

Climate change and its implications

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Lecture-1



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Course outline: 2 credit

- Introduction to climate & climate change
- Evidence of climate change
- Global climate models & future climate projections
- Implications to
 - : Biodiversity, mitigation practices
 - : Agriculture, mitigation practices
 - : Water resources, mitigation practices

QGIS-Quantum GIS

<https://qgis.org/en/site/>

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Class outline:

Earth system Components

- Atmosphere
- Oceans
- Cryosphere
- Biosphere
- Earth's crust and mantle

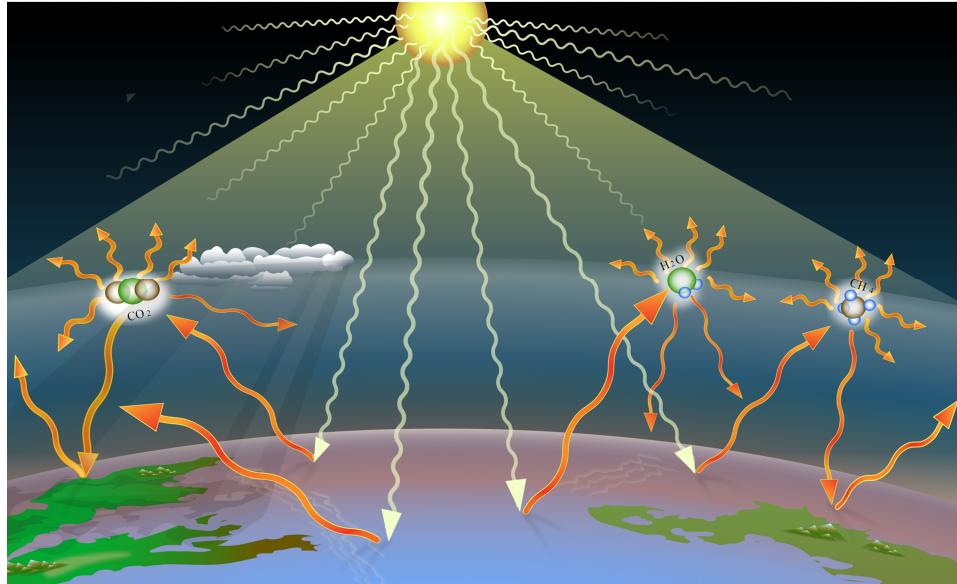
Class outline:

Earth system Components: 1) Atmosphere

Characteristics of Earth's atmosphere

- Optical properties
- Mass
- Composition
- Vertical structure: temperature, general circulations

Optical properties



- ▶ Earth's atmosphere is transparent to incoming solar radiation
- ▶ The outgoing radiation emitted by Earth is absorbed by the atmosphere (green house effect), and this makes the Earth's atmosphere warm
- ▶ About 22% of incoming solar rad is backscattered to space without absorption

Mass of the atmosphere



Mass of the atmosphere

- ▶ At any point on the earth's surface, the atmosphere exerts a downward force on the underlying surface due to earth's gravitational attraction.
- ▶ The downward force (i.e., the weight) of a unit volume of air with density ρ is given by,

$$F = \rho g$$

Where g is the acceleration due to gravity.

- ▶ Integrating the equ from earth's surface to the top of the atmosphere, we obtain the atmospheric pressure on the earth's surface (P_s) due to the weight (per unit area) of the air in the overlying column.

$$\text{i.e., } P_s = \int_0^{\infty} \rho g dz$$

- ▶ Neglect the small variation of g with lat, long, and height, we can take the mean value g , which is equal to $9.807 \text{ m}^2/\text{s}$, we can take it outside the integral.

$$\text{Then } Ps = g \int_0^{\infty} \rho dz,$$

which is again equal to $= g m$

where m is the vertically integrated mass per unit area of the overlying air

Exercise 1

- ▶ The globally averaged surface pressure is 985 hPa. Estimate the mass of the atmosphere.

Earth's radius= 6.37×10^6 m

Chemical composition

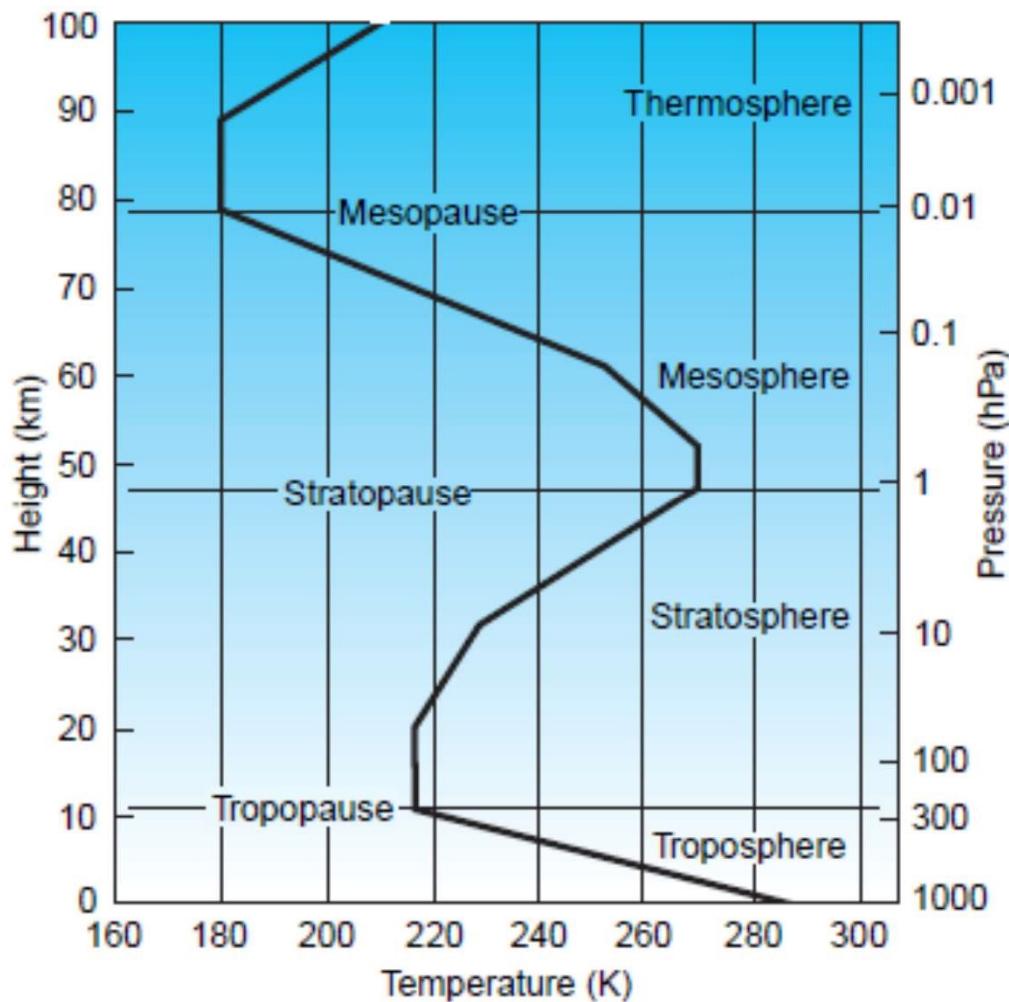
Constituent ^a	Molecular weight	Fractional concentration by volume
Nitrogen (N ₂)	28.013	78.08%
Oxygen (O ₂)	32.000	20.95%
Argon (Ar)	39.95	0.93%
Water vapor (H ₂ O)	18.02	0–5%
Carbon dioxide (CO ₂)	44.01	380 ppm
Neon (Ne)	20.18	18 ppm
Helium (He)	4.00	5 ppm
Methane (CH ₄)	16.04	1.75 ppm
Krypton (Kr)	83.80	1 ppm
Hydrogen (H ₂)	2.02	0.5 ppm
Nitrous oxide (N ₂ O)	56.03	0.3 ppm
Ozone (O ₃)	48.00	0–0.1 ppm

- ▶ Water vapour accounts for 0.25% of the mass of the atmosphere
- ▶ Exposure to ozone **concentration>0.1 ppmv** is considered hazardous to human health
- ▶ Gas molecules with certain structures are highly effective in trapping outgoing radiation and are called **green house gases**
eg. CH₄, N₂O, CO, and chlorofluorocarbons (CFCs) - enter into the atmosphere via burning of plant matter, fossil fuels, emission from plants, decay of plants and animals etc.

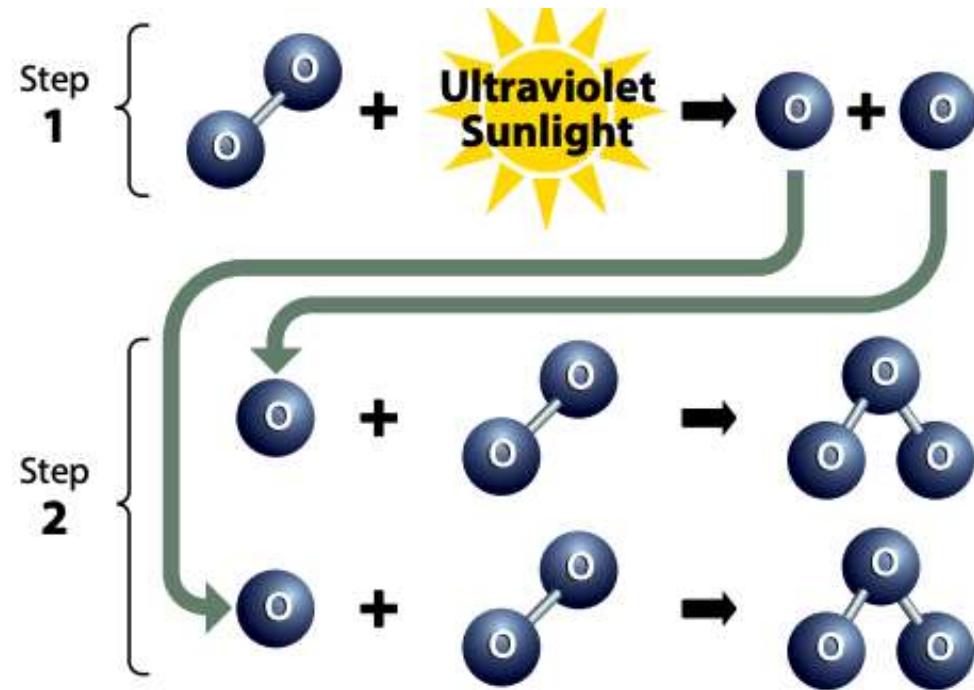
Vertical structure of atmosphere



Vertical structure



- Tropo-(turning or changing/vertical mixing) - sphere
- Temperature decreases with height ($\sim 6.5^\circ\text{C}$)
- Tropospheric air accounts for the 80% of the mass of the atmosphere
-
- Strato-(layered)-sphere, vertical mixing is prohibited due to the increase of temp with height
- Residence time of particles are longer
- Air is extremely dry and ozone rich
- They absorb the UV from the spectrum
- This increases the temperature
-
- Meso-(inbetween)-sphere: temperature decreases with height
-
- Thermosphere-temp increases with height due to the absorption of solar rad, and lots of ionization processes occurs



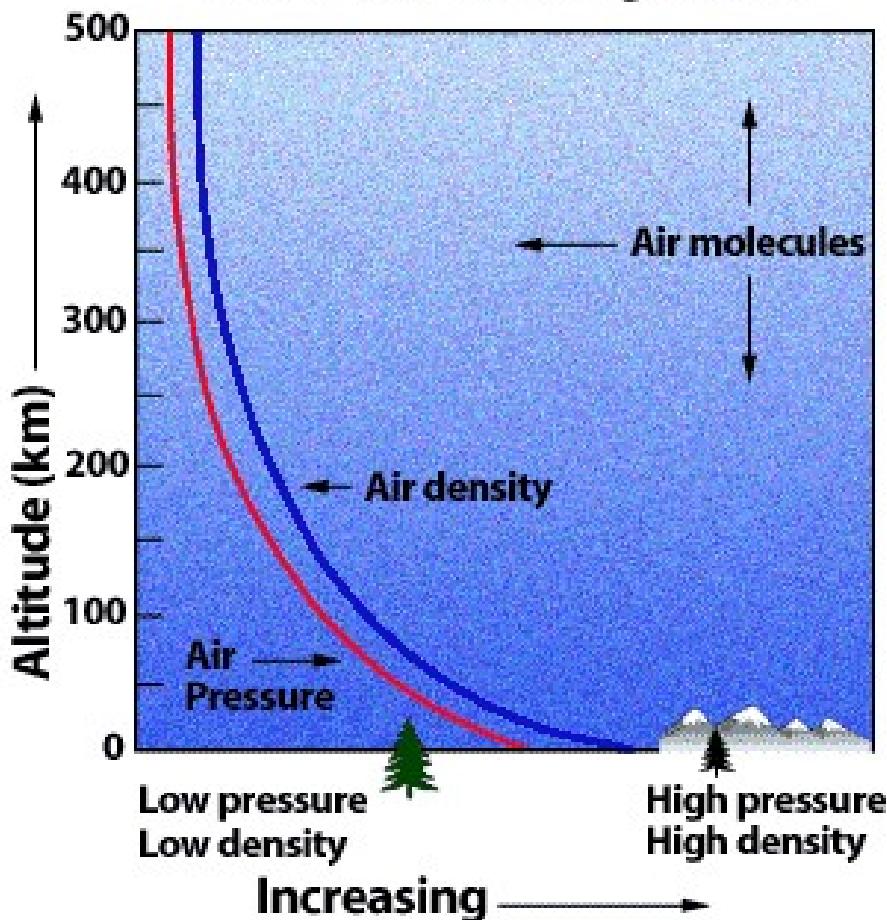
Ozone formation in stratosphere



Anvil cloud (Cloud flattening) at the tropopause

- All the weather and climate activities are under the tropopause

Both air pressure and air density decrease with increasing altitude.



Density of air @ sea level is
1.25 kg/m³

Pressure at any height:

$$p \approx p_0 e^{-z/H}$$

p_0 is the pressure @ sea level
(reference level)

H- scale height; e-folding
depth (height at which
pressure becomes 1/e times
 p_0), 7 to 8 Km

$$\ln \frac{p}{p_0} \approx -\frac{z}{H}$$

$$z = H \ln(p_0/p)$$

Exercise 2

- ▶ Assuming an exponential pressure and density dependence with $H=7.5$ km, estimate the heights in the atmosphere at which (a) the air density is equal to 1 kg/m^3 and (b) the height at which the pressure is equal to 1 hPa.

HW: Exercise 3

- ▶ At approximately what height above sea level does half the mass of the atmosphere lie above and other half lie below?

Assume an exponential pressure dependence with $H=8 \text{ km}$.

Climate change and its implications

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Lecture-2

1st lecture: Earth's Atmosphere

- ▶ Optical properties of Earth's atmosphere
- ▶ Mass of Earth's atmosphere
- ▶ Vertical structure of the atmosphere: troposphere, stratosphere, mesosphere, thermosphere
- ▶ Temperature, pressure, density variations in the atmosphere

Class outline: Introduction (Conti...)

Earth system components

- Oceans
- Cryosphere
- Biosphere
- Earth's crust and mantle

- ▶ Climate depends on atmosphere as well as physical, chemical, and biological processes involving other components of **earth system**

1. The Oceans



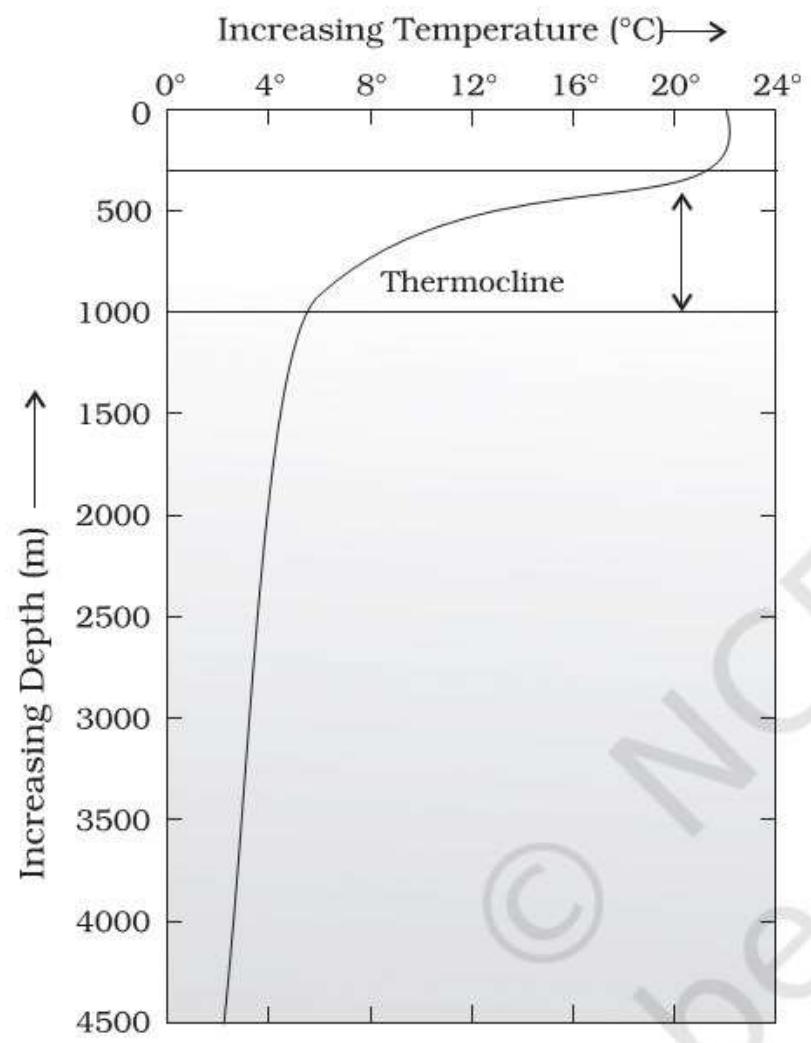
There are 5 Main Oceans
The Pacific Ocean is the largest ocean – by far!

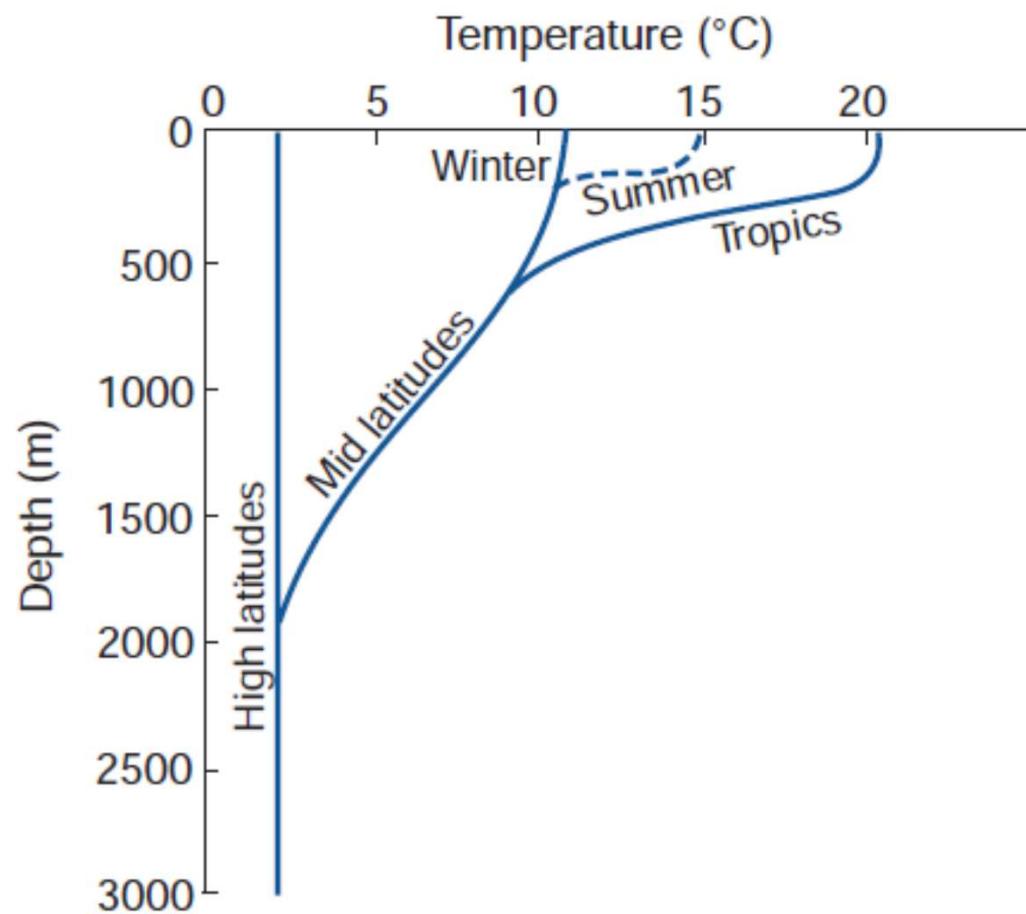
- ▶ Oceans cover 72% of the area of the earth's surface
- ▶ Reaches to an extreme depth of 11 km
- ▶ Mass of the ocean is approx. 250 times as that of atmosphere

Composition and vertical structure of ocean:

- ▶ Density of sea water linearly proportional to the concentration of dissolved salt
- ▶ Sea water contains salt ~34 -36 g/kg of fresh water
- ▶ Sea water is ~ 2.4% denser than fresh water @ same temperature







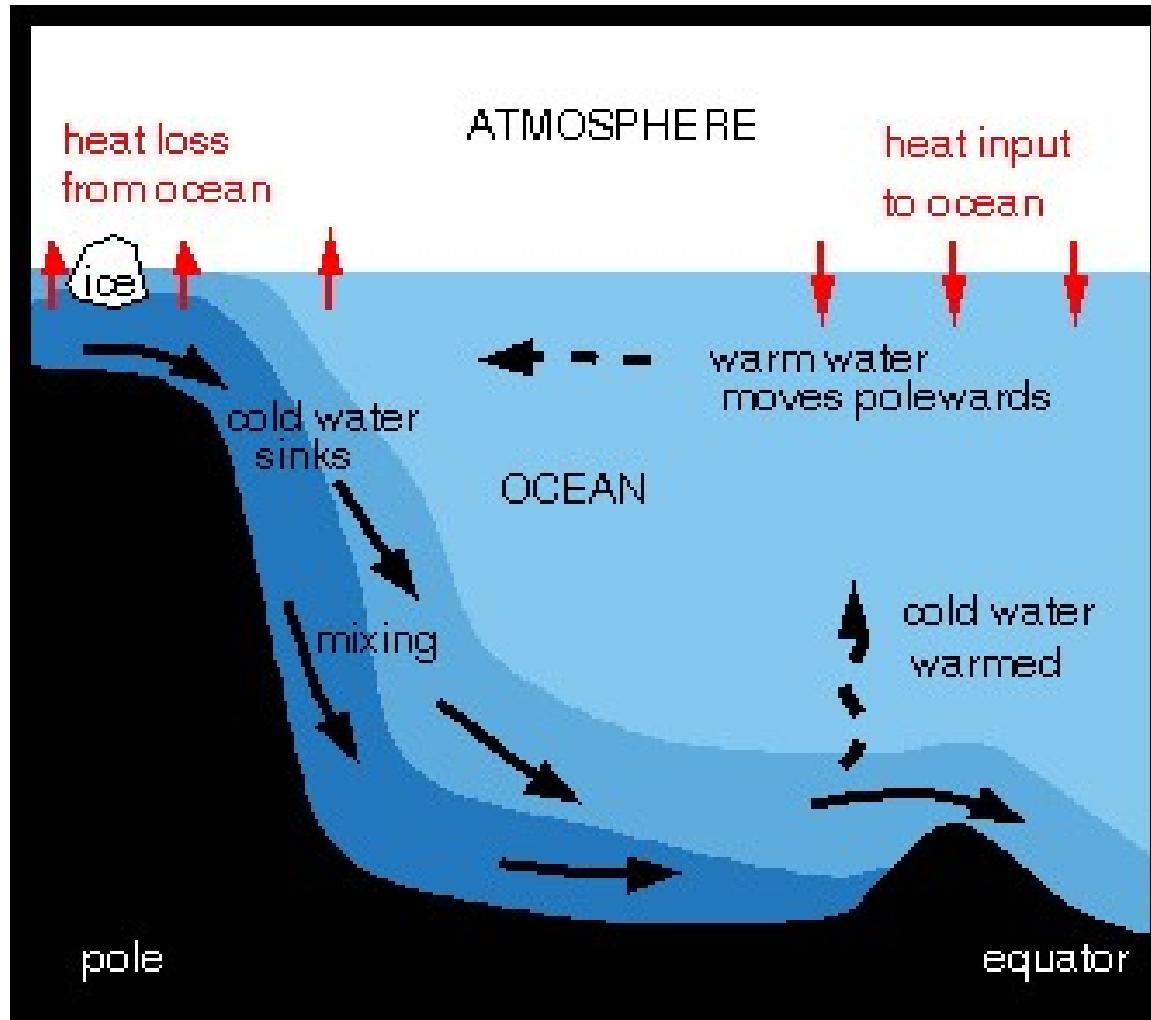
- ▶ The density of sea water ranges from 1.02 to 1.03 kg/m^3
- ▶ Density of water in the wind-stirred layer (**mixed layer**) is smaller by a few tenths of a percent than density of water below it
- ▶ **Thermocline:** Layer in which there is a strong temperature gradient exist with respect to depth

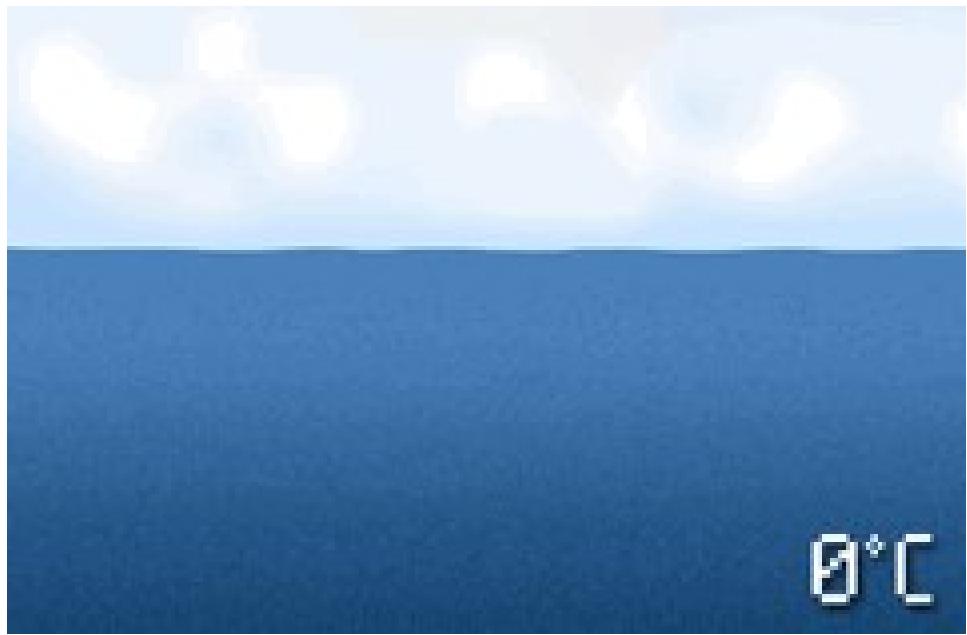
- ▶ Precipitation lowers the salinity by diluting the salts that are present in the oceanic mixed layer
- ▶ But evaporation increases the salinity by removing fresh water and thereby concentrating the residual salts

Exercise-1

- ▶ A heavy tropical storm dumps 20 cm of rainfall in a region of the ocean in which the salinity is 35 g kg^{-1} and the mixed layer depth is 50 m. Assuming that the water is well mixed, by how much does the salinity decrease?

