Climate Change Notes

Hankertrix

April 29, 2025

Contents

1 Definitions

1.1 Climate

Climate is defined in terms of the **average (mean)** of weather elements, such as temperature and precipitation, over a specified period, which is at least **30 years** according to the World Meteorological Organisation (WMO).

1.2 Weather

Weather is defined as the state of the atmosphere at some place and time, usually expressed in terms of temperature, air pressure, humidity, wind speed and direction, precipitation, and cloudiness.

1.3 Climate change

Climate change specifically applies to **longer-term variations (years and longer)**, in contrast to the shorter fluctuations in weather that last hours, days, weeks, or a few months.

1.4 Thermal radiation

- Thermal radiation is electromagnetic radiation generated by the thermal motion of particles in matter.
- All objects emit electromagnetic radiation as long as they have a temperature above absolute zero on the Kelvin (K) scale. The radiation represents a conversion of a body's internal energy into electromagnetic energy.

1.5 Flux

Flux is the energy per unit area.

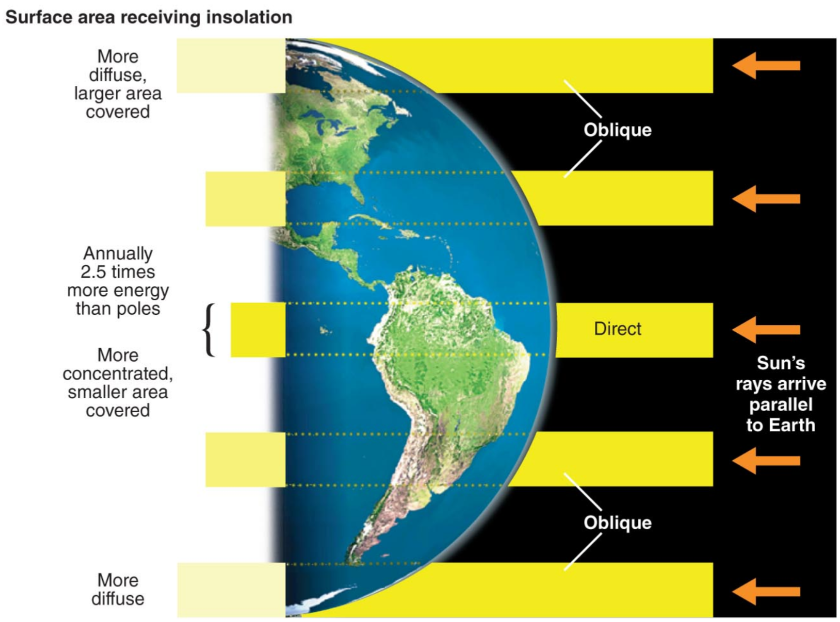
1.6 Albedo

The albedo is the fraction of the Sun's energy flux that gets reflected into space.

1.7 Blackbody

- Blackbody is an object that absorbs all radiation falling on it at all wavelengths.
- Blackbody is an idealised non-reflective body, which does not exist in nature.
- However, many objects can approximate the behaviour of a blackbody over a limited range of wavelengths or temperatures.
- The sun emits shortwave radiation due to it being hotter (shorter wavelength means higher energy) while the Earth emits longwave radiation due to it being cooler (longer wavelength means lower energy).

1.8 Differential heating



The radiative power absorbed by the Earth decreases with latitude as energy from the sun is constant, but the area increases with latitude.

1.9 Pressure

Pressure is the **force exerted per unit are perpendicular to the force**.

$$P = \frac{F}{A}$$

In a fluid, the pressure at a location is the same from all directions.

1.10 Ideal gas law

$$P = \rho R T$$

Where:

- ρ is the density
- T is the temperature in K
- R is the specific gas constant ($287\,\mathrm{J\,K^{-1}\,kg^{-1}}$ for air)

This means that the pressure of air:

- Increases with increasing density if temperature is kept constant
- Increases with increasing temperature if density is kept constant.

1.11 Vertical pressure gradient

Vertical pressure gradient is the differential of the pressure in the vertical direction, and it is equal to the negative of the density of the fluid multiplied by the gravitational acceleration.

$$\frac{dp}{dz} = -\rho g$$

1.12 Hydrostatic balance

$$\frac{\Delta p}{\Delta z} = \frac{dp}{dz} = -\rho g = -\frac{p}{RT} g$$

Hydrostatic balance is the equilibrium that exists between **the force due to vertical pressure gradient** and the **weight of a fluid** such that the fluid remains at rest in the vertical direction.

This is a **very good approximation** for the atmosphere and the oceans because vertical motion is generally weak.

Since the right-hand-side of the equation is negative, **pressure must decrease upwards** for the fluid to support its own weight.

1.13 Meridional

Meridional just means from north to south or vice versa.

1.14 Trade winds

Trade winds are winds that blow form the east (i.e. easterly winds) throughout the year.

1.15 Monsoons

- Monsoons are winds that blow in one direction for half a year and in the **opposite direction** in the other half-year.
- "American monsoons" change directions less dramatically.

1.16 Walker circulation

- The Walker circulation is the circulation that exists in the equatorial plane of the atmosphere.
- The Walker circulation blows from east to west.
- Due to the coupled interaction between the tropical atmosphere and the upper layer of the Pacific Ocean, it undergoes an **irregular** interannual oscillation known the **El Niño Southern Oscillation (ENSO)**.

