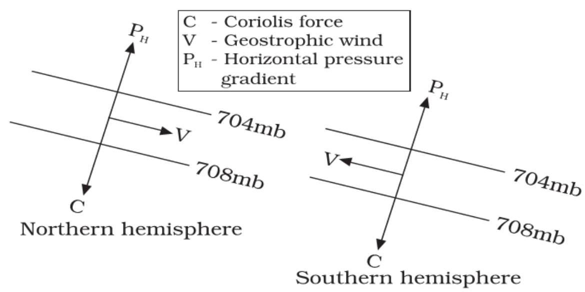
- As the earth spins in a counter-clockwise direction on its axis any object flying over a long distance appears to be deflected.
- This occurs because as something moves freely above the earth's surface, the earth is moving east under the object at a faster speed.
- As the object moves away for the equator the speed of the earth's rotation decreases and Coriolis effect (deflection) increases.
- A plane flying along the equator itself would be able to continue flying on the equator without any apparent deflection. A little to the north or south of the equator, the plane would be deflected.

Myth about Coriolis Effect: One of the biggest misconceptions associated with the Coriolis effect is that it causes the rotation of water down the drain of a sink or toilet. But such rotation is result of shape and orientation of the container. Coriolis effect is negligible to cause any deflection at such minor distances.

- The Coriolis effect is related to the motion of the object, the motion of the Earth, and the latitude.
- For this reason, the magnitude (Coriolis force) of the effect is given by $2\nu\omega \sin \phi$, in which ν is the velocity of the object, ω is the angular velocity of the Earth, and ϕ is the latitude.
- At the equator, $\phi = 0°$ and at the poles, $\phi = 90°$. Thus, the **Coriolis force is zero at the equator but increases with latitude, reaching a maximum at the poles**.

Geostrophic Wind

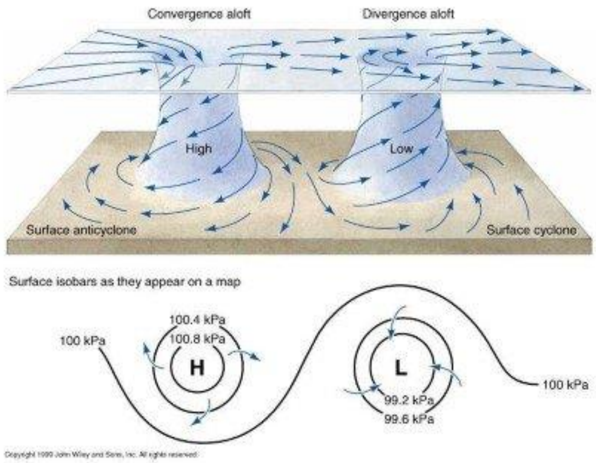
- The Coriolis force acting on a body increases with increase in its velocity.
- The winds in the upper atmosphere, 2-3 km above the surface, are free from frictional effect of the surface and are controlled by the pressure gradient and the Coriolis force.
- When isobars are straight, and when there is no friction, the **pressure gradient force is balanced by the Coriolis force, and the resultant wind blows parallel to the isobar** (deflection of the wind is maximum).
- This wind is known as the **geostrophic wind.**



Geostrophic wind vector parallel to the isobars

Centripetal Acceleration

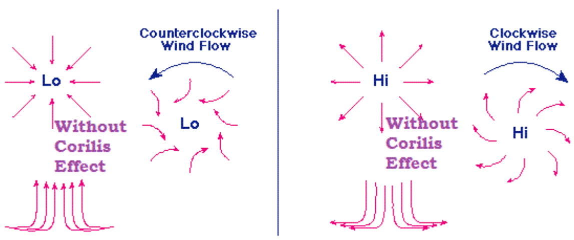
- It acts only on air that is flowing around centres of circulation.
- Centripetal acceleration creates a force directed at right angles to the wind movement and inwards towards the centres of rotation.
- This force produces a circular pattern of flow (vortex) around centres of high and low pressure.



Centripetal acceleration produces a circular flow

Why are there no tropical cyclones at the equator?

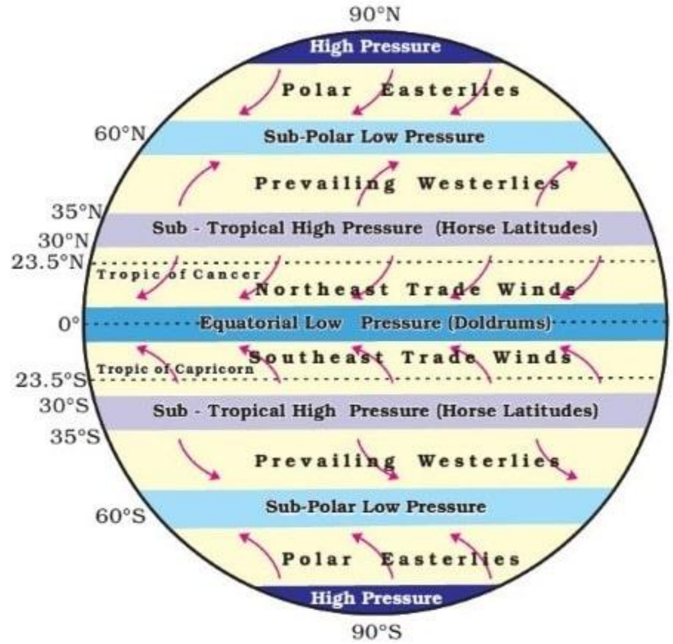
- The low pressure close to the equator gets filled instead of getting intensified, i.e., there is **no spiralling of air due to zero Coriolis effect**. The winds directly get uplifted vertically to form thunderstorms.



Vertical movement of air with and without Coriolis effect

5.6 Horizontal Distribution of Pressure

- Horizontal distribution of pressure is studied by drawing isobars at constant levels by eliminating the effect of altitude on pressure.
- There are seven distinctly identifiable zones of horizontal pressure systems or **pressure belts**.
  1. ***equatorial low,***
  2. ***the sub-tropical highs*** (along 30° N and 30° S),
  3. ***the sub-polar lows*** (along 60° N and 60° S), and
  4. ***the polar highs.***
- Except the equatorial low, all others form matching pairs in the northern and southern hemispheres.



Major Pressure Belts and Wind Systems

- The pressure belts are **not permanent** in nature. They oscillate with the apparent movement of the sun. In the northern hemisphere in winter they move southwards and in the summer northwards.

Equatorial Low-Pressure Belt or 'Doldrums'

- Th equatorial low-pressure belt lies between **10°N and 10°S latitudes**.
- The position of the belt varies with the apparent movement of the Sun.
- Its width may vary seasonally between 5°N and 5°S and 20°N and 20°S.
- This belt happens to be the **zone of convergence of trade winds (Intertropical Convergence Zone or ITCZ)** from two hemispheres from sub-tropical high-pressure belts.
- This belt is also called the **doldrums**, because of the **extremely calm air movements**.

Zone of convergence of trade winds - ITCZ

Formation

- As this region lies along the equator, it receives highest amount of insolation.
- Due to intense heating, the air gets heated up creating a low-pressure region (**thermally formed**).

Climate

- The air at the margins of the low-pressure region rises (convection) giving rise to clouds and turbulent weather along the margins.
- **Only vertical currents are found,** and the **surface winds** are almost absent since winds rise near the margin itself.
- Hence the region within the belt is characterised by **extremely low pressure** yet **calm weather conditions**.
- As the larger part of the low-pressure belt passes along the oceans, the winds obtain huge amount of moisture.
- Vertical winds carrying moisture from **cumulonimbus thunderstorm clouds** (convectional rainfall).
- The rising air loses all its moisture by the time it reaches the upper parts of the troposphere.
- In spite of high temperatures and moisture, **cyclones are not formed 5°N and 5°S of the equator because of negligible Coriolis force**.

Sub-Tropical High-Pressure Belt or Horse Latitudes

- The sub-tropical highs extend from near the tropics to about **35°N and S.**

Formation

- After complete loss of moisture, the air moving away from the equatorial low-pressure belt and the subtropical low-pressure belt in the upper troposphere is dry and cold.
- The **blocking effect of air at upper levels** because of the **Coriolis force forces the cold, dry air to** subside at 30°N and S.
- So, the high pressure (**dynamically formed**) along this belt is due to **subsidence of air coming from the equatorial region and the subpolar region**.

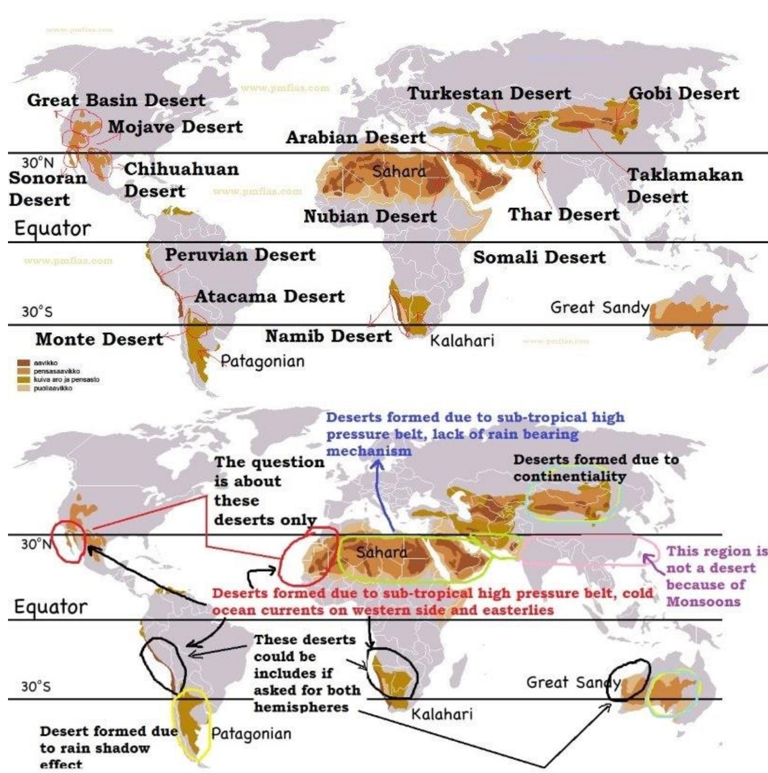
Climate

- The **subsiding air is warm (heated due to increases in ambient pressure) and dry, therefore, most of the deserts are present along this belt, in both hemispheres**.
- A calm condition **(anticyclonic)** with feeble winds is created in this high-pressure belt.
- The descending air currents feed the winds blowing towards adjoining low-pressure belts.
- This belt is **frequently invaded by tropical and extra-tropical disturbances**.

Horse Latitudes

- The corresponding latitudes of sub-tropical high-pressure belt are called **horse latitudes.**
- In early days, the sailing vessels with cargo of horses found it difficult to sail under calm conditions of this high-pressure belt.
- They used to throw horses into the sea when fodder ran out. Hence the name horse latitudes.

Mains 2013: Major hot deserts in northern hemisphere are located between 20-30 degree north and on the western side of the continents. Why?



Major Deserts of the World

Why between 20 – 30 degree?

- The subsiding air is warm and dry; therefore, most of the deserts are present along this belt, in both hemispheres.

Why on western side of the continents?

- We will get answer for this while studying ocean currents.

Sub-Polar Low-Pressure Belt

- The subpolar low-pressure belts are located between **45°N** and the **Arctic circle (66.5° N) and 45°S and the Antarctic circles (66.5° S) respectively.**
- Owning to low temperatures the subpolar low-pressure belts are not very well pronounced year long.

Formation

- These are **dynamically produced** due to
  1. **Coriolis Force** (produced by **rotation of the earth on its axis) and**.
  2. **Ascent of air as a result of convergence of westerlies (coming from the subtropical high-pressure regions) and polar easterlies (coming from the polar regions)**.
- Subpolar low-pressure belts are mainly encountered above **oceans.**

Seasonal behaviour

- During winter, because of a high contrast between land and sea, this belt is broken into two distinct low centres – one in the vicinity of the Aleutian Islands and the other between Iceland and Greenland.
- During summer, a lesser contrast results in a more developed and regular belt.
- The belt in the southern hemisphere is not as well differentiated.

Climate

- The area of contrast between cold and warm air masses produces **polar jet streams** which encircles the earth at 60 degrees latitudes and is focused in these low-pressure areas.

Polar High-Pressure Belt

- The polar highs are small in area and extend around the poles.
- They lie around poles between 80 – 90° N and S latitudes.

Formation

- The air from sub-polar low-pressure belts after saturation becomes dry. This dry air becomes cold while moving towards poles through upper troposphere.
- The cold air (heavy) on reaching poles subsides creating a high-pressure belt at the surface of earth.

Factors Controlling Pressure Systems

Thermal Factors

- When air is heated, it leads to low pressure, and when it is cooled, it leads to high pressure.
- Formation of **equatorial low and polar highs** are examples of thermal lows and thermal highs.

Dynamic Factors

- Apart from variations of temperature, the formation of pressure belts may be explained by dynamic factors arising out of **pressure gradient forces, apparent movement of sun and rotation of the earth (Coriolis force).**

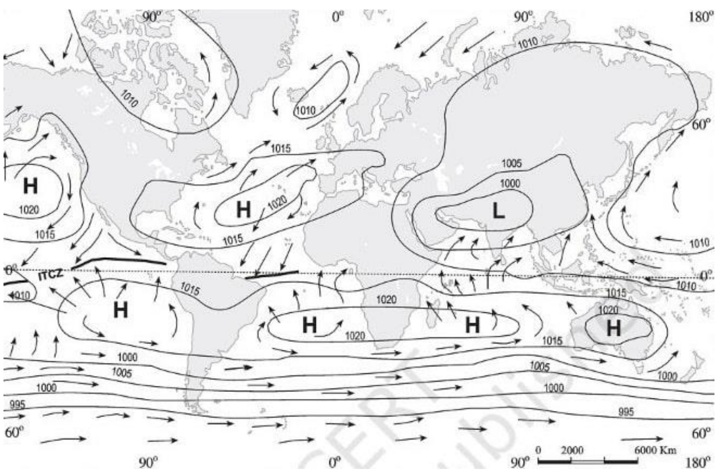
Example

- The **rate of deflection of wind increases with distance from the equator (Coriolis force).**
- The defection is higher in the upper troposphere due to less friction.
- As a result, by the time the poleward directed winds in the upper troposphere reach 25° latitude, they are deflected into a nearly west-to-east flow.

- Similarly, equatorward directed winds in the upper troposphere are deflected into a nearly east-to-west flow.
- This produces a **blocking effect** and the air piles up. This causes a general subsidence in the areas between the tropics and 35°N and S, and they develop into high-pressure belts.

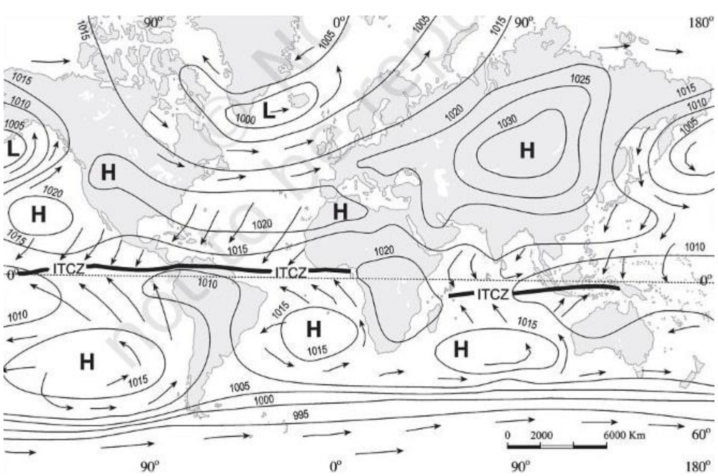
Pressure belts in July

- In the northern hemisphere, during summer, with the apparent northward shift of the sun, the thermal equator (belt of highest temperature) is located north of the geographical equator.
- The pressure belts shift slightly north of their annual average locations.



Pressure belts in July

Pressure belts in January

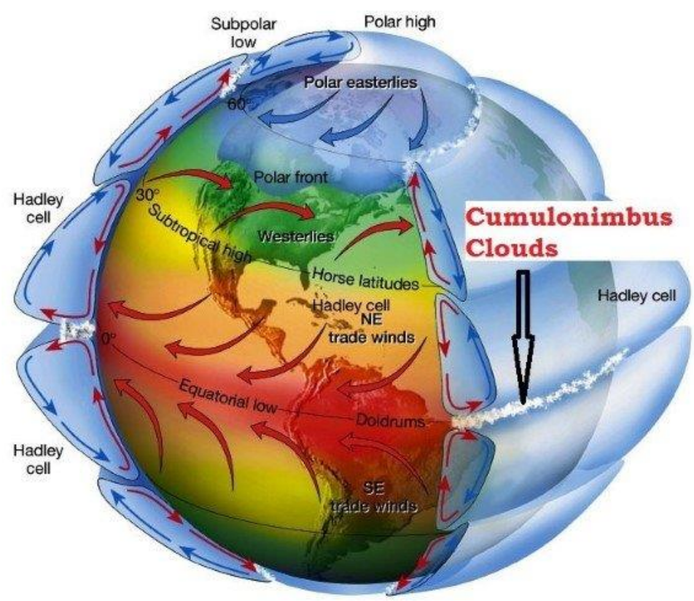


Pressure belts in January

- During winter, the conditions are reversed, and the pressure belts shift south of their mean locations.
- Opposite conditions prevail in the southern hemisphere. The amount of shift is, however, less in the southern hemisphere due to predominance of water.

5.7 Pressure systems and General Circulation

- The pattern of planetary winds depends on:
  - ✓ latitudinal variation of atmospheric heating;
  - ✓ emergence of pressure belts;
  - ✓ the migration of belts following apparent path of the sun;
  - ✓ the distribution of continents and oceans;
  - ✓ the rotation of earth.
- The pattern of the movement of the planetary winds (permanent winds) is called the **general circulation** of the atmosphere.
- The general circulation of the atmosphere also sets in motion the **ocean water circulation** which influences the earth's climate.



General Circulation

Hadley Cell

- The air at the equatorial low-pressure belt rises because of the convection currents.
- The air reaches the top of the troposphere up to an altitude of 14 km and moves towards the poles.

- This causes accumulation of air at about 30° N and S.
- Part of the accumulated air sinks to the ground and forms a subtropical high.
- At the surface a component of the diverging wind from the subtropical high flows towards the equator as the **easterlies (northeast to southwest)**.
- The easterlies from either side of the equator converge at the equatorial low pressure and the cycle repeats.
- Such circulations of wind is called a cell. Such a cell in the tropics is called **Hadley Cell.**

Ferrel Cell

- In the middle latitudes, the circulation is that of sinking cold air that comes from the poles and the rising warm air that blows from the subtropical high.
- At the surface, these winds are called westerlies, and the cell is known as the **Ferrel cell.**

Polar Cell

- At polar latitudes, the cold dense air subsides near the poles and blows towards middle latitudes as the polar easterlies. This cell is called the **polar cell.**

These three cells set the pattern for the general circulation of the atmosphere. The transfer of heat energy from lower latitudes to higher latitudes maintains the general circulation.

5.8 Classification of Winds

Permanent winds or Primary winds or Prevailing winds or Planetary Winds

- ❑ The **trade winds, westerlies and polar easterlies.**

Secondary or Periodic Winds

- ❑ Seasonal winds: These winds change their direction in different seasons. E.g. Monsoons in South Asia.
- ❑ Periodic winds: **Land and sea breeze, mountain and valley breeze** etc.

Local winds

- ❑ These blow only during a particular period of the day or year in a small area.
- ❑ Winds like **Loo, Mistral, Foehn, Bora** etc.

Primary winds or Prevailing Winds or Planetary Winds

- The winds blowing almost in the same direction throughout the year are called prevailing or permanent winds.
- These are also called as invariable or planetary winds because they involve larger areas of the globe.
- The two most significant winds for climate and human activities are **trade winds** and **westerly winds**.

The Trade Winds

- The trade winds are those blowing from the **sub-tropical high-pressure** areas towards the **equatorial low-pressure belt**.
- Therefore, these are confined to a region between **30°N and 30°S** throughout the earth's surface.
- They flow as the **north-eastern trades** in the northern hemisphere and the **south-eastern trades** in the southern hemisphere.
- Trade winds are **descending** and stable in areas of their origin (sub-tropical high-pressure belt), and as they reach the equator, they become **humid and warmer** after picking up moisture on their way.
- The trade winds from two hemispheres meet near the equator, and **due to convergence, they rise and cause heavy rainfall.**
- The eastern parts of the trade winds associated with the cool ocean currents are drier and more stable than the western parts of the ocean.

The Westerlies

- The westerlies are the winds blowing from the **sub-tropical high-pressure belts** towards the **sub-polar low-pressure belts**.
- They blow from **southwest to northeast** in the northern hemisphere and **northwest to southeast** in the southern hemisphere.

- The westerlies of the southern hemisphere are **stronger** and persistent due to the vast expanse of water, while those of the northern hemisphere are **irregular** because of uneven relief of vast land-masses.
- The westerlies are best developed between **40° and 65°S latitudes**. These latitudes are often called **Roaring Forties, Furious Fifties, and Shrieking Sixties** – dreaded terms for sailors.
- The poleward boundary of the westerlies is highly fluctuating.
- These winds produce **wet spells** and variability in weather.

The Polar easterlies

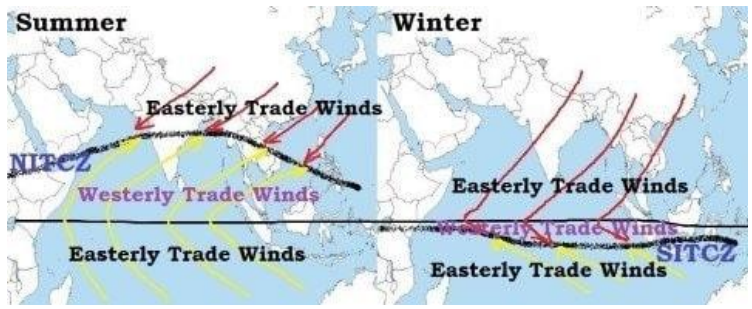
- The Polar easterlies are dry, cold prevailing winds blowing from **north-east to south-west direction** in Northern Hemisphere and **south-east to north-west** in Southern Hemisphere.
- They blow from the **high-pressure polar** areas of the **sub-polar lows**.

Secondary or Periodic Winds

- These winds **change their direction with change in season**.
- **Monsoons** are the best example of large-scale modification of the planetary wind system.
- Other examples of periodic winds include **land and sea breeze, mountain and valley breeze, cyclones and anticyclones,** and **air masses.**

Monsoons

- Monsoons were traditionally explained as **land and sea breezes on a large scale.**
- They were earlier considered as a **convectional circulation on a giant scale.**
- The monsoons are characterized by **seasonal reversal** of wind direction.
- During summer, the trade winds of southern hemisphere are pulled northwards by an apparent northward movement of the sun and by an intense low-pressure core in the north-west of the Indian subcontinent.
- While crossing the equator, these winds get deflected to their right under the effect of **Coriolis force.**
- These winds now approach the Asian landmass as south-west monsoons.
- During winter, these conditions are reversed, and a high-pressure core is created to the north of the Indian subcontinent.
- **Divergent winds** are produced by this **anticyclonic movement** which travels southwards towards the equator. This movement is enhanced by the apparent southward movement of the sun.
- These are north-east or winter monsoons which are responsible for some precipitation along the east coast of India.

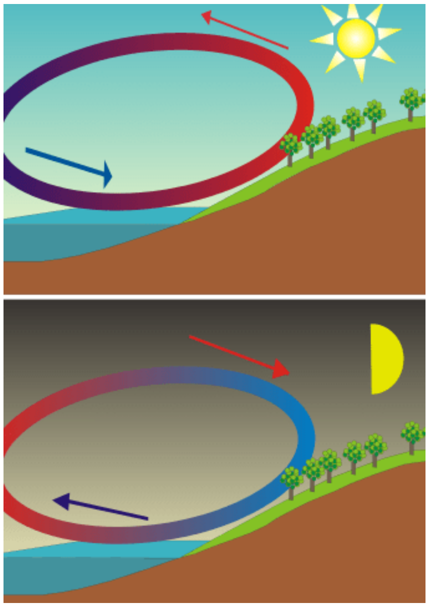


Indian Monsoon seasonal wind direction

- The monsoon winds flow over India, Pakistan, Bangladesh, Myanmar (Burma), Sri Lanka, the Arabian Sea, Bay of Bengal, south-eastern Asia, **northern Australia, China** and **Japan.**
- Outside India, in the eastern Asiatic countries, such as China and Japan, the **winter monsoon is stronger** than the summer monsoon.

Land Breeze and Sea Breeze

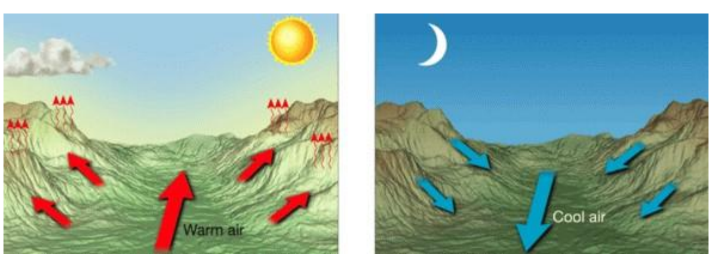
- During the day the land heats up faster and becomes warmer than the sea.
- Therefore, over the land, the air rises giving rise to a low-pressure area, whereas the sea is relatively cool and the pressure over sea is relatively high.
- Thus, pressure gradient from sea to land is created, and the wind blows from the sea to the land as the sea breeze.
- In the night the reversal of condition takes place. The land loses heat faster and is cooler than the sea.
- The pressure gradient is from the land to the sea and hence land breeze results.



Land Breeze and Sea Breeze (Ingwik, via Wikimedia Commons)

Valley Breeze and Mountain Breeze

- In mountainous regions, during the day the slopes get heated up, and air moves upslope.
- The air from the valley blows up the valley to fill the resulting gap. This wind is known as the valley breeze.
- During the night the slopes get cooled, and the dense air descends into the valley as the mountain wind.
- The cool air, of the high plateaus and ice fields draining into the valley, is called **katabatic wind (high-density air flowing down the slope).**



Valley Breeze and Mountain Breeze (Credits)

Tertiary or Local Winds

- Local differences of temperature and pressure produce local winds.
- Such winds are local in extent and are confined to the lowest levels of the troposphere. Some examples of local winds are discussed below.

Loo

- In the plains of northern India and Pakistan, sometimes a very hot and dry wind blows from the west in **May and June**, usually in the afternoons. It is known as **loo.**
- Its temperature invariably ranges between **45 °C and 50 °C**. It may cause **sunstroke** to people.

Foehn or Fohn

- Foehn is a **hot wind** of local importance in the **Alps**.
- It is a strong, gusty, dry and warm wind which develops on the leeward side of a mountain range.
- As the windward side takes away whatever moisture there is in the incoming wind in the form of orographic precipitation, the air that descends on the leeward side is dry and warm **(katabatic wind).**
- The temperature of the wind varies between 15°C and 20°C.
- The wind **helps animal grazing** by melting snow and **aids the ripening of grapes**.

Chinook

- Chinooks are foehn like winds in **USA and Canada** move down the west slopes of the **Rockies.**
- It is **beneficial to ranchers** east of the Rockies as it keeps the grasslands clear of snow during much of the winter.

Mistral

- Mistral is one of the local names given to such winds that blow from the Alps over France towards the Mediterranean Sea.
- It is channelled through the Rhone valley. It is **very cold and dry with a high speed**.
- It brings blizzards into southern France.

Sirocco

- Sirocco is a **Mediterranean wind** that comes from the **Sahara** and reaches hurricane speeds in North Africa and Southern Europe.
- It arises from a warm, dry, tropical air mass that is pulled northward by low-pressure cells mov-

ing eastward across the Mediterranean Sea, with the wind originating in the **Arabian or Sahara deserts.**

- The hotter, drier continental air mixes with the cooler, wetter air of the maritime cyclone, and the counter-clockwise circulation of the low propels the mixed air across the southern coasts of Europe.
- The Sirocco causes dusty dry conditions along the northern coast of Africa, storms in the Mediterranean Sea, and cool, wet weather in Europe.

Major Local Winds across the world

Cold Wind	Warm Wind
Pampero	***Foehn***
Gregale	***Chinook***
Bora	***Zonda***
Tramontane	***Loo***
Mistral	***Sirocco***

Loo	Hot	Harmful	Plains of northern India and Pakistan
Mistral	Cold	Harmful	Rhine valley – Southern France
Sirocco	Hot	Harmful	Mediterranean wind that comes from the Sahara
Fohn	Hot	Beneficial	Leeward side of Alps
Chinook	Hot	Beneficial	Leeward side of Rockies

Prelims Practise

1. If the surface air pressure is 1,000 mb, the air pressure at 1 km above the surface will be: (a) 700 mb (c) 900 mb (b) 1,100 mb (d) 1,300 mb
2. The Inter Tropical Convergence Zone normally occurs: (a) near the Equator (b) near the Tropic of Cancer (c) near the Tropic of Capricorn (d) near the Arctic Circle
3. The direction of wind around a low pressure in northern hemisphere is: (a) clockwise (c) anti-clockwise (b) perpendicular to isobars (d) parallel to isobars

Answers: 1) c. 900 mb; 2) a. Equator 3) c. anti-clockwise

30 words

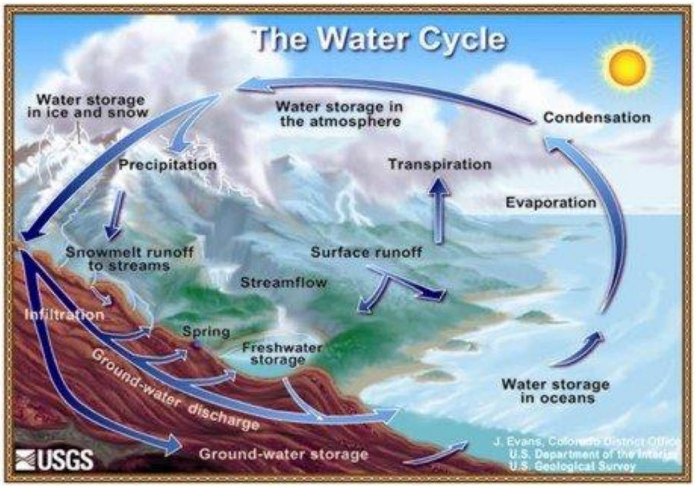
1. While the pressure gradient force is from north to south, i.e. from the subtropical high pressure to the equator in the northern hemisphere, why are the winds north easterlies in the tropics? (Hint: Coriolis force)
2. What are the geostrophic winds?
3. Explain the land and sea breezes.

150 words

- Discuss the factors affecting the speed and direction of wind.
- Draw a simplified diagram to show the general circulation of the atmosphere over the globe. What are the possible reasons for the formation of subtropical high pressure over 30° N and S latitudes?

6. Hydrological Cycle (Water Cycle)

- There is a continuous exchange of water between the atmosphere, the oceans and the continents through the processes of **evaporation, transpiration, condensation and precipitation.**
- The moisture in the atmosphere is derived from water bodies through **evaporation** and from plants through **transpiration (evapotranspiration)**.
- Evaporated water undergoes **condensation** and forms clouds.
- When saturation is reached, clouds give away water in the form of **precipitation.**
- Since the total amount of moisture in the entire system remains constant, a balance is required between evapotranspiration and precipitation. The hydrological cycle maintains this balance.



Water Cycle

6.1 Water Vapour in Atmosphere

- Water vapour in air varies from **zero to four per cent** by volume of the atmosphere (averaging around **2%** in the atmosphere).
- Amount of water vapour in atmosphere (humidity) is measured by, an instrument called **hygrometer.**

Significance of Atmospheric Moisture

- Water vapour absorbs **both incoming and outgoing** radiation and hence plays a crucial role in the **earth's heat budget**.
- The amount of water vapour present decides the **quantity of latent energy stored** up in the atmosphere for development of storms and cyclones.
- The atmospheric moisture affects the human body's rate of cooling by influencing the sensible temperature.

Humidity

- Water vapour present in the air is known as **humidity.**

Absolute Humidity

- The **actual** amount of the water vapour present in the atmosphere is known as the **absolute humidity.**
- It is the **weight** of water vapour per unit volume of air and is expressed in terms of grams per cubic metre.
- The absolute humidity **differs** from place to place on the surface of the earth.
- The ability of the air to hold water vapour depends entirely on its **temperature.**
- **Warm air can hold more moisture than cold air**.
- Absolute humidity is greater over oceans because of greater availability of water for evaporation.

Relative Humidity

- The percentage of moisture present in the atmosphere as compared to its full capacity at a given temperature is known as the **relative humidity**.

Relative Humidity = [Actual amount of water vapour in air (absolute humidity)/humidity at saturation point (the maximum water vapour air can hold at a given temperature)] X 100

- With the change of air temperature, the capacity to retain moisture increases or decreases and the relative humidity is also affected.
- The relative humidity determines the amount and rate of evaporation, and hence it is an important climatic factor.
- Air containing moisture to its full capacity at a given temperature is said to be **saturated**.
- At this temperature, the air cannot hold any additional amount of moisture. Thus, **relative humidity of the saturated air is 100%**.
- If the air has half the amount of moisture that it can carry, then it is unsaturated, and its relative humidity is only 50%.
- **Relative humidity is greater over the oceans and least over the continents** (absolute humidity is greater over oceans because of greater availability of water for evaporation).

Change in Relative humidity

Relative humidity can be changed in either of the two ways:

1. **By adding moisture through evaporation** (by increasing absolute humidity): **if moisture is added by evaporation, the relative humidity will increase** and vice versa.

2. **By changing temperature of air** (by changing the saturation point): **a decrease in temperature (hence, decrease in moisture-holding capacity/decrease in saturation point) will cause an increase in relative humidity** and vice versa.

- Consider 1 m^3 of air at a temperature 'T'.
- Let us assume that saturation occurs when 0.5 kg of water vapour is present in 1 m^3 of air.
- That is, relative humidity will be 100% if 1 m^3 of air contains 0.5 kg of water vapour at temperature T (saturation temperature or saturation point).
- Assume that 1 m^3 of air at a given time consists of 0.2 kg of water vapour at a temperature 'T'.

Here,
Absolute Humidity = 0.2 kg/m3 and
Relative Humidity = 40% (0.2/0.5 X 100)
Relative humidity is expressed as % whereas absolute humidity is expressed in absolute terms.

- Now to make the air saturated (100% relative humidity),
  1. we can add that additional 0.3 kg of water vapour by evaporation. OR
  2. we can decrease the temperature.
- If we decrease the temperature, the saturation point will come down.

Explanation:

- Let us assume that the temperature of 1 m^3 of air is decreased by 2 °C.
- The water holding capacity will fall due to decrease in temperature.
- Let us assume that the water holding capacity decreases by 0.1 kg/m^3 for 1 °C fall in temperature.
- So, for 2 °C fall in temperature, the fall in water holding capacity is 0.2 kg/m^3.
- Hence the new saturation point occurs at 0.3 kg/m^3 of air [0.5 kg/m^3 – 0.2 kg/m^3].
- So now we can saturate 1 m^3 of air by adding just 0.1 kg instead of 0.3 kg as in the earlier case.

[because, initially, we assumed that 1 m3 of air at a given time consists of 0.2 kg of water vapour at a temperature 'T'.]

Dew point

- The air containing moisture to its full capacity at a given temperature is said to be **saturated.**
- It means that the air at the given temperature is incapable of holding any additional amount of moisture.
- The temperature at which saturation occurs in a given sample of air is known as **dew point.**
- **Dew point occurs when Relative Humidity = 100%.**

Specific Humidity

- It is expressed as the **weight of water vapour per unit weight of air** (grams of water vapour per kilogram of air).
- Specific humidity is **not** affected (does not vary) by changes in pressure or temperature (because weight of water vapour in atmosphere is not significantly influenced by temperature).
- The only way of changing specific humidity is by adding (evaporation) or removing (precipitation) of moisture.

6.2 Evaporation

- Evaporation is a process by which water is transformed from **liquid to gaseous state**.
- The oceans contribute **84%** of the annual total and the continents **16%.**
- The highest annual evaporation occurs in the **sub-tropics of the western North Atlantic** and **North Pacific** because of the influence of the **Gulf Stream** and the **Kurishino Current**, and in the **trade wind zone of the southern oceans**.
- The land maximum occurs in equatorial region because of **high insolation** and luxuriant **vegetation.**

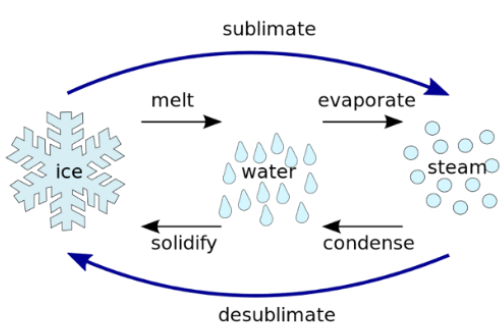
Factors Affecting Rate of Evaporation

- **Amount of water available.**
- **Area of evaporating surface.**
- **Temperature.**
- **Relative humidity:** air with low relative humidity has more space for moisture and hence evaporation increases.

- **Wind:** Movement of air replaces the saturated layer with the unsaturated layer. Hence, greater the wind speed, the greater is the evaporation.
- Whenever there is a combination of **high temperature**, very **low relative humidity** and **strong winds**, the rate of evaporation is exceptionally high. This leads to **dehydration of soil** to a depth of several inches.
- **Air Pressure:** Evaporation is also affected by the atmospheric pressure exerted on the evaporating surface. Lower pressure over open surface of the liquid results in a higher rate of evaporation.
- **Composition of water:** Evaporation is **inversely proportional to salinity of water.**
- Rate of evaporation is always greater over fresh water than over salt water. [Because of the reduction in the vapour pressure (ability of the water molecules to bounce off the surface) at the water surface due to salinity.]
- Under similar conditions, ocean water evaporates about 5% more slowly than fresh water.
- **More evaporation by plants:** Water from plants generally evaporates at a faster rate than from land.

6.3 Condensation

- The transformation of **water vapour into water** is called **condensation**.
- Condensation is caused by the **loss of heat** (**latent heat of condensation, opposite of latent heat of vaporisation).**
- When moist air is cooled, it may reach a level when its capacity to hold water vapour ceases (Saturation Point = 100% Relative Humidity = Dew Point reached).



Phase change

- Then, the excess water vapour condenses into liquid form. If it directly condenses into solid form, it is known as **sublimation**.
- In free air, condensation results from cooling around very small particles termed as **hygroscopic condensation nuclei**.
- Particles of **dust, smoke, pollen** and **salt** from the ocean are particularly good nuclei because they absorb water.
- Condensation also takes place when the moist air comes in contact with some colder object and it may also take place when the temperature is close to the **dew point.**
- Condensation, therefore, depends upon the **amount of cooling** and the **relative humidity** of the air.
- Condensation takes place:
  1. **when the temperature of the air is reduced to dew point** with its volume remaining constant (**adiabatically**),
  2. **when both the volume and the temperature are reduced** (brings down saturation temperature),
  3. **when moisture is added to the air through evaporation** (increase in relative humidity),
- After condensation, the water vapour or the moisture in the atmosphere takes one of the following forms — **dew, frost, fog and clouds**.
- Condensation takes place when the **dew point is lower than the freezing point as well as higher than the freezing point**.

Processes of Cooling for Producing Condensation

Adiabatic Temperature Changes

- When the air rises, it expands. Thus, heat available per unit volume is reduced and, therefore, the temperature is also reduced.
- Such a temperature change which does not involve any subtraction of heat, and cooling of air takes place only by ascent and expansion, is termed 'adiabatic change'.
- The vertical displacement of the air is the major cause of **adiabatic and katabatic** (cold, dense air flowing down a slope) temperature changes.

- Near the earth's surface, most processes of change are **non-adiabatic** because horizontal movements often produce mixing of air and modify its characteristics.

Non-Adiabatic Temperature Changes

- Non-adiabatic processes include cooling by **radiation, conduction or mixing** with colder air. The air may be cooled due to loss of heat by radiation.
- The non-adiabatic processes of cooling produce only dew, fog or frost. They are **incapable** of producing a substantial amount of precipitation.
- In case there is direct radiation from moist air, the cooling produces **fog or clouds**, subject to presence of hygroscopic nuclei in the air.
- Cooling by contact with a cold surface produces **dew, frost or fog** depending on other atmospheric conditions.

6.4 Forms of Condensation

- The forms of condensation can be classified on the basis of temperature at which the dew point is reached.
- Condensation can take place when the dew point is
  - ✓ **lower than the freezing point,**
  - ✓ **higher than the freezing point.**
- **White frost, snow, hailstones and some clouds (cirrus clouds)** are produced when the temperature is lower than the freezing point.
- **Dew, fog and clouds** result even when the temperature is higher than the freezing point.
- Forms of condensation may also be classified on the basis of their location, i.e. at or near the earth's surface and in free air.
- **Dew, white frost, fog and mist** come in the first category, whereas **clouds** are in the second category.

Dew

- When the moisture is deposited in the form of water droplets on cooler surfaces of solid objects (rather than nuclei in air above the surface) such as stones, grass blades and plant leaves, it is known as dew.
- The ideal conditions for its formation are **clear sky, calm air, high relative humidity**, and **cold and long nights**.

For the formation of dew, it is necessary that the **dew point is above the freezing point.**

Dew

White Frost

- Frost forms on cold surfaces when condensation takes place **below freezing point (0° C)**, i.e. the **dew point** is at or below the freezing point.
- The excess moisture is deposited in the form of **minute ice crystals** instead of water droplets.
- The ideal conditions for the formation of white frost are the same as those for the formation of dew, except that the **air temperature must be at or below the freezing point.**

White Frost

Fog

- When the temperature of an air mass containing a large quantity of water vapour falls all of a sudden (mostly due to temperature inversion), condensation takes place within itself on fine dust particles.
- So, the fog is a **cloud with its base at or very near to the ground**.

- Because of the **fog and mist**, the visibility becomes poor to zero.

Fog

- In urban and industrial centres smoke provides plenty of nuclei which help the formation of fog and mist. Such a condition when fog is mixed with smoke is described as **smog.**
- **Radiation fog** results from radiation, cooling of the ground and adjacent air. These fogs are **not very thick and** are usual in winters.
- Fogs formed by condensation of warm air when it moves horizontally over a cold surface, are known as **advectional fog**. These fogs are **thick and persistent**. Occurs over warm and cold water mixing zones in oceans.
- **Frontal or precipitation fog** is produced due to convergence of warm and cold air masses where warm air mass is pushed under by the heavier cold air mass.
- Precipitation in the warm air mass condenses to produce fog at the boundary of the two air masses. These are called **frontal or precipitation fog**.
- **In fog visibility is less than one kilometre**.

Mist

- The difference between the mist and fog is that mist contains more moisture than fog.
- In mist, each nucleus contains a thicker layer of moisture.
- Mists are frequent over mountains as the rising warm air up the slopes meet a cold surface.
- Water droplets also form mist, but with less merging or coalescing. This means mist is less dense and quicker to dissipate.
- Fogs are drier than mist, and they are prevalent where warm currents of air come in contact with cold currents.
- **In mist, visibility is more than one kilometre but less than two kilometres.**

Mist

Smog

- Smog = **smoke + fog (smoky fog)** caused by the burning of large amounts of **coal, vehicular emission** and **industrial fumes** (primary pollutants).
- Smog contains soot particulates like smoke, **sulphur dioxide, nitrogen dioxide** and other components.
- At least two distinct types of smog are recognised: **sulphurous smog** and **photochemical smog**.

Smog

Primary and secondary pollutants

- A primary pollutant is an air pollutant emitted directly from a source.
- A secondary pollutant is not directly emitted as such, but forms when other pollutants (primary pollutants) react in the atmosphere.
- Examples of a secondary pollutant include **ozone**, which is formed

- ✓ **when hydrocarbons (HC) and nitrogen oxides (NO_x) combine in the presence of sunlight;**
- ✓ **when NO combines with oxygen in the air; and**
- ✓ **due to acid rain (sulphur dioxide or nitrogen oxides react with rainwater to form acid rain).**

Sulphurous smog

- Sulphurous smog is also called **London smog** (first formed in London due to industrial revolution).
- Sulphurous smog results from a high concentration of **sulphur oxides** in the air and is caused by the use of **sulphur-bearing fossil fuels, particularly coal** (coal was the mains source of power in London during nineteenth century. The effects of coal burning were observed in early twentieth century).
- This type of smog is aggravated by **dampness** and a **high concentration of suspended particulate matter** in the air.

Sulphurous smog

Photochemical smog

- Photochemical smog is also known as **summer smog or Los Angeles smog.**
- Photochemical smog occurs most prominently in urban areas that have large numbers of automobiles (**nitrogen oxides** are the primary emissions).
- Photochemical smog forms when **nitrogen oxides** (primary pollutant) and **volatile organic compounds** (primary pollutants) react together in the presence of sunlight to form **ozone** (secondary pollutant).

NO + VOC (volatile organic compounds) ——→ NO_2 (Nitrogen Dioxide)

NO2 + UV (sunlight) ——→ NO + O (Nitrogen Oxide + atomic oxygen)

O + O_2 ——→ O_3 (Ozone)

NO_2 + VOC ——→ PAN (peroxyacetyl nitrate), etc.

Final result: ***NO + VOC + O_2 + UV ——→ O_3, PAN, and other oxidants***

Ozone in stratosphere it is beneficial, but near the earth's surface it results in global warming as it is a greenhouse gas

- The resulting smog causes a light brownish colouration of the atmosphere, reduced visibility, plant damage, irritation of the eyes, and respiratory distress.

Photochemical smog

Effects of Smog

- Smog is a combination of airborne particulate matter, like soot, and invisible toxic gases including **ozone (O3), carbon monoxide (CO), sulphur dioxide (SO2)**, which are **carcinogens (cancer-causing agents).**
- The **atmospheric pollution** levels of Los Angeles, Beijing, Delhi, Mexico City and other cities are increased by **inversion** that traps pollution close to the ground.
- It is usually highly toxic to humans and can cause severe sickness, shortened life or death.
- Temperature inversions are accentuated, and **precipitation is reduced**.
- Smog-related Haze lowers visibility.

Mains 2015: Mumbai, Delhi and Kolkata are the three megacities of the country, but the air pollution is much more serious problem in Delhi as compared to the other two. Why is this so? (200 words)

- In spite of similar urbanisation, air pollution is much more severe in Delhi compared to that in Mumbai and Kolkata. This is because of

Geography and Climate

- This the **most detrimental factor**. Delhi is a **continental city** while the other two are coastal. Land and See Breezes in Mumbai and Kolkata carry pollutants away from the city. There is no such advantage to Delhi as it is land locked.
- Also, the **duration of monsoon winds** is short in Delhi compared to the other two.
- Delhi faces severe cold wave in winter compared to the other two. Cold climate here creates temperature inversion which traps the pollutants, mainly smog, for a longer duration.

Polluting Industry in close vicinity in Delhi.

- Delhi and its immediate neighbourhood are the hotbed of polluting industries which are primarily coal-fuelled. Burning coal releases oxides of sulphur which forms sulphurous smog.
- This type of smog is more pronounced in Delhi than in the other two cities due to geography and climate.

Vehicular Emissions

- All the three cities contribute nearly equal vehicular emissions rich in CO_2 and NO_2. NO_2 results in photochemical smog. Here again, Delhi is worst hit due to its geography and climate.

Farm Straw Burning

- Delhi is at the heart of major agricultural region. Burning of farm straw in the surrounding regions also adds to Delhi's pollution levels.

226 words.

Haze

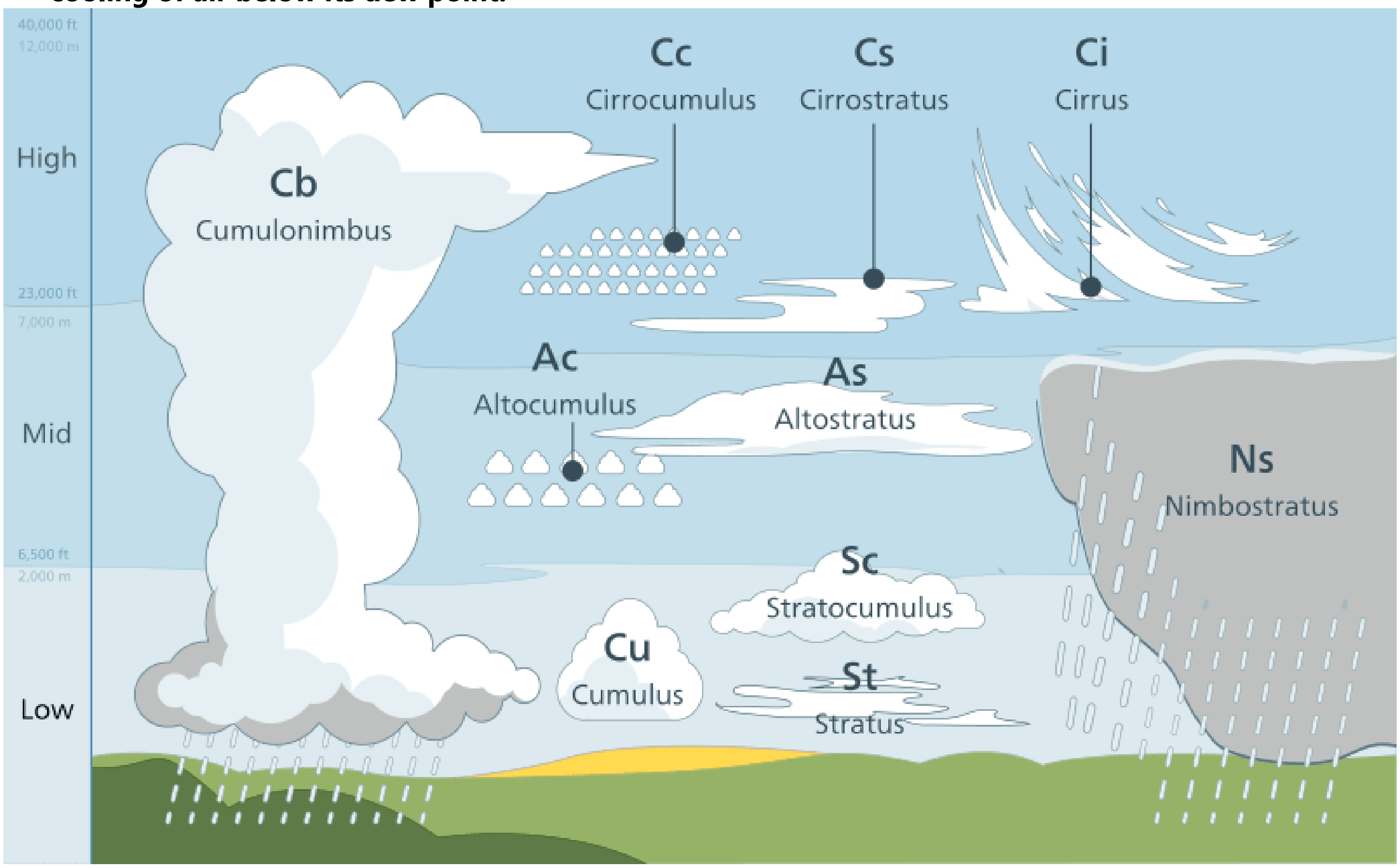
- In a haze dust, smoke and other dry particles obscure the clarity of the sky.
- There is no condensation in haze. Smog is similar to haze, but there is condensation in smog.
- Sources for haze particles include farming (ploughing in dry weather), traffic, industry, and wildfires.

Haze

Toxic Chemical	Sources	Environmental Effects
Nitrogen Oxides (NO and NO_2)	• combustion of oil, coal, gas • bacterial action in soil • forest fires, volcanic action • lightning	• decreased visibility due to yellowish colour of NO_2 • NO_2 can suppress plant growth
Volatile Organic Compounds (VOCs)	• evaporation of fuels • incomplete combustion of fossil fuels	• eye irritation • respiratory irritation • some are carcinogenic • decreased visibility due to blue-brown haze
Ozone (O_3)	• formed from photolysis of NO_2 • sometimes results from stratospheric ozone intrusions	• decreased crop yields • retards plant growth • **damages plastics** • breaks down rubber
Peroxyacetyl Nitrates (PAN)	• formed by the reaction of NO_2 with VOCs	• eye irritation • high toxicity to plants • **damaging to proteins**

Clouds

- Cloud is a mass of minute water droplets or tiny crystals of ice formed by the condensation of the water vapour in free air at considerable elevations.
- Clouds are caused mainly by the **adiabatic cooling of air below its dew point.**
- As the clouds are formed at some height over the surface of the earth, they take various shapes.
- According to their height, expanse, density and transparency or opaqueness clouds are grouped under four types: **(i) cirrus; (ii) cumulus; (iii) stratus; (iv) nimbus.**



Types of clouds (Valentin de Bruyn / Coton, from Wikimedia Commons)

Cirrus Clouds

- Cirrus clouds are formed at high altitudes (8,000-12,000m). They are made of ice crystals.
- They are thin and detached clouds having a feathery appearance. They are always white.

Cumulus Clouds

- Cumulus clouds look like cotton wool. They are generally formed at a height of 4,000-7,000 m.
- They exist in patches and can be seen scattered here and there. They have a flat base.

Stratus Clouds

- As their name implies, these are layered clouds covering large portions of the sky.
- These clouds are generally formed either due to loss of heat or the mixing of air masses with different temperatures.

Nimbus Clouds

- Nimbus clouds are black or dark grey. They form at middle levels or very near to the surface of the earth.
- These are extremely dense and opaque to the rays of the sun.
- Sometimes, the clouds are so low that they seem to touch the ground.
- Nimbus clouds are shapeless masses of thick vapour.

A combination of these four basic types can give rise to the following types of clouds:

- **High clouds – cirrus, cirrostratus, cirrocumulus;**
- **Middle clouds – altostratus and altocumulus;**
- **Low clouds – stratocumulus and nimbostratus (long duration rainfall cloud; rain bands in tropical cyclones) and**
- **Clouds with extensive vertical development – cumulus and cumulonimbus (thunderstorm cloud)**

Types of Clouds

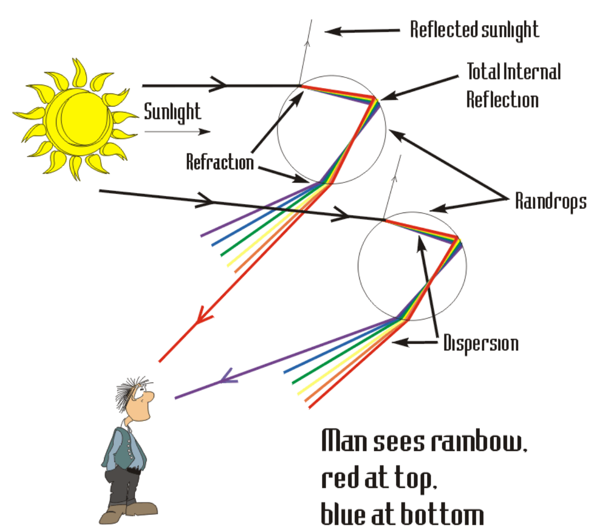
Sun's halo is produced by the refraction of light in: [2002]

a) water vapour in Stratus clouds
b) ice crystals in Cirro-Cumulus clouds
c) ice crystals in Cirrus clouds
d) dust particles in Stratus clouds

- Halos (22° halo) are caused by both **refraction and reflection of sunlight by ice crystals in cirrus clouds**.

Sun's halo

- Just like a rainbow (caused due to **reflection, refraction, dispersion and total internal reflection** of light by water droplets), halos around the sun (or moon — moon ring or winter halo) are personal.
- Everyone sees their particular halo, made by particular ice crystals, which are different from the ice crystals making the halo of the person standing next.



Formation of a rainbow (Credits: Rebecca McDowell)

Answer: b) ice crystals in Cirrus clouds

6.5 Precipitation

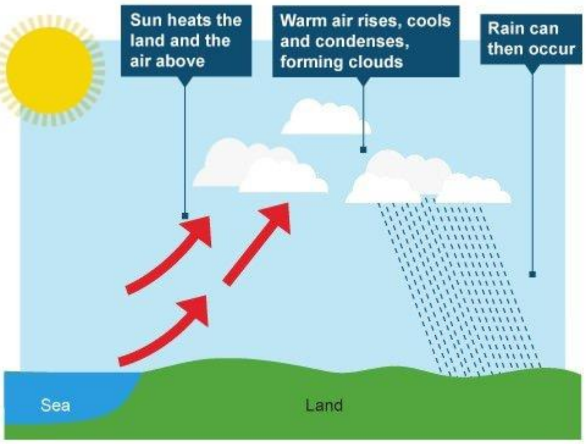
- Condensation of water vapour followed by release of moisture is known as precipitation.
- The process of continuous condensation in air helps the condensed particles to grow in size.
- When the resistance of the air fails to hold them against the force of gravity, they fall on to the earth's surface as different forms of precipitation. Precipitation may happen in liquid or solid form.
- Precipitation in the form of drops of water is called rainfall when the drop size is more than **0.5 mm**.
- It is called **Virage** when raindrops evaporate before reaching the earth while passing through dry air.
- **Drizzle** is light rainfall with drop size being less than 0.5 mm, and when evaporation occurs before reaching the ground, it is referred to as **mist.**
- When the temperature is lower than the 0° C, precipitation takes place in the form of fine flakes of snow and is called **snowfall**. Moisture is released in the form of hexagonal crystals.
- Besides rain and snow, other forms of precipitation are **sleet** and **hail**, though the latter are limited in occurrence and are sporadic in both time and space.
- **Sleet** is frozen raindrops and refrozen melted snow-water. When a layer of air with the temperature above freezing point overlies a subfreezing layer near the ground, precipitation takes place in the form of sleet.
- Raindrops, which leave the warmer air, encounter the colder air below. As a result, they solidify and reach the ground as small pellets of ice not bigger than the raindrops from which they are formed.
- Sometimes, drops of rain after being released by the clouds become solidified into small rounded solid pieces of ice and which reach the surface of the earth are called **hailstones**.
- These are formed by the rainwater passing through the colder layers. Hailstones have several **concentric** layers of ice one over the other.
- **Rainfall:** drop size more than 0.5 mm.
- **Virage:** raindrops evaporate before reaching the earth.
- **Drizzle:** light rainfall; drop size less than 0.5 mm.
- **Mist:** evaporation drizzle occurs before reaching the ground leading to foggy weather.
- **Snowfall:** fine flakes of snow fall when the temperature is less than 0° C.
- **Sleet:** frozen raindrops and refrozen melted snow; mixture of snow and rain or merely partially melted snow.
- **Hail:** precipitation in the form of hard rounded pellets (5 to 50 mm) is known as hail.

6.6 Types of Rainfall

- On the basis of origin, rainfall may be classified into three main types – the **convectional, orographic or relief** and the **cyclonic or frontal.**

Convectional Rainfall

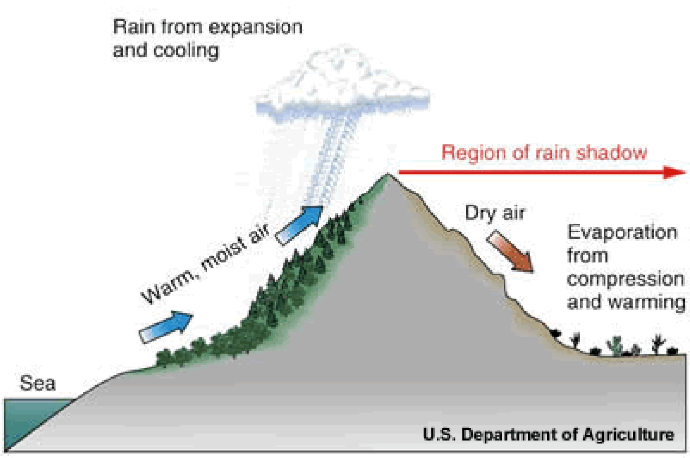
- The air on being heated, becomes light and rises in convection currents.
- As it rises, it expands and loses heat, and consequently, condensation takes place, and cumulous clouds are formed (when convection is rapid and intense cumulonimbus clouds are formed).
- This process releases **latent heat of condensation** which **further heats the air and forces the air to go further up**.
- Convectional precipitation is heavy but of **short duration**, **highly localised** and is associated with minimum amount of cloudiness.
- It occurs mainly during **summer** and is common over **equatorial doldrums** in the Congo basin, the Amazon basin and the islands of south-east Asia.



Convectional rainfall

Orographic Rainfall

- This type of precipitation occurs when warm, humid air strikes an orographic barrier (a mountain range).
- Because of the initial momentum, the air is forced to rise. As the moisture-laden air gains height, it expands (because of fall in ambient pressure) and the temperature falls (adiabatic).
- Condensation sets in, and soon saturation (dew point) is reached. The surplus moisture falls as orographic rainfall along the windward slopes.
- After giving rain on the windward side, the winds are relatively dry and cold. They reach the leeward slope and descend (katabatic wind), and their temperature rises due to increase in ambient pressure.

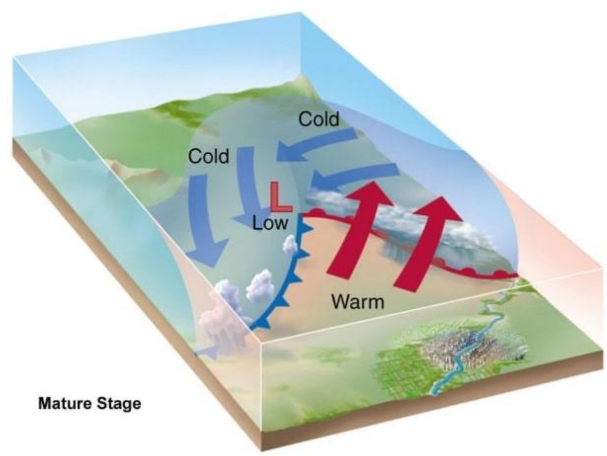


Orographic rainfall

- Their capacity to take in moisture increases (relative humidity decreases) and hence **the leeward slopes remain rainless and dry**.
- The area situated on the leeward side, which gets less rainfall is known as the **rain-shadow area** (some arid and semi-arid regions are a direct consequence of rain-shadow effect. Example: **Patagonian Desert in Argentina, Eastern slopes of Western Ghats, etc.**).
- The rainfall in rain shadow area is known as the **relief rain**. Example: Mahabaleshwar, situated on the windward side of Western Ghats, receives more than 600 cm of rainfall, whereas Pune, lying in the rain shadow area, receives only about 70 cm.

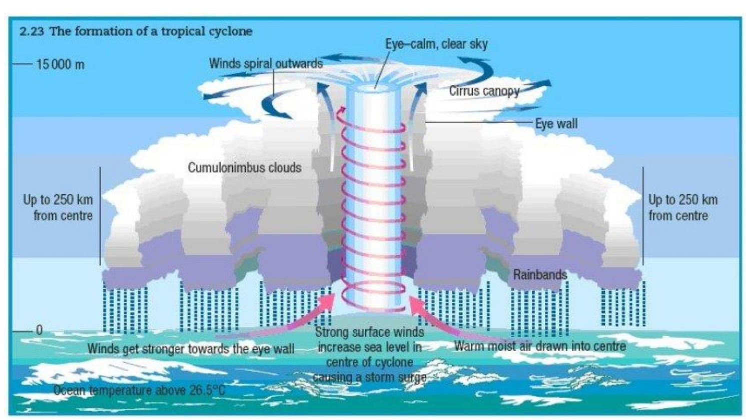
Frontal Rainfall

- When two air masses with different temperatures meet, turbulent conditions are produced.
- Along the front convection occurs and causes precipitation (we will study this in Fronts).
- For instance, in north-west Europe, cold continental air and warm oceanic air converge to produce **heavy rainfall** in adjacent areas.