Ocean circulation

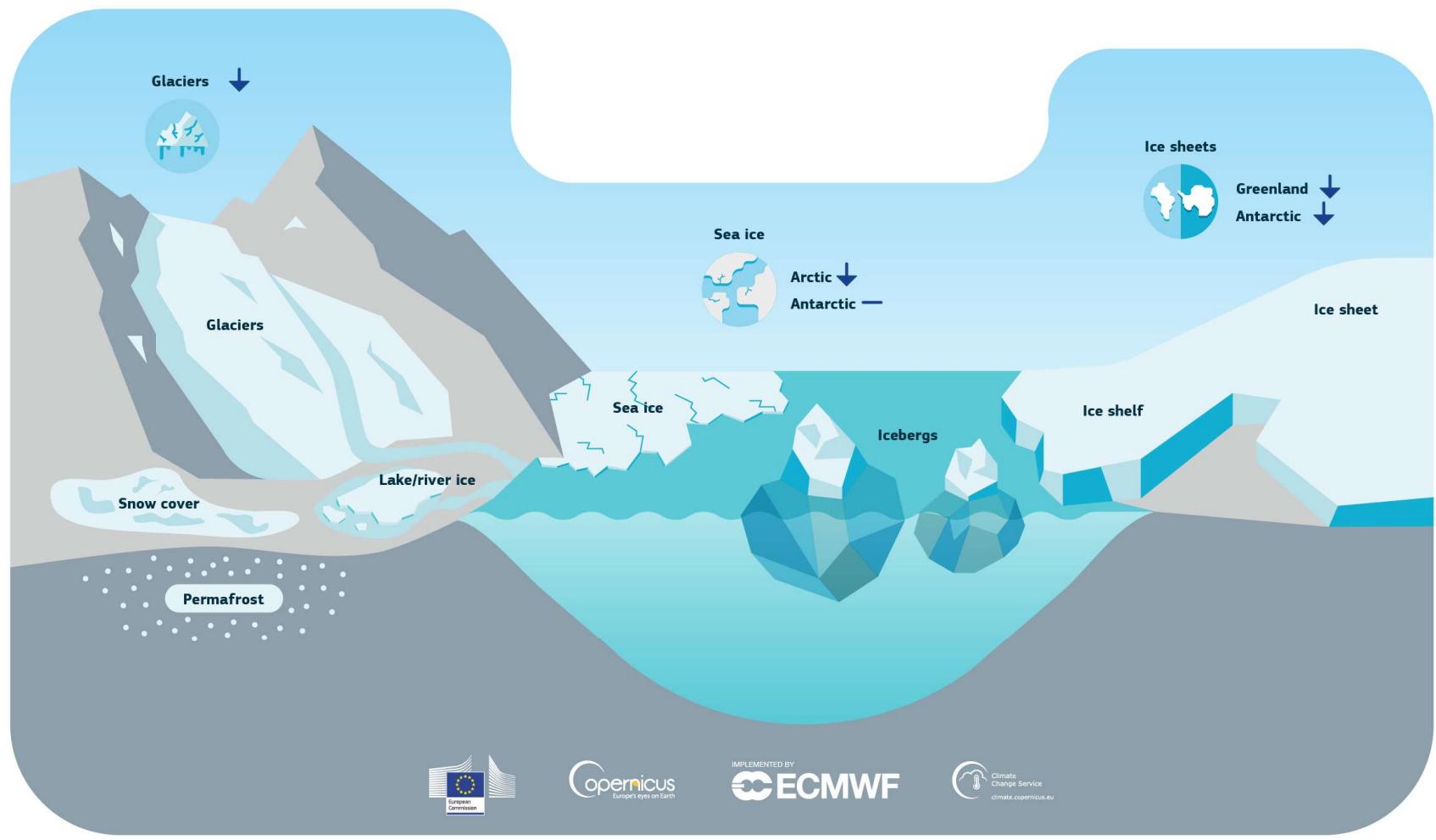




Ocean circulation

- ▶ The ocean circulation is composed of a **wind-driven** component and a **thermohaline** (density-dependent) component
- ▶ The wind driven circulation dominates the surface currents, and it is restricted to the topmost few hundred meters
- ▶ The circulation deeper in the oceans is dominated by the slower thermohaline circulation
- ▶ Velocities in wind driven currents are on the order of 10 cm/s
- ▶ The timescale in which a parcel completes a circuit of this thermohaline circulation is on the order of hundreds of years

2. Cryosphere



- ▶ Cryo (frozen)-sphere refers to the components of the earth system comprised of water in its solid state
- ▶ Taking up and releasing fresh water in the polar regions and influences oceanic thermohaline circulation
- ▶ It stores enough water to significantly influence global sea level
- ▶ The continental ice sheets dominated by Antarctica and Greenland are the most massive elements of the cryosphere
- ▶ Ice sheets are replenished by snowfall

Cryospheric component	Area	Mass
Antarctic ice sheet	2.7	53
Greenland ice sheet	0.35	5
Alpine glaciers	0.1	0.2
Arctic sea ice (March)	3	0.04
Antarctic sea ice (September)	4	0.04
Seasonal snow cover	9	<0.01
Permafrost	5	1

Area is expressed in percentage of the area of the surface of Earth; Mass is expressed in 10^3 kg/m^2

Total surface area of Earth (m^2)= 5.12×10^{14}

Land area (m^2)= 1.45×10^{14}

- ▶ Permafrost is any ground that remains completely frozen (0°C) or colder—for at least two years straight
- ▶ These permanently frozen grounds are most common in regions with high mountains and in Earth's higher latitudes—near the North and South Poles



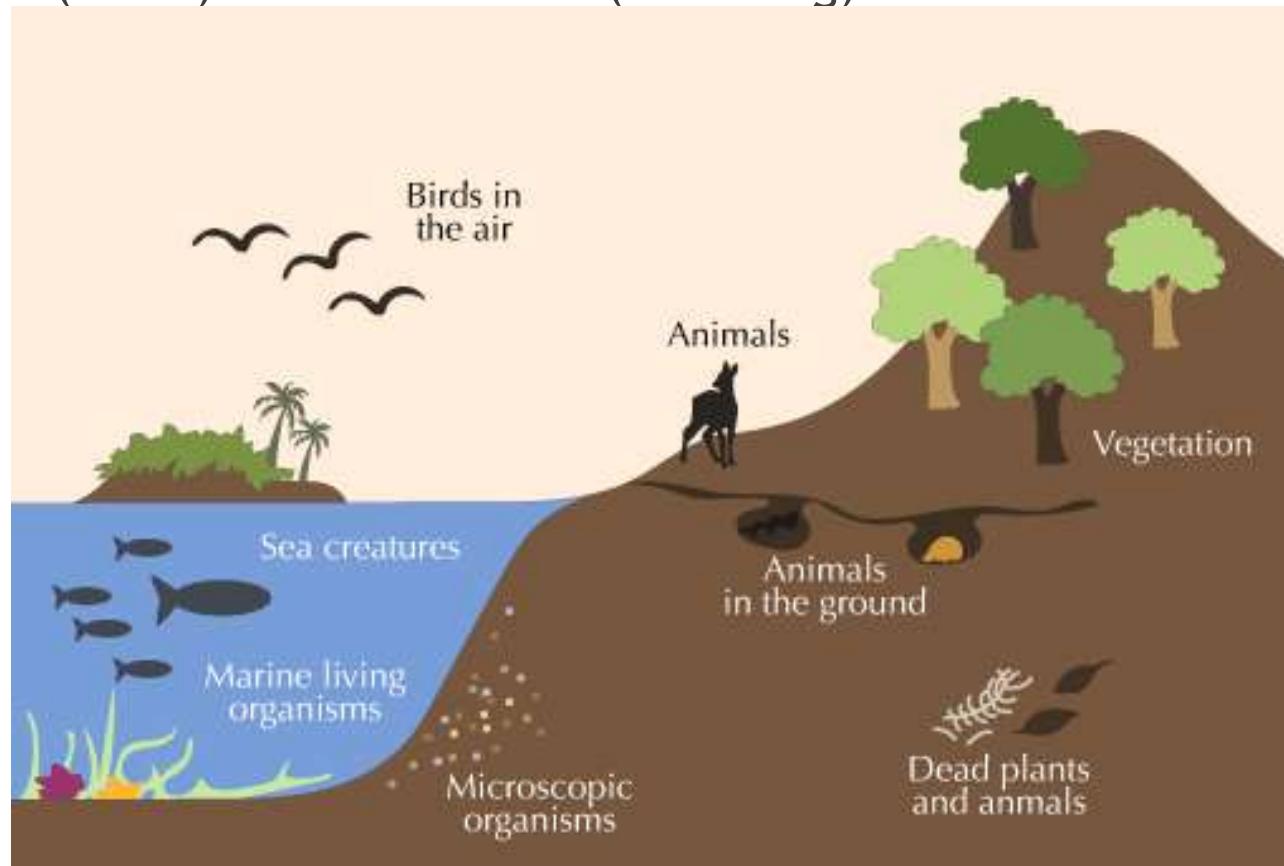
Exercise-2

Estimate how much the sea level would rise if the entire Arctic ice sheet were to melt.
Area covered by Arctic sea ice is 3% of the area of the surface of the Earth, land area
is 29.5% of the surface of Earth. [Earth's radius=6371 km; mass of Artic ice
sheet= 0.04×10^3 kg/m²]

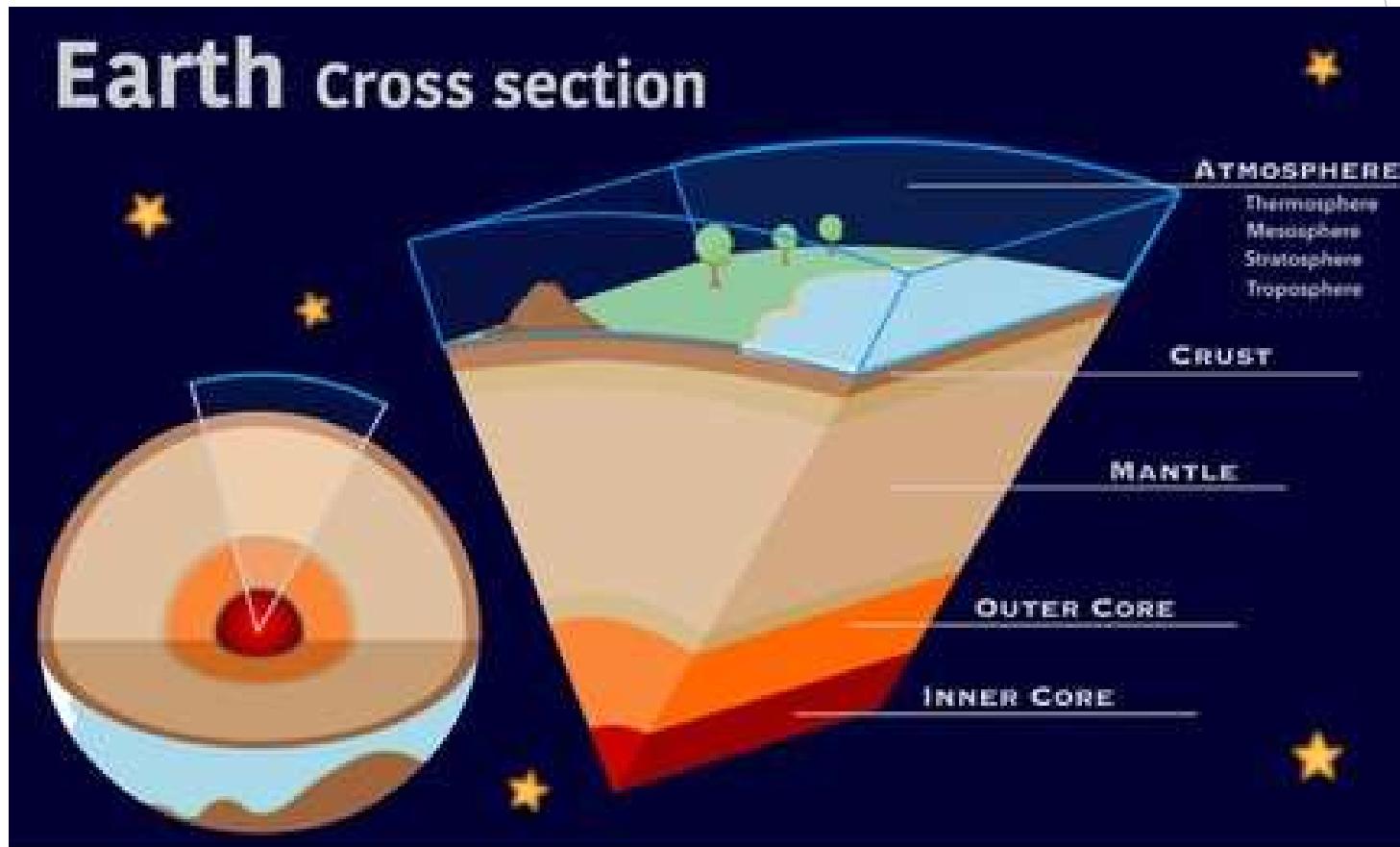
Estimate how much the sea level would rise if the entire permafrost were to melt.
Area covered by permafrost is 5% of the area of the surface of the Earth, land area is
28.5% of the surface of Earth. [Earth's radius=6371 km; mass of Artic ice sheet= 1×10^3
kg/m²]

3. Biosphere

- ▶ The biosphere is a global ecosystem composed of living organisms (biota) and the abiotic (nonliving) factors



4. Earth's crust and mantle





Climate Change And Its Implications (CCI)

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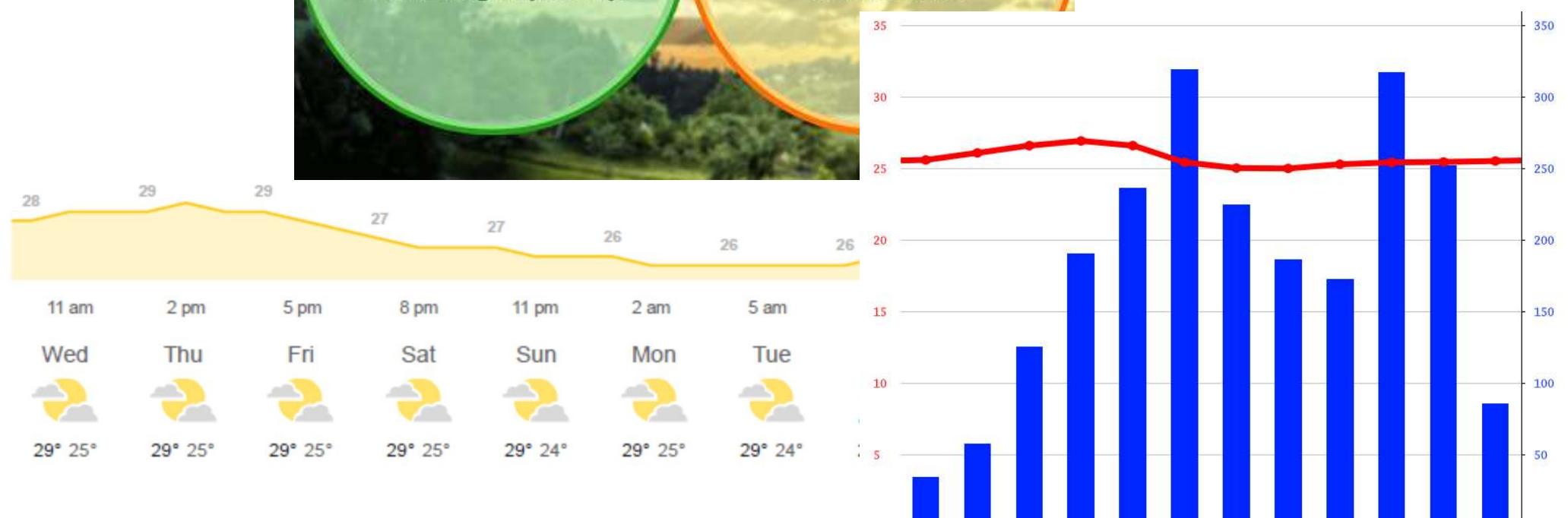
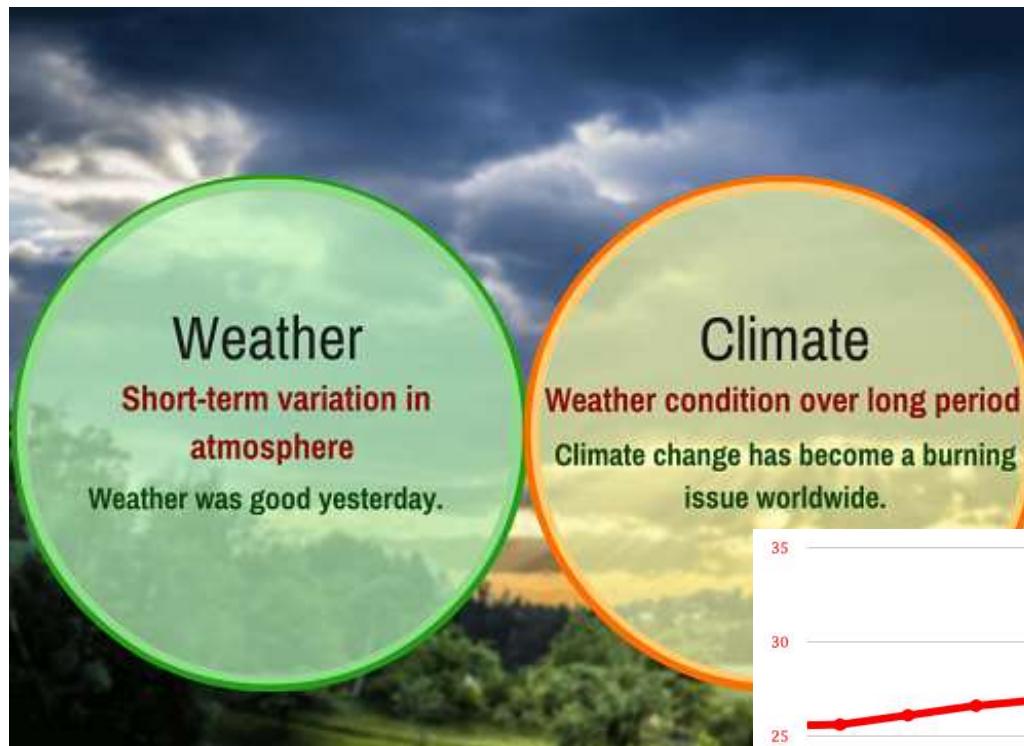
Lecture-3

Lecture-1&2

- Earth's atmosphere
- Oceans
- Cryosphere
- Biosphere
- Earth's crust and mantle

Class outline

- Introduction to weather & climate
- Weather parameters
- Measurements of weather parameters

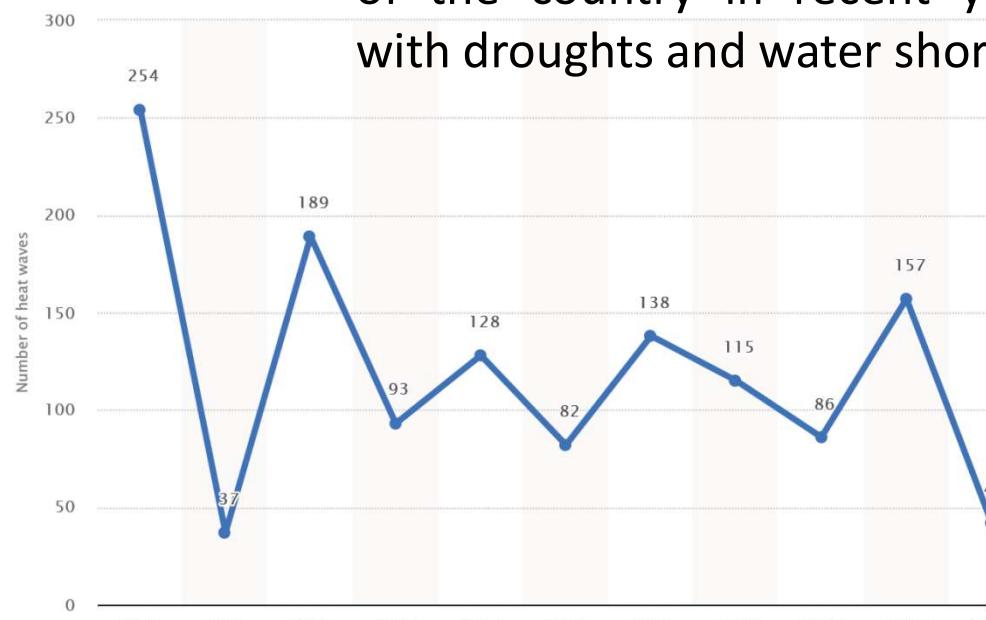
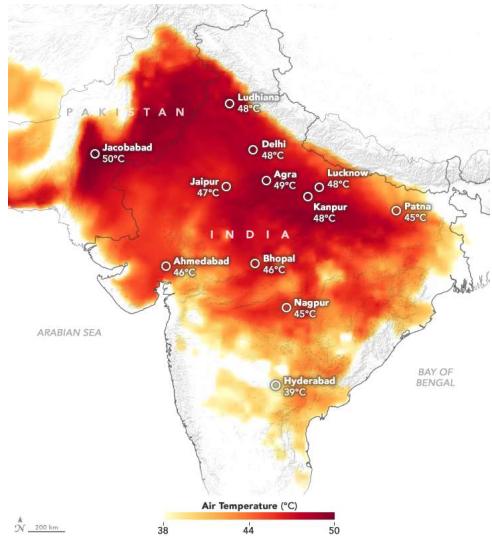


Weather & Climate

- Weather is the state of the atmosphere experienced at a given time
- It is defined by variables such as temperature, wind, rainfall, pressure, and other dynamical variables –Meteorology
- Climate is the averages of weather elements obtained from their time series for a location or any region
- Climate refers to the monthly, seasonal or annual mean distributions of temperature, rainfall or any other weather parameter
- Any change in the incoming and outgoing radiations would affect its climate

Where do we use weather information?