1.17 El Niño Southern Oscillation (ENSO)

- El Niño / La Niña refers the phase of the ocean conditions.
- Southern Oscillation refers to the atmospheric conditions.
- Southern Oscillation Index (SOI) is the surface pressure at Tahiti minus that at Darwin, Australia. It is used to characterise the phase of ENSO.

1.17.1 El Niño

- El Niño is basically a reversal or relaxation of the walker circulation.
- Trade winds weaken or even change direction and blow the other way, and the warm water piled up near Australia sloshes to the east.
- During El Niño, Australia and Asia's temperature will **decrease**, and South America's temperature will **increase**.

1.17.2 La Nina

- During La Niña, Australia and Asia's temperature will **increase**, and South America's temperature will **decrease**.

1.18 Cyclones

Cyclones are low-pressure systems at the surface. Cyclones have **surface** winds that spiral **inward** in the **anticlockwise** direction in the **Northern** Hemisphere. The rotation of the cyclone is **opposite** in the **Southern** Hemisphere, which means the surface winds spiral **outward** in the **clockwise** direction in the **Southern** Hemisphere.

1.18.1 Extratropical cyclone

- Extratropical cyclones are cyclones that occur in areas outside tropical and equatorial areas.
- Mid-latitude weather is dominated by extratropical cyclones.

1.19 Anticyclones

Anticyclones are high-pressure systems at the surface. They have **surface** winds that spiral **outward** in the **clockwise** direction in the **Northern** Hemisphere. The rotation of the anticyclone is **opposite** in the **Southern** Hemisphere, which means the surface winds spiral **inward** in the **anticlockwise** direction in the **Southern** Hemisphere.

1.20 Tropical cyclones (TC)

- They are circulating storms that have a typical diameter of about $500\,\mathrm{km} - 2000\,\mathrm{km}$ (for winds $> 15\,\mathrm{m\,s^{-1}}$).
- They have the **warmest** air and the **lowest pressure** at the centre and last a few days.
- The surface flow is **anticlockwise** in the **Northern** Hemisphere and clockwise in the **Southern** Hemisphere.
- Tropical cyclones have become more intense, and more destructive tropical cyclones are forming more often.

1.21 Madden-Julian Oscillations (MJO)

- Madden-Julian Oscillations are part of a planetary-scale mode of tropical variability, in which convection develops over the western tropical Indian Ocean south of the equator, propagates slowly eastward across the Indian Ocean and Maritime Continent

- It is a coupled ocean-atmosphere system with a 30 - 60 day oscillation in the tropical atmosphere, with super-clusters of cloud or rain **moving eastward** from the East African coast across the Indian Ocean, through Southeast Asia, and into the Pacific Ocean.

1.22 Rossby waves

Rossby waves are **westward** moving **equatorial** waves of convection along the equator for 3 - 10 days.

1.23 Kelvin waves

Kelvin waves are **eastward** moving **equatorial** waves of convection along the equator for 3 - 10 days.

1.24 Cold surge

Cold surge events typically occur during the **northeast winter monsoon season**. Bursts of cool dense air from the Asian continent penetrate into the South China Sea and persist for a few days.

1.25 Borneo vortex

A Borneo vortex typically appears off the northwestern coast of northern Borneo. When a Borneo vortex encounters a cold surge, they can spin up into an **anticlockwise vortex** near Borneo island and bring lots of rain into the region.

1.26 Squall

Squall is just a long line of clouds.

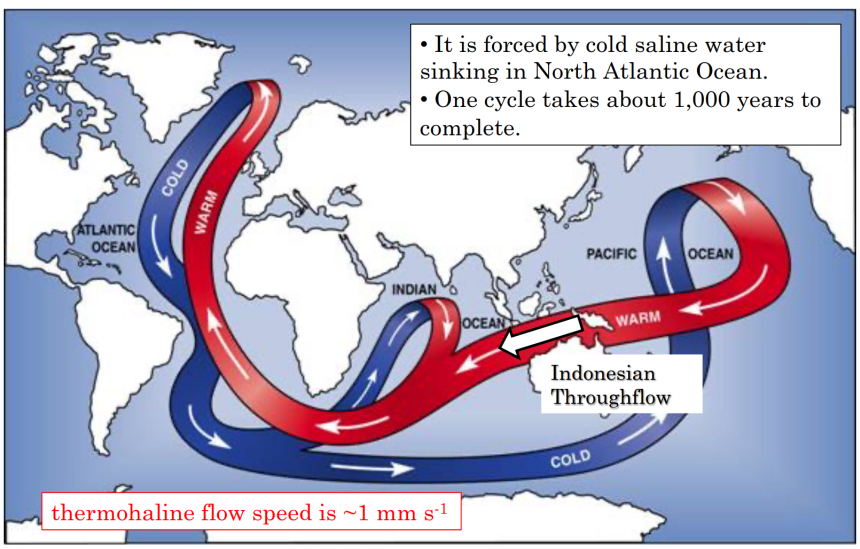
1.27 Sumatra squalls

- Sumatra squalls are initiated by convergent effects at night over the Sumatra west coast or the Malacca Straits, and then move east towards Singapore and the Malaysian Peninsula during the early morning, and later dissipate in the South China Sea.
- They typically appear during **the southwest summer monsoons season**, bringing in wind gusts and thunderstorms.