Frontal Rainfall

Cyclonic Rain



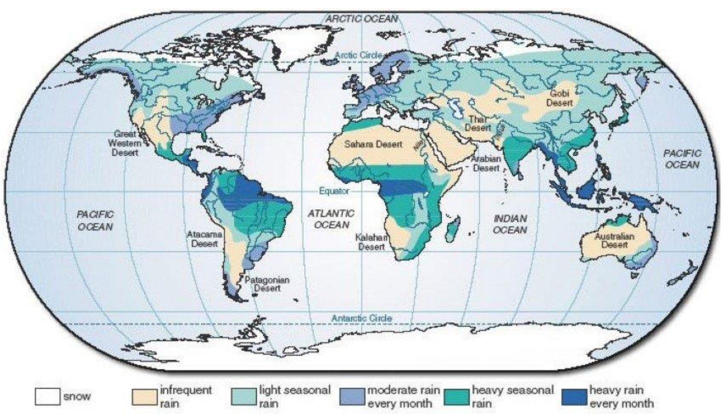
Cyclonic Rainfall in Tropical Cyclones

- Cyclonic Rainfall is **convectional rainfall on a large scale** (we will see this in detail later).
- The precipitation in a tropical cyclone is of convectional type while that in a temperate cyclone is because of frontal activity.

Monsoonal Rainfall

- This type of precipitation is characterized by **seasonal reversal of winds** which carry oceanic moisture (especially the south-west monsoon) with them and cause extensive rainfall in south and southeast Asia.

World Distribution of Rainfall



World Distribution of Rainfall

- Different places on the earth's surface receive different amounts of rainfall in a year and that too in different seasons. In general, as we proceed from the equator towards the poles, rainfall goes on decreasing steadily.
- The coastal areas of the world receive greater amounts of rainfall than the interior of the continents.
- The rainfall is more over the oceans than on the landmasses of the world because of being great sources of water.
- Between the latitudes 35° and 40° N and S of the equator, the rain is heavier on the eastern coasts (because of warm ocean currents) and goes on decreasing towards the west.
- But, between 45° and 65° N and S of equator, due to the **westerlies**, the rainfall is first received on the western margins of the continents, and it goes on decreasing towards the east.
- Wherever mountains run parallel to the coast, the rain is greater on the coastal plain, on the windward side and it decreases towards the leeward side. E.g. Rainfall along Western Ghats.
- On the basis of the total amount of annual precipitation, major precipitation regimes of the world are identified as follows.
- The equatorial belt, the windward slopes of the mountains along the western coasts in the cool temperate zone and the coastal areas of the monsoon land receive heavy rainfall of over 200 cm per annum.
- Interior continental areas receive moderate rainfall varying from 100-200 cm per annum.
- The coastal areas of the continents receive moderate amount of rainfall.
- The central parts of the tropical land and the eastern and interior parts of the temperate lands receive rainfall varying between 50-100 cm per annum.
- Areas lying in the **rain shadow zone** of the interior of the continents and high latitudes receive very low rainfall — less than 50 cm per annum.
- In some region's rainfall is distributed evenly throughout the year such as in the equatorial belt and in the western parts of cool temperate regions.
- In the other regions, the rainfall distribution is variable seasonally.

Prelims Practise

1. Which one of the following process is responsible for transforming liquid into vapour? (a) Condensation (b) Transpiration (c) Evaporation (d) Precipitation
2. The air that contains moisture to its full capacity: (a) Relative humidity (b) Specific humidity (c) Absolute humidity (d) Saturated air
3. Which one of the following is the highest cloud in the sky? (a) Cirrus (b) Stratus (c) Nimbus (d) Cumulus

Answers: 1. c) Evaporation; 2. d) Saturated air 3. c) Cirrus

30 words

- Name the three types of precipitation.
- Explain relative humidity.
- Why does the amount of water vapour decrease rapidly with altitude? (Hint: Lapse rate → Condensation)
- Why is winter air dry compared to the summer air? (Hint: Low temperature aids condensation)
- How are clouds formed? Classify them

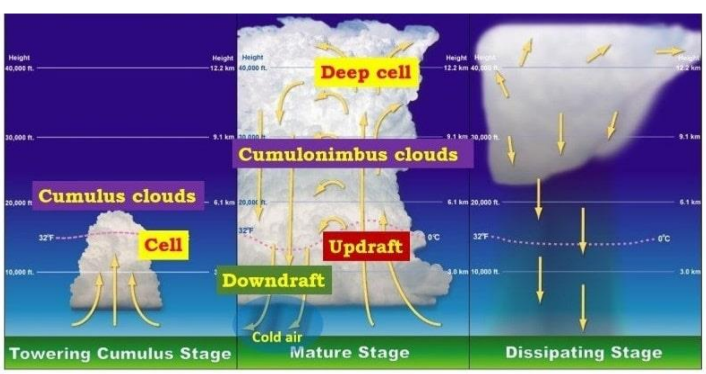
150 words

- Discuss the salient features of the world distribution of precipitation.
- What are forms of condensation? Describe the process of dew and frost formation.

7. Thunderstorm

- Thunderstorms and tornadoes are **severe local storms that involve rapid convection or upliftment of air**.
- They are of **short duration**, occurring over a **small area** but are **violent**.
- Thunderstorm is a storm with **thunder and lightning** and typically also **heavy rain or hail.**
- Thunderstorms **mostly occur on ground** where the temperature is high.
- Thunderstorms are less frequent on water bodies due to low temperature.
- Worldwide, there are an estimated 16 million thunderstorms each year, and at any given moment, there are roughly 2,000 thunderstorms in progress.

7.1 Formation of a thunderstorm



Formation of a Thunderstorm

Stage 1: Cumulus stage

- Ground is significantly heated due to solar insolation.
- A low pressure starts to establish due to intense upliftment of an air parcel (convention).
- Air from the surroundings start to rush in to fill the low pressure.
- Intense convection of moist hot air builds up a towering cumulonimbus cloud.

Stage 2: Mature stage

- Condensation releases **latent heat of condensation** making the air warmer.
- It becomes much lighter and is further uplifted.
- Intense updraft of rising warm air causes the cloud to grow bigger and rise to greater height.
- The space is filled by fresh moisture-laden air.
- Condensation occurs in this air, and the cycle is repeated **as long as the moisture is supplied**.
- Later, downdraft brings down to earth the cool air and rain.
- The incoming of thunderstorm is indicated by violent gust of wind. This wind is due to the intense downdraft.

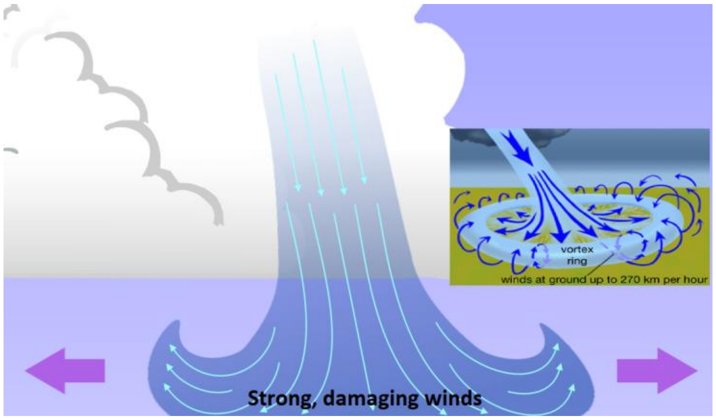
Motion of a thunderstorm

- Path of a thunderstorm is erratic. Motion is primarily due to **interactions of its updrafts and downdrafts.**
- The speed of isolated storms is typically about 20 km (12 miles) per hour, but some storms move much faster.
- In extreme circumstances, a supercell storm may move 65 to 80 km (about 40 to 50 miles) per hour.

Downbursts

- Downdrafts are referred to as macrobursts or microbursts.
- Macroburst is more than 4 km in diameter and can produce winds as high as 60 metres per second, or 215 km per hour.
- A microburst is smaller in dimension but produces winds as high as 75 metres per second, or 270 km per hour

- They are **seriously hazardous to aircraft**, especially during take-offs and landings.

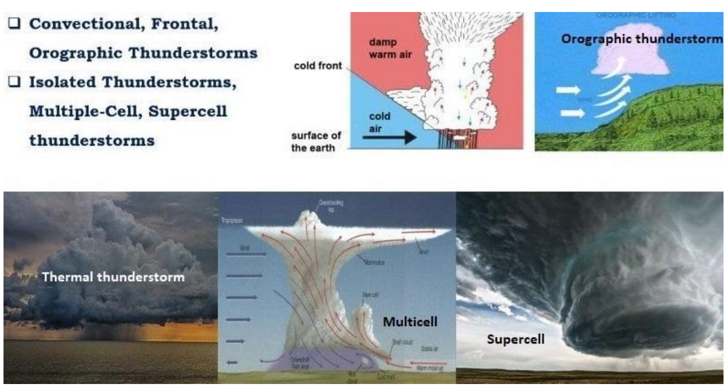


Downburst (Credits)

Stage 3: Dissipating stage

- When the clouds extend to heights where sub-zero temperature prevails, hails are formed, and they come down as hailstorm. Intense precipitation occurs.
- In a matter of few minutes, the storm dissipates, and clear weather starts to prevail.

7.2 Types of Thunderstorms



Types of Thunderstorms

- Convectional, Frontal, Orographic Thunderstorms.
- Isolated Thunderstorms, Multiple-Cell Thunderstorms, Supercell thunderstorms.

Thermal thunderstorm

- Caused due to intense heating of ground during summer (cumulonimbus cloud and convectional rain).

Orographic thunderstorm

- Forceful upliftment of warm moist air parcel when it passes over a mountain barrier creates cumulonimbus cloud causing heavy precipitation on the windward side.
- **Orographic cloudbursts are common in Jammu and Kashmir, Cherrapunji and Mawsynram.**

Frontal thunderstorm

- Thunderstorms occurring along cold fronts.

Single-cell thunderstorm (Isolated thunderstorm)

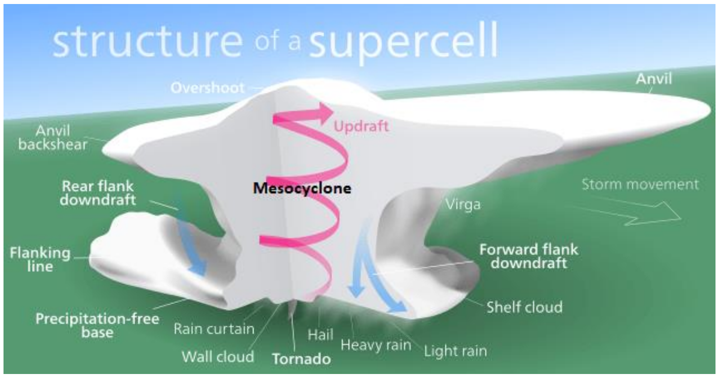
- Single-cell thunderstorms are small, brief, weak storms that grow and die within an hour or so. They are typically driven by heating on a summer afternoon.
- Single-cell storms may produce brief heavy rain and lightning.
- They are very common in India during summers, mostly April, May.
- In **Kerala,** they are called **Mango Showers** and in Karnataka **Blossom showers**.

A multi-cell thunderstorm

- A multi-cell storm is a thunderstorm in which new updrafts form along the leading edge of rain-cooled air (the gust front).
- Individual cells usually last 30 to 60 minutes, while the system as a whole may last for many hours.
- Multicell storms may produce hail, strong winds, brief tornadoes, and flooding.

A supercell thunderstorm

- A supercell is a long-lived (greater than 1 hour) and highly organised storm feeding off an updraft (a rising current of air) that is tilted and rotating.
- Most large and violent tornadoes come from supercells.



Supercell (Wikipedia)

Mesocyclone

- A mesocyclone is a rotating vortex of air within a supercell thunderstorm.
- Mesocyclones sometimes produce tornadoes.

7.3 Tornado

- Tornado is a small-diameter column of violently rotating air developed within a convective cloud and in contact with the ground.
- Tornados occur most often in association with thunderstorms during the spring and summer in the mid-latitudes of both the Northern and Southern Hemispheres.
- Tornadoes generally occur in **middle latitudes because of convergence of warm and cold air masses**.

Formation

- When warm, humid air meets a cold airmass, horizontally spinning winds are created.
- As the warm air rises, it begins rotating vertically forming a mesocyclone in the centre of the Cumulonimbus cloud. This is a supercell.
- The rotating warm air condenses into rain which in turn pulls the mesocyclone closer to the ground; then the tornado begins to form.


Composite of five shots of Tornadogenesis (Wiki)

- Heavy rains in front of the tornado cause downdrafts.
- These whirling atmospheric vortices can generate the strongest winds known on Earth: wind speeds in the range of 500 km (300 miles) per hour.
- They are often referred to as **twisters.**

Waterspout

- Waterspout is an intense columnar vortex (usually appearing as a funnel-shaped cloud) that occurs over a body of water.


Waterspout

- They are connected to a towering cumulonimbus cloud.
- They are weaker than most of its land counterparts, i.e. tornadoes.
- Most waterspouts do not suck up water; they are small and weak rotating columns of air over water.

Distribution of tornadoes

Distribution of tornadoes

- The temperate and tropical regions are the most prone to thunderstorms and tornadoes.
- Tornadoes have been reported on all continents except Antarctica.
- United States has the most violent tornadoes.

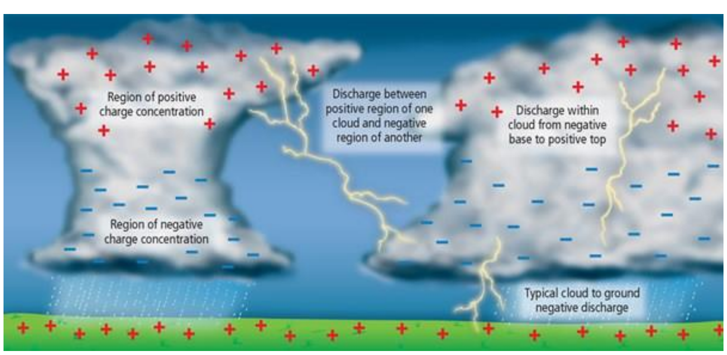
- Canada reports the second largest number of tornadoes.
- In the Indian sub-continent, **Bangladesh** is the most prone country to tornadoes.

7.4 Lightning and thunder

- Water vapour condenses into small ice crystals when it moves upward in the cumulonimbus cloud.
- The ice crystals continue to move up until they gather enough mass that can overcomes the buoyant force.
- This leads to a system where smaller ice crystals move up while bigger crystals come down.
- The resulting collisions trigger the **release of electrons**, in a process very similar to the generation of electric sparks (this is called as **ionisation**)

In ionisation, an electron in the outer shell is peeled out of the atom, and the atom become an ion.
There are two types of ions based on charge – cation and anion.
Cation: A cation is an atom or a molecule which is positively charged, i.e. it has a greater number of protons than electrons.
Anion: An anion is an atom or molecule which is negatively charged, i.e. it has a greater number of electrons than protons.

- The moving free electrons cause more collisions and more electrons are released and a chain reaction ensues.
- The process results in a situation in which the **top layer of the cloud gets positively charged (cations) while the middle and bottom layers are negatively (anions) charged**.



Lightning (Credits)

- The electrical potential difference between the top and the bottom layers is huge, of the order of 109 or 1010 volts.
- In little time, a huge current, of the order of 105 to 106 amperes, starts to flow between the layers.
- It produces heat, leading to the heating of the air column between the two layers of cloud.
- It is because of this heat that the air column looks red during lightning.
- The heated air column expands and produces shock waves that result in thunder.

Thunder

- Thunder is the sound caused by the discharge of atmospheric electrical charge (plasma — ionised gas medium — 30,000 °C) by lightning.
- The channel pressure of the electric charge greatly exceeds the ambient (surrounding) pressure, and the channel expands at a supersonic rate (speed of sound).
- The resultant shock wave decays rapidly with distance and is eventually heard as thunder once it slows to the speed of sound.
- Thunderbolt is a flash of lightning accompanied by a crash of thunder.

Lightning from cloud to Earth

- Earth is a good conductor of electricity but is electrically neutral.
- In comparison to the middle layer of the cloud, however, it becomes positively charged.
- As a result, a flow of current (about 20-15%) gets directed towards the Earth as well.
- It is this current flow that results in the damage to life and property.
- Once about 80-100 m from the surface, lightning tends to change course to hit the taller objects (guess why very tall buildings have a vertical pole above).
- This is because travelling through air, which is a bad conductor of electricity, electrons try to find a better conductor, and also the shortest route to the relatively positively charged Earth's surface.

Lightning strikes the metallic tower of the building

- The most lightning activity on Earth is seen on the shore of **Lake Maracaibo in Venezuela**.

Lightning deaths

- Several thousand thunderstorms occur over India every year.
- Incidents of lightning have been showing an increasing trend over the last 20 years, especially near the foothills of the Himalayas.
- People are rarely hit directly by lightning. But such strikes are almost always fatal.
- The most common way in which people are struck by lightning are by ground currents.
- The electrical energy, after hitting a tree or any other object, spreads laterally on the ground for some distance, and people in this area receive electrical shocks.
- It becomes more dangerous if the ground is wet, or there is conducting material like metal on it.

Precautions

- Moving under a tree or lying flat on the ground can increase risks.
- Even indoors, electrical fittings, wires, metal and water must be avoided.

(Source)

7.5 Hailstorm

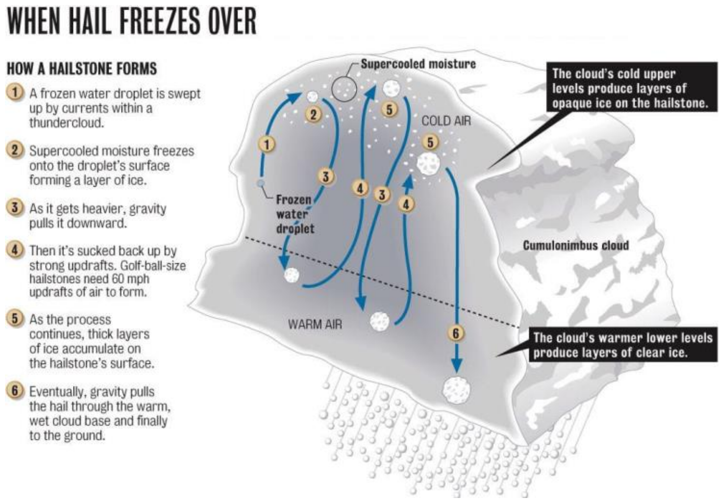
- Hail is a form of **solid precipitation** in which frozen pellets fall in showers from a **cumulonimbus cloud**.
- Any thunderstorm which produces hail that reaches the ground is known as a hailstorm.
- A hailstone is a layered irregular lump of ice. It is made of thick and translucent layers, alternating with layers that are thin, white and opaque.
- Hailstones are produced in almost all thunderstorms, but in most of the cases, they don't reach the surface.

Favourable conditions for hail formation

- Strong, upward motion of air (updraft) within the parent thunderstorm.
- High liquid water content.
- Great vertical extent of the cumulonimbus cloud.
- **Good portion of the cloud layer is below freezing 0 °C**.
- High surface temperatures. Hail growth is greatly inhibited during cold surface temperatures.

Formation of hail

- Hail begins as water droplets in a cumulonimbus cloud. As the droplets rise and the temperature goes below freezing, they freeze on contact with **condensation nuclei**.
- The storm's updraft with great wind speeds (180 kmph) blows the forming hailstones up the cloud.
- When the hailstone moves into an area with a high concentration of supercooled water droplets, it acquires new opaque layer.
- The hailstone will keep rising in the thunderstorm until its mass can no longer be supported by the updraft.
- It doesn't fall immediately to the surface because of melting, friction with air, wind, and interaction with rain and other hailstones that slow its descent. In the process, it acquires more layers.
- It then falls toward the ground while continuing to grow, based on the same processes, until it leaves the cloud.
- Finally, it may fall to the surface as hailstone if it can overcome the frictional force of the wind and ground temperature.



Hailstorm formation

- Hailstones can grow up to 15 centimetres and weigh more than 0.5 kg. Generally, the larger hailstones will form some distance from the stronger updraft where they can pass more time growing.
- Hail is less common in the tropics despite a much higher frequency of thunderstorms than in the mid-latitudes because the atmosphere over the tropics tends to be warmer over a much greater altitude.

Feb 2019: Severe hailstorm in Delhi-NCR

- Delhi and the surrounding regions experienced a very severe hailstorm in February 2019.
- A hailstorm is not unusual in the winter months. However, a hailstorm this severe was unprecedented.
- A number of factors contributed to making it severe.
    1. Western disturbance supplied enough moisture for the formation of thundercloud and hail formation.
    2. Confluence of winds from Bay of Bengal and Arabian Sea met over northern India (confluence of air masses with varying physical properties can cause severe thunderstorms).
    3. At the same time, jet streams were passing over the northern plains and helped in deep cloud formation at the lower level (upper-level divergence will cause convergence at the surface).

7.6 Hazards posed by thunderstorms and associated phenomenon

- Many hazardous weather events are associated with thunderstorms.
- Under the right conditions, rainfall from thunderstorms causes flash flooding (cloudburst).
- Lightning is responsible for many fires around the world each year and causes fatalities.
- Hail damages crops, vehicle windshields, windows, and kills livestock caught out in the open.
- Strong (120 mph) winds associated with thunderstorms knock down trees, power lines and mobile homes.
- Downbursts pose a huge risk to aircraft during take-off and landing (especially in the ITCZ zone).
- Tornadoes (with winds up to about 300 mph) can destroy all but the best-built human-made structures.

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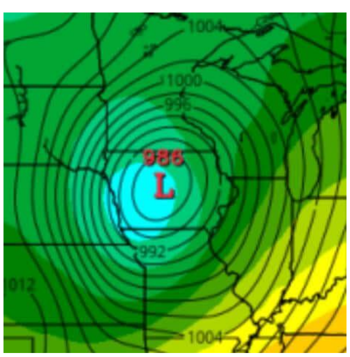
Climatology Part II

Print Friendly PDF

1. Tropical Cyclones

- Tropical cyclones originate over oceans in **tropical areas in late summers**.
- They are rapidly rotating violent storms characterised by
  - ✓ a **closed low-pressure centre with steep pressure gradients** (category 1 cyclones have a barometric pressure of greater than 980 millibars; category 5 cyclones can have central barometric pressure of **less than 920 millibars**),



Closed Isobars in a Tropical Cyclone

  - ✓ a **closed low-level atmospheric circulation** (winds converging from all directions — cyclonic circulation),
  - ✓ **strong winds** (squalls — a sudden violent gust of wind), and
  - ✓ a **spiral arrangement of thunderstorms** that produce very heavy rain **(torrential rainfall**).
- The low-pressure at the centre is responsible for the wind speeds.
- The closed air circulation (cyclonic circulation) is a result of **rapid upward movement of hot moist air** which is subjected to **Coriolis force**.

1.1 Conditions necessary for the Formation of a Tropical Cyclone

- **Large sea surface with temperature higher than 27° C.**
- **Presence of the Coriolis force enough to create a cyclonic vortex.**
- **A pre-existing weak low-pressure area or low-level-cyclonic circulation.**
- **Low wind shear.**
- **Upper-level divergence.**

Good Source of Latent Heat

- Ocean waters having temperatures of **27° C** and depth of warm water extending for **60-70 m** deep supply enough moisture, and hence **latent heat of condensation**, to generate and drive a tropical storm.
- Thick layer of warm water ensures that the deep convection currents within the water do not churn and mix the cooler water below with the warmer water near the surface.

Why tropical cyclones form mostly on the western margins of the oceans?

- Because of **warm ocean currents** (easterly trade winds drag ocean waters towards west) that flow from east towards west forming a thick layer of warm water with temperatures greater than 27°C.

Why are tropical cyclones very rare on the eastern margins of the oceans?

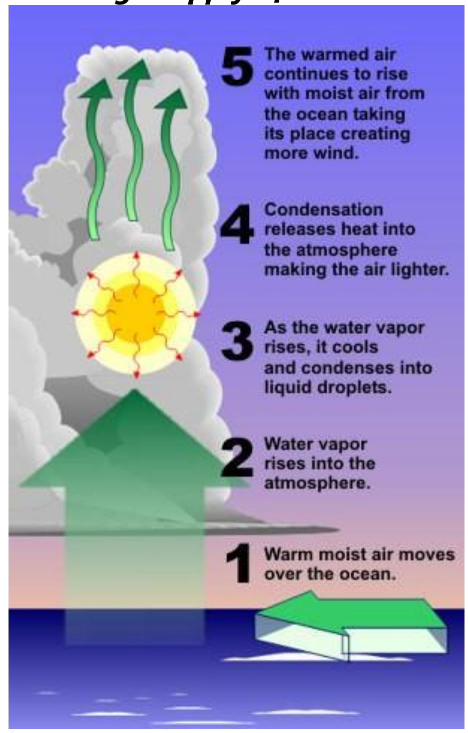
- The **cold currents** lower the surface temperatures of the eastern parts of the tropical oceans making them unfit for the breeding of cyclonic storms.

*Exceptional case: During **strong El Nino years**, strong hurricanes occur in the eastern Pacific. This is due to the accumulation of warm waters in the eastern Pacific due to **weak Walker Cell**.*

Why do tropical cyclones weaken on landfall?

- On landfall, the storm is cut-off from adequate moisture supply and hence it is deprived of latent heat of condensation. Thus, the storm dissipates (weakens or dies off) on landfall.

*Rising of humid air parcel ➔ ambient pressure on the air parcel decreases with altitude ➔ adiabatic lapse rate (fall in temperature of air parcel) ➔ condensation of moisture in air parcel due to low temperature ➔ **latent heat of condensation** is released in the process ➔ air parcel is heated further due to the release of latent heat of condensation and becomes less denser ➔ air parcel is further uplifted ➔ more air comes in to fill the gap ➔ new moisture is available for condensation ➔ latent heat of condensation is released. **The cycle repeats as long as there is enough supply of moisture**.*



Coriolis Force

- The **Coriolis force is zero at the equator,** but it increases with latitude.
- Coriolis force at 5° latitude is significant enough to create a storm (cyclonic vortex).
- About 65 per cent of cyclonic activity occurs between **10° and 20° latitude**.
- The cyclonic circulation is **anti-clockwise (counterclockwise) in the northern hemisphere** and **clockwise in the southern hemisphere**.

Why cyclones occur mostly in late summers?

1. Due to high specific heat of water, and mixing, the **ocean waters in northern hemisphere attain maximum temperatures in August** (in contract continents attain maximum temperatures in June-July).
2. Whirling motion (cyclonic vortex) is enhanced when the **doldrums** (region within ITCZ) over oceans are farthest from the equator (**Coriolis force increases with distance from the equator**).

Why do 'tropical cyclones' winds rotate counter-clockwise in the Northern Hemisphere?

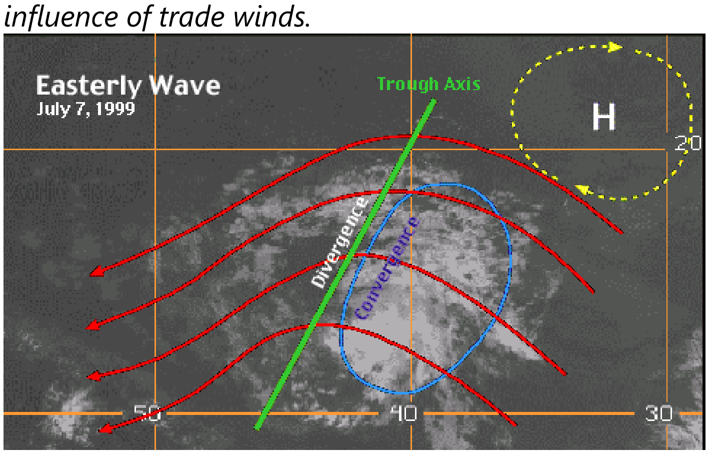
- As the earth's rotation sets up an apparent force (called the Coriolis force) that pulls the winds to the **right** in the Northern Hemisphere (and to the left in the Southern Hemisphere).
- So, when a low-pressure starts to form over north of the equator, the surface winds will flow inward trying to fill in the low and will be deflected to the right, and a **counter-clockwise rotation** will be initiated.
- The opposite (a deflection to the left and a clockwise rotation) will occur south of the equator.

Coriolis force is too tiny to effect rotation in water that is going down the drains of sinks and toilets.
The rotation in those will be determined by the geometry of the container and the original motion of the water.

Low-level Disturbances

- Low-level disturbance is a **low-pressure trough (an extended region of low-pressure)** that moves from east to west in the form of **easterly wave disturbances** in the Inter-Tropical Convergence Zone (ITCZ).

A disturbance is a persistent group of thunderstorms with heavy rains and strong wind gusts.
***Easterly wave disturbances:** it is a convective trough (thermal origin) — a persistent group of thunderstorms travelling together in east to west direction (westward traveling disturbances) under the influence of trade winds.*



Easterly wave disturbances

- Easterly wave disturbances act as **seedling circulations (birthplace)** for a large number of tropical cyclones. However, not all disturbances develop into cyclones.

Temperature Contrast Between Air Masses

- The convergence of air masses of different temperatures results in instability causing low-level disturbances which are a prerequisite for the origin and growth of violent tropical storms.
- Trade winds from both the hemispheres meet along the inter-tropical front (ITCZ). Temperature contrasts between these air masses must exist when the ITCZ is farthest from the equator so that the low-level disturbances can intensify into a depression (intensifying low-pressure cell).

Wind Shear

- Wind Shear is the difference between wind speeds at different altitudes.
- Tropical cyclones develop when the wind is uniform.

Why is convective cyclogenesis (tropical cyclogenesis) confined to tropics?

- **Because of weak vertical wind shear, cyclone formation processes are limited to latitude equatorward of the subtropical jet stream.**
- In the temperate regions, wind shear is high due to westerlies, and this inhibits convective cyclogenesis.

Why there are very few Tropical Cyclones during southwest monsoon season?

Large vertical wind shear

- The southwest monsoon is characterized by the presence of strong westerly winds (south-west monsoon winds) in the lower troposphere (below 3 km) and strong easterly winds in the upper troposphere (above 9 km). This results **in large vertical wind shear**. **Strong vertical wind shear inhibits cyclone development**.

Less time for development

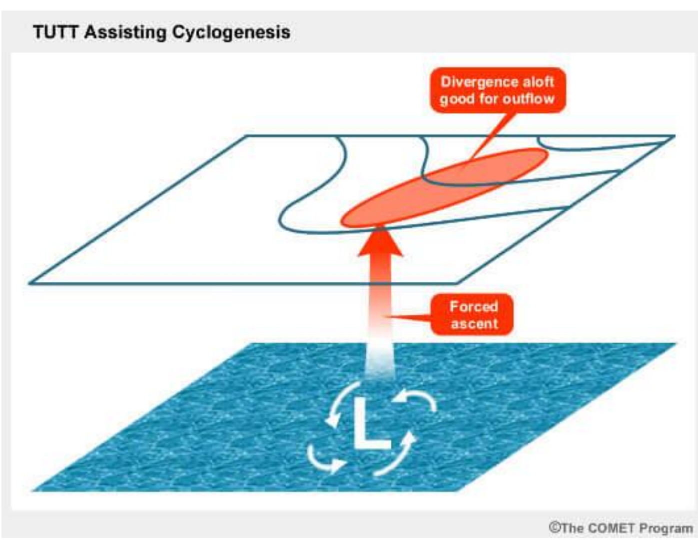
- The potential zone for the development of cyclones shifts to North Bay of Bengal during southwest monsoon season.
- Low-pressure system up to the intensity of depressions form along the monsoon trough (along ITCZ), which extends from northwest India to the north Bay of Bengal.
- The Depression forming over this area crosses Orissa-West Bengal coast in just a day or two as the bay is narrower to the north.
- These systems thus have shorter oceanic stay (they make landfall very quickly) and hence cannot intensify beyond the depression stage.

Upper Air Disturbance

- An **upper tropospheric cyclone** usually moves slowly from east to west and is prevalent in summer.
- Its circulations generally do not extend below 6000 m in altitude.
- The remains of this cyclone (**upper tropospheric westerly trough or tropical upper tropospheric trough**) from the westerlies move deep into the tropical latitude regions.

Troughs may be at the surface, or aloft. They may be convective (thermal origin — tropics), or frontal (dynamic origin — temperate regions).

- These troughs can assist tropical cyclogenesis and intensification by providing additional forced ascent.



Upper tropospheric westerly trough assisting convective cyclogenesis

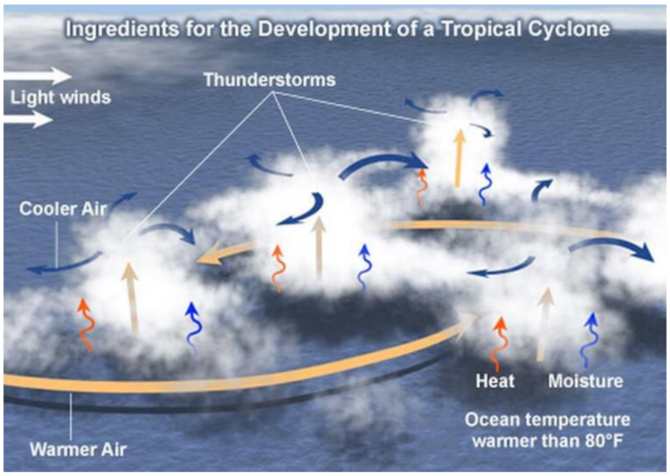
- As divergence prevails (upper tropospheric divergence) on the eastern side of the **troughs**, a rising motion occurs at the surface; this leads to the development of thunderstorms or intensification of existing storms.
- Further, these **abandoned troughs (remnants of temperate cyclones)** usually have cold cores, suggesting that the environmental lapse rate is steeper. Such instability encourages thunderstorms.
- An upper tropospheric westerly trough is important for **tropical cyclone forecasting**. This is because,
  1. Fast moving upper tropospheric westerly troughs can create **large vertical wind shear** over tropical disturbances and tropical cyclones which may inhibit their strengthening.
  2. Slow moving upper tropospheric westerly troughs can drive the tropical cyclones eastward or north-eastward.

Upper tropospheric trough can influence the Direction of a tropical cyclone

1.2 Convective Cyclogenesis (Development of Tropical Cyclones)

- **Cyclogenesis** is the development or strengthening of cyclonic circulation in the atmosphere.
- Cyclogenesis involves any of these three processes:
  1. **Convective cyclogenesis or tropical cyclone formation**.
  2. **Frontal cyclogenesis of extratropical cyclone formation**.
  3. **Mesocyclones forming as warm core cyclones giving rise to tornadoes and waterspouts**.

- The tropical cyclones have a **thermal origin**, and they develop over tropical seas during **late summers (August to mid-November)**.
- At these locations, under favourable conditions, **multiple thunderstorms** (strong local convectional currents) merge and create an intense **low-pressure system (low-level disturbance)**.



Multiple thunderstorms

Tropical depression (maximum sustained wind speed < 63 kmph)

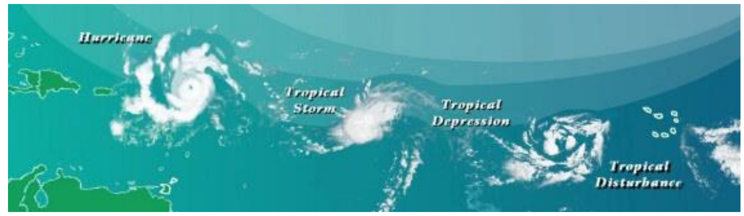
- The intense low-pressure system might acquire a whirling motion because of the **Coriolis force** giving rise to a tropical depression.
- A tropical depression has sustained winds below 63 kmph.

Tropical storm (63 kmph < maximum sustained wind speed < 119 kmph)

- Tropical depression develops into a tropical storm when the cyclonic circulation becomes more organised with maximum sustained winds at or above 63 kmph but below 119 kmph.
- At this point, the distinctive cyclonic shape starts to develop, although an **eye is not usually present**.

Tropical cyclone (maximum sustained wind speed > 119 kmph)

- As the tropical storm intensifies and acquires a maximum sustained wind speed of 119 kmph it develops into a tropical cyclone.
- A cyclone of this intensity (119 kmph) **tends to develop an eye, an area of relative calm (lowest surface atmospheric pressure in a tropical cyclone) at the centre of circulation**.



Stages of Cyclone Formation (Credits)

Maximum sustained wind speed

- India Meteorological Department (IMD) uses a 3 minutes averaging for the sustained wind.
- Maximum sustained wind is the **highest 3 minutes surface wind** occurring within the circulation of the system.

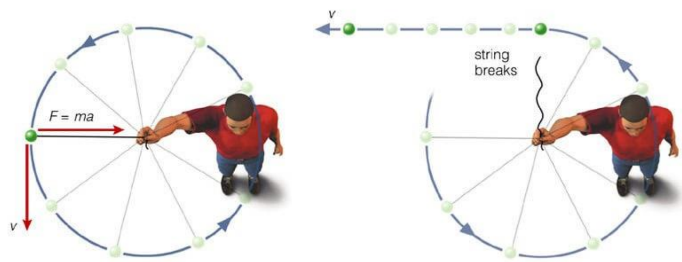
Mechanism – Early stage

- In the thunderstorm, air is uplifted as it is **warm and light**. At certain height, due to **lapse rate and adiabatic lapse rate**, the temperature of air falls, and moisture in the air undergoes **condensation**.
- Condensation releases **latent heat of condensation** making the air warmer. It becomes much lighter and is further uplifted.
- The space is filled by fresh moisture-laden air. Condensation occurs in this air, and the **cycle is repeated as long as the moisture is supplied**.
- Due to excess moisture over oceans, the thunderstorm intensifies and sucks in air at much faster rate.
- The air from surroundings rushes in and undergoes deflection due to **Coriolis force** creating a **cyclonic vortex (spiralling air column).**
- Due to **centripetal acceleration**, the air in the vortex is forced to form a region of calmness called an **eye** at the centre of the cyclone.

Centripetal force pulling towards the centre is countered by an opposing force called centrifugal force.

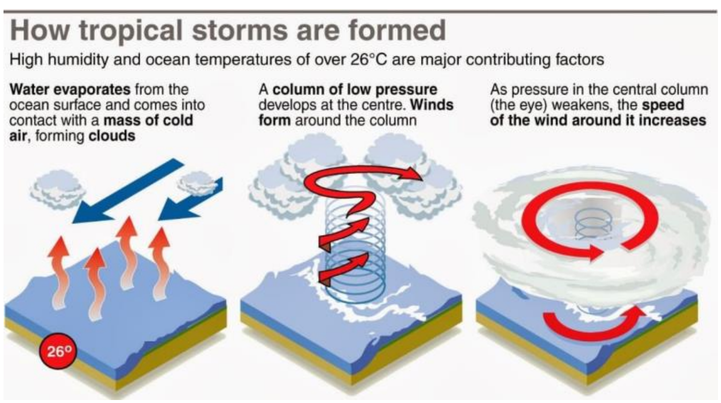
- The eye is created due to the tangential force acting on the high-speed wind that is flowing in a curvy path (intense low-pressure ➔ greater wind speeds ➔ greater Coriolis force ➔ greater deflection).

- The diameter of the eye depends on the wind speed. **Greater the wind speed, larger the eye region**.



In a cyclonic vortex, the intense low-pressure acts as the string that holds the vortex in place

- All the wind that is carried upwards loses its moisture and becomes cold and dense.
- It descends to the surface through the cylindrical eye region and at the edges of the cyclone.
- If the storm doesn't make landfall and if the ocean can supply more moisture, the storm will reach a mature stage.



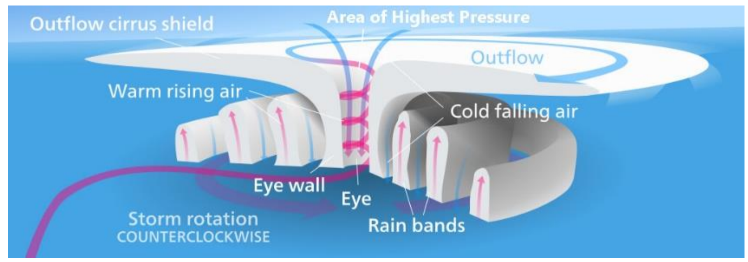
Characteristics of the eye

- The eye is a roughly circular area of comparatively **light winds and fair weather**.
- There is little or **no precipitation,** and sometimes blue sky or stars can be seen.
- Along the eye, the air is **slowly sinking** and is heated due to **compressional warming** (adiabatic).
- The eye temperature may be 10°C warmer or more at an altitude of 12 km than the surrounding environment, but only 0-2°C warmer at the surface in the tropical cyclone.
- Eyes range in size from 8 km to over 200 km across, but most are approximately 30-60 km in diameter.

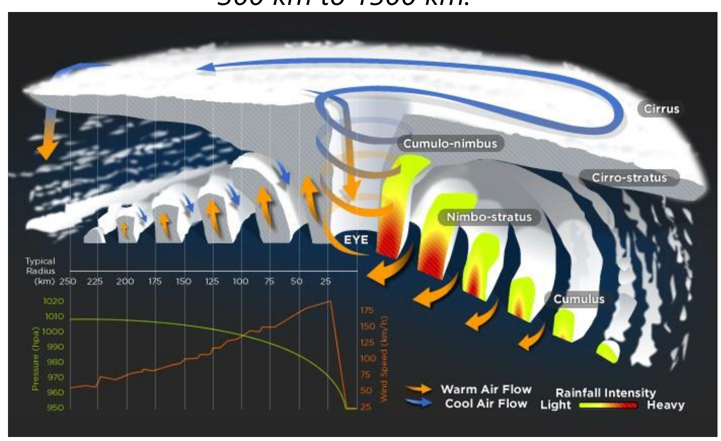
Characteristics of eyewall

- The eye is surrounded by an eyewall, the **most violent region** of the cyclone.
- It is a roughly circular ring of **deep convection (heaviest rainfall in a cyclone)**.
- Eyewall region experiences the **maximum sustained winds,** i.e. **fastest winds in a cyclone**.

Mechanism – Mature stage



A tropical cyclone in the northern hemisphere (anti-clockwise circulation) (Kelvinsong, [Wikipedia])
Tropical cyclones have symmetrical elliptical shapes. They have a compact size can span in the range of 300 km to 1500 km.



A tropical cyclone in the southern hemisphere (clockwise circulation)

- At this stage, the spiralling winds create **multiple convective cells** called **rain bands** with **successive calm and violent regions**.
- Cloud formation is dense at the centre. The cloud size decreases from centre to periphery.

Central Dense Overcast (CDO)

- CDO is the **cirrus cloud shield** (mostly made up of hexagonal ice crystals) that results from the thunderstorms in the eyewall of a tropical cyclone and its rainbands.

- Before the tropical cyclone reaches very severe cyclonic storm (119 kmph), typically the CDO is uniformly showing the cold cloud tops of the cirrus with **no eye apparent**.
- The dry air flowing along the central dense overcast descends at the periphery and the eye region.

Rain bands (Spiral bands)

- Convection in tropical cyclones is organized into long, narrow rain bands which are oriented in the same direction as the horizontal wind.
- A direct circulation develops in which warm, moist air converges at the surface, ascends through these bands, diverges aloft, and descends on both sides of the bands.
- Because these bands **seem to spiral into the centre** of a tropical cyclone, they are called spiral bands.
- Rain bands are mostly made up of **cumulonimbus clouds (highest rainfall)**.
- The ones at the periphery are made up of **nimbostratus (prolonged rainfall)** and **cumulus clouds (least)**.

Vertical Structure of a Tropical Cyclone

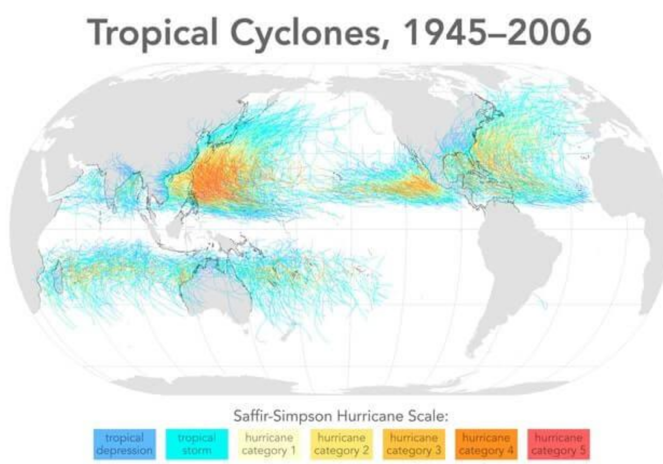
There are three divisions in the vertical structure of tropical cyclones.

- The lowest layer, extending up to 3 km and known as the inflow layer, is responsible for **driving the storm**.
- The middle layer, extending from 3 km to 7 km, is where the **main cyclonic storm** takes place.
- The outflow layer lies above 7 km. The maximum outflow is found at 12 km and above. The movement of air is **anticyclonic** in nature.

1.3 Breeding Grounds for Tropical Cyclones

The breeding grounds for tropical cyclones coincide with tropical regions with warm ocean currents.

- **Western Pacific (highest number of tropical cyclones)**: Philippines islands, eastern China and Japan where they are called typhoons.
- Western Atlantic (South-east Caribbean region) and Eastern Pacific where they are called hurricanes.
- Bay of Bengal and Arabian Sea where they are called cyclones.
- Around south-east African coast and Madagascar-Mauritius islands.
- North-west Australia.



Breeding Grounds for Tropical Cyclones

Regional names for Tropical Cyclones

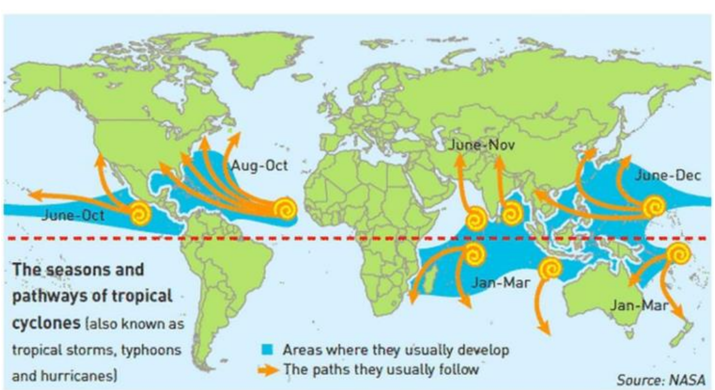
Regions	**What they are called**
Indian Ocean	Cyclones
Atlantic	Hurricanes
Western Pacific and South China Sea	Typhoons
Western Australia	**Willy-willies**

Regional names for various categories

Category	Australian name	US	NW Pacific	Arabian Sea /Bay of Bengal
—	Tropical low	Tropical depression	Tropical depression	Depression or severe depression
1	Tropical cyclone	Tropical storm	Tropical storm	Cyclonic storm
2	Tropical cyclone	Tropical storm	Severe tropical storm	Severe cyclonic storm
3	Severe tropical cyclone	Hurricane	Typhoon	Very severe cyclonic storm
4	Severe tropical cyclone	Hurricane	Typhoon	Very severe cyclonic storm
5	Severe tropical cyclone	Hurricane	Typhoon	Super cyclonic storm

1.4 Path of Tropical Cyclones

- Tropical cyclones generally follow a **parabolic path** with the parabolic axis being parallel to the isobars.
- Coriolis force, easterly and westerly winds, and upper tropospheric westerly trough influence the path of tropical cyclones.
- In the northern hemisphere**,** tropical cyclones **start with a westward movement** as the zone of formation is under the influence of easterlies (**trade winds**). The average speed is 15-20 kmph (360-480 km per day).
- They then turn northwards around 20° latitude because of the **Coriolis force** that deflects the path of the storm to its right. Their speed decreases to 10 kmph or even less.
- They turn further north-eastwards at around 25° latitude (Coriolis force deflects it further).
- They then turn **eastwards** around **30° latitude** (because of **westerly winds**).
- The **westward movement is the fastest** and they attain speeds of 25 kmph or more.
- They then lose energy and subside beyond 30° latitude because of **cool ocean waters** and **increasing wind shear due to westerlies**.
- In some instances, a tropical cyclone may avoid the general path and continue with its westward movement.
- Sometimes tropical cyclones are stalled near the coastline, dropping unprecedented amounts of rainfall.
- This could happen due to weak prevailing winds linked to a greatly expanded subtropical high-pressure system and northward migration of westerlies.



Which sector of the cyclone experiences strongest winds?

- Wind velocity, in a tropical cyclone, is more in right side of the storm (in most of the cases it is the poleward margin of the storm) than at centre and is moreover oceans than over landmasses.
- The "right side of the storm" is defined with respect to the storm's motion: if the cyclone is moving to the west, the right side would be to the north of the storm; if the cyclone is moving to the north, the right side would be to the east of the storm, etc.
- The strongest wind on the right side of the storm is mainly due to the fact that the **motion of the cyclone also contributes to its swirling winds**.
- A cyclone with a 145 kmph winds while stationary would have winds up to 160 kmph on the right side and only 130 kmph on the left side if it began moving (any direction) at 16 kmph.

1.5 Why only a fewer cyclones form over the Arabian Sea as compared to the Bay of Bengal?

- The average annual frequency of tropical cyclones in the north Indian Ocean (Bay of Bengal and Arabian Sea) is about **5 (about 5-6 % of the global annual average),** and about 80 cyclones form around the globe in a year. (**Most of them occur in Western Pacific and Western Atlantic**)
- The frequency is more in the Bay of Bengal than in the Arabian Sea, the ratio being **4:1.**

More low-level disturbances in Bay of Bengal

- Cyclones that form over the Bay of Bengal are either those that develop in-situ over southeast Bay of Bengal or remnants of typhoons over Northwest Pacific that move across south China sea to Indian Seas.
- As the frequency of typhoons over Northwest Pacific is quite high (about **35%** of the global

annual average), the Bay of Bengal also gets its increased quota.

- The cyclones over the Arabian Sea either originate in-situ over southeast Arabian Sea or remnants of cyclones from the Bay of Bengal that move across south peninsula.
- As the majority of Cyclones over the Bay of Bengal weaken over land after landfall, the frequency of migration into Arabian Sea is low.

The surface temperature of Bay of Bengal is higher

- Surface temperature in the Bay of Bengal is usually between 22 °C and 31 °C. It is cooler by 1-2 °C in the Arabian Sea because of the monsoon winds.

Arabian Sea surface has higher salinity

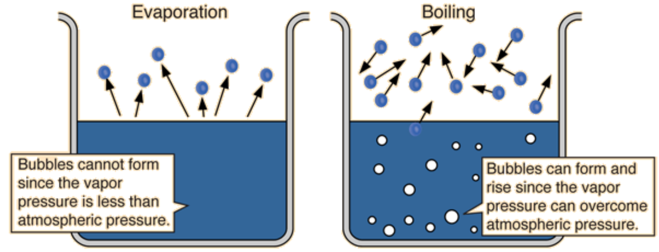
- Salinity near the surface in the northern Bay of Bengal can be as low as 31 ppt because the bay **receives lots of freshwater** from the Ganga, Brahmaputra, Irrawaddy, Godavari, and others.
- Salinity near the surface in the Arabian Sea is much higher than in the Bay of Bengal because evapouration over the Arabian Sea is much greater than precipitation and river runoff (**it loses more freshwater than it receives**).

Vapour pressure of water and rate of evapouration

- The rate of evapouration is controlled by vapour pressure of water.
- Just like air molecules exert pressure on water, water molecules exert a counter-pressure on the air molecules. This counter pressure is called as **vapour pressure of water**.
- **Higher the vapour pressure of water, higher is the rate of evapouration** and vice versa.
- The vapour pressure of water can be modified by:
    1. **Changing the air pressure:** higher wind speeds decreases air pressure and hence increase evapouration.

Bernoulli's principle: *Within a horizontal flow of fluid, points of higher fluid speed will have less pressure than points of slower fluid speed. Practical examples: Swinging Cricket Ball; Lift achieved by aeroplane wings.*

2. **Changing the temperature of water:** when temperature of water is increased, the water molecules attain higher kinetic energy and hence the vapour pressure of water increases. This increases evapouration.
3. **Changing salinity:** Increased salinity reduces the kinetic energy of the water molecules. This decreases evapouration.



Vapour Pressure and Rate of Evapouration (Credits)

Higher stratification in Bay of Bengal

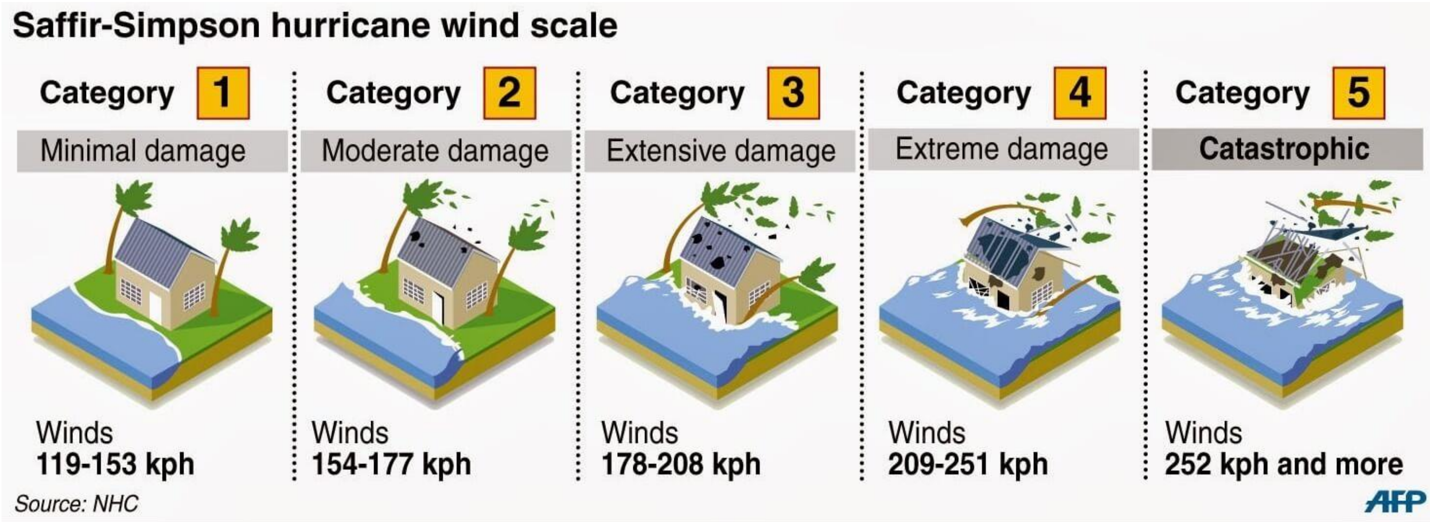
- If all the freshwater that the bay receives during a year is accumulated and spread uniformly over its entire surface, it would form a layer over a metre thick.
- Freshwater is less dense compared to saline water. Hence **vertical mixing is inhibited in Bay of Bengal**.
- On the other hand, high evapouration and low inflow of fresh water increases salinity (water becomes denser) at the surface in the Arabian Sea, and this increases vertical mixing.

Monsoon winds drive away moisture

- Though the monsoon winds increase evapouration in the Arabian Sea, the moisture is constantly driven away by the winds towards India.

1.6 Tropical Cyclone Scale

Cyclone Category	Wind Speed in Kmph	Damage Capacity
01	120-150	Minimal
02	150-180	Moderate
03	180-210	Extensive
04	210-250	Extreme
05	250+	Catastrophic
Values rebounded off to make it easy to remember		



Saffir-Simpson hurricane wind scale

Tropical Cyclone Scale by Indian Meteorological Department

S. No.	Intensity	Strength of wind	Wave height (m)
1.	Depression (L)	31- 49 kmph (17-27 knots)	1-4
2.	Deep Depression (DD)	50 - 61 kmph (28-33 knots)	4-6
3.	Cyclonic Storm (CS)	62 - 87 kmph (34-47 knots)	6-9
4.	Severe Cyclonic Storm (SCS)	88-117 kmph (48-63 knots)	9-14
5.	**Very Severe Cyclonic Storm (VSCS)**	**118-166 kmph (64-89 knots)**	**14+**
6.	**Extremely Severe Cyclonic Storm (ESCS)**	**167-221 kmph (90-119 knots)**	**14+**
7.	**Super Cyclonic Storm (SuCS)**	**222+ kmph (120+ knots)**	**14+**

Source

- The knot is a unit of speed equal to one nautical mile (1.852 km) per hour.
- A vessel travelling at 1 knot along a meridian travels approximately one minute of geographic latitude in one hour.

1 international knot = 1 nautical mile per hour = 1.852 kilometres per hour = 0.514 metres per second

1.7 Damage associated with Tropical Cyclones

- The dangers associated with cyclonic storms are generally three fold.

1. **Floods**
2. **Winds**
3. **Storm Surge**

Intensity	Damage expected	Measures to be taken
Depression **Deep Depression**	• Minor damage to unsecured structures	• Fishermen advised not to venture into the open seas.
Cyclone	• Damage to thatched huts. • Breaking of tree branches. • Minor damage to power and communication lines.	• Total suspension of fishing operations
Severe Cyclone	• Extensive damage to thatched huts. • Flooding of escape routes.	• Coastal hutment dwellers to be moved to safer places.
Very Severe Cyclone	• Extensive damage to kutcha houses. • Minor disruption of rail and road traffic. • Potential threat from flying debris.	• Mobilise evacuation from coastal areas.

Extremely Severe Cyclone	• Extensive damage to kutcha houses. • Large-scale disruption of power and communication lines. • Disruption of rail and road traffic due to extensive flooding.	• Extensive evacuation from coastal areas. • Diversion or suspension of rail and road traffic.
Super Cyclone	• Extensive structural damage to residential and industrial buildings. • Total disruption of communication and power supply. • Extensive damage to bridges causing large-scale disruption of rail and road traffic. • Large- scale flooding and inundation of sea water.	• Large-scale evacuation of coastal population. • Total suspension of rail and road traffic.

Floods

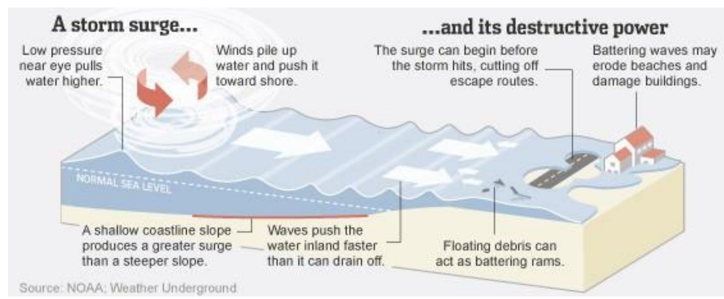
- Precipitation of about 50 cm/day is quite common within a cyclonic storm.
- Record rainfall in a cyclonic storm has been as low as trace to **as high as 250 cms**.
- The intensity of rainfall is about 85 cms/day within a radius of 50 km and about 35 cms/day between 50 to 100 km from the centre of the storm.

Wind

- The strong wind speed associated with a cyclonic storm (60-90 kmph) can result into some damage to kutcha houses and tree branches likely to break off.
- Winds of a severe Cyclonic storm (90-120 kmph) can cause uprooting of trees, damage to pucca houses and disruption of communications.
- The wind associated with a very severe Cyclonic storm and super cyclonic storm can uproot big trees, cause widespread damages to house and installations and total disruption of communications.
- The maximum wind speed associated with a very severe Cyclonic storm that hit Indian coast in the past 100 years was **260 kmph** in Oct 1999 (**Paradeep Super cyclone**).

Storm surge

- Storm Surge (tidal wave — long wavelength) is an abnormal rise of sea level as the cyclone makes landfall.
- The rise of sea level occurs due to the convergence of winds at great speeds that drag water and cause accumulation of high water column just below the centre of the cyclone.



Storm surge

- The destructive power of the storm surge depends on intensity of the cyclone and coastal bathymetry (shallower coastlines face surges of greater heights).
- Seawater inundates the coastal strip causing loss of life, large scale destruction to property & crop.
- Increased salinity in the soil makes the land unfit for agricultural use for two or three seasons.

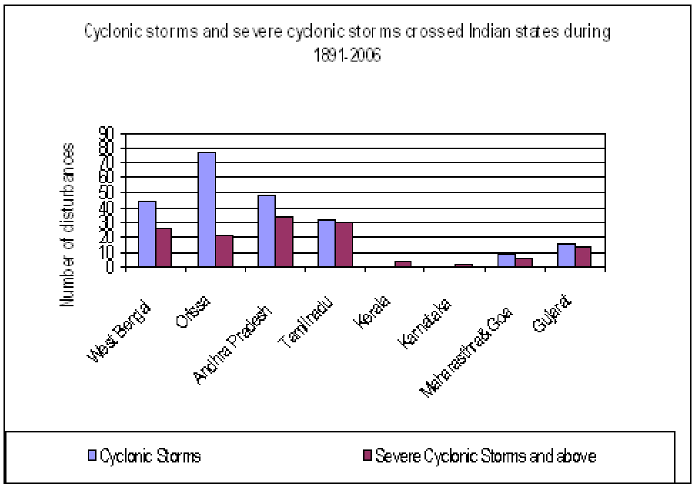
What is storm tide?

- The storm tide is the combination of **storm surge and the astronomical tide**.
- Storm surge is accentuated if the landfall time **coincides with that of high tides**.

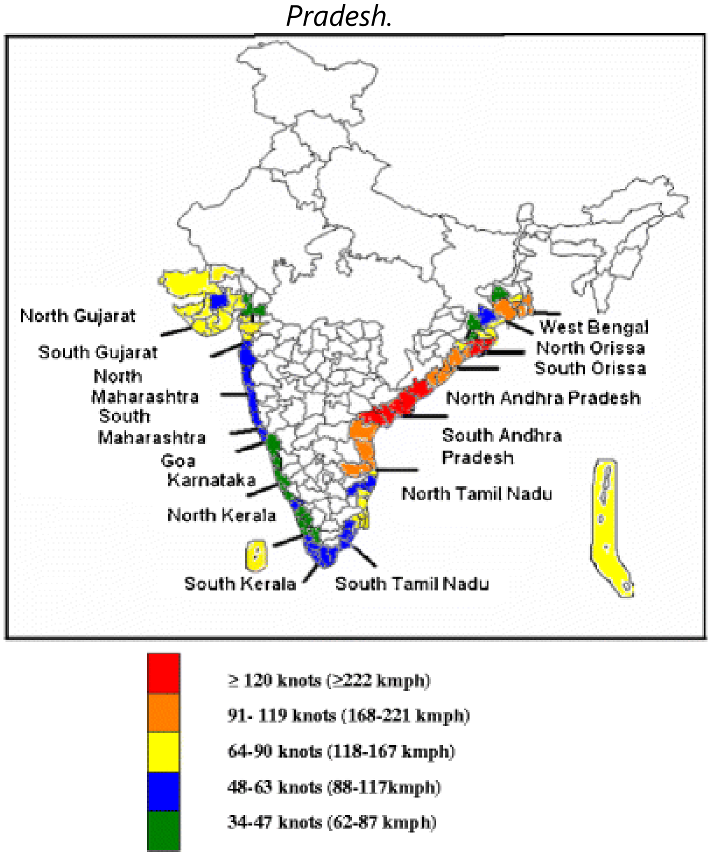
Cyclone	Strength	Region affected	Damage
1970 Bhola cyclone	Extremely Severe Cyclone	West Bengal and Bangladesh	• Deadliest tropical cyclone • 5,00,000+ fatalities
1999 Odisha Cyclone	Super Cyclone	Odisha	• Strongest recorded tropical cy-

(Paradeep Super cyclone)	**Maximum sustained wind speed of 260 kmph**		clone in the North Indian Ocean • 30,000+ fatalities
2008 Nargis Cyclone	Extremely Severe Cyclone	Irrawaddy delta (Myanmar)	• 1,00,000+ fatalities • Costliest cyclone in the region
High number of fatalities in all these cyclones was due to **storm surge**. The delta regions are always at higher risk because of low gradient.			

States Vulnerable to Cyclones



Most number of severe cyclonic storms strike Andhra Pradesh.



Andhra Pradesh and Odisha are at greater risk of receiving strong cyclones

1.8 Positive effects of Tropical Cyclones

Tropical cyclones bring rainfall to rain shadow and other parched regions

- Rainshadow regions of Western Ghats ad semi-arid regions in south India (Telangana, Rayalaseema, Hyderabad-Karnataka, Vidarbha) sometimes receive copious rain during the cyclone season.