Heat waves

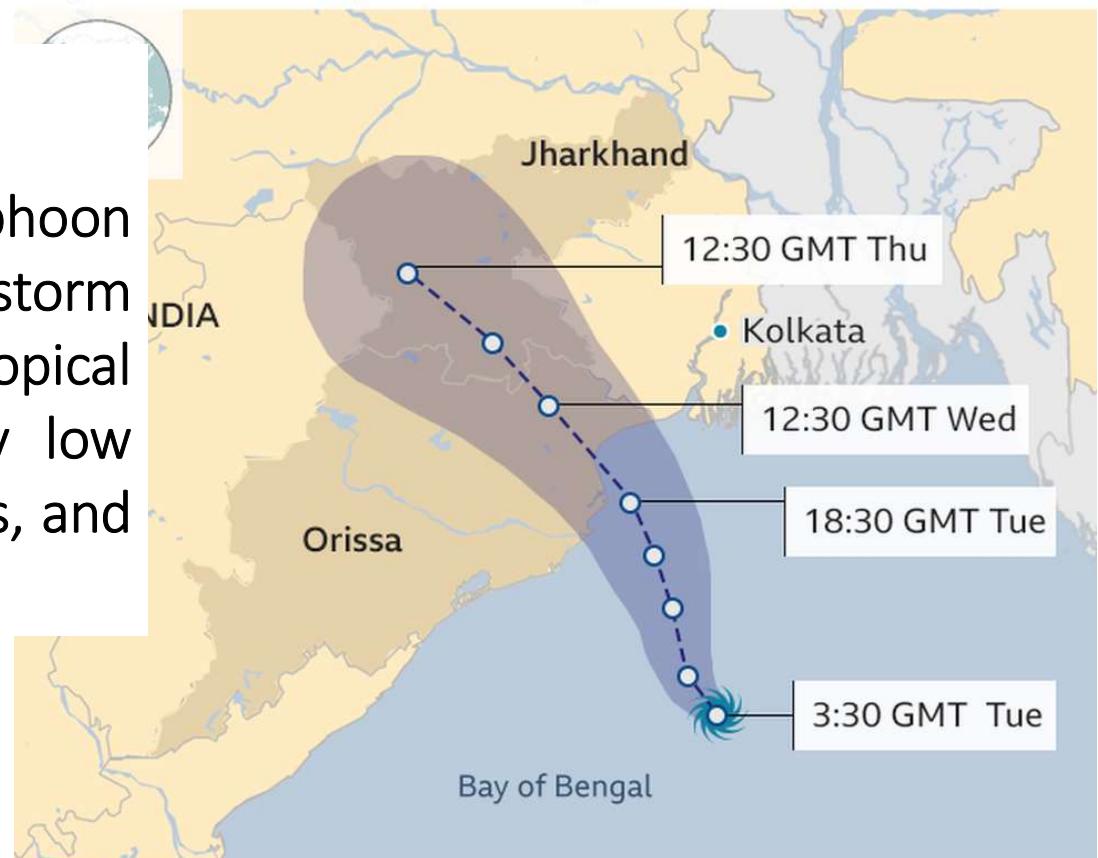


- Heat wave is considered if maximum temperature of a station reaches at least 40°C or more for Plains and at least 30°C or more for Hilly regions.
- About 42 heat wave days are reported in India in 2020
- These are more intense in northern regions of the country in recent years, coinciding with droughts and water shortage

Tropical cyclones

- Tropical cyclone, also called typhoon or hurricane, an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain

Cyclone Yaas predicted path



Source: Indian Meteorological Department

BBC

Extreme rainfall



Tornadoes

- A tornado is a narrow, violently rotating column of air that extends from a thunderstorm to the ground





Weather Parameters

Temperature

- Maximum and minimum temperatures (most important for agriculture)
- Average temperature
- Diurnal temperature

Measurements: Thermometers



Stevenson's screen



Dry Bulb Thermometer

Minimum Temperature Thermometer

Maximum Temperature Thermometer

Wet Bulb Thermometer

Satellite measurements



- Satellite measures the atmosphere in radiance (W/m^2), and then using mathematical and statistical equations, temperature is derived from this

INSAT-3D is a meteorological, data relay and satellite aided search and rescue satellite developed by the Indian Space Research Organisation (in 2013)

Precipitation

Hail



Sleet



Rain



Glaze



Snow



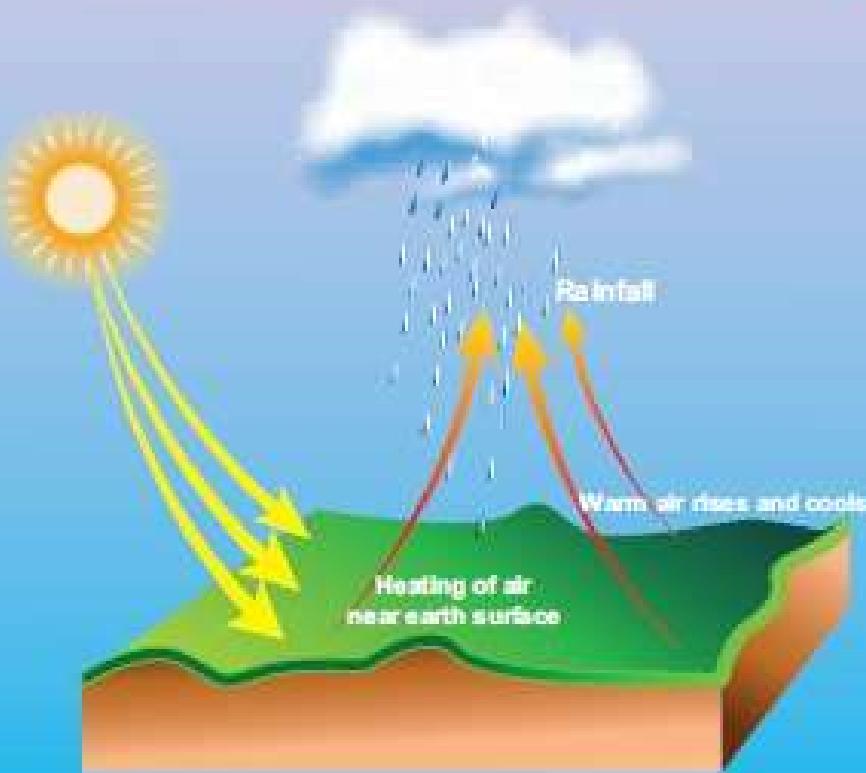
Forms of precipitation

- **Rain** – It is the main form of precipitation with water drop size >0.5 mm
- **Snow** – Ice crystals, which combines to form flakes
- **Drizzle**-Fine sprinkle of numerous water droplets of size <0.5 mm
- **Glaze**- when rain or drizzle comes in contact with cold ground at 0°C, the water drops freeze to form an ice coating called freezing rain
- **Sleet** – frozen raindrops forms when rain falls through air at subfreezing temperature
- **Hail** – precipitation in the form of ice crystals of size >8 mm

Weather systems for precipitation

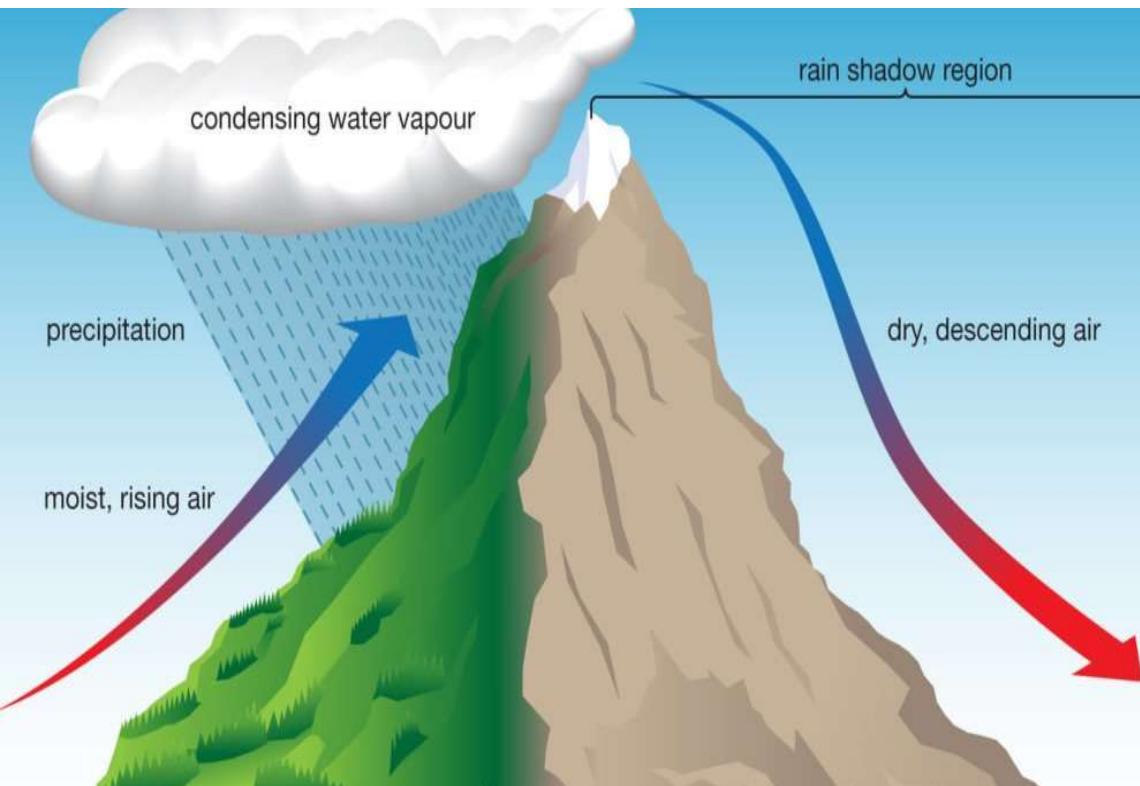
Convective precipitation

Convectional rainfall



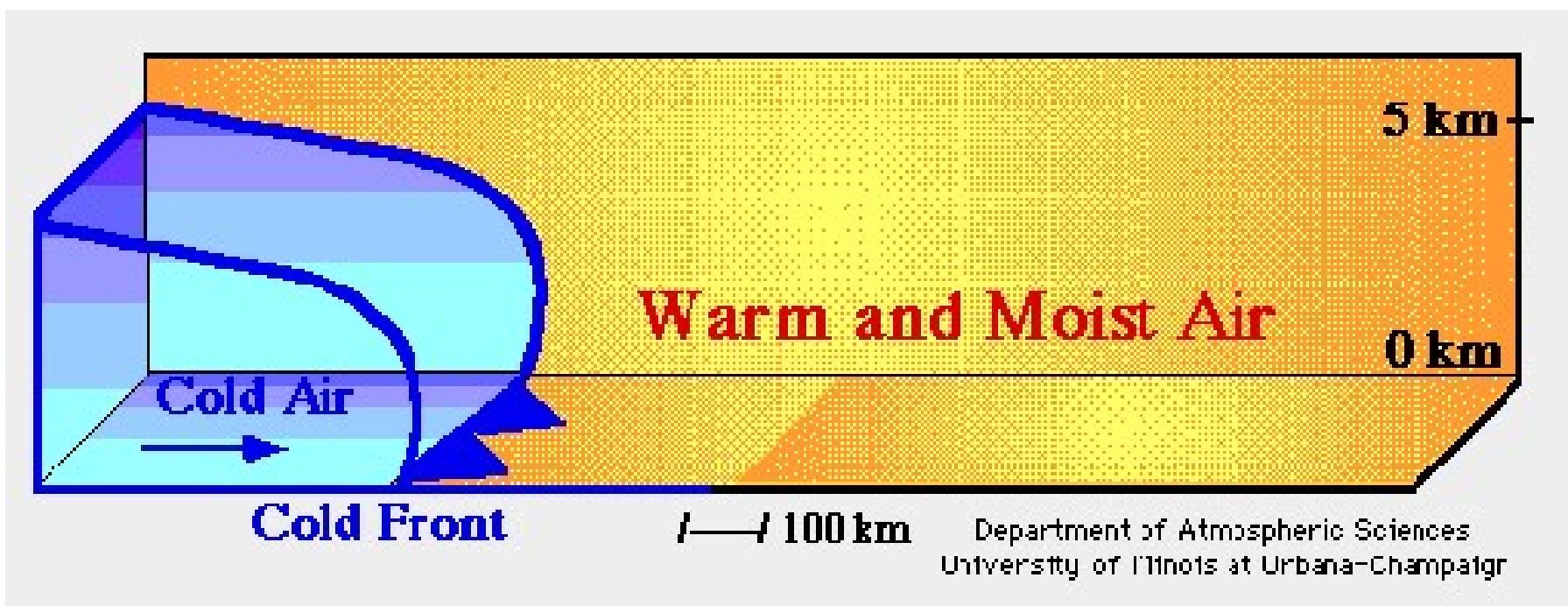
- On a hot day the ground surface becomes heated, as does the air in contact with it
- This causes the air to rise, expand, and cool dynamically, causing condensation and precipitation

Orographic precipitation



- Lifting an air mass occurs when air flows up and over a topographic feature such as a mountain barrier
- Orographic barriers often supply the lift to set off precipitation
- For this reason, precipitation is heavier on windward slopes, with rain shadows (areas of lighter precipitation) on leeward slopes
- Orographic precipitation is associated with low intensity with relatively long durations

Precipitation along cold front: A cold front is defined as the transition zone where a cold air mass is replacing a warmer air mass



Characteristics of precipitation in India

1) South-West Monsoon (June-September)

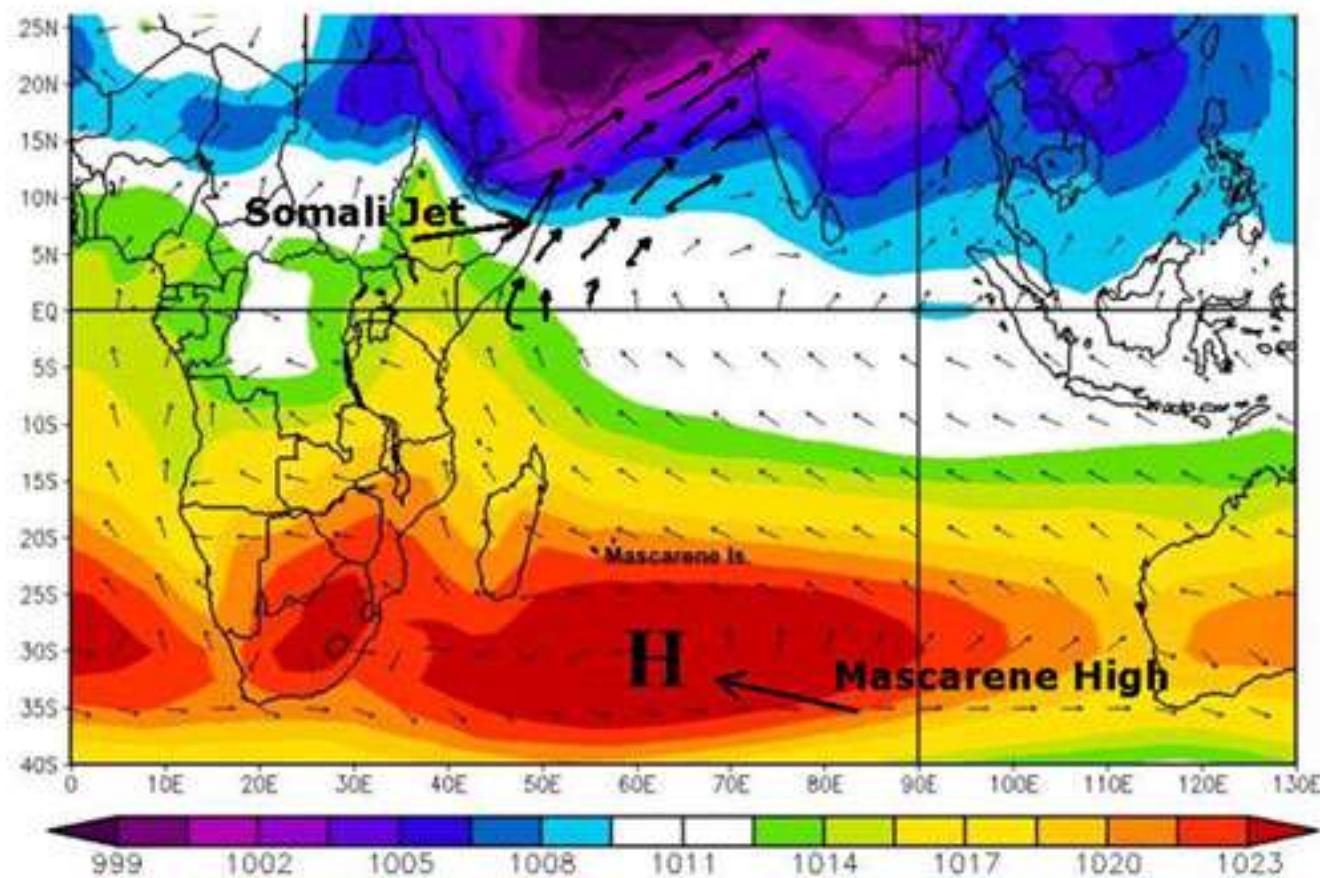
- It originates in Indian ocean
- Receives 75% of annual rainfall
- Starts from Kerala, and extends towards all states except Tamil Nadu and Jammu & Kashmir

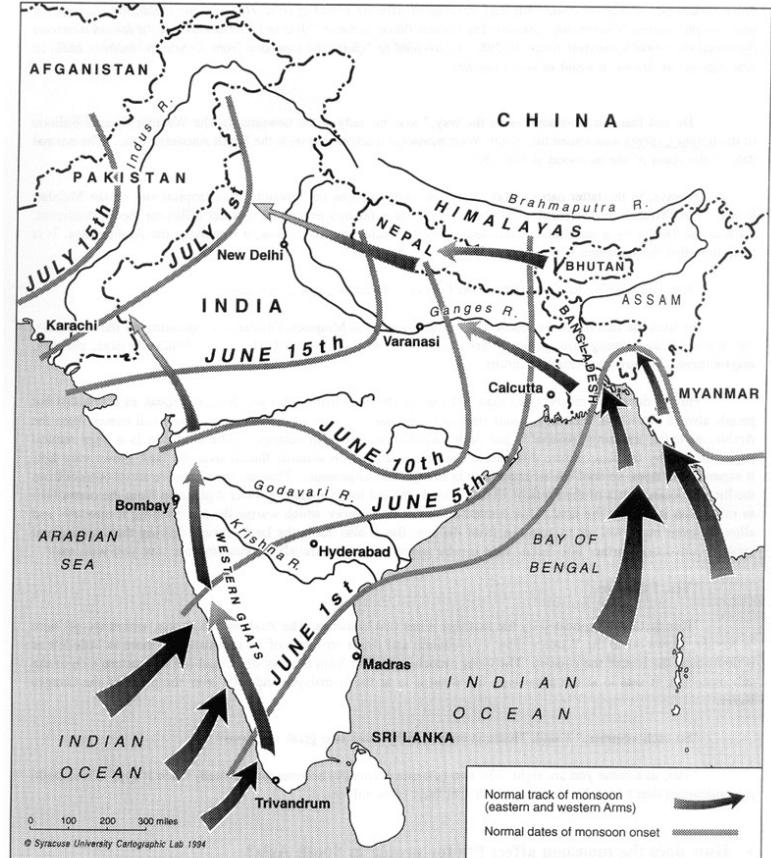
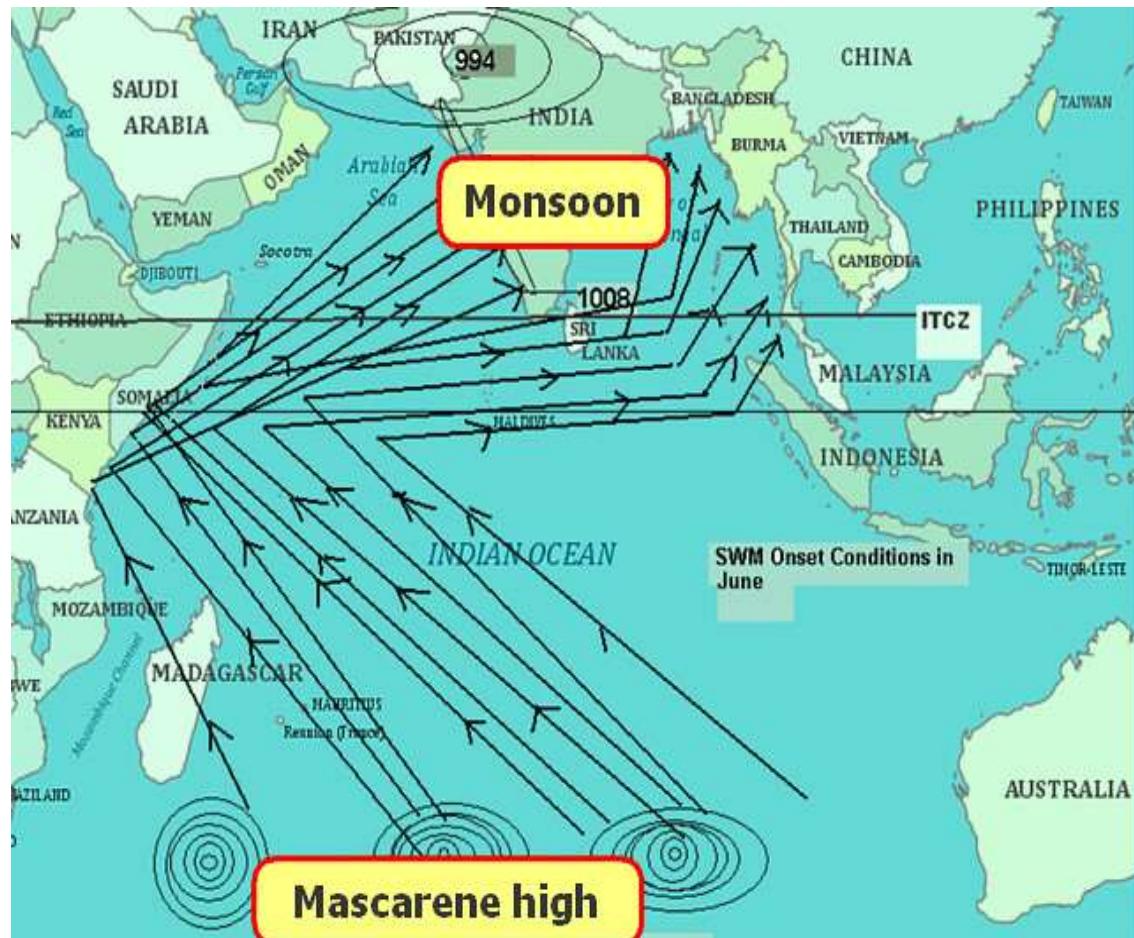
2) Post-Monsoon or NE Monsoon (October-November)

- It mainly strikes the east coast of Southern Peninsula (Tamil Nadu)

3) Pre-Monsoon (March-May)

Indian monsoon and its friends





ITCZ-Inter Tropical Convergence Zone: The region that circles the Earth, near the equator, where the trade winds of the Northern and Southern Hemispheres come together

- The **Mascarene High** (MH) is a semi-permanent subtropical high-pressure zone in the South Indian Ocean
- A trough extends from this low over Pakistan (994 hPa) to Head Bay with strong pressure gradient to the south. This trough is often referred to as the ‘monsoon trough’.

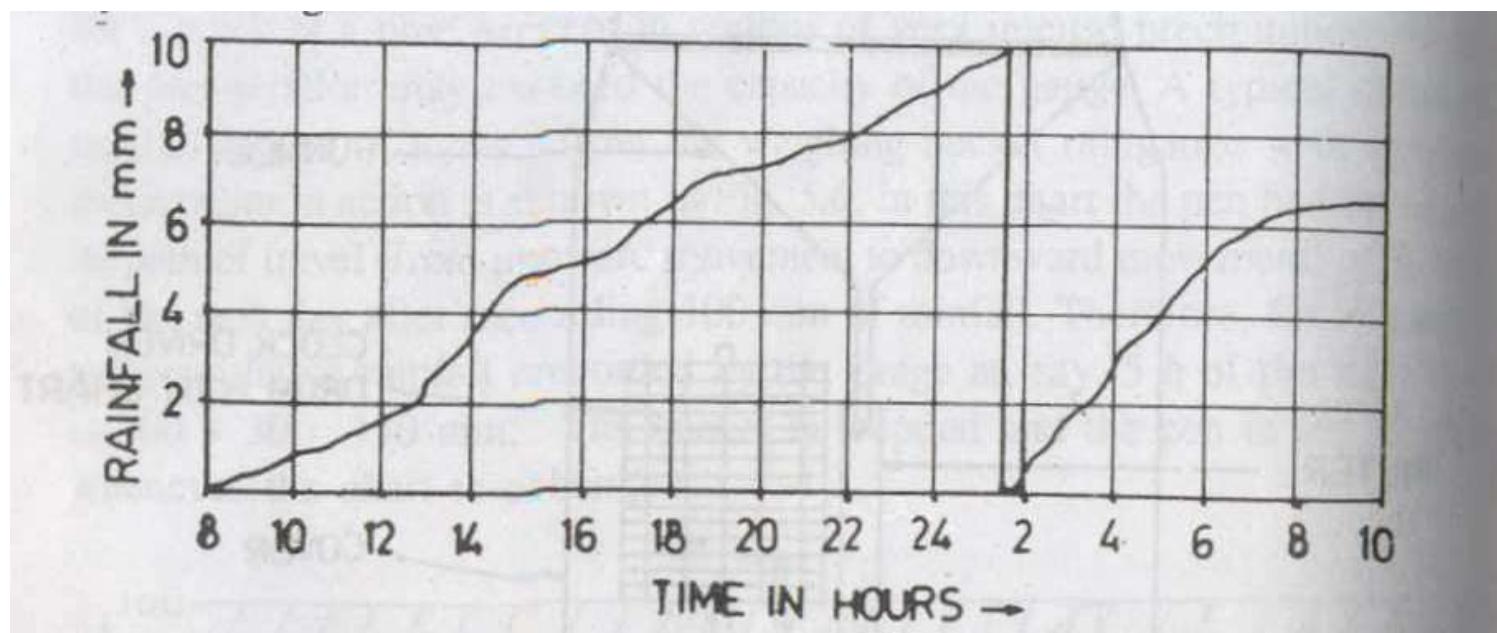


Measurement of rainfall

- Rainfall is expressed in terms of depth (mm)
- Rainfall is measured using rain gauges: Recording & non-recording gauges
- Radar/satellite measurement

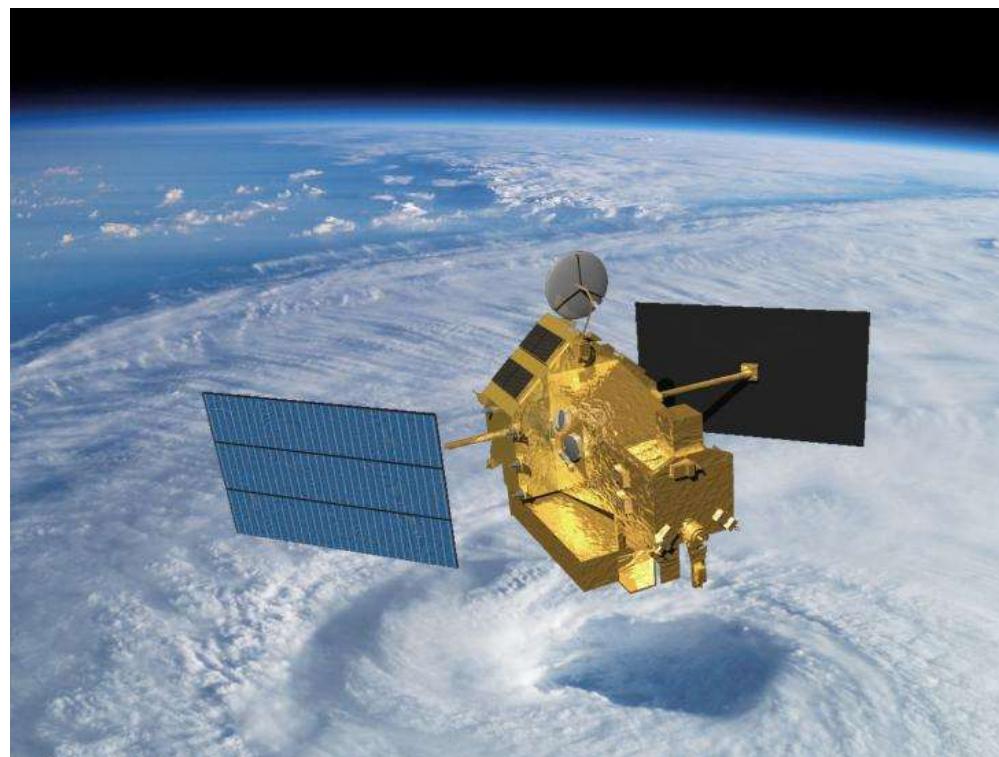
Rain gauges





Rain gauge chart

Tropical Rainfall Measuring Mission (TRMM)-1997



- A joint space mission between NASA and the Japan Aerospace Exploration Agency JAXA designed to monitor and study tropical rainfall

Solar radiation

Meaurement (W/m^2)

- **Pyranometer**: It is designed to measure the solar radiation flux density (W/m^2) from the hemisphere above within a wavelength range $0.3 \mu\text{m}$ to $3 \mu\text{m}$
- **Satellite**



Meteorological observatories

IMD (Indian Meteorological Department)

<http://weather.uwyo.edu/upperair/sounding.html>- University of Wyoming

<https://power.larc.nasa.gov/data-access-viewer/>- NASA Power data

Climate Change And Its Implications (CCI)