1.28 Bathymetry

Bathymetry refers to the topography of the sea floor.

1.29 Thermohaline conveyor belt



1. Deep water formation
2. Spreading of deep water
3. Upwelling
4. Near-surface currents

1.30 Ocean eddies

- Ocean eddies are created by **surface winds** on weather timescales, by **bathymetry (sea-floor topography)** and by instabilities in the currents.

- Ocean eddies are relatively small, contained pockets of moving water that break off from the main body of a current and travel independently of their parent. They can form in almost any part of a current.

- Ocean eddies, in a sense, are the weather of the ocean. They do not only influence heat uptake or heat transport in the oceans, but also the distribution of nutrients or the ability to absorb carbon from the atmosphere. This makes them important for global ocean circulation.

1.31 Waves

- Surface waves are created by **friction with surface winds**.

- They can grow very large as they propagate into shallow seas.

- Tsunamis are created by underwater **earthquakes**, **landslides**, **volcanic eruptions**.

1.32 Vapour pressure (e)

Vapour pressure (e) is the partial pressure exerted by the water vapour in moist air. It is a measure of the amount of water vapour in the air.

1.33 Saturated vapour pressure (e_s)

Saturated vapour pressure with respect to water or ice is the vapour pressure attained when the water vapour is in equilibrium with liquid water or ice.

1.33.1 Bolton (1980) empirical formula

$$e_s \approx 6.112 e^{\frac{17.67 T_C}{T_C + 243.5}}$$

Where:

- T_C is the temperature in degrees Celsius

Saturated vapour pressure increases exponentially with T, which is the *Clausius-Clapeyron* relationship.

When $e > e_s$, condensation occurs.

1.34 Relative humidity (H)

Relative humidity is the ratio of the observed vapour pressure to the saturated vapour pressure with respect to water or ice at the **same temperature and pressure**. The relative humidity is expressed as a percentage.

$$H = \frac{e}{e_s} \times 100\%$$

1.35 Specific humidity (q)

Specific humidity is the mass of water vapour per unit mass of moist air.

$$q = \frac{\rho_v}{\rho_m}$$

Where:

- ρ_v is the density of water vapour
- ρ_m is the density of moist air

1.36 Adiabatic

Adiabatic means that there is no net input of heat.

1.37 Adiabatic lapse rate

- The rate at which temperature decreases in a rising, expanding air parcel.
- Dry adiabatic lapse rate, i.e., without condensation produced, is a constant at $9.8\,^{\circ}\mathrm{C\,km^{-1}}$.
- However, if moist air saturates and condensation occurs, saturated adiabatic lapse rate can be significantly lower, going down to $4\,^{\circ}\mathrm{C\,km^{-1}}$.

1.38 Paleoclimate

Paleoclimate refers to the climate of the Earth at a specified point in geologic time.

1.39 Paleoclimate archives

Paleoclimate archives consist of geologic (e.g. sediment cores) and biologic (e.g. tree rings) materials that **preserve evidence of past changes in climate**.

1.39.1 Examples

- Corals
- Marine and lake sediments
- Sediment cores
- Tree rings
- Ice cores
- Speleotherms (cave carbonate deposits)

1.40 Paleoclimate proxies

Paleoclimate proxies are **preserved physical characteristics** of the **past** that **stand in** for direct meteorological measurements and enable scientists to reconstruct the climatic conditions over a longer fraction of the Earth's history.

1.40.1 Examples

- Physical properties
- Chemical composition

1.40.2 Using oxygen as a climate proxy

- In 1950, Harold Urey determined that the abundance of ^{18}O relative to ^{16}O in carbonates could be used as a way of determining temperature.
- Foraminifera use oxygen in the seawater to make their shells.
- If the water molecules in the ocean are relatively richer in ^{18}O when they form their shells (like during an ice age), the foraminifera's shells will also have a relatively greater concentration of ^{18}O. Hence, their tiny shells are chemical records of the waxing and waning of Earth's great ice sheets.

1.40.3 Using ice cores as a climate proxy

- The interglacial period has less land ice. Hence, there is more ^{18}O in ice, and less ^{18}O in the ocean.
- The glacial period means there is more land ice. Hence, there is less ^{18}O in ice and more ^{18}O in the ocean.
- Temperature is positively correlated with CO_2 and CH_4, and negatively correlated with ice volume. But a change in global-mean surface temperature of about $4 - 5$ °C between glacial periods and interglacial periods is a massive climate shift.
- Glacial-interglacial cycles have a sawtooth shape and there is an abrupt warming towards the end of the glacial periods.
- The end of glacial periods are called terminations.

1.41 Circumpolar

Circumpolar means something is located or found in one of the polar regions, so either in the Arctic or in Antarctica.

1.42 Anthropocene

- Anthropocene refers to the age of humans.
- The proposed beginning of the Anthropocene is 1950.

1.43 Global warming

- Global warming is the phenomenon of increasing average air temperatures near the Earth surface (**surface warming**) over the past **100 - 200** years.
- In contrast, the stratosphere is experiencing cooling (**stratospheric cooling**).
- From 1986 to 2022, temperatures declined in the higher levels of Earth's atmosphere, while increasing in the layers of the atmosphere closest to the Earth's surface.
- The mesosphere and lower thermosphere are also experiencing cooling.
- **Stratospheric cooling is faster than surface warming**.