Break up Red Tide

- Red tide is a phenomenon which involves **discolouration of coastal waters caused by algal blooms**.
- The algal bloom **deplete oxygen** in the waters and release harmful toxins.
- As tropical cyclones move across the ocean, winds and waves mix and break up patches of bacteria and can bring an earlier end to the red tide.

Replenish Barrier Islands

- Tropical cyclones have the power to pick up substantial amounts of sand, nutrients and sediment on the ocean's bottom and bring it towards barrier islands.
- Storm surge, wind and waves will often move these islands closer to the mainland as sand is pushed or pulled in that direction.

Speed dispersal to faraway locations

- Tropical cyclone wind blow spores and seeds further inland from where they would normally fall; this effect can be seen a thousand miles inland as storms move away from the shoreline.
- These seeds can replenish lost growth after fires and urbanisation.

1.9 Naming of Cyclones

Mains 2013: The recent cyclone on east coast of India was called 'Phailin'. How are the tropical cyclones named across the world? Elaborate.

- WMO (World meteorological organisation) divided the world Oceans into Basins and assigned the responsibility of naming the Cyclones to the respective regional bodies.
- Each regional body has its own rules in naming cyclones.
- In most regions, pre-determined alphabetic lists of alternating male and female names are used.

Why name them?

- Since the storms can often last a week or even longer and more than one cyclone can be occurring in the same region at the same time, names can reduce the confusion about what storm is being described.
- Naming them after a person/flower/animal etc. makes it easier for quick information exchange.

Northern Indian Ocean Region

- The names of cyclones in Indian Seas are not allocated in alphabetical order but are arranged by the name of the country which contributed the name.
- It is usual practice for a storm to be named when it reaches tropical storm strength (**63 kmph**).
- The Indian Meteorological Department (IMD) which issues cyclone advisories to eight countries has a list of names contributed by each of them.
- Every time a cyclone occurs, a name is picked in the order of the names that are already submitted.
- Each country gets a chance to name a cyclone. After all the countries get their turn, the next list of names is followed.

Contributed by	Name			
Bangladesh	Helen	Chapala	Ockhi	Fani
India	**Lehar(2013)**	**Megh**	**Sagar**	**Vayu**
Maldives	Madi	Roanu	Mekunu	Hikaa
Myanmar	Na-nauk	Kyant	Daye	Kyarr
Oman	**Hudhud**	Nada	Luban	Maha
Pakistan	**Nilofar**	Vardah	Titli	Bulbul
Sri Lanka	Priya	Asiri	Gigum	Soba
Thailand	Komen	Mora	Phethai	Amphan

Names contributed by countries in the Northern Indian Ocean Region

1.10 Warning of Tropical Cyclones

- Detection of any unusual phenomena in the weather leading to cyclones has three main parameters: **fall in pressure, increase in wind velocity, and the direction and movement (track) of storm.**
- Monitoring is also done by aircraft which carry a number of instruments including a weather radar.
- Cyclone monitoring by satellites is done through very high-resolution radiometers to obtain an image of the cloud cover and its structure.
- Today, it is possible to detect a cyclone right from its genesis in the high seas and follow its course, giving a warning at least 48 hours before a cyclone strike.
- However, the predictions of a storm course made only 12 hours in advance do not have a very high rate of precision.

4-stage IMD warning system for tropical cyclones

IMD and Cyclone Disaster Management

- 1999, IMD introduced a 4-Stage warning system to issue cyclone warnings to the disaster managers.

Pre-Cyclone Watch

- Issued when a depression forms over the Bay of Bengal irrespective of its distance from the coast.
- The pre-cyclone watch is issued at least 72 hours in advance of the commencement of adverse weather.
- It is issued at least once a day.

Cyclone Alert (Colour code Yellow)

- Issued at least 48 hours before the commencement of the bad weather when the cyclone is located beyond 500 Km from the coast.

- It is issued every three hours.

Cyclone Warning (Colour code Orange)

- Issued at least 24 hours before the commencement of the bad weather when the cyclone is located within 500 Km from the coast.
- Information about time/place of landfall are indicated in the bulletin.
- Accuracy in estimation increases as the cyclone comes closer to the coast

Post-landfall outlook (Colour code Red)

- It is issued 12 hours before the cyclone landfall when the cyclone is located within 200 km from the coast.
- More accurate information about time/place of landfall and associated bad weather are indicated in the bulletin.

2. Jet streams

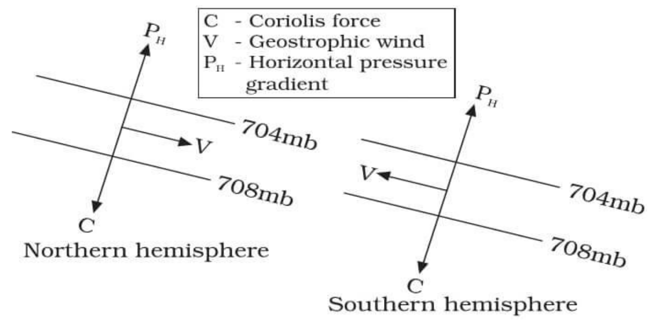
Jet streams are

- ✓ **Circumpolar** (circle around the earth with poles as their centres),
- ✓ **narrow, concentrated bands of** (the air in the stream is directed towards the axis of the stream making it very narrow — 50-150 km across)
- ✓ **upper tropospheric,**
- ✓ **westerly,**
- ✓ **geostrophic streams,**
- ✓ **flowing at high velocity,**
- ✓ **with a degree of meandering.**

2.1 Explanation of Jet Streams

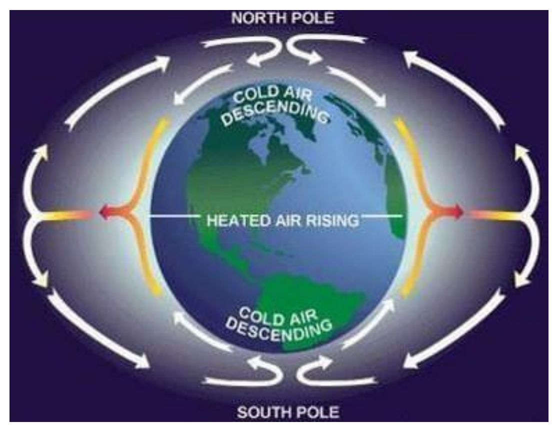
Geostrophic Wind

- The Coriolis force acting on a body increases with increase in its velocity.
- The winds in the upper atmosphere, 2-3 km above the surface, are free from frictional effect of the surface and are controlled by the pressure gradient and the Coriolis force.
- When isobars are straight, and when there is no friction, the **pressure gradient force is balanced by the Coriolis force, and the resultant wind blows parallel to the isobar** (deflection of the wind is maximum).
- This wind is known as the **geostrophic wind. Jet Stream is a geostrophic wind.**



Geostrophic wind vector parallel to the isobars

Why don't winds flow from tropical high-pressure (in upper troposphere) to polar low (in upper troposphere) directly as shown in figure below?



General air circulation when the effect of Coriolis force is ignored

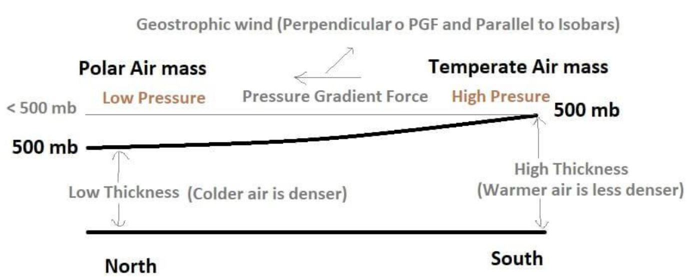
- Because these winds are **geostrophic**, i.e., they flow at **great speeds** due to **low friction** and are subjected to **greater Coriolis force**.
- Thus, they are deflected greatly giving rise to three distinct cells called **Hadley cell, Ferrel Cell** and **Polar cell**.
- That is, instead of one big cell we have three small cells that combinedly produces the same effect.
- *Hadley Cell and Polar Cell are thermal in origin (convection). Ferrel Cell is dynamic in origin*

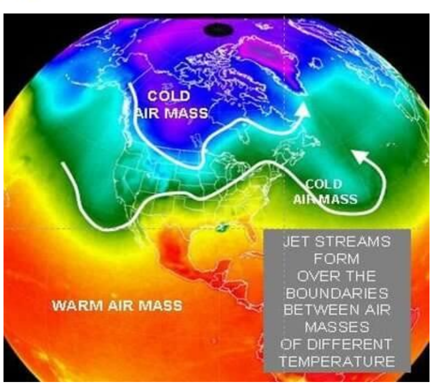
(Coriolis Force and blocking effect of converging winds). These cells are part of general circulation.

- *Jet Streams are formed due to pressure difference between air masses and Coriolis Force.*

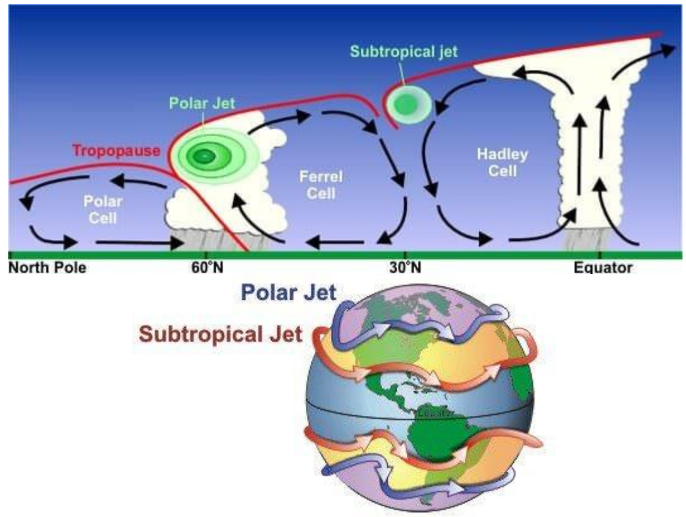
Upper tropospheric westerlies

- Jet streams are produced due to winds flowing from tropics towards poles in the upper troposphere (just below the tropopause).
- Jet stream produced between polar and temperate air masses is called as **polar jet stream or polar jet**.
- Jet stream produced between temperate and tropical air masses is called as **subtropical jet stream**.
- In **polar jet streams** wind flows from **temperate region towards polar region**, and in **subtropical jet streams,** winds flow from **subtropics towards temperate region**.
- *In the upper troposphere, the wind flows from less denser air mass towards the poles due to* ***thermal effect*** *(poles receive less heat and equator receives more heat. So, at the surface the winds flow from pole towards the equator whereas at an altitude the winds flow from equator towards poles).*
- *The high-pressure gradient force is directed from south to north.*





Polar Jet Stream is formed between temperate and polar air masses



Polar jet is stronger; Subtropical jet is higher

- Anything moving from tropics towards poles deflects towards their right in the northern hemisphere and towards their left in the southern hemisphere due to **Coriolis effect**.
- Thus, jet streams flow from **west to east** in both the hemispheres and hence they are called westerlies or upper-level westerlies.
- Both the Northern and Southern hemispheres have jet streams, although the jet streams in the north are more forceful due to greater temperature gradients.

Why does polar jet and subtropical jet flow at different altitudes?

- Polar jet streams flow **6 – 9 km** above the ground and Sub-tropical jet streams flows **10 – 16 km** above the grounds.
- This is because the troposphere is thicker at equator (17 to 18 km) than at poles (8 to 9 km).

High velocity

- The friction in the upper troposphere is also quite low due to less dense air.
- Temperature also influences the velocity of the jet stream.
- The greater the difference in air temperature, the faster the jet stream.
- Jet stream can reach speeds of up to 400 kmph or greater.
- The jet streams have an average velocity of 120 kmph in winter and 50 kmph in summer.

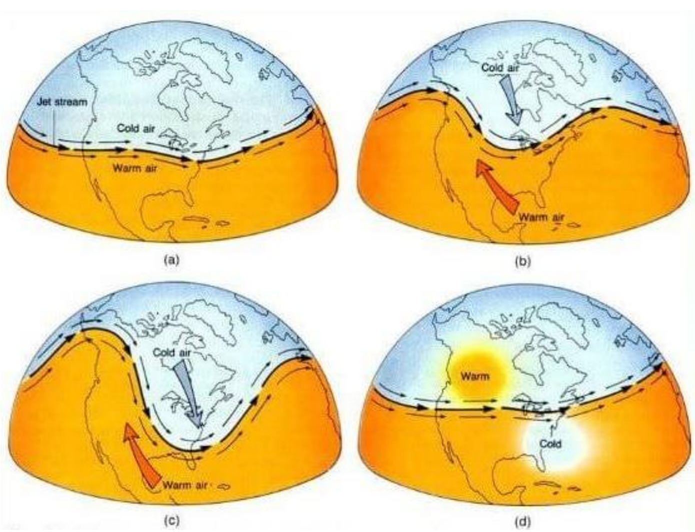
- These jet streams also have cores where the speed is much greater.

Winds are highest in the core

Meandering

- When the temperature contrast is maximum, jet stream flows in near straight path.
- But when temperature contrast reduces (jet stream is weak), the jet stream starts to follow a meandering path (wavy, irregular manner with a poleward or equatorward component).
- Thus, meandering depends on **temperature contrast (temperature gradient).**
- *High temperature gradient ➔high-pressure gradient ➔ greater wind speed ➔ greater Coriolis force ➔ geostrophic stream ➔ wind direction is parallel to isobars (perfect west-east flow).*
- *Low temperature gradient ➔ low variable Coriolis force ➔ winds start to meander*

Rossby Waves

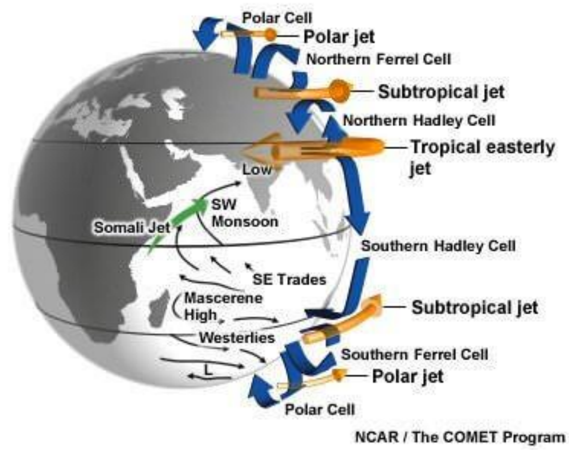


Meandering Jet Streams or Rossby Waves

- The meandering jet streams are called **Rossby Waves.**
- Rossby waves are natural phenomenon in the atmosphere and oceans due to rotation of earth.
- In Rossby waves are polar air moves toward the equator while tropical air moves poleward.
- A meander is called **peak or ridge** if it is towards poles and **trough** if it is towards equator.
- The existence of these waves explains the low-pressure cells **(cyclones)** and high-pressure cells **(anticyclones)**.

2.2 Permanent jet streams

- Polar jet and subtropical jet are **permanent jet streams** that breeze through the upper troposphere for most part of the year.



Permanent and Temporary Jet Streams

Subtropical jet stream (STJ)

- During winter, the STJ is nearly continuous in both hemispheres.
- The STJ exists all year in the southern hemisphere. However, it is intermittent in the northern hemisphere during summer when it migrates north.
- The STJ can be temporarily displaced when strong mid-latitude troughs (remnants of temperate cyclones) extend into subtropical latitudes.
- When these displacements occur, the subtropical jet can merge with the polar front jet (related to cloudbursts. We will study this in Indian Monsoons).
- STJ is closely connected to the Indian and African summer monsoons (we will study this in Indian Monsoons).

Polar front jet (PFJ)

- The strongest jet streams are the polar jets, and subtropical jets are somewhat weaker.
- The northern Polar jet stream follows the sun, i.e., it slowly migrates northward in summer, and southward in winter.
- The polar front jet is closely related to the polar front (frontogenesis process in mid-latitudes).
- It has a more variable position than the sub-tropical jet.
- In summer, its position shifts towards the poles and in winter towards the equator.
- The jet is strong and continuous in winter.
- It greatly influences climates of regions lying close to 60° latitude.
- It determines the path and speed and intensity of temperate cyclones.

2.3 Temporary jet streams

- Other than polar jet and subtropical jet, there are **temporary jet streams** which appear only in a particular season.
- They are few. Important ones are Somali Jet and The African Easterly Jet.
- They are major high-velocity winds in the lower troposphere, and hence they are called low-level jets (LLJs).

The Somali Jet

- The Somali Jet is a south-westerly jet.
- The Somali jet occurs during the summer over northern Madagascar and off the coast of Somalia.
- The jet is most intense from June to August.
- The jet remains relatively steady from June to September before moving southward to the southern Indian Ocean during the winter.

(More details about Somali Jet is given under Indian Monsoons)

The Tropical Easterly Jet or African Easterly Jet

- The TEJ is a unique and dominant feature of the northern hemispheric summer over southern Asia and northern Africa. The TEJ is found near between 5° and 20°N.
- It is fairly persistent in its position, direction, and intensity from June through the beginning of October.
- During the South Asian summer monsoon, the TEJ induces secondary circulations that enhance convection over South India and nearby ocean.
- The establishment and maintenance of the TEJ is not fully understood, but it is believed that the jet may be caused by the uniquely high temperatures and heights over the Tibetan Plateau during summer (dry air encounters more humid air at high altitudes).
- The TEJ is the upper-level venting system for the strong southwest monsoon.
- In recent years due to the decrease in the temperature contrast between the land and sea over the Indian subcontinent, the TEJ has shown a decreasing trend (not good).

2.4 Influence of Jet Streams on Weather

- Jet streams help in maintenance of latitudinal heat balance by mass exchange of air.
- Sub-tropical jet stream and some temporary jet streams together influence Indian Monsoon patterns. (more about this while studying India Monsoons in Indian geography)
- Jet streams also exercise an influence on movement of air masses which may cause prolonged drought or flood conditions.

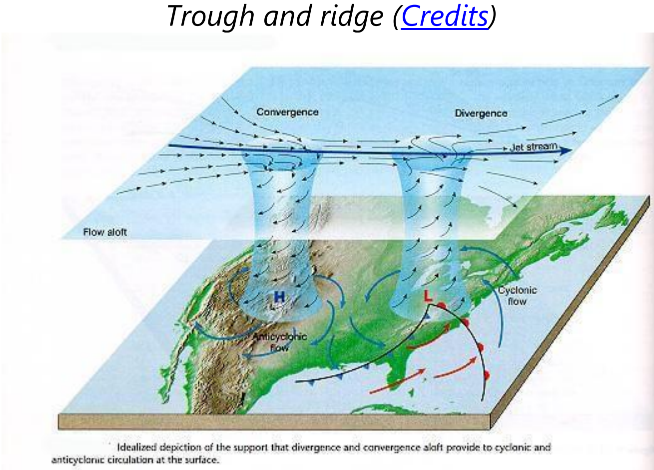
Jet Streams and Weather in Temperate Regions

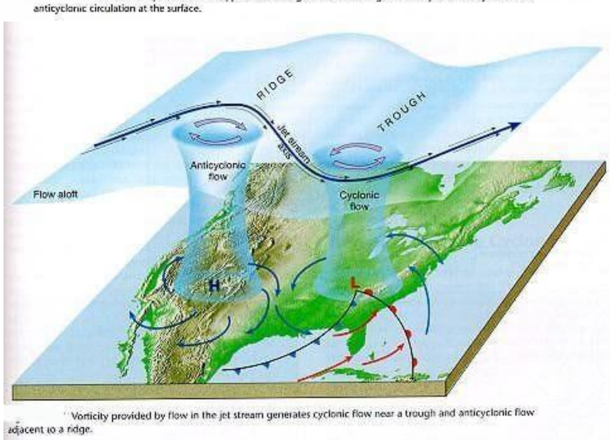
- PFJ play a key role in determining the weather because they usually separate colder air and warmer air.
- Jet streams generally push air masses around, moving weather systems to new areas and even causing them to stall if they have moved too far away.
- PFJ play a major role in determining the **path and intensity of frontal precipitation and frontal cyclones**.
- Weak PFJ also results in **slipping of polar vortex** into temperate regions.

Explanation

- The jet stream drives temperate weather through phenomena called troughing, ridging, and jet streaks.
- Ridges occur where the warm air (at high-pressure) pushes against the cold air.
- Troughs occur where cold air (at lower pressure) drops into warm air.
- This condition occurs due to weak jet stream (lesser temperature contrast between air masses).

Trough and ridge (Credits)



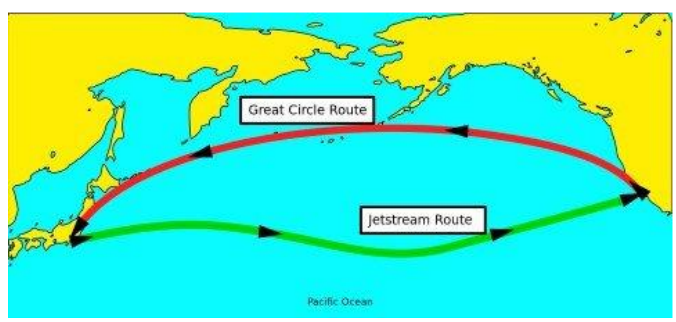


Jet Streak; Ridge and Trough

- Troughs and ridges are analogous to low-pressure (troughs) and high-pressure (ridges).
- Active weather occurs ahead of a trough and quiet weather beneath a ridge.
- The ridges and troughs give rise to jet streaks.
- They form in response to localised but major temperature-gradients.
- The process of winds exiting a trough or a jet streak, known as divergence, creates a void in the upper atmosphere. Air will rush up from lower altitudes to fill the void.
- This upward rush of air from the surface creates a low-pressure system.
- The Coriolis effect creates the cyclonic rotation that is associated with depressions.
- The winds entering the jet streak are rapidly converging, creating a high-pressure at the upper level in the atmosphere. This leads to divergence (high-pressure) at the surface (anticyclonic condition).
- The Coriolis effect creates the anticyclonic rotation that is associated with clear weather.

2.5 Jet Streams and Aviation

- Jet streams are used by aviators if they have to fly in the direction of the flow of the jet streams and avoid them when flying in opposite direction.



- Jet streams can also cause a bumpy flight because the jet stream is sometimes unpredictable and can cause sudden movement, even when the weather looks calm and clear.
- During volcanic eruptions plumes of volcanic ash tend to get sucked into the same jet stream that aeroplanes use for travel.

3. Temperate Cyclones

- Cyclonic systems developing in the mid and high latitude **(35° latitude and 65° latitude in both hemispheres)**, beyond the tropics are called temperate cyclones.
- They are known as **mid-latitude cyclones, extratropical cyclones, frontal cyclones or wave cyclones**.
- Unlike the **tropical cyclones (convective cyclogenesis)** which have a **thermal origin**, the **temperate cyclones (frontal cyclogenesis)** have a **dynamic origin** (complex interaction of air masses under the influence of Coriolis force).
- To understand the mechanism of frontal cyclogenesis (origin and development of temperate cyclones) it is important for us to understand the concepts of **air masses** and **fronts**.

3.1 Air Masses

- An air mass is a large body of air having **little horizontal variation** in **temperature** and **moisture**.
- Air masses are an integral part of the planetary wind system and are associated with one or other wind belt.
- They extend from **surface to lower stratosphere** and are across thousands of kilometres.

Source regions

- When a large parcel of the air remains over a homogenous area for a sufficiently longer time, it acquires the characteristics of the area.
- The homogenous regions can be the vast ocean surface or vast plains and plateaus.
- The homogenous surfaces, over which air masses form, are called the **source regions.**
- The main source regions are the **high-pressure belts** in the **subtropics (giving rise to tropical air masses)** and around the **poles (the source for polar air masses).**
- Source region establishes **heat and moisture equilibrium** with the overlying air mass.
- When an air mass moves away from a source region, the upper level maintains the physical characteristics for a longer period.
- This is possible because air masses are stable with stagnant air which **do not facilitate convection**.
- Conduction and radiation in such stagnant air is not effective.

Conditions for the formation of Air Masses

- Source region should be extensive with **gentle, divergent air circulation** (gentle anticyclonic circulation).
- Areas with **high-pressure but little pressure difference** or pressure gradient are ideal source regions.
- There are **no** major source regions in the mid-latitudes as these regions are dominated by frontal cyclones and other disturbances.

Air masses based on Source Regions

There are five major source regions. These are:

1. Warm tropical and subtropical oceans;
2. The subtropical hot deserts;
3. The relatively cold high latitude oceans;
4. The very cold snow covered continents in high latitudes;
5. Permanently ice-covered continents in the Arctic and Antarctica.

Accordingly, following types of airmasses are recognised:

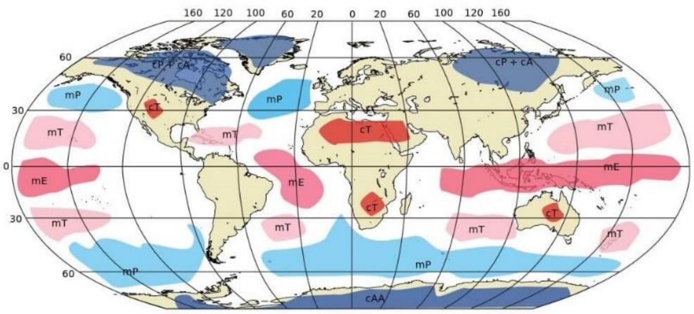
1. Maritime tropical (mT);
2. Continental tropical (cT);
3. Maritime polar (mP);
4. Continental polar (cP);
5. Continental arctic (cA).

The first letter describes moisture properties of the air mass.

- c: continental air masses (dry)
- m: maritime air masses (moist)

The second letter describes source region of the air mass.

- T: Tropical
- P: Polar
- A: Arctic or Antarctic



Air masses (Wikipedia)

- Tropical air masses are warm, and polar air masses are cold.
- The heat transfer processes that warms or cools the air takes place slowly.

Cold Air Mass

- A cold air mass is one which is colder than the underlying surface.

Cold source regions (polar air masses)

- Arctic Ocean – cold and moist
- Siberia – cold and dry
- Northern Canada – cold and dry
- Southern Ocean – cold and moist

Warm Air Mass

- A warm air mass is one which is warmer than the underlying surface.

Warm source regions (tropical air masses)

- Sahara Desert - warm and dry
- Tropical Oceans - warm and moist

Continental Polar Air Masses (cP)

- Source regions of these air masses are the Arctic basin, northern North America, Eurasia and Antarctica.
- Dry, cold and stable conditions characterize these air masses.
- The weather during winter is frigid, clear and stable. During summer, the weather is less stable with lesser prevalence of anticyclonic winds, warmer landmasses and lesser snow.

Maritime Polar Air Masses (mP)

- The source region of these air masses are the oceans between **40° and 60° latitudes**.
- These are those continental polar air masses which have moved over the warmer oceans, got heated up and have collected moisture.
- The conditions over the source regions are **cool, moist and unstable**.
- The weather during winters is characterized by high humidity, overcast skies and occasional fog and precipitation. During summer, the weather is clear, fair and stable.

Continental Tropical Air Masses (cT)

- The source regions of the air masses include tropical and sub-tropical deserts of Sahara in Africa, and of West Asia and Australia.
- These air masses are **dry, hot and stable** and do not extend beyond the source.
- They are dry throughout the year.

Maritime Tropical Air Masses (mT)

- The source regions of these air masses include the oceans in tropics and sub-tropics such as Mexican Gulf, the Pacific and the Atlantic oceans.
- These air masses are **warm, humid and unstable.**
- The weather during winter has mild temperatures, overcast skies with fog.
- During summer, the weather is characterized by high temperatures, high humidity, cumulous clouds and convectional rainfall.

Influence of Air Masses on World Weather

- The properties of an air mass which influence the accompanying weather are **vertical temperature distribution** (indicating its stability and coldness or warmness) and the **moisture content.**

- The air masses carry atmospheric moisture from oceans to continents.
- They transport **latent heat**, thus contributing to latitudinal heat balance.
- Most of the migratory atmospheric disturbances such as cyclones and storms originate at the **contact zone** between different air masses called as fronts.
- Characteristics of the air masses involved determine the weather associated with the disturbances.

3.2 Fronts

- Understanding front formation and types of fronts is important to understand the formation of **mid-latitude cyclones and the dominant weather patterns of mid-latitudes.**
- Fronts are the typical features of **mid-latitudes weather (temperate region – 30° - 65° N and S).** They are uncommon (unusual) in tropical and polar regions.
- Front is a three-dimensional **boundary zone formed between two converging air masses** with **different physical properties** (temperature, humidity, density).
- The two air masses **don't merge readily** due to the effect of the converging atmospheric circulation, different physical properties, relatively low diffusion coefficient and a low thermal conductivity.

Front Formation

- The process of formation of a front is known as **frontogenesis** **(war between two air masses)**, and dissipation of a front is known as **frontolysis** **(one of the air masses win against the other).**
- Frontogenesis involves **convergence** of two distinct air masses.
- Frontolysis involves overriding of one of the air masses by another.
- In northern hemisphere **frontogenesis** (convergence of air masses) happens in **anti-clockwise direction** and southern hemisphere, **clockwise direction**. This is due to **Coriolis force**.
- **Mid-latitude cyclones** **(temperate cyclones or extra-tropical cyclones) occur due to frontogenesis.**

General Characteristics

- The temperature contrast influences the thickness of frontal zone in an **inversely proportional manner**.
- That is, two air masses with higher temperature difference do not merge readily.
- Thus, the front is less thick when it is formed between two air masses with higher temperature difference.
- With a sudden change in temperature through a front, there is a change in pressure also.
- The frontal activity is invariably associated with **cloudiness and precipitation** because of ascent of warm air which cools down **adiabatically**, condenses and causes rainfall.
- The intensity of precipitation depends on the **slope of ascent and amount of water vapour present in ascending air.**
- Front experiences wind shift since the wind motion is a function of pressure gradient and Coriolis force.

Wind Shift: *A change in wind direction of 45 degrees or more in less than 15 minutes with sustained wind speeds of 10 knots or more throughout the wind shift.*
1 knot = 1.852 kmph
1 Nautical Mile = 1.852 km

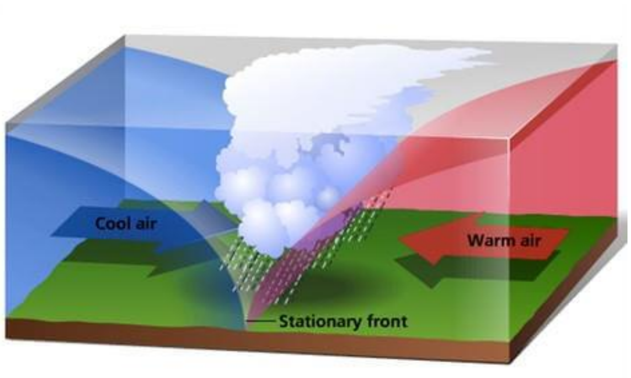
Classification of Fronts

- Based on the mechanism of frontogenesis and the associated weather, the fronts can be studied under the following types.

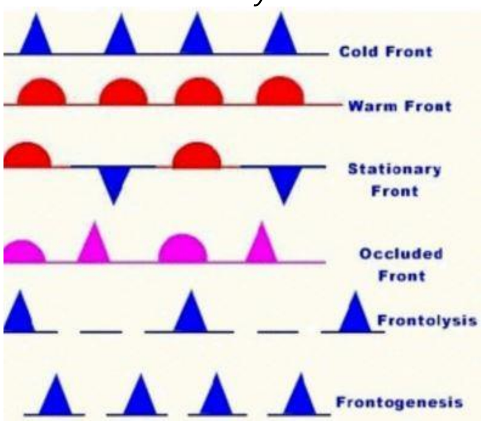
Stationary Front

- When the surface position of a front does not change (when two air masses are unable to push against each other; a draw), a stationary front is formed.
- The wind motion on both sides of the front is **parallel to the front**.
- Warm or cold front stops moving, so the name stationary front.

- Once this boundary resumes its forward motion, it becomes a warm front or cold front.



Stationary Front



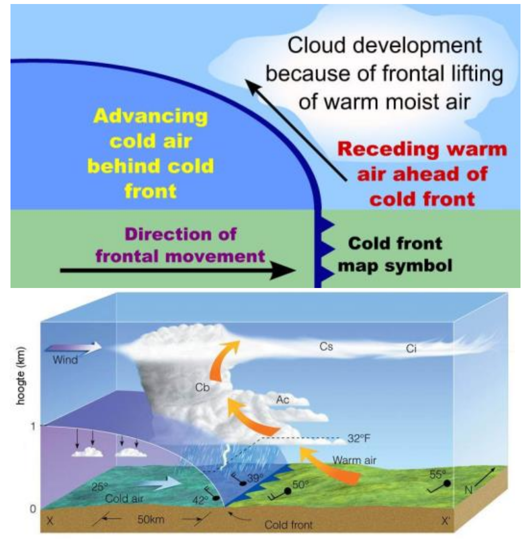
Symbols to indicate various fronts, frontogenesis and frontolysis.

Weather along a stationary front

- **Cumulonimbus clouds** are formed.
- Overrunning (uplifted air) of warm air along such a front causes **frontal precipitation**.
- Frontal cyclones migrating along a stationary front can dump **heavy amounts of precipitation**, resulting in **significant flooding** along the front.

Cold Front

- Such a front is formed when a cold air mass replaces a warm air mass by advancing into it or that the warm air mass retreats and cold air mass advances (cold air mass is the clear winner).
- In such a situation, the transition zone between the two is a **steep sloped** cold front.
- **Cold front moves up to twice as quickly as warm fronts**.
- Frontolysis begins when the warm air mass is completely uplifted by the cold air mass.

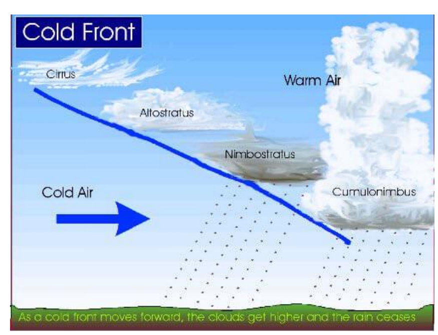


Cold Front

Weather along a cold front

- The weather depends on a narrow band of cloudiness and precipitation (because the slope is steep).
- Severe storms can occur. During the summer months, **thunderstorms** are common in **warm sector.**
- In some regions, **tornadoes** occur in warm sector.
- Cold fronts produce **sharper changes in weather (because upliftment of air is quite rapid)**.
- Temperatures can drop more than 15 degrees within the first hour.

Cloud formation along a cold front



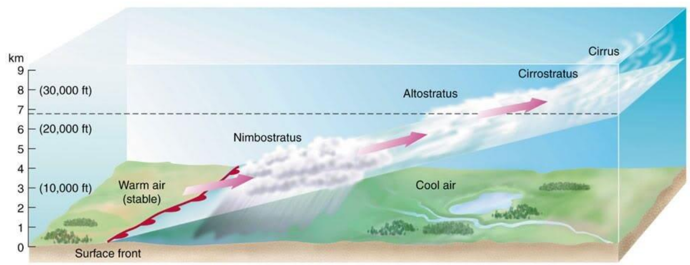
Cloud formation along a cold front

- The approach of a cold front is marked by increased wind activity in warm sector and the appearance of **cirrus clouds**, followed by lower, **denser altocumulus** and **altostratus.**
- At actual front, dark **nimbus and cumulonimbus clouds** cause heavy showers.

- A cold front passes off rapidly, but the **weather along it is violent**.

Warm Front

- It is a **sloping frontal surface** along which active movement of warm air over cold air takes place (warm air mass is too weak to beat the cold air mass).
- Frontolysis (front dissipation) begins when the warm air mass makes way for cold air mass on the ground, i.e. when the warm air mass completely sits over the cold air mass.



*Warm front; There is **no cumulonimbus cloud formation** along a warm front*

Weather along a warm front

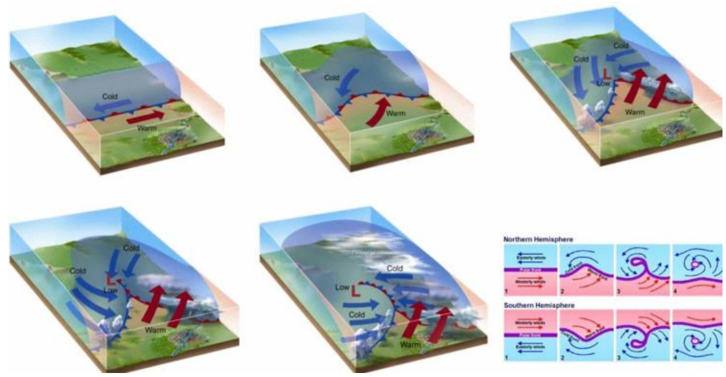
- As the warm air moves up the slope, it condenses and causes precipitation but, unlike a cold front, the temperature and wind direction changes are **gradual.**
- Such fronts cause **moderate to gentle precipitation** over a large area, over several hours.
- The passage of warm front is marked by **rise in temperature and pressure**.

Clouds along a warm front

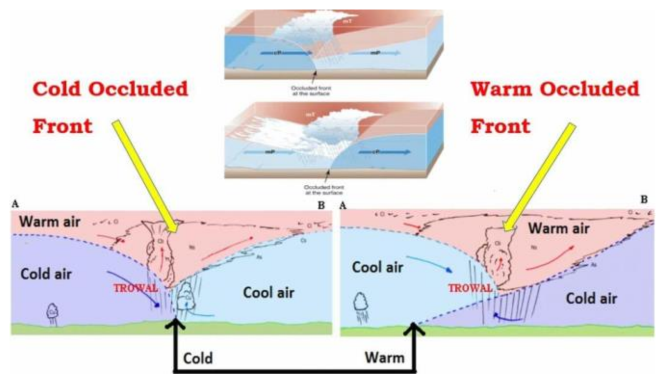
- With the approach, the hierarchy of clouds is—-cirrus, stratus and nimbus (**no cumulonimbus clouds** as the gradient is gentle).
- **Cirrostratus clouds** ahead of the warm front create a halo around sun and moon.

Occluded Front

- **Occlusion:** a process by which the cold front of a rotating low-pressure system catches up the warm front so that the **warm air between them is forced upwards.**
- Such a front is formed when a **cold air mass overtakes a warm air mass** and goes underneath it.



- Frontolysis begin when warm sector diminishes, and the cold air mass completely undertakes the warm sector on ground.
- Thus, a long and backward swinging occluded front is formed which could be a **warm front type or cold front type occlusion**.

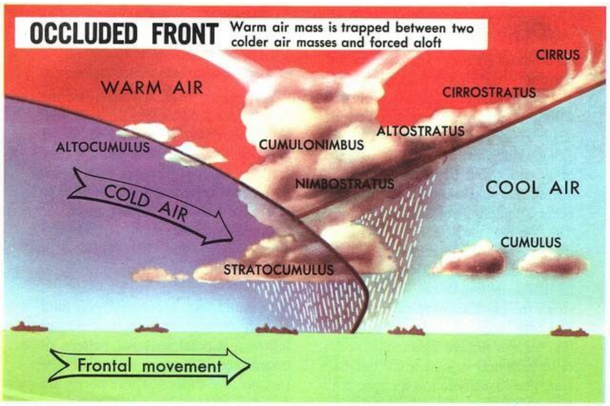


Weather along an occluded front

- Weather along an occluded front is complex — a **mixture of cold front type and warm front type weather**. Such fronts are common in western Europe.
- **The formation mid-latitude cyclones involve the formation of occluded front**.

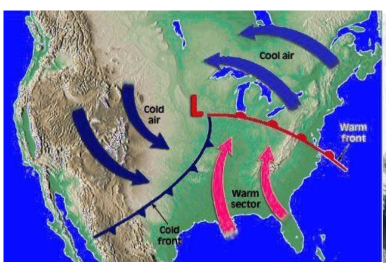
Clouds along an occluded front

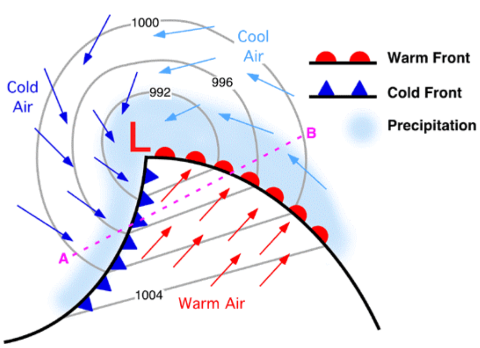
- A combination of clouds formed at cold front and warm front.
- Warm front clouds and cold front clouds are on opposite side of the occlusion.



Stationary Front	• **Tie – No clear Winner**
Cold Front	• **Cold Air mass is the clear winner.**
Warm Front	• **The warm air mass picks up a fight but fails to beat the cold air mass.** • **Cold Air mass is the winner.**
Occluded Front	• **Cold Front + Warm Front** • **Double win for cold air mass**
Cold Front, Warm Front and Occluded front are examples of Temperature Inversion.	

3.3 Origin and Development of Temperate Cyclones





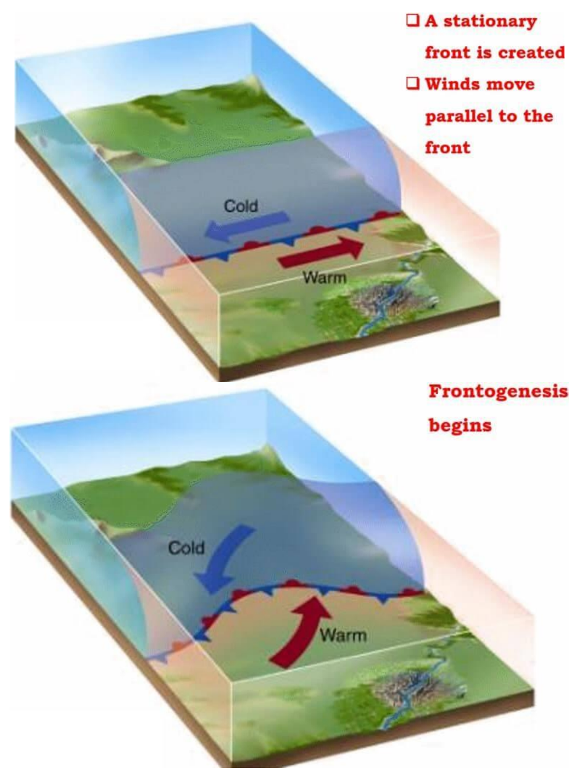
The isobars are not closed in a temperate Cyclones

Polar Front Theory

- According to this theory, the warm-humid air masses from the tropics meet the dry-cold air masses from the poles and thus a polar front is formed as a surface of discontinuity.
- Such conditions occur over **sub-tropical high, sub-polar low-pressure belts** and along the **tropopause**.

Explanation

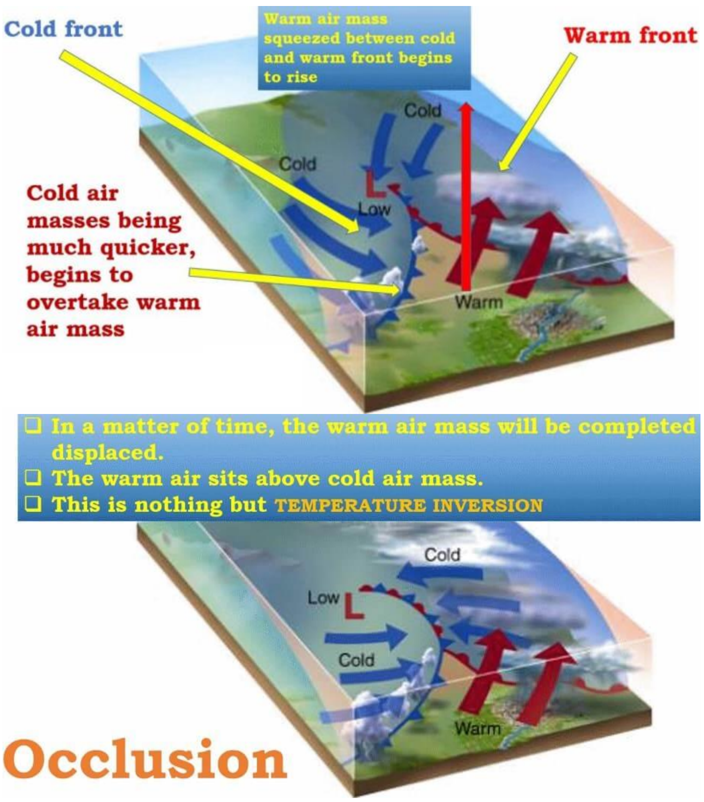
- In the northern hemisphere, warm air blows from the south and cold air from the north of the front.
- When the pressure drops along the front, the warm air moves northwards, and the cold air move towards south setting in motion an **anti-clockwise cyclonic circulation (Coriolis Force; northern hemisphere).**



Convergence of air masses

- The warm air glides over the cold air and a sequence of clouds appear over the sky ahead of the warm front and cause precipitation.
- The cold front approaches the warm air from behind and pushes the warm air up. As a result, cumulus clouds develop along the cold front.
- This leads to a **well-developed extratropical cyclone**, **with a warm front and a cold front**.
- There are pockets of warm air or warm sector wedged between the warm front and the cold front.

- The **cold front moves faster** than the warm front ultimately overtaking the warm front.
- The wedged warm air is completely uplifted (frontolysis), and the front is **occluded (occluded front),** and the cyclone dissipates.
- **Thus, temperate cyclone is intense frontogenesis involving mainly occlusion type fronts**.



Cold front moves faster

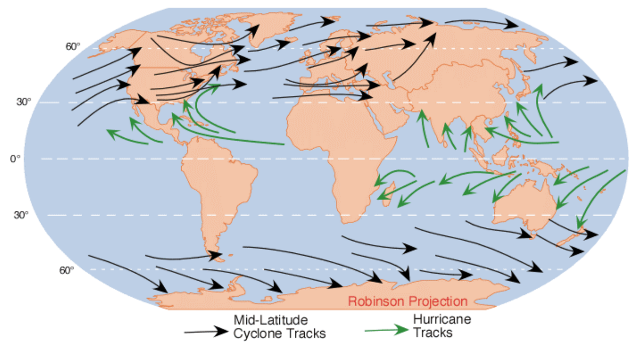
- Normally, individual frontal cyclones exist for about 3 to 10 days moving in a generally **west to east direction**.
- Precise movement of this weather system is controlled by the orientation of the **polar jet stream** in the upper troposphere.

Seasonal Occurrence of Temperate Cyclones

- The temperate cyclones occur mostly in **winter, late autumn and spring**.
- They are generally associated with rainstorms and cloudy weather.
- During summer, all the paths of temperate cyclones shift northwards, and there are only few temperate cyclones over sub-tropics and the warm temperate zone, although a high concentration of storms occurs over Bering Strait, USA and Russian Arctic and sub-Arctic zone.

Distribution of Temperate Cyclones

1. USA and Canada – extend over Sierra Nevada, Colorado, Eastern Canadian Rockies and the Great Lakes region,
2. the belt extending from Iceland to Barents Sea and continuing over Russia and Siberia,
3. winter storms over Baltic Sea,
4. Mediterranean basin extending up to Russia and even up to India in winters (called **western disturbances**) and the Antarctic frontal zone.



Distribution of Temperate Cyclones and Tropical Cyclones

Characteristics of Temperate Cyclones

Size and Shape

- The temperate cyclones are asymmetrical and shaped like an inverted 'V'.
- They stretch over 500 to 600 km.
- They may spread over 2500 km over North America.
- They have a height of 8 to 11 km.

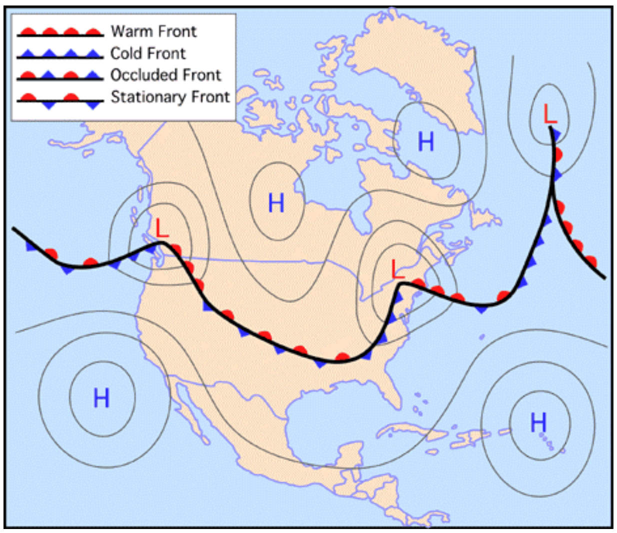
Shape of a Temperate Cyclone

Wind Velocity and Strength

- The wind strength is more in eastern and southern portions, moreover North America compared to Europe.
- The wind velocity increases with the approach but decreases after the cyclone has passed.

Orientation and Movement

- Polar jet stream plays a major role in the formation and hence influences the path of temperate cyclones.



Westerly Path of a Frontal Cyclone System

- Since these cyclones move with the **westerlies**, they are oriented **east-west**.
- If the storm front is east-west, the centre moves swiftly eastwards.
- If the storm front is directed northwards, the centre moves towards the north, but after two or three days, the pressure difference declines and the cyclone dissipate.
- In case the storm front is directed southwards, the centre moves quite deep southwards-even up to the Mediterranean region (sometimes causing the Mediterranean cyclones or **Western Disturbances** — they are very important as they bring rains to North-West India – Punjab, Haryana).

Structure

- The north-western sector is the cold sector and the north-eastern sector is the warm sector (Because cold air masses in north and warm air masses in south push against each other and rotate anti-clockwise in northern hemisphere).

Associated Weather

- The approach of a temperate cyclone is marked by fall in temperature, fall in the mercury level, wind shifts and a **halo around the sun and the moon**, and a thin veil of **cirrus clouds**.
- A light drizzle follows which turns into a heavy downpour. These conditions change with the arrival of the warm front which halts the fall in mercury level and the rising temperature.
- Rainfall stops and clear weather prevails until the cold front of an anticyclonic character arrives which causes a fall in temperature, brings cloudiness and rainfall with thunder. After this, once again clear weather is established.
- The temperate cyclones experience more rainfall when there is slow movement and a marked difference in rainfall and temperature between the front and rear of the cyclone. Anticyclones generally accompany these cyclones.

4. Tropical Cyclones and Temperate Cyclones — Comparison

	Tropical Cyclone	**Temperate Cyclone**
Origin	• **Thermal Origin.**	• **Dynamic Origin:** Coriolis Force, Movement of air masses.
Latitude	• Confined to 10-30° N and S of equator.	• Confined to 35-65° N and S of equator. • More pronounced in Northern hemisphere due to **greater temperature contrast**.
Frontal system	• Absent.	• The very cyclone formation is due to frontogenesis. (Occluded Front).
Formation	• They form only on seas with temperature more than 26-27^{0} C.	• Can form **both** on land as well as seas.

	• They dissipate on reaching the land.	
Season	• Seasonal: Late summers (Aug-Nov).	• Irregular. But few in summers and **more in winters**.
Size	• Limited to small area. • Typical size: 100 – 500 kms in diameter. • Varies with the strength of the cyclone.	• They cover a larger area. • Typical size: 300 – 2000 kms in diameter. Varies from region to region.
Shape	• Elliptical	• Inverted 'V'
Rainfall	• Heavy but does not last beyond a few hours. • If the cyclone stays at a place, the rainfall may continue for a few days.	• In a temperate cyclone, rainfall is slow and continues for many days, sometimes even weeks.
Wind Velocity and destruction	• Much greater. • 100 – 250 kmph • 200 – 1200 kmph in upper troposphere) • Greater destruction due to **winds, storm surges and torrential rains.**	• Comparatively low. • Typical range: 30-150 kmph. • Less destruction due to winds but more destruction due to **flooding.**
Isobars	• Complete circles and the **pressure gradient is steep**	• Isobars are usually 'V' shaped and the pressure gradient is low.
Lifetime	• Doesn't last for more than a week	• Lasts for 2-3 weeks.
Path	• East – West. Turn North at 20^0 latitude and west at 30^0 latitude. • Move away from equator. • The movement of Cyclones in Arabian Sea and Bay of Bengal is a little different. • Here, these storms are superimposed upon the **monsoon circulation** of the summer months, and they move in northerly direction along with the monsoon currents.	• West – East (Westerlies; Jet Streams). • Move away from equator.
Temperature distribution	• The temperature at the centre is almost equally distributed.	• All the sectors of the cyclone have different temperatures
Calm region	• The centre of a tropical cyclone is known as the eye. The wind is calm at the centre with no rainfall.	• In a temperate cyclone, there is not a single place where winds and rains are inactive.
Driving force	• The tropical cyclone derives its energy from the **latent heat of condensation**, and the difference in densities of the air masses does not contribute to the energy of the cyclone.	• The energy of a temperate cyclone depends on the temperature, humidity and **density differences of air masses**.
Influence of Jet streams	• The relationship between tropical cyclones and the upper level air-flow is not very clear.	• The temperate cyclones, in contrast, have a distinct relationship with upper level air flow (jet streams, Rossby waves etc.)
Clouds	• The tropical cyclones exhibit fewer varieties of clouds – cumulonimbus, nimbostratus, etc.	• The temperate cyclones show a variety of cloud development at various elevations.
Surface anti-cyclones	• The tropical cyclones are not associated with surface anticyclones and they have a greater destructive capacity.	• The temperate cyclones are associated with anticyclones which precede and succeed a cyclone. • These cyclones are not very destructive.
Influence on India	• Both coasts affected. But east coast is the hot spot.	• Bring rains to North-West India. • The associated instability is called '**Western Disturbances**'.
Weather Prediction	• Tough as the movement can be erratic due to a lot of factors.	• Easy because of the general westerly path of the cyclone, less variable jet stream path and simple frontal system.

- Titbit: In certain instances, two cyclones move toward each other and revolve around one another, with the smaller and less intense one moving more quickly. This phenomenon is called the **Fujiwhara effect**.

5. Polar Vortex

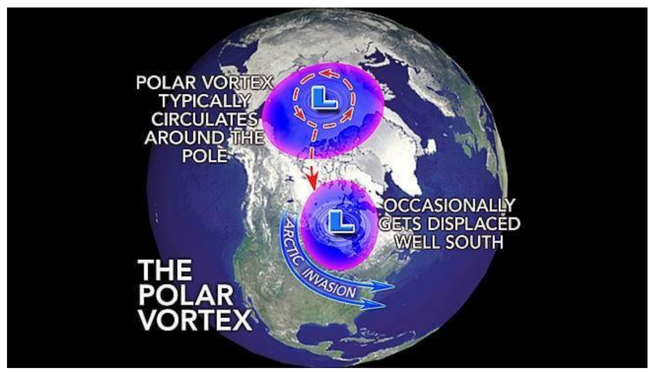
- Polar vortex (circumpolar vortex) is a **polar cyclone.**
- Arctic or polar cyclones occur in polar regions and can reach up to 2,000 km wide.
- Polar cyclones differ with others because they are not seasonal. They can occur at any time of the year.
- Polar cyclones **can also form quickly (sometimes less than 24 hours)**, and their direction or movement **cannot be predicted**.
- They can last from a **day up to several weeks**.
- Most frequently, polar cyclones develop above northern Russia and Siberia.
- A polar vortex is a large pocket of very cold air, typically the coldest air in the Northern Hemisphere, which sits over the polar region during the winter season.
- Polar Vortex is a
  - ✓ Cold;
  - ✓ Circumpolar;
  - ✓ Upper tropospheric low-pressure: sometimes extending till the lower levels of **stratosphere** (at poles, the troposphere extends only up to 8-9 km);
  - ✓ Large cyclonic parcel of air (about 1000 km across) (counter-clockwise in the Northern Hemisphere)
- Polar vortex is closely associated with **jet streams (Rossby waves).**
- It is formed mainly in winter and gets **weaker in summer**.
- It surrounds **polar highs** and lie within the polar front (boundary separating the temperate and polar air masses).

5.1 Polar Vortex Cold Wave

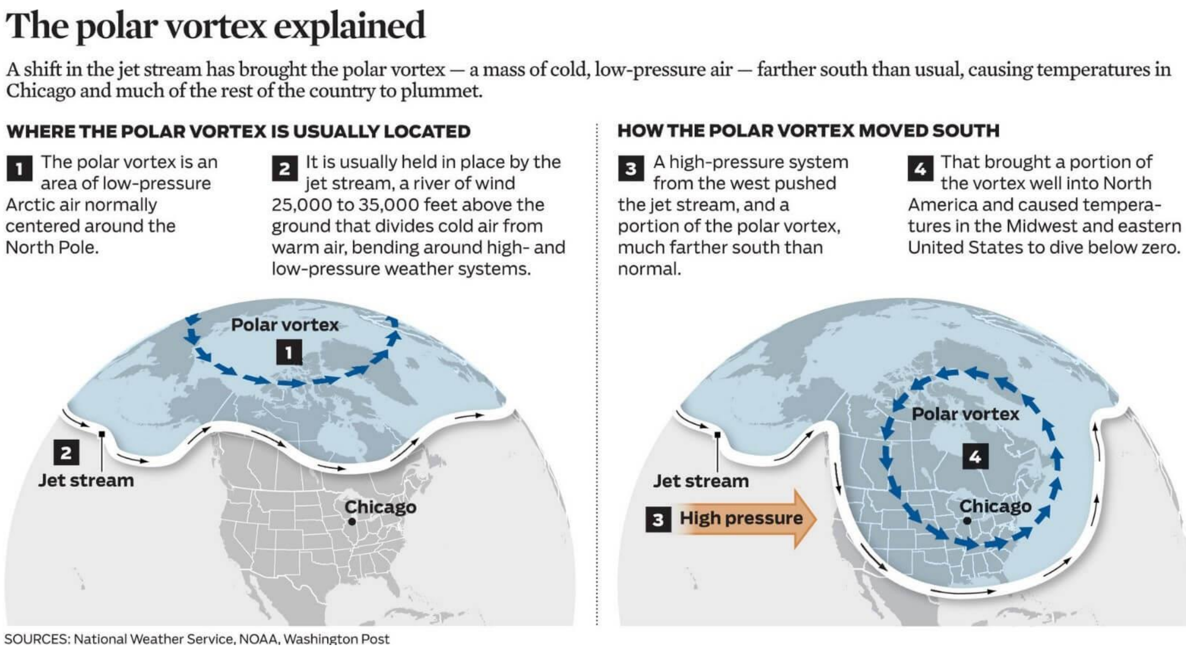
Polar Vortex slipping into Mid-latitudes,
Breakdown of the polar vortex,
Sudden stratospheric warming,
Polar vortex event.
All the above terms mean the same — Polar Vortex Cold Wave.

- The polar vortex will remain in its place when the westerlies along with the polar jet are strong (strong polar vortex means that there is **huge temperature contrast** between the temperate and polar regions).
- **When the polar vortex is weak**, it intrudes into the mid-latitude regions by buckling the general wind flow pattern. This leads to **significant cold outbreaks** in the mid-latitude regions.
- The vortex is capable of delivering sub-zero temperatures to the United States and Canada where is occurs the most.

How it slips



- The Polar jet traverses somewhere over 65° N and S latitudes. When the temperature contrast between polar and temperate regions is maximum, the jet is very strong, and the meandering is negligible.
- But when the temperature contrast is low, the jet starts to meander (Rossby waves).
- Meandering jet creates alternating low and high-pressure cells.
- High-pressure cells are created below the ridges and the low-pressure cells below the troughs (this is because of the upper air circulations created by the jet).
- With severe meandering, the high-pressure cells push over to north and displace the polar cyclone from its normal position i.e. the cyclone moves away from the pole and slips into the temperate regions.
- With the strengthening of the jet, the high-pressure cells become weak and retreat to their normal latitudinal positions.



Polar Vortex slipping into temperate regions

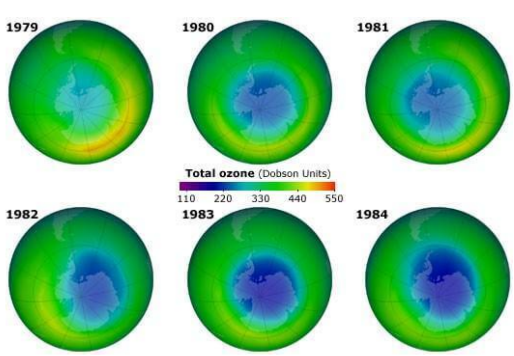
- With the retreat of the high-pressure cells, the polar cyclone moves back to its normal position.

5.2 Polar Vortex and Ozone Depletion at South Pole

- Polar vortex and ozone depletion are two distinct but related phenomena.

Ozone depletion

- There is a steady decline of about 4% in the total volume of ozone in Earth's stratosphere.
- Much larger decrease in stratospheric ozone is observed around **Earth's polar regions**.
- Depletion of ozone is due to increase in **halocarbons** in the atmosphere.



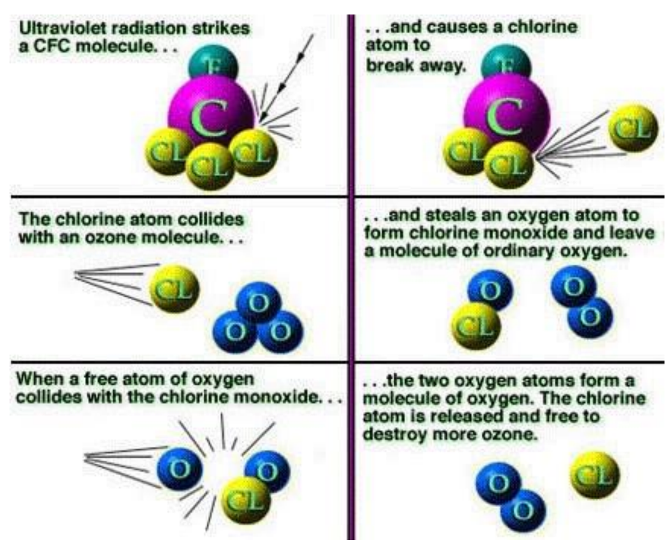
Ozone Hole at the South Pole

Halocarbon: a compound in which the hydrogen of a hydrocarbon is replaced by halogens like chlorine, bromine, iodine etc.

Halogen: group of reactive non-metallic elements like fluorine, chlorine, bromine, iodine, etc.

Halogen atoms like chlorine destroy ozone

- **Photodissociation** (under the influence of sunlight) of **ozone-depleting substances** (ODS) like **halocarbon refrigerants, solvents, propellants, and foam-blowing agents (CFCs, HCFCs, carbon tetrachloride and trichloroethane, freons, halons)** creates **free chlorine atoms** that destroy ozone.

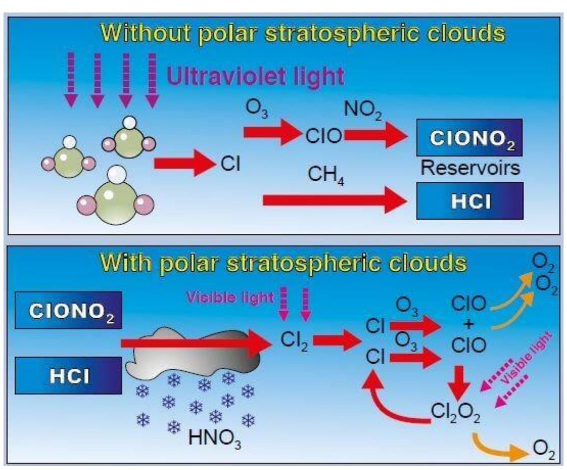


Photodissociation of ozone-depleting substances break O_3 into O_2

But how does a chlorine atom reach to such high levels of atmosphere?