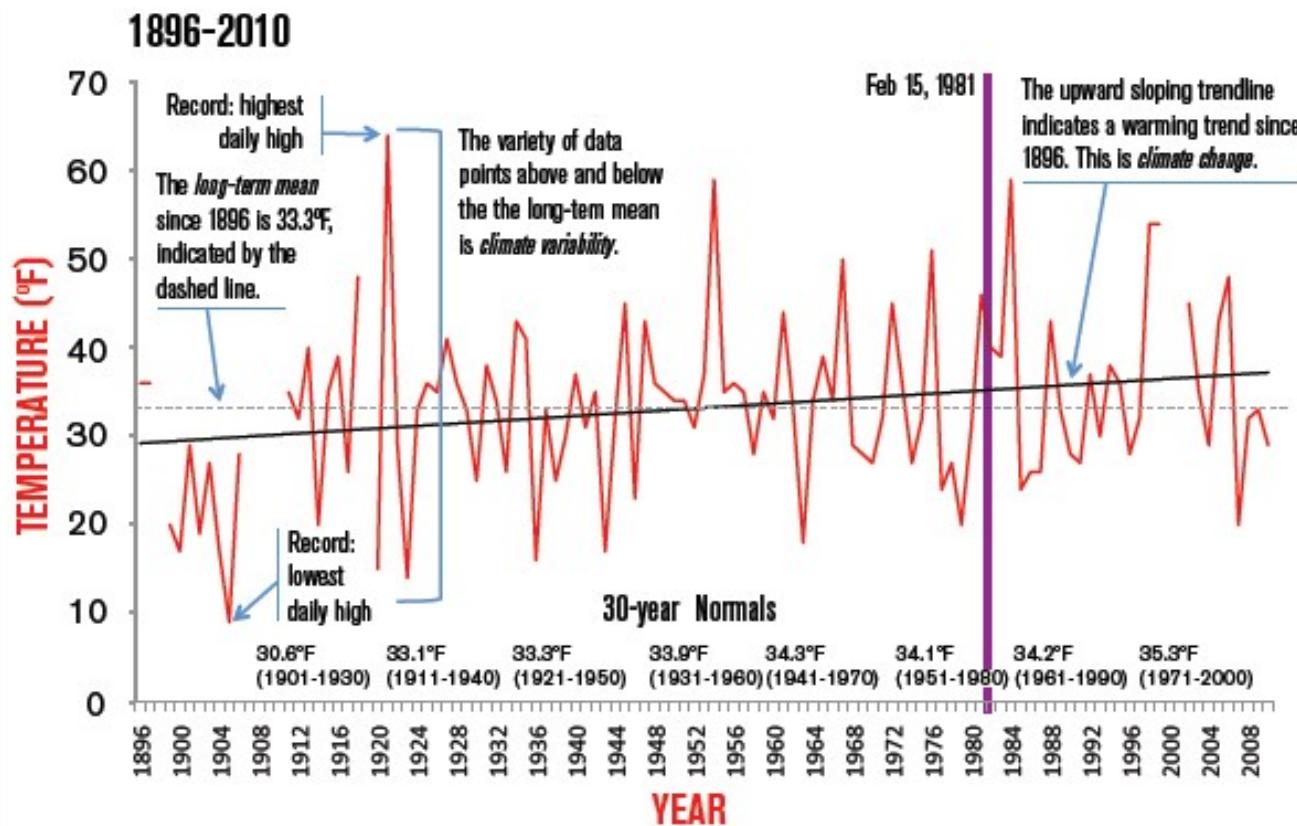
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Lecture-4

Class outline

- Climate variability and climate change
- Reasons for climate variability & change

Climate Variability & Climate Change



- Climate varies over seasons and years instead of day to day like weather
- Some summers are colder than others and some years precipitations are higher than others
- **Climate variability:** The way the climate fluctuates yearly above or below a long term average
- **Climate change:** Long term continuous change to average weather conditions
- Climate change is slow and continuous unlike variability

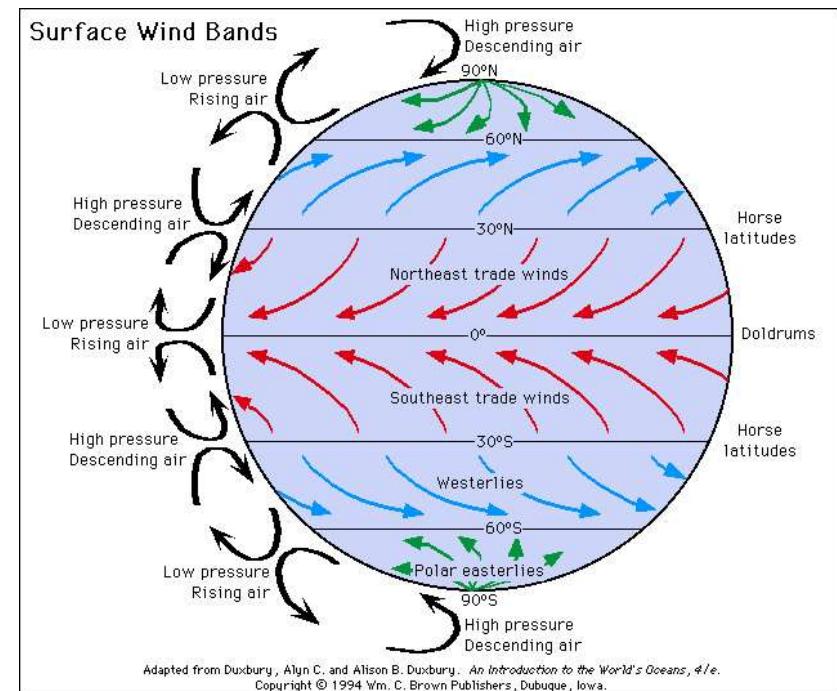
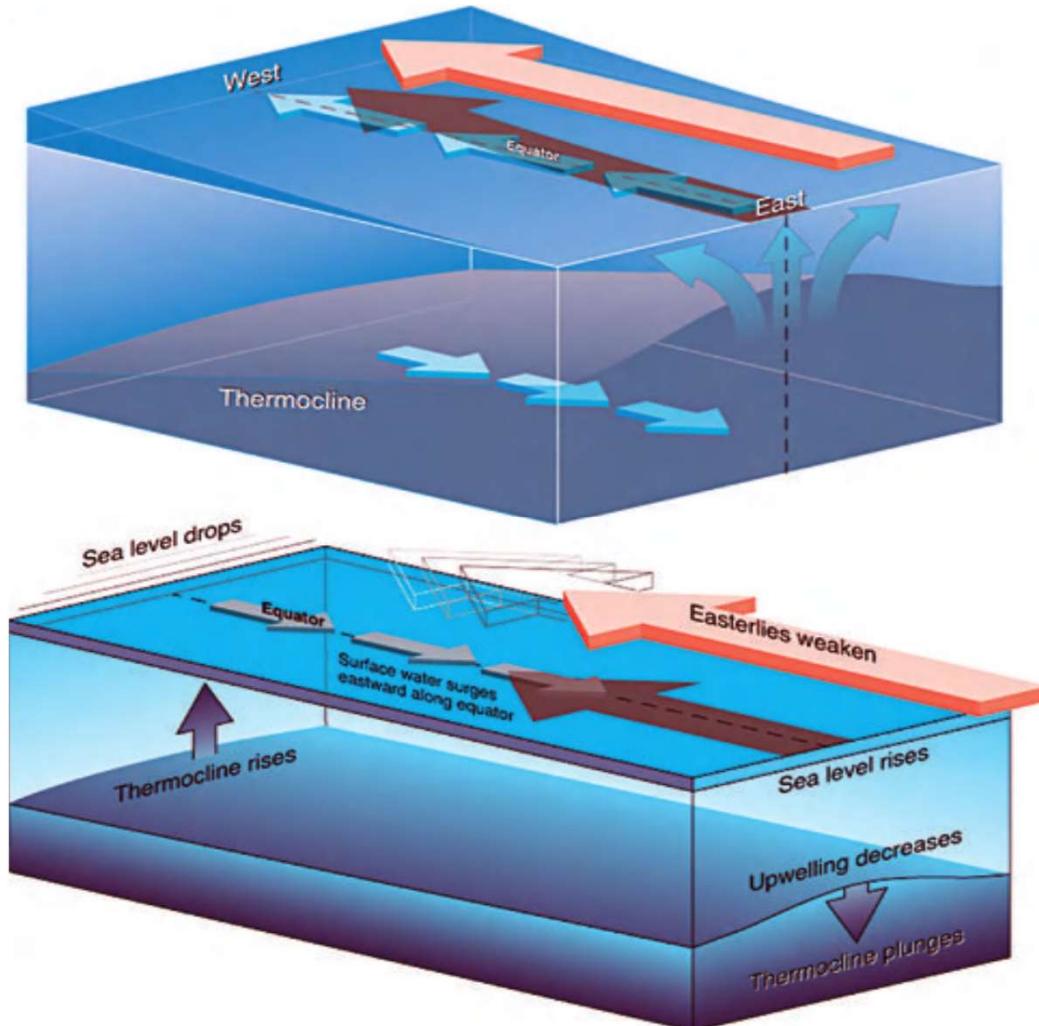
Assignment-1

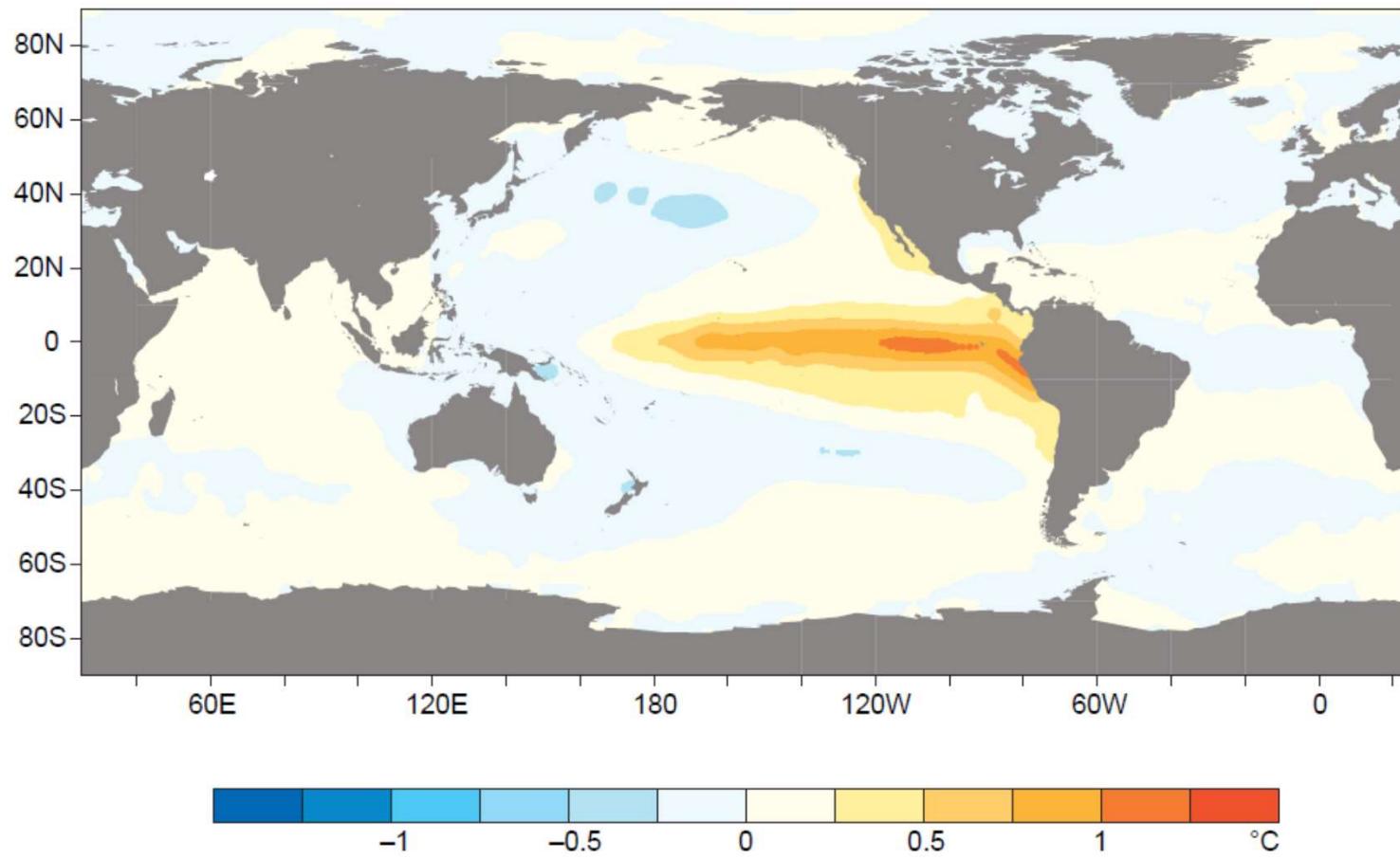
- Identify the trend in temperature and rainfall in your location from the historical data.

Download the data from 1980 to 2020 (30 years daily data) from **NASA Power data (<https://power.larc.nasa.gov/data-access-viewer/>)**

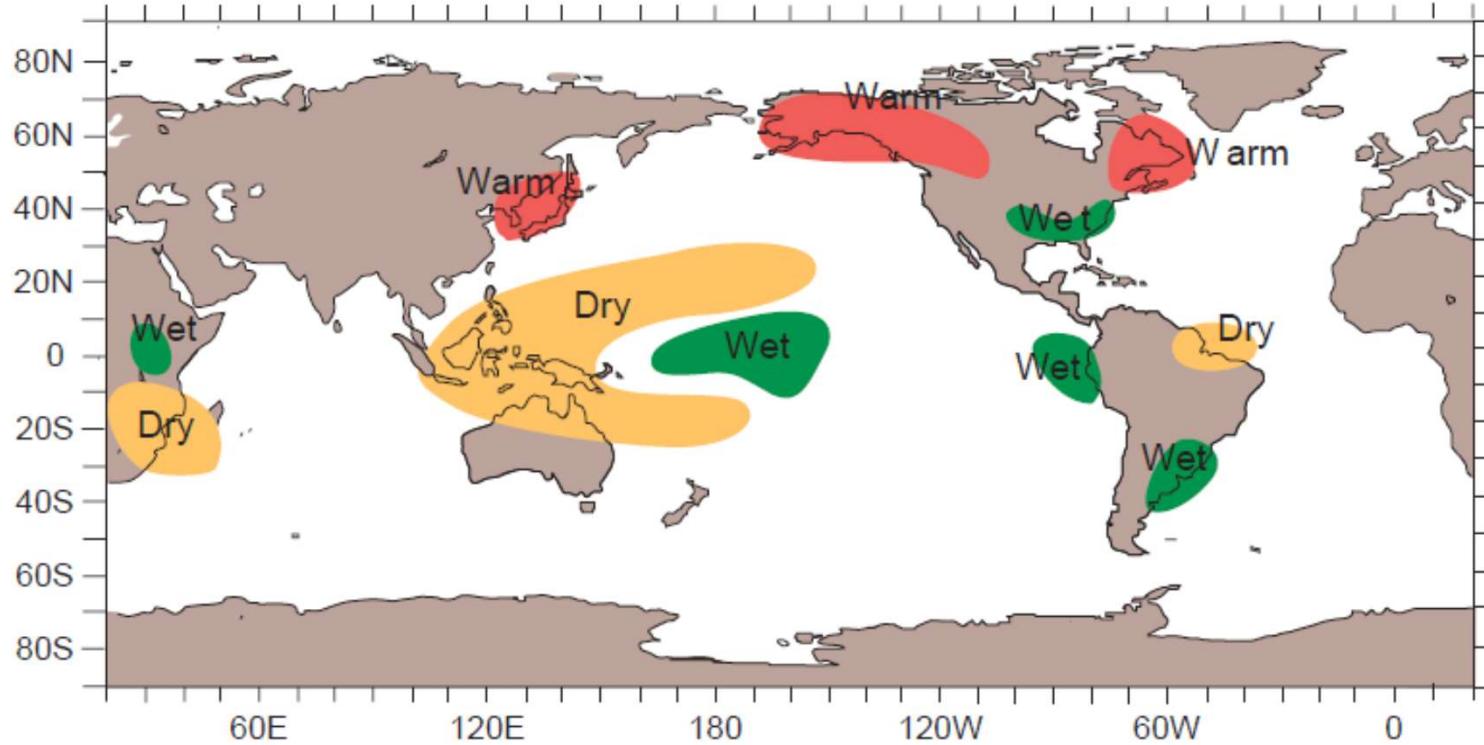
Submission due date: [10.02.2022](#)

General circulation of the atmosphere

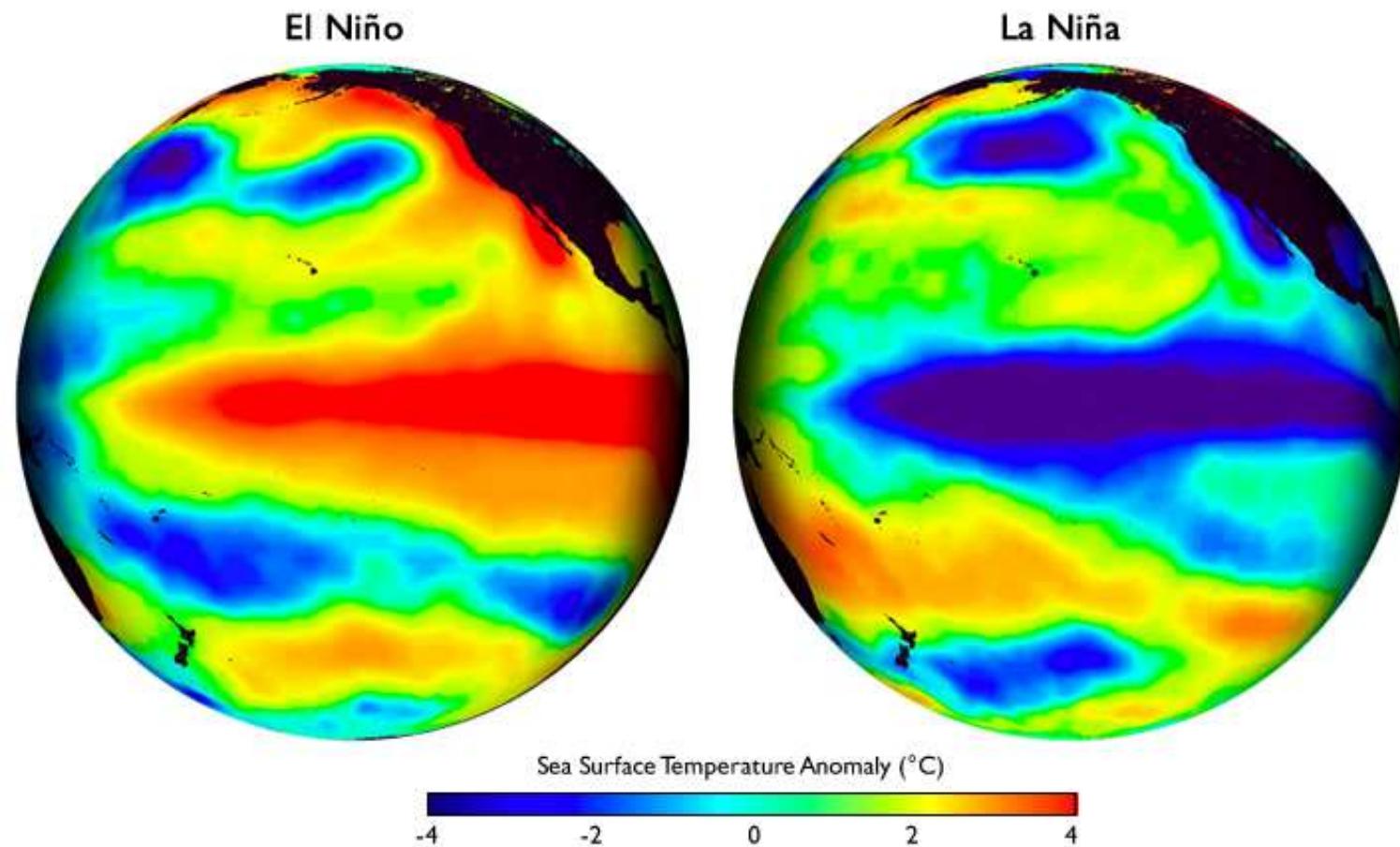




Global pattern of sea surface temperature ($^{\circ}\text{C}$) anomalies observed during El Niño years

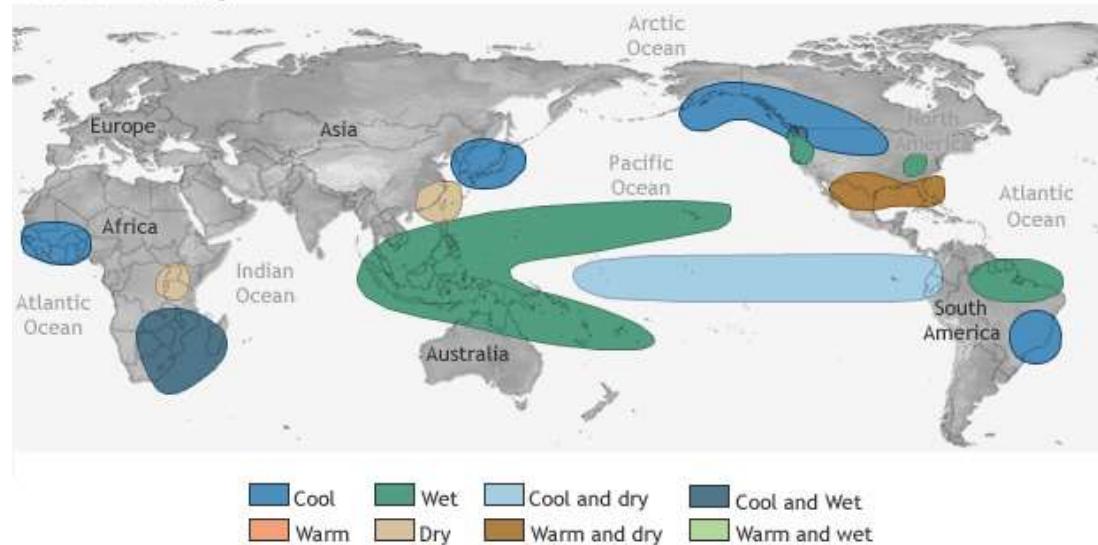


Impacts of El Niño on weather and climate

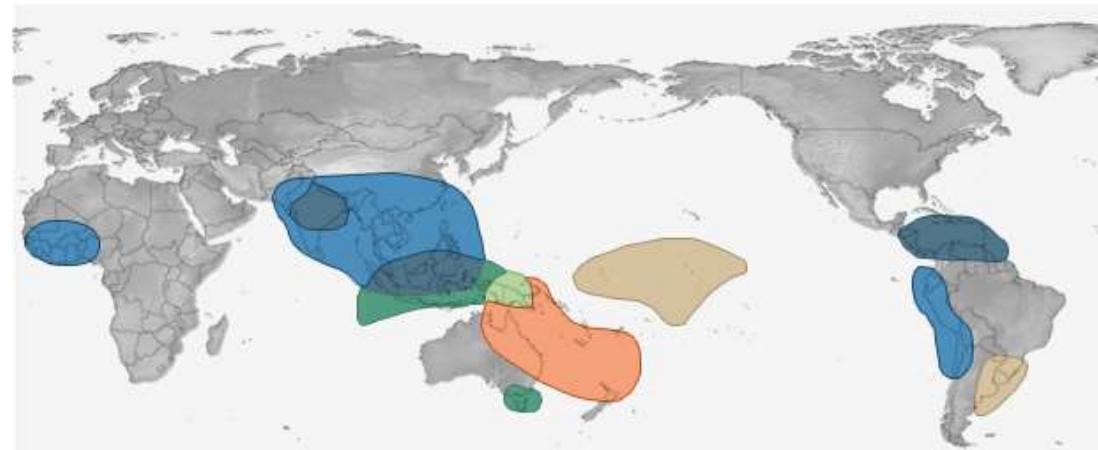


LA NIÑA CLIMATE IMPACTS

December-February



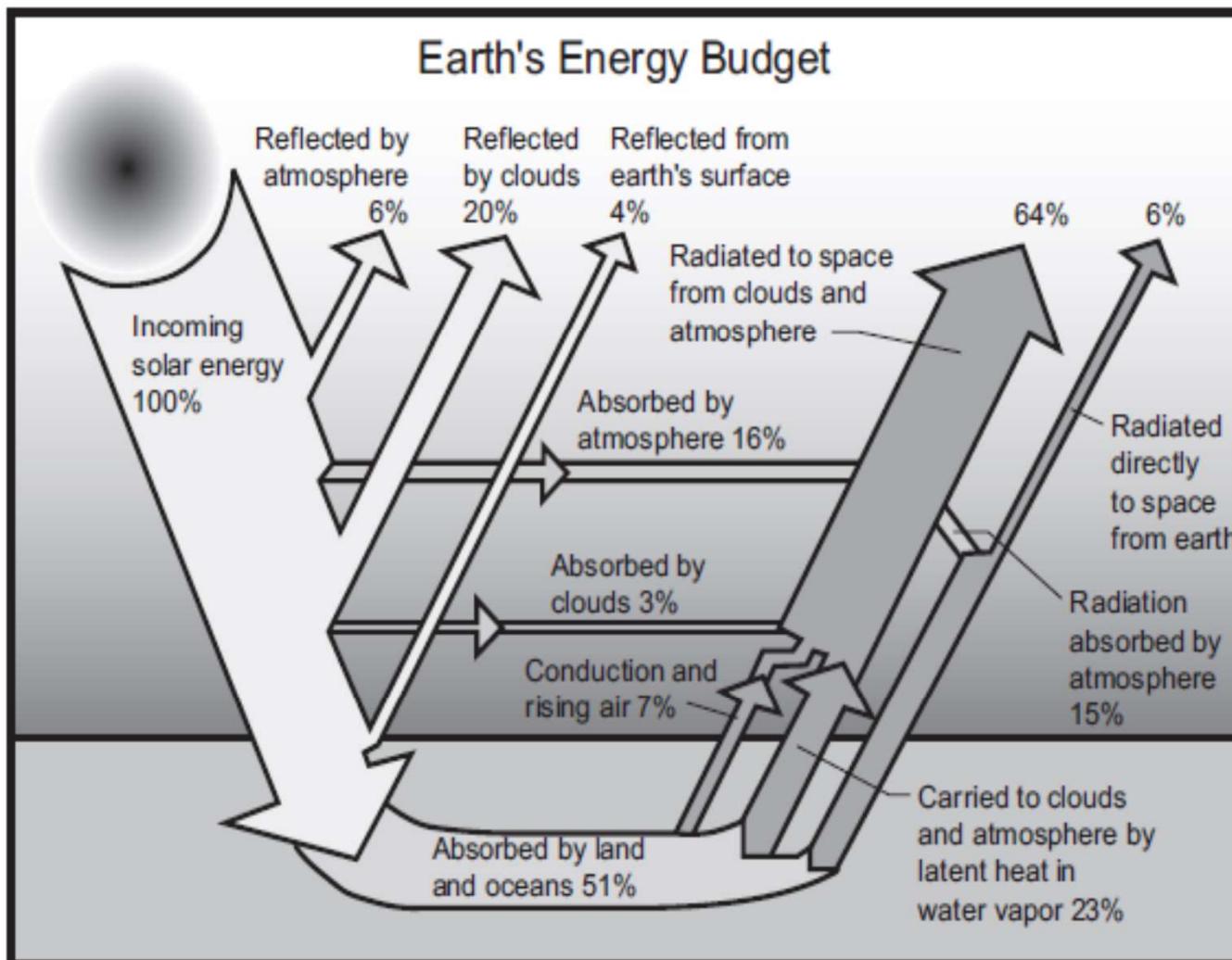
June-August



NOAA Climate.gov

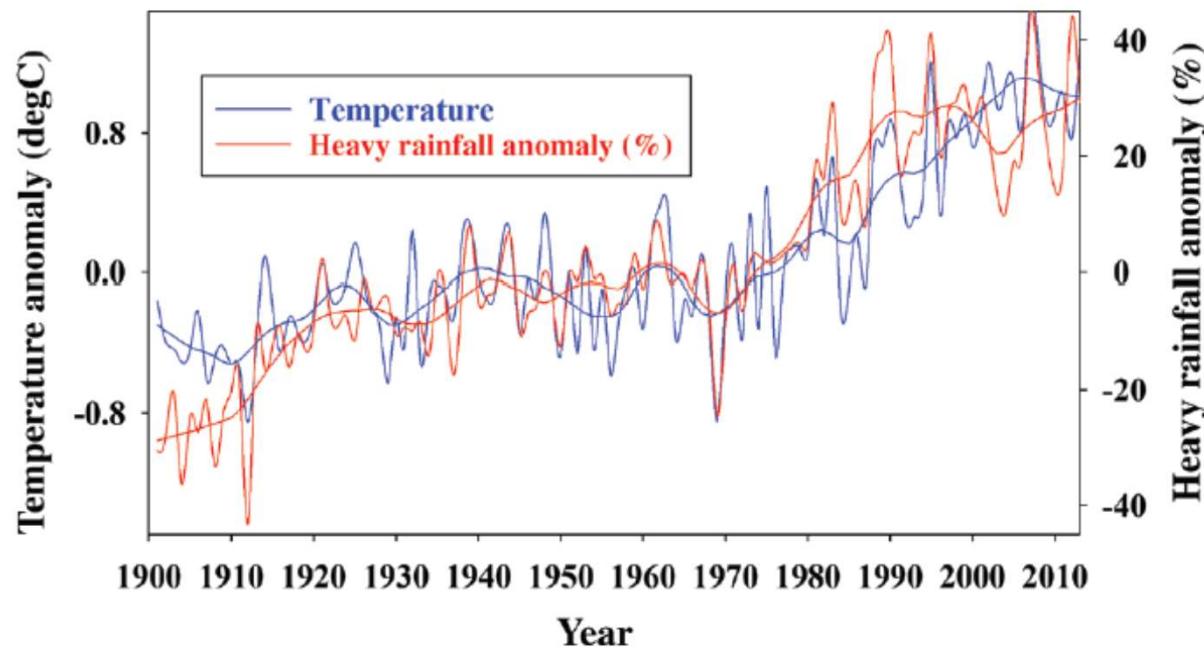
- El Niño and La Niña are opposite phases of a natural climate pattern across the tropical Pacific Ocean that swings back and forth every 3-7 years on average
- Together, they are called ENSO (pronounced “en-so”), which is short for **El Niño-Southern Oscillation**
- El Niño (the warm phase) and La Niña (the cool phase) lead to significant differences from the average ocean temperatures, winds, surface pressure, and rainfall across parts of the tropical Pacific
- Climate Change is making El Niños more intense, leading to intensifying droughts, worsening floods, and shifting hurricane patterns
- Strong El Niños can cause severe drought in dry climates such as Australia and India, intense flooding in wetter climates such as the Pacific Northwest and Peru, and causes more hurricanes to form in the Pacific and fewer in the Atlantic

How the climate is changing?