1.44 Heat capacity

Heat capacity is the amount of heat required to raise the temperature of the object by exactly 1 °C (or 1 K).

- Specific heat capacity (one gram)
- Molar heat capacity (one mole)

$$\text{Heat capacity} = \text{Specific heat capacity} \times \text{mass}$$

Substance	Specific heat capacity at 25 °C ($J\,g^{-1}\,K^{-1}$)	Earth system	Mass (kg)
Water (liquid)	4.18	Oceans (covers 70% of the Earth's surface)	1.4×10^{21}
Air (typical room conditions)	1.012	Atmosphere	5.15×10^{18}
Soil or sand	Roughly 0.8	Land (Solid Earth)	6.0×10^{24}

1.45 Orbital cycles

Three periodic motions in Earth's orbit, known as Milankovitch cycles contribute a predictable amount of variation to Earth's climate over timeframes of tens of thousands to hundreds of thousands of years.

1.45.1 Changes in eccentricity (orbit shape)

100,000-year cycles

1.45.2 Axial precession (wobble)

26,000-year cycles

1.45.3 Changes in obliquity (tilt)

41,000-year cycles

1.46 Anthropogenic CO_2 multiplier (ACM)

The anthropogenic CO_2 multiplier (ACM) is the ratio of annual anthropogenic CO_2 to maximum preferred estimate for annual volcanic CO_2, which is an index of anthropogenic CO_2's dominance over volcanic CO_2 emissions.

1.47 Carbon cycle

- The carbon cycle is a whole system of processes that move the element carbon in various forms through the Earth's biosphere (living matter), atmosphere (air), hydrosphere (water), cryosphere (frozen ground), and geosphere (land).
- As only a tiny number of atoms reach the Earth from space, the Earth is a closed system.
- **Earth does not gain or lose carbon. But carbon does move constantly from place to place.**

1.47.1 Importance of the carbon cycle

- Carbon is the 4th most abundant element in the universe.
- Carbon is the foundation of all life on Earth, required to form complex molecules like proteins and DNA.
- Carbon is a key ingredient in the food that sustains us (carbohydrates).
- Carbon provides a major source of the energy consumed by human civilisation (fossil fuels).
- Carbon helps to regulate the Earth's temperature (CO_2).

1.47.2 Forms of carbon in the non-living environments

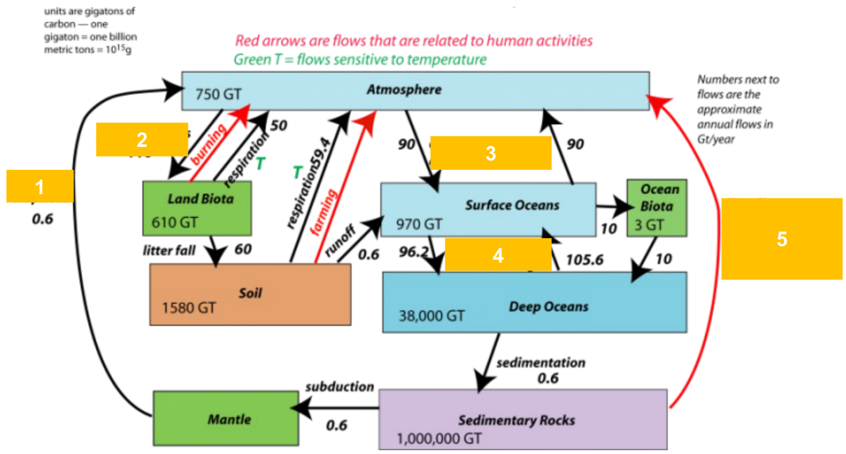
- Carbon dioxide (CO_2) in the air
- Carbon dioxide dissolved in water to form the bicarbonate ion HCO_3^-
- Carbonate rocks such as limestone ($CaCO_3$)
- Dead organic matter in the soil such as humus
- Fossil fuels from dead organic matter (coal, oil natural gas)

1.47.3 Main reservoirs of carbon

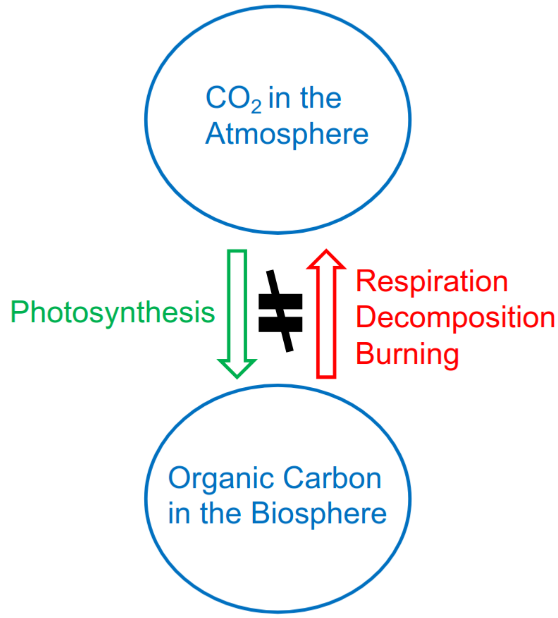
On Earth, most carbon is stored in rocks and sediments, while the rest is in the ocean, atmosphere, and in living organisms.