Polar Stratospheric Clouds (PSCs)

- They are nacreous clouds that extend from 12-22 km above the surface.
- Nacreous clouds are rare clouds in frigid regions of the **lower stratosphere**.
- They are mostly visible within two hours after sunset or before dawn.
- They are bright even after sunset and before dawn because at those heights there is still sunlight.
- They are seen mostly during winter at high latitudes.
- PSCs or nacreous clouds contain water, **nitric acid and/or sulfuric acid**.
- They are **formed mainly during the event of polar vortex in winter**; **more intense at south pole**.
- The **Cl-catalysed ozone depletion is enhanced in the presence of polar stratospheric clouds.**
- PSCs convert **reservoir compounds** into reactive **free radicals (Cl and ClO)** thereby significantly **increasing the reactive halogen radicals**. These **free radicals accelerate depletion of ozone**.
- Thus, **polar vortex, in the form of PSCs, accelerate ozone depletion**.



Ozone Depletion is Enhanced by PSCs

Prelims question: The formation of ozone hole in the Antarctic region has been a cause of concern. What could be the reason for ozone depletion at poles?

a) Presence of prominent tropospheric turbulence; and inflow of chlorofluorocarbons
b) Presence of prominent polar front and stratospheric Clouds and inflow of chlorofluorocarbons
c) Absence of polar front and stratospheric clouds; and inflow of methane and chlorofluorocarbons
d) Increased temperature at polar region due to global warming

Explanation:

- Ozonosphere lies at an altitude between 20 km and 55 km from the earth's surface and spans the stratosphere and lower mesosphere. But the highest concentration occurs between 20 km and 30 km.
- **To destroy ozone, ozone-depleting substances** (ODS) like **CFCs, HCFCs, etc. needs to be carried up to the lower levels of stratosphere**.
- **And the only weather phenomenon that can reach to this level are Polar Vortex and** towering tropical cumulus clouds.
- But **towering cumulus clouds do not occur at the poles**.

Question: The formation of ozone hole in the Antarctic region has been a cause of concern. What could be the reason for ozone depletion at poles?

- Presence of prominent tropospheric turbulence: they don't reach the stratosphere.
- Presence of prominent polar front: essential to keep polar vortex in its place. Polar vortex gives rise to stratospheric Clouds.
- Presence of stratospheric Clouds: they have the necessary ingredients (**nitric acid and/or sulfuric acid**) to amplify ozone depletion.
- Absence of polar front and stratospheric clouds: polar vortex slips into the temperate region.
- Inflow of methane: **methane (CH_4) is not in the list of ozone-depleting substances**.
- It doesn't contain a halogen like chlorine, bromine, fluorine, etc. But it reacts with halogens to create **reservoir compounds**.

- Increased temperature at polar region due to global warming: this doesn't have any direct impact on ozone depletion at the poles.

6. El Nino

- Warming and cooling of the Pacific Ocean is most important in terms of general atmospheric circulation.

6.1 Normal Conditions

- In a normal year, a surface **low-pressure** develops in the region of **northern Australia and Indonesia** and a **high-pressure** system over the **coast of Peru**.
- As a result, the **trade winds** over the Pacific Ocean move strongly from **east to west.**
- The easterly flow of the trade winds carries warm surface waters **westward**, bringing **convective storms (thunderstorms)** to Indonesia and coastal Australia.
- Along the coast of Peru, cold bottom **cold nutrient-rich water wells up** to the surface to replace the warm water that is pulled to the west.

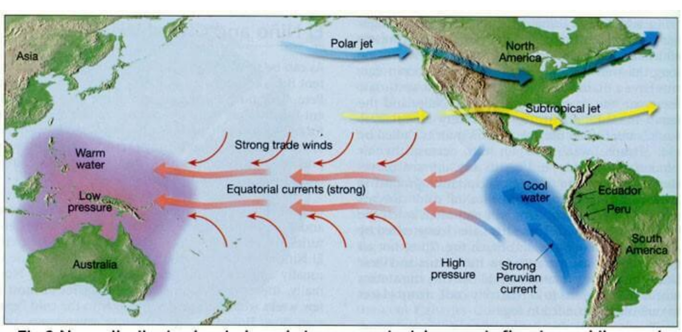
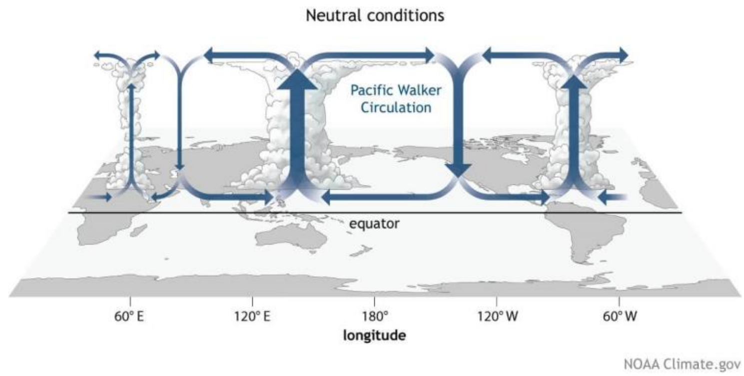


Fig.6 Normally, the trade winds and strong equatorial currents flow toward the west. At the same time, an intense Peruvian current causes upwelling of cold water along the west coast of South America.

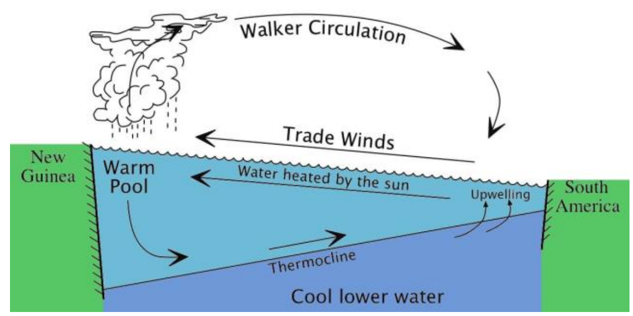
Normal Conditions: Warm water accumulation in Western Pacific and cold water upwelling in Eastern Pacific

Walker circulation (Normal Years)

- The Walker circulation (Walker cell) is caused by the pressure gradient force that results from a **high-pressure system over the eastern Pacific Ocean**, and a **low-pressure system over Indonesia.**
- The Walker cell is indirectly related to upwelling off the coasts of Peru and Ecuador. This brings **nutrient-rich cold water to the surface**, increasing **fishing stocks.**



Normal Conditions: Thunderstorms in equatorial western Pacific and calm conditions in equatorial eastern Pacific



Atmospheric circulation typically found at the equatorial Pacific. (Photo: W.S. Kessler, NOAA/PMEL)
Thermocline: *a temperature gradient in a body of water, separating layers at different temperatures.*

6.2 During El Nino year

- El Niño is the name given to the occasional development of **warm ocean surface waters along the coast of Ecuador and Peru**.
- In an El Niño year, air pressure drops over large areas of the central Pacific and along the coast of South America.
- The normal low-pressure system is replaced by a weak high in the western Pacific (the **southern oscillation**).
- This change in pressure pattern causes the **trade winds to be reduced — Weak Walker Cell.** Sometimes Walker Cell might even get reversed.
- This reduction allows the **equatorial counter current (west to east current along calm doldrums)** to accumulate warm ocean water along

the coastlines of Peru and Ecuador replacing the cool Peruvian current.

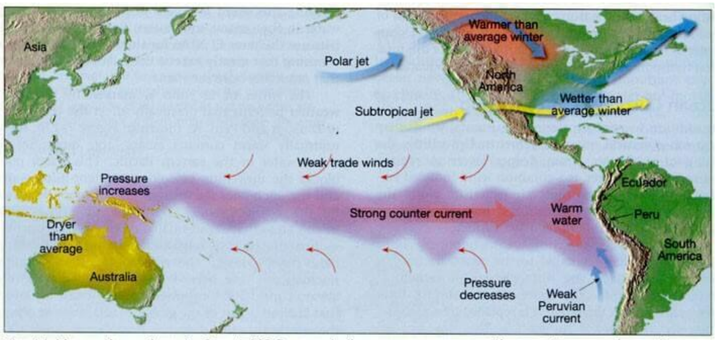
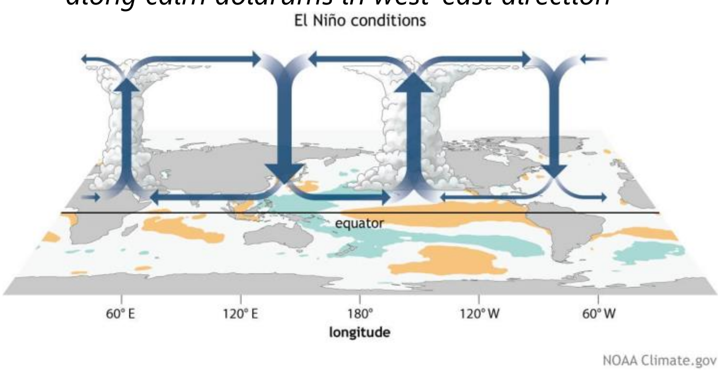


Fig.14 Upon the advent of an ENSO event, the pressure over the eastern and western Pacific flip-flops. This causes the trade winds to diminish, leading to an eastward movement of warm water along the equator. As a result, the surface waters of the central and eastern Pacific warm, with far-reaching consequences to weather patterns.

El Nino conditions: Equatorial counter current flows along calm doldrums in west-east direction



El Nino conditions: Drought in Northern Australia and floods in Central America

- The accumulation of warm water causes the thermocline to drop in the eastern part of Pacific Ocean which **cuts off the upwelling of cold deep ocean water** along the coast of Peru.
- Climatically, the development of an El Niño brings **drought to the western Pacific**, **rains to the equatorial coast of South America**, and **convective storms and hurricanes to the central Pacific.**
- El Niño normally occurs around **Christmas** and usually lasts for a few weeks to a few months.
- Sometimes an extremely warm event can develop that lasts for much longer periods.
- In the 1990s, strong El Niños developed in 1991 and lasted until 1995.

El Nino Southern Oscillation (ENSO)

- This phenomenon is closely monitored and is used for long-range forecasting in major parts of the world.
- The formation of an **El Niño (circulation of surface ocean current)** is linked with Pacific Ocean circulation pattern known as the **southern oscillation (circulation of atmospheric pressure).**
- Southern Oscillation, in oceanography and climatology, is a coherent inter-annual **fluctuation of atmospheric pressure** over the tropical Indo-Pacific region.
- El Nino and Southern Oscillation coincide most of the times hence their combination is called **ENSO – El Nino Southern Oscillation.**
- In the years when the ENSO is strong, large-scale variations in weather occur over the world.
- The arid west coast of South America receives heavy rainfall, drought occurs in Australia and sometimes in India and floods in China.

Only El Nino == Warm water in Eastern Pacific + Cold water in Western Pacific.

Only SO == Low-pressure over Eastern Pacific + High-pressure over Western Pacific

ENSO = (Warm water in Eastern Pacific + Low-pressure over Eastern Pacific) + (Cold water in Western Pacific + High-pressure over Western Pacific).

Effects of El Nino

- The warmer waters had a **devastating effect on marine life** existing off the coast of Peru and Ecuador.
- Fish catches off the coast of South America were lower than in the normal year.
- **Severe droughts occur in Australia, Indonesia, India and southern Africa.**
- Heavy rains in California, Ecuador, and the Gulf of Mexico.

Normal Conditions

- ***Eastern Pacific == Coast of Peru and Ecuador == Cold Ocean Water == Good for Fishing.***
- ***Western Pacific == Indonesia and Australia == Warm Ocean Water == Plenty of rains.***

El Nino

- ***Eastern Pacific == Coast of Peru and Ecuador == Warm Ocean Water == Fishing industry takes a hit.***
- ***Western Pacific == Indonesia and Australia == Cold Ocean Water == Drought.***

El Nino impact on Indian Monsoons

- El Nino and Indian monsoon are **inversely related**.
- The location of low-pressure and hence the rising limb over Western Pacific is considered to be conducive to good monsoon rainfall in India.
- **Its shifting eastward** from its normal position, such as in El Nino years, **reduces** monsoon rainfall in India.
- The most prominent droughts in India have been El Nino droughts, including the recent ones (2014-16).
- However, not all El Nino years led to a drought in India. For instance, 1997/98 was a strong El Nino year, but there was no drought (this is because of **Indian Ocean Dipole – IOD**).
- On the other hand, a moderate El Nino in 2002 resulted in one of the worst droughts.
- El Nino directly impacts India's agrarian economy as it tends to lower the production of summer crops such as rice, sugarcane, cotton and oilseeds.
- The ultimate impact is seen in the form of high inflation, and low gross domestic product growth as agriculture contributes around 14 per cent to the Indian economy.

Southern Oscillation Index and Indian Monsoons

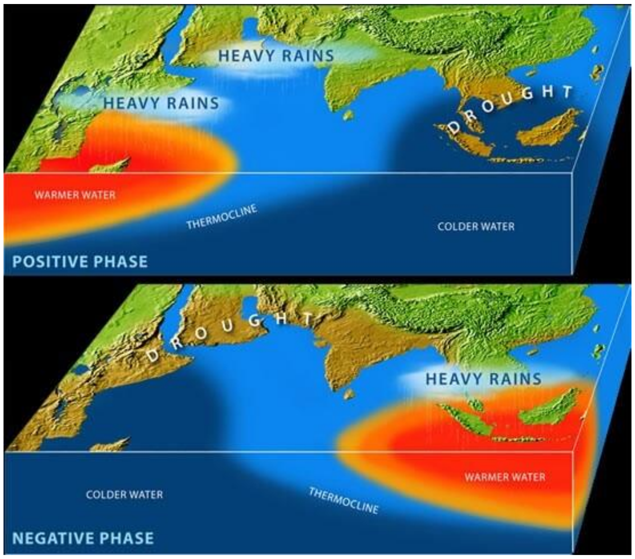
- Southern Oscillation Index (SOI) is used to measure the intensity of the Southern Oscillation.
- This is the difference in pressure between **Tahiti in French Polynesia** (Central Pacific), representing the Central Pacific Ocean and **Port Darwin**, in northern Australia representing the Eastern Pacific Ocean.
- The positive and negative values of the SOI, i.e. Tahiti minus the Port Darwin pressure are pointers towards good or bad rainfall in India.

Positive SOI	Negative SOI
Tahiti (eastern Pacific) pressure greater than that of Port Darwin (western Pacific)	**Reverse**
Drought conditions in Eastern Pacific and good rainfall in Western Pacific	**Reverse**
Good for Indian Monsoons	**Bad for Indian Monsoons**

Indian Ocean Dipole effect (Not every El Nino year is same in India)

- In the recent decades, the ENSO-Monsoon relationship seemed to weaken in the Indian subcontinent. For e.g. the 1997, strong ENSO failed to cause drought in India.
- It was discovered that just like ENSO was an event in the Pacific Ocean, a similar seesaw ocean-atmosphere system in the Indian Ocean was also at play.
- It was discovered in 1999 and named the **Indian Ocean Dipole (IOD).**
- The Indian Ocean Dipole (IOD) is defined by the **difference in sea surface temperature between two areas** (or poles, hence a dipole) — a western pole in the **Arabian Sea** (western Indian Ocean) and an eastern pole in the **eastern Indian Ocean** south of Indonesia.
- IOD starts to develop in the equatorial region of Indian Ocean in April and is best devolved in October.
- With a **positive IOD** winds over the Indian Ocean blow from east to west (**from Bay of Bengal towards Arabian Sea**).
- This results in the Arabian Sea (western Indian Ocean near African Coast) being much warmer and eastern Indian Ocean around Indonesia becoming colder and dry.

- In the negative dipole year (**negative IOD**), reverse happens making Indonesia much warmer and rainier.



Indian Ocean Dipole

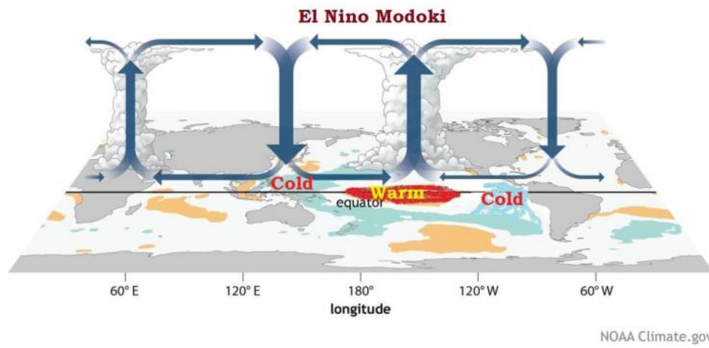
- It was demonstrated that a positive IOD index often negated the effect of ENSO, resulting in increased Monsoon rains in several ENSO years like the 1983, 1994 and 1997.
- Similar to ENSO, the atmospheric component of the IOD was later discovered and named as **Equatorial Indian Ocean Oscillation (EQUINOO: oscillation of warm water and atmospheric pressure between Bay of Bengal and Arabian Sea).**

Impact of IOD on Cyclogenesis in Northern Indian Ocean

- Positive IOD (Arabian Sea warmer than Bay of Bengal) results in more cyclones than usual in Arabian Sea.
- Negative IOD results in stronger than usual cyclogenesis in Bay of Bengal. Cyclogenesis in Arabian Sea is suppressed.

6.3 El Niño Modoki

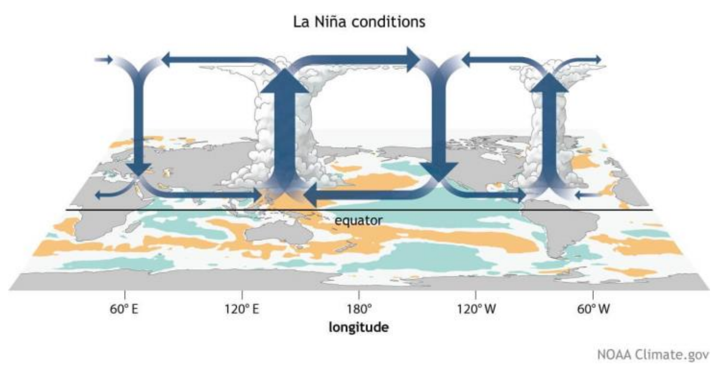
- El Niño Modoki is a coupled ocean-atmosphere phenomenon that is slightly different from El Niño.
- Conventional El Niño is characterised by **strong anomalous warming in the eastern equatorial Pacific**.
- Whereas, El Niño Modoki is associated with **strong anomalous warming in the central tropical Pacific and cooling in the eastern and western tropical Pacific**.
- Such zonal gradients result in anomalous **two-cell Walker Circulation** over the tropical Pacific, with a wet region in the central Pacific and dry region in the western and eastern Pacific.



El Niño Modoki: Droughts in Western and Eastern Pacific; copious rainfall in the Central Pacific

6.4 La Nina

- After an El Niño event weather conditions usually return to normal.
- However, in some years the trade winds can become **extremely strong,** and an abnormal accumulation of cold water can occur in the central and eastern Pacific. This event is called a La Niña.



La Nina: Abnormally heavy monsoons in India and Southeast Asia

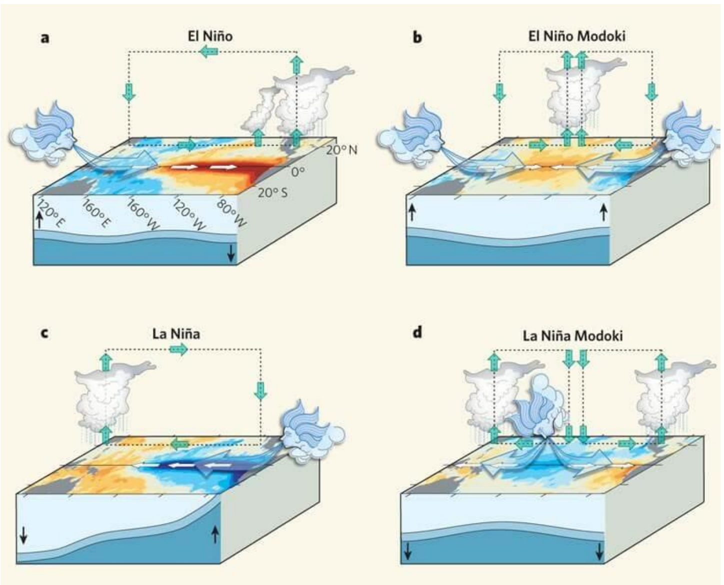
Effects of La Nina

- A strong La Niña occurred in 1988 and scientists believe that it may have been responsible for the summer drought over central North America.

- During this period, the Atlantic Ocean has seen very active hurricane seasons in 1998 and 1999.
- One of the hurricanes that developed, named **Mitch**, was the strongest October hurricane ever to develop in about 100 years of record keeping.

Some of the other weather effects of La Niña include

- **Abnormally heavy monsoons in India and Southeast Asia**,
- Cool and wet winter weather in south-eastern Africa, wet weather in eastern Australia,
- Cold winter in western Canada and north-western United States,
- Winter drought in the southern United States.



7. Koppen's Scheme of Classification of Climate

- The most widely used classification of climate is the empirical climate classification scheme developed by V. Koppen.
- **Empirical**: verifiable by observation or experience rather than theory or pure logic. E.g. when dropped stone falls to the ground – logic. Drop a stone to confirm that it falls to the ground – empirical.
- Koppen identified a close relationship between the **distribution of vegetation** and **climate.**
- He selected certain values of **temperature** and **precipitation** and related them to the **distribution of vegetation** and used these values for classifying the climates.
- Koppen recognized five major climatic groups; four of them are based on temperature and one on precipitation.
- The capital letters: **A, C, D and E delineate humid climates** and **B dry climates**.
- The climatic groups are subdivided into types, designated by small letters, based on seasonality of precipitation and temperature characteristics.
- The seasons of dryness are indicated by the small letters: f, m, w and s.

f	**no dry season**
m	**monsoon climate**
w	**winter dry season**
s	**summer dry season**

- The small letters a, b, c and d refer to the degree of severity of temperature.
- The small letters h and k refer to tropical and mid-latitude regions respectively.
- The B - Dry Climates are subdivided using the capital letters **S for steppe or semi-arid** and **W for deserts**.

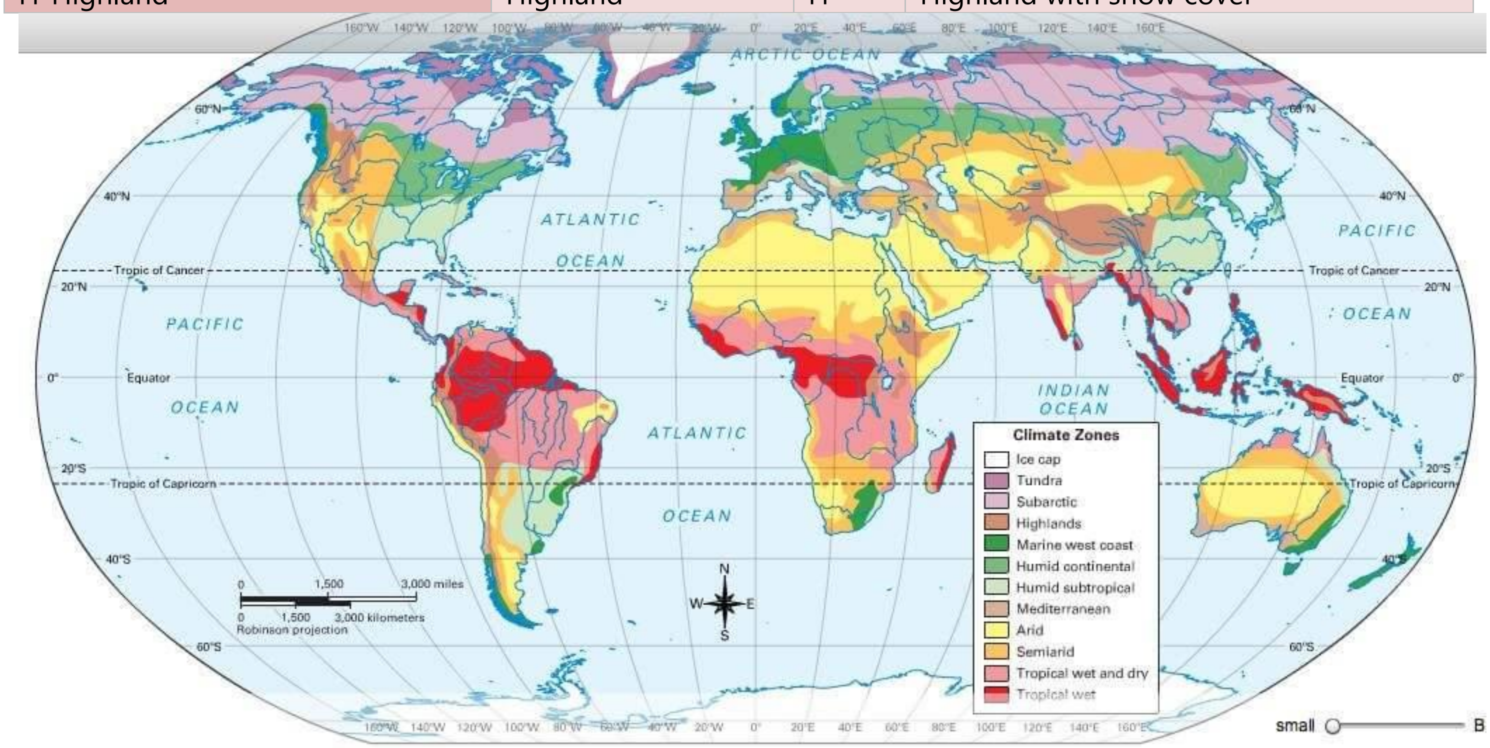
S	Steppe
W	Desert

Climatic Groups According to Koppen

Climatic Group	Characteristics
A – Tropical	Average temperature of the coldest month is 18 °C or higher
B – Dry Climates	Potential evapouration exceeds precipitation
C – Warm Temperate	The average temperature of the coldest month of the (Mid-latitude) climates years is higher than minus 3 °C but below 18 °C (-3 °C to 18 °C)
D – Cold Snow Forest Climates	The average temperature of the coldest month is minus 3 °C or below
E – Cold Climates	Average temperature for all months is below 10 °C
H – High Land	Cold due to elevation

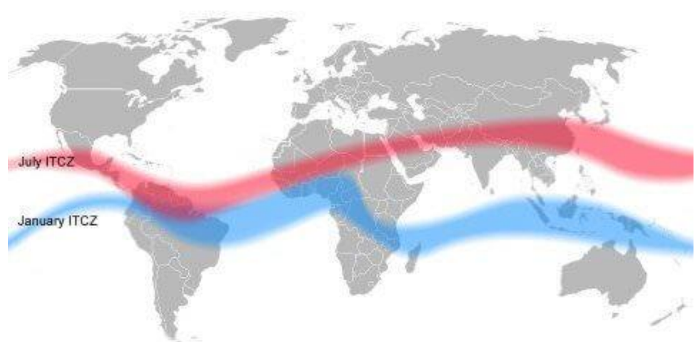
Climatic Types According to Koppen

Climatic Group	Type	Code	Characteristics
A-Tropical Humid Climate	Tropical wet	Af	No dry season
	Tropical monsoon	Am	Monsoonal. Short dry season
	Tropical wet and dry	Aw	Winter dry season
B-Dry Climate	Subtropical steppe	BSh	Low-latitude semi-arid or dry
	Subtropical desert	BWh	Low-latitude arid or dry
	Mid-latitude steppe	BSk	Mid-latitude semi-arid or dry
	Mid-latitude desert	BWk	Mid-latitude arid or dry
C-Warm temperate (Mid-latitude) Climates	Humid subtropical	Cfa	No dry season, warm summer
	Mediterranean	Cs	Dry hot summer
	Marine west coast	Cf	No dry season, warm and cool summer
D-Cold Snow-forest Climates	Humid continental	Df	No dry season, severe winter
	Subarctic	Dw	Winter dry and very severe
E-Cold Climates	Tundra	ET	No true summer
	Polar ice cap	EF	Perennial ice
H-Highland	Highland	H	Highland with snow cover



7.2 A – Tropical Humid Climates

- Tropical humid climates exist between Tropic of Cancer and Tropic of Capricorn.
- The sun being overhead throughout the year and the presence of **Inter Tropical Convergence Zone (ITCZ)** make the climate hot and humid.
- **Annual range of temperature is very low,** and **annual rainfall is high**.



ITCZ in summer and winter

- The tropical group is divided into three types, namely
  1) **Af – Tropical wet climate;**
  2) **Am – Tropical monsoon climate;**
  3) **Aw – Tropical wet and dry climate.**

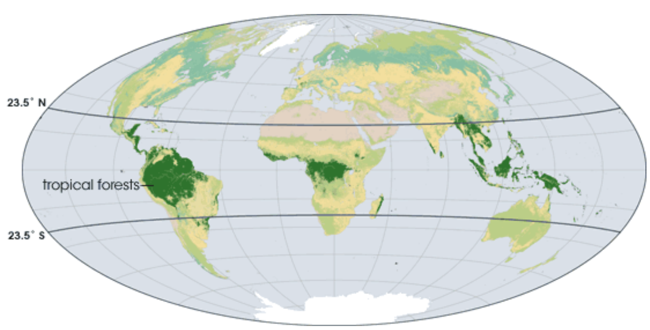
Tropical Wet Climate (Af: A – Tropical, f – no dry season)

- Also known as **The Hot, Wet Equatorial Climate**, **Equatorial Rainforest Climate**.
- The regions are generally referred as **Equatorial Rainforests, Equatorial Evergreen Forests, Tropical Moist Broadleaf Forest, Lowland Equatorial Evergreen Rainforest**.

Evergreen forest

Distribution

- Mostly between **5° N and S of Equator**. (little or no Coriolis Force == **no tropical cyclones**)
- Its greatest extent is found in the **lowlands of the Amazon, the Congo, Malaysia and the East Indies.**



Distribution of tropical wet climate

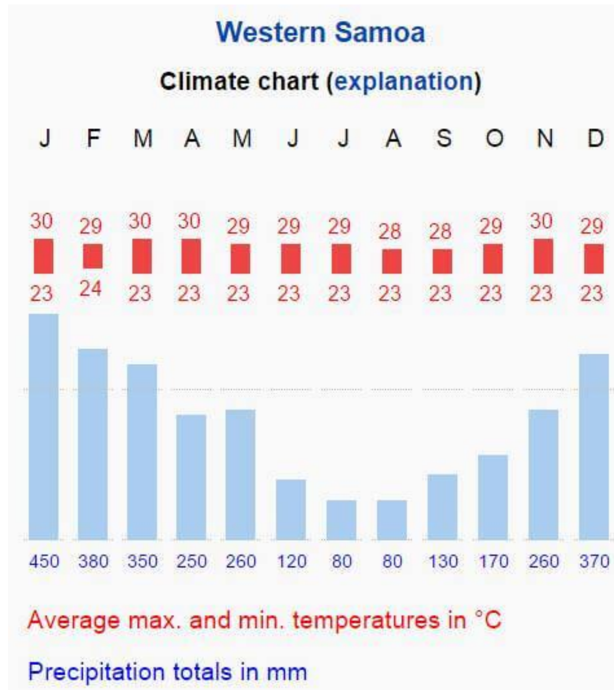
Equatorial Climate

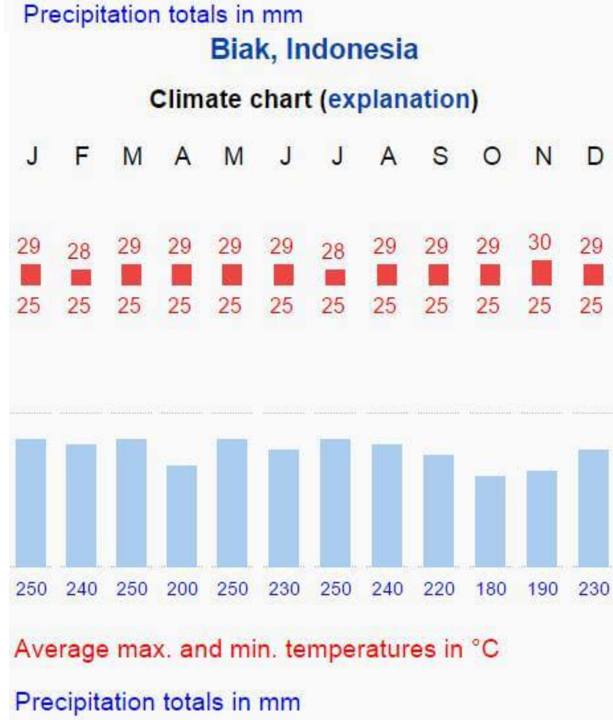
- The climate is dominated by **maritime tropical air masses (high humidity)**.

Temperature

- Temperature is **uniform** throughout the year.
- The mean monthly temperatures are always around **27°C** with very little variation.
- **There is no winter** (typical to equatorial rain-forest climate).
- Cloudiness and **heavy precipitation** moderate the daily temperature.
- Regular land and sea breezes assist in maintaining a truly equable climate.
- The diurnal range of temperature is **small**, and so is the annual range.

Climate Graphs





Climate Graphs for regions with tropical wet climate

Precipitation

- **Heavy thunderstorms occur almost every day in the afternoons**.
- Precipitation is heavy and **well distributed throughout the year**.
- Annual average is always above **150 cm**.
- In some regions, the annual average may be as high as 250-300 cm.
- There is **no month without rain (distinct dry season is absent)**.
- The monthly average is above **6 cm** most of the times.
- There are two periods of maximum rainfall, **April** and **October** (shortly after the equinox).
- Least rainfall occurs in June and December (solstice: sun is farthest from the equator).
- The **double rainfall peaks coinciding with the equinoxes is typical to equatorial climates** (not found in any other type of climate).

Equatorial Vegetation

- High temperature and abundant rainfall support a luxuriant **tropical rain forest**.
- In the Amazon lowlands, the forest is so dense that it is called **selvas**.

Selvas: *A dense tropical rainforest usually having a cloud cover (dense canopy).*

- The **growing season here is all the year round** — seeding, flowering, and decaying do not take place in a seasonal pattern.
- The equatorial vegetation comprises a multitude of evergreen trees that yield tropical hardwood, e.g. **mahogany, ebony, dyewoods** etc.
- Many parts of the tropical rain forests have been cleared either for lumbering or shifting cultivation.
- In the coastal areas and brackish swamps, **mangrove forests** thrive.

Canopy

- From the air, the tropical rain forest appears like a thick canopy of foliage, broken only where it is crossed by large rivers or cleared for cultivation.

Canopy

- All plants struggle upwards (most **epiphytes**) for sunlight resulting in a peculiar layer arrangement.

Epiphytes

Epiphyte: *An epiphyte is a plant that grows **harmlessly** upon another plant (such as a tree) and derives its moisture and nutrients from the air, rain, and sometimes from debris accumulating around it.*

- The tallest trees attain a height close to **50 m**.
- The smaller trees beneath form the next layer.
- The ground is rooted with ferns and herbaceous plants which can tolerate shade.
- Because the trees cut out most of the sunlight, the **undergrowth is not dense**.

Multiple species

In spite of dense forests, countries in equatorial regions are net importers of timber. Comment.

- Though the tropics have great potential in timber resources, commercial extraction is **difficult.**
- **Multiple species** of trees occur in a particular area (trees **do not occur in homogenous stands or pure stands**) making commercial exploitation a difficult task.

- Many of the tropical hardwoods (very heavy) **do not float** readily on water, and this makes transportation an expensive matter.
- It is therefore not surprising that many tropical countries are **net timber importers**.

Life and Economy

Agriculture

- The forests are sparsely populated.
- In the forests, most primitive people live as **hunter-gatherers**.
- The more advanced ones practice **shifting cultivation.**
- Food is abundantly available. People generally don't stock food for the next day.

Commercial

- In the **Amazon Basin,** the **Indian tribes** collect wild **rubber**.
- In the Congo Basin, the **Pygmies** gather nuts.
- In the jungles of Malaysia, the **Orang Asli** make all sorts of cane products.

The names of the tribes come under Social Geography – Prelims

Shifting Cultivation or Slash and Burn Cultivation.

- This type of cultivation is followed in many parts of the world where dense forests are common (In India, North-East is known for this type of cultivation).
- Tribes cut the trees in a plot, burn them and cultivate the plot till the fertility is exhausted.
- Once the fertility is exhausted, the clearing is abandoned, and they move on to a new plot.
- In the clearings for shifting cultivation, crops like, maize, bananas and groundnuts are grown.

Plantation Boom

- With the coming of the Europeans, many large plantations have been established, especially in **Java, Sumatra, Malaysia, West Africa and Central America**.
- The climate is very Favourable for the cultivation of certain crops that are highly valued in the industrial West. The most important is **natural rubber.**
- **Malaysia and Indonesia** are the leading producers. The home country, **Brazil** exports practically no natural rubber.
- **Cocoa** is another important crop which is cultivated in **West Africa**, bordering the **Gulf of Guinea**. The two most important producers are **Ghana and Nigeria**. All the cocoa here goes into American and European **chocolate industry**.
- From the same area another crop, **oil palm**, has done equally well and many countries like Indonesia have now taken to its cultivation.

Palm plantations in Indonesia

- Other important crops include coconuts, sugar, coffee (Brazil), tea, tobacco, spices, etc.
- The plantations destroyed nearly half of equatorial forests.

Plantations	Region(s)
Palm	Malaysia, Indonesia
Sugarcane	Brazil
Coffee	Brazil
Rubber	Malaysia, Indonesia
Cocoa	Ghana, Nigeria

Factors Affecting the Development of Equatorial Regions

Equatorial climate and health

- Excessive heat (sun-stroke) and high humidity creates serious physical and mental handicaps.
- High humidity feeds many tropical diseases such as malaria and yellow fever.
- Communicable diseases are rampant as germs and bacteria are transmitted through moist air.

- Insects and pests not only spread diseases but are injurious to crops.

Jungle hinders development

- The construction of roads and railways is a risky business as workers are exposed to wild animals, poisonous snakes, insects and most importantly tropical diseases.
- Once completed, they have to be maintained at a high cost.

Rapid deterioration of tropical soil

Why does restoration of lost forests take decades in equatorial regions?

- The fertility of topsoil in rainforest regions is very poor.
- Torrential downpours leach out most of the topsoil nutrients.

***Leaching**: percolation and draining way of nutrients due to rainwater action.*

- The soil deteriorates rapidly with subsequent soil erosion and soil impoverishment.
- It takes **decades** to replenish the soil of lost nutrients.
- Thus, a seed doesn't usually germinate, and even if it does, its development is hindered due to little availability of sunlight.
- **Lalang (tall grass)** and thick undergrowth spring up as soon as the trees are cut. They choke the restoration of forests.
- Indonesian island of Java is an exception because of its rich volcanic ashes.

Difficulties in livestock farming

- Livestock farming is greatly handicapped by an **absence of meadow grass**.
- The grass is so **tall and coarse** that it is not nutritious.
- The few animals like buffaloes are kept mainly for domestic use. Their yield in milk or beef is well below those of the cattle in the temperate grasslands.
- In Africa, domesticated animals are attacked by **tsetse flies** that cause ngana, a deadly disease.

Mineral resources

- Gold, copper, diamonds, and other precious metals and gemstones are important resources that are found in rainforests around the world.
- Extracting these natural resources is a destructive activity that damages the rainforest ecosystem.
- Examples are **gold mining in the Brazilian and Peruvian Amazon**, **rare earth mining in the Congo**, and **gold and copper mining in Indonesia and Papua New Guinea.**
- Some of the world's most promising oil and gas deposits lie deep in tropical rainforests.
- **Oil and gas development** often take a heavy toll on the environment and local people (this happened in Ecuador — **resource curse**).
- More than 70 per cent of the Peruvian Amazon is now under concession for oil and gas.

Tropical Monsoon Climate (Am: A – Tropical, m – monsoon)

- Monsoons are **land and sea breezes** on a much larger scale.
- Unlike equatorial wet climate, monsoon climate is characterized by **distinct wet and dry seasons** associated with **seasonal reversal of winds**.
- **Floods** in wet season and **droughts** in dry season are common.

Tropical Monsoon Climate: Floods in wet season and droughts in dry season

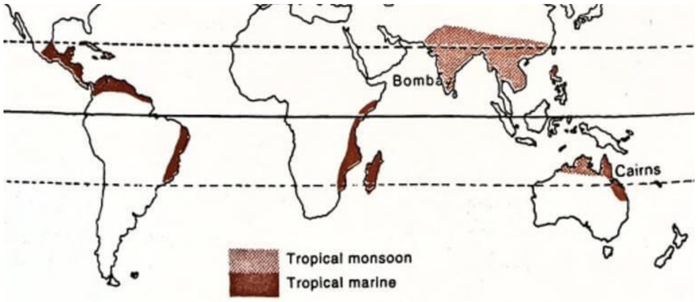
- Usually, there are three seasons namely **summer, winter and rainy** season.

Distribution

- Occur within **5° to 30°** N and S of the equator.
- **On-shore** (winds flowing from sea to land) tropical monsoons occur in the summer and

off-shore (winds flowing from land to sea) dry monsoons in the winter.

- They are best developed in the **Indian sub-continent, Burma, Thailand, Laos, Cambodia, parts of Vietnam and south China and northern Australia**.



Tropical Monsoon Climate Distribution

Climate

- The basic cause of monsoon climates is the difference in the **rate of heating** and cooling of land and sea (This is old theory. New theory explained in Indian Climate).

Temperature

- Monthly mean temperatures **above 18 °C.**
- Temperatures range from 30-45 °C in summer. Mean summer temperature is about 30 °C.
- In winters, temperature range is 15-30 °C with mean temperature around 20-25 °C.

Precipitation

- Annual mean rainfall ranges from **200-250 cm**. In some regions, it is around 350 cm.
- Places like **Cherrapunji and Mawsynram** receive an annual rainfall of about **1000 cm.**

Cherrapunji and Mawsynram *(wettest places on earth by annual rainfall — a little over 1150 cm per year) lie on the windward side of the Meghalaya hills, so the resulting* ***orographic lift (orographic rainfall)*** *enhances precipitation. Also, they are located between mountains which enhances cloud concentration due to* ***funnelling effect.***

Seasons

- Seasons are chief characteristics of monsoon climate.

The cool, dry season (October to February)

- Out blowing dry winds, the North-East Monsoon, bring little or no rain to the Indian sub-continent.
- However, a small amount of rain falls in Punjab from cyclonic sources (**Western Disturbances**: Frontal precipitation brought by jet streams), and this is vital for the survival of winter cereals.
- North-East Monsoons blowing over the Bay of Bengal acquires moisture and bring rains to the south-eastern tip of the peninsula at this time of the year (Nov-Dec).

The hot dry season (March to mid-June)

- The temperature rises sharply with the sun's northward shift to the Tropic of Cancer.
- Day temperatures of 35 °C are usual in central India and the mean temperature in Sind, and south India may be as high as 44 °C.
- Coastal districts are a little relieved by sea breezes.
- There is practically little rain. **Hailstorms** occurs here and there in April, May.

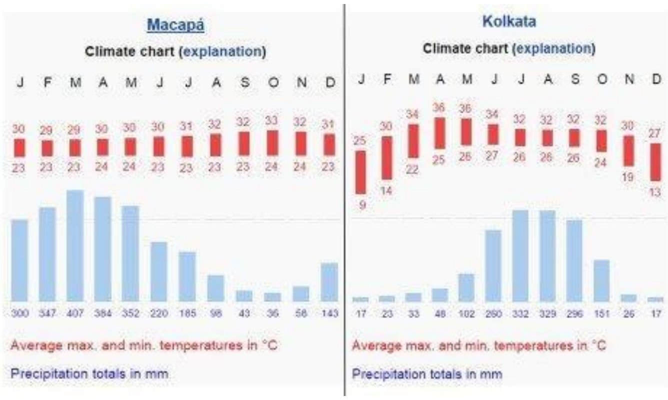
The rainy season (mid-June to September)

- With the 'burst' of the South-West Monsoon in mid-June, torrential downpours sweep across the country. Almost all the rain for the year falls within this rainy season.
- This pattern of **concentrated heavy rainfall** in summer is a characteristic feature of the tropical monsoon climate.

The Retreating Monsoon

- The amount and frequency of rain decreases towards the end of the rainy season.
- It retreats gradually southwards after mid-September until it leaves the continent altogether.
- The skies are clear again and the cool, dry season returns in October, with the out blowing North-East Monsoon.

Climate Graph



Climate Graphs of regions with Tropical Monsoon Climate

Tropical Marine Climate

- Outside the monsoon zone, the climate is **modified by the influence of the on-shore trade winds all the year round**. This type of climate is called Tropical Marine Climate.
- Such a climate has a more **evenly distributed rainfall**.
- Such a climate is experienced in Central America, West Indies, north-eastern Australia, the Philippines, parts of East Africa, Madagascar, the Guinea Coast and eastern Brazil.
- The rainfall is both **orographic** where the moist trades meet upland masses as in eastern Brazil, and **convectional** due to intense heating during the day and in summer.
- Its tendency is towards a **summer maximum without any distinct dry period**.
- Due to the steady influence of the trades, the Tropical Marine Climate is **more favourable for habitation**, but it is **prone to severe tropical cyclones, hurricanes or typhoons.**

Tropical Monsoon Forests

- **Also known as drought-deciduous forest; dry forest; dry-deciduous forest; tropical deciduous forest.**
- **Broad-leaved hardwood trees are found here**. They are well developed in **southeast Asia.**
- Trees are normally deciduous, because of the marked dry period, during which they shed their leaves to withstand the drought (they shed their leaves to prevent loss of water through **transpiration**).
- The forests are more open and **less luxuriant** than the equatorial jungle, and there are far **fewer species.**
- Where the rainfall is heavy, e.g. in southern Burma, peninsular India, northern Australia and coastal regions with a tropical marine climate, the resultant vegetation is luxuriant.
- With a decrease in rainfall in summer, the forests thin out into **thorny scrubland or savanna** with scattered trees and tall grass.
- In parts of the Indian sub-continent (rain shadow regions — regions east of Western Ghats like north Karnataka, Telangana, Vidarbha), rainfall is so deficient that semi-desert conditions are found in summer.
- Monsoonal vegetation is thus most varied, ranging from forests to thickets, and from savanna to scrubland.

Population and Economy in Monsoon Climate

- Monsoon climatic regions support **high population density**.
- Income levels are low as most of these regions are still developing.
- **Subsistence farming** is the main occupation.

Subsistence farming: crops grown with an intention to secure food for the season. The crops are not sold as the production is very low.

- Intensive cultivation is common in regions with irrigational facilities.
- **Shifting cultivation** is followed in North-East India and South-East countries.
- Major crops include **rice, sugar, cotton, jute, spices**, etc.
- Cattle and sheep rearing are carried out for domestic and commercial purposes.
- **Livestock industry is not as profitable as in temperate regions**.

Lumbering

- Most of the forests yield valuable timber and are prized for their **durable hardwood.**
- Lumbering is undertaken in the more accessible areas. This is particularly important in continental South-East Asia.

- Of the tropical deciduous trees, **teak,** of which **Burma** is the leading producer (three – quarters of the world's production), is the most sought after.
- It is valuable on account of its **durability, strength, immunity to shrinkage, fungus attack and insects.**
- Teak logs are so heavy that they will not float readily on water. It is therefore necessary to 'poison' the tree several years before actual felling so that it is dry and light enough to be floated down the **Chindwin** and the **Irrawaddy** to reach the sawmills at **Rangoon.**
- Other kinds of timber include **Neem, Banyan, Mango, Teak, Sal, Acacia, Eucalyptus.**
- Together with the forests are bamboo thickets, which often grow to great heights.

Agricultural Development in the Monsoon Lands

- Much of the monsoon forest has been cleared for agriculture to support the very dense population.
- Farms are small, and the people are forever **land hungry.** Industrialisation makes things worse.
- Farming is the dominant occupation of the Indian sub-continent, China, South- East Asia, eastern Brazil and the West Indies. The following types of agriculture are recognisable.

Crops

- **Rice** is the most important staple crop.
- Irrigation water from rivers, canals, dams or wells is extensively used in the major rice producing countries.
- Other food crops like **maize, millet, sorghum, wheat, gram and beans** are of subsidiary importance. They are cultivated in the drier or cooler areas where rice cannot be grown.

Lowland cash crops

- The most important crop in this category is **cane sugar**.
- As much as two-thirds of world's sugar production comes from tropical countries.
- Some of the major producers include **India, Java, Formosa, Cuba, Jamaica, Trinidad and Barbados.**
- **Jute** is confined almost entirely to the **Ganges - Brahmaputra delta**, in India and Bangladesh.
- Other crops include cotton, a major commercial crop of the Indian sub-continent.

Highland plantation crops

- The colonisation of tropical lands by Europeans gave rise to a new form of cultivated landscape in the cooler monsoonal highlands.
- Thousands of acres of tropical upland forests were cleared to make way for plantation agriculture in which tea and coffee are the most important crops.

Coffee

- Coffee originated in **Ethiopia** and **Arabia**.
- But **Brazil** accounts for almost half the world's production of coffee.
- It is mainly grown on the **eastern slopes of the Brazilian plateau**.
- The crop is also cultivated on the highland slopes in the Central American states, India and eastern Java.

Tea

- Tea originated in **China** and is still an important crop there.
- It requires **moderate temperatures** (about 15°C), **heavy rainfall** (over 150 cm) and **well-drained highland slopes.**
- It thrives well in the tropical monsoon zone (highlands).
- The best regions are thus the **Himalayan foothills of India and Bangladesh**, the **central highlands of Sri Lanka** and **western Java**, from all of which it is exported.
- In China, tea is grown mostly for local consumption.

Shifting Cultivation

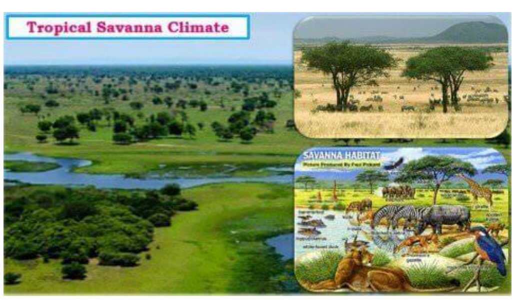
- This most primitive form of farming is widely practised.

- Instead of rotating the crops in the same field to preserve fertility, the tribesmen move to a new clearing when their first field is exhausted.
- Farming is entirely for **subsistence**.
- As tropical soils are **rapidly leached and easily exhausted, the first crop may be bountiful, but the subsequent harvests deteriorate.**

Region	Name of Shifting Cultivation
Malaysia	Lacking
Burma	Taungya
Thailand	Tamrai
Philippines	Caingin
Java	Humah
Sri Lanka	Chena
Africa and Central America	Milpa
North-east India	**Jhum**

Savanna or Tropical Wet and Dry Climate (Aw: A – Tropical, w – dry winter)

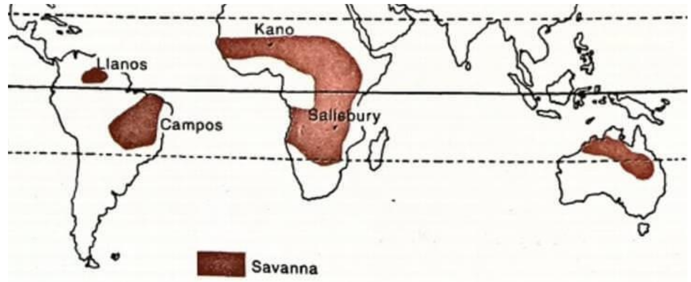
- Savanna climate has **alternate wet and dry seasons**
- There is **no distinct rainy season** like in monsoon climate.
- **Rains occur in warm summer** months.
- Floods and droughts are common.
- Vegetation, wildlife and human life are quite different from monsoon climate regions.



Typical savanna climate conditions

Distribution of Savanna Climate

- It is confined within the tropics and is best developed in **Sudan**, hence its name the **Sudan Climate**.
- It is a **transitional type** of climate found between the **equatorial rainforests** and **hot deserts.**



Savanna climate distribution: transitional zones between the equatorial rainforests and hot deserts

African Savanna

- The belt includes **West African Sudan** and then curves southwards into East Africa and southern Africa north of the Tropic of Capricorn.

South American Savanna

- There are two distinct regions namely the **Llanos** of the **Orinoco** basin (north of the equator) and the **Compos** of the Brazilian Highlands (south of the equator).

Australian savanna

- The Australian savanna is located south of the monsoon strip (northern Australia) running from west to east north of the Tropic of Capricorn.

Indian Savanna

- Certain parts across Northern Karnataka, Southern Maharashtra and Telangana exhibit characteristics of both semi-arid and savanna climate.
- Irrigational projects that came up after independence have drastically modified the savanna characteristic of the region.

Savanna Climate

Rainfall

- Savanna climate receives **considerably less annual rainfall**.
- Mean annual rainfall ranges from **80 – 160 cm**.
- Rainfall **decreases with distance from equator**.
- In the northern hemisphere, the rainy season begins in May and lasts till September.

- In the southern hemisphere, the rainy season is from October to March.

Temperature

- Mean annual temperature is **greater than 18°C.**
- The monthly temperature hovers between 20 °C and 32 °C for lowland stations.
- **Highest temperatures do not coincide with the period of the highest sun** (e.g. June in the northern hemisphere) but occur just before the onset of the rainy season, i.e. April in Northern Hemisphere and October in Southern Hemisphere.
- **Days are hot and nights are cold**. This **extreme diurnal range** of temperature is another characteristic feature of the Sudan type of climate.

Winds

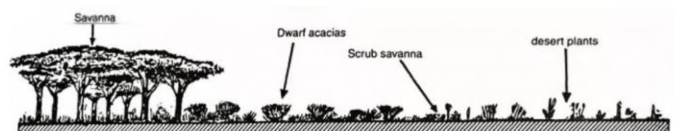
- The prevailing winds of the region are the **trade winds**, which bring rain to the coastal areas.
- They are strongest in the summer (favourable position of ITCZ) but are relatively dry by the time they reach the continental interiors or the western coasts (trade winds are easterlies – flow from east to west. Hence, **rainfall decreases from east to west**).
- In West Africa, the North-East Trades blow offshore (continent to sea) from the Sahara Desert and reach the Guinea coast as a dry, dust-laden winds.

What is the reason for alternating wet and dry seasons in Savanna type climate?

- On-shore winds is summer bring rains.
- Off-shore winds in winter keep the climate dry.

Natural Vegetation of Savanna Climate

- The savanna landscape is typified by **tall and coarse grass** (6 to 12 feet high) **and short trees**.
- The **elephant grass** may attain a height of even 15 feet.
- The grasslands are also called as **bush-veld.**
- Grasses appear greenish and well-nourished in the rainy season.
- Grasses die down in the dry season increasing the risk of forest fires.
- The trees are **deciduous**, shedding their leaves in the cool, dry season to prevent transpiration, e.g. acacias.
- Trees usually have **broad trunks**, with water-storing devices to survive through the prolonged drought.
- Many trees are umbrella shaped, exposing only a narrow edge to the strong winds.
- As the rainfall diminishes towards the deserts, the savanna merges into thorny scrub (semi-arid).



Vegetation in the savanna regions

Animal Life of the Savanna

- Rich animal diversity is the characteristic of savanna climate.
- Most of the National Geographic and Animal Planet documentaries on wild animals are shot in savanna regions.
- The herbivorous include the zebra, antelope, deer, elephant etc. and carnivorous animals include the lion, tiger, leopard, hyena, panther, jaguar, jackal etc.
- Species of reptiles and mammals including crocodiles, alligators, giant lizards live together with the larger rhinoceros and hippopotamus in rivers and marshy lakes.
- Seasonal migration of animals in search of food is typical characteristic of savanna animal life.
- The savanna is known as the **big game country** as animals are hunted down both legally and illegally.

Life and Economy in the Savanna

- Many tribes live in savanna region.
- Tribes like the **Masai** tribes of the East African plateau are pastoralists whereas **Hausa** of northern Nigeria are settled cultivators.
- The old grazing grounds of Masai tribes in the **Kenyan Highlands** were taken over by the

white immigrant settlers for plantation agriculture (coffee, tea, cotton) and dairy farming.

- The cattle kept by the Masai are kept entirely for the supply of milk. They don't slaughter cattle for meat. **Agriculture is barely practised**.
- The Hausa are a tribe of settled cultivators who inhabit the savanna lands of the Nigeria. They are more advanced in their civilisation.
- They do not practice shifting cultivation. Instead, they clear a piece of land and use it for several years.

Farming

- Droughts are long due to unreliable rainfall.
- Political instability hinders the development of agricultural infrastructure.
- The Sudan Climate, with **distinct wet-and-dry periods,** is also responsible for the **rapid deterioration of soil fertility**.
- During the rainy season, torrential downpours of heavy rain cause leaching of nitrates, phosphates and potash.
- During the dry season, intense heating and evapouration dry up most of the water.
- Many savanna areas, therefore, have **poor lateritic soils** which are incapable of supporting good crops.

Crops in Savanna

- Settlements in central Africa, northern Australia and eastern Brazil have shown that the savannas have immense agricultural potential for **plantation agriculture** of cotton, cane sugar, coffee, oil palm, groundnuts and even tropical fruits.
- Tropical Queensland, despite its scarcity of labour force, has been very successful in developing its huge empty land.
- Kenya, Uganda, Tanzania and Malawi have already taken to large-scale production of cotton.
- In West Africa, the commercial cultivation of groundnuts, oil palm and cocoa have been gradually extended into the savanna lands.
- In the cooler highlands, temperate crops have been successfully raised.

Cattle rearing

- The savanna is said to be the **natural cattle country,** and many of the native people are pastoralists.
- But the **quality of grass doesn't support large scale ranching (typical to all tropical climates)**.
- Grasses here are no match to nutritious and soft grasses of temperate grasslands.
- The cattle varieties are also poor and yield little meat or milk.
- The export of either beef or milk from the tropical grasslands is so far not important.
- Few regions progressed with the adaptation of science and technology.
- **Queensland** has become Australia's largest cattle producing state. Both meat and milk are exported.

7.3 B – Dry Climate

- Grasslands and deserts are classified under B – dry climate.
- Grasslands include **subtropical savanna grasslands (BSh)** and **temperate steppe grasslands (BSk)**.
- Deserts are regions where **evapouration exceeds precipitation.**
- There are mainly two types:
  1. hot like the **hot deserts** of the Saharan type (BWh) and
  2. **temperate or mid-latitude deserts** like the **Gobi Desert** (BWk).

Hot Desert Climate (BWh: B – Dry, W – Desert, h – low latitude)

- The aridity of the hot deserts is mainly due to the effects of **off-shore trade winds**; hence they are also called **trade wind deserts.**
- The major hot deserts of the world are located on the **western coasts of continents** between latitudes **15° and 30°N and S**.
- They include the biggest **Sahara Desert** (3.5 million square miles), **Great Australian Desert, Arabian Desert, Iranian Desert, Thar Desert, Kalahari** and **Namib Deserts**.
- In North America, the desert extends from Mexico into U.S.A. and is called by different names

at different places, e.g. the **Mohave, Sonoran, Californian** and **Mexican Deserts.**

- In South America, the **Atacama or Peruvian Desert is the driest of all deserts** (driest place on earth — **rain shadow effect of the Andes**, **off-shore trade winds, westerlies blow to the south of Tropic of Capricorn, cold ocean currents: upwelling of cold water due to Walker Circulation**) with less than 2 cm of rainfall annually.

Atacama Desert is the driest place on earth with less than 2 cm annual rainfall.

Mid-Latitude Desert Climate (BWk: B – Dry, W – Desert, k – high latitude)

- The temperate deserts are rainless because of either **continentality (e.g. Gobi Desert) or rain-shadow effect** (**e.g. Patagonian Desert** due to **rain-shadow effect of Andes**).
- Amongst the mid-latitude deserts, many are found on plateau and are at a considerable distance from the sea.
- These are **Ladakh, The Kyzyl Kum, Turkestan, Taklimakan and Gobi deserts of Central Asia, drier portions of the Great Basin Desert of the western United States** and **Patagonian Deserts of Argentina etc.**
- The Patagonian Desert is more due to its rain-shadow position on the leeward side of the lofty Andes than due to continentality.

Desert Climate

Rainfall (Both Hot and Cold deserts)

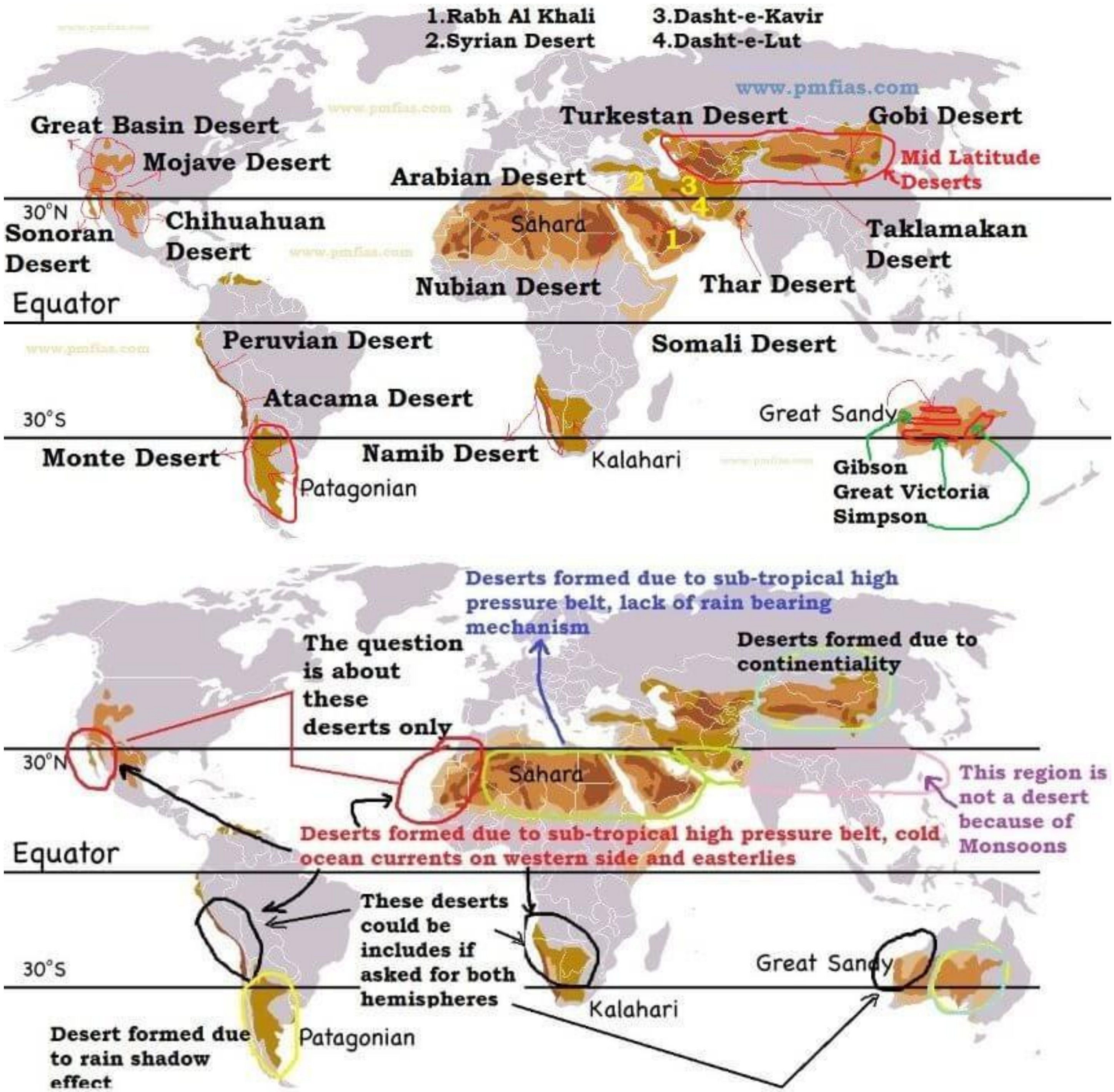
- Deserts, whether hot or mid-latitude have an annual precipitation of **less than 25 cm.**
- **Atacama (driest place on earth)** has practically no rain at all.
- Rain normally occurs as violent thunderstorms of the convectional type occasionally causing flash floods.