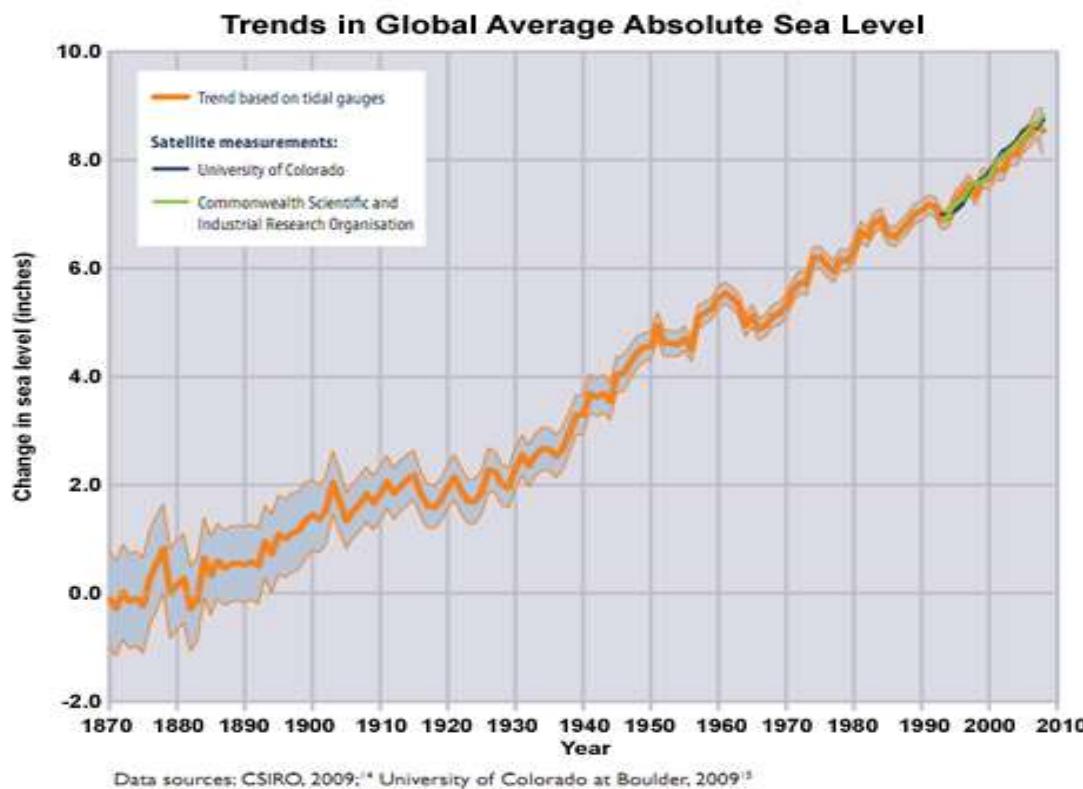
Atmosphere is responsible for radiating ~90% of total absorbed solar energy back to space!!

Climate Change: Is it real ?



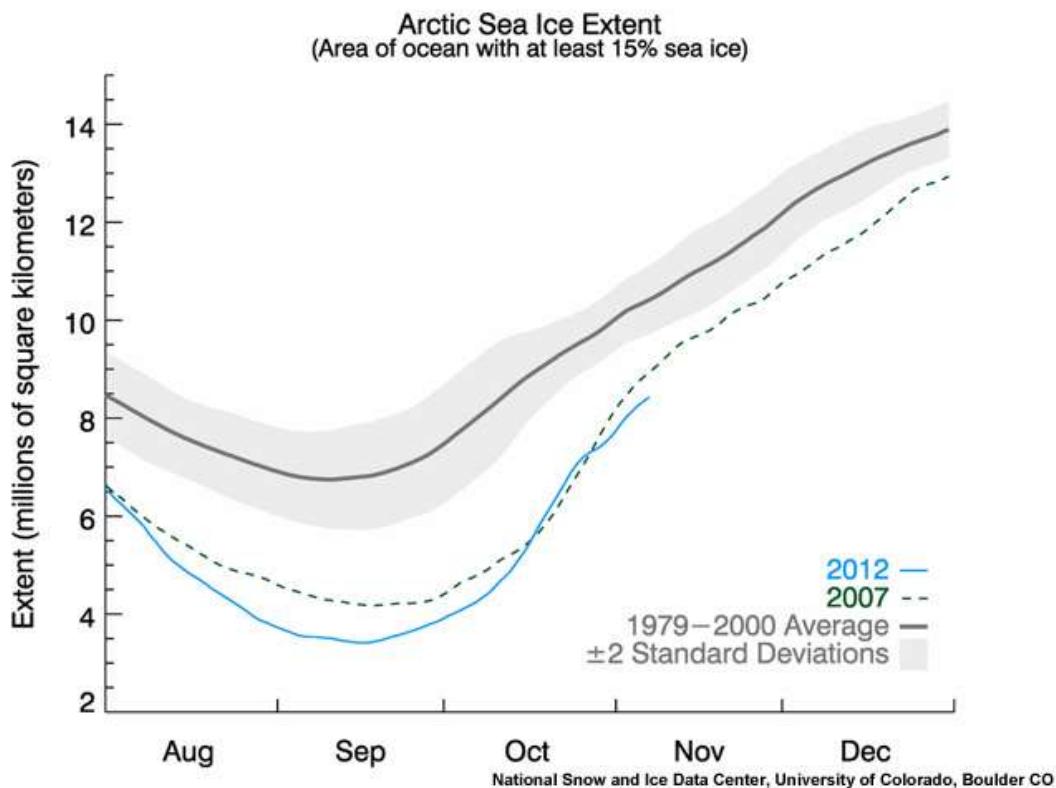
Earth is getting warmer and the temperature has been well above normal for more than 25 years.

Evidence of change: Oceans



The IPCC estimates that the oceans rose 4 to 10 inches (10-25 cm) in the 20th century from melting ice and snow and the physical expansion of warmer water.

Evidence of change: Sea Ice



Sea ice is diminishing in the Arctic. Satellites have observed winter Arctic sea ice shrink by about 3-4% per decade from 1979, and an even higher rate in summer.

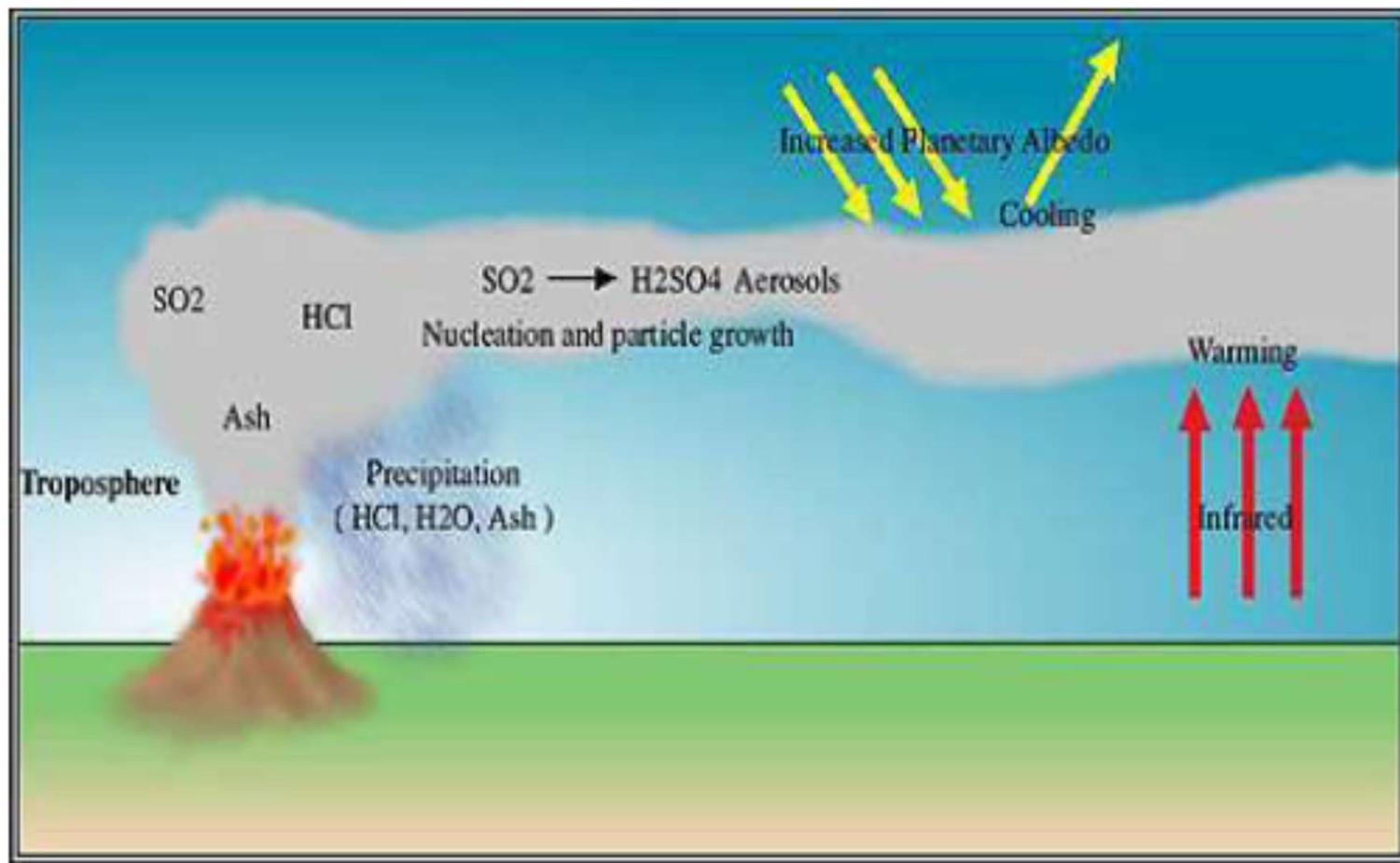
Natural reasons for climate change

Natural reasons

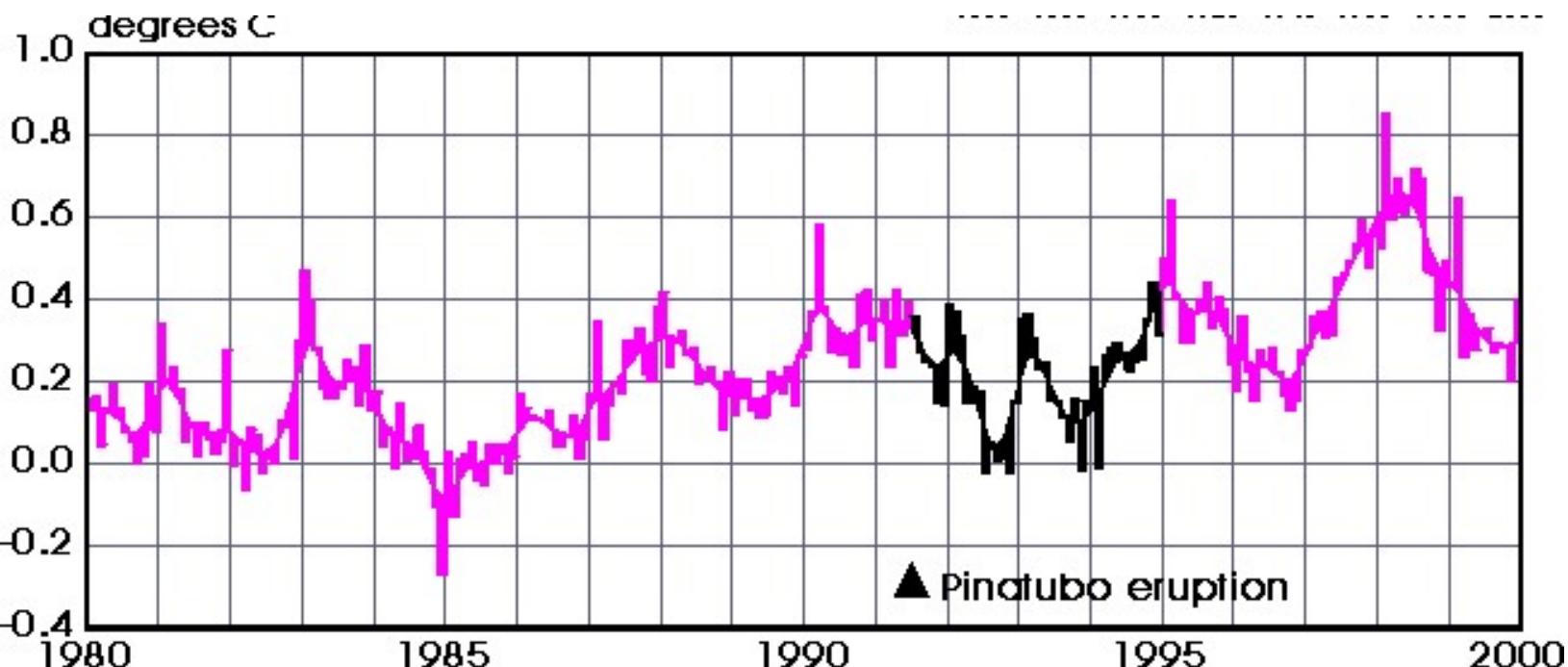
- The earth's climate is influenced and changed through natural causes like volcanic eruptions, ocean currents, the Earth's orbital changes, solar variations and internal variability

➤ Volcanic eruptions:

- Volcanic eruptions pump out clouds of dust and ash, which block out some sunlight
- The ash particles are relatively heavy, they fall to the ground within about three months, so their cooling effect is very short-lived
- But volcanic debris also includes sulfur dioxide. This gas combines with water vapor and dust in the atmosphere to form sulphate aerosols, which reflect sunlight away from the Earth's surface- can lead cooling of Earth's surface
- These aerosols are lighter than ash particles and can remain in the atmosphere for a year or more

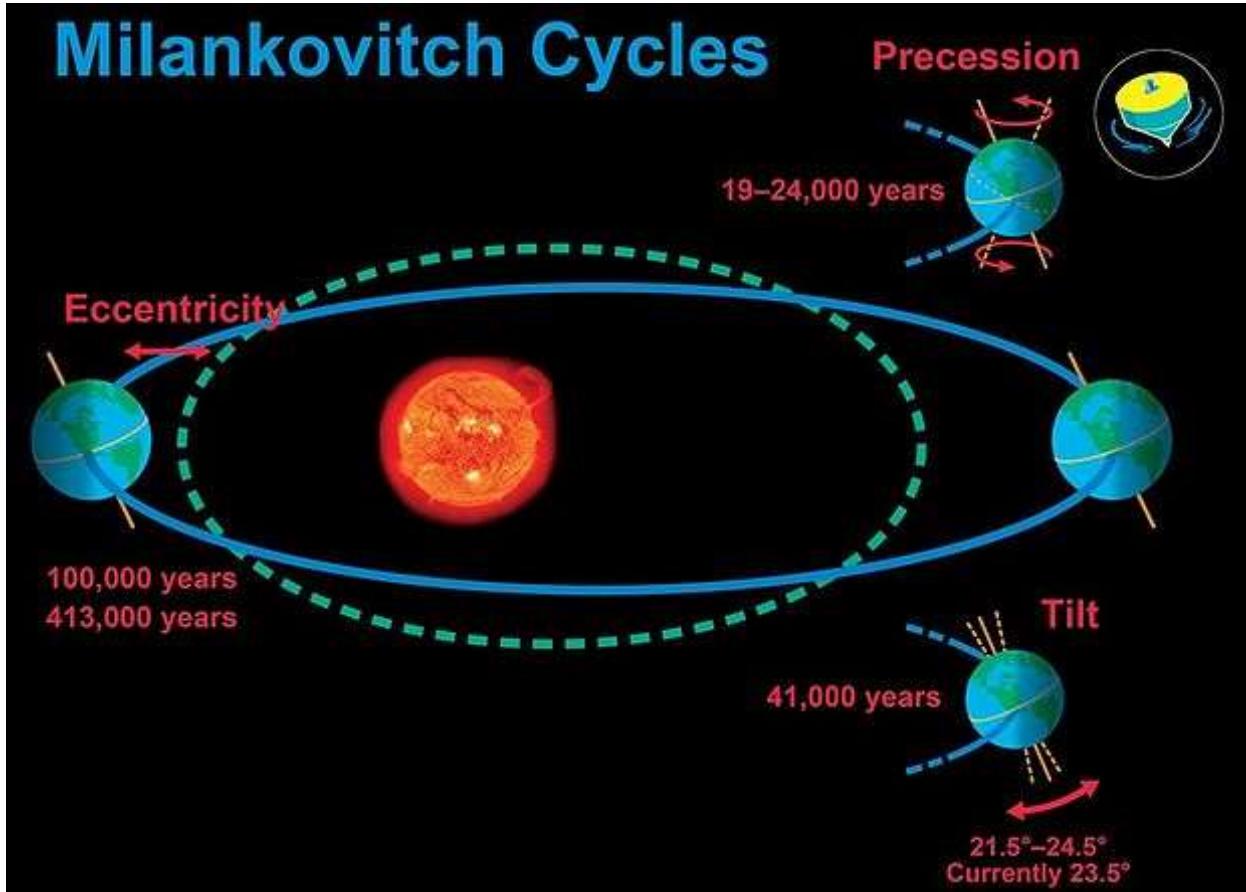


Mount Pinatubo-1991



- Large volumes of gases and ash can influence climatic patterns for years by increasing planetary reflectivity causing atmospheric cooling
- The eruption of Mount Pinatubo in 1991 caused a **0.5 °C** drop in global temperature

➤Earth's orbital changes:



- Milankovitch cycles describe the collective effects of changes in the Earth's movements on its climate over thousands of years

Cycle includes:

- shape of Earth's orbit, known as **eccentricity**
- angle Earth's axis is tilted with respect to Earth's orbital plane, known as **obliquity**
- direction Earth's axis of rotation is pointed, known as **precession**

Ice Age: Did it exist ?

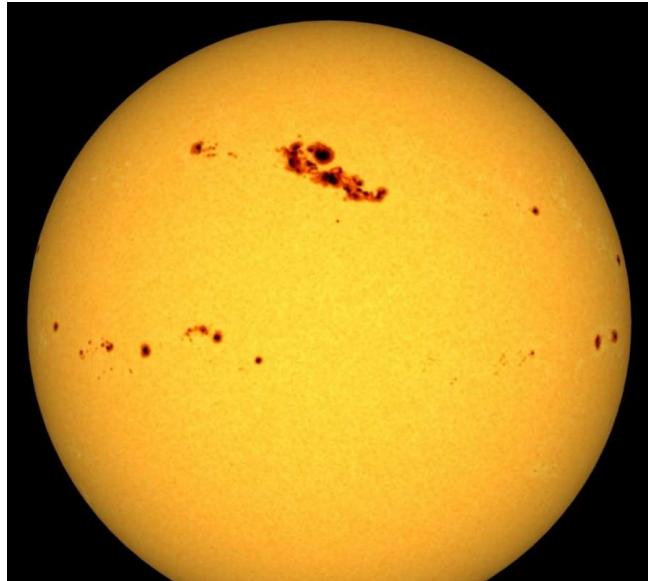


- The last ice age ended about 12,000 years ago and the next cooling cycle may begin in about 30,000 years

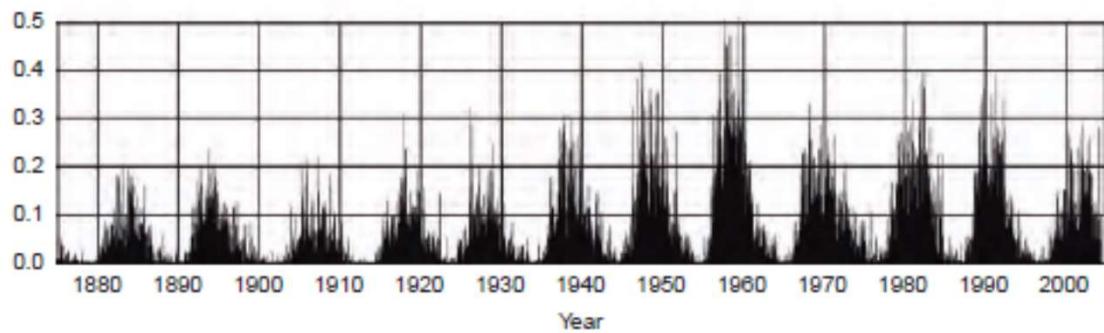
- An **ice age** is a long period of reduction in the temperature of Earth's surface and atmosphere, resulting in the presence or expansion of continental and polar ice sheets and alpine glaciers
- *Ice age* implies the presence of extensive ice sheets in both northern and southern hemispheres – **5** major ice ages
- Earth is currently in an interglacial period

- Orbital changes are so gradual they're only noticeable over thousands of years – not decades or centuries
- The earth makes one full orbit around the sun each year, it is tilted at an angle of 23.5° to the perpendicular plane of its orbital path
- Changes in the tilt of the earth can lead to small but climatically important changes in the strength of the seasons, more tilt means warmer summers and colder winters; less tilt means cooler summers and milder winters
- Slow changes in the Earth's orbit lead to small but climatically important changes in the strength of the seasons over tens of thousands of years

➤ Solar variations:



- Sunspots are temporary phenomena on the Sun's photosphere that appear as spots darker than the surrounding areas
- They are regions of reduced surface temperature caused by concentrations of magnetic field flux that inhibit convection



The fractional area of the surface of the entire solar photosphere (in %) covered by sunspots as a function of time

- That could lead to **fewer solar storms**, as well as a cooler climate on Earth

Little Ice Age (François E. Matthes in 1939)