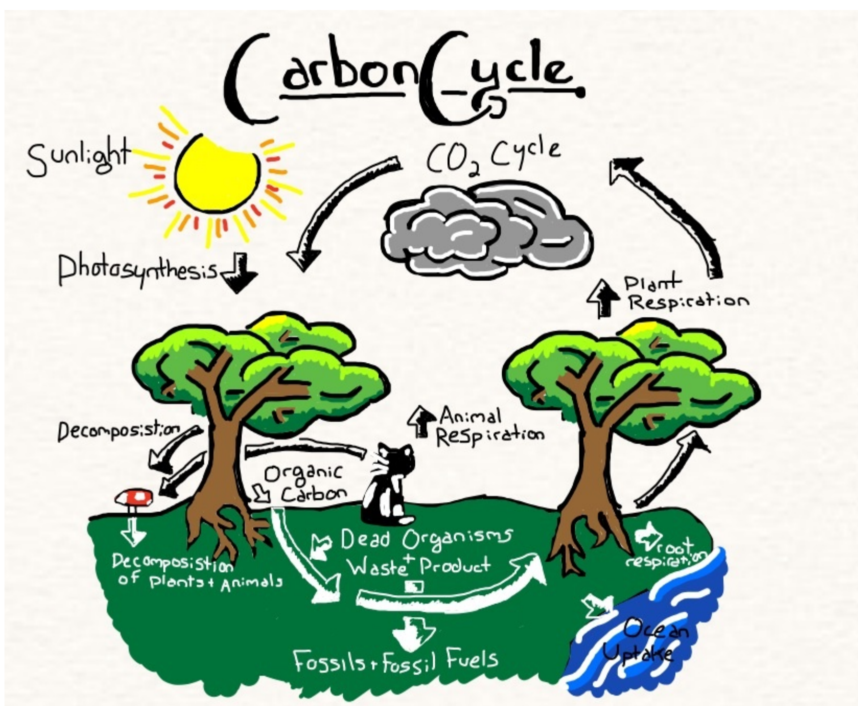
Reservoir	Amount of carbon (GT or 10^{15}g)
Mantle	Huge amount (exact amount unknown)
Sedimentary rocks	1,000,000
Deep oceans	38,000
Soil	1580
Surface oceans	970
Atmosphere	750
Land biota	610
Ocean biota	3