Temperature of Hot deserts

- There is **no cold season** in the hot deserts and the average summer temperature is high around 30°C.
- The highest temperature recorded is **57.77 °C in 1922 at Al Azizia, Libya**.
- The reasons for the high temperatures are obvious — a clear, cloudless sky, intense insolation, dry air and a rapid rate of evapouration.
- Coastal deserts by virtue of their maritime influence and the cooling effect of the cold currents have much lower temperatures.
- The desert interiors, however, experience much higher summer temperatures and the winter months are rather cold.
- The **diurnal range of temperature in the deserts is very great**. Intense insolation by day in a region of dry air and no clouds causes the temperature to rise with the sun.
- But as soon as the sun sets, the land loses heat very quickly by radiation and the mercury levels drop.
- **High diurnal temperature range** is a typical feature of hot deserts. Average diurnal range (difference between maximum and minimum temperature that occur within a day) varies from 14 to 25 °C.
- Frosts may occur at night in winter.

Climatic Conditions in the Mid-latitude deserts

- These inland basins lie hundreds of miles from the sea and are sheltered by the high mountains all around them. As a result, they are **cut off from the rain-bearing winds**.



Major Deserts of the World

- Occasionally depressions may penetrate the Asiatic continental mass and bring light rainfall in winter. Due to their coldness and elevation, snow falls in winter.
- The **annual range of temperature is much greater than that of the hot deserts**.
- **Continentality** accounts for these extremes in temperature.
- Winters are often severe, freezing lakes and rivers, and strong cold winds blow all the time. When the ice thaws in early summer, floods occur in many places.

Desert Vegetation

- The predominant vegetation of both hot and mid-latitude deserts is **xerophytic** or drought-resistant.
- This includes the cacti, thorny bushes, long-rooted wiry grasses and scattered dwarf acacias.
- Trees are rare except where there is abundant groundwater to support clusters of **date palms.**

- Along the western coastal deserts washed by cold currents as in the Atacama Desert, support a thin cover of vegetation.
- Intense evapouration increases the salinity of the soil so that the dissolved salts tend to accumulate on the surface forming hard pans (Bajada, Palaya).
- Absence of moisture retards the rate of decomposition and desert soils are very deficient in humus.
- Most desert shrubs have long roots (in search of groundwater) and are well spaced out to gather moisture.
- Plants have **few or no leaves,** and the foliage is either **way, leathery, hairy or needle-shaped** to reduce the loss of water through transpiration.
- The seeds of grasses and herbs have **thick, tough skins** to protect them while they lie dormant for years.

Desert vegetation

Life in the Deserts

- Despite its inhospitality, the desert has always been peopled by different groups of inhabitants.

Tribe	Desert	Occupation
Bedouin Arabs	Arabia	nomadic herdsmen
Tuaregs	Sahara	nomadic herdsmen
Gobi Mongols	Gobi	nomadic herdsmen
Bushmen	Kalahari	primitive hunters and collectors.
Bindibu	Australia	primitive hunters and collectors.

The settled cultivators

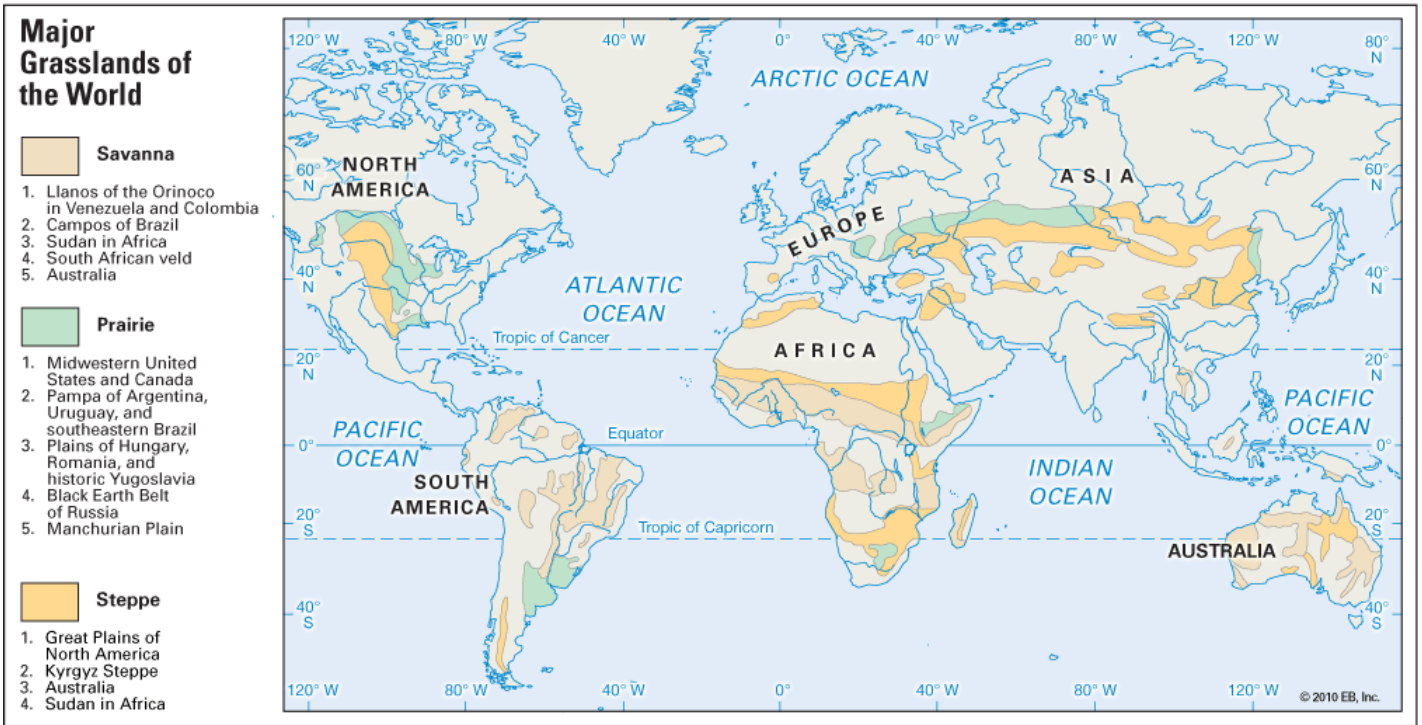
- Modem concrete dams constructed across the Nile, e.g. **Aswan and Sennar Dams** improved agriculture.
- In the same way, desert cultivators rely on the **Indus in Pakistan**, the **Tigris-Euphrates in Iraq**, and the **Colorado in the Imperial Valley of California**.
- In the deserts, wherever there are oases (depressions where underground water reaches the surface), some form of settled life is bound to follow.
- Some of them are abnormally large like the **Tafilalet Oasis in Morocco** which measures 5,000 square miles.
- A wall is usually constructed around the oasis to keep out the violent dust storms called **simooms.**
- The most important tree is the date palm. The fruit is consumed locally and also exported.
- Other crops cultivated include maize, barley, wheat, cotton, cane sugar, fruits and vegetables.

The mining settlers

- **Gold** is mined in Great Australian Desert. **Kalgoorlie and Coolgardie** have become large towns.
- In the Kalahari Desert (thirstland), the discovery of **diamonds** and **copper** has brought many white men.
- In Atacama, in northern Chile, large mining camps have been established for the mining of **caliche (cemented gravels)** from which **sodium nitrate**, a valuable fertiliser, is extracted.
- Besides nitrates, **copper** is also mined. **Chuquicamata** is the world's largest copper town.
- In the deserts of North America, **silver is mined in Mexico**, **uranium in Utah** and **copper in Nevada**.
- Discovery of oil, in many parts of the Saharan and Arabian Deserts, has transformed the region.

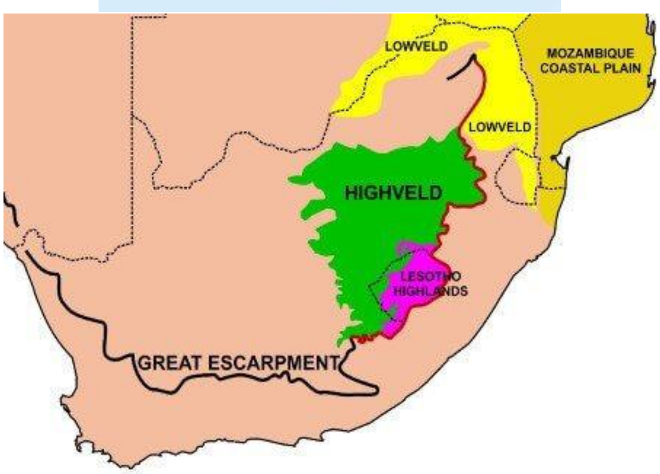
Steppe or Temperate Grassland Climate (BSk: B – Dry, S – Steppe, k – high latitude)

- Steppe climate is also known as Temperate Continental Climate.



Distribution of temperate and tropical grasslands

Steppe grasslands in the Mongolian region



Distribution

- Most of the temperate grasslands lie in the **interiors of the continents** in the **westerly wind belt**.
- Some of the grasslands are formed due to rain shadow effect of the mountains (good rains on the windward side; on the leeward side deserts or grasslands are formed).

- Grasslands are **practically treeless** due to continentality (deep within the interiors of the continents where rain-bearing winds don't reach) and/or rain shadow effect.
- In Eurasia, they are called the **steppes** and stretch eastwards from the shores of the Black Sea to the foothills of the Altai Mountains.

Temperate Grassland	Region
Pustaz	**Hungary and surrounding regions**
Prairies	**North America (between the foothills of the Rockies and the Great Lakes)**
Pampas	**Argentina and Uruguay (Rain-shadow effect)**
Bush-veld (more tropical)	**Northern South Africa**
High Veld (more temperate)	**Southern South Africa**
Downs	**Australia: Murray-Darling basin of southern Australia**
Canterbury	**New Zealand (rain shadow effect of Southern Alps)**

Climate

Temperature

- Climate is continental with **extremes of temperature**.
- The summers are hot, and the winters are cold.
- Summers are very warm and over 18-20 °C.
- In the southern hemisphere, the summers are never severe due to very narrow landmasses.

Precipitation

- The average rainfall may be taken as about **45 cm**.
- But precipitation varies according to location from **25 cm to 75 cm (below 25 cm it is desert climate)**.
- The heaviest rain comes in June and July (late spring and early summer).
- Most of the winter months have about 2.5 cm of precipitation, brought by the occasional depressions of the Westerlies and coming in the form of snow.
- The maritime influence in the southern hemisphere causes more rainfall.

Chinook (Snow eaters)

- Chinook is a **hot local katabatic wind** that blows down the eastern slopes of the Rockies.
- It is similar to the Fohn in Switzerland and comes in a south-westerly direction to the **Prairies**.
- It comes with the depressions in winter from the Pacific coast ascending the Rockies and then descending to the Prairies (katabatic wind).
- It is a hot wind and may raise the temperature by 5 °C within a matter of 20 minutes.
- It melts the snow-covered pastures and benefits agriculture and animal ranching.

Natural Vegetation of Steppe Climate

Grasses

- Greatest difference from the tropical savanna is that steppes are practically **treeless,** and the **grasses are much shorter**.
- Grasses are tall, fresh and **nutritious**. This is typical of the grass of the wheat-lands in North America, the **rich black earth or chernozem areas of Ukraine** and the better-watered areas of the Asiatic Steppes.
- Where the rainfall is light or unreliable, or the soil is poor, as in the continental interiors of Asia the short steppe type of grass prevails.
- The grasses are not only shorter but also **wiry** (lean, tough) and **sparse** (thinly dispersed or scattered).
- These areas are **less suitable for arable farming** and are used for some form of **ranching** as in the High Plains of U.S.A.
- The growth of grasses is not abruptly checked by summer droughts or winter cold.

Trees

- Poleward, an increase in precipitation gives rise to a transitional zone of wooded steppes where some **conifers** gradually appear.
- In the cultivated regions, such as the wheat farms of the Prairies, double rows of trees are planted around the house to shield the occupants from the strong wind.

Animals

- Temperate grasslands do not have much animal diversity (Savanna: high animal diversity).
- **Horses** are common in Asian Steppes.

Economic Development of Steppes

Wheat and Maize Cultivation

- Cultivation was unknown just before a century, and the region was one of the most sparsely populated parts of the world.
- In recent years, the grasslands have been ploughed up for extensive, mechanised wheat cultivation and are now the **'granaries of the world' (Prairies).**
- Besides wheat, maize is increasingly cultivated in the warmer and wetter areas.

Ranching

- The tufted grasses have been replaced by the more **nutritious Lucerne or alfalfa grass** for cattle and sheep rearing.
- These temperate grasslands are now the **leading ranching regions** of the globe (e.g. **Pampas of Argentina**).

Nomadic herding in Asian Steppes

- This type of migratory animal grazing has almost disappeared from the major grasslands.
- The herders were wandering tribes, e.g. the **Kirghiz**, and the **Kazakhs.**
- Now under the Communist regime, they are being forced to settle down.
- The steppes have been made into huge **collective farms** and state farms for ranching or producing cereals.

Extensive mechanised wheat cultivation

- The **temperate grasslands** are ideal for **extensive wheat cultivation**.
- The **levelness** of the Steppes and other temperate grasslands all over the world makes ploughing and harvesting a comparatively easy job.
- In the **Prairies, the Argentinian Pampas, the Ukrainian Steppes** and the **Downs of Australia**, agriculture is completely mechanised.

Pastoral farming

- The natural conditions suit animal farming.
- With the development of refrigerated ships in the late nineteenth century, the temperate grasslands became major pastoral regions, exporting large quantities of beef, mutton, wool, hides.
- Milk, butter, cheese and other dairy products are also important in some parts of the North American grasslands.

Grassland	Major Economic Activity
Prairies	• **Wheat Granaries** • **Extensive Ranching**
Pustaz	• **Rich black soil** • **Abundant wheat production** • **Sugar from Sugar beet (Beta vulgaris, is a plant whose root contains a high concentration of sucrose)** • **Countries like Hungary, Ukraine, Romania etc.**
Pampas	• **Alfalfa: nutrient-rich grass** • **Ranching, cattle rearing; Dairy products** • **Extensive wheat producing region** • **Economy depends on wheat and beef export**

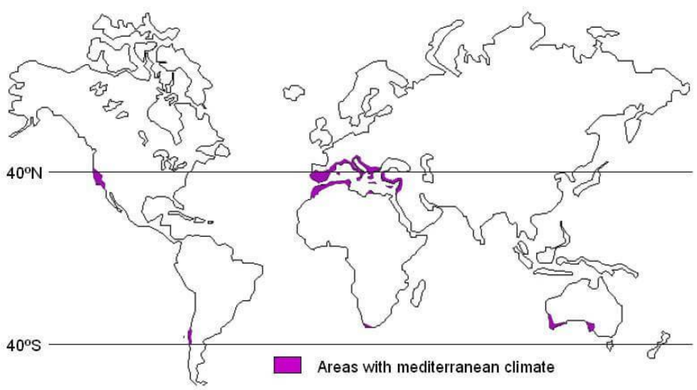
Downs and Canterbury	• **Sheep and Cattle rearing,** • **Merino sheep: wool production**
Veldts	• **Maize farms** • **Sheep and Cattle rearing**

7.4 C – Warm Temperate (Mid-latitude) Climates

C-Warm temperate (Mid-latitude) Climates	Humid subtropical	Cfa	No dry season, warm summer
	Mediterranean	Cs	Dry hot summer
	Marine west coast	Cf	No dry season, warm and cool summer

Mediterranean Climate (Cs: C – Warm Temperate, s – Dry summer)

- Mediterranean Climate is also known as **Warm Temperate Western Margin Climate** or **Warm Temperate West Coast Climate**.



Distribution of Mediterranean Climate

Distribution

- They are confined to the western portion of continents, between **30° and 45°** N and S of the equator.
- The basic cause of this type of climate is the **shifting of the wind belts (westerly wind belt)**.
- Mediterranean Sea has the greatest extent of this type of **winter rain climate (winter maxima)**.
- The best-developed form of this climatic type is found in **central Chile.**

Other Mediterranean regions include:

- **California (around San Francisco),**
- **The south-western tip of Africa (around Cape Town),**
- **Southern Australia, and south-west Australia (Swanland).**

Climate

- Climate is characterised by clear **skies and high temperatures.**
- **The summers are hot and dry, and the winters are cool and wet**.
- Mean annual precipitation ranges from **35-90 cm.**
- Temperature of warmest month is greater than or equal to 10° C.
- Temperature of coldest month is less than 18° C but greater than –3° C.
- Climate is **not extreme** because of cooling from water bodies.

A dry, warm summer with off-shore trades

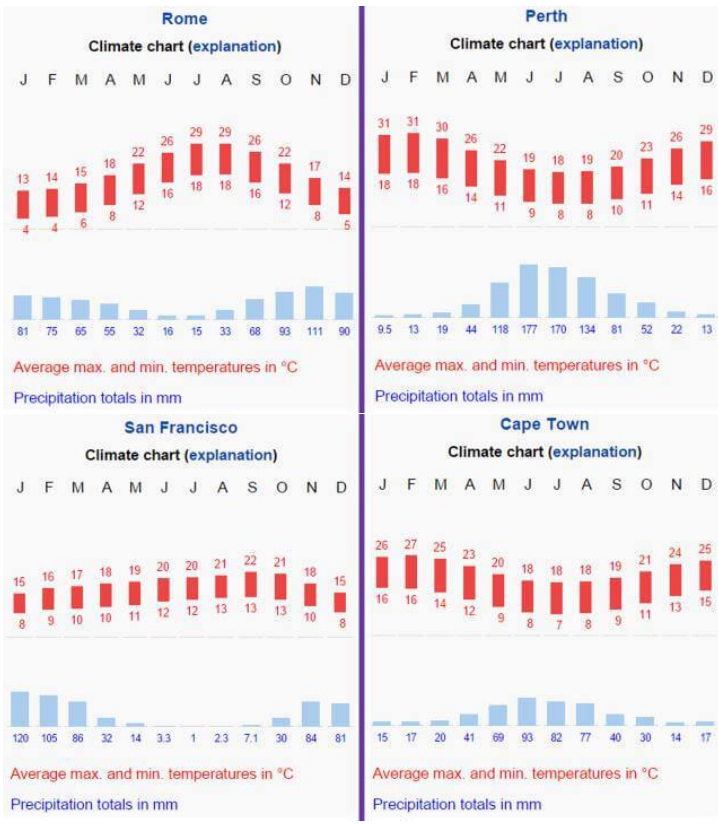
- In summer, the belt of influence of the **Westerlies is shifted a little poleward**.
- Rain-bearing winds are therefore not likely to reach the Mediterranean lands.
- The **prevailing trade winds (tropical easterlies) are off-shore,** and there is practically no rain.
- Strong winds from inland desert regions pose the risk of wildfires.

Rainfall in winter with on-shore Westerlies

- The Mediterranean lands receive most of the precipitation in **winter** when the westerlies shift equatorward.
- In the northern hemisphere, the prevailing **on-shore westerlies** bring much cyclonic rain from the Atlantic (winter rain is a characteristic feature of Mediterranean Climate).

- The **rain comes in heavy showers and only on a few days with bright sunny periods between them**. This is another characteristic feature of the Mediterranean winter rain.
- Though the downpours are infrequent, they are often very torrential, and in mountainous districts, **destructive floods** occur.

Climate Graphs



Climate graphs of cities with Mediterranean climate

Local winds of the Mediterranean Climate

- Many local winds, some hot, others cold are common around the Mediterranean Sea.

Sirocco

- This is a hot, dry dusty wind which originates in the **Sahara Desert**.
- After crossing the Mediterranean Sea, the Sirocco is slightly cooled by the absorption of the water vapour.
- Its scorching heat withers (dry up or shrivel from loss of moisture) vegetation and crops.
- This may be **blood rain** because the wind is carrying the red dust of the Sahara Desert.

Mistral

- Mistral is a **cold wind** from the north, rushing down the **Rhone valley** in violent gusts.
- The velocity of the Mistral is intensified by the **funnelling effect** in the valley between the **Alps** and the **Central Massif (Plateau in France)**.

Local winds in the Mediterranean

- A similar type of cold north-easterly wind experienced along the **Adriatic coast** is called the **Bora.**
- **Tramontane** and **Gregale** are similar **cold winds** of the Mediterranean Sea.

Natural Vegetation in the Mediterranean Climate

Mediterranean Climate

- Trees with **small broad leaves** are widely spaced and **never very tall**.

- The **absence of shade** is a distinct feature of Mediterranean lands.
- Plants are in a continuous struggle against heat, dry air, excessive evapouration and prolonged droughts.
- They are, in short **xerophytic (drought tolerant)**.

Mediterranean evergreen forests

- These are open woodlands with **evergreen oaks** found only in the climatically most favoured regions.
- The trees are stunted, with massive trunks, small leathery leaves and a wide-spreading root system.
- The **cork oaks** are valued for their thick barks, used for making **wine-bottle corks**.
- In Australia, the **eucalyptus** forests replace the evergreen oak.
- The giant **redwood** is typical of the **Californian** trees.

Evergreen coniferous trees

- These include the various kinds of **pines, firs, cedars** and **cypresses** which have evergreen, needle-shaped leaves and tall, straight trunks.

Mediterranean bushes and shrubs

- This is perhaps the most predominant type of Mediterranean vegetation.

Grass

- Conditions in the Mediterranean **do not suit grass**, because most of the rain comes in the cool season when growth is slow.
- Even if grasses do survive, they are so wiry (lean, tough) and bunchy that they are **not suitable for animal farming.** Cattle rearing is thus unimportant in the Mediterranean.

Agriculture in the Mediterranean Climate

Orchard farming

- The Mediterranean lands are also known as the **world's orchard lands.**
- The Mediterranean lands account for 70 per cent of the world's exports of citrus fruits.
- The **olive tree** is probably the most typical of all Mediterranean cultivated vegetation.
- A wide range of citrus fruits such as oranges, lemons, limes, citrons and grapefruit are grown.
- Besides citrus fruits, many nut trees like chestnuts, walnuts, and almonds are grown.
- The fruit trees have long roots to draw water from considerable depths during the long summer drought.
- The thick, leathery skin of the citrus fruits prevents excessive transpiration.
- The long, sunny summer enables the fruits to be ripened and harvested.

Crop cultivation and sheep rearing

- **Wheat** is the leading food crop. **Barley** is the next most popular cereal.
- The mountain pastures, with their cooler climate, support a few sheep, goats and sometimes cattle.
- **Transhumance** is widely practised (seasonal movement up and down the hills in search of pastures).

Wine production

- **Viticulture** is by tradition a Mediterranean occupation.
- The Mediterranean regions account for three-quarters of the world's production of wine.
- Some 85 per cent of grapes produced, go into wine.

Economy

- **The regions are a net exporter of citric fruits and net importer of dairy products.**
- Clear skies in summer and good landscapes **encourage tourism (a lot of Indian Songs are shot here).**
- European Mediterranean has many ancient cities and are famous for their health and pleasure resorts.

Warm Temperate Eastern Margin Climate (Cfa)

- Cfa: C – warm temperate, f – no dry season, a – hot summer.
- It is also known as Humid subtropical climate.
- This type of climate is found between **20° and 35° N and S latitude** (warm temperate latitudes or subtropics; hence it is also known as Humid subtropical climate); on the **east coast** in both hemispheres.

Different variants of Warm Temperate Eastern Margin Climate include the

a) **Temperate monsoon Climate or China Type Climate,**
b) **Gulf Type Climate and**
c) **Natal Type Climate.**

China Type

- Temperate Monsoon or China Type climate is observed in most parts of China.
- The climate is also observed in **southern parts of Japan**.

Summer

- Intense heating within interiors (Tibet, desert region) sets up a region of low-pressure in summer attracting tropical Pacific air stream (South-East Monsoon).
- Monsoon does not 'burst' as suddenly, nor 'pour' as heavily as in India.
- Typhoons form mostly in late summer, from July to September.

Winter

- In winter, there is **intense pressure over Siberia,** and the continental polar air stream flows outwards as the North-West Monsoon, bitterly cold and very dry.
- There is little rain but considerable snow on the windward slopes.

Gulf Type

- Found in **south-eastern U.S.A**., bordering the Gulf of Mexico where continental heating in summer induces an inflow of air from the cooler Atlantic Ocean.
- Monsoonal characteristics are **less intense** compared to China type.
- There is **no complete seasonal wind reversal**.
- Hurricanes occur in September and October.

Natal Type

- Found in in **New South Wales (Australia), Natal (South Africa), Parana-Paraguay-Uruguay basin (South America).**
- Natal type is different from temperate monsoon or China type as it **receives rainfall from on-shore Trade Winds all the year round**.
- The narrowness of the continents and the dominance of maritime influence **eliminate the monsoonal elements.**
- The South-East Trade Winds bring about a more even distribution of rainfall throughout the year

Climate type	Feature
China type	Temperate monsoonal
Gulf type	Slight-monsoonal
Natal type	Non-monsoonal

Climate

- Characterised by a **warm moist summer** and a **cool, dry winter** (winters are also moist in Natal Type).

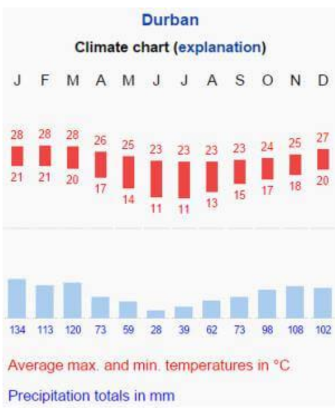
Temperature

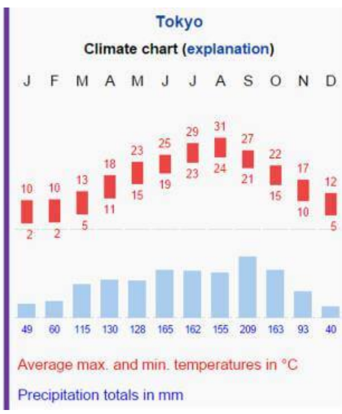
- The mean monthly temperature varies between 4 °C and 25 °C and is strongly modified by **maritime influence.**
- Occasionally, the penetration of **cold air (Polar Vortex)** from the continental interiors may bring down the temperature to freezing point.
- Though frosts are rare, they occasionally occur in the colder interiors.

Precipitation

- Rainfall is more than moderate, anything from **60 cm to 150 cm**.
- This is adequate for all agricultural purposes and hence supports a wide range of crops.
- Areas which experience this climate are **very densely populated**.
- There is a **fairly uniform distribution of rainfall throughout the year**.
- Rain comes either from convectional sources or as orographic rain in summer, or from depressions in prolonged showers in winter.
- **In summer, the regions are under the influence of moist, maritime airflow from the subtropical anticyclonic cells.**
- Local storms, e.g. **typhoons**, and **hurricanes**, also occur.

Climate Graphs





Climate graphs of places with Humid subtropical climate

Natural Vegetation

- Supports a luxuriant vegetation.
- The lowlands carry **both evergreen broad-leaved forests and deciduous trees** (**hard-wood**).
- On the highlands, are various species of conifers such as pines and cypresses which are important **softwoods.**
- Perennial plant growth is not checked by either a dry season or a cold season.

Timber

- The forests of China and southern Japan also have considerable economic value and include oak, camphor, etc.
- South-eastern Brazil, eastern Paraguay, north-eastern Argentina have Parana pine, and the **quebracho** (axe-breaker, an extremely hard wood used for tanning).
- Eastern Australia have Eucalyptus forests.
- In Natal, palm trees thrive.
- The Gulf states of U.S.A. have lowland deciduous forests.

Economic Development

Region	**Major Cropping Patterns**
South-Eastern China	• Rice, tea and mulberries (sericulture) • Sericulture is declining
South-Eastern USA	• Widespread cultivation of maize and cotton in the Corn and Cotton Belts of U.S.A • Fruit and tobacco are also grown
Natal, South Africa	• Sugarcane
South America	• Coffee and maize and dairying

Farming in monsoon China

- A third of the world's rice is grown in China, though the huge population leaves very little for export.
- Monsoon China has all the ideal conditions for padi cultivation; a warm climate, moderately wet throughout the year, and extensive lowlands with fertile moisture-retentive alluvial soil, which if necessary, can be easily irrigated.
- As the flat lands are insufficient for rice cultivation, farmers move up the hill-slopes and grow padi on terraced uplands.

Agriculture in the Gulf states

- Lack of population pressure and the urge to export gave rise to **corn, cotton and tobacco.**

Corn

- The humid air, the sunny summer and the heavy showers suit the crop well.
- It is grown right from the Gulf coast to the Mid-west south of the Great Lakes, with the greatest concentration in the Corn Belt of Nebraska, Iowa, Indiana and Ohio.
- The region accounts for more than half the world's production of corn, but only 3 per cent of the world's export.
- This is because most of the corn is used for **fattening animals**, mostly **cattle and pigs (thriving beef and pork industry).**
- The fattened animals are then sold to the meat plants in Chicago and Cincinnati to be processed into **'corned beef' (**from here the beef is exported through **Great Lakes** and **St Lawrence waterway**).
- Apart from its ease of cultivation, corn's most outstanding feature is its prolific yield.
- It gives almost twice as much food (mainly starch) per acre as wheat or other cereals.
- This explains why it is so widely cultivated in both the warm temperate and the tropical latitudes.

Cotton

- Of the cash crops grown in the Gulf states, none is comparable with cotton.
- The Gulf type of climate is undoubtedly the **best for cotton growing**.
- Its long, hot growing season with 200 days frost free and a moderately high temperature permits the crop to grow slowly and mature within six months.
- In the very south, in the Gulf-lands, the heavy rainfall damages the lint. This area is, therefore, less suitable for cotton and is devoted to **citrus fruits**, **cane sugar** and **market gardening**, as in Florida.
- The commercial cultivation of cotton is now concentrated only in the most favourable areas which are the **Mississippi flood plains** and **Atlantic coastlands**.
- The most dreaded enemy of the Cotton Belt is the **boll-weevil**. The pest multiplies rapidly. The pest is responsible for the **westward migration of the Cotton Belt**.

Tobacco

- It is a native crop of America.
- Virginia tobacco is famous.
- The humid atmosphere, the warmth and the well-drained soils of the Gulf states, enable tobacco to be successfully cultivated in many of the eastern states of U.S.A.
- No less than half the tobacco that enters international trade comes from these states.

Crops in Southern Hemisphere

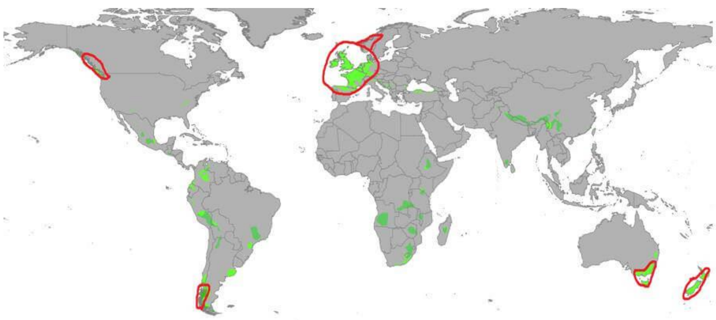
- In the coastlands of Natal, **cane sugar** is the dominant crop, followed by **cotton** and **tobacco** in the interior.
- Maize is extensively cultivated for use both as food and animal fodder for cattle rearing.
- In South America where rainfall is less than 120 cm, there is much grassland on which many cattle and sheep are kept for meat, wool and hides.
- The extensive natural pastures provide valuable forage for both cattle and sheep.
- Further north in southern Brazil, the rainfall increases to more than 120 cm, and forest gradually replaces grass.
- Here the important occupations are the cultivation of yerba mate (Paraguay tea) and the lumbering of araucaria or Parana pine. Cattle and sheep are reared, and maize and cane sugar are grown.
- In eastern Australia, Giant eucalyptus trees rise one above the other right up the Eastern Highlands.
- But with the influx of European immigrants, much of the forest has been cleared for settlement and dairying.
- The eastern margin of New South Wales is now the chief source of Australia's milk, butter and cheese, besides cotton, cane sugar and maize which are increasingly grown in the north.

British Type Climate or Cool Temperate Western Margin Climate (Cf)

- Cf: C – Warm temperate, f – no dry season
- It is also known as North-West European Maritime Climate.

- The cool temperate western margins are **under the influence of the Westerlies all-round the year.**
- They are the regions of **frontal cyclonic activity (temperate cyclones)**.
- This type of climate is typical to Britain, hence the name 'British Type'.
- Also called as North-West European Maritime Climate due to **greater oceanic influence.**

Distribution of British Type Climate



Distribution of British Type Climate

Europe

- Most pronounced in and around Britain.
- In Europe, the climate extends far inland into the lowlands of North-West Europe (northern and western France, Belgium, the Netherlands, Denmark, western Norway and also north-western Iberia).

North America

- High Rockies prevent the on-shore westerlies from penetrating far inland.
- Hence, it is confined mainly to the coastlands of British Columbia.

Southern Hemisphere

- The climate is experienced in southern **Chile, Southern Australia, Tasmania** and most parts of **New Zealand (regions east of Southern Alps).**

Climate .

- The climate is very favourable for maximum human output.

Temperature

- The mean annual temperatures are usually between 5 °C and 15 °C.
- Summers are moderately warm.
- Winters are **abnormally mild** because of the warming effect brought by **warm North Atlantic Drift.**
- Sometimes, unusual cold spells are caused by the invasion of **cold polar continental air** from the interiors.
- Ports are never frozen, but frosts do occur on cold nights.

Precipitation

- **Rainfall occurs throughout the year with winter maxima (due to frontal cyclones).**
- Western margins have the heaviest rainfall due to westerlies.
- In New Zealand, the western margins are subjected to heavy orographic rainfall whereas the eastern **Canterbury plains** receive comparatively less rainfall due to **rain-shadow effect.**

Canterbury Plains are to the east of Southern Alps

The seasons

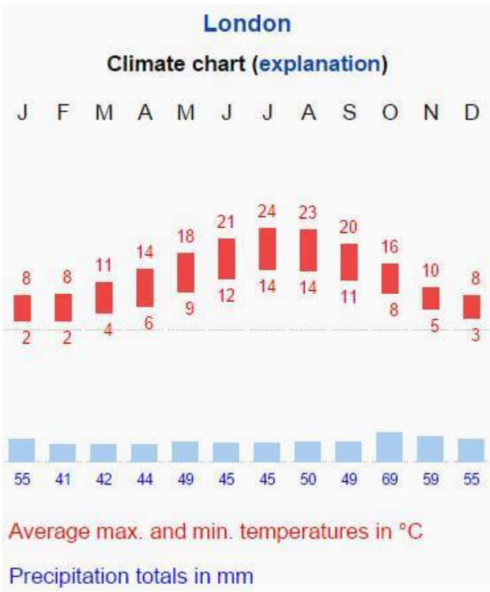
- As in other temperate regions, there are **four distinct seasons** (something that is conspicuously absent in the tropics).

Rainforest: Only Rainy season; Tropical Monsoon: Summer, Winter and Rainy: Tropical Savanna: Summer (rains) and Winter.

- Winter is the season of cloudy skies, foggy mornings, and many rainy days from the passing depressions.

- Spring is the driest and the most refreshing season when people emerge from the depressing winter.
- This is followed by the long, sunny summer.
- Next is the autumn with the roar of gusty winds; and the cycle repeats itself.

Climate Graph British Type Climate



Climate graph of London

Natural Vegetation in British Type Climate

- The natural vegetation of this climatic type is **deciduous forest** (trees shed their leaves in the **cold season**).
- This is an adaptation for protecting themselves against the winter snow and frost.
- Shedding begins in **autumn, the fall season**.
- Some of the common species include oak, elm, ash, birch, beech, and poplar.
- In the wetter areas grow willows (lightweight cricket bats are made from willows. In India willows are found in Kashmir).
- Higher up the mountains, deciduous trees are generally replaced by the **conifers** which can survive a higher altitude, a lower temperature and poorer soils.

Economy in British Type Climate

Lumbering is quite profitable

- Unlike the equatorial forests, the **deciduous trees** occur in **pure stands** and have greater lumbering value.
- The open forests with **sparse undergrowth** mean that logging, transportation are easy and economical.
- The **deciduous hardwoods** are excellent for both fuel and industrial purposes.
- In Tasmania, the **temperate eucalypts** are also extensively felled for the lumbering industry.
- Higher up the mountains, **conifers (softwood)** are felled and transported to **paper and pulp industry**.
- They are extensively used in cardboard making.

Industrialisation

- The regions are **highly industrialized** with high standard of living.
- Britain, France and Germany have significant mineral resources and are heavily industrialised.
- The countries are concerned in the production of machinery, chemicals, textiles rather than agriculture, fishing or lumbering, though these activities are well represented in some of the countries.
- **Ruhr region in Germany, Yorkshire, Manchester and Liverpool** regions in Britain are significant for wide-ranging manufacturing industries.
- Automobile industry is the most significant (BMW, Volkswagen, Audi, Mercedes-Benz and many other world leading car manufacturers have their headquarters in Germany).
- Industries based on dairy products thrive in **Denmark, Netherlands and New Zealand.**
- Tasmania is important for **merino wool production**. Wool produced here is exported to textile factories in England, Japan, China etc.
- Fishing is particularly important in Britain, Norway and British Columbia.

Agriculture

- A large range of cereals, fruits and root crops are raised, mainly for home consumption.
- North-West Europe, which includes some of the most crowded parts of the globe, has little sur-

plus for export. It is, in fact, a **net importer of food crops, especially wheat**.

Market gardening

- All the north-western European countries are highly industrialised and have high population densities.
- There will normally be great demand for fresh vegetables, eggs, meat, milk and fruits.
- As the crops are perishable, a good network of transport is indispensable.
- The produce is shipped by high-speed trucks (truck farming, which is commonly used in the United States)
- In Australia, high-speed boats ply across the Bass Strait daily from Tasmania (**garden state**) to rush vegetables and fruits to most of the large cities in mainland Australia.

Mixed farming

- Arable farms are devoured by factories and **wheat is now a net import item in Europe**.
- Throughout north-western Europe, farmers practice both arable farming (cultivation of crops on ploughed land) and pastoral farming (keeping animals on grass meadows).
- Amongst the cereals, wheat is the most extensively grown, almost entirely for home consumption.
- The next most important cereal raised in the mixed farm is **barley**.
- The better quality barley is sold to the breweries for **beer-making or whisky distilling**.
- The most important animals kept in the mixed farm are cattle.
- The countries bordering the North Sea (Britain, Denmark, the Netherlands) are some of the most advanced dairying countries where cattle are kept on a **scientific and intensive basis.**

Dairying

- The temperate western margin type of climate is almost ideal for **intensive dairying.**
- Cheese is a specialized product of the Netherlands.
- From Denmark and New Zealand comes high-quality butter.
- Milk is converted to cream (**less perishable** than fresh milk) and is exported to all regions across the globe.
- Fresh milk is converted into various forms of **condensed or evapourated milk**, and exported around the world for baby-feeding, confectionery, ice-cream and chocolate making.

Beef cattle

- Besides dairying, some cattle are kept as beef cattle.
- In Argentina or Australia, meat production is the primary concern.
- The high rate of beef consumption in Europe necessitates large imports of **frozen and chilled beef.**
- The **pigs and poultry** act as **scavengers** that feed on the left-overs from root-crops and dairy processes.
- In this way, Denmark is able to export large quantities of bacon (cured meat from the back or sides of a pig) from pigs that are fed on the **skimmed milk, a by-product of butter-making.**

Sheep rearing

- Sheep are kept both for wool and mutton.
- Britain is the home of some of the best-known sheep breeds.
- With the greater pressure exerted on land by increased urbanisation, industrialisation and agriculture, sheep rearing is being pushed further and further into the less-favoured areas.
- Britain was once an exporter of wool (but now it imports from Australia).
- Today it exports only British pedigree animals to the **newer sheep lands of the world (Australia).**
- In the southern hemisphere, sheep rearing is the **chief occupation of New Zealand**, with its greatest concentration in the **Canterbury Plain (the rain shadow region)**.
- Favourable conditions include extensive meadows, a mild temperate climate, well-drained level ground, scientific animal breeding, refrigera-

tion (enables the export of chilled Canterbury lamb and Corriedale mutton to every corner of the globe).

Other agricultural activities

Potatoes

- **Potatoes** feature prominently in the domestic economy of the cool temperate regions.
- It is the staple food in supplementing wheat or bread for millions of people.
- Potato yields far more starch than any cereals and can be cultivated over a range of climatic and soil types.

Beet Sugar

- Found almost exclusively in north-western Europe (including European Russia) and parts of U.S.A.
- The beet is crushed for sugar, and the green tops are used as animal fodder. Producing sugar from beet sugar started during the Napoleonic Wars when military blockades caused a scarcity of sugar.

7.5 D – Cold Snow-forest Climates

Taiga Climate or Boreal Climate (Dfc: f – no dry season, c – cold summer)

- It is also known as Siberian Climate OR Cool Temperate Continental Climate OR Continental Sub-Polar Climate (**just below Arctic circle — 50° to 70° N**).
- Taiga Climate is found **only** in the northern hemisphere due to great east-west extent.
- It is absent in the southern hemisphere because of the narrowness of landmasses and **strong oceanic influence** in the high latitudes.
- On its poleward side, it merges into the **Arctic tundra**; equatorward it fades into **steppe climate.**

Distribution

- It stretches along a continuous belt across **central Canada**, some parts of **Scandinavian Europe** and most of **central and southern Russian**.

Taiga Climate or Boreal Climate

Taiga Climate

Taiga Vegetation

Temperature

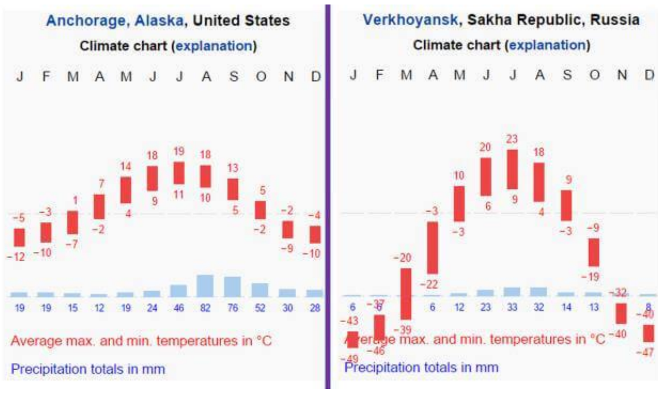
- Summers are brief and warm (20-25 °C) whereas winters are long and cold (30-40 °C below freezing).
- Some of the lowest temperatures in the world are recorded in **Verkhoyansk** (68° N) where -67 °C was once recorded.
- Annual temperature range of is the greatest due to continentality (almost 50-60 °C in Siberia).
- In North America, the extremes are less severe, because of the continent’s lesser east-west stretch.
- All over Russia, nearly all the rivers are **frozen**. In normal years, the Volga is ice-covered for about 150 days.
- Occasionally cold, polar local winds such as the **blizzards of Canada** and **buran of Eurasia** blow violently.
- Permafrost (subsurface layer of soil that remains below freezing throughout the year) are generally absent as **snow is a poor conductor of heat** and protects the ground from the severe cold above.

Precipitation

- Maritime influence in the interiors is absent.

- Frontal disturbances might occur in winter.
- Typical annual precipitation ranges from 38 cm to 63 cm.
- It is quite **well distributed throughout the year**, with a **summer maximum** (convectional rains).
- In winter the precipitation is in the form of snow.

Climate Graph



Climate graphs of places with Taiga Climate

Natural Vegetation

- The predominant vegetation is **evergreen coniferous forest** as they require little moisture.
- Pine, fir (e.g. douglas fir and balsam fir), spruce and larch are the four major species of conifers.
- The greatest single band of the coniferous forest is the **taiga** (Russian word for coniferous forest) in Siberia.
- In Europe, the countries that have a similar type of climate and forests are **Sweden** and **Finland**.
- There are small amounts of natural coniferous forest in Germany, Poland, Switzerland, and other parts.
- In North America, the belt stretches from **Alaska** across **Canada** into **Labrador**.
- In the southern hemisphere, coniferous forests are found only on the mountainous uplands of southern Chile, New Zealand, Tasmania and south-east Australia.

Characteristics of Coniferous forests

- Coniferous forests are of **moderate density** and are more uniform.
- The trees in coniferous forests grow straight and tall.
- Almost all conifers are **evergreen**. There is no annual replacement of new leaves as in deciduous trees.
- The same leaf remains on the tree for as long as five years.
- Food is stored in the trunks, and the bark is thick to protect the trunk from excessive cold.
- Conifers are conical in shape with sloping branches that prevent snow accumulation.
- Their shape also offers little grip to the violent winds.
- Transpiration can be quite rapid in the warm summer. So, leaves are small, thick, **leathery** and needle-shaped **to check excessive transpiration.**
- The soils of the coniferous forests are **poor.** They are excessively **leached** and very **acidic**.
- Humus content is also low as the evergreen leaves barely fall and the rate of decomposition is slow.
- Under-growth is negligible because of the poor soil conditions.
- Absence of direct sunlight and the short duration of summer are other contributory factors.
- Coniferous forests are also found in regions with high elevation (Example: the forests just below the snowline in Himalayas).
- But on very steep slopes where soils are immature or non-existent, even the conifer cannot survive (Example: Southern slopes of Greater Himalayas).

Economic Development

- Lot of coniferous forests in the northern hemisphere are still untouched due to **remoteness.**
- Only a small fraction of coniferous forests in Canada, Russia etc. are exploited.
- Agriculture is most unlikely as few crops can survive in the sub-Arctic climates.

Trapping

- Many fur-bearing animals are trapped in northerly lands of Canada and Eurasia.
- Wherever the cold is severe, the quality and thickness of the fur increases.
- In Canada trappers and hunters, armed with automatic rifles, reside in log cabins in the midst

of the coniferous forests to track down these animals.

- Muskrat, ermine, mink, and silver fox are the most important fur-bearing animals.
- To ensure a more regular supply of furs, many fur farms have been established in Canada and Siberia.

Lumbering

- This is the **most important occupation** of the Siberian type of climate.
- The vast reserves of softwood coniferous forests provide the basis for the lumbering industry.
- The world's greatest softwood producers are Russia, U.S.A., Canada and the **Fennoscandian countries (Finland, Norway and Sweden).**
- Contract labourers called lumberjacks used to temporarily move to the forest regions to fell the trees. Now felling is done by machines.
- **Rivers for transportation:** The softwood logs easily float on rivers. Hence rivers are used to transport logs to the sawmills located down the stream.
- **Sawmilling:** Logs are processed in sawmills into timber, plywood, and other constructional woods.
- **Paper and pulp industry:** Timber is pulped by both chemical and mechanical means to make wood pulp. Wood pulp is the raw material for paper-making and newsprint. U.S.A. is the leader.
- But in the field of newsprint, **Canada** accounts for almost half of the world's total annual production.
- **As a fuel:** Very little softwood is burnt as fuel as its industrial uses are far more significant.
- **As an industrial raw material:** In Sweden, matches form a major export item.
- From the by-products of the timber, many chemically processed articles are derived such as rayon turpentine, varnishes, paints, dyes, liquid resins, wood-alcohols, disinfectants and cosmetics.

Factors that favour lumbering in Taiga climate

Softwood trees

- The coniferous forest belts of Eurasia and North America are the **richest sources of softwood.**

Demand

- Softwood is used in construction, furniture, matches, **paper and pulp, rayon** and chemical industry.

Limited species

- The conifers are **limited in species**. Pine, spruce and fir in the northern forests and larch in the warmer south are the most important.

Pure stands

- Unlike rainforests, they occur in **homogeneous groups (pure stands)**.
- This saves time, costs and enhances the commercial value of the felled timber.
- Lumbering is normally carried out in the winter when the sap ceases to flow (sap stays in the ground, and the wood is lighter).

Cheap means of transportation

- The snow-covered ground makes logging and haulage (commercial transport) a relatively easy job.
- The logs are dragged to the rivers and float to the saw-mills downstream when the rivers thaw in spring.
- It is quite easy in Canada, Norway and Sweden as the rivers are not frozen for a greater part of the year.
- But in Russian taiga, most of Siberian rivers drain poleward into the Arctic Ocean which is frozen for three-quarters of the year, and there are few saw-mills there.
- However, with the use of the Northern Sea Route, which links Murmansk and Vladivostok via the Arctic Ocean, development is increasing.

Cheap electricity

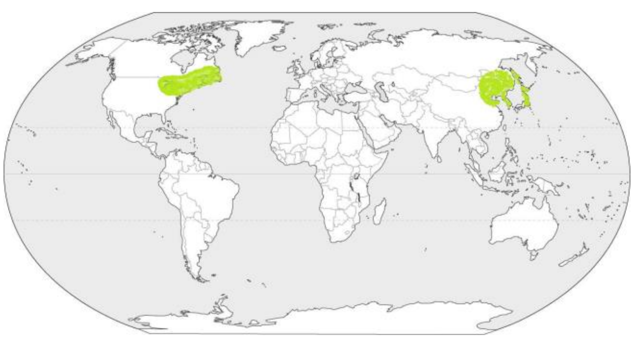
- Cheap hydro-electricity for driving the saw-mills is harnessed in the mountainous uplands of North America and Europe and has greatly assisted the lumbering industry.

Laurentian Climate or Cool Temperate Eastern Marine Climate (Dfc)

- Dfb: f – no dry season, b – warm summer.
- It is an intermediate type of climate between the **British Type Climate (moderate)** and the **Taiga Type Climate (extreme)**.
- It has features of **both** the maritime and the continental climates.

Distribution of Laurentian Climate

- Laurentian type of climate is found only in two regions and that too only in the northern hemisphere.
- North-eastern North America, including **eastern Canada, north-east U.S.A.**, and **Newfoundland**. This may be referred to as the North American region.
- Eastern coastlands of Asia, including eastern **Siberia, North China, Manchuria, Korea and northern Japan.**



Absent in Southern Hemisphere

- In the southern hemisphere only a small section of continents extends south of 40° S latitude.
- Some of these small sections come under the rain-shadow region of Andes (Patagonia).
- So, these regions are subjected to **aridity** rather than continentality.
- In other regions, the oceanic influence is so profound that neither the continental nor the eastern margin type of climate exists.

Climate

Temperature

- Characterized by **cold, dry winters and warm, wet summers**.
- Winter temperatures is below freezing-point and snow fall is quite natural.
- Summers are as warm as the tropics (~25 °C).

Precipitation

- Rainfall occurs throughout the year with **summer maxima** (easterly winds from the oceans bring rains).
- Annual rainfall ranges from 75 to 150 cm (two-thirds of rainfall occurs in the summer).
- Dry **westerlies** that blow from continental interiors dominate winters.

The North American region

- In summer, prolonged heat waves cause discomfort.
- In winter, the temperature drops below freezing and snowfall occurs.
- Precipitation occurs **all-round the year** due to the influence of **warm Gulf Stream** (increases the moisture of easterly winds in summer) and the **Great Lakes** (westerlies, temperate cyclones in winter).
- The **warm Gulf Stream** increases the moisture of easterly winds.
- Convergence of the warm Gulf Stream and the cold Labrador Current near Newfoundland produces dense mist and fog and gives rise to much precipitation.
- It is said that Newfoundland experiences more **drizzles** than any other part of the world.

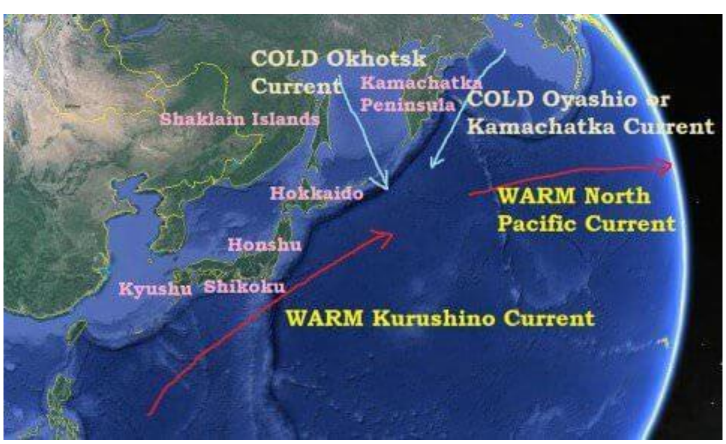
Cold and warm ocean current mixing zone off Newfoundland

The Asiatic region

- Rainfall distribution of the Asiatic region is **far less uniform** when compared to North American Region.
- Winters are cold and **very dry** while summers are very warm and **exceptionally wet**.
- The rainfall regime resembles the **tropical monsoon type** in India.
- Intense heating in interior of China in summer creates a region of low-pressure, and moisture-laden winds from the Pacific Ocean and the Sea of Japan blow in as the **South-East Monsoon**.
- Thus, the Laurentian type of climate in China is often described as the **Cool Temperate Monsoon Climate**.
- It has a very long, cold winter, and a large annual range of temperature.
- Much of the winter precipitation in northern China, Korea and Hokkaido, Japan, is in the form of **snow.**

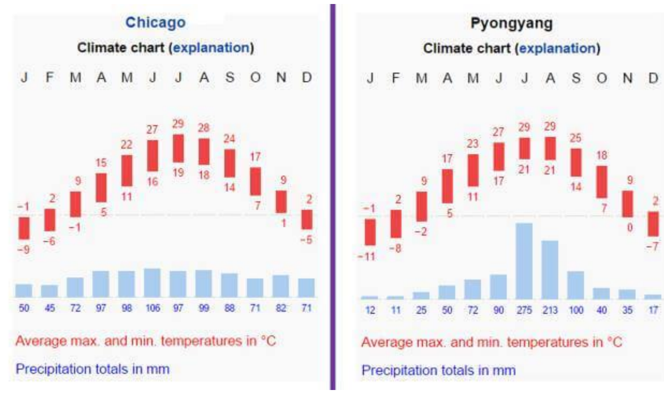
Japan

- The climate of Japan is modified by the **meeting of warm and cold ocean currents.**
- It receives adequate rainfall from both the South-East Monsoon in summer and the North-West Monsoon in winter (western coasts of Japan)
- The **warm Kuroshio** makes the climate of Japan less extreme.
- The meeting zone between **warm Kuroshio** from south and **cold Oyashio** from the north produce fog and mist, making north Japan a **second Newfoundland**.
- **Fishing** replaces agriculture as the main occupation in many of the **indented coastlands**.



Cold and warm ocean current mixing zone off Japan

Climate Graph



Climate graph of places with Laurentian climate

Natural Vegetation

- The predominant vegetation is **cool temperate forest**.
- The heavy rainfall, the warm summers and the damp air from fogs, all **favour** the growth of trees.
- Forest tend to be **coniferous** north of the 50° N latitude.
- In the Asiatic region (eastern Siberia and Korea), the coniferous forests are a continuation of the great coniferous belt of the taiga.

Lumbering

- From Laurentian Climate regions, both temperate hardwood and temperate softwood are obtained.
- Much of the coniferous forests of fir, spruce and larch are exploited to a great extent.
- Conifers are present in **pure stands** with only a handful of species.
- Eastern Canada is the heart of the Canadian timber and wood pulp industry (**St. Lawrence River helps in export**).
- South of latitude 50° N., the coniferous forests give way to *deciduous forests*. Oak, beech, maple and birch are most common.
- They have been extensively felled for the extraction of **temperate hardwood.**
- In Manchuria, Korea and Japan, the forests have made way for the **agriculture.**

Economic Development

- Lumbering, **timber, paper and pulp** industries are the most important economic undertakings.
- Agriculture is less important because of long and severe winters.
- In the North American region, farmers are engaged in **dairy farming.**
- The **Annapolis Valley in Nova Scotia** is the world's most renowned region for **apples.**
- Fishing is, however, the most outstanding economic activity.

Fishing off Newfoundland

- Regions around the **Grand Banks of Newfoundland** are the **world's largest fishing grounds.**
- Mixing of **warm Gulf Stream** and **cold Labrador currents** make the region the most productive fishing ground on earth.
- The gently sloping continental shelves stretch for over 200 miles south-east of Newfoundland, and off the coasts of the Maritime Provinces and New England. Hence microscopic plankton are abundant.

Fish feed on minute marine organisms called plankton. Plankton is abundantly available in shallow waters (continental shelves) where they have access to both sunlight as well as nutrients. Also, cold and warm water mixing creates upwelling of cold nutrient-rich water to the surface.

- Fish of all types and sizes feed and breed here and support a **thriving fishing industry.**
- In Newfoundland, fishing industry employs almost the entire population.
- Further inland, in lakes and rivers (St. Lawrence and the Great Lakes), freshwater fish like salmon are caught.
- All the fishing activities are carried out by highly mechanised trawlers which can store fish in refrigerated chambers for months.
- St. John's, chief port of Newfoundland is the headquarters of the Grand Banks fishing industries.
- All processing activities like cutting, cleaning, packing for disposal are done at the ports itself.
- Along with Canada and U.S.A., countries like Norway, France, Britain, Portugal, Denmark, Russia and Japan, also send fishing fleets to the Grand Banks.
- Over-fishing is a growing problem.

Fishing off Japan

- North-west Pacific surrounding the islands of Japan is another very important fishing grounds of the world.
- Majority of the people in the region depend on fishing for survival.
- **Hakodate** and **Kushiro** are large fishing ports with complete refrigeration facilities.
- Japan accounts for a sixth of the world's total annual fish caught.
- The Japanese fishing trawlers venture far and wide into the Arctic, Antarctic and the Atlantic waters.
- Large whaling fleets with processing plants venture into distant regions as far as Arctic and Antarctic (**Japan is criticized for its whaling operations**).
- The Japanese make use of fish wastes, fish meal and seaweeds as fertilizers in their farms.
- Japan is one of the few countries that has taken to seaweed cultivation (India is taking baby steps).
- Coastal farms that are submerged in water grow weeds for sale as fertilizers, chemical ingredient and food.
- Another aspect of Japanese fishing is pearl culture. Pearls are harvested from **pearl oysters**.
- As natural pearls are difficult to obtain, the Japanese have begun to harvest cultured pearls.

Why is fishing the dominant occupation of Japan?

- The mountainous nature of Japan and parts of mainland eastern Asia support little agricultural activity (80 per cent land in Japan is classified as 'non-agricultural'. Around 50% of the total land is covered by forests).
- Japan is not well endowed with natural resources. Hence fishing forms a dominant aspect of the economy.
- The scarcity of meat (there is little pasture in Japan for livestock farming of any kind) popularised fish as the principal item of diet

and the chief protein food of the Japanese and the Chinese as well.

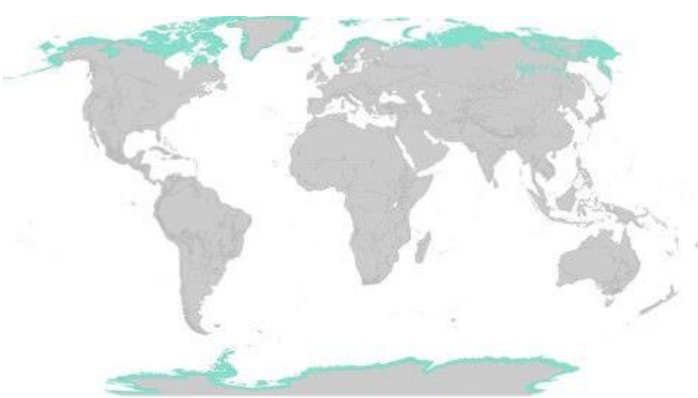
- There exists a great demand for fish and fish products in the nearby countries where fishing industry is under-developed.
- Japan has huge stakes in international fishing enterprises and her advanced fishing techniques give her an edge over competitors.
- Advanced financial services, encouraging government policy, advanced technology at hand, skilled workforce with decades of experience in fishing and the only available natural resource to exploit, make Japan a leader in fishing industry.

Geographical advantage

- The continental shelves around the islands of Japan are rich in plankton, due to the meeting of the warm Kuroshio and the cold Oyashio currents and provide excellent breeding grounds for all kinds of fish.
- The **indented coastline of Japan** provides **sheltered fishing ports**, calm waters and safe landing places, ideal for the fishing industry.

7.6 E – Cold Climates

Tundra Climate or Polar Climate or Arctic Climate



Distribution of Tundra Climate

Distribution

- Found in regions **north of the Arctic Circle and south of Antarctic Circle**.
- The ice-caps are confined to highlands and high latitude regions of Greenland and Antarctica.
- In the southern hemisphere, Antarctica is the greatest single stretch of ice-cap (10,000 feet thick).
- The lowlands – coastal strip of Greenland, the barren grounds of northern Canada and Alaska and the Arctic seaboard of Eurasia, have tundra climate.

Climate

Temperature

- The tundra climate is characterized by a very **low mean annual temperature**.
- In mid-winter temperatures are as low as 40 – 50 °C below freezing. Summers are relatively warmer.
- Normally not more than four months have temperatures above freezing-point.
- Within the Arctic and Antarctic Circles, there are weeks of continuous darkness (earth's tilted axis and revolution around the sun).
- The ground remains solidly frozen and is inaccessible to plants.
- Frost occurs at any time and blizzards, reaching a velocity of 130 miles an hour is not infrequent.

Precipitation

- Precipitation is mainly in the form of snow and sleet.
- Convectional rainfall is generally absent.

Natural Vegetation

- There are **no trees** in the tundra.
- Lowest form of vegetation like mosses, lichens etc. are found here and there.
- Climatic conditions along the coastal lowlands are a little favourable.
- Coastal lowlands support hardy grasses and reindeer moss which provide the only pasturage for reindeers.
- In the brief summer, berry-bearing bushes and Arctic flowers bloom.
- In the summer, birds migrate north to prey on the numerous insects which emerge when the snow thaws.

- Mammals like the wolves, foxes, musk-ox, Arctic hare and lemmings also live in tundra regions.
- Penguins live only in Antarctic regions.

Human Activities

- Human activities of the tundra are largely confined to the coast.
- People live a semi-nomadic life.
- In Greenland, northern Canada and Alaska live the **Eskimos.**
- During winter they live in compact **igloos.**
- Their food is derived from fish, seals, walruses and polar bears.
- Nowadays rifles instead of traditional harpoons are used to track down animals.

Recent Development of the Arctic Region

- New settlements have sprung up because of the discovery of minerals.
- Gold is mined in Alaska, petroleum in the Kenai Peninsula, Alaska; and copper at the Rankin Inlet, Canada.
- With the declining reserves of iron ore around the Great Lakes, iron ore deposits in Labrador are gaining importance. New railway lines have been constructed to bring the ores to the St. Lawrence River.
- Rich deposits of iron ores at Kiruna and Gallivare helped Sweden enjoy a prosperous export trade in iron and steel and other metallurgical products.
- New ports on the Arctic seaboard of Eurasia has made it possible to ship timber and fur from Siberia. Modern ice-breakers makes the frozen seas navigable.

7.7 Questions

Previous prelims questions

Q1.

Assertion (A): Areas near the equator receive rainfall throughout the year.

Reason (R): High temperatures and high humidity cause convectional rain in most afternoons near the equator.

In the context of the above two statements, which one of the following is correct?

a) Both A and R are true, and R is the correct explanation of A
b) Both A and R true but R is not a correct explanation of A
c) A is true but R is false
d) A is false but R is true

Q2.

Assertion (A): Areas lying within five to eight degrees latitude on either side of the equator receive rainfall throughout the year.

Reason (R): High temperatures and high humidity cause convectional rain to fall mostly in the afternoons near the equator. [2003]

a) Both A and R are individually true, and R is the correct explanation of A
b) Both A and R are individually true, but R is not the correct explanation of A
c) A is true but R is false
d) A is false but R is true

Q3.

A geographic area with an altitude of 400 metres has following characteristics. [2010]

Month	J	F	M	A	M	J	J	A	S	O	N	D
Average maximum temp °C	31	31	31	31	30	30	29	28	29	29	30	31
Average minimum temp °C	21	21	21	21	21	21	20	20	20	20	20	20
Rainfall (mm)	51	85	188	158	139	121	134	168	185	221	198	86

If this geographic area were to have a natural forest, which one of the following would it most likely be?

a) Moist temperate coniferous forest
b) Montane subtropical forest
c) Temperate forest
d) Tropical rain forest

Q4.

Assertion (A): Unlike temperate forests, the tropical rain forests, if cleared, can yield productive farmland that can support intensive agriculture for several years even without chemical fertilizers.