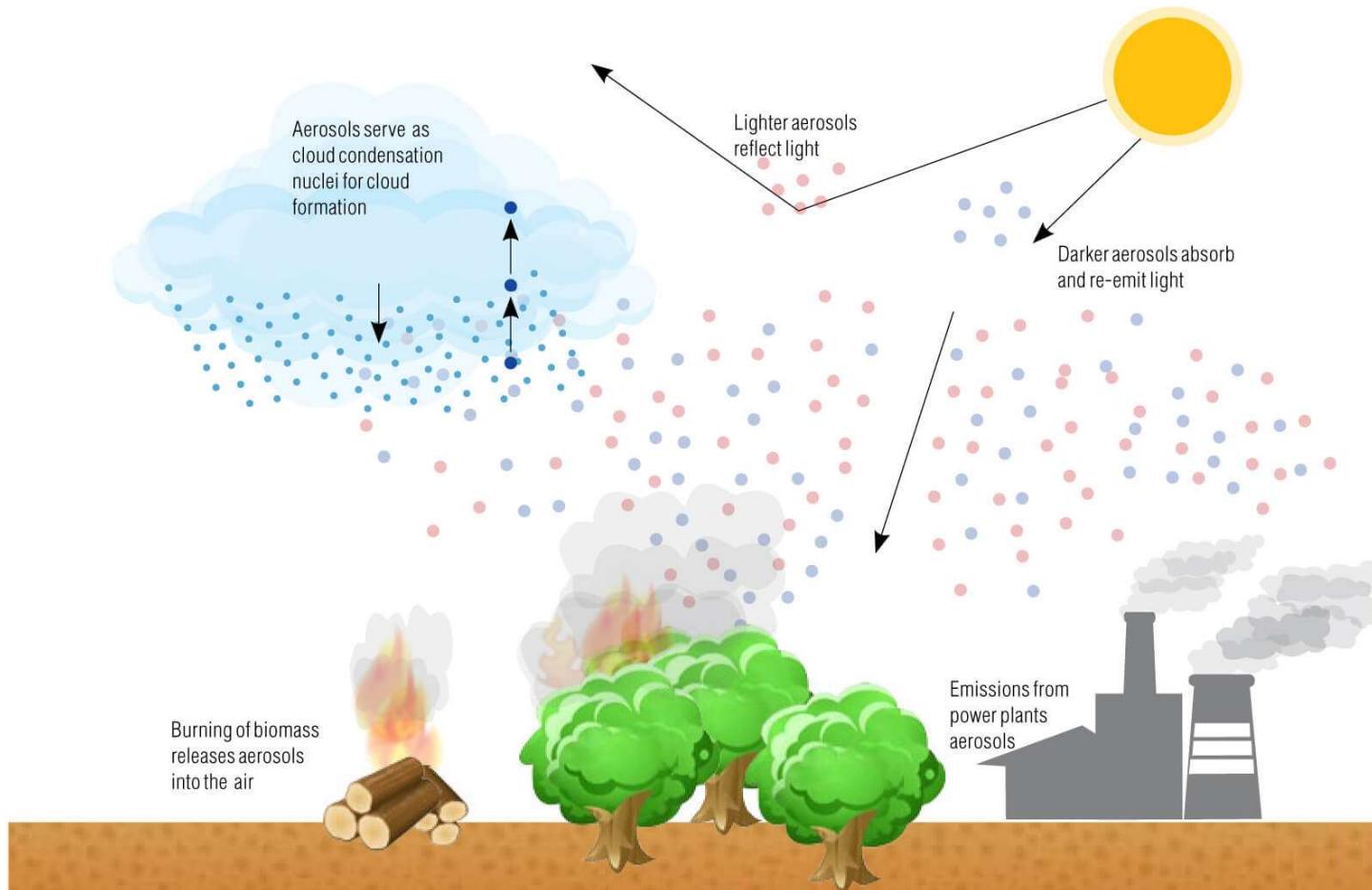
- The Little Ice Age (LIA) was a period of regional cooling that occurred after the Medieval Warm Period (The time period has been conventionally defined as extending from the 16th to the 19th centuries)
- The Intergovernmental Panel on Climate Change (IPCC) 3rd Assessment Report: timing and the areas affected by the Little Ice Age suggested largely-independent regional climate changes, rather than a globally-synchronous increased glaciation

Climate Change And Its Implications (CCI)

Dr. Raji P

Lecture-6

Aerosols

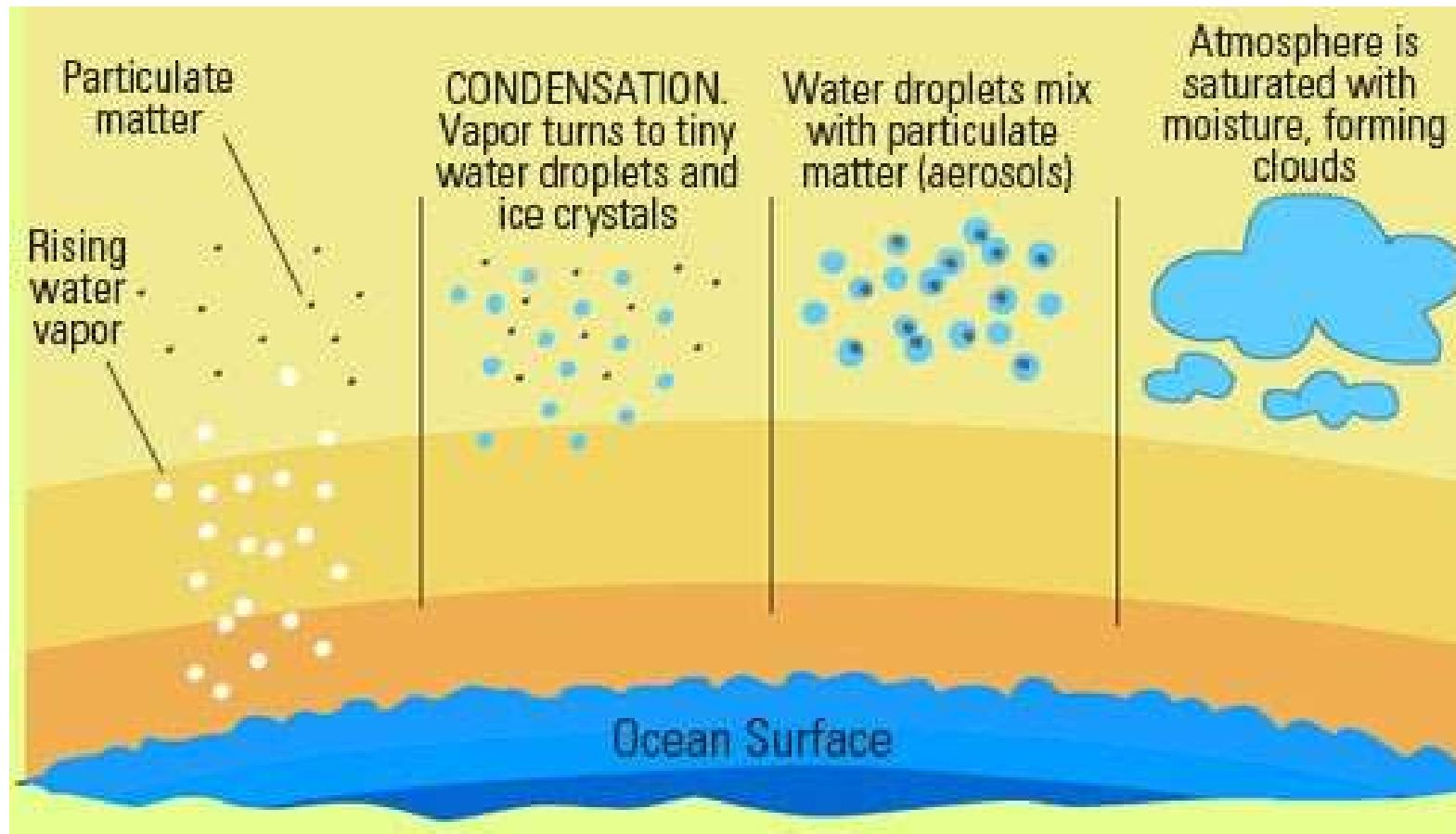


What are aerosols?

- Aerosols/particulates are microscopic particles of solid or liquid matter suspended in the air/gas
- Aerosols occur in both the troposphere and the stratosphere, but there are considerable differences in the size ranges, chemical nature and sources of the aerosols
- Aerosol is to be stable for few seconds to several months
- Aerosol includes particles size: 0.002 to more than 100 μm

How aerosols are useful?

Cloud formation



- Aerosols have important consequences for global climate, ecosystem processes, and human health
- Aerosols affect the earth-atmosphere radiation budget and leads to
 - ✓ Direct effects - scattering and absorption of solar radiation
 - ✓ Indirect effects- changes in cloud characteristics



Forms of aerosols

Dust: Solid particles formed by mechanical breakage of parent materials or crushing (size $>1\mu\text{m}$)

Fumes: Particles formed by condensation or chemical reaction ($<1\mu\text{m}$)

Fog: Suspension of water droplets (2 to 15 μm)

Mist: Suspension of droplets and they affect visibility >1 km ($<0.5\ \mu\text{m}$)

Smog: Consists of solid and liquid particles formed by the presence of sunlight and vapour (0. 3-1.0 μm)

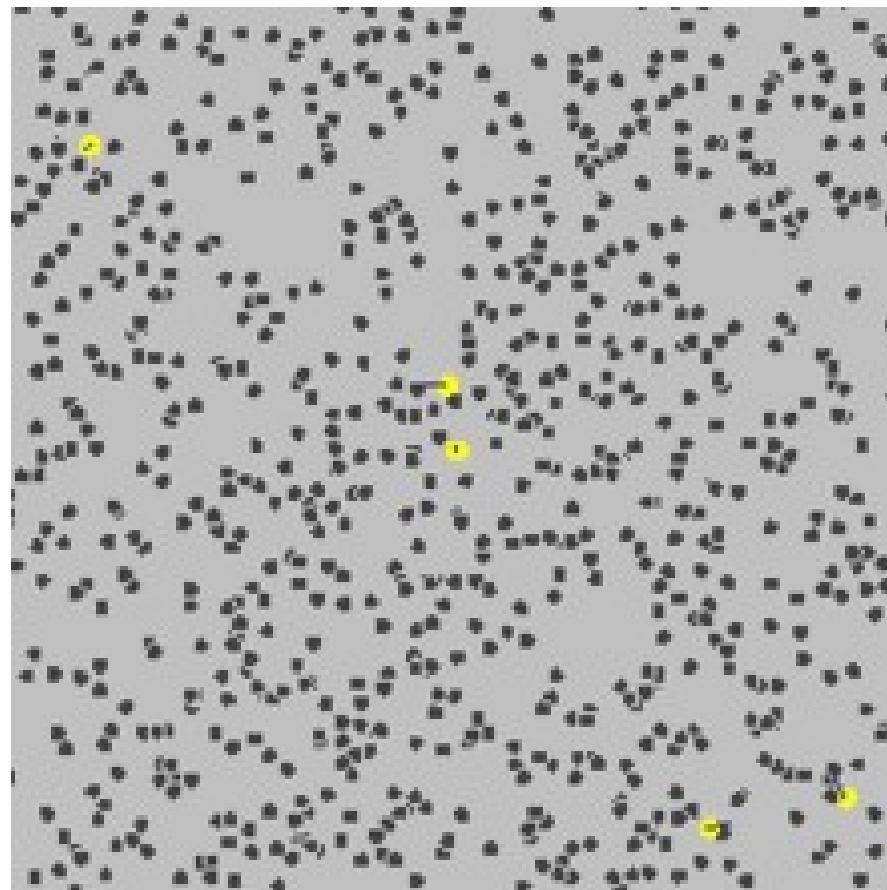
Smoke: Visible aerosol from incomplete combustion ($<1\mu\text{m}$)

Cloud: Visible aerosol with defined boundaries

Haze: Visibility reducing aerosol with fine suspended particles (0.02 to 0.06 μm)

- Aerosol concentration varies from place to place, and also varies with height
- The total concentration of aerosol particles in the lower atmosphere is maximum near the surface and it decreases with height (altitude)

Brownian coagulation



- Most aerosol particles are much smaller than cloud droplets and can be influenced easily by the constant bombardment of air molecules and perform random motions called **Brownian motion**
- Brownian motion is especially pronounced for particles $<0.5 \text{ } \mu\text{m}$ because of their small size, and they can collide and coagulate to form larger particles

Aging of aerosols

Types of aerosols based on source

Primary: They directly reaches to the atmosphere (wind action, burning etc)

Secondary: Forms from the atmosphere itself- Gas to particle conversion (GPC) and drop to particle conversion (DPC)

Major sources of aerosols from the Earth surface

Dust storms

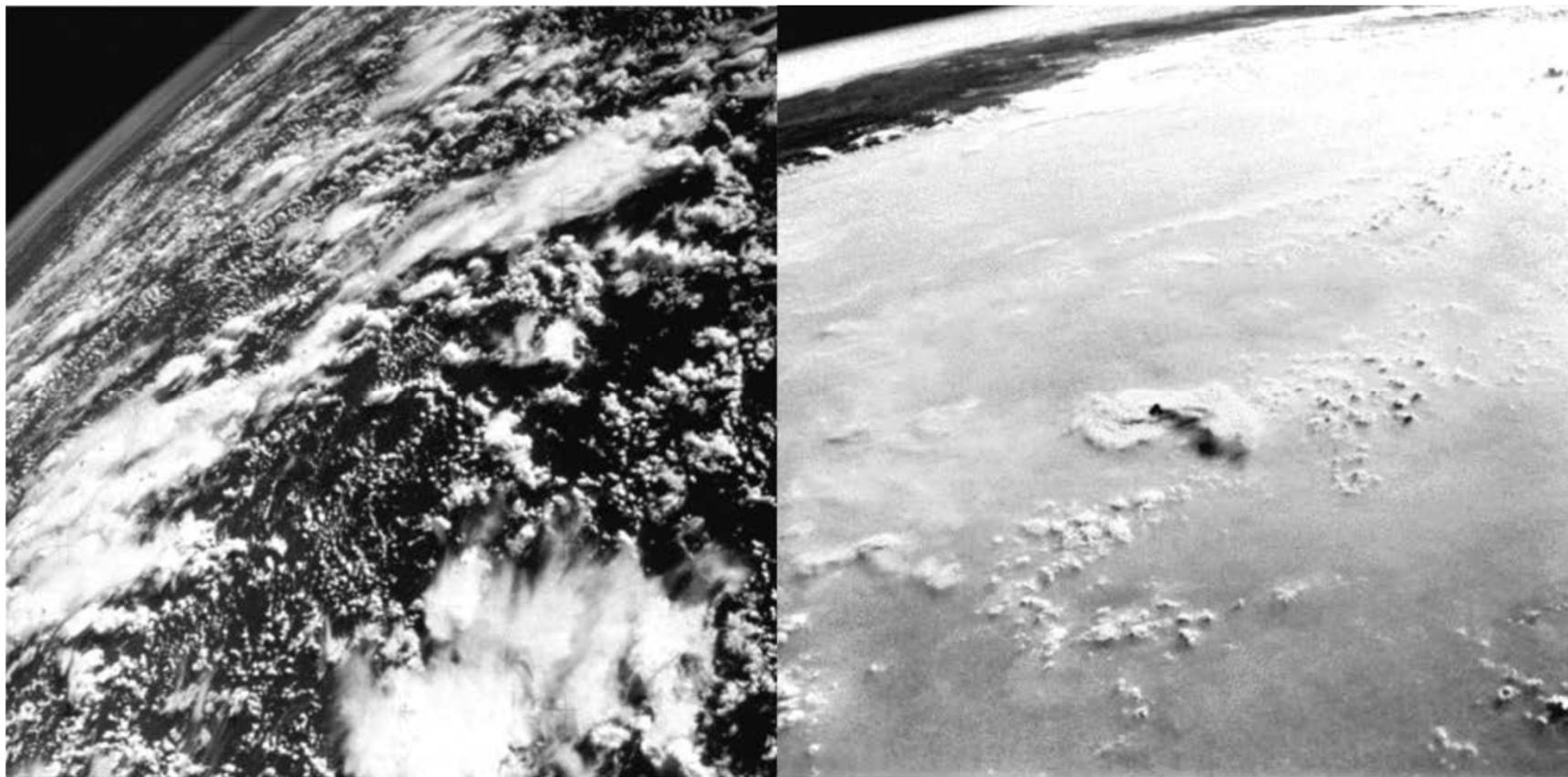


- A dust storm (sandstorm) is a meteorological phenomenon common in arid and semi-arid regions
- Dusts can travel thousands of kilometers and inject a huge number of aerosol particles into the atmosphere
- Clay particles such as SiO_2 , Al_2O_3 , Fe_2O_3 , and MgO

Biomass burning



- Natural or man-made fires that destroy large areas of forests and other vegetated surfaces – Biomass burning
- Large-scale biomass burning can cause significant changes in **local albedo** (will increase)



Satellite images of the Amazon basin area during (left) a day with no biomass burning and (right) a day with massive biomass burning (Source: NASA)

- The air became opaque due to strong reflection of sunlight by fire-produced aerosol particles
- The local albedo will increase dramatically

- Biomass burning particles are efficient cloud condensation nuclei and hence they have great impact on the global climate process through their cloud formation ability
- Biomass burning particles can travel a long range, and thus may have a far greater impact on the global climate

Will aerosol travel from Tropics to Antarctica?

- Biomass burning particles have been collected in Antarctica and their origin is in central Brazil (Amazon basin), a tropical region (Fiebig et al., 2009)
- Detection of aerosols in Antarctica From Long-Range Transport of the Australian Wildfires in 2009 (Jumelet et al., 2020)
- Tropical biomass burning particles, and whatever climatic implications they have, can reach the polar regions in a short time

Volcanic activity



Eruption of Mt. Pinatubo, Philippines on 12 June 1991

- The volcanic eruption was a near-vertical one and the plumes reached the stratosphere (up to 24 km)
- They inject directly into the atmosphere not only aerosol particles but a large amount of other gases as well
- The most abundant volcanic gas turns out to be water vapor, followed by CO₂ and SO₂
- Among these gases, SO₂ is the precursor for the formation of sulfate aerosols

- In the Mt. Pinatubo eruption, SO₂ injection is estimated at more than 2×10^7 tons
- Pure sulfates and nitrates reflect nearly all radiation they encounter, **cooling the atmosphere**
- **Black carbon** absorbs radiation readily, **warming** the atmosphere but also shading the surface

Human industrial activity



- Aerosol particles from burning fuels (wood, coal, etc.) to obtain energy-produces smoke
- The most conspicuous particle sources due to industry are the thick smoke coming out of numerous tall stacks in the world's industrial complexes
- The most common outputs from these stacks are **sulfates** and **black carbon**
- SO_2 produced by burning fossil fuels is a common precursor that usually ends up as sulfate particles through DPC or GPC

- 
- Another familiar aerosol production due to human activity is the photochemical **smog in big cities**
 - This is mainly due to high automobile traffic volumes that produce large amounts of nitrogen oxides, which, in the presence of sunlight, produce ozone, several radicals, and some stable products

Ocean surface process

Ocean surface process



- Aerosol particles produced over the ocean surface are largely NaCl particles, smaller amounts of K⁺, Mg²⁺, CO₃²⁻; and SO₄²⁻, organic and biological materials
- The production of sea salt particles is due to the bubble burst mechanism (also called sea spray mechanism)

- The sea surface is constantly subject to winds, air is trapped in the surface layer to form bubbles
- Some of these droplets eventually evaporate to leave dry sea salt particles that may be carried up higher by winds

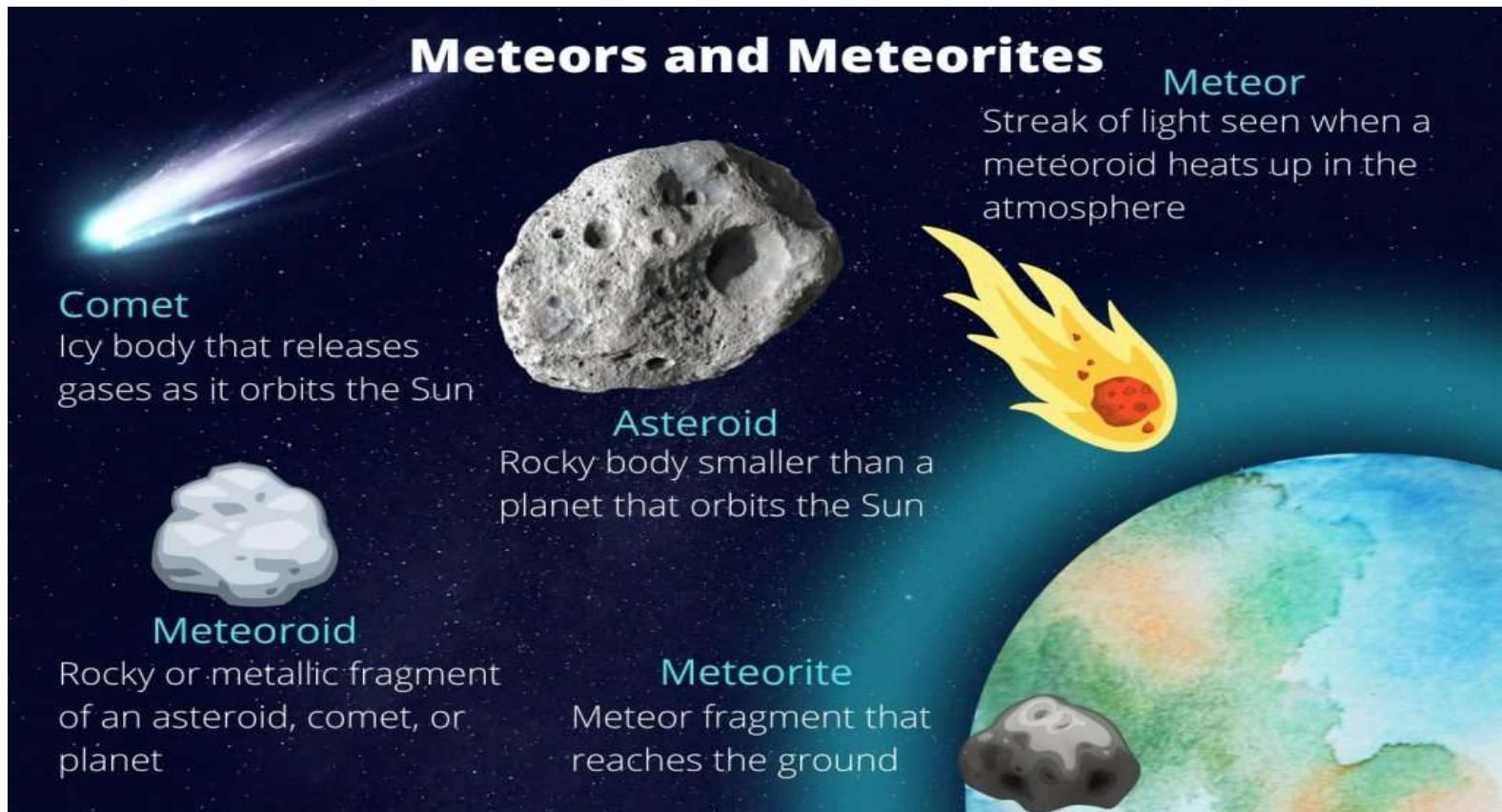
Biogenic aerosol

- Aerosol particles are produced by biological systems during their life cycle and plants are the main source of these biogenic aerosols
- Pollens released by the flowers of various plants are spread in the air during pollination to become aerosol particles
- They are typically about 10 μm or larger in size
- Some of these biogenic aerosol particles may serve as efficient nuclei for condensation and freezing



- Measurements in the Amazon basin by Pöschl et al. (2010) showed that sub-micrometer biogenic aerosol particles are the main cloud condensation nuclei during the wet season in contrast to the dry season, when the biomass burning particles dominate the condensation

Natural Sources -Extraterrestrial sources



- The Earth's atmosphere is constantly bombarded by meteoroids, which are basically rocks of various sizes
- Some are larger than a few centimeters but most are probably just of dust particle size
- These rocks are widely distributed in the interplanetary space in the Solar System and are attracted to the Earth by the gravitational force if their orbits happen to intercept that of the Earth
- Meteoric aerosols are known to contain elements such as Fe, Si, Mg, S, Ca, Ni, Al, Cr, Mu, Cl, K, Ti, and Co

Black carbon

BLACK CARBON (BC)

SOURCES



HOUSEHOLD ENERGY

51%



TRANSPORT

26%



AGRICULTURE

8%



INDUSTRIAL PRODUCTION

5%



WASTE

5%



FOSSIL FUEL OPERATIONS

3%



LARGE-SCALE COMBUSTION

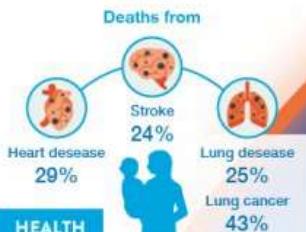
2%

Black carbon, or soot, is part of fine particulate air pollution ($PM_{2.5}$) and contributes to climate change.

IMPACTS

CLIMATE

Absorbs sunlight and converts it to heat



- 7 million pollution-related deaths every year

LIFETIME IN ATMOSPHERE: UP TO 2 WEEKS

Since black carbon does not last long in the atmosphere, efforts to reduce it will bring immediate benefits for the climate and human health.