1.47.4 Exchanges between the main carbon reservoirs

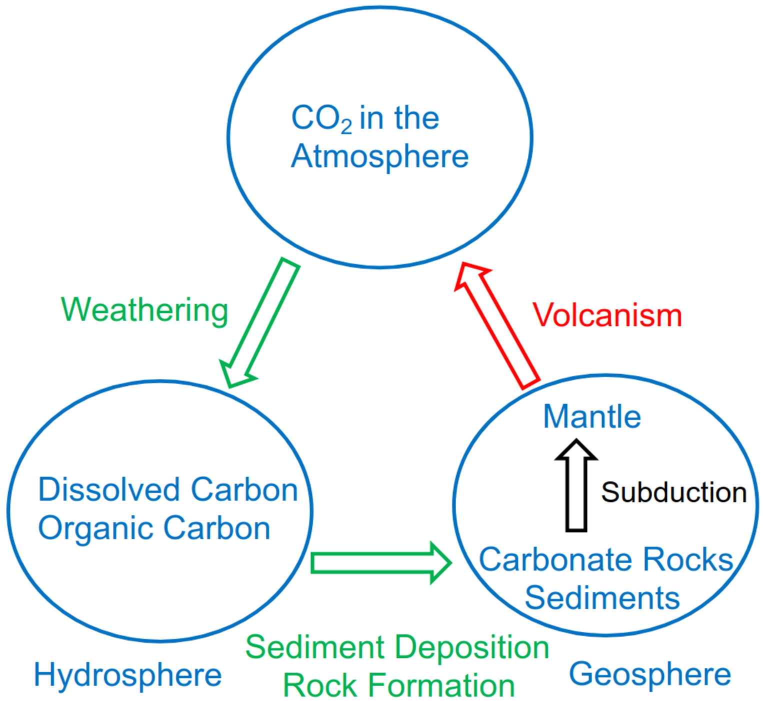


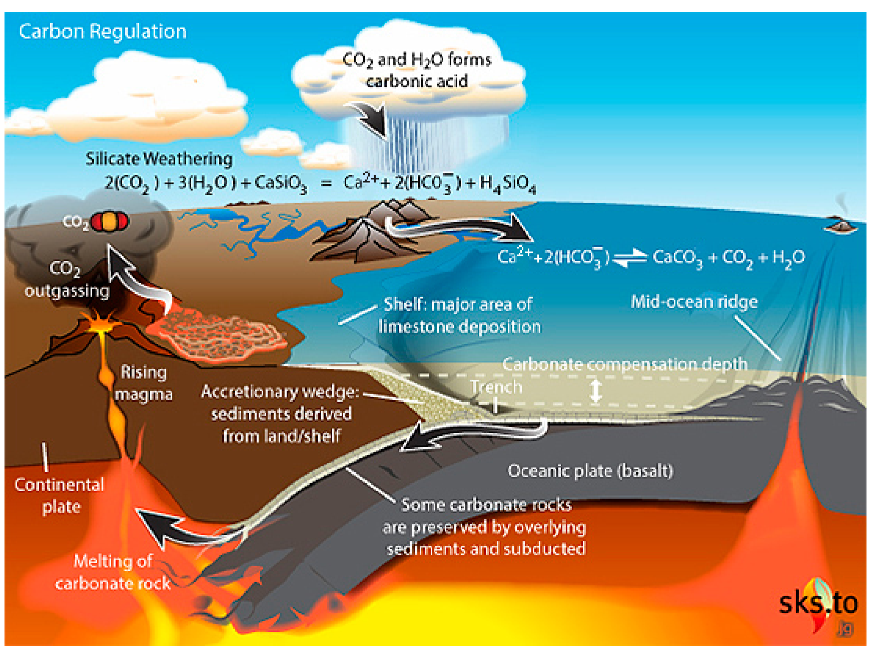
1.47.5 Fast carbon cycle





1.47.6 Slow carbon cycle



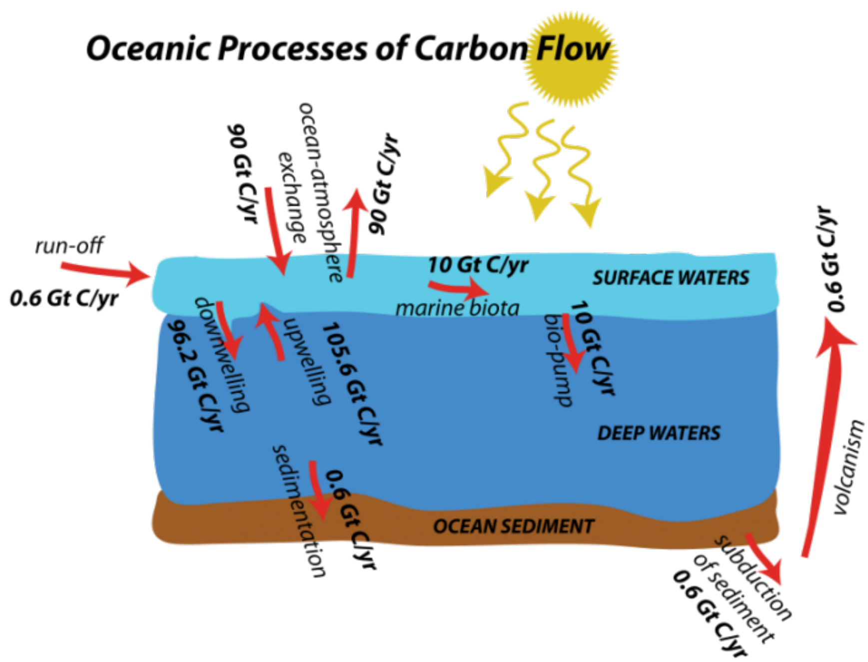


1.47.7 Comparison between the carbon cycles

Human emissions due to fossil fuel burning as well and land-use changes such as forest cutting, soil erosion, forest burning, and soil disruption due to ploughing have altered the carbon cycle.

Carbon cycle	Period	Carbon moved or emitted per year
Slow cycle	100 - 200 million years	10 to 100 million metric tons
Fast cycle	Years to decades	1,000 to 100,000 million metric tons
Human emission	100 - 200 years	10,000 million metric tons

1.47.8 Marine carbon cycle



1.48 Radiative forcing

- Radiative forcing is the change in average net radiation at the top of the troposphere which occurs because of a change in the concentration of a greenhouse gas or because of some other change in the overall climate system.
- A **positive** radiative forcing tends to **warm** the surface on average and a **negative** radiative forcing tends to **cool** the surface on average.
- It is also a measure of how the energy balance of the Earth-atmosphere system is influenced, and is the change in the balance between incoming solar radiation and outgoing IR radiation within the Earth's atmosphere.
- Forcing indicates that Earth's radiative balance is pushed away from its normal state.

1.48.1 Representative concentration pathways (RCPs)

RCP	Timeline of peak radiative forcing	Peak CO_2 concentration
8.5	More than 8.5 W m^{-2} by 2100 and constant after 2250	1370 ppm
6.0	Peaks at around 6.0 W m^{-2} before 2100, and then declines. It is constant after 2150	850 ppm
4.5	Peaks at around 4.5 W m^{-2} before 2100 and then declines. It is constant after 2150	650 ppm
2.6	Peaks at around 3 W m^{-2} before 2100 and then declines	490 ppm

1.49 Carbon sinks

Carbon sinks refer to places where carbon is stored away from the atmosphere.

1.50 Carbon budget

Carbon budget refers the total net amount of CO_2 that can still be emitted by human activities while limiting global warming to a specified level.

1.51 Earth Observatory of Singapore

The Earth Observatory of Singapore conducts fundamental research on earthquakes, volcanic eruptions, tsunamis and climate change in and around Southease Asia, toward safer and more sustainable societies.

1.52 King tide

When the Earth, Sun, and Moon are aligned such that the tides at the highest levels. This happens twice a year.