Reason (R): The primary productivity of the tropical rain forest is very high when compared to that of temperate forests. [2003]

a) Both A and R are individually true, and R is the correct explanation of A.
b) Both A and R are individually true, but R is not the correct explanation of A
c) A is true, but R is false
d) A is false, but R is true

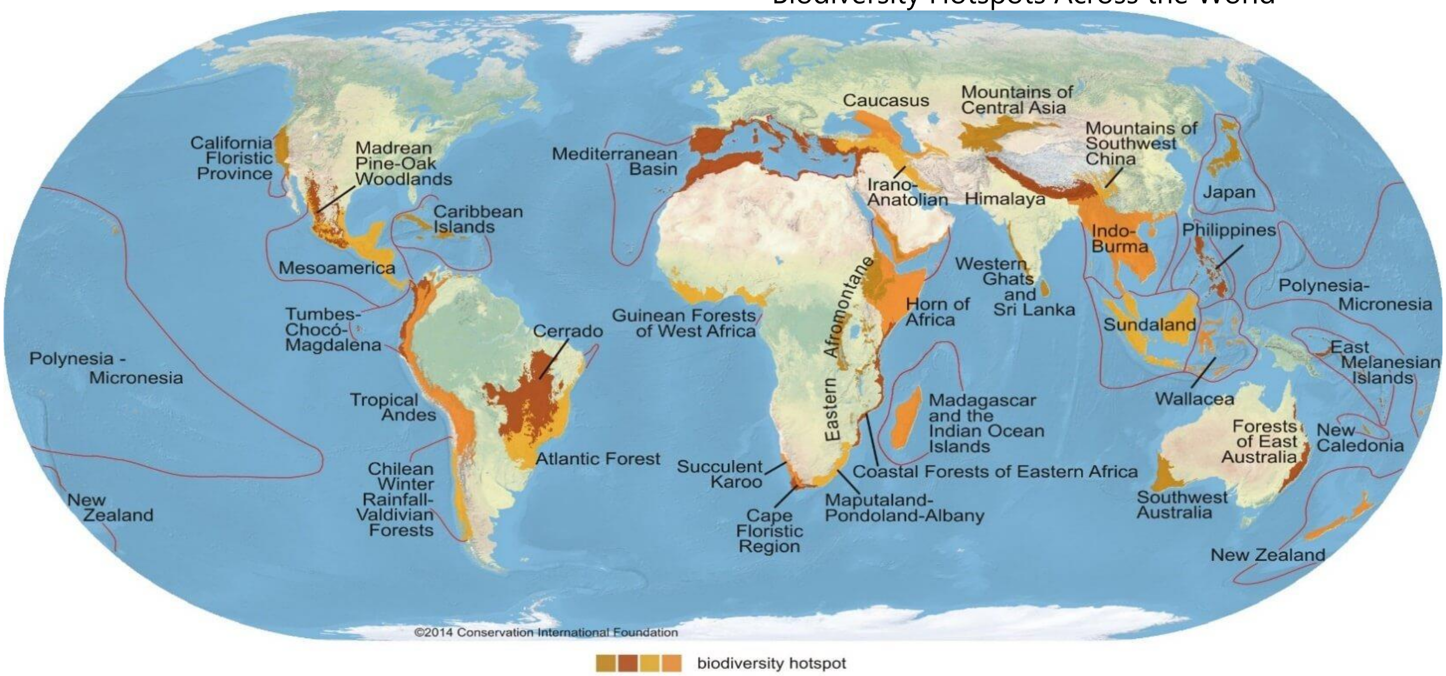
Q5.
Consider the following statements: [2010]

1) Biodiversity hotspots are located only in tropical regions.
2) India has four biodiversity hotspots, i.e., Eastern Himalayas, Western Himalayas, Western Ghats and Andaman and Nicobar Islands.

Which of the statements given above is/are correct?

a) 1 only
b) 2 only
c) Both 1 and 2
d) Neither I nor 2

Biodiversity Hotspots Across the World



Q6.
The seasonal reversal of winds is the typical characteristic of

a) Equatorial climate
b) Mediterranean climate
c) Monsoon climate
d) All of the above climates

Q7.
Which one of the following is the characteristic climate of the Tropical Savannah Region? [2012]

a) Rainfall throughout the year
b) Rainfall in winter only
c) An extremely short dry season
d) A definite dry and wet season

Q8.
A geographic region has the following distinct characteristics: [2010]

1. Warm and dry climate
2. Mild and wet winter
3. Evergreen Oak trees

The above features are distinct characteristics of which one of the following regions?

a) Mediterranean
b) Eastern China
c) Central Asia
d) Atlantic coast of North America

Q9.

Which one among the following covers the highest percentage of forest area in the world? [2003]

a) Temperate coniferous forests
b) Temperate deciduous forests
c) Tropical monsoon forests
d) Tropical rain forests

Answers:
Q1. a) Both A and R are true, and R is the correct explanation of A
Q2. a) Both A and R are true, and R is the correct explanation of A
Q3. d) Tropical rain forest
Q4. d) A is false but R is true

- The tropical rain forests, if cleared, can yield productive farmland: this statement is wrong. The tropical soils are heavily leached. Some fertility is added by burning down the felled trees. This little fertility is lost after 2-3 crops.
- Can support intensive agriculture for several years even without chemical fertilizers: this is also wrong. Intensive agriculture for several years is not possible without adding fertilizers.

Q5. d) Neither

- Biodiversity hotspots are located even outside tropics. E.g. Eastern Himalayas, Parts of Mediterranean, etc.
- India has three biodiversity hotspots i.e., Eastern Himalayas, Western Ghats and Andaman and Nicobar Islands.
- The is no biodiversity hotspot called Western Himalaya.

Q6. C) Monsoon
Q7. d) A definite dry and wet season

- Equatorial Rainforest: Rainfall throughout the year
- Mediterranean: Rainfall in winter only
- An extremely short dry season: I don't think there is any specific climate that fits this description
- Savanna: A definite dry winter and wet summer

Q8. Ans: a) Mediterranean (Evergreen oaks and winter maxima)

- Eastern China (China Type – it is not dry)
- Central Asia (Temperate Desert – it is dry but there are no oaks)
- Atlantic coast of North America (it is not dry)

Q9. Ans: a) Temperate coniferous forests

- In Indian **Tropical Moist Deciduous (37%)** cover the highest percentage followed by **Tropical Dry Deciduous (28%)**

Descriptive questions

1. Distinguish between hardwoods and softwoods. What are industrial uses made of them? Account for their large scale production for export in any one country.
2. What is meant by
   - ✓ the taiga
   - ✓ the veld
   - ✓ the selvas
3. Describe the role played by forest products in the economy of either Canada or Sweden.
4. Compare and contrast the climate of the following pairs of areas.
   - ✓ Laurentian Climate in the North American region and the Asiatic region.
   - ✓ Tropical monsoon Climate of India and the Warm Temperate Eastern Margin (China type) Climate in S. China.
   - ✓ The Steppe type of climate in Eurasia and the Siberian type (Taiga climate) of climate in northern Canada.
   - ✓ The Tundra Climate of Greenland and Trade Wind Desert Climate of central Australia.
5. Name the major fishing areas of the world. Explain the geographical factors which have contributed to its importance.
6. Write brief notes on
   - ✓ The economy of the forests of the Laurentian regions.
   - ✓ Fishing in Japan.
7. Why does tropical cyclone originate over the seas? In which part of the tropical cyclone do torrential rains and high-velocity winds blow and why?
8. What type of climate is characterized by two periods of maximum rainfall? Explain why this is so.

- Hint: Equatorial Rainforest. Sun is overhead during Equinoxes. So, the ITCZ passes twice over the region.

9. Write brief notes on any three of the following statements about the equatorial regions.
    - ✓ Large-scale livestock farming is least developed in wet equatorial areas.
    - ✓ The greatest single drawback to commercial lumbering in equatorial regions is inaccessibility.
    - ✓ The equatorial environment is best suited to plantation agriculture (Good rainfall, humid climate, cheap labour, good markets in Europe and North America).
10. Explain the following statements.
    - ✓ The east coasts of continents within the tropics have much heavier rainfall than the interiors or the west coasts [Hint: Easterly trade winds].
    - ✓ Near the equatorial latitudes, the period of maximum rainfall is closely related to the movements of the overhead sun [Hint: Inter-Tropical Convergence Zone shifts according to the apparent movement of the Sun].
    - ✓ There is a marked difference in temperature between the east and west coasts of countries in latitudes 20° to 35°N [Hint: Ocean currents].
11. Explain why
    - ✓ The savanna is the natural home of cattle.
    - ✓ Rainfall in the Sudan Climate is concentrated in the summer.
12. Give an explanatory account of any two of the following.
    - ✓ Sheep outnumber the population of New Zealand by 20:1.
    - ✓ No country produces and exports more wool than Australia.
    - ✓ Market-gardening is a product of urbanisation.
13. Write a geographical account of the following economic activities.
    - ✓ Mixed farming
    - ✓ Beet sugar cultivation
    - ✓ Cool temperate orchard farming
    - ✓ Sheep rearing
    - ✓ Woollen textile industry
14. Give a reasoned account of any two of the following.
    - ✓ Cotton cultivation in the United States of America.
    - ✓ Padi growing in monsoon China.
    - ✓ Dairying in eastern Australia.
    - ✓ Lumbering in Canada.
15. Give an explanatory account of any three of the following.
    - ✓ Local storms (e.g. typhoon, hurricane, pampero) are often associated with the Warm Temperate Eastern Margin Climate.
    - ✓ U.S.A. accounts for more than 50 per cent of world production of corn (i.e. maize) but only 3 per cent of world exports.
    - ✓ Farming in monsoon China is usually on a subsistence basis, and the peasants are permanently ‘land-hungry’.
16. Explain how the aridity of the desert is related to
    - ✓ off-shore Trade Winds
    - ✓ the Sub-Tropical High-pressure Belts (the Horse Latitudes)
    - ✓ cold ocean currents
17. Bring out any distinct differences between the hot deserts and mid-latitude deserts in
    - ✓ climate
    - ✓ vegetation
    - ✓ way of life
18. Explain any three of the following.
    - ✓ The hot deserts of the world are located on the western coasts of continents.
    - ✓ Patagonia is a desert in the rain shadow of the Andes.
    - ✓ The annual range of temperature is much greater at Kashgar (Gobi) than at Iquique (Atacama).
19. Write brief notes on any three of these topics.
    - ✓ Date palm cultivation in an oasis.
    - ✓ The role of oil in the development of desert economy.
20. Compare and contrast tropical and temperate grasslands in respect of
    - ✓ their seasonal responses to climatic changes
    - ✓ their economic importance
21. Give a reasoned account
    - ✓ Asiatic Steppes: nomadic herding
    - ✓ Canadian Prairies: spring wheat cultivation
    - ✓ Argentine Pampas: beef cattle ranching
    - ✓ S. African Veld: maize growing
    - ✓ Australian Downs: sheep grazing

22. Explain why when Chinooks are more frequent in the Prairies, the winters are milder.
23. Give an explanatory account of the following statements about economic activities of the Mediterranean lands.
    - ✓ Orchard farming is the predominant occupation.
    - ✓ The chief cereal cultivated is hard, winter wheat.
    - ✓ Pastoral farming is of little importance.
24. Write geographical notes on any three of the following.
    - ✓ The Mediterranean Climate is typified by dry, sunny summers and wet, mild winters.
    - ✓ Hot, dusty Sirocco and cold stormy Mistral.
    - ✓ Mediterranean woodlands, shrubs and scrub.
    - ✓ Three-quarters of the world's wine comes from the Mediterranean regions of Europe.

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Oceanography

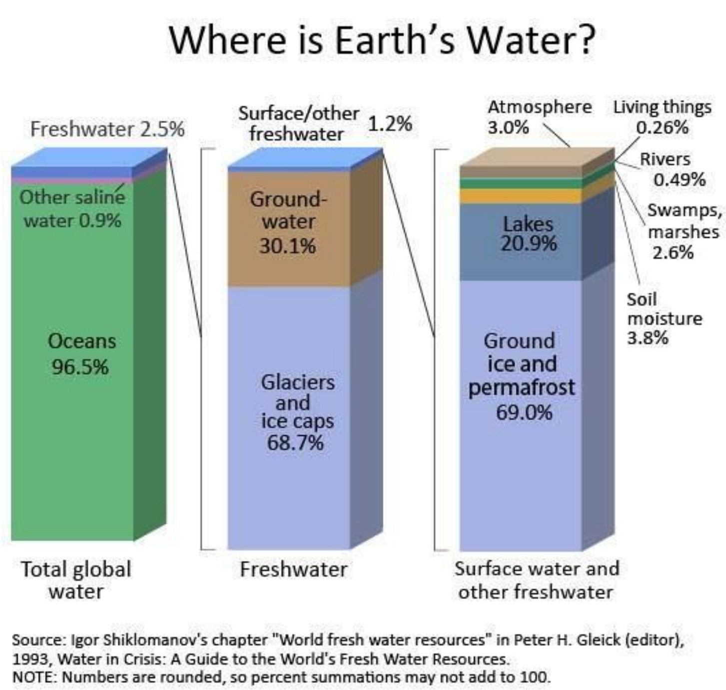
Print Friendly PDF

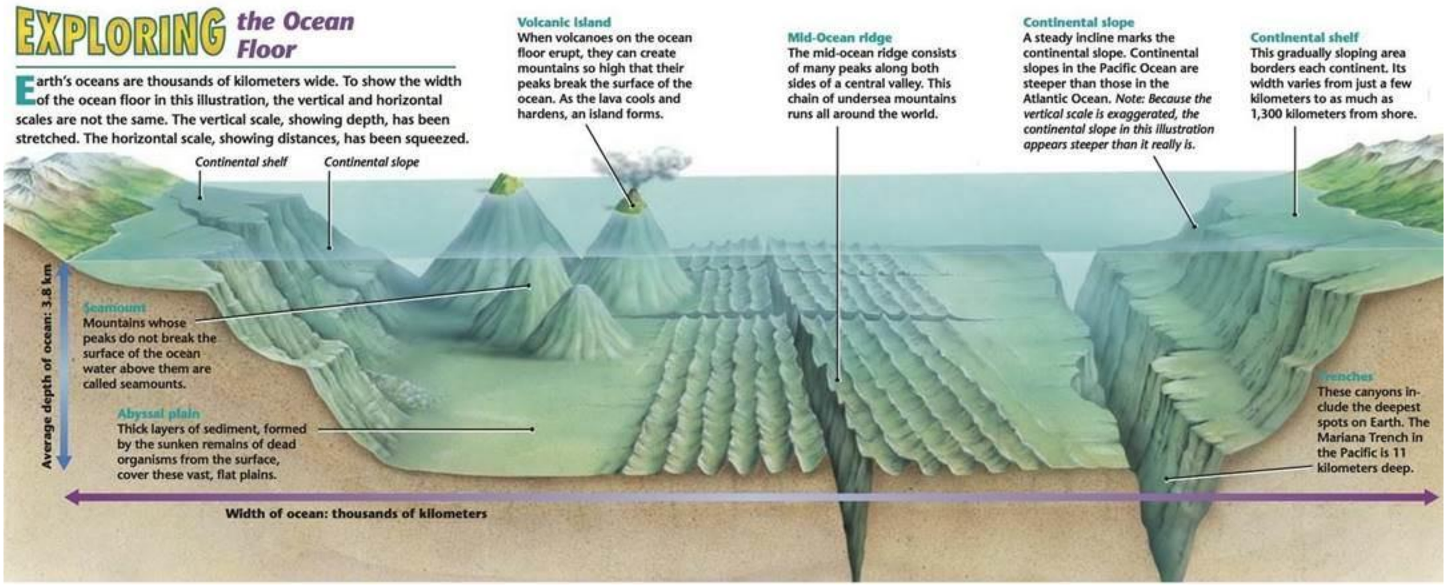
World Water Day – March 22

Water on the Earth's surface

Reservoir	Volume (Million Cubic km)	% of the Total
Oceans	**1,370**	**97.25**
Icecaps and Glaciers	**29**	**2.05**
Groundwater	**9.5**	**0.68**
Lakes	**0.125**	**0.01**
Soil Moisture	**0.065**	**0.005**
Atmosphere	**0.013**	**0.001**
Streams and Rivers	**0.0017**	**0.0001**
Biosphere	**0.0006**	**0.00004**

- Water on earth in liquid form came into existence in Hadean Eon (4,540 – 4,000 mya).
- During the Hadean Eon, temperature on earth was extremely hot, and much of the Earth was molten.
- **Volcanic outgassing** created the primordial atmosphere which consisted of various gases along with water vapour.
- Over time, the Earth cooled, causing the formation of a **solid crust**.
- The water vapour condensed to form rain and rainwater gradually filled the depressions on the newly solidified crust.
- The water in the depressions merged to give rise to mighty oceans.
- During the Hadean Eon, the atmospheric pressure was **27 times greater** than it is today and hence even at a surface temperature of close to 200° C water remained liquid in the oceans.
- Over time, both temperature and atmospheric pressure dropped, and water continues to stay as liquid in the oceans.





Ocean Relief Features

1. Ocean Relief

- Ocean relief is largely due to **tectonic, volcanic, erosional and depositional processes and their interactions.**
- Ocean relief controls the **motion of seawater.**
- The oceanic movement in the form of currents, in turn, causes many variations in both oceans and atmosphere.
- The bottom relief of oceans also influences **navigation and fishing.**

Ocean relief features are divided into major and minor relief features:

1.1 Major Ocean Relief Features

Four major divisions in the ocean relief are:

1. the continental shelf,
2. the continental slope,
3. the continental rise,
4. the Deep Sea Plain or the abyssal plain.

Continental Shelf

- Continental Shelf is the gently sloping (**gradient of 1° or less**) seaward **extension of a continental plate**.
- Continental Shelves cover **7.5%** of the total area of the oceans.
- **Shallow seas** and **gulfs** are found along the continental shelves.
- The shelf typically ends at a very steep slope, called the **shelf break.**
- Examples of continental shelves: Continental Shelf of South-East Asia (Sunda Plate), Grand Banks around Newfoundland, Submerged region between Australia and New Guinea, etc.

Formation

- The shelf is formed mainly due to
  1. **submergence of a part of a continent**
  2. **relative rise in sea level**
  3. **Sedimentary deposits brought down by rivers, glaciers**
- There are various types of shelves based on different sediments of terrestrial origin —
  1. **glaciated shelf (e.g. Shelf Surrounding Greenland),**
  2. **coral reef shelf (e.g. Queensland, Australia),**
  3. **shelf of a large river (e.g. Shelf around Nile Delta),**
  4. **shelf with dendritic valleys (e.g. shelf at the Mouth of Hudson River)**
  5. **shelf along young mountain ranges (e.g. Shelves between Hawaiian Islands).**

Various types of shelves

Width and depth of continental shelves

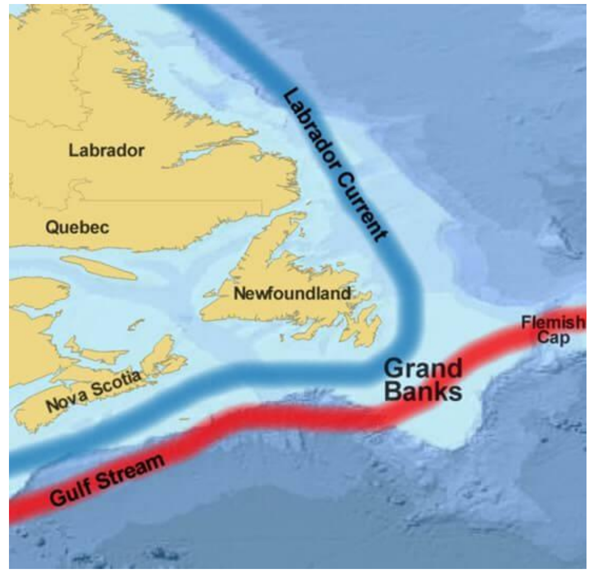
- Continental shelves have an average width of **70-80 km.**
- The shelves are almost absent or very narrow along a convergent boundary. E.g. coasts of Chile.
- The width of continental shelf of eastern coast of USA varies between 100-300 km.
- **Siberian shelf** in the Arctic Ocean is the largest in the world and stretches up to 1,500 km from the coast.

Width of various continental shelves

- Continental shelves may be as shallow as 30 m in some areas while in some areas it is as deep as 600 m.

Importance of continental shelves

- 20% of the world production of **petroleum** and gas comes from shelves.
- Continental shelves form the richest fishing grounds. E.g. Grand Banks around Newfoundland.



Grand Banks, the richest fishing grounds on earth

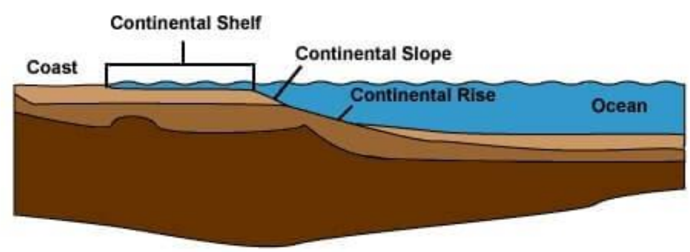
- Marine food comes almost entirely from continental shelves.
- They are sites for **placer deposits** and **phosphorites** (explained in Ocean Resources).

Continental Slope

- The gradient of the slope region varies between **2-5°.**
- The continental slope connects the continental shelf and the ocean basins.
- The depth of the slope region varies between 200 and 3,000 m.
- The seaward edge of the continental slope loses gradient at this depth and gives rise to **continental rise.**
- The **continental slope boundary indicates the end of the continents**.
- Canyons and trenches are observed in this region.

Continental Rise

- The continental slope **gradually** loses its steepness with depth.
- When the slope reaches a level of between **0.5° and 1°**, it is referred to as the continental rise.
- With increasing depth, the rise becomes virtually flat and merges with the **abyssal plain.**



Shelf, Slope and Rise (Wikipedia)

Deep Sea Plain or Abyssal Plain

- Deep sea planes are gently sloping areas of the ocean basins.
- These are the **flattest** and smoothest regions of the world because of **terrigenous** (marine sediment eroded from the land) **and shallow water sediments** that buries the irregular topography.
- It covers nearly **40%** of the ocean floor.
- The depths vary between 3,000 and 6,000 m.
- These plains are covered with fine-grained sediments like clay and silt.

1.2 Minor Ocean Relief Features

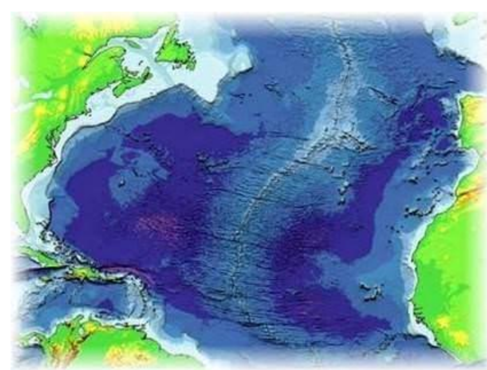
- Ridges (along a divergent boundary),
- Abyssal Hills (submerged volcanic mountains): Seamounts and Guyots,
- Trenches (along a convergent boundary),
- Canyons (erosional landform),
- Island arcs (formed due to volcanism along a convergent boundary or hotspot volcanism),
- Atolls and Coral reefs.

Oceanic Deeps or Trenches

- The trenches are relatively steep-sided, narrow basins (Depressions).
- These areas are the deepest parts of the oceans.
- They are of tectonic origin and are formed during ocean-ocean convergence and ocean-continent convergence.
- They are some 3-5 km deeper than the surrounding ocean floor.
- The trenches lie **along the fringes of the deep-sea plain** at the bases of continental slopes and along island arcs.
- The trenches run **parallel to the bordering fold mountains** or the **island chains**.
- The trenches are very common in the Pacific Ocean and form an almost continuous ring along the western and eastern margins of the Pacific.
- The **Mariana Trench off the Guam Islands** in the Pacific Ocean is the deepest trench with, a depth of more than **11 kilometres.**
- Trenches are associated with **active volcanoes** and **strong earthquakes** (like in Japan).
- Majority of the trenches are in the Pacific Ocean followed by the Atlantic Ocean and Indian Ocean.

Mid-Oceanic Ridges or Submarine Ridges

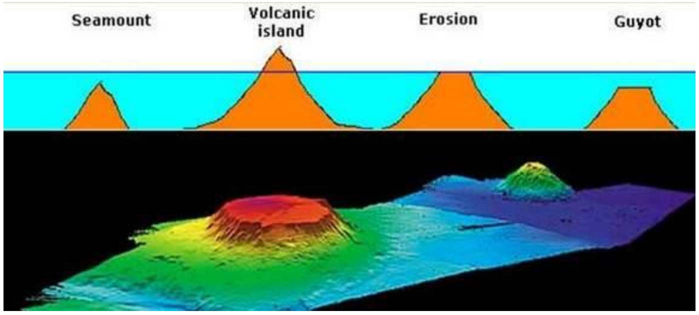
- A mid-oceanic ridge is composed of two chains of mountains separated by a large depression (divergent boundary).
- The mountain ranges can have peaks as high as 2,500 m and some even reach above the ocean's surface.
- Running for a total length of **75,000 km**, these ridges form the **largest mountain systems on earth.**



Mid Ocean Ridge

- The ridges are either broad, like a plateau, gently sloping or in the form of steep-sided narrow mountains.

Abyssal Hills



Abyssal Hills

- **Seamount:** It is a mountain with pointed summits, rising from the seafloor that **does not reach the surface** of the ocean. Seamounts are volcanic in origin. These can be 3,000-4,500 m tall.
- The **Emperor seamount**, an extension of the **Hawaiian Islands** in the Pacific Ocean, is a good example.
- **Guyots:** The flat-topped mountains (seamounts) are known as guyots.
- Seamounts and guyots are very common in the Pacific Ocean.

Submarine Canyons

Canyon: a deep gorge, especially one with a river flowing through it.
Gorge: a steep, narrow valley or ravine.
Valley: a low area between hills or mountains typically with a river or stream flowing through it.


Canyon, George, Valley

- Submarine canyons are deep valleys often extending from the mouths of the rivers to the abyssal plains.
- They are formed due to erosion by sediments brought down by rivers that cut across continental shelves, slopes and rises. The sediments are deposited on the abyssal plains.
- Submarine canyons can be far higher in scale compared to those that occur on land.


Submarine Canyon

Broadly, there are three types of submarine canyons:

- Small gorges which begin at the edge of the continental shelf and extend down the slope to very great depths, e.g., **Oceanographer Canyons** near New England.
- Those which begin at the mouth of a river and extend over the shelf, such as the **Indus canyons**.
- Those which have a dendritic appearance and are deeply cut into the edge of the shelf and the slope, like the canyons off the coast of southern California.
- The **Hudson Canyon** is the best-known canyon in the world.
- The largest canyons in the world occur in the **Bering Sea** off Alaska.

Atoll

- These are low islands found in the tropical oceans consisting of coral reefs surrounding a central depression.
- It may be a part of the sea (**lagoon**), or sometimes form enclosing a body of fresh, brackish, or highly saline water.


Atoll

Bank, Shoal and Reef

- These marine features are formed as a result of **erosional, depositional and biological activity.**
- These are produced upon features of **diastrophic (earth movements)** origin. Therefore, they are located on upper parts of elevations.

Bank

- These marine features are formed as a result of erosional and depositional activity.
- A bank is a flat-topped elevation located in the continental margins.
- The depth of water here is shallow but enough for navigational purposes.
- The **Dogger Bank** in the North Sea and **Grand Bank** in the north-western Atlantic, Newfoundland are examples.
- **The banks are sites of some of the most productive fisheries of the world**.

Shoal

- A shoal is a detached elevation with shallow depths.
- Since they project out of water with moderate heights, they are **dangerous for navigation.**

Shoal

Reef

- A reef is a predominantly organic deposit made by living or dead organisms that forms a mound or rocky elevation like a ridge.
- Coral reefs are a characteristic feature of the Pacific Ocean where they are associated with **seamounts and guyots.**
- The largest reef in the world is found off the **Queensland coast of Australia**.
- Since the reefs may extend above the surface, they are generally **dangerous for navigation.**

Reef

2. Major Oceans and Seas

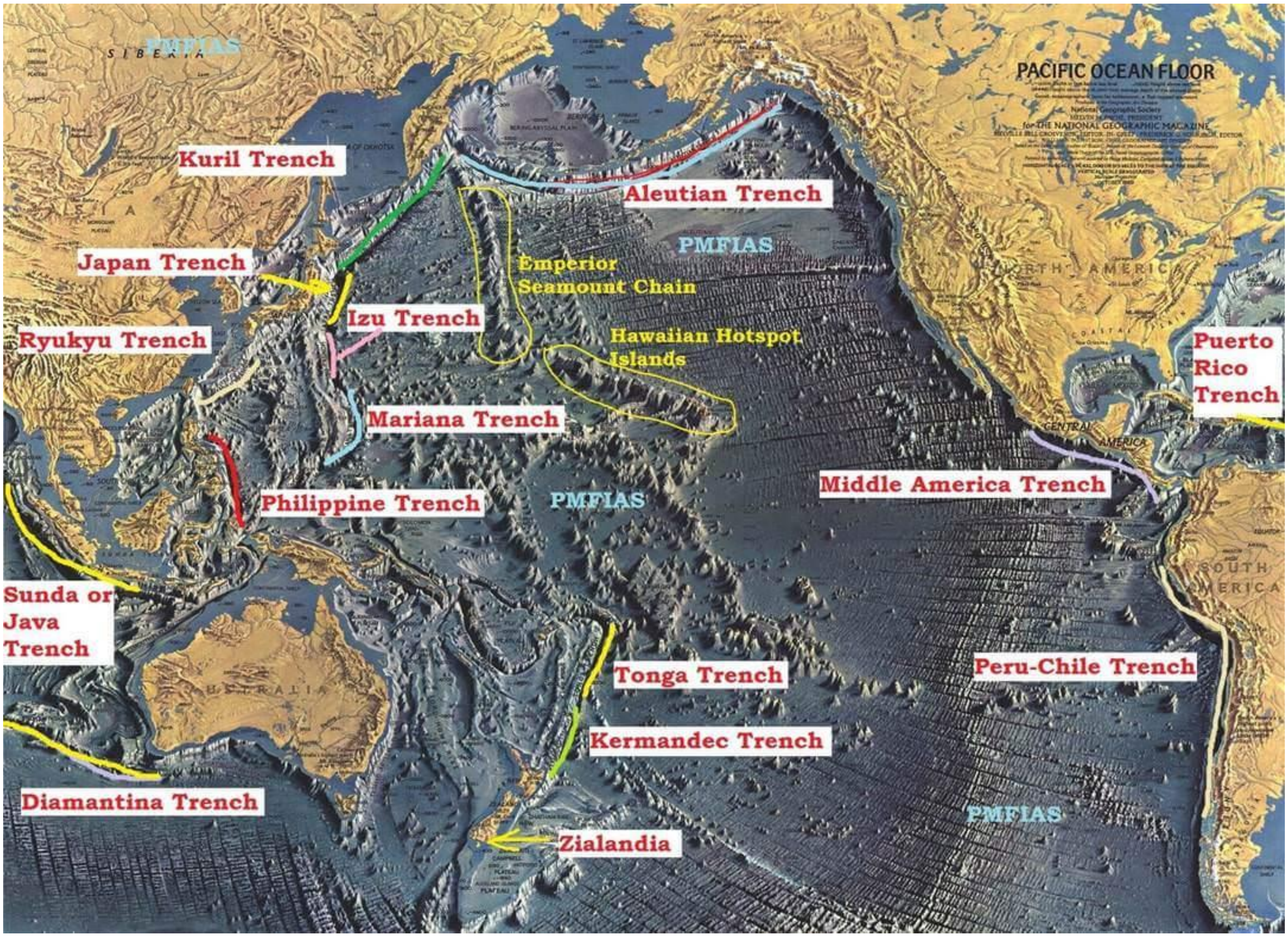
2.1 Oceans of the World by Size

Rank	Ocean	Area (million km^2) (%)	Average Depth (m)
1	Pacific Ocean	168 (46.6%)	3,970
2	Atlantic Ocean	85 (23.5%)	3,646
3	Indian Ocean	70 (19.5%)	3,741
4	Antarctic Ocean	21 (6.1%)	3,270
5	Arctic Ocean	15 (4.3%)	1,205

- **Total surface area of earth: 510 million km^2**
- **Total water surface area: 70.8% (361 million km^2)**
- **Total land surface area: 29.2% (149 million km^2)**

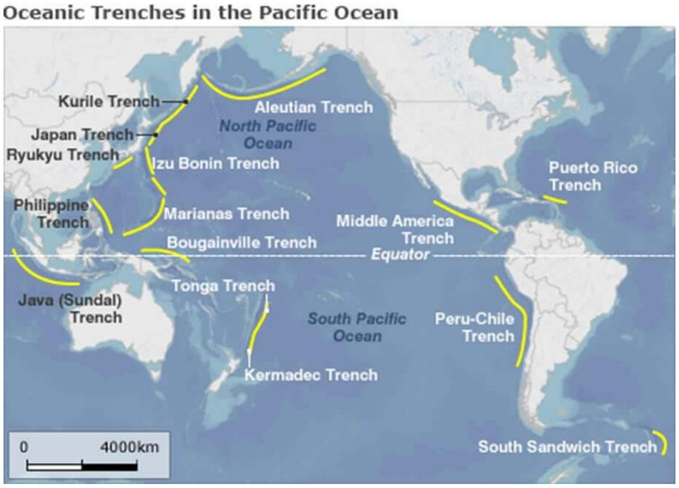
2.2 The Pacific Ocean

- Largest and deepest ocean.
- Covers about **one-third** of the earth's surface.
- Its shape is roughly **triangular** with its apex in the north at the **Bering Strait**.
- Many marginal seas, bays and gulfs occur along its boundaries.
- Nearly 20,000 islands dot this vast ocean.



Pacific Ocean Topography (Exaggerated) showing trenches and spreading sites

Oceanic Trenches in the Pacific Ocean



North and Central Pacific

- Characterized by **maximum depth** and a large number of **deeps, trenches and islands.**
- Some well-known trenches are **Aleutian** and **Kuril**.
- There are also a large number of **seamounts** and **guyots** (E.g. Hawaiian Hotspot).

West and South-West Pacific

- Average depth is about **4,000 m.**
- It is marked by a variety of islands, marginal seas, continental shelves and submarine trenches.
- **Mariana Trench** and **Mindanao Trench** are very deep with a depth of more than 10,000 metres.

South-East Pacific

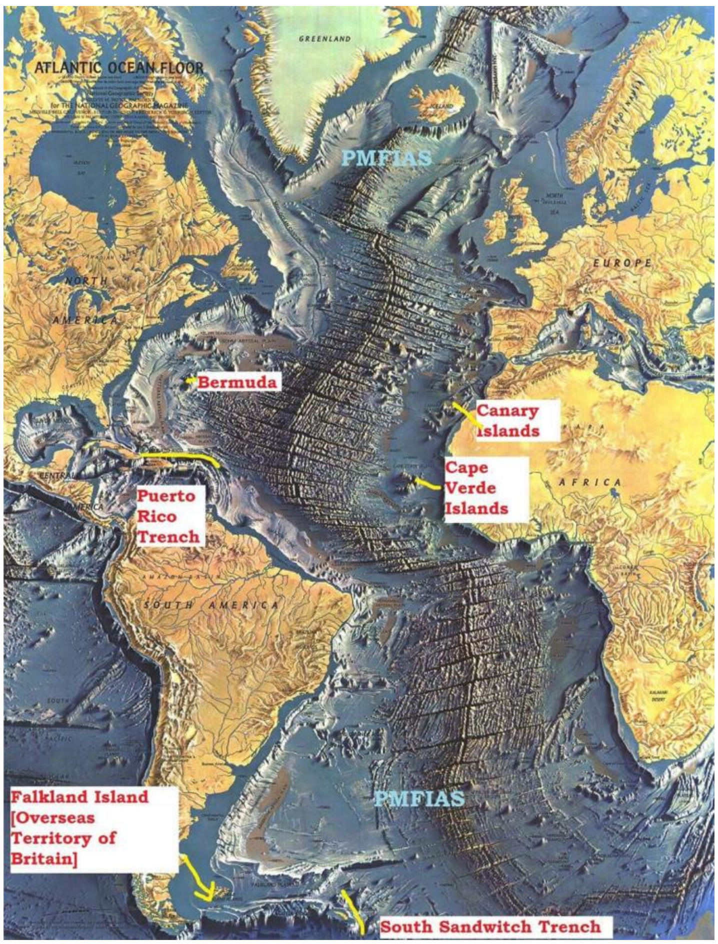
- This part is conspicuous for the **absence of marginal seas** and has submarine ridges and plateaus.
- The **Tonga** and **Atacama** trenches are prominent.

2.3 The Atlantic Ocean

- The Atlantic is the **second largest** ocean after the Pacific.
- It is roughly **half** the size of the Pacific Ocean.
- Its shape resembles the letter '**S'**.
- In terms of **trade**, it is the most significant of all oceans.

Continental Shelf

- It has prominent continental shelf with varying widths.
- The length of the continental shelf is maximum in Northern Atlantic coasts.
- The largest width occurring off north-east America and north-west Europe.



Atlantic Ocean Topography (Exaggerated) showing trenches and spreading sites

- **Grand banks continental shelf is the most productive continental shelf in the world**.
- The Atlantic Ocean has numerous marginal seas occurring on the shelves, like the Hudson Bay, the Baltic Sea, and the North Sea, and beyond the shelves like the Gulf of Florida (Mexican Gulf).

Mid-Atlantic Ridge

- The most remarkable feature of the Atlantic Ocean is the Mid-Atlantic Ridge which runs from north to the south paralleling the 'S' shape of the ocean.
- The ridge has an average height of 4 km and is about **14,000 km long.**

Seamounts and guyots

- They are present in significant numbers but not as significant as in Pacific Ocean.
- Several seamounts form islands of the mid-Atlantic. Examples include **Pico Island of Azores, Cape Verde Islands, Canary Islands etc.**
- Also, there are coral islands like **Bermuda** and volcanic islands like **St Helena** etc.

Trenches

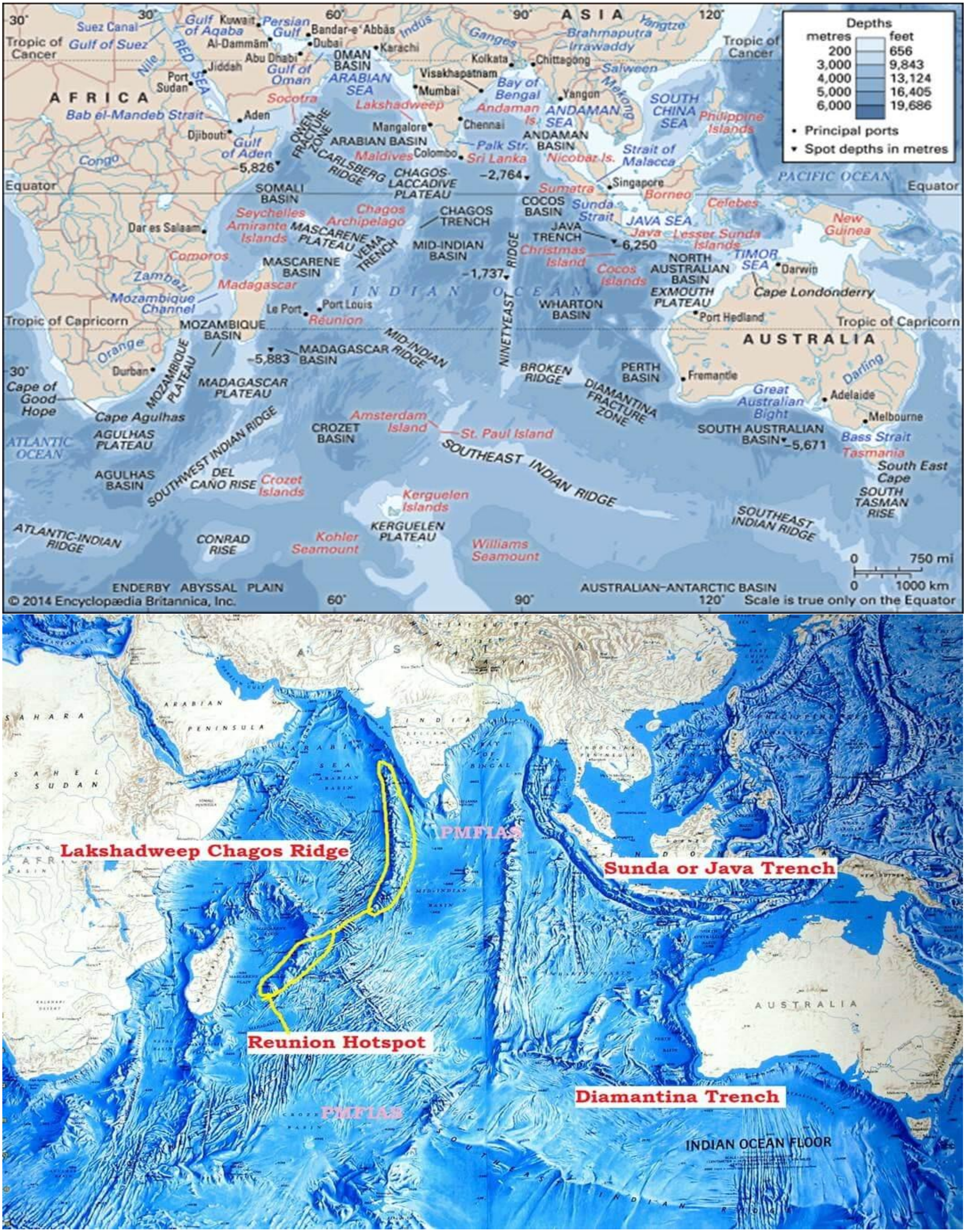
- Atlantic Ocean **lacks** significant troughs and trenches, which are most characteristic to the Pacific Ocean.
- **North Cayman** and **Puerto Rico** are the two troughs and **Romanche** and **South Sandwich** are the two trenches in the Atlantic Ocean.

2.4 The Indian Ocean

- Indian Ocean is the third largest of the world's oceanic divisions.
- Smaller and less deep than the Atlantic Ocean.

Submarine ridges

- Submarine ridges in this ocean include the **Lakshadweep-Chagos Ridge (Reunion Hotspot Volcanism)**, the **Socotra-Chagos Ridge**, the **Seychelles Ridge**, the **South Madagascar Ridge**, **Carlsberg Ridge etc.**
- These ridges divide the ocean bottom into many basins. Chief among these are the Central Basin, Arabian Basin, South Indian Basin, Mascarene Basin, West Australian and South Australian Basins.



Indian Ocean Topography (Exaggerated) showing trenches and spreading sites

Islands

- Most of the islands in the Indian Ocean are **continental islands** and are present in the north and west.
- These include the Andaman and Nicobar, Sri Lanka, Madagascar and Zanzibar.
- The **Lakshadweep** and **Maldives** are **coral islands** and **Mauritius** and the **Reunion Islands** are of volcanic origin.

Continental Shelf

- The ocean's continental shelves are narrow, averaging 200 kilometres (120 mi) in width.
- An exception is found off Australia's northern coast, where the shelf width exceeds 1,000 kilometres (620 mi).
- The average depth of the ocean is 3,890 m (12,762 ft).

Trenches

- **Linear deeps are almost absent.** Few exceptions are **Sunda Trench**, which lies to the south of the island of Java and **Diamantina Trench**, west of Australia.
- Its deepest point is **Diamantina Deep in Diamantina Trench**, at 8,047 m. Sunda Trench off the coast of Java is also considerably deep.

Straits

- Most of the straits in Indian Ocean are important trade roots.
- The major chokepoints include **Bab el Mandeb (between Yemen and Djibouti, Eritrea), Strait of Hormuz (separates Persian Gulf from the Gulf of Oman),** the **Lombok Strait (connects Java Sea to the Indian Ocean)**, the **Strait of Malacca (between Malay peninsula and Sumatra Island)** and the Palk Strait.

2.5 Marginal Seas

- In oceanography, a marginal sea is a sea **partially enclosed** by islands, archipelagos, or peninsulas.
- Some of the major marginal seas include the **Arabian Sea, Baltic Sea, Bay of Bengal, Bering Sea, Black Sea, Gulf of California, Gulf of Mexico, Mediterranean Sea, Red Sea,** and all four of the **Siberian Seas (Barents, Kara, Laptev, and East Siberian).**
- The primary differences between marginal seas and open oceans are associated with depth and proximity to landmasses.
- Marginal seas, which are generally shallower than open oceans, are more influenced by human activities, river runoff, climate, and water circulation.

Human Impact on marginal seas

- Marginal seas are **more susceptible to pollution** than open ocean regions.
- The greatest human impact on marginal seas is related to the **fisheries industry**.
- 90% of the world's fisheries exist within coastal waters that are located less than 200 km from the shoreline.
- Other human activities that have adversely affected marginal seas include industrial sewage disposal, offshore oil drilling, accidental releases of pollutants, radioactive waste, etc.
- Pollutants from the nearby landmasses are introduced into marginal seas in concentrations that are thousands of times greater than in open oceans.

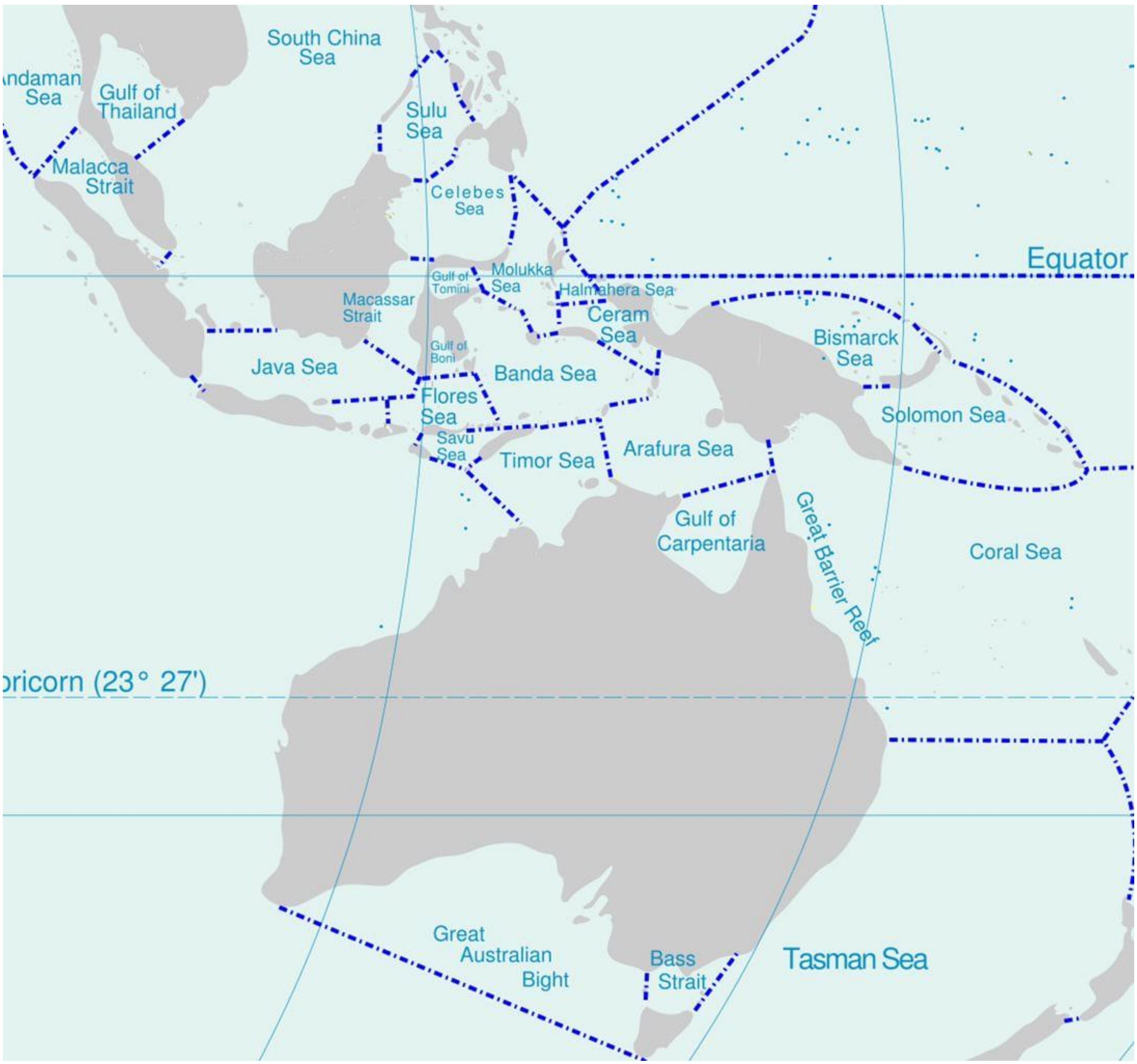
Phytoplankton Bloom (Algal Bloom) in Marginal Seas

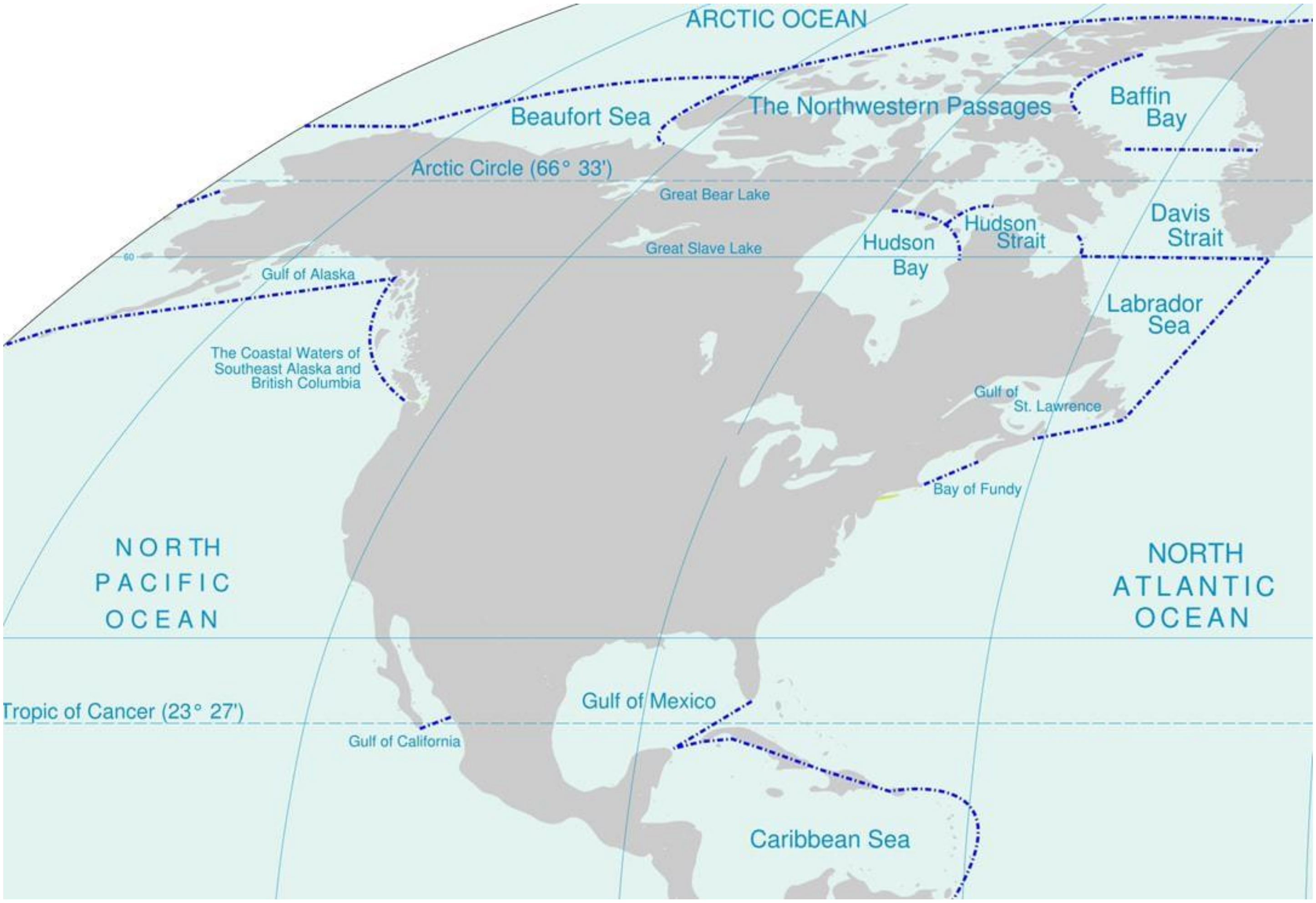
- The Mediterranean Sea and the Black Sea are marginal seas found in proximity to one another. The colors difference is due to a **phytoplankton bloom** occurring in the Black Sea.
- Phytoplankton are good as fish feed on them. But when they proliferate indiscriminately, they **consume too much oxygen during nights**, thus **depriving other marine organisms of oxygen**.
- For example, the discharge of domestic sewage leads to elevated nutrient concentrations (particularly **phosphates**) which can result in harmful algal blooms.

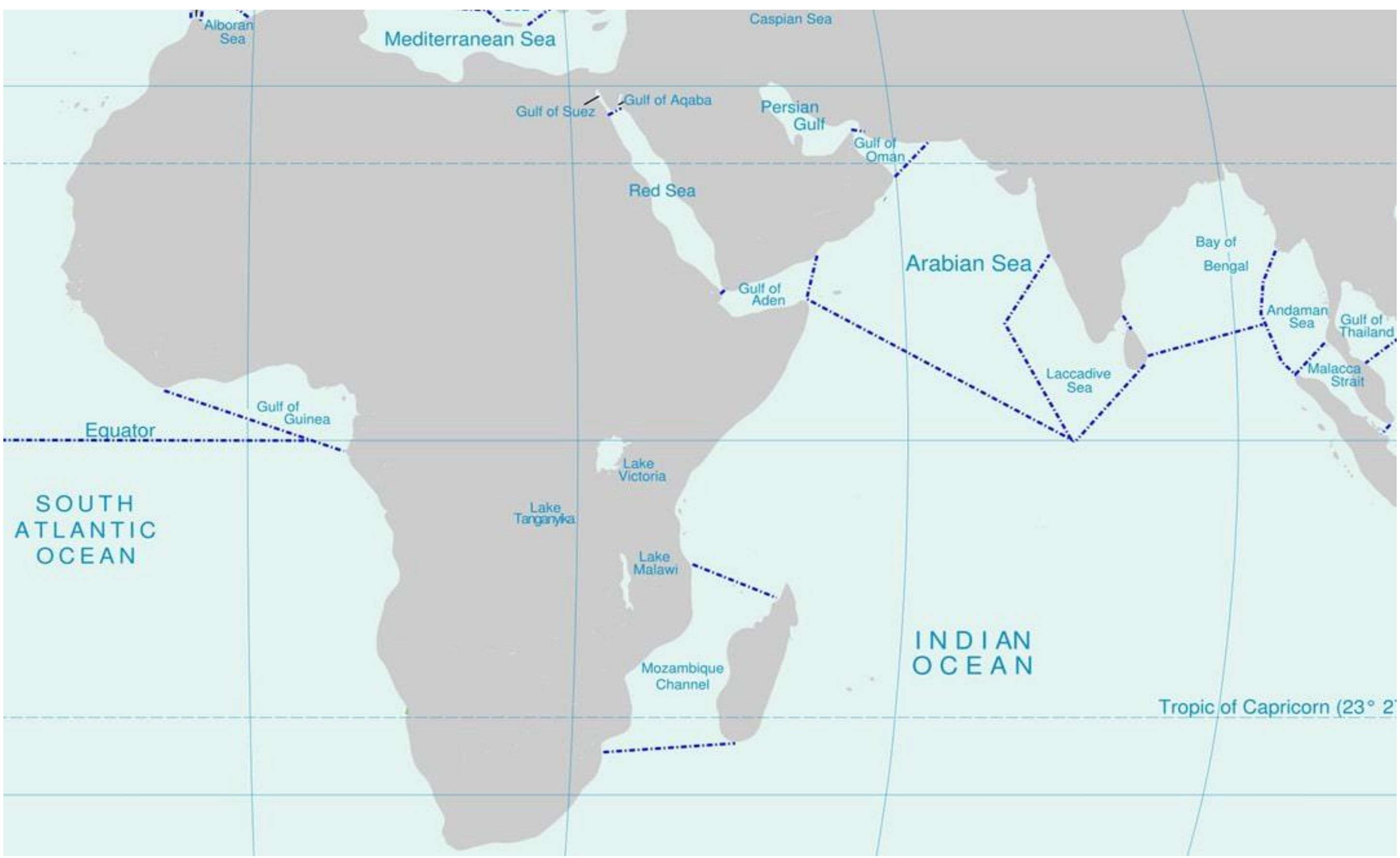
Phytoplankton bloom in the Black Sea

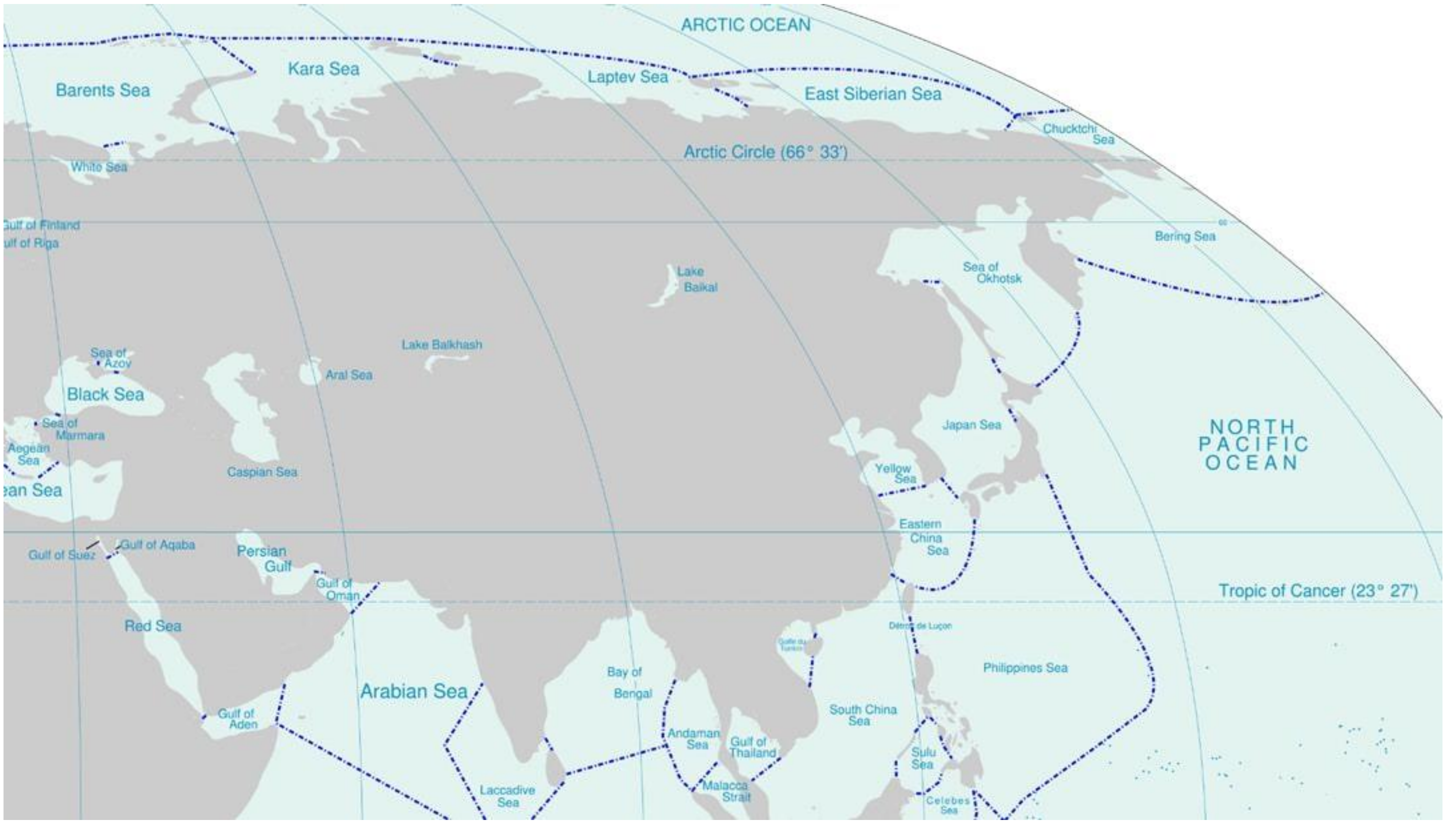
Biomass Production and Primary Productivity

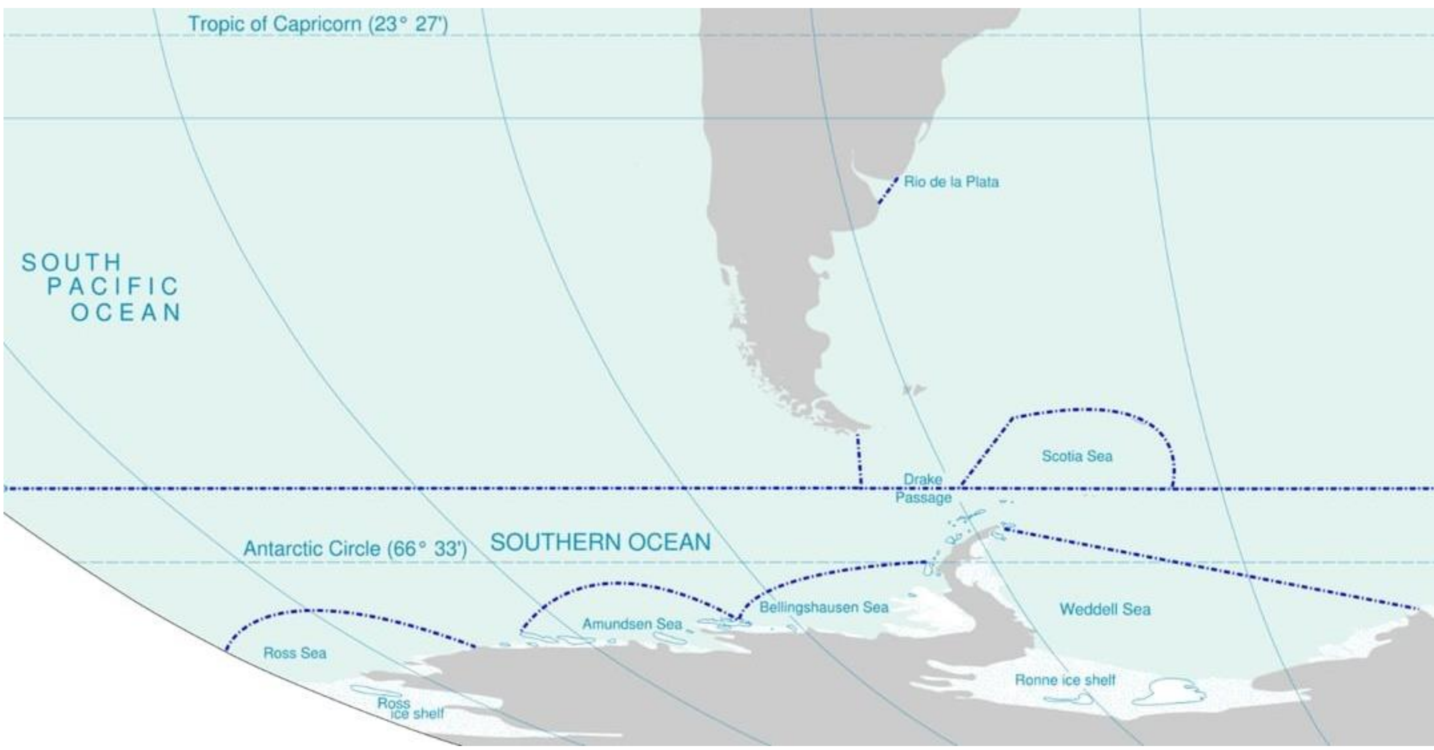
- Marine biomass production originates with primary productivity, which in turn is affected by the availability of sunlight, carbon dioxide, nutrients such as **nitrates and phosphates**, and trace elements.
- Marginal seas generally exhibit intermediate levels of primary production, with the **highest rates found in coastal upwelling regions** and the **lowest primary production occurring in open ocean regions**.