SNOW & ICE

Accelerates the melting of snow and ice

WEATHER

- Prevents clouds from being formed
- Alters regional weather patterns and rainfall

AGRICULTURE & ECOSYSTEMS

- Reduces sunlight
- Affects plant health and productivity



- Aerosol BC is released from the incomplete combustion of fossil fuels, bio-fuels and biomass
- It exerts considerable influence on regional precipitation and surface cooling, northern hemispheric tropical expansion, Arabian Sea tropical cyclones and the hydrological cycle in general
- Among aerosol chemical constituents, black carbon (BC) is the most potent climate forcing agent ~**65% of that of CO₂**

- India is the 2nd largest emitter of BC in the world, with emissions projected to rise steadily in the coming decades
- Unlike developed economies (USA, UK and Europe) where aerosol BC is predominantly sourced from on-road and off-road diesel engines
- Indian BC emissions are from low efficiency combustion of domestic fuels followed by industrial emissions

Removal mechanism of aerosol

- The pathways via which aerosol particles are removed from the atmosphere can be divided into two broad categories – **dry removal** and **wet removal**
- Dry removal mechanisms are those not involving cloud and precipitation processes, while wet removals are those related to clouds and precipitation

Dry removal

- Aerosol particles can stay afloat by updrafts that are strong enough to support them
- If the updraft weakens or disappears, particles will go down to the surface by the pull of gravity of the Earth –gravitational settling
- The settling velocity of an aerosol particle depends on the density and size of the particle and where it is located in the atmosphere
- Settling time-exercise

Attachment on obstacle surfaces

- Aerosol particles carried by air flow can become attached to the surface of plants, buildings or other obstacles above the ground either by their own Brownian motion, electrostatic forces, interception or inertial impaction

Particle coagulation

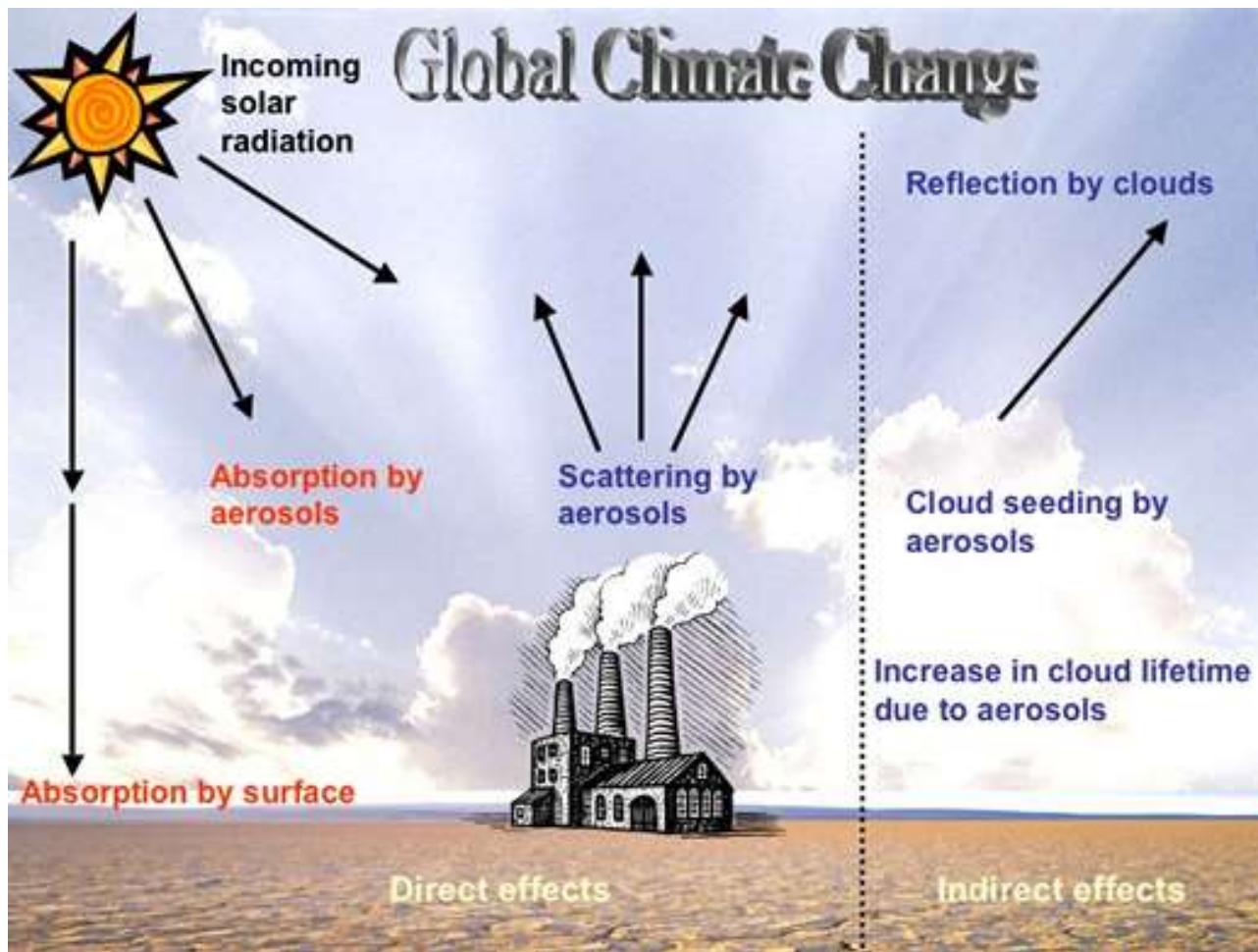
- Small particles collide and stick together to become larger particles
- In accounting for the aerosol budget, coagulation causes particle concentration to decrease and also the coalesced particles are “removed” from their original size categories, so it should be considered as a sink of aerosol particles

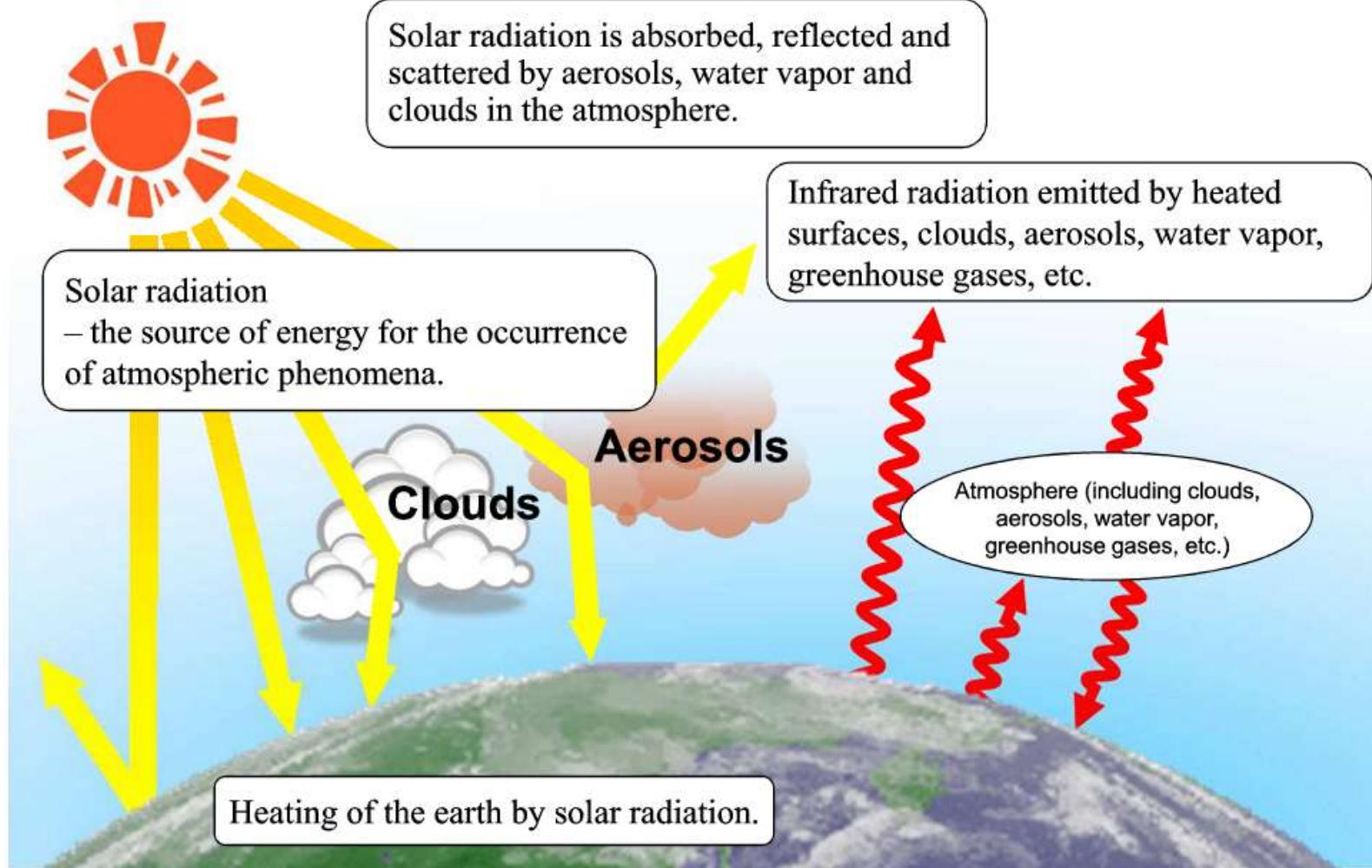
Wet removal

Cloud and precipitation processes are the most efficient way to remove aerosol particles from the atmosphere, and the process that removes aerosol particles is wet removal, also called **precipitation scavenging**

Aerosol & Climate

How aerosol affect climate?



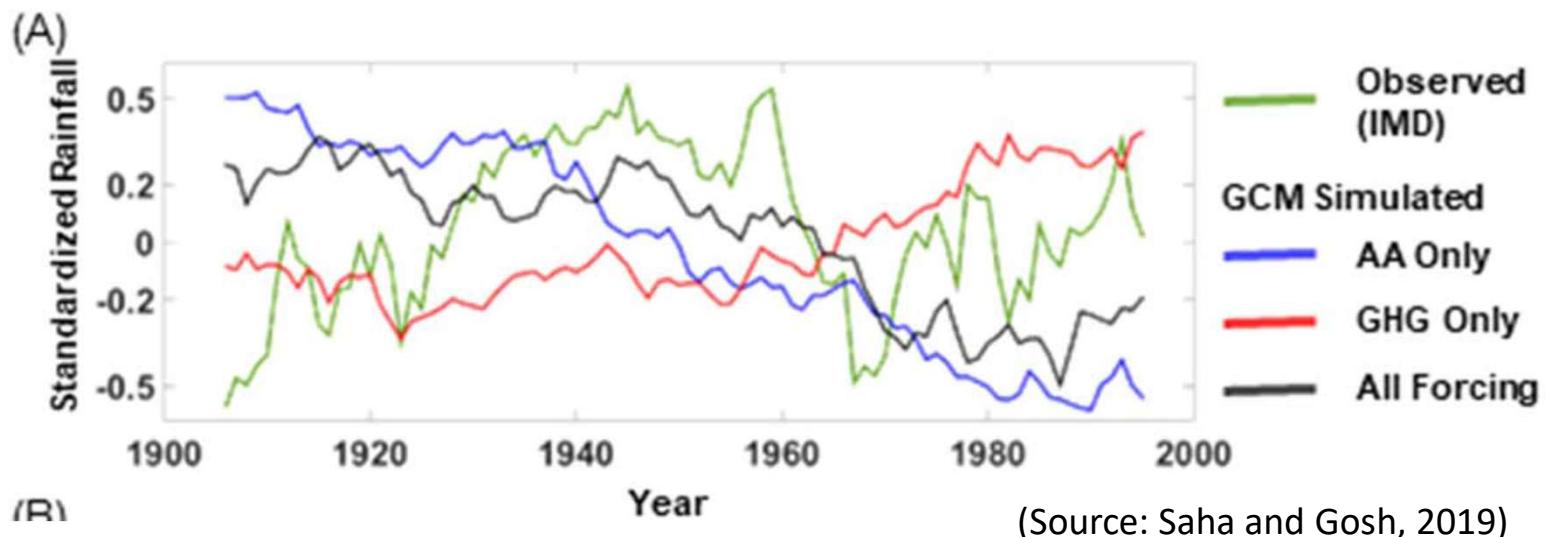


- All atmospheric aerosols scatter incoming solar radiation, and a few aerosol types can also absorb solar radiation
- BC is the most important of the latter, but mineral dust and some OC components are also sunlight absorbers
- Aerosols that mainly scatter solar radiation have a cooling effect, by enhancing the total reflected solar radiation from the Earth
- Strongly absorbing aerosols have a warming effect
- In the atmosphere, there is a mixture of scattering and absorbing aerosols, and their net effect on Earth's energy budget is dependent on surface and cloud characteristics

Aerosol and Indian Monsoon

Can the weakening of Indian Monsoon be attributed to anthropogenic aerosols?

- The greenhouse gas (GHG)-induced warming of the Indian Ocean, as well as the direct and indirect effects of anthropogenic aerosols have been documented as possible reasons for weakening of Indian monsoon



Effects of Black Carbon Aerosols on the Indian Monsoon

- Observed decreases of rainfall over parts of India due to BC aerosols (Meehl et al., 2008)

Aerosols cause intra-seasonal short-term suppression of Indian monsoon rainfall

- The causal influence of aerosols on precipitation suppression is relevant to the inter-annual variability of monsoon precipitation and the timing of monsoon break spells
- Prolonged and intense breaks in the monsoon were associated with rainfall deficits, which have been linked to reduced food grain production during latter half of the twentieth century
- Thus, aerosol-induced precipitation suppression and aggravation of break spells, uncovered here, could influence future rainfall deficits and agricultural vulnerability in India

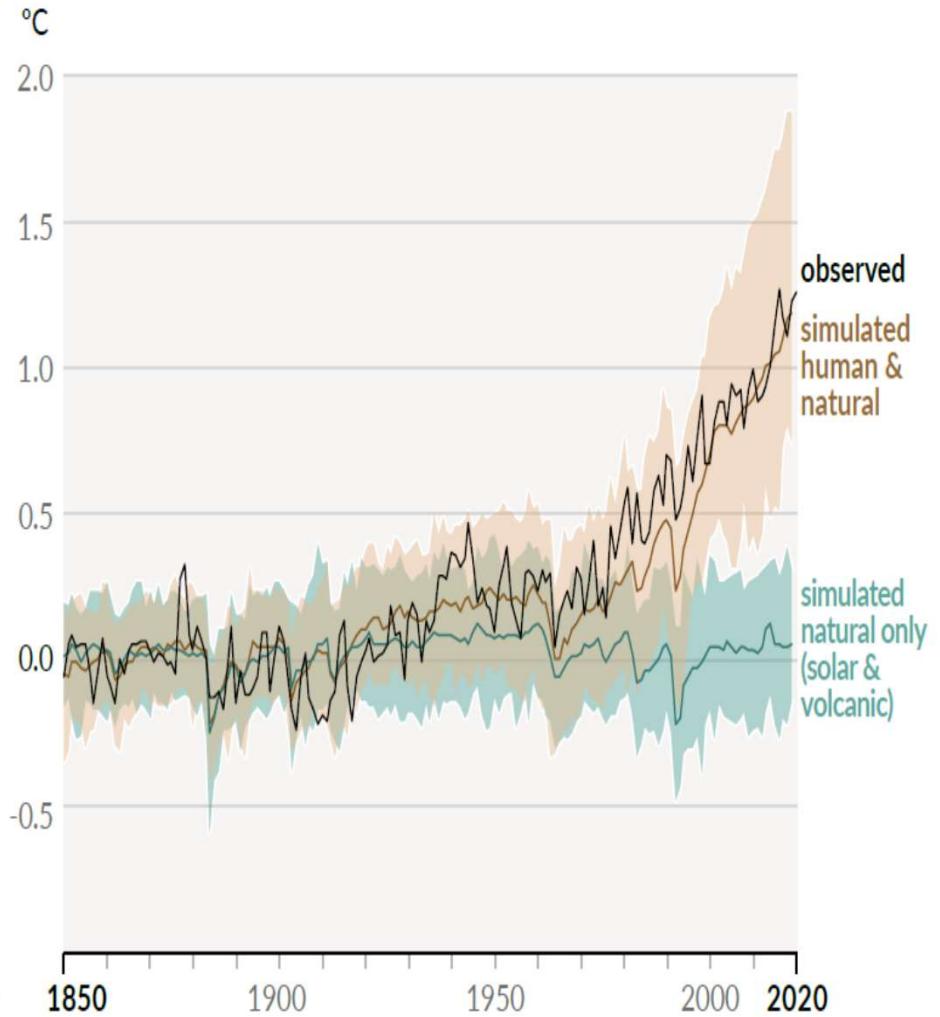
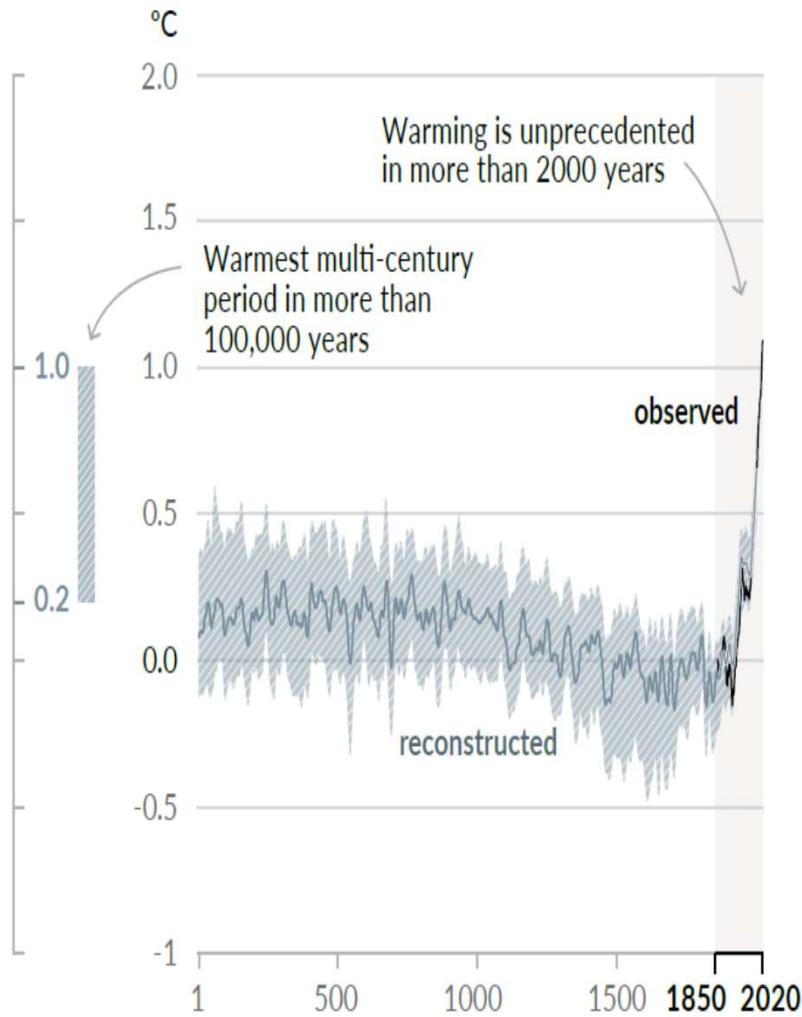
(Source: Dave et al., 2017)

Climate Change And Its Implications (CCI)

Dr. Raji P

Lecture-7&8

Evidences of climate change



- Extreme heat: India is already experiencing a warming climate
 - Unusual and unprecedented spells of hot weather are expected to occur far more frequently and cover much larger areas
 - Under 4°C warming, the west coast and southern India are projected to shift to new, high-temperature climatic regimes with significant impacts on agriculture

- Change in rainfall pattern:

- A decline in monsoon rainfall since the 1950s has already been observed. The frequency of heavy rainfall events has also increased
- A 2°C rise in the world's average temperatures will make India's summer monsoon highly unpredictable
- At 4°C warming, an extremely wet monsoon that currently has a chance of occurring only once in 100 years is projected to occur every 10 years by the end of the century

- An abrupt change in the monsoon could precipitate a major crisis, triggering more frequent droughts as well as greater flooding in large parts of India
- India's northwest coast to the south eastern coastal region could see higher than average rainfall
- Dry years are expected to be drier and wet years wetter

- **Drought**: Evidence indicates that parts of South Asia have become drier since the 1970s with an increase in the number of droughts
 - In 1987 and 2002-2003, droughts affected more than half of India's crop area and led to a huge fall in crop production
 - Droughts are expected to be more frequent in some areas, especially in north-western India

- **Groundwater**: More than 60% of India's agriculture is rain-fed, making the country highly dependent on groundwater
- Even without climate change, 15% of India's groundwater resources are overexploited
- **Glacier melt**: At 2.5°C warming, melting glaciers and the loss of snow cover over the Himalayas are expected to threaten the stability and reliability of northern India's primarily glacier-fed rivers, particularly the Indus and the Brahmaputra

- Sea level rise: With India close to the equator, the sub-continent would see much higher rises in sea levels than higher latitudes
- Sea-level rise and storm surges would lead to saltwater intrusion in the coastal areas, impacting agriculture, degrading groundwater quality, contaminating drinking water, and possibly causing a rise in diarrhea cases and cholera outbreaks, as the cholera bacterium survives longer in saline water
- Kolkata and Mumbai, both densely populated cities, are particularly vulnerable to the impacts of sea-level rise,⁹ tropical cyclones, and riverine flooding

- Agriculture and food security: Seasonal water scarcity, rising temperatures, and intrusion of sea water would threaten crop yields, jeopardizing the country's food security
- Should current trends persist, substantial yield reductions in both rice and wheat can be expected in the near and medium term
- Under 2°C warming by the 2050s, the country may need to import more than twice the amount of food-grain than would be required without climate change

- Energy security: The increasing variability and long-term decreases in river flows can pose a major challenge to hydropower plants and increase the risk of physical damage from landslides, flash floods, glacial lake outbursts, and other climate-related natural disasters
- Decreases in the availability of water and increases in temperature will pose major risk factors to thermal power generation

- **Water security**: An increase in variability of monsoon rainfall is expected to increase water shortages in some areas
- Studies have found that the threat to water security is very high over central India, along the mountain ranges of the Western Ghats, and in India's northeastern states

- Health:
- Migration & conflict: Climate change impacts on agriculture and livelihoods can increase the number of climate refugees

The Intergovernmental Panel on Climate Change (IPCC)

- The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change
- The IPCC provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation

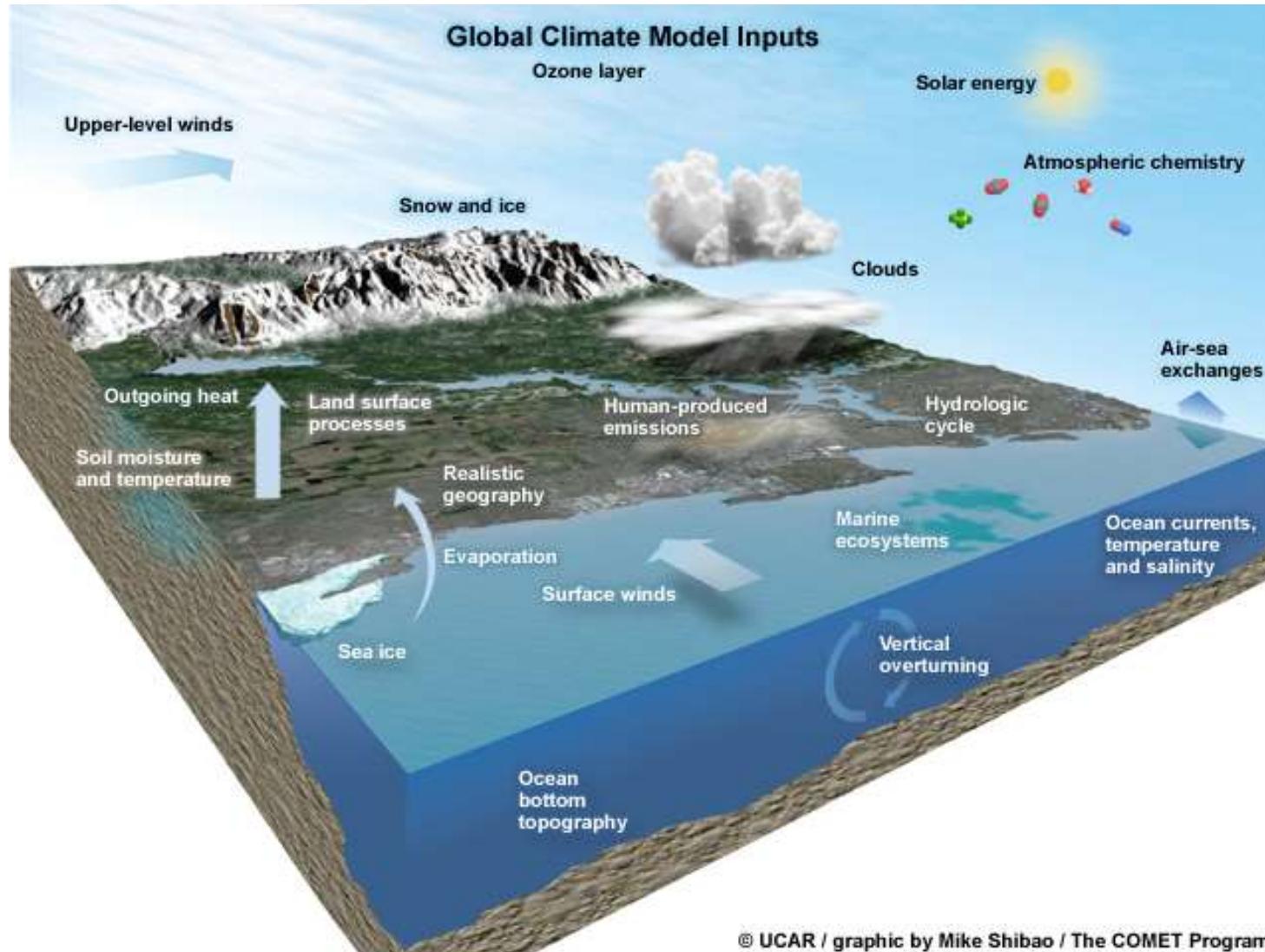
- Created in 1988 by the WMO and the United Nations Environment Programme (UNEP), the objective of the IPCC is to provide governments at all levels with scientific information that they can use to develop climate policies
- IPCC reports are key input into international climate change negotiations
- The IPCC is an organization of governments that are members of the United Nations or WMO
- The IPCC currently has 195 members. Thousands of people from all over the world contribute to the work of the IPCC

- Since 1988, the IPCC has **six** assessment cycles and delivered six Assessment Reports, the most comprehensive scientific reports about climate change produced worldwide
- In 1990, the First IPCC Assessment Report (FAR) underlined the importance of climate change as a challenge with global consequences and requiring international cooperation
- The Second Assessment Report (SAR) (1995) provided important material for governments to draw from in the run-up to adoption of the **Kyoto Protocol** in 1997
- The Third Assessment Report (TAR) (2001) focused attention on the impacts of climate change and the need for adaptation