1.53 Pro-glacial forebulge

A pro-glacial forebulge is formed due to the weight of an ice sheet pressing down on the earth, lifting the surrounding land around the ice sheet up.

1.54 Hazard

The potential occurrence of a natural or human-induced **physical event or trend** that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

1.55 Climate hazard

Climate-related physical events or trends that have the potential to cause damage and loss. Climate hazards can be climatological, meteorological, or hydrological.

1.55.1 Physical events

- Flood
- Tornado
- Tropical cyclone
- Convective storm
- Drought
- Haze
- Wildfire
- Heat wave
- Extreme temperature

1.55.2 Trends

- Global warming
- Sea level rise
- Drying trend
- Ocean acidification

1.56 Climate disaster

- Events caused by climate hazards, resulting in severe damage and loss.
- **Not all hazards** result in disasters!

1.57 Extreme event

1.57.1 General definition

- Extreme **weather** event: an event that is **rare** at a particular **place and time** of the year.
- Extreme **climate** event: a pattern of extreme weather that persists from some time, such as a season.
- For simplicity, both extreme weather events and extreme climate events are referred to collectively as **"climate extremes"**.

1.57.2 Statistical definition

The occurrence of a value of a weather or climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable.

- Relative (e.g. 90th percentile or 10th percentile) thresholds
- Absolute (e.g. 35 °C$forahotday$) thresholds

1.57.3 Changes in extremes

Changes in extremes can be examined from two perspectives:

1. Changes in the frequency for a given magnitude of extremes.
2. Changes in the magnitude for a particular return period (frequency).

1.58 Climate risk framework

1.58.1 Exposure

The **presence** of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure or economic, social, or culrutal assets in places and settings that could be adversely affected.

1.58.2 Vulnerability

The **propensity or predisposition** to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

1.58.3 Risk

The potential for **adverse** consequences for **human or ecological systems**, recognising the diversity of values and objectives associated with such systems.

- Risks can arise from the dynamic interactions among climate-related hazards, the exposure and vulnerability of affected human and ecological systems.

- Risk can arise from potential impacts of climate change as well as human responses to climate change.

1.58.4 Impacts

The consequences of realised risks on **natural and human systems**, where risks result from the interaction of climate-related hazards, exposure, and vulnerability.

- Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure.

1.59 Climate impact-driver (CID)

A physical climate system condition that directly affects society or ecosystems. Depending on system tolerance, CIDs and their changes can be **detrimental, beneficial, neutral, or a mixture** of each across interacting system elements and regions. These conditions include:

1. **Mean**: A long-term average condition (such as the average winter temperatures that affect indoor heating requirements)

2. **Event**: A common event (such as a frost that kills off warm-season plants)

3. **Extreme**: An extreme event (such as a one-in100-year flood that destroys homes)

A CID or its change caused by climate change is not universally hazardous or beneficial, but we refer to it as a "hazard" when experts determine it is detrimental to a specific system. CIDs includes climate hazards.

1.60 Climatic threshold

A level beyond which there are either gradual changes in system behaviour or abrupt, non-linear and potentially irreversible impacts.

1.60.1 Natural thresholds

For example, the growth of a crop.

1.60.2 Structural thresholds

For example, the height at which a building is built at.

1.61 Thermodynamic changes

The local exchanges in heat, moisture, and other related quantities.

1.62 Dynamic changes

Changes associated with atmospheric and oceanic motions.

1.63 Global climate model (GCM)

- A global climate model uses hundreds of mathematical equations to describe processes that happen on our planet, processes like wind, ocean currents, and plant growth. Maths and Physics are also used to describe how Earth processes are related to each other.

- A global climate model typically contains enough computer code to fill 18,000 pages of printed text. It takes hundreds of scientists many years to build and improve.

1.63.1 Importance

- We do not have observations from every portion of Earth.

- It allows for better understanding of the present climate system and its sensitivity to external perturbations.

- Future climate cannot be extrapolated from the past, as future concentration of greenhouse gases is unknown.

- Climate models help us attribute past climate changes to quantify the contribution from natural forcing and human-induced forcing.

1.64 Courate-Friedrichs-Lewy (CFL) condition

- This condition is needed for numerical simulations.
- The computational time step is less than the wave travel time to adjacent grid points.

1.65 Coupled model intercomparison project (CMIP)

- WCRP working group on climate modelling (WGCM) fosters the development and review of coupled climate models.
- WGCM formed (1995) CMIP to better understand past, present, and future climate changes in response to radiative forcing in a multimodel context.
- CMIP phase 3 (CMIP3) was in 2007.
- CMIP phase 5 (CMIP3) was in 2009.
- CMIP phase 6 (CMIP3) was in 2016.

1.66 Socioeconomic pathways (SSPs)

- SSPs are scenarios of projected socioeconomic global changes up to 2100
- They are used to derive greenhouse gas emissions scenarios with different climate policies, like population, economic growth, and urbanisation, that could shape our societies.

1.67 Uncertainties in climate projections

- Uncertainty in climate projections refers to a value or relationship that is unknown. Uncertainty can be represented by quantitative measure.
- In other words, uncertainty is any departure from complete deterministic knowledge of the relevant system.
- As time progresses, uncertainty increases and the relative role of internal variability decreases.
- As time progresses, human sources of uncertainties, like the differences among RCPs, increases.