ARCTIC OCEAN
Beaufort Sea
The Northwestern Passages
Baffin Bay
Arctic Circle (66° 33')
Great Bear Lake
Hudson Bay
Hudson Strait
Davis Strait
Great Slave Lake
60
Gulf of Alaska
Labrador Sea
The Coastal Waters of Southeast Alaska and British Columbia
Gulf of St. Lawrence
Bay of Fundy
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
Gulf of Mexico
Tropic of Cancer (23° 27')
Gulf of California
Caribbean Sea


Alboran Sea
Mediterranean Sea
Caspian Sea
Gulf of Suez
Gulf of Aqaba
Persian Gulf
Gulf of Oman
Red Sea
Arabian Sea
Bay of Bengal
Gulf of Aden
Andaman Sea
Gulf of Thailand
Malacca Strait
Laccadive Sea
Gulf of Guinea
Equator
Lake Victoria
SOUTH ATLANTIC OCEAN
Lake Tanganyika
Lake Malawi
INDIAN OCEAN
Mozambique Channel
Tropic of Capricorn (23° 2





- For nearshore regions, the dominant processes influencing primary productivity are river runoff, water column mixing, and **turbidity.**
- River runoff and water column mixing introduce dissolved nutrients and trace elements into the photic (light) zones of nearshore regions.
- Although the addition of dissolved nutrients and trace elements serve to increase primary production, the addition of suspended particles increases water **turbidity**, which results in reduced sunlight penetration and **decreased** primary productivity.

Water Circulation in Marginal Seas

- Water circulation patterns in marginal seas depend largely on shape of the sea, fresh-water input (e.g., river runoff and precipitation) and evaporation.
- If river **runoff and precipitation exceed evaporation**, as is the case in the Black and Baltic Seas, the excess fresh water will tend to flow seaward near the sea surface.
- If evaporation exceeds river runoff and precipitation, as in the Mediterranean Sea, the marginal sea water becomes **saltier**, then sinks and flows towards the less salty open ocean region.

Circulation Patterns in Major Marginal Seas:

Black Sea and Baltic Sea

The Black Sea and Baltic Sea basins both possess **sills** that restrict subsurface water circulation.

- While the surface waters of the Black and Baltic Seas are able to flow over the sills and introduce lower salinity water into the open ocean, the flow of the saltier subsurface waters is blocked by these sills.
- This type of subsurface-water restriction often leads to **stagnation**, which may eventually result in **local oxygen depletion**.

Mediterranean Sea

- The Mediterranean Sea, which is divided by a 400-meter sill into two sub-basins, is connected to the Atlantic Ocean via the **Straits of Gibraltar**, to the Black Sea via the **Bosporus Strait**, and to the Red Sea via the **humanmade Suez Canal**.
- Atlantic Ocean water enters this marginal sea through the Straits of Gibraltar as a surface flow. This ocean water replaces a fraction of the water that evaporates in the eastern Mediterranean Sea.
- In Mediterranean Sea **evaporation exceeds precipitation** and hence salinity increases.

Gulf of Mexico

- The Gulf of Mexico is connected to the Atlantic Ocean via the **Straits of Florida** and the Caribbean Sea via the **Yucatán Strait.**
- In the northern Gulf of Mexico region, Mississippi River runoff influences surface waters as far as 150 meters away from the shore, resulting in salinities as low as 25.
- A unique feature of the Gulf of Mexico's surface circulation pattern is the **Loop Current**, which results from the **Caribbean Current** entering the **Gulf of Mexico** through the **Yucatán Strait** and upon arrival, turning in a clockwise direction and "looping" around a warm "dome" of Gulf of Mexico surface water.

2.6 Bays, gulfs, and Straits

Bays, gulfs, and straits are types of water bodies that are contained within a larger body of water near land.

- These three water bodies are usually located at important points of human activities; thus, conflicts with nature and neighbours are common.

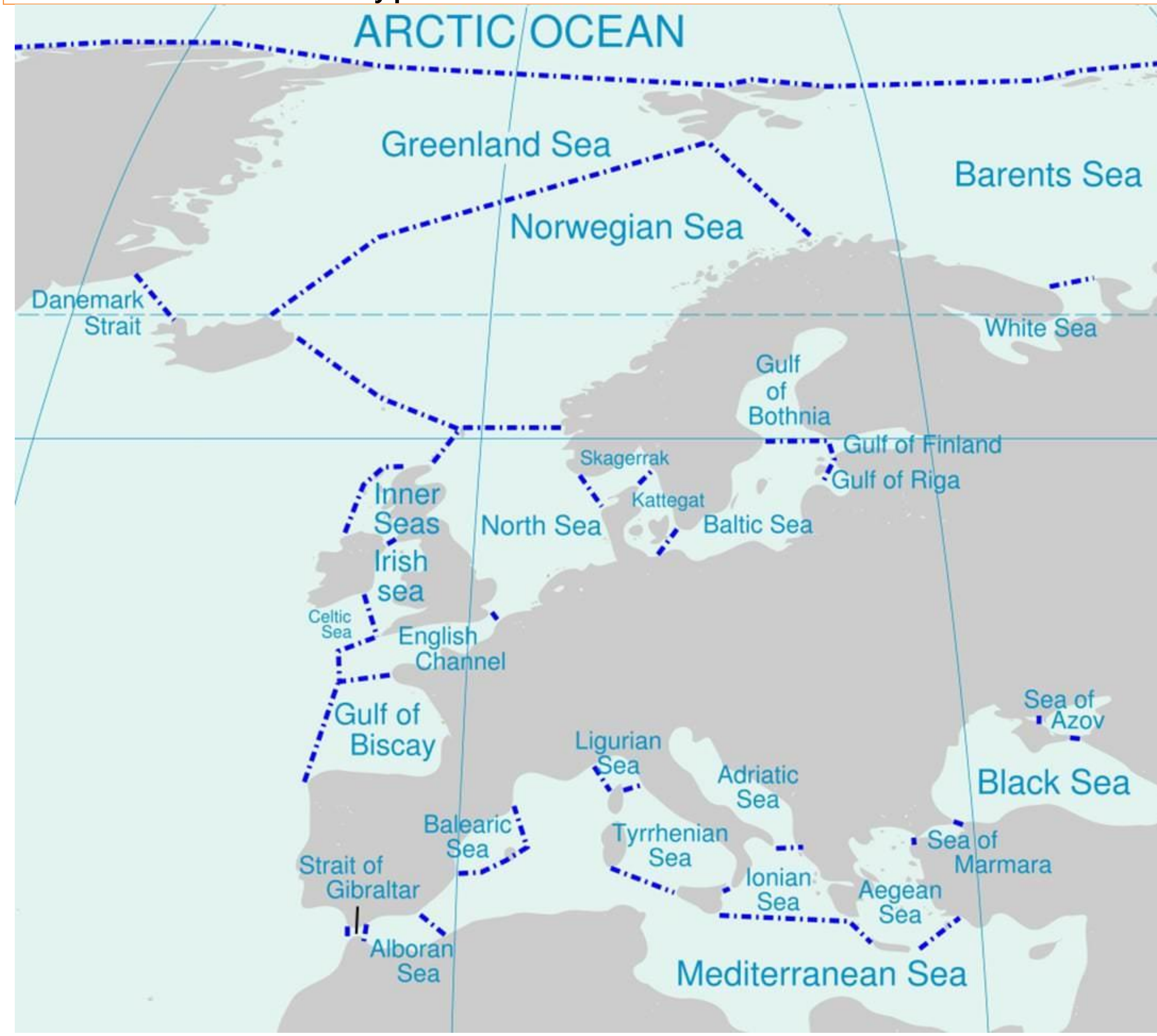
Bays

- A bay is a small body of water that is set off from a larger body of water generally where the land curves inward.
- In simple words, bay is a water body surrounded on three sides by land with the fourth side (mouth) wide open towards oceans. (In Gulfs, the mouth is narrow).
- A bay is usually smaller and **less enclosed than a gulf**.
- Example: The Bay of Pigs (Cuba), Hudson Bay (Canada), Bay of Bengal etc.
- An example of a bay at a river's mouth is **New York Bay**, at the mouth of the **Hudson River (Hudson Estuary).**

Guantánamo Bay

- Guantánamo Bay is a sheltered inlet within the Caribbean Sea.

- During the Spanish-American War in 1898, the United States gained access to the outer harbour of Guantánamo Bay.
- Through an agreement signed with Cuba in 1903, the United States obtained the right to maintain a naval base at Guantánamo Bay.
- In 1934, a treaty reaffirmed the U.S. right to lease the site. The treaty gave the United States a perpetual lease on Guantánamo Bay.
- The infamous **Guantánamo Bay prison** is here.



Major Marginal Seas

Marginal Seas map:
https://drive.google.com/file/d/0B1myJlOn-mMCNWJYSWtMZTItVGM/view?usp=sharing

Gulfs

- A gulf is a large body of water, sometimes with a **narrow mouth**, that is almost completely surrounded by land. The world's largest gulf is the **Gulf of Mexico.**
- Examples of other gulfs include the Gulf of California, Gulf of Aden (between the Red Sea and the Arabian Sea), and the Persian Gulf (between Saudi Arabia and Iran).

- The Persian Gulf is important with respect to world energy because petroleum is transported through its waters in oil tankers.

Straits

- A strait is a narrow passageway of water, usually between continents or islands, or between two larger bodies of water.
- The **Strait of Gibraltar** is probably the world's most famous strait. It connects the Atlantic Ocean on its west with the Mediterranean Sea on its east.
- Two other well-known straits are the **Strait of Bosporus** and the **Strait of Hormuz**.
- The Strait of Bosporus connects the **Black Sea (from the north) and the Sea of Marmara (from the south)** and splits north-western Tur-key.
- The Strait of Hormuz is located at the **south-eastern end of the Persian Gulf**. It is a narrow waterway that can be (and has been) controlled to prevent ships from sailing through the gulf.

Choke Point

- When a body of water such as a strait is capable of being blocked or even closed in order to control transportation routes, the body is called a "choke point."
- Historically, the **Strait of Gibraltar** has been one of the world's most important choke points.
- However, the **Strait of Hormuz** has become an important choke point in recent years because of increasing Middle East tensions.
- The Strait is surrounded by the United Arab Emirates and Oman (on one side) and Iran (on the other side).

Isthmus

Isthmus of Panama and Isthmus of Suez

- Isthmus is the land-equivalent of a strait. i.e., a narrow strip of land connecting two larger land masses.
- Example: **Isthmus of Panama** and **Isthmus of Suez.**

3. Ocean Movements

- The movements that occur in oceans are categorized as **waves, tides and currents.**
- Waves are formed due to **friction** between wind and surface water layer. The stronger the wind, the bigger the wave. They die out quickly on reaching the shore or shallow waters.
- Horizontal currents arise mainly due to **friction** between wind and water.
- Coriolis force and differences in water level gra-dient also play a major role.
- Vertical currents arise mainly due to density dif-ferences caused by temperature and salinity changes.
- Tsunami, storm surge and tides are **tidal waves (meaning waves with large wavelengths)**.

3.1 Ocean Currents

- Ocean currents are the most important ocean movements because of their **influence on cli-matology** of various regions.
- Ocean currents are like river flow in oceans. They represent a **regular** volume of water in a **definite** path and direction.
- Ocean currents are influenced by two types of forces namely:
  1. primary forces that initiate the movement of water;
  2. secondary forces that influence the currents to flow.
- The primary forces that influence the currents are:
  1. **heating by solar energy;**
  2. **wind;**
  3. **gravity;**
  4. **Coriolis force.**
- The secondary forces that influence the currents are:
  1. **Temperature difference;**
  2. **Salinity difference**

Primary Forces Responsible for Ocean Currents

Explain the factors responsible for the origin of ocean currents. How do they influence regional climates, fishing and navigation? (Mains 2015)

Influence of insolation

- Heating by solar energy causes the water to expand.
- **Near the equator, the ocean water is about 8 cm higher in level than in the middle latitudes**.
- Gravity tends to level the differences by pulling the water down the pile (along the gradient).

Influence of wind (atmospheric circulation)

- Frictional force of the wind drags the surface ocean water.
- Winds are responsible for both magnitude and direction (Coriolis force) of the ocean currents.
- Example: **Monsoon winds** are responsible for the seasonal reversal of ocean currents in the Indian ocean.
- The oceanic circulation pattern roughly corresponds to the earth's atmospheric circulation pattern.
- The air circulation over the oceans in the middle latitudes is mainly anticyclonic (sub-tropical High-Pressure Belt) The oceanic circulation pattern also corresponds with the same.
- At higher latitudes, where the wind flow is mostly cyclonic, the oceanic circulation follows this pattern.

Influence of Coriolis force

- The Coriolis force intervenes and causes the water to move to the **right** in the northern hemisphere and to the **left** in the southern hemisphere.
- These large accumulations of water and the flow around them are called **Gyres.** These produce large circular currents in all the ocean basins. One such circular current is the **Sargasso Sea.**

Secondary Forces Responsible for Ocean Currents

- **Temperature difference** and **salinity difference** are the secondary forces. They create **density differences**.
- Differences in water density affect **vertical mobility** of ocean currents (vertical currents).
- Water with high salinity is denser than water with low salinity.
- Similarly, cold water is denser than warm water.
- Denser water tends to sink, while relatively lighter water tends to rise.

Types of Ocean Currents

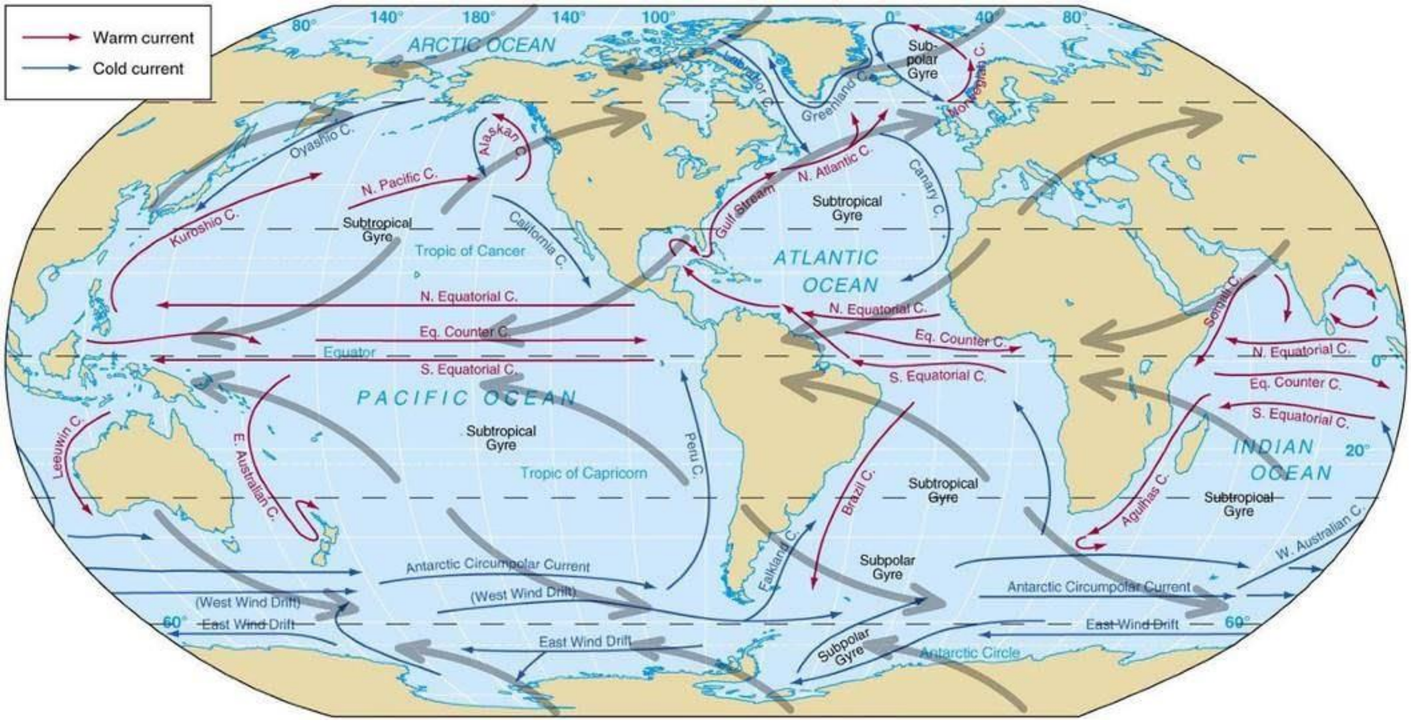
Based on depth the ocean currents may be classified based on their depth as **surface currents** and **deep water currents**:

- Surface currents constitute about 10 per cent of all the water in the ocean; these waters are the upper **400 m** of the ocean.
- Deep water currents make up the other 90 per cent of the ocean water. These waters move around the ocean basins due to variations in the density and gravity.
- For instance, heavy surface water (due to increase in salinity) of the Mediterranean Sea sinks and flows westward past Gibraltar as a sub-surface current.

Based on temperature ocean currents are classified as **cold currents** and **warm currents**.

- **Cold-water ocean currents** occur when the cold water at the poles sinks and slowly moves towards the equator as **subsurface flow**.
- **Warm-water currents** travel out from the equator along the surface, flowing towards the poles to replace the sinking cold water.

1. Cold currents are usually found on the **west coast of the continents** (because of clockwise flow in northern hemisphere and anti-clockwise flow in southern hemisphere) in the low and middle latitudes (true in both hemispheres) and on the east coast in the higher latitudes in the Northern Hemisphere.

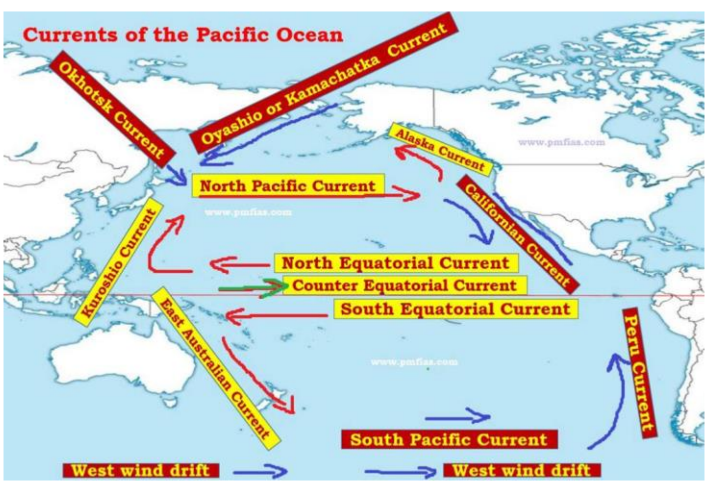


Cold and Warm Ocean Currents

2. Warm currents are usually observed on the east coast of continents in the low and middle latitudes (true in both hemispheres). In the northern hemisphere, they are found on the west coasts of continents in high latitudes.

Convergence: *warm and cold currents meet.*
Divergence: *a single current splits into multiple currents flowing in different directions.*

Pacific Ocean Currents



Pacific Ocean Currents

Equatorial currents – warm

- Under the influence of **prevailing trade winds [tropical easterlies]**, the **north equatorial current** and the **south equatorial current** start from the eastern Pacific (west coast of Central America) and traverses a distance of 14,500 km moving from **east to west.**
- This raises the level of western Pacific (near Indonesia and Australia) ocean by few centimetres.
- And this creates a **counter-equatorial current** which flows between the north equatorial current and the south equatorial current in **west-east** direction.

Factors that aid the formation of Counter-Equatorial current

1. Piling up of water in the western Pacific due to trade winds.
2. The presence of doldrums (calm region in equatorial low-pressure belt) in between the north equatorial current and the south equatorial current.

Question Prelims 2015: What explains the eastward flow of the equatorial counter-current?

a) The Earth's rotation on its axis
b) Convergence of the two equatorial currents
c) Difference in salinity of water
d) Occurrence of the belt of calm near the equator

Point 1: Earth's rotation creates Coriolis force, but Coriolis force is not responsible for counter-current.
Point 2: Convergence is a prerequisite, but not all convergences lead to counter-currents.
Point 3: Salinity greatly influences vertical currents and its influence on horizontal movement is less significant. So, ruled out.
Point 4: This is the main reason behind counter equatorial current (the backward movement of equatorial waters). Doldrums are calm regions facilitating the backward movement of water.
Answer: D

Kuroshio current – warm

- The north equatorial current turns northward off the Philippines to form the **Kuroshio current.**
- It flows in the **sub-tropical high-pressure belt,** and its northern part is under the influence of **westerlies.**

Oyashio Current and Okhotsk current – cold

- **Oyashio flows** across the east coast of Kamchatka Peninsula to merge with the warmer waters of Kuroshio.
- Okhotsk current flows past **Sakhalin Islands** to merge with the Oyashio current off Hokkaido (Northern Japanese Island).
- The **convergence of cold and warm currents makes the zone one of the richest fishing grounds**.

North-Pacific current – warm

- From the south-east coast of Japan, under the influence of prevailing westerlies, the **Kuroshio current** turns eastwards and moves as the North-Pacific current, reaches the west coast of North America, and bifurcates into two.

Alaska current – warm

- The northern branch of North-Pacific current flows anti-clockwise along the coast of British Columbia and Alaska and is known as the **Alaska current**.
- The water of this current is relatively warm as compared to the surrounding waters in this zone.

Californian current – cold

- The southern branch of the North-Pacific current moves as a cold current along the west coast of USA and is known as the **Californian current**.
- The Californian current joins the north equatorial current to complete the circuit.

East Australian current – warm

- Following the pattern in the northern hemisphere, the south equatorial current flows from east to west and turns southwards as the East Australian current.
- It then meets the South Pacific current near Tasmania which flows from west to east.

Peru current or Humboldt Current – cold

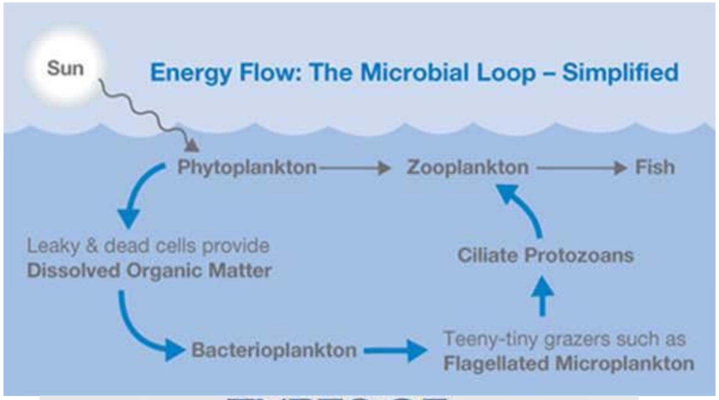
- Reaching the south-western coast of South America, South Pacific current turns northward as the Peru current. It is a cold current, which finally feeds the south equatorial current, thus completing the great circuit.
- **The zone where Peru Cold current meets the warm equatorial ocean waters is an important fishing zone**.

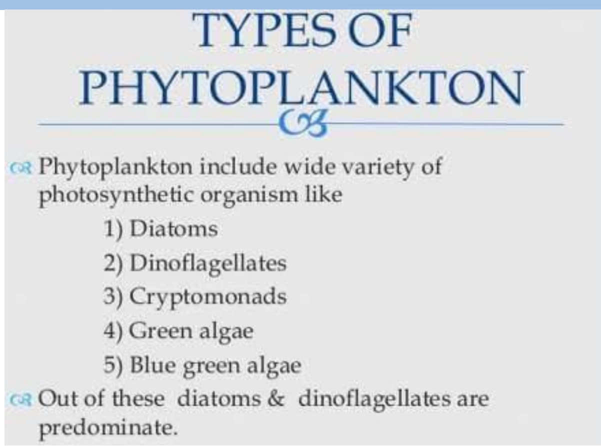
Phytoplankton and Fishing

Mixing zones of Cold and Warm Ocean Currents (Grand Banks) and cold water upwelling zones (Peru coast) are the most productive fishing grounds on earth. Why?

- Phytoplankton are the **primary producers** in the marine food chain and hence they are called the **grass of the sea**.
- Phytoplankton are predominantly **microscopic, single-celled** organisms.
- Some species of algae are large, multicellular and live on the ocean bottom.

- They are insignificant players in the marine ecosystem compared to the phytoplankton as they only inhabit a narrow zone around the coast.





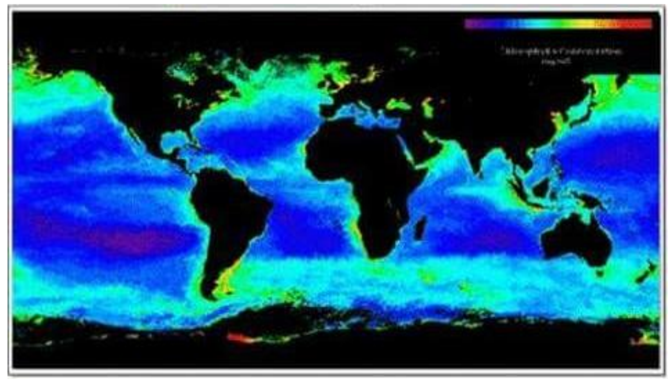
Aquatic Food Web (Left); Types of Phytoplankton (Right)

Why are cold and warm current mixing zones the good fishing grounds? Why are tropical waters highly unproductive?

- Algae and other plants are able to **photosynthesise** to produce **organic material** from inorganic nutrients.
- And the organic material forms the building block for all animals higher up in the food chain.
- Almost all biomass in the ocean is derived from the **phytoplankton** and to a lesser extent the **benthic algae** *(found on the bottom of a sea or lake)*.
- However, there is a fundamental problem phytoplankton in the open ocean have to face. They **need both sunlight and nutrients** (such as **nitrate** and **phosphate**) to be able to photosynthesise.
- Sunlight is only available in the uppermost layers.
- During photosynthesis, the nutrients are quickly used up by phytoplankton, so they are not available for long periods in the upper layers under normal circumstances.

This is indeed the case in tropical waters, and as a result, they are very unproductive.

- To escape this problem the seawater needs to be **mixed regularly** to bring the **nutrient-rich deep waters** up to the sunlight zone where the phytoplankton can grow.



Phytoplankton production is highest at high latitudes

This is one of the reasons why cold and warm currents convergence zones (mixing happens; e.g. Grand Banks) and upwelling zones (e.g. upwelling near Peruvian coast) are very productive.

- Furthermore, in surroundings where atmospheric temperatures are often colder than oceanic temperatures, the top layers of the ocean are cooled by the atmosphere.
- This increases the density of the surface waters and causes them to sink and therefore causes mixing (nutrient deficient water sinks, and nutrient-rich water is upwelled).

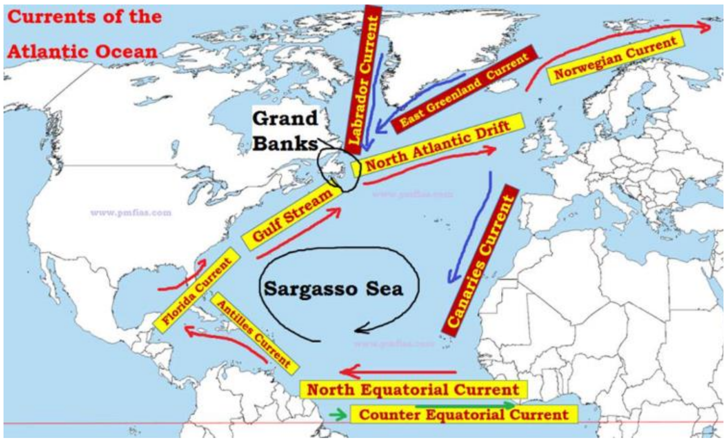
Both of these factors play a role in Icelandic waters, resulting in the very productive ocean environment around Iceland.

Atlantic Ocean Currents

Equatorial Atlantic Ocean Currents – warm

- Under the influence of **prevailing trade winds (easterly trade winds)**, the north equatorial current and the south equatorial current start from the eastern Atlantic (west coast of Africa), moving from east to west.

- This raises the level of western Atlantic (north of the Brazil bulge) ocean by few centimetres.
- And this creates a **counter-equatorial current** which flows between the north equatorial current and the south equatorial current in **west-east** direction.



North Atlantic Ocean Currents

Antilles current – warm

- The south equatorial current bifurcates into two branches near **Cape de Sao Roque (Brazil).**
- Part of the current enters the Caribbean Sea along with north equatorial current into the Mexican Gulf, while the remainder passes along the eastern side of the West Indies as the **Antilles current.**
- There is a rise in water level in the Mexican Gulf because of large amounts of water brought by the **Mississippi River** and branches of north and south equatorial currents.

Gulf Stream and North Atlantic Drift – warm

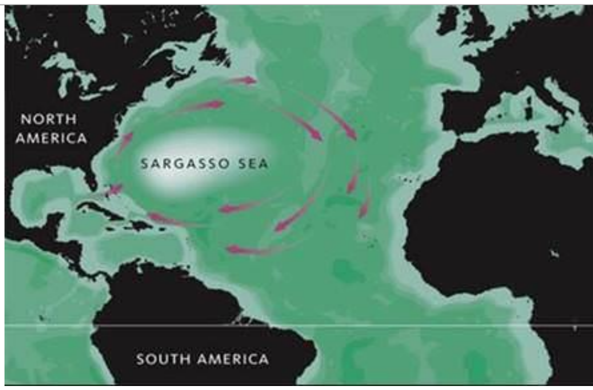
- **Antilles current** creates a current that flows out through the Strait of Florida as **Florida current**, which mixes with Antilles current from the south.
- This combined current moves along the east coast of USA and is known as the Florida current up to the **Cape Hatteras** and as the **Gulf Stream** beyond that.
- Near the **Grand Banks, the Gulf Stream mixes with cold Labrador and East Greenland currents and flows eastward across the Atlantic as the North Atlantic Drift**.
- Here, westerly movement of North Atlantic Drift is due to the influence of **westerlies.**

Norwegian current – warm

- The North Atlantic Current breaks up into two branches on reaching the eastern part of the ocean.
- The main current, continuing as the North Atlantic Drift, reaches the British Isles from where it flows along the coast of Norway as the **Norwegian current** and enters the Arctic Ocean.
- Norwegian current is **very important** as it **keeps ocean to the north of Norway partly free from ice** and also moderates the extremes of climate.
- It is because of this current, Russia is able to move cargo in summers through **Arctic ocean (Barents Sea).**
- The southerly branch flows between Spain and Azores as the cold Canary current.
- This current finally joins the north equatorial current completing the circuit in the North Atlantic.
- The **Sargasso Sea**, lying within this circuit, is full of large quantities of **seaweed** and is an important geographical feature.

Sargasso Sea – a sea without a land boundary

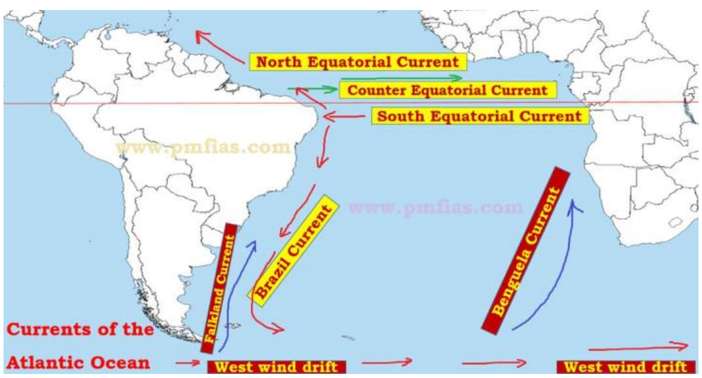
- The Sargasso Sea is a region in the gyre in the middle of the North Atlantic Ocean.
- It is the only sea on Earth which has **no coastline.**
- It is bounded on the
  1. west by the **Gulf Stream**;
  2. north, by the **North Atlantic Current**;
  3. east, by the **Canary Current**; and
  4. south, by the **North Atlantic Equatorial Current**.
- This system of ocean currents forms the **North Atlantic Gyre**.
- All the currents deposit the marine plants they carry into this sea.



Sargasso Sea

Grand Banks-Richest Fishing Grounds on Earth

- The two cold currents—East Greenland current and the Labrador current—flow from the Arctic Ocean into the Atlantic Ocean.
- The Labrador current flows along part of the east coast of Canada and meets the warm Gulf Stream.
- The confluence of these two currents, one hot and the other cold, produce the famous **fogs around Newfoundland**.
- As a result of mixing of cold and warm waters, **one of the world's most important fishing grounds is created.**



South Atlantic Ocean Currents

Brazil current – warm

- In the South Atlantic Ocean, the south equatorial current, flowing from east to west, splits into two branches near **Cape de Sao Roque (Brazil).**
- The northern branch joins the north equatorial current (a part of it flows in Antilles Current and other into Gulf of Mexico), whereas the southern branch turns southward and flows along the South American coast as the warm Brazil current.
- The south-flowing Brazil current swings eastward at about latitude 35°S (due to westerlies) to join the **West Wind Drift** flowing from west to east.
- A small branch of West Wind Drift splits and flows between Argentinian coast and **Falkland Islands,** and this current is called as **Falkland cold current**.
- It mixes with warm Brazil current at the southern tip of Brazil.

Benguela current – cold current

- A branch of the South Atlantic splits at the southern tip of Africa and flows along the west coast of South Africa as the cold Benguela current, which joins the south equatorial current to complete the circuit.

Prelims 1999: In the given map, which one of the following pairs of ocean currents are shown?

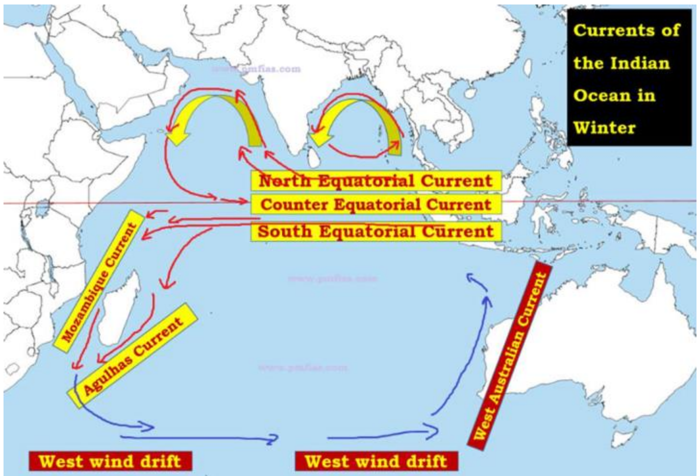
a) Bengula and Falkland
b) Canary and Humboldt
c) Agulhas and Guinea
d) Benguela and Guinea

Indian Ocean Currents

- Indian ocean is **half an ocean**, hence the behaviour of the North Indian Ocean Currents is different from that of Atlantic Ocean Currents or the Pacific Ocean Currents.
- Also, **monsoon winds** in Northern Indian ocean are peculiar to the region, which directly influence the ocean surface water movement (North Indian Ocean Currents)

Indian Ocean Currents and Monsoons

- The currents in the northern portion of the Indian Ocean change their direction from season to season in response to the **seasonal rhythm of the monsoons**.
- The effect of winds is comparatively more pronounced in the Indian Ocean.



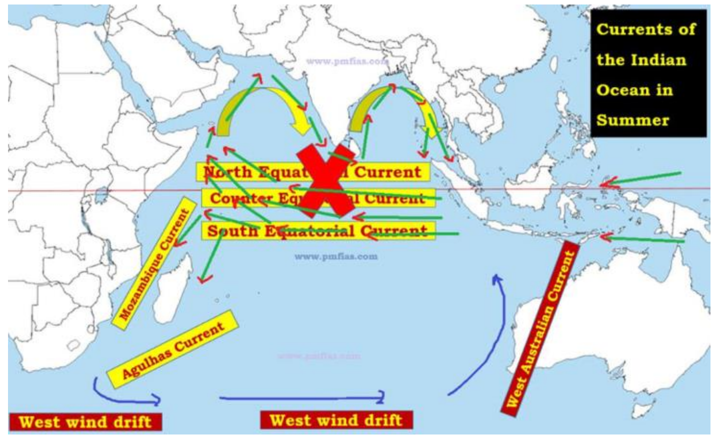
North Indian Ocean Currents

Winter Circulation

- Under the influence of **prevailing trade winds**, the north equatorial current and the south equatorial current start from the south of Indonesian islands, moving from east to west.
- This raises the level of western Indian (south-east of horn of Africa) ocean by few centimetres.
- And this creates a **counter-equatorial current** which flows between the north equatorial current and the south equatorial current in **west-east** direction.
- The **north-east monsoons** drive the water along the coast of **Bay of Bengal** to circulate in an **anti-clockwise direction**.
- Similarly, the water along the coast of **Arabian Sea** also circulate in an **anti-clockwise circulation**.

Summer Circulation – North Equatorial Current & Counter-Equatorial Current are Absent

- In summer, due to the effects of the strong south-west monsoon and the absence of the north-east trades, a strong current flow from west to east, which completely **obliterates the north equatorial current**.
- Hence, there is **no counter-equatorial current as well.**
- Thus, the circulation of water in the northern part of the ocean is **clockwise** during this season.



South Indian Ocean Currents

Southern Indian Ocean Currents

- The general pattern of circulation in southern part of the Indian Ocean is quite similar to that of southern Atlantic and Pacific oceans. It is **less marked by the seasonal changes.**
- The south equatorial current, partly led by the corresponding current of the Pacific Ocean, flows from east to west.
- It splits into two branches, one flowing to the east of Madagascar known as **Agulhas current** and the other between Mozambique and Western Madagascar coast known as **Mozambique current**.
- At the southern tip of Madagascar, these two branches mix and are commonly called as the Agulhas current. It still continues to be a warm current, till it merges with the West Wind Drift.
- The **West Wind Drift**, flowing across the ocean in the higher latitudes from west to east, reaches the southern tip of the west coast, of Australia.
- One of the branches of this cold current turns northwards along the west coast of Australia. This current, known as the **West Australian current**, flows northward to feed the south equatorial current.

Effects of Ocean Currents

- Ocean currents have a number of direct and indirect influences on human activities.

Desert formation

- Cold ocean currents have a direct effect on **desert formation** in west coast regions of the **tropical and sub-tropical continents**.
- There is **fog,** and most of the areas are **arid due to desiccating effect (loss of moisture — fog or temperature inversion inhibits convection).**

Rains

- Warm ocean currents bring rain to coastal areas and even interiors. Example: Summer Rainfall in **British Type climate (North Atlantic Drift)**.
- Warm currents flow parallel to the east coasts of the continents in tropical and subtropical latitudes. This results in warm and rainy climates. These areas lie in the western margins of the subtropical anti-cyclones.

Moderating effect

- They are responsible for moderate temperatures at coasts. (**North Atlantic Drift brings warmness to England**. **Canary cold current brings cooling effect to Spain, Portugal** etc.)

Fishing

- Mixing of cold and warm ocean currents bear richest fishing grounds in the world.
- Example: **Grand Banks around Newfoundland, Canada and North-Eastern Coast of Japan**.
- The mixing of warm and cold currents helps to replenish the oxygen and favour the growth of **planktons**, the primary food for fish population.
- The best fishing grounds of the world exist mainly in these mixing zones.

Drizzle

- Mixing of cold and warm ocean currents create foggy weather where precipitation occurs in the form of drizzle (**Newfoundland**).

Climate

- **Warm and rainy climates in tropical and sub-tropical latitudes (Florida, Natal etc.),**
- **Cold and dry climates on the western margins in the sub-tropics due to desiccating effect**,
- **Foggy weather and drizzle in the mixing zones,**
- **Moderate clime along the western costs in the sub-tropics**.

Tropical cyclones

- They pile up warm waters in tropics, and this warm water is the major force behind tropical cyclones.

Navigation

- Currents are referred to by their "drift". Usually, the currents are strongest near the surface and may attain speeds over five **knots (1 knot = ~1.8 kmph)**.
- At depths, currents are generally slow with speeds less than 0.5 knots.
- Ships usually follow routes which are aided by ocean currents and winds.
- Example: If a ship wants to travel from Mexico to Philippines, it can use the route along the North Equatorial Drift which flows from east to west.
- When it wants to travel from Philippines to Mexico, it can follow the route along the doldrums when there is counter equatorial current flowing from west to east.

Explain the factors responsible for the origin of ocean currents. How do they influence regional climates, fishing and navigation? (Mains 2015)

Desert Formation and Ocean Currents

Mains 2013: Major hot deserts in northern hemisphere are located between 20-30 degree north and on the western side of the continents. Why?

- Major hot wind deserts include the biggest **Sahara Desert (3.5 million square miles)**. The next biggest desert is the **Great Australian Desert**.
- The other hot deserts are the **Arabian Desert, Iranian Desert, Thar Desert, Kalahari and Namib Deserts**.
- The aridity of the hot deserts is mainly due to the effects of off-shore Trade Winds; hence they are also called **Trade Wind Deserts.**

Why between 20 – 30 degree?

- The hot deserts lie along the **Horse Latitudes or the Sub-Tropical High-Pressure Belts** where the air is descending, a condition least favourable for precipitation of any kind to take place.

Offshore winds

- The rain-bearing Trade Winds blow **off-shore** and the Westerlies that are on-shore blow outside the desert limits (outside tropics).
- Whatever winds reach the deserts **blow from cooler to warmer regions**, and their **relative humidity is lowered**, making condensation almost impossible.
- Under such conditions, every bit of moisture is evaporated.

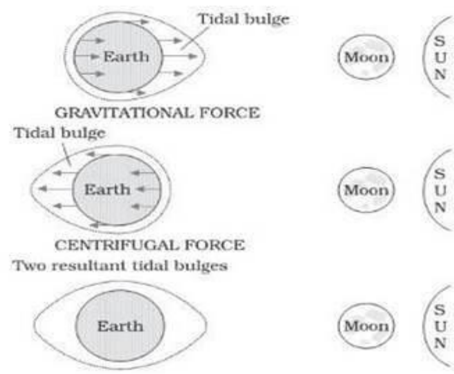
Why on western coast?

- On the western coasts, the presence of cold currents gives rise to **mists and fogs** by chilling the on-coming air. This inhibits convection in the air (because of temperature inversion).
- This air is later warmed by contact with the hot land, and little rain falls.
- The desiccating effect of the **cold Peruvian Current** along the Chilean coast is so pronounced that the mean annual rainfall for the **Atacama Desert** is not more than 1.3 cm.

3.2 Tides

- The periodical rise and fall of the sea level, once or twice a day, mainly due to the attraction of the sun and the moon, is called a tide.
- The study of tides is very complex, spatially and temporally, as it has great variations in frequency, magnitude and height.
- The **moon's gravitational pull** to a great extent and to a lesser extent the **sun's gravitational pull**, are the major causes for the occurrence of tides.
- Another factor is **centrifugal force** which acts **opposite** to **gravitational pull** of earth.
- Tides occur due to a balance between all these forces.

Tidal Bulge: Why there are two tidal bulges?

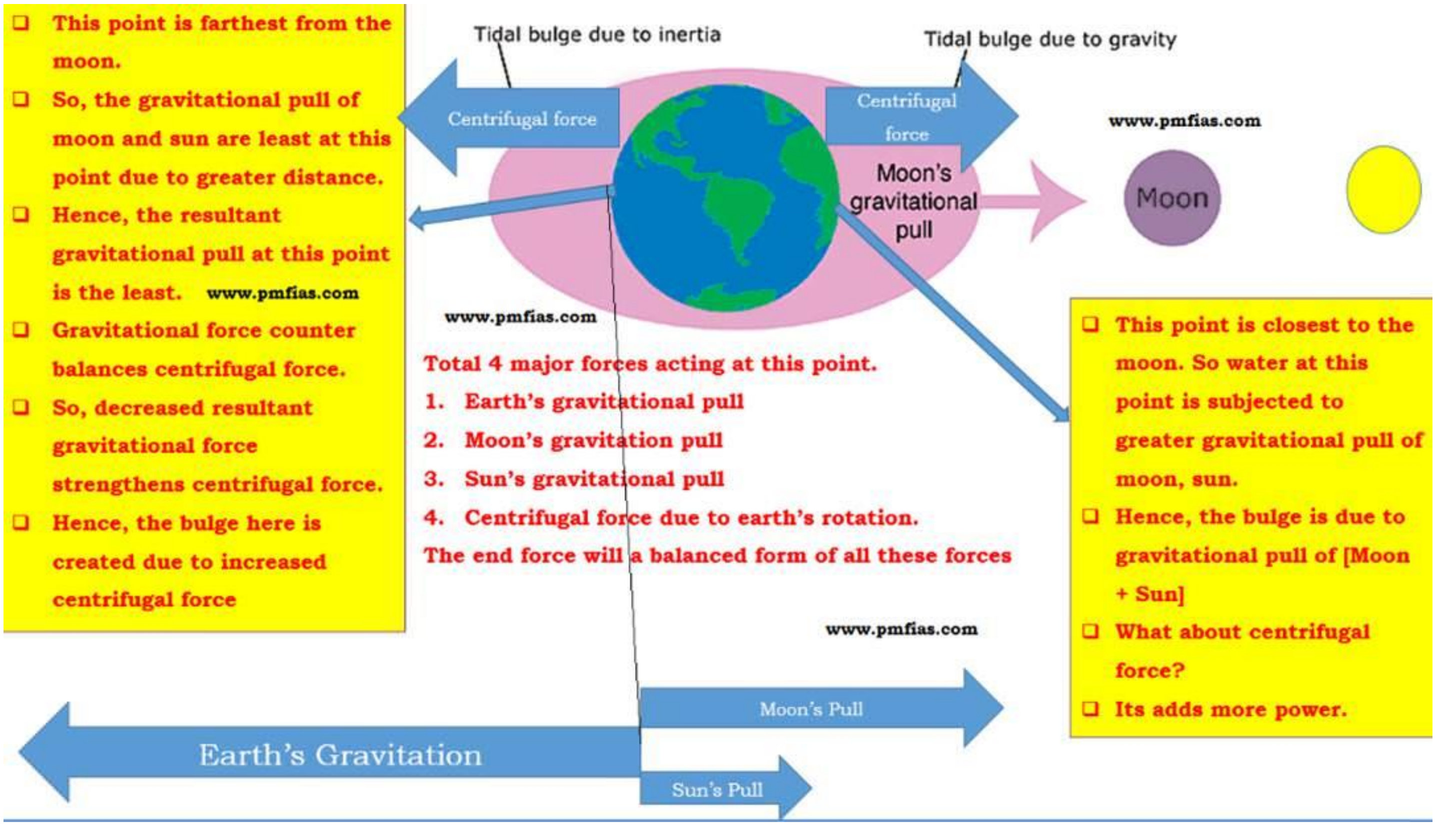


Gravitational and Centrifugal Forces

- Together, the gravitational pull and the centrifugal force are responsible for creating the two major **tidal bulges** on the earth.
- The 'tide-generating' force is the difference between these two forces; i.e. **the gravitational attraction of the moon and the centrifugal force.**
- On the surface of the earth nearest to the moon, pull or the attractive force of the moon is greater than the centrifugal force, and so there is a net force causing a bulge towards the moon.

Why is there a tidal bulge on the other side?

- On the opposite side of the earth, the **attractive force is less**, as it is farther away from the moon, the **centrifugal force is dominant**. Hence, there is a **net force away from the moon**.
- This creates the **second bulge** away from the moon.



Formation of Tidal Bulges

Factors Controlling the Nature and Magnitude of Tides

- The movement of the moon in relation to the earth.
- Changes in position of the sun and moon in relation to the earth.
- Uneven distribution of water over the globe.
- Irregularities in the configuration of the oceans.

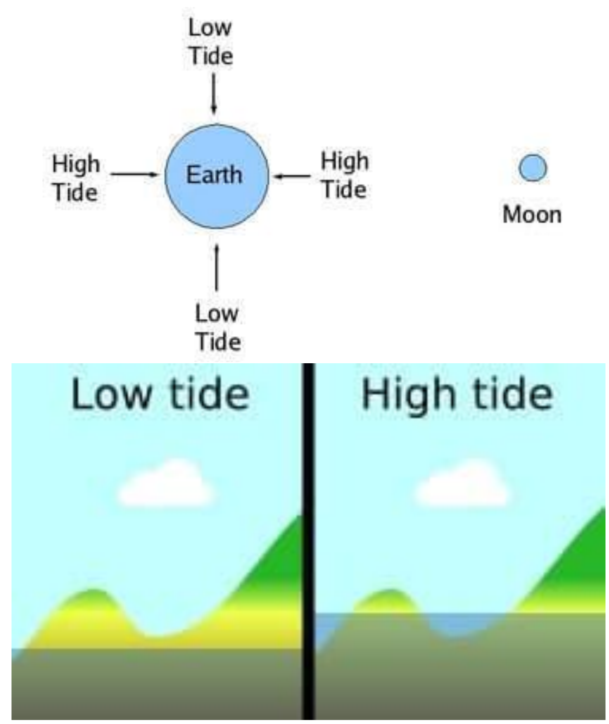
Types of Tides

- Tides vary in their frequency, direction and movement from place to place and also from time to time.
- Tides may be grouped into various types based on their frequency of occurrence in one day or 24 hours or based on their height.

Tides based on Frequency

Semi-diurnal tide

- It is the most common tidal pattern, featuring **two high tides and two low tides each day (it varies between 3 tides to 4 tides — 3 tides in rare cases but 4 is normal)**.
- The successive high or low tides are approximately of the same height.

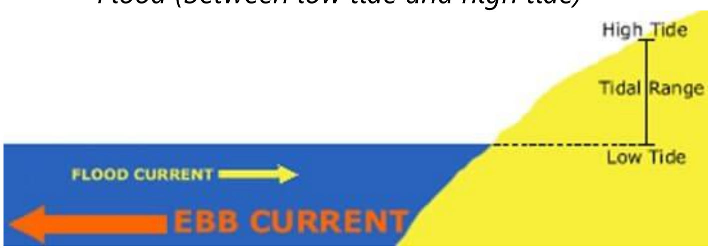


High tide and low tide ([Wikipedia](#)). Hide tides and low tides are formed due to earth's rotation relative to moon

Ebb and Flood

- The time between the high tide and low tide, when the water level is **falling**, is called the **ebb.**
- The time between the low tide and high tide, when the tide is **rising**, is called the **flow or flood.**

Flood (between low tide and high tide)



Ebb (between high tide and low tide)

Although tides occur twice a day, their interval is not exactly 12 hours. Instead, they occur at regular intervals of 12 hours and 25 minutes. (This is because of the changing relative positions of the moon and the sun)

- This is because the moon revolves around the earth from west to east, and each day it moves a bit to the east if observed from the same place on earth at the same time on two consecutive days.
- This time lag explains the tide interval of 12 hours and 25 minutes, as tides occur twice a day.

Southampton

- **Southampton** experiences **tides 6-8 times a day (2 high tides from North Sea + 2 high tides from English Channel + 2 low tides from North Sea + 2 low tides from English Channel)**.
- This happens because the **North Sea** and the **English Channel** push the water at different intervals.

Diurnal tide

- There is only one high tide and one low tide during each day.
- The successive high and low tides are approximately of the same height.

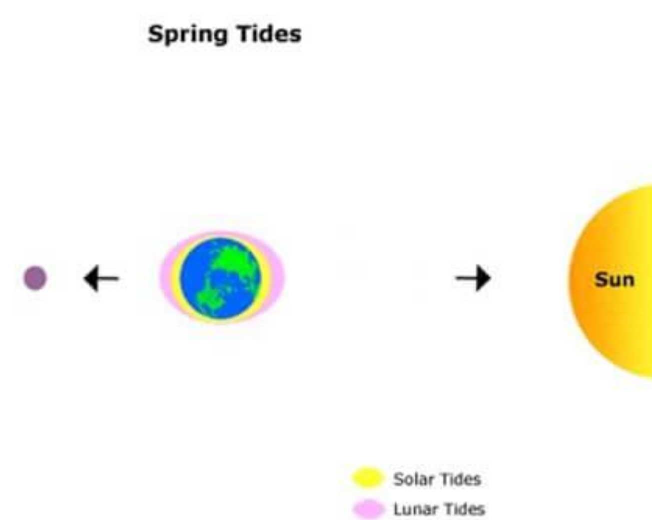
Mixed tide

- Tides having variations in height are known as mixed tides. These tides generally occur along the **west coast of North America** and on many islands of the Pacific Ocean.

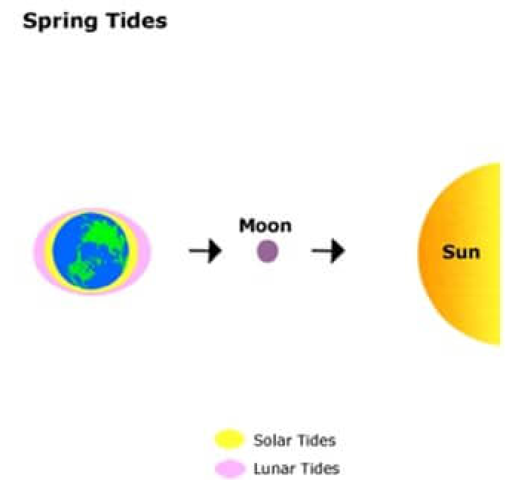
Tides based on the Sun, Moon and the Earth Positions

- The height of rising water (high tide) varies appreciably depending upon the position of sun and moon with respect to the earth. **Spring tides** and **neap tides** come under this category.

Spring tides



- The position of both the sun and the moon in relation to the earth has direct bearing on tide height.

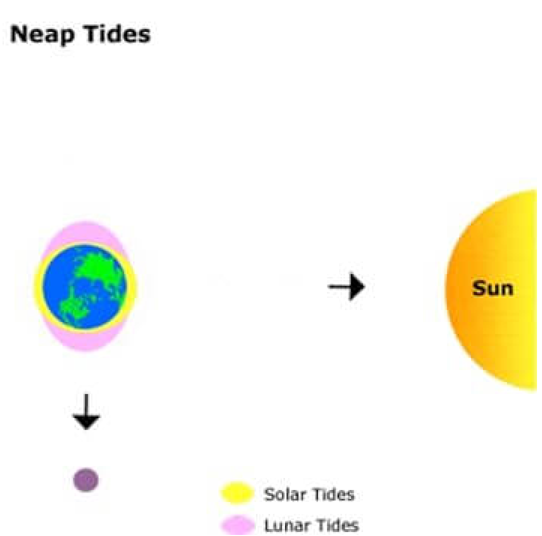


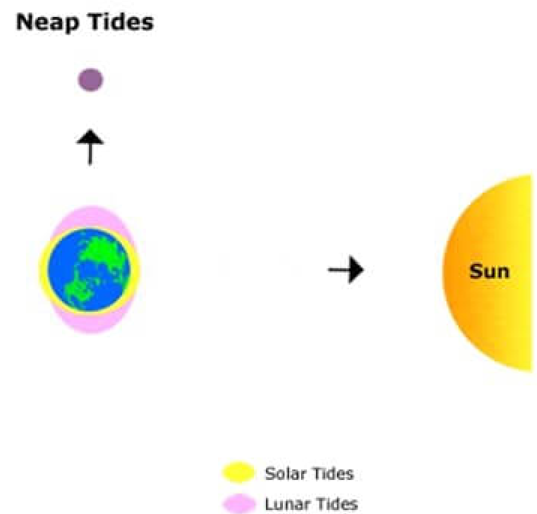
Spring Tides (New Moon and Full Moon)

- When **the sun, the moon and the earth are in a straight line**, the height of the tide will be higher.
- These are called **spring tides** and they occur **twice a month**, one on **full moon period** and another during **new moon period**.

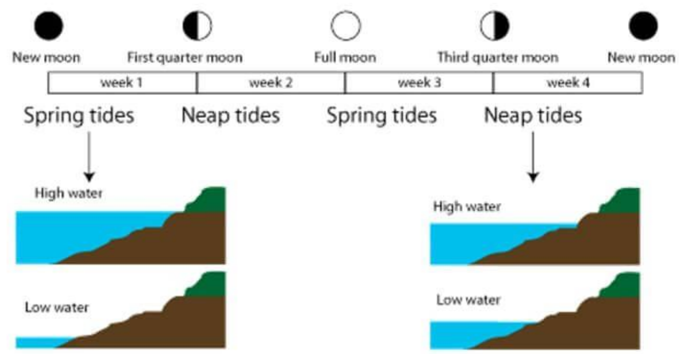
Neap tides

- Normally, there is a **seven-day interval** between the spring tides and neap tides.
- At this time the sun and moon are at **right angles** to each other, and the forces of the sun and moon tend to counteract one another.
- The Moon's attraction, though more than twice as strong as the sun's, is diminished by the counteracting force of the sun's gravitational pull.
- Like spring tides, these tides also occur **twice a month.**





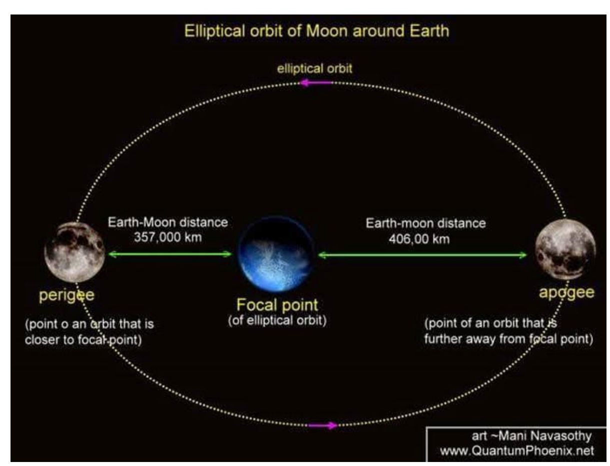
Neap tide (Half Moon – First Quarter and Last Quarter)



Spring tide: high tide is higher than normal; low tide is lower than normal

Neap tide: high tide is lower than normal; low tide is higher than normal

Magnitude of tides based on Perigee and Apogee



Perigee and Apogee

- Once in a month, when the moon's orbit is closest to the earth **(perigee)**, unusually high and low tides occur. During this time the tidal range is greater than normal.

- Two weeks later, when the moon is farthest from earth **(apogee)**, the moon's gravitational force is limited, and the tidal ranges are less than their average heights.

Magnitude of tides based on Perihelion and Aphelion

- When the earth is closest to the sun **(perihelion)**, around **3rd January** each year, tidal ranges are also much greater, with unusually high and unusually low tides.
- When the earth is farthest from the sun **(aphelion)**, around **4th July** each year, tidal ranges are much less than average.

Importance of Tides

- Since tides are caused by the earth-moon-sun positions which are known accurately, the tides **can be predicted well in advance**. This helps the navigators and fishermen plan their activities.

Navigation

- Tidal heights are very important, especially harbours near rivers and within estuaries having shallow **'bars'** at the entrance, which prevent ships and boats from entering into the harbour.
- High tides help in navigation. They raise the water level close to the shores. This helps the ships to arrive at the harbour more easily.
- Tides generally help in making some of the rivers navigable for ocean-going vessels. **Port of London and Haldia Port, Kolkata (tidal ports)** have become important ports owing to the tidal nature of the mouths of the Thames and Hooghly respectively.

Fishing

- The high tides also help in fishing. Many more fish come closer to the shore during the high tide. This enables fishermen to get a plentiful catch.

Desilting

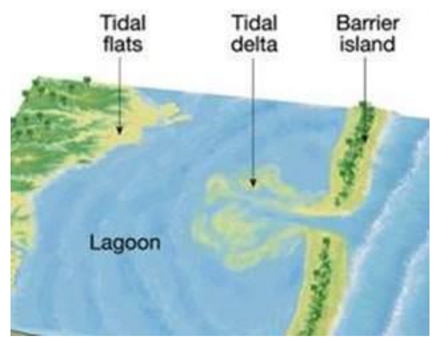
- Tides are also helpful in desilting the sediments and in removing polluted water from river estuaries.

Other

- Tides are used to generate electrical power (in Canada, France, Russia, and China).
- A 3 MW tidal power project was constructed at **Durgaduani in Sundarbans of West Bengal**.

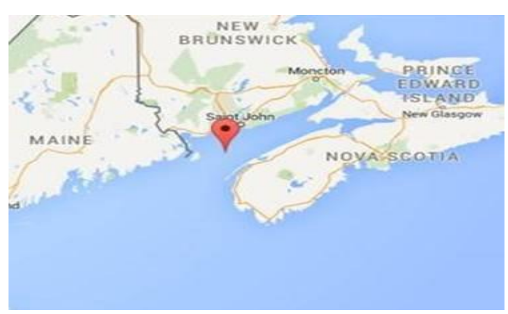
Characteristics of Tides

- On the surface of the earth, the horizontal tide-generating forces are more important than the vertical forces in generating the tidal bulges.
- The **tidal bulges on wide continental shelves have greater height**. **When tidal bulges hit the mid-oceanic islands, they become low**.
- The shape **of bays and estuaries along a coastline can also magnify the intensity of tides**.



Landform affected by tides

- When the tide is channelled between islands or into bays and estuaries, they are called **tidal currents (tidal bore is one such tidal current).**
- **Funnel-shaped bays** greatly change tidal magnitudes. Example: **Bay of Fundy — Highest tidal range.**



Bay of Fundy in Nova Scotia, Canada

- The highest tides occur in the **Bay of Fundy in Nova Scotia, Canada**. The tidal bulge is **15-16 m**.

Tidal bore

- Tides also occur in gulfs. The gulfs with wide fronts and narrow rears experience higher tides.
- The in and out movement of water into a gulf through a channel is called a tidal current.

Tidal bore

Enormous Tidal bore

- When a tide enters the narrow and shallow estuary of a river, the front of the tidal wave appears to be vertical owing to the piling up of water of the river against the tidal wave and the friction of the river bed.
- The steep-nosed tide crest looks like a vertical wall of water rushing upstream and is known as a **tidal bore**.
- The favourable conditions for tidal bore include strength of the incoming tidal wave, slim and depth of the channel and the river flow.
- There are exceptions. The **Amazon River** is the largest river in the world. It empties into the Atlantic Ocean. The mouth of the Amazon is not narrow, but the river still has a **strong tidal bore**.
- A tidal bore develops here because the mouth of the river is shallow and dotted by many low-lying islands and sand bars.
- In India, tidal bores are common in the **Hooghly river**.
- Most powerful tidal bores occur in **Qiantang River** in China.
- The name 'bore' is because of the **sound** the tidal current makes when it travels through narrow channels.
- Bores occur in relatively **few locations** worldwide, usually in areas with a **large tidal range**, typically more than 6 metres (20 ft) between high and low water.
- A **tidal bore takes place during the flood tide** and **never during the ebb tide** (Tidal bores almost never occur during neap tides).

Impact of Tidal Bore

- Tides are stable and can be predicted. Tidal bores are **less predictable** and hence can be **dangerous.**
- The tidal bores adversely affect the shipping and navigation in the estuarine zone.
- Tidal bores of considerable magnitude can capsize boats and ships of considerable size.
- Strong tidal bores disrupt fishing zones in estuaries and gulfs.
- The tidal-bore affected estuaries are the rich feeding zones and breeding grounds of several forms of wildlife. Tidal bores have an adverse impact on the ecology of estuaries.
- Animals slammed by the leading edge of a tidal wave can be buried in the silty water. For this reason, carnivores and scavengers are common sights behind tidal bores.

Multiple Choice Questions

1. Upward and downward movement of ocean water is known as the:
(a) tide
(b) wave
(c) current
(d) none of the above

2. Neap tides are caused:
(a) As result of the moon and the sun pulling the earth gravitationally in the same direction.
(b) As result of the moon and the sun pulling the earth gravitationally in the opposite direction.
(c) Indention in the coastline.