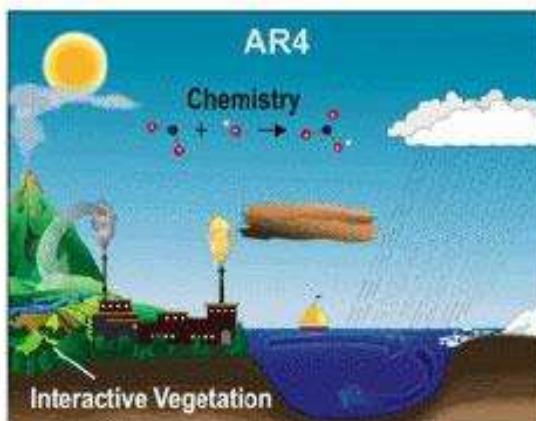
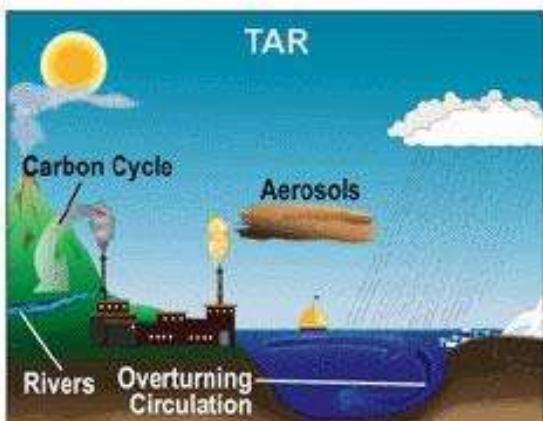
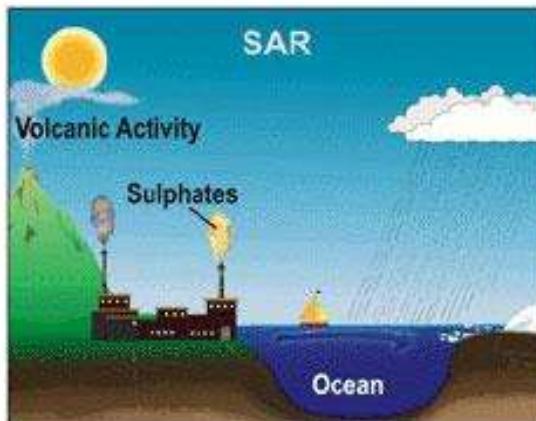
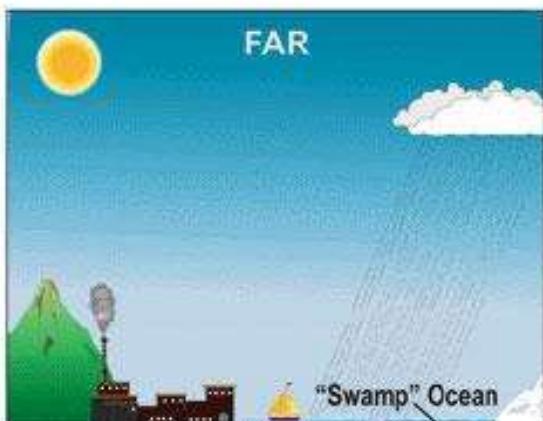
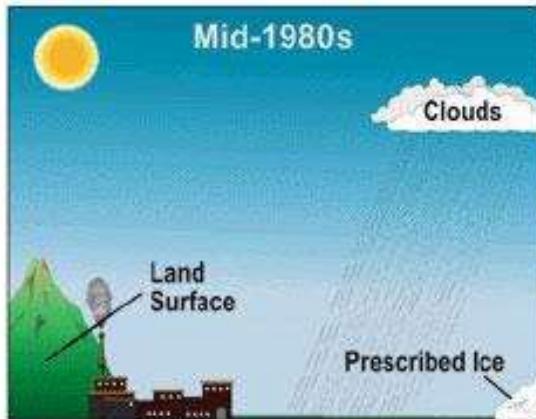
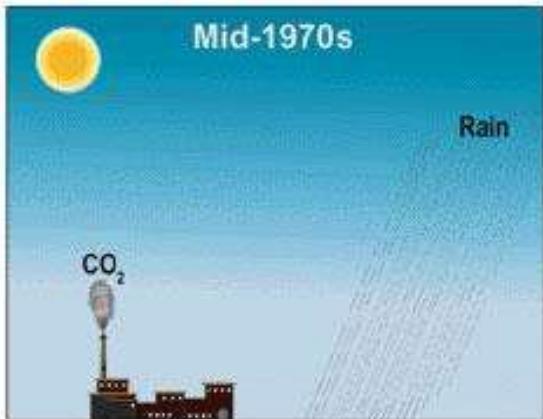
- The 4th Assessment Report (AR4) (2007) laid the ground work for a post-Kyoto agreement, focusing on limiting warming to 2°C
- The 5th Assessment Report (AR5) was finalized between 2013 and 2014. It provided the scientific input into the Paris Agreement
- Global Warming of 1.5°C (SR15), was requested by world governments under the Paris Agreement
- The IPCC is currently released its Sixth Assessment Reports (9 August 2021)

Climate models

Coupling with Earth System components



The World in Global Climate Models

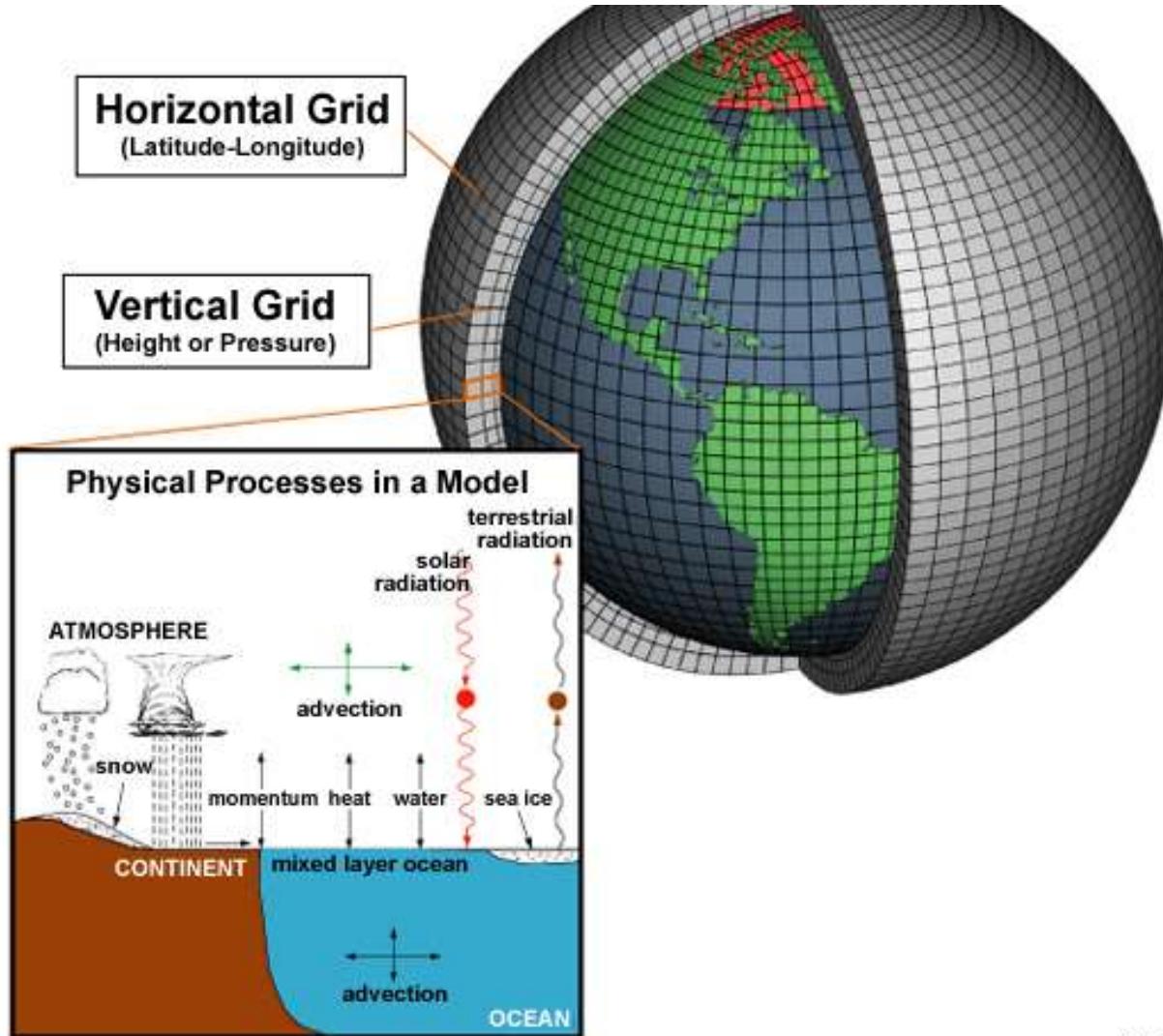


Time Scale of Interaction

Processes

Timescale

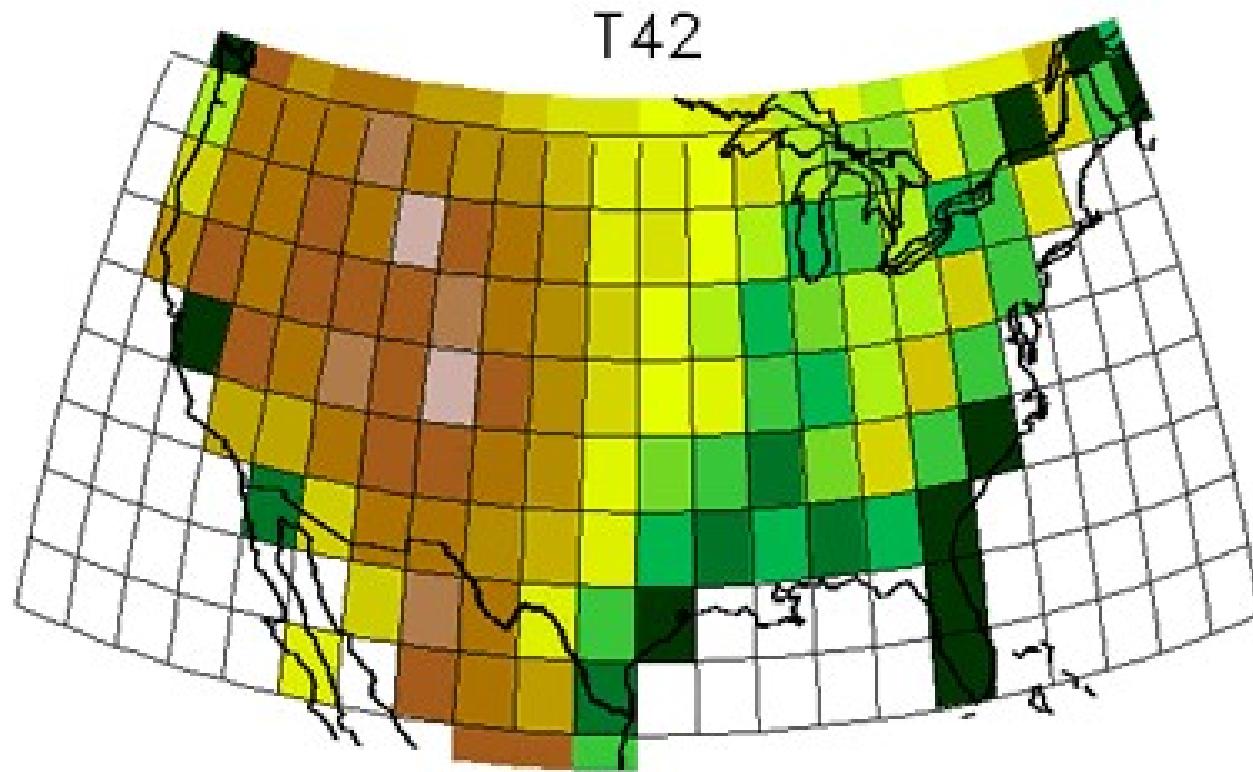
Climate Models: discretize the space



NOAA

23

Climate Models: Resolution



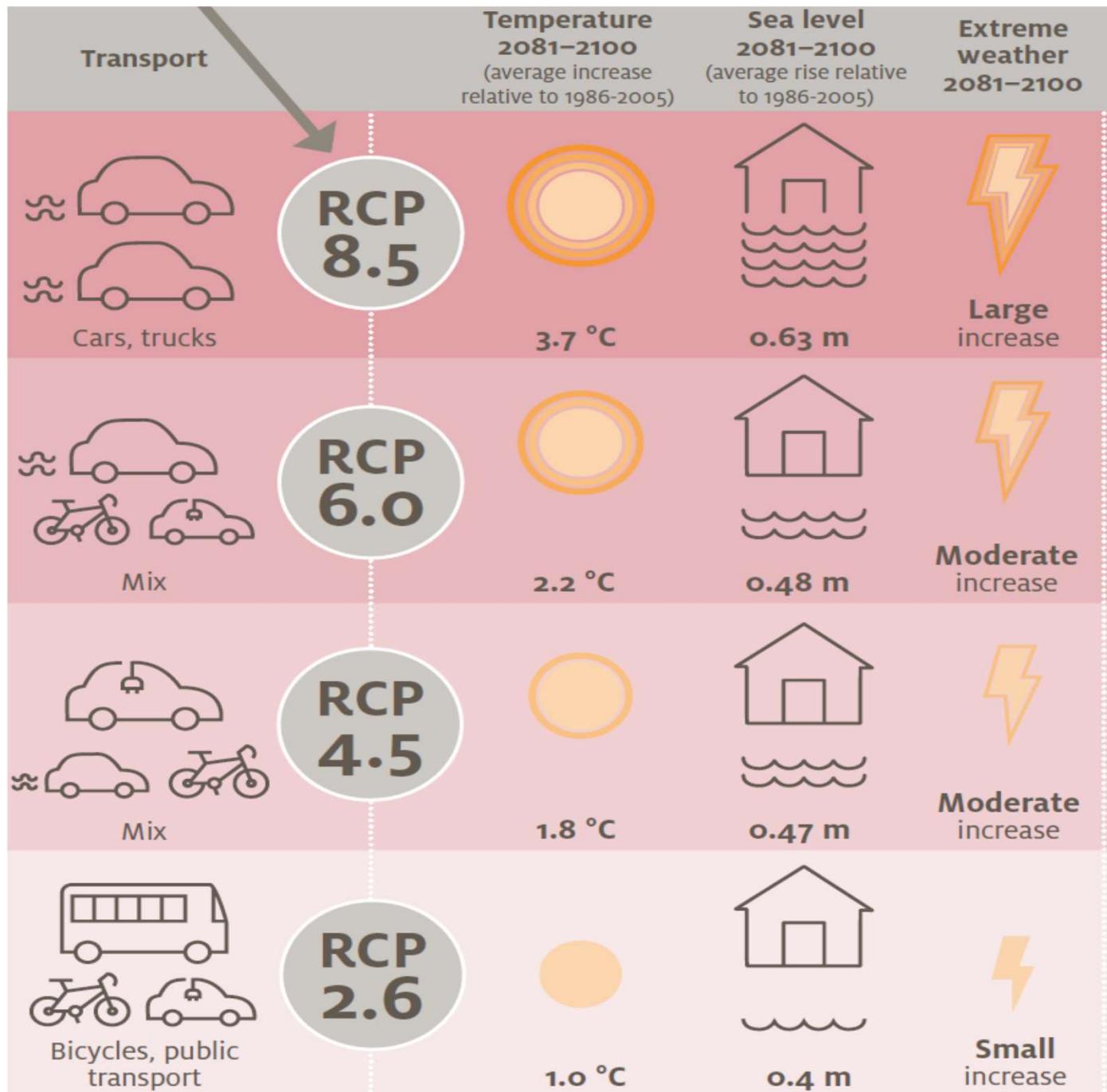
GCM output

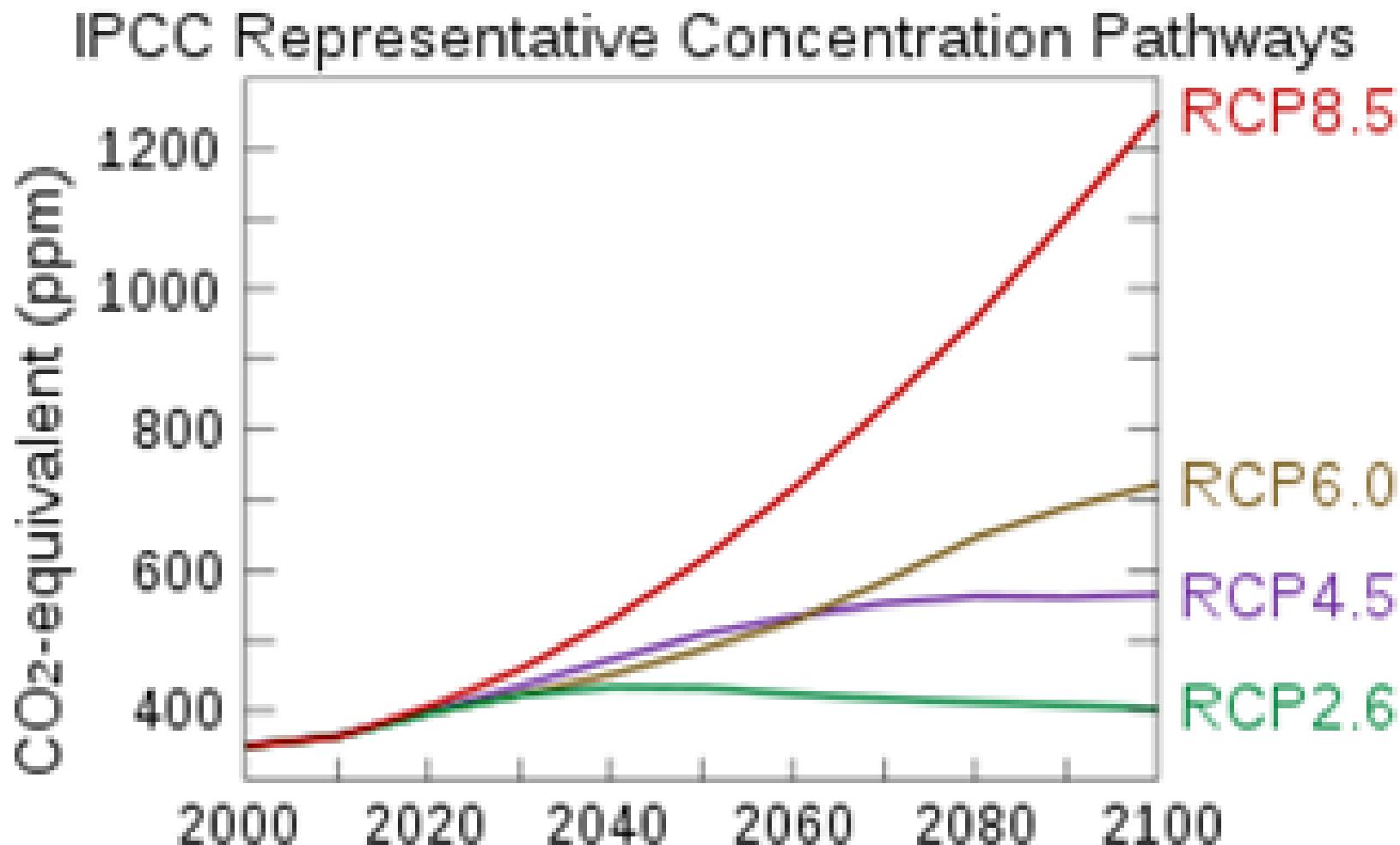
- Temperatures and humidity of different layers of the atmosphere from the surface to the upper stratosphere
- Temperatures, salinity and acidity (pH) of the oceans from the surface down to the sea floor
- Estimates of snowfall, rainfall, snow cover and the extent of glaciers, ice sheets and sea ice
- They generate wind speed, strength and direction, as well as climate features, such as the jet stream and ocean currents

- Cloud cover and height
- Produce an estimate of climate sensitivity. They calculate how sensitive the Earth is to increases in greenhouse gas concentrations

Representative Concentration Pathways (RCP)

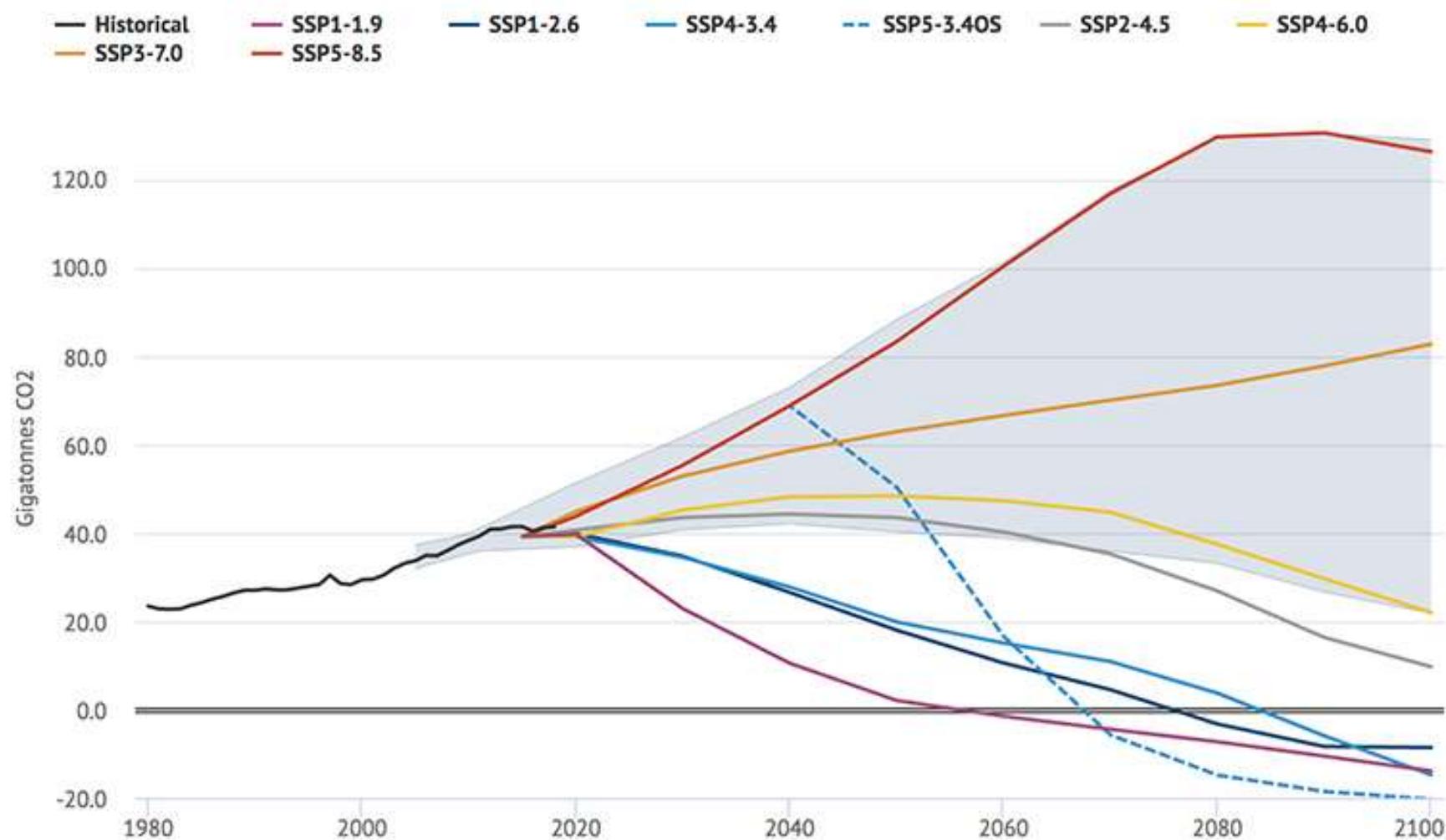
- A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by the IPCC
- Four pathways were used for climate modeling and research for the IPCC 5th Assessment Report (AR5) in 2014
- The pathways describe different climate futures, all of which are considered possible depending on the volume of GHG emitted in the years to come
- The RCPs – originally RCP2.6, RCP4.5, RCP6, and RCP8.5 – are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m², respectively)



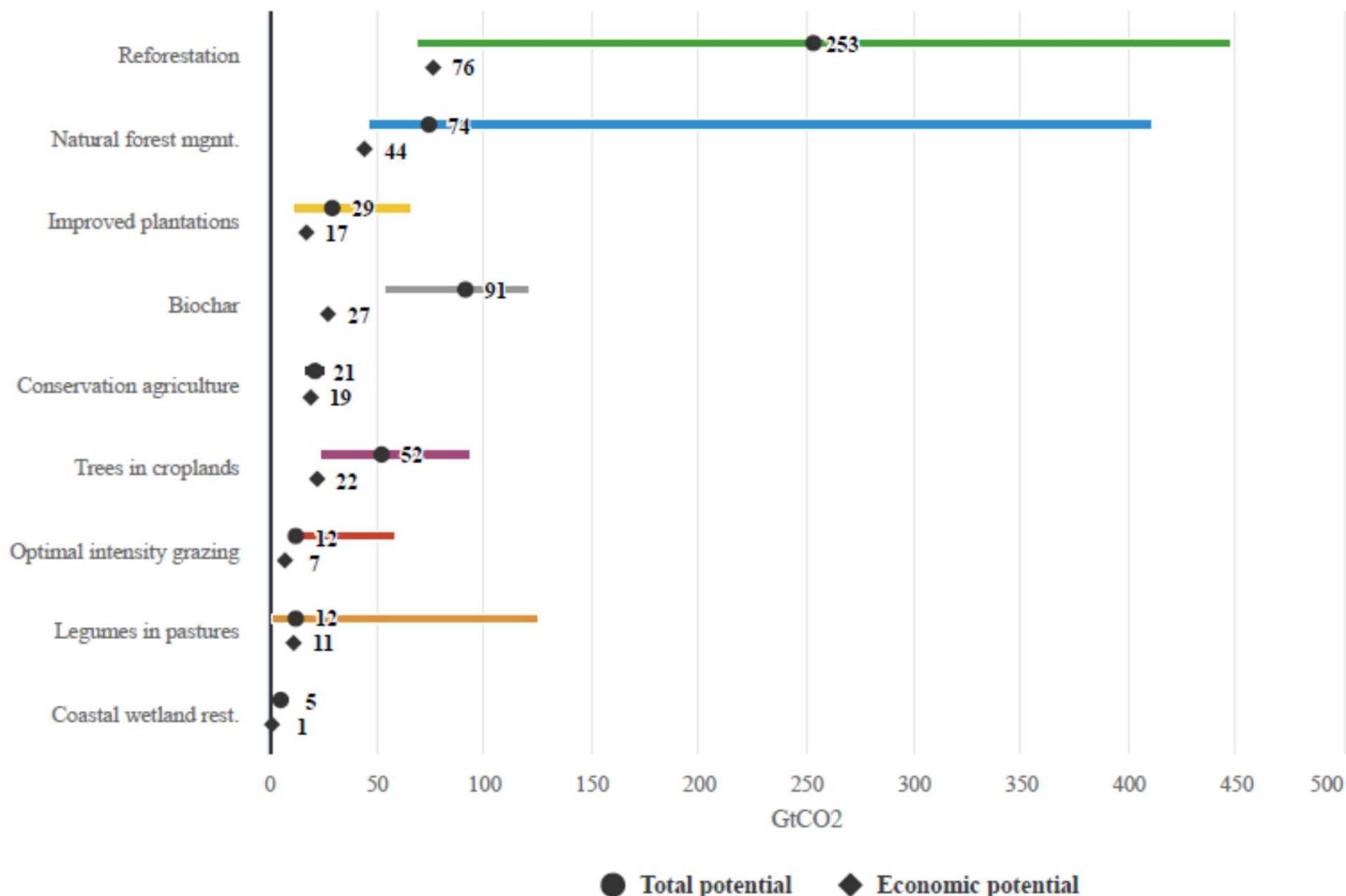


All forcing agents' atmospheric CO₂-equivalent concentrations (ppm) according to the four RCPs used by the fifth IPCC Assessment Report to make predictions

CO2 emissions in CMIP6 scenarios



Negative emissions potential of natural climate solutions



Negative emissions potentials from different NCS, in cumulative GtCO₂ between 2018 and 2100. Bars show uncertainties in total potential, while black circles show best-estimates of total potential and diamonds show economic potential at a cost of less than \$100 per ton CO₂. Estimates are based on both the rate of sequestration and the time horizon over which the sequestration can continue from [Griscom et al. 2017](#)

IPCC 6th Assessment Report

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely Range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO ₂ emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0 – 1.8
SSP1-2.6	low GHG emissions: CO ₂ emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4
SSP2-4.5	intermediate GHG emissions: CO ₂ emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	high GHG emissions: CO ₂ emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6
SSP5-8.5	very high GHG emissions: CO ₂ emissions triple by 2075	2.4 °C	4.4 °C	3.3 – 5.7