1.67.1 Internal variability

Very similar initial conditions or forcing leads to different results for a single climate model.

1.67.2 Model uncertainty

Different models yield different results for the same emission scenario.

1.67.3 Scenario uncertainty

Spread of model solutions created using different RCP scenarios, related to out lack of knowledge in how future anthropogenic emissions will evolve.

1.67.4 Dealing with uncertainties

Understanding and incorporating uncertainties in climate projections is essential for robust decision-making and mitigation of climate change risks. The ways to deal with uncertainties include:

- Incorporating multiple scenarios.
- Incorporating multimodel or large-ensemble simulation results
- Incorporating multiple sources (model, paleo-climate data, observations, expert judgment, etc.)
- Enhanced effort on climate model development and reduction in model biases.

2 Radiative balance model

- The Sun's energy flux F_s comes through a disk of radius a, which is the Earth's radius.
- A fraction A (albedo) of the Sun's energy flux gets reflected into space.
- The remaining fraction $1 - A$ is absorbed by the Earth. The Earth re-emits the radiation into space uniformly in all directions.
- Assuming the Earth is a blackbody, the radiative flux emitted by the Earth can be calculated using the Stefan-Boltzmann law.

$$F_B = \sigma T^4$$

  Where:

  - T is the absolute temperature of the body and σ is the Stefan-Boltzmann constant $5.670 \times 10^{-8}\mathrm{W\,m^{-2}\,K^{-4}}$

- Radiative balance requires that the energy received from the Sun equals the energy emitted by the Earth:

$$F_s(1 - A)\pi a^2 = F_B(4\pi a^2)$$

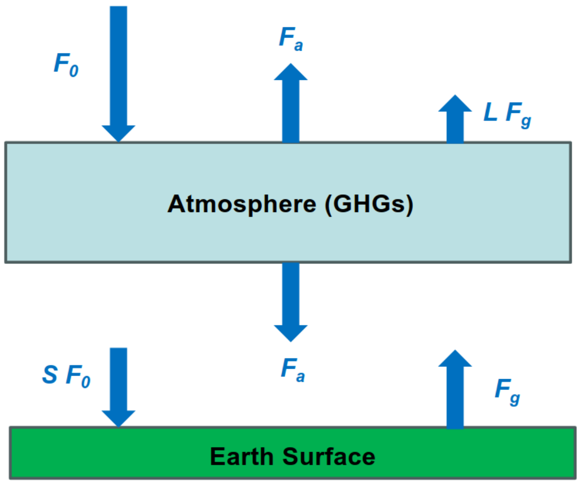
$$F_B = \frac{1}{4}F_s(1 - A)$$

- Plug in the Stefan-Boltzmann law:

$$\sigma T^4 = \frac{1}{4}F_s(1 - A)$$

$$T = \left[\frac{F_s(1 - A)}{4\sigma}\right]^{\frac{1}{4}}$$

2.1 With atmosphere



- Assume the Earth atmosphere transmits fraction S of the incident solar flux F_0 and a fraction L of the incident terrestrial flux F_g at the surface (ground or sea).
- Having absorbed this radiation, the atmosphere re-emits with a flux of F_a back to the Earth's surface and to space.
- From above, we know that the average incident solar flux that is absorbed by the Earth is less than what is scattered back to space, specifically:
$$F_0 = \frac{1}{4}F_s(1-A)$$
- At the top of the atmosphere, radiative balance requires:
$$F_0 = F_a + LF_g \Rightarrow F_a = F_0 - LF_g$$
- At the bottom of the atmosphere, radiative balance requires:
$$F_a + SF_0 \Rightarrow F_a = F_g - SF_0$$
- Hence:
$$F_0 - LF_g = F_g - SF_0$$
$$F_g = F_0\frac{1+S}{1+L}$$
$$T_g = \left[\frac{F_s(1-A)}{4\sigma}\frac{1+S}{1+L}\right]^{\frac{1}{4}} \quad \left(\because\ F_0 = \frac{1}{4}F_s(1-A)\right)$$

2.2 Summary

2.2.1 Without atmosphere

$$T = \left[\frac{F_s(1-A)}{4\sigma}\right]^{\frac{1}{4}}$$

2.2.2 With atmosphere

$$T = \left[\frac{F_s(1-A)}{4\sigma}\frac{1+S}{1+L}\right]$$

3 Structure of the atmosphere

From the lowest layer to the highest layer:

Name	Height above the ground (km)	Temperature range (°C)
Troposphere	9 to 16	30 to -75
Stratosphere	15.5 to 50	-75 to 0
Mesosphere	50 to 85	0 to -90
Thermosphere	85 to 600	-90 to 1500+
Exosphere	600 to 100,000	?

4 Atmospheric composition

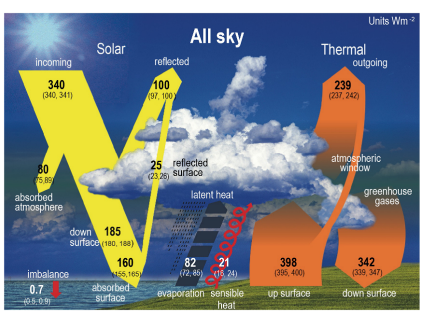
Gas