(d) None of the above.
3. The distance between the earth and the moon is minimum when the moon is in:
(a) Aphelion
(b) Perihelion
(c) Perigee
(d) Apogee
4. The earth reaches its perihelion in:
(a) October
(b) July
(c) September
(d) January
Answers: 1. A) Tide 2. D) None 3. C) Perigee 4. B) July

4. Temperature Distribution of Oceans

- The study of the temperature of the oceans is important for determining the
  1. movement of large volumes of water (vertical and horizontal ocean currents),
  2. type and distribution of marine organisms at various depths of oceans,
  3. climate of coastal lands, etc.

4.1 Source of Heat in Oceans

- The sun is the principal source of energy (Insolation).
- The ocean is also heated by the inner heat of the ocean itself (at the ocean bottom, the crust is only about 5 to 30 km thick). But this heat is negligible compared to that received from sun.

The ocean water is heated by three processes

- **Absorption of sun's radiation.**
- **The conventional currents:** Since the temperature of the earth increases with increasing depth, the ocean water at great depths is heated than the subsurface and intermediate water layers.
- Also, the temperate are high along mid-ocean ridges because of volcanism.
- So, convectional oceanic circulations develop causing circulation of heat in water.
- **Heat is produced due to friction** caused by the surface wind and the tidal currents.

The ocean water is cooled by

1. **Back radiation (heat budget)** or **long wave terrestrial radiation** from the seawater.
2. **Exchange of heat** between the sea and the atmosphere if there is temperature difference.
3. **Evaporation:** Heat is lost in the form of **latent heat of evaporation** (atmosphere gains this heat in the form of latent heat of condensation).

How does deep water marine organisms survive in spite of absence of sunlight?

- Photic zone (the zone that receives sunlight) is only about few hundred meters.
- It depends on a lot of factors like **turbidity**, presence of algae etc.
- There are no enough primary producers below few hundred meters till the ocean bottom.
- At the sea bottom, there are bacteria that make use of heat supplied by earth's interior to prepare food. So, they are the primary producers at the depths.
- Other organisms feed on these primary producers and subsequent secondary producers.
- So, the heat from earth supports wide-ranging deep water marine organisms.

But the productivity is too low compared to ocean surface.

Why is diurnal range of ocean temperatures too small?

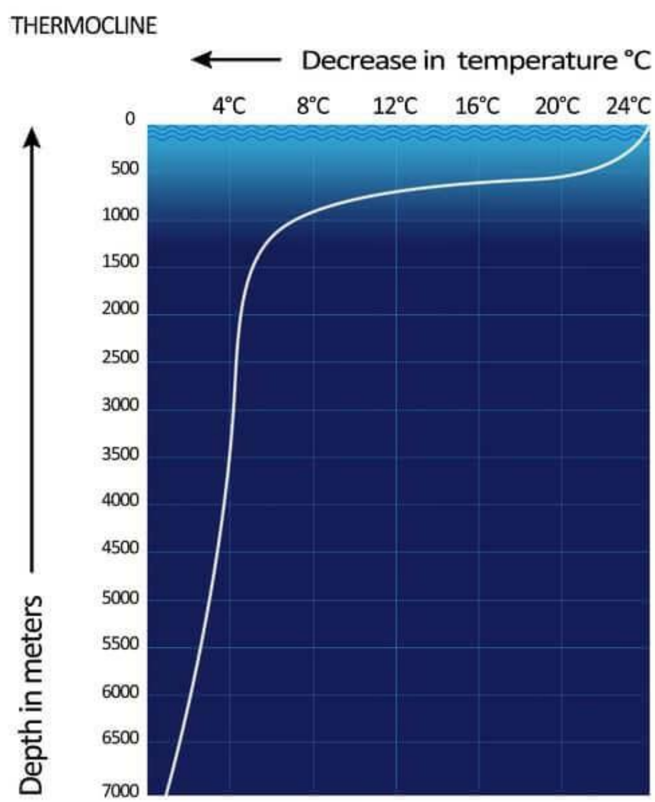
- The process of heating and cooling of the oceanic water is slower than land due to **vertical and horizontal mixing** and **high specific heat of water**.
- (More time is required to heat a Kg of water compared to heating the same unit of a solid at same temperatures and with equal energy supply).

4.2 Factors Affecting Temperature Distribution of Oceans

- **Insolation:** The average daily duration of insolation and its intensity.
- **Heat loss:** The loss of energy by reflection, scattering, evaporation and radiation.
- **Albedo:** The albedo of the sea (depending on the angle of sun rays).
- **The physical characteristics of the sea surface:** Boiling point of the sea water is increased in the case of higher salinity and vice versa **(if Salinity is increased ➔ Boiling point will increase ➔ Evaporation will decrease).**
- **The presence of submarine ridges and sills:** Temperature is affected due to lesser mixing of waters on the opposite sides of the ridges or sills (e.g. subsurface layers in Mediterranean Sea).
- **The shape of the ocean (enclosed seas):** enclosed seas in the low latitudes record relatively higher temperature than the open seas (due to less mixing and higher overall insolation); whereas the enclosed seas in the high latitudes have lower temperature than the open seas.
- E.g. Mediterranean Sea records higher temperature than the longitudinally extensive Gulf of California.
- **Local weather conditions such as cyclones.**
- **Unequal distribution of land and water:** The oceans in the northern hemisphere receive more heat due to their contact with larger extent of land than the oceans in the southern hemisphere.
- **Prevalent winds** generate horizontal and sometimes vertical ocean currents: The winds blowing from the land towards the oceans (**offshore winds**: moving away from the shore) drive warm surface water away from the coast resulting in the **upwelling of cold water** from below (this happens near **Peruvian Coast during normal years**).
- Contrary to this, the **onshore winds** (winds flowing from oceans into continents) pile up warm water near the coast, and this raises the temperature (this happens near the **Peruvian coast during El Nino event**).
- **Ocean currents:** Warm ocean currents raise the temperature in cold areas while the cold currents decrease the temperature in warm ocean areas.
- **Gulf stream (warm current)** raises the temperature near the eastern coast of North America and the West Coast of Europe while the **Labrador current (cold current)** lowers the temperature near the north-east coast of North America (Near Newfoundland).

4.3 Vertical Temperature Distribution of Oceans

- **Photic or euphotic zone** extends from the upper surface to ~200 m. The photic zone receives adequate solar insolation.
- **Aphotic zone** extends from 200 m to the ocean bottom; this zone does not receive adequate sunrays.



Thermocline (Praveenron, Wikipedia)

Thermocline

- The profile shows a boundary region between the surface waters of the ocean and the deeper layers.
- The boundary usually begins around 100-400 m below the sea surface and extends several hundred of meters downward.

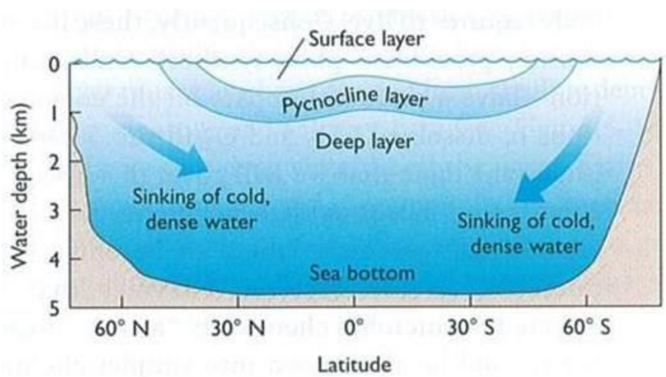
- This boundary region, from where there is a rapid decrease of temperature, is called the **thermocline**.
- About 90 per cent of the total volume of water is found below the thermocline in the deep ocean. In this zone, temperatures approach 0° C.

Three-Layer System

- The temperature structure of oceans over middle and low latitudes can be described as a three-layer system from surface to the bottom.
- The first layer represents the top layer of warm oceanic water, and it is about 500m thick with temperatures ranging between **20° and 25° C.**
- This layer, within the tropical region, is present throughout the year but in mid-latitudes, it develops only during summer.
- The second layer called the **thermocline layer** lies below the first layer and is characterized by rapid decrease in temperature with increasing depth. The thermocline is 500-1,000 m thick.
- The third layer is very cold and extends up to the deep ocean floor. Here the temperature becomes almost stagnant.

Pycnocline

- Pycnocline is a boundary separating two liquid layers of different densities.
- Pycnocline exists in oceans at a depth of 100-1000 m because of large density difference between surface waters and deep ocean water.
- Pycnocline effectively prevents vertical currents except in polar regions.

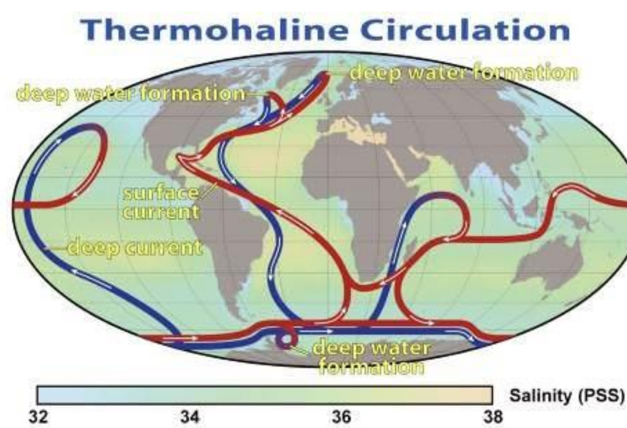


Pycnocline

- Similar Terms: **Thermocline, Halocline.**
- Pycnocline is almost absent in polar regions. This is because of the sinking of cold water near poles.
- Formation of pycnocline may result from changes in salinity or temperature.
- Because the pycnocline zone is **extremely stable**, it acts as a barrier for surface processes.
- Thus, changes in salinity or temperature are very small below pycnocline but are seasonal in surface waters.

Thermohaline Circulation

- Winds drive ocean currents in the upper 100 meters of the ocean's surface.
- However, ocean currents also flow thousands of meters below the surface.
- These deep-ocean currents are driven by differences in the water's density, which is controlled by temperature (thermo) and salinity (haline).
- This process is known as thermohaline circulation.
- The thermohaline circulation is sometimes called the **ocean conveyor belt**, the great ocean conveyor, or the global conveyor belt.
- Ocean bottom relief greatly influences thermohaline circulation.

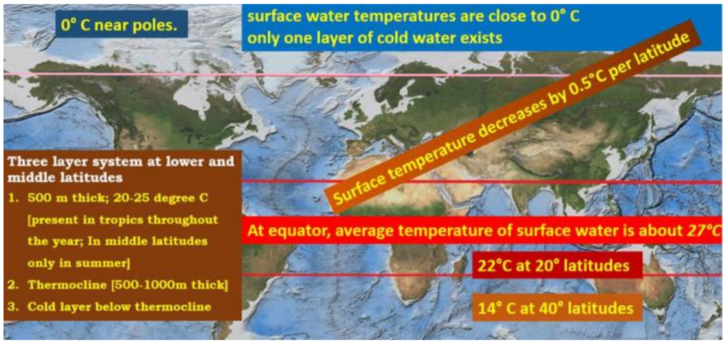


Thermohaline Circulation (Wikipedia)

4.4 Horizontal Temperature Distribution

- The average temperature of surface water of the oceans is about 27°C, and it gradually decreases from the equator towards the poles.

- The rate of decrease of temperature with increasing latitude is generally **0.5°C per latitude**.



Ocean Temperature Distribution

4.5 General behaviour

- In the Arctic and Antarctic circles, the surface water temperatures are close to 0° C and so the temperature change with the depth is **very slight** (**ice is a very bad conductor of heat**).
- Here, **only one layer of cold water exists**, which extends from surface to deep ocean floor.

The rate of decrease of temperature with depths is greater at the equator than at the poles.

- The surface temperature and its downward decrease is influenced by the upwelling of bottom water (e.g. near Peruvian coast during normal years).
- In cold Arctic and Antarctic regions, sinking of cold water and its movement towards lower latitudes is observed.
- In equatorial regions the surface, water sometimes exhibits **lower temperature and salinity** due to high rainfall, whereas the layers below it has higher temperatures.
- The enclosed seas in both the lower and higher latitudes record **higher temperatures at the bottom.**
- The enclosed seas of low latitudes like the **Sargasso Sea**, the **Red Sea** and the **Mediterranean Sea** have high bottom temperatures due to high insolation throughout the year and lesser mixing.
- In the case of the **high latitude enclosed seas, the bottom layers of water are warmer as water of slightly higher salinity and temperature moves from outer ocean as a subsurface current**.
- The presence of submarine barriers may lead to different temperature conditions on the two sides of the barrier.
- For example, at the Strait of Bab-el-Mandeb, the submarine barrier (sill) has a height of about 366 m.
- The subsurface water in the strait is at high temperature compared to water at same level in Indian ocean. The temperature difference is greater than nearly 20° C.

4.6 Range of Ocean Temperature

- The oceans and seas get heated and cooled slower than the land surfaces.
- Therefore, ocean surface temperature is **highest at 2 p.m.** and the **lowest, at 5 a.m.**
- The average diurnal or daily range of temperature is barely 1 degree in oceans and seas.
- The annual range of temperature is influenced by the annual variation of insolation, the nature of ocean currents and the prevailing winds.
- The maximum and the minimum temperatures in oceans are slightly delayed than those of land areas (the **maximum being in August** and the minimum in February (tropical cyclones occur mostly between August and October. It is **slightly different in Indian Ocean due to its shape**).
- The northern Pacific and northern Atlantic oceans (less intense prevailing winds) have a greater range of temperature than their southern parts (more extensive ocean currents).
- Besides annual and diurnal ranges of temperature, there are periodic fluctuations of sea temperature also.
- For example, the 11-year sunspot cycle causes sea temperatures to rise after a 11-year gap.

Sunspot

- Sunspots are **temporary phenomena** on the **photosphere** of the Sun that appear visibly as dark spots compared to surrounding regions.
- They correspond to concentrations of **magnetic field** that inhibit convection and result in reduced surface temperature compared to the surrounding photosphere.

- Sunspot activity cycles about every **eleven years**. The point of highest sunspot activity during this cycle is known as Solar Maximum, and the point of lowest activity is Solar Minimum.

5. Ocean Salinity

- Salinity is the term used to define the total content of dissolved salts in seawater.
- It is calculated as the amount of salt (in gm) dissolved in 1,000 gm (1 kg) of seawater.
- It is usually expressed as parts per thousand or ppt.
- Salinity of **24.7 ppt** (the symbol for ppt is ‰) has been considered as the upper limit to demarcate '**brackish water'.**
- Salinity determines compressibility, thermal expansion, temperature, density, absorption of insolation, evaporation and humidity.
- It also influences the composition and movement of the sea: water and the distribution of fish and other marine resources.

Share of different salts is as shown below

- **sodium chloride — 77.7%**
- **magnesium chloride—10.9%**
- **magnesium sulphate — 4.7%**
- **calcium sulphate — 3.6%**
- **potassium sulphate — 2.5%**

Dissolved Salts in Sea Water (gm of Salt per kg of Water)

1. Chlorine	**18.97**
2. Sodium	**10.47**
3. Sulphate	**2.65**
4. Magnesium	**1.28**
5. Calcium	**0.41**
6. Potassium	**0.38**

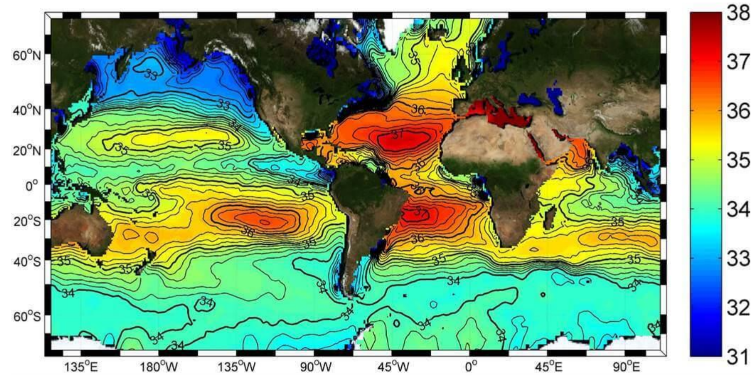
5.2 Factors Affecting Ocean Salinity

- The salinity of water in the surface layer of oceans depend mainly on **evaporation and precipitation.**
- Surface salinity is greatly influenced in coastal regions by the **freshwater flow** from rivers, and in polar regions by the processes of freezing and thawing of ice.
- Wind also influences salinity of an area by transferring water to other areas.
- The ocean currents contribute to the salinity variations.
- Salinity, temperature and density of water are interrelated. Hence, any change in the temperature or density influences the salinity of an area.

Horizontal distribution of salinity

All values are in ppt (parts per thousand or ‰)

- The salinity for normal open ocean ranges between **33 and 37**.



Ocean surface salinity (Source)

- The regions of high salinity in vast oceans coincide with high-pressure cells.
- Here, there is hardly any rain and subsiding dry winds cause lots of evaporation.

High salinity regions

- In the landlocked Red Sea, it is as high as 41.
- In the Mediterranean Sea in Europe the salinity is very high – 38 or more.
- In hot and dry regions, where evaporation is high, the salinity sometimes reaches to 70.

Low salinity regions

- In the estuaries (enclosed mouth of a river where fresh and saline water get mixed) and the Arctic and Antarctic, the salinity fluctuates from

0 to 35, seasonally (fresh water coming from ice caps).

Atlantic

- The average salinity of the Atlantic Ocean is around 36-37.
- The equatorial region of the Atlantic Ocean has a salinity of about 35.
- Near the equator, there is **heavy rainfall**, high relative humidity, cloudiness and calm air of the doldrums.
- The polar areas experience very little evaporation and receive large amounts of fresh water from the melting of ice. This leads to low levels of salinity, ranging between 20 and 32.
- **Maximum salinity (37) is observed between 20° N and 30° N and 20° W - 60° W (high-pressure cells)**.

Indian Ocean

- The average salinity of the Indian Ocean is 35.
- The low salinity trend is observed in the Bay of Bengal due to influx of river water by the river Ganga.
- On the contrary, the Arabian Sea shows **higher salinity** due to high evaporation and low influx of fresh water.

Marginal seas

- **The North Sea**, in spite of its location in higher latitudes, records higher salinity due to more saline water brought by the North Atlantic Drift.
- **Baltic Sea** records low salinity due to influx of river waters in large quantity.
- The **Mediterranean Sea** records higher salinity due to high evaporation.
- Salinity is, however, very low in **Black Sea** due to enormous freshwater influx by rivers.

Inland seas and lakes

- The salinity of the inland seas and lakes is very high because of the regular supply of salt by the rivers falling into them.
- These water bodies becomes progressively more saline due to evaporation.
- For instance, the salinity of the **Great Salt Lake**, (Utah, USA), the **Dead Sea** and the **Lake Van** in Turkey is more than 200.

Highest salinity in water bodies

- **Lake Van in Turkey (330 ppt)**
- **Dead Sea (238 ppt)**
- **Great Salt Lake, Utah (220 ppt)**

Cold and warm water mixing zones

- Salinity decreases from 35 to 31 on the western parts of the northern hemisphere because of the influx of melted water from the Arctic region.

5.3 Vertical Distribution of Salinity

- With depth, the salinity also varies, but this variation again is subject to latitudinal difference.
- The decrease is also influenced by cold and warm currents.
- In high latitudes, salinity increases with depth. In the middle latitudes, it increases up to 35 metres and then it decreases. At the equator, **sub-surface salinity is lower.**
- Salinity, generally, increases with depth and there is a distinct zone called the **halocline** (compare this with thermocline), where salinity increases sharply.
- High salinity seawater general, sinks below the lower salinity water. This leads to **stratification by salinity**.

Questions

1. Salinity is expressed as the amount of salt in grams dissolved in seawater per (a) 10 gm (b) 1,000 gm (c) 100 gm (d) 10,000 gm
2. Which one of the following is the smallest ocean? (a) Indian Ocean (b) Arctic Ocean (c) Atlantic Ocean (d) Pacific Ocean

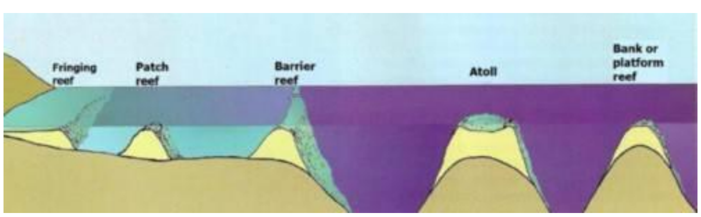
Answers: 1. B) 1000 gm 2. B) Arctic

6. Coral Reefs

- Coral reefs are made up of calcareous skeletons of thousands of tiny marine organisms called **coral polyps**
- Polyps are related to **anemones and jellyfish.**
- They are **shallow warm water organisms** which have a soft body covered by a **calcareous skeleton**.
- The polyps extract calcium salts from seawater to form these hard skeletons.
- The polyps live in colonies fastened to the rocky seafloor.
- The tubular skeletons grow as a cemented calcareous rocky mass, collectively called corals.
- When the coral polyps die, they shed their skeleton (coral) on which new polyps grow.
- The cycle is repeated for over millions of years leading to accumulation of layers of corals.
- Shallow rock layers created by the depositions of corals is called a **coral reef**.
- Coral reefs over a period of time transform or evolve into **coral islands (e.g. Lakshadweep).**
- The corals occur in different forms and colours, depending upon the **nature of salts** they are made of.
- Small marine plants **(algae)** also deposit calcium carbonate contributing to coral growth.

6.1 Coral Reef Relief Features

- **Fringing reef, barrier reef** and **atoll (coral islands are formed on atolls)** are the most important relief features.



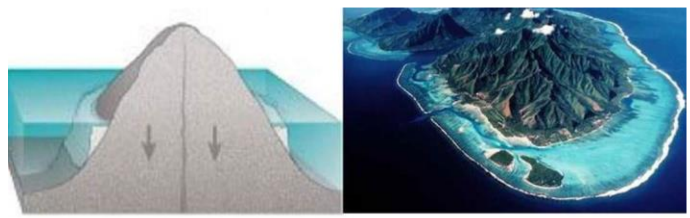
Coral Reef Relief Features

Fringing Reefs (Shore Reefs)

- Fringing reefs are reefs that **grow directly from a shore**.
- They are very narrow (1-2 km wide) and are located very **close** to the land.
- A **shallow lagoon** exists between the beach and the main body of the reef.

A lagoon refers to a comparatively wide band of water that lies between the shore and the main area of reef development and contains at least some deep portions.

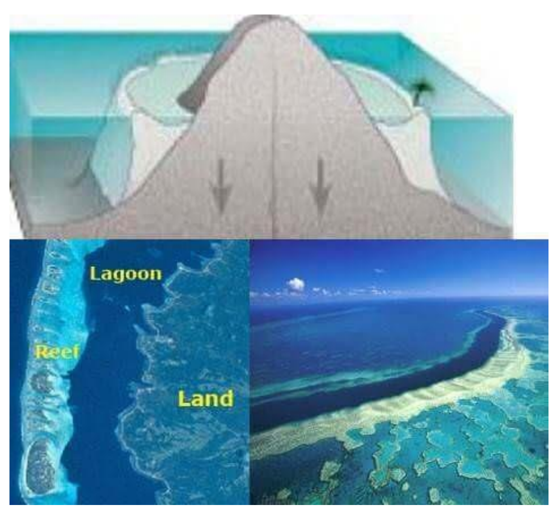
- Fringing reef grows from the deep sea bottom with the seaward side sloping steeply into the deep sea.
- Coral polyps do not extend outwards because of **sudden and large increase in depth**.
- The fringing reef is by far the most common of the three major types of coral reefs.
- Fringing reefs can be seen at the New Hebrides Society islands off Australia and off the southern coast of Florida.



Fringing Reef

Barrier Reefs

- Barrier reefs are **extensive linear reefs** that run parallel to the shore and are separated from it by a **lagoon**.
- This is the **largest (in size, not distribution)** of the three reefs, runs for hundreds of kilometres and is several kilometres wide.
- It extends as a broken, irregular ring around the coast or an island, running almost parallel to it.
- Barrier reefs are **far less common** than fringing reefs or atolls.

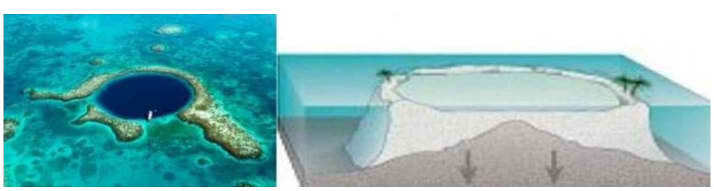


Barrier Reef

- The **1200-mile long Great Barrier Reef** off the NE coast of Australia is the world's largest barrier reef.
- The GBR is not a single reef, but rather a very large complex consisting of **many reefs**.

Atolls

- An atoll is a roughly circular oceanic reef system surrounding a large **central lagoon**.
- The lagoon has a depth of 80-150 metres and may be joined with sea water through a number of channels cutting across the reef.
- Atolls are located at **great distances** from deep sea platforms.
- They form on submarine features such as a **submerged island or a volcanic cone** which reaches a level suitable for coral growth.
- An atoll may have any one of the following three forms-
  1. **true atoll: a circular reef enclosing a lagoon with no island;**
  2. **an atoll surrounding a lagoon with an island;**
  3. **a coral island or an atoll island which is, in fact, an atoll reef, built by the process of erosion and deposition of waves with island crowns formed on them.**
- Atolls are **far more common in the Pacific** than any other ocean.
- The **Fiji atoll** is a well-known example of atolls.
- In the South Pacific, most atolls occur in mid-ocean. Examples of this reef type are common in **French Polynesia**, the **Caroline and Marshall Islands**, **Micronesia**, and the **Cook Islands.**
- A large number of atolls occur in the **Lakshadweep Islands.**
- Others are found in the **Maldives** and **Chagos island groups,** the **Seychelles,** and in the **Cocos s**.



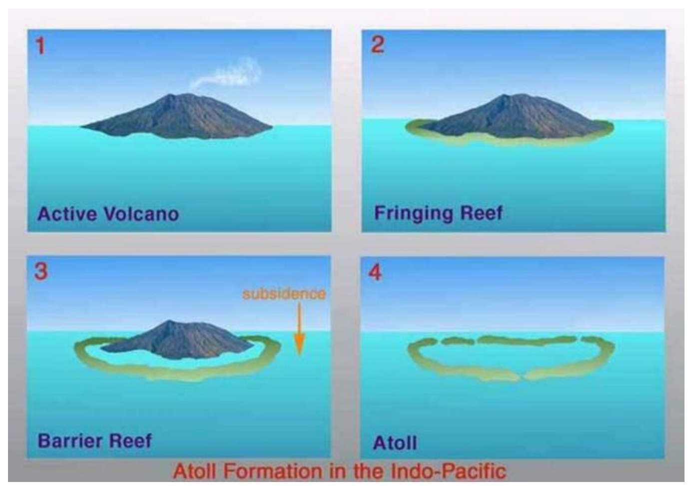
Atoll

6.2 Development of Major Coral Reef Types

Formation of Lakshadweep Islands (You must include the concept of Reunion Hotspot)

- The basic coral reef classification scheme described earlier was first proposed by **Charles Darwin** and is still widely used today.

1. Step 1: A **fringing reef forms first** and starts growing in the shallow waters close to a tropical island.
2. Step 2: Over time, the **island subsides, and the reef grows outwards**, and the distance between the land and the reef increases. The fringing reef develops into a barrier reef.
3. Step 3: If the island completely subsides, all that is left is the reef. The reef retains the approximate shape of the island it grew around, forming a ring enclosing a lagoon (**atoll**).



Development of Major Coral Reef Types

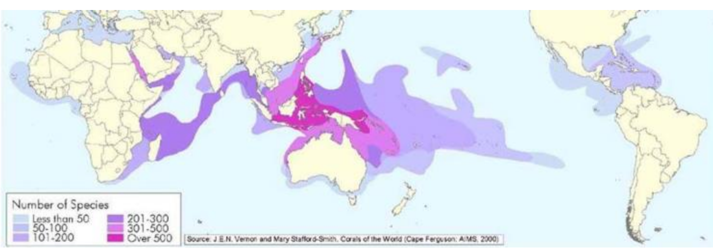
6.3 Ideal Conditions for Coral Growth

- **Stable climatic conditions:** Corals are highly susceptible to quick changes. They grow in regions where climate is significantly stable for a long period (Equatorial oceans with warm ocean currents).
- **Perpetually warm waters:** Corals thrive in **tropical waters** (30°N and 30°S latitudes, the temperature of water is around 20°C) where diurnal and annual temperature ranges are very narrow.

Why are coral reefs absent on west coast of tropical continents? Because of Cold Ocean Currents.

- **Shallow water:** Coral require fairly good amount of **sunlight** to survive. The ideal depths for coral growth are 45 m to 55 m below sea surface, where there is enough sunlight available.
- **Clear salt water:** Clear salt water is suitable for coral growth, while both freshwater and highly saline water are harmful.
- **Abundant Plankton:** Adequate supply of oxygen and microscopic marine food, called **plankton (phytoplankton)**, is essential for growth. As the plankton is more abundant on the **seaward side**, corals grow rapidly on the seaward side.
- **Little or no pollution:** Corals are highly fragile and are vulnerable to climate change and pollution and even a minute increase in marine pollution can be catastrophic.

Distribution of Coral Reefs



Distribution of Coral Reefs

6.4 Corals and Zooxanthellae

- Many invertebrates, vertebrates, and plants live in close association with corals, with **tight resource coupling and recycling**, allowing coral reefs to have **extremely high productivity and biodiversity**, such that they are referred to as **the Tropical Rainforests of the Oceans.**
- Scleractinian corals build skeletons of calcium carbonate **sequestered** from the water.
- Scleractinian corals come under **Phylum Cnidaria**, and they receive their nutrient and energy resources in two ways.
  1. They use the traditional cnidarian strategy of capturing tiny planktonic organisms with their tentacles.
  2. Having a symbiotic relationship with a **single cell alga** known as **zooxanthellae.**
- Zooxanthellae are **autotrophic (prepare their own food) microalgae** belonging to various taxa in the **Phylum Dinoflagellata.**

Coral ➔ Phylum Cnidaria
Zooxanthellae ➔ Phylum Dinoflagellata

Symbiotic Relationship Between Corals and Zooxanthellae

- Zooxanthellae live symbiotically within the coral polyp tissues and **assist the coral in nutrient production through its photosynthetic activities**.
- These activities provide the coral with **fixed carbon compounds for energy, enhance calcification, and mediate elemental nutrient flux.**
- The host coral polyp in return provides zooxanthellae with a **protected environment** to live within, and a **steady supply of carbon dioxide** for its **photosynthetic processes**.
- The symbiotic relationship allows the slow-growing corals to compete with the faster growing multicellular algae.
- The corals feed by day through **photosynthesis** and by night through **predation**.

The tissues of corals themselves are actually not the beautiful colours of the coral reef but are instead clear. The corals receive their colouration from the zooxanthellae living within their tissues.

6.5 Coral Bleaching or Coral Reef Bleaching

- Disturbances affecting coral reefs include anthropogenic and natural events.
- Recent accelerated coral reef decline is related mostly to anthropogenic impacts **(overexploitation, overfishing, increased sedimentation and nutrient overloading).**
- Natural disturbances which cause damage to coral reefs include **violent storms, flooding, high and low-temperature extremes, El Nino Southern Oscillation (ENSO) events,**

subaerial exposures, predatory outbreaks and epizootics.

- Coral reef bleaching is a common **stress response** of corals to many of the various disturbances mentioned above.
- Bleaching occurs when
  1. **the densities of zooxanthellae decline and/or**
  2. **the concentration of photosynthetic pigments within the zooxanthellae fall. (it is no more useful for the coral and the coral will bleach it)**

Coral Bleaching

Coral Bleaching

- When corals bleach, they commonly **lose 60-90% of their zooxanthellae** and each zooxanthellae may **lose 50-80% of its photosynthetic pigments**.
- If the **stress-causing** bleaching is not too severe and if it decreases in time, the affected corals usually regain their symbiotic algae within several weeks or a few months.
- If zooxanthellae loss is prolonged, i.e. if the stress continues and depleted zooxanthellae populations do not recover, the coral host eventually dies.

Ecological Causes of Coral Bleaching

Temperature

- Coral species live within a relatively narrow temperature margin, and **anomalously low, and high sea temperatures** can induce coral bleaching.
- Bleaching events occur during sudden temperature drops accompanying intense upwelling episodes (El-Nino), seasonal cold-air outbreaks.
- While the rising temperatures have increased the frequency and intensity of bleaching, **acidification** has **reduced corals calcifying ability.**
- Small temperature increases over many weeks or large increase (3-4 °C) over a few days will result in **coral dysfunction.**
- Coral bleaching has occurred mostly during the summer seasons or near the end of a protracted warming period.
- They are reported to have taken place during times of **low wind velocity, clear skies, calm seas and low turbidity.** The conditions favour localised heating and high ultraviolet (UV) radiation.
- UV radiation readily penetrates clear sea waters. The corals actually contain UV-absorbing compounds, but rising temperatures mean reduction in the concentration of these UV absorbing compounds in corals.

Subaerial exposure

- Sudden exposure of corals to the atmosphere during events such as extreme low tides, ENSO-related sea level drops or tectonic uplift can potentially induce bleaching.
- The consequent exposure to high or low temperatures, increased solar radiation, desiccation, and seawater dilution by heavy rains could all play a role in **zooxanthellae loss**.

Fresh Water Dilution

- Rapid dilution of reef waters from storm-generated precipitation and runoff has been demonstrated to cause coral reef bleaching.
- Generally, such bleaching events are rare and confined to relatively small, near shore areas.

Inorganic Nutrients

- Rather than causing coral reef bleaching, an increase in ambient elemental nutrient concentrations (e.g. **ammonia and nitrate**) actually increases zooxanthellae densities 2-3 times.
- Although **eutrophication (excessive nutrients that results in harmful algal blooms)** is not directly involved in zooxanthellae loss, it could cause secondary adverse effects such as **lowering of coral resistance and greater susceptibility to diseases.**

Xenobiotics

- When corals are exposed to high concentrations of chemical contaminants like copper, herbicides and oil, coral bleaching happens.

Epizootics

- **Pathogen** induced bleaching is different from other sorts of bleaching.
- Most coral diseases cause patchy or whole colony death and sloughing of soft tissues, resulting in a white skeleton (not to be confused with bleached corals).

Bleaching may also be Beneficial: Recent research has revealed that corals that are consistently exposed to low levels of stress may develop some kind of resistance to bleaching.

Spatial and temporal range of coral reef bleaching

- Nearly all of the world's major coral reef regions (Caribbean/ western Atlantic, eastern Pacific, central and western Pacific, Indian Ocean, Arabian Gulf, Red Sea) experienced some degree of coral bleaching and mortality during the 1980s.
- Prior to the 1980s, most mass coral moralities were related to non-thermal disturbances such as storms, aerial exposures during extreme low tides, and **Acanthaster planci outbreaks** (**crown-of-thorns seastar**, a **large starfish that preys upon coral polyps**).

7. Resources from the Ocean

7.1 Ocean Deposits

- Ocean deposits are unconsolidated sediments deposited on the ocean floor.
- They are broadly divided into two types —
    1. the **terrigenous deposits** (deposits derived from land; found mainly on the continental shelves and slopes), and
    2. the **pelagic deposits** (found over deep sea plains and the deeps).

Terrigenous Deposits

- They are **mainly inorganic deposits** (compounds not containing carbon) derived from disintegrated rock material (due to weathering and water erosion).
- The proportion of organic matter (in the form of shells, corals and skeletons) is quite negligible.
- The disintegrated rock material is carried from land to the sea mainly by running water.
- The terrigenous deposits are found mainly on the **continental shelves and slopes**.
- Except for fine volcanic ash, little terrigenous material is carried on to the sea surface.

Pelagic Deposits

- Pelagic deposits cover nearly 75% of the total sea floor.
- The pelagic deposits consist of both organic (remains of plants and animals) and inorganic material.
- Organic material is in the form of liquid mud called **ooze** which contains remnants of shells and skeletons.
- Inorganic material is in the form of red clay which is of volcanic origin.
- The chief constituents of red clay are silicon and aluminium dioxide.
- The red clay is the most widely spread pelagic deposit of the sea floor.
- The red clay covers more than half of the Pacific floor.

7.2 Mineral Resources

- Both metallic and non-metallic resources are found in seas.
- Most of these minerals are carried from land to sea by running water.
- The remaining are formed from to undersea volcanism and detritus (leftover parts) of marine organisms.
- At present, mining of only a handful of marine mineral resources is economically viable.
- Among them are offshore oil and natural gas, extraction of sodium chloride, salts of magnesium and bromine, etc.

Mineral deposits found on continental shelves and slopes

- The surface deposits on the continental shelves and slopes are found mixed with sand.
- Sands are mined to extract calcium carbonate along the Bahamas coast.
- Coral sands are mined in Hawaii and Fiji for calcium carbonate.

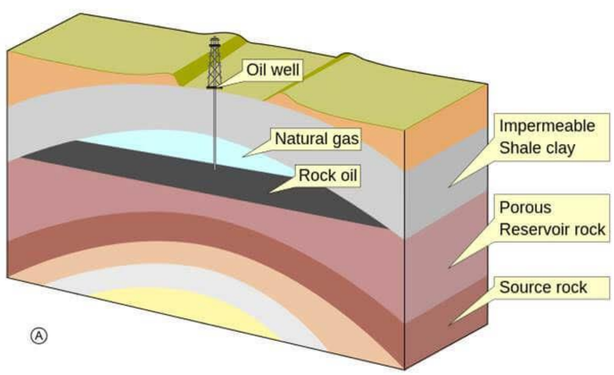
Marine Placer deposits

- A placer deposit is an accumulation of valuable **heavy minerals** that have been weathered and eroded from their source rocks.
- As a result of their high density, placer minerals **accumulate just a few tens of kilometres away** from their source rocks.
- Marine placers deposits accumulate on the continual shelves very close to the shoreline.
- The most economically important of placer minerals are **cassiterite (ore of tin), ilmenite (titanium), rutile (titanium), zircon (zirconium), chromite (chromium), monazite (thorium), magnetite (iron), gold and diamonds**.
- The beach sands of western India, coastal Brazil, Australia have zircon, monazite (**thorium is extracted form monazite sands found across the Kerala coast**) and rutile.
- **Kerala's placer deposits** contain **90 per cent of the world's monazite reserves**.
- The eastern and western coasts of **Australia** account for about 30 per cent of **rutile**.
- Placer diamonds are mainly mined in shelf sediments along the west coast of South Africa and Namibia.

- Gold placers occur along the coast of Alaska on the East Pacific shelf.
- The **tin ore, cassiterite**, a residue of granite weathering, occurs in the shelf of South East Asia.

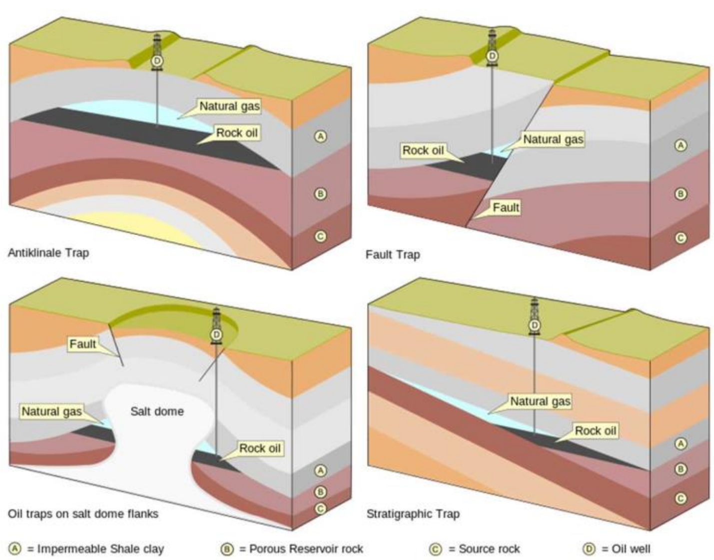
Marine hydrocarbon deposits

- Generally, large quantities of hydrocarbons can be formed only at depths within **organic-rich layers greater than 1,000 - 2,000 meters**.
- Formation of exploitable reservoirs of hydrocarbons requires migration (from their source rocks) to **geological traps** comprising a **porous reservoir rocks** and **overlain by an impermeable horizon**.



Anticline trap (MagentaGreen, [Wikipedia Commons](#))

- Common geological traps for hydrocarbons include **shales, salt domes (evaporites; also rich in sulphur), and anticlinal folds of permeable and non-permeable strata**.
- In addition to liquid hydrocarbons, natural gas is also common.



Oil and Gas traps (MagentaGreen, [Wikipedia Commons](#))

- The estimated reserves of oil worldwide at the beginning of the 21st Century are about one trillion barrels.
- Of this amount, about 252 billion barrels (**25%**) lie in marine environments.
- Similarly, the total worldwide resources of natural gas are estimated at about 4,000 trillion cubic feet, of which about 26 per cent are marine.
- These reserves of oil and gas are located as subsurface deposits almost exclusively on the **continental shelves**.
- The abyssal plains probably contain insufficient thickness of sediments (less than 1 km) to yield hydrocarbon accumulations.
- Of the twenty-five largest offshore production fields, eight are in the Persian Gulf and eight others are in the **North Sea** (**here hydrocarbons are available at a shallow depth**).
- The remaining ones are located in the Gulf of Mexico, East Asia (South China Sea), South Asia, etc.
- The western coast of India has shown promising reserves.
- Besides oil, submerged coal deposits are to be found in the **coast of Maharashtra in India**.

Challenges in harnessing marine hydrocarbon resources

- The cost of production from deep marine environments is economically unviable considering the present demand.
- Gas and oil exploration increase the risk of marine pollution from accidental oil spills. Existing response technologies are inadequate to contain and recover spills.

Marine phosphorite deposits

- Phosphorites are natural compounds containing **phosphate (used in the production of fertilizers)**.
- They are found in shallow waters and in the form of nodules on the **continental shelves and slopes**.

- At present, no offshore deposits are being mined because of the availability of non-marine phosphates.

Mineral deposits found on deep sea floor

- The deep sea has two main types of mineral deposits of economic importance: **manganese nodules (also called as polymetallic nodules)** and **metalliferous sediments**.

Marine manganese nodules (Polymetallic nodules) and crusts

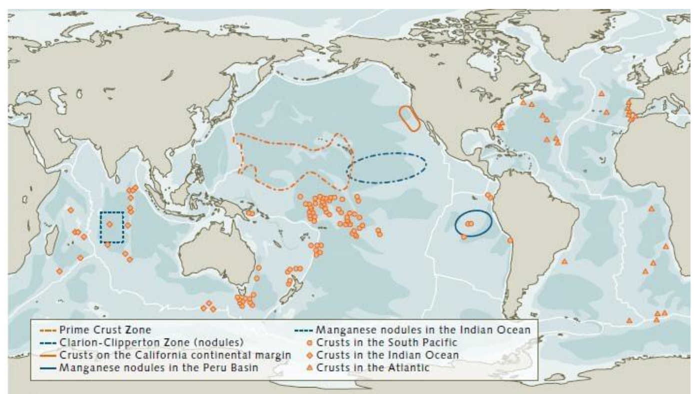
- Manganese nodules are concentrations of **iron and manganese oxides**, that can contain economically valuable concentrations of **manganese (~30%), nickel (1.25-1.5%), copper (~1%) and cobalt (~0.25%)**.
- Other constituents include iron (6%), silicon (5%) and aluminium (3%).
- They are thought to have formed from the precipitation of metals from seawater, hot springs associated with volcanic activity and metal hydroxides through the activity of microorganisms.
- Their abundance, composition, and their occurrence as loose material lying on the surface of the seabed make nodules potentially attractive to future mining.
- Manganese-rich crusts, similar in composition to the nodules, occur on rocky outcrops.
- The top ten countries that have the greatest resource potential of nodules and crusts are the United States of America, Madagascar, Brazil, Antarctica, Argentina, Japan, South Africa, Canada and India.
- Papua New Guinea is one of the few places where nodules were located in shallow waters.
- However, the expense of bringing the ore up to the surface proved to be expensive.

Central Indian Ocean Basin (CIOB)

- Manganese nodules in Indian Ocean cover a large area, over 10 million sq. km.
- Large areas in the basins east of the Central Indian Ridge (ridge along the Reunion Hotspot) contains nodules with a **high percentage of manganese, nickel and copper**.
- India has exclusive rights to explore polymetallic nodules from seabed in Central Indian Ocean Basin (CIOB).
- These rights are over 75000 sq. km of area in international waters allocated by International Seabed Authority for developmental activities for polymetallic nodules.

Challenges

- Difficulty and expense of developing and operating mining technology that could economically remove the nodules from depths of five or six kilometres.
- Continuing availability of the key minerals from land-based sources like **nickel** at market prices.
- Mining is not economically viable for the next two decades.

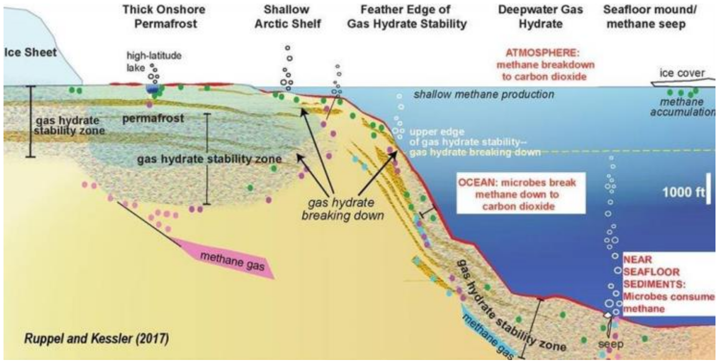


Locations of known polymetallic nodules. From World Ocean Review 3, (2014) (Source)

Marine gas hydrate deposits

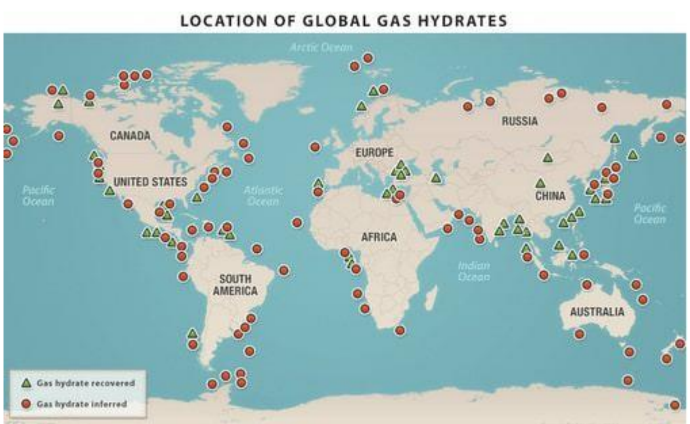
- Gas hydrate is an icy crystalline compound located at great ocean depths and in shallow polar waters.
- It is composed of gas molecules, normally **methane**, encaged within water molecules.
- At great ocean depths due to cold temperatures and high ocean pressure gas hydrate remain **solid**.
- The source of the dissolved gas is from the breakdown of organic matter trapped within marine sediment.

- Hence, gas hydrate deposits are likely to occur everywhere the seafloor exceeds 500 m (or 300 m in high latitudes), and where there is a source of unoxidsed organic carbon in marine sediments.



Gas Hydrate deposits ([Source](#))

- On dissociation at standard atmospheric pressure, gas hydrate yields approximately 164 times its own volume of methane gas.
- Gas hydrates are estimated to **hold many times more methane than presently exists in the atmosphere and up to twice the amount of energy of all fossil carbon-based fuels combined**.
- Gas hydrates are known from the Atlantic and Pacific margins of both North and South America, especially at equatorial latitudes.



Global gas hydrate deposits

Challenges in economic exploitation of gas hydrate deposits

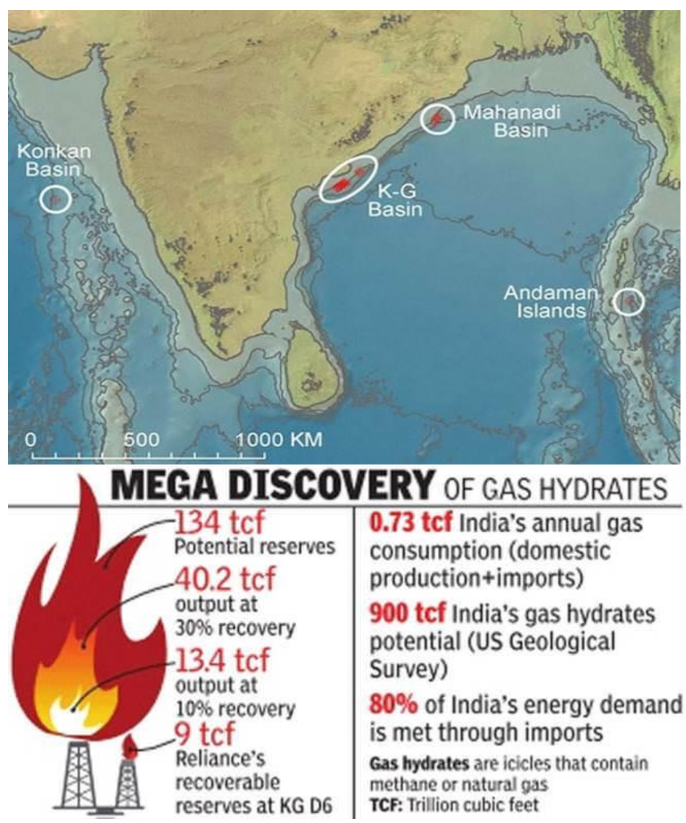
- Harnessing methane from gas hydrates is extremely challenging as they are stored deep in the ocean.
- Methane hydrates break at higher temperatures and lower pressures, presenting a challenge in the mining.

Methane is a greenhouse gas that traps heat twenty times more proficiently than carbon dioxide

- Gas hydrate reservoirs are extremely sensitive to climate change.
- They can catastrophically accentuate global warming by releasing methane.
- Gas hydrates break into smaller pieces and float upwards.
- Once they hit warmer waters and lower pressures, they break down into methane gas.
- The driving force behind the release of methane gas is the warming of oceans worldwide.
- Mining could unlock excess methane into atmosphere.

Natural gas hydrate in North Indian Ocean

- 2016: [ONGC discovered](#) large, highly enriched accumulations of natural gas hydrate in the Bay of Bengal.
- ONGC plans to start pilot production from its discovery from 2017.



Accumulations of natural gas hydrate in North Indian Ocean

Marine Polymetallic sulphides

- Deep seabed Poly-Metallic Sulphides (PMS) containing **iron, copper, zinc, silver, gold, platinum** in variable constitutions.
- They are formed due to the **precipitation of hot fluids from upwelling hot magma** discharged along the mid-ocean ridges.
- Considerable interest has been sparked by the discovery of **polymetallic sulphides in Western Indian Ocean**.
- India has received a 15 years contract from International Seabed Authority (ISA) for exploration of PMS in the area of 10,000 sq km in parts of Central and South - West Indian Ridges (SWIR).
- In the SWIR, PMS found near the Galapagos rift system contain 48 per cent sulphur, 43 per cent iron, 11 per cent copper and smaller quantities of **zinc, tin, molybdenum, lead and silver**.

Marine evaporite deposits

- Marine evaporites, formed by evaporation of sea water in geologic basins comprise mainly anhydrite and gypsum (calcium sulphates), sodium and magnesium salts and potash-bearing minerals.
- Rock salt cause upward protrusion forming salt domes, plugs, and other diapiric structures (salt domes explained in Volcanism).
- They can form structures in the sedimentary strata that are favourable for the accumulation of hydrocarbons.
- However, rock salts are abundantly available on land, and there is little value in marine deposits.

7.3 Energy Resources

Energy from Tides

- The tides, during rise and fall, release a lot of energy by striking against the shore. This piston action can be used to operate a turbine and produce electricity.
- The USA, the CIS, Japan and France are producing power from tides.

Ocean Thermal Energy Conversion (OTEC)

- In tropical seas, the surface temperature is about 25 °C to 30 °C, while the sub-surface temperature is 5 °C.
- This vertical difference of 25 °C is enough to generate electricity, but it is an expensive option.
- Belgium and Cuba are producing power in this way.
- 2008: An experimental 1MW plant at Kulasekarapattinam in Tamil Nadu was set up.

Geothermal Energy

- This means tapping heat from fracture zones and active volcanoes undersea.

7.4 Fresh Water

- Several desalination technologies are in operation, but as yet they are not being used on a large scale, as they are costly.

Technologies adopted in desalinization of sea water

- **Electrodialysis** employs iron-selective membranes for the desalination of brackish water.
- **Flash distillation** technique is in use in Saudi Arabia, Kuwait, Island, Pakistan, Chile, and India.
- **Reverse osmosis** is the most widely used method. Suitable osmotic membranes are used which reject salts and allow water to pass through when sea water is put under high pressure.

7.5 Biotic Resources

- At the base of the food chain are the planktons—phytoplankton and zoo-planktons. These are the food for many marine animal species.
- Benthos (sea surface) resources include animals such as crustaceans (prawn, shrimp, crab, lobster) and shellfish or molluscs (mussels, oysters).
- Marine animals provide oil, fur, leather, glue and cattle feed.

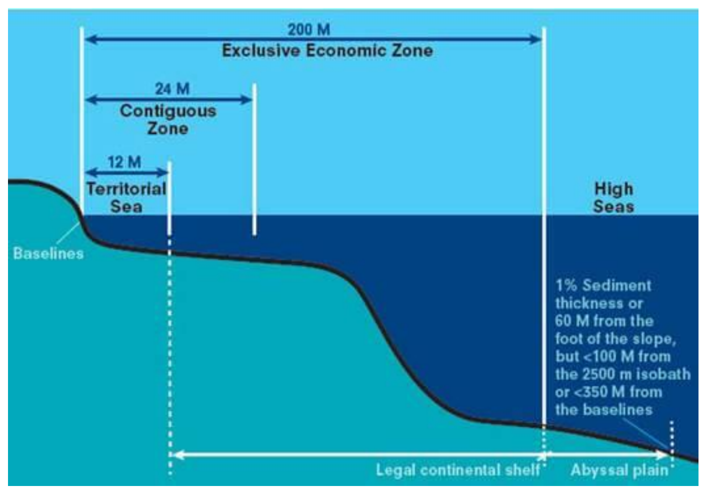
- Marine plants and animals are used in curative medicine.
- Seafoods are of high nutritional value.
- Edible fish are of three main types, based on the location of habitat.
    1. Pelagic fish (mackerel, herring, anchovies, tuna) breed near the surface of seas.
    2. Demersal fish (haddock, cod, halibut, sole in the temperate region, and snapper and garoupa in tropical waters) feed on or near the sea bed of the continental shelf.
    3. Then there are the migratory anadromous fish (salmon) that live in the sea but move into fresh water of coastal rivers every year.
- Whales are mammals of the ocean and have been caught not only for food but for industrial and medicinal purposes as well.

Algae

- Algae such as sea lettuces are used in soups and salads and as flavouring.
- Kelp can be cultivated for producing methane gas and used as an energy source by bioconversion
- Brown algae produce algin.
- Algin used as stabilisers in the paints industry, to strengthen ceramics, and to thicken jams.
- Red algae provide agar and carrageenan.
- Agar is an important medium for bacterial culture in research.
- It is also an ingredient in desserts and pharmaceutical products.
- Carrageenan is used as a stabiliser and emulsifier in ice-creams, and in cosmetics and medicines.

7.6 United Nations International Conferences on the Law of the Sea (UNCLOS)

- UNCLOS is an **international agreement** that defines the **rights and responsibilities of nations** where **use of the oceans' waters** by them is concerned.
- UNCLOS deal with aspects like delimitation, control of environmental pollution, commercial activities in the seas, technology transfer and settlement of disputes between States with reference to ocean matters.
- It also creates a legal regime for controlling mineral resource exploitation in deep seabed areas beyond national jurisdiction, through an International Seabed Authority.
- The UNCLOS came into force in the year 1994.
- As of today, it has been signed by more than 150 countries.
- The **USA has signed the treaty but has not ratified it**.
- The UN provides support for Convention meetings. However, the UN does not have a direct part in the implementation of the Convention.
- But organizations like the **International Maritime Organisation** and the **International Whaling Commission** have a role to play.
- UNCLOS uses a **consensus** process rather than a majority vote to discourage groups of nation-states dominating negotiations.
- Four main decisions have been widely accepted since 1978.



UNCLOS Coastal Zones

Territorial waters

- Territorial waters are those waters over which a state has full sovereignty
- Territorial waters extend for 19 km (**12 miles**) from the coast.
- Territorial waters include fjords, estuaries and land between the mainland and offshore islands in the internal waters.

Contiguous Zone or Pursuit Zone

- A further contiguous zone of 19 km is recognized in which the coastal state can act against those who break the law (smugglers, pirates, illegal immigrants etc.) within the true territorial waters.
- This, in other words, is a **pursuit zone**.

Exclusive Economic Zone (EEZ)

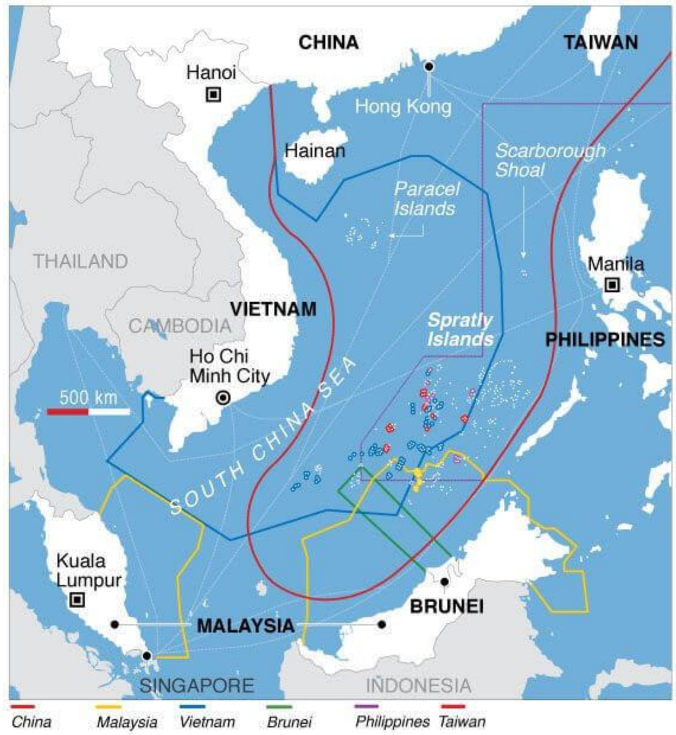
- Exclusive economic zone (EEZ) starts at the same baseline as the territorial waters.
- EEZ extend for 320-km (**200-mile**) from the baseline.
- Within the EEZ the coastal state has the right to **exploit all economic resources** — fish, minerals, oil and gas and energy production.
- The state may extend these rights to the edge of the shelf — as much as 1280 km (800 miles) in some cases — though this does not include rights to the sea itself beyond the 320 km EEZ.
- Land-locked and geographically disadvantaged states can participate on an equitable basis in exploiting an appropriate part of the surplus of the living resources of the EEZs of coastal states.
- In the EEZ and on the continental shelf, all marine scientific research is subject to relevant coastal State's consent. The coastal states, in turn, are expected to grant consent for peaceful purposes to other States.

High Seas

- Beyond all the zones in which individual countries can claim control are the high seas.
- The high seas are **free for navigation** by vessels of all nations.
- The oceans may also be used freely for the laying of submarine cables, and the airspace over them is also free.
- The oceans may also be freely fished by all nations, though some international agreements seek to control overfishing, which endangers some species.
- The States must share with the international community part of the revenue derived from exploiting resources on the continental shelf extending beyond 200 miles.

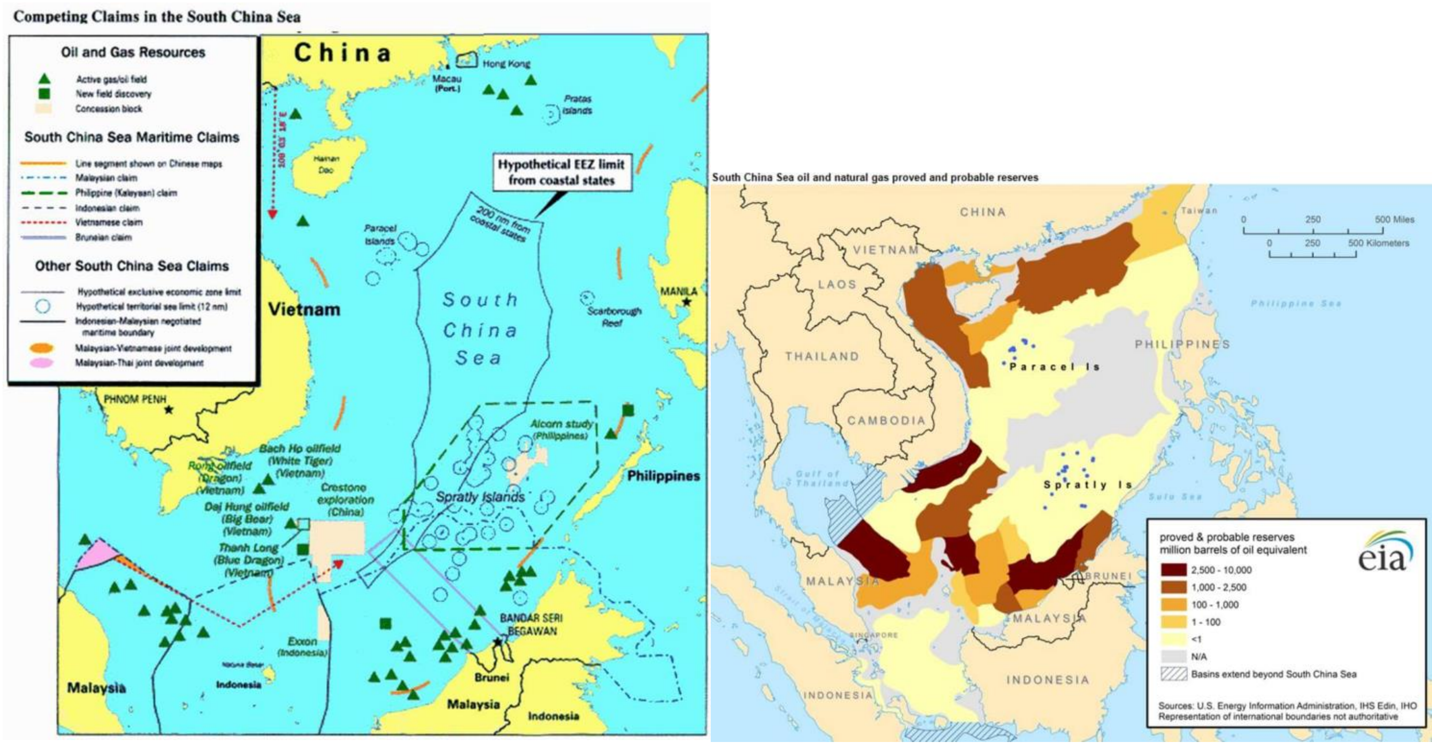
- Special protection should be accorded to highly migratory species of fish and sea mammals.

Land Disputes in South China Sea: Parcel Islands and Spratly Islands



Parcel Islands and Spratly Islands in South China Sea (Voice of America, Wikipedia)

- The **Spratly Islands and Paracel Islands** are two of the most contested areas in the South China Sea.
- However, unlike other parts of the South China Sea, these areas do not hold large resources of oil and natural gas.
- Most fields containing discovered oil and natural gas are clustered in uncontested parts of the South China Sea, close to shorelines of the coastal countries.
- The Paracel Islands, however, contain significant natural gas hydrate resources.
- Under the UNCLOS, ownership of habitable islands can, however, extend the exclusive access of a country to surrounding energy resources (**200 mile EEZ**).
- Hence, the country that wins the dispute would have the right to explore and develop whatever the resources that are available in the EEZ.



Oil and Gas reserves around Spratly Islands and Parcel Islands (Source)

Economic and Strategic importance of South China Sea

- 10% of world's fisheries.
- 30% of global shipping trade.
- Population is 2.2 billion in the region.
- 11 billion barrels of oil.
- 190 trillion cubic feet of natural gas.

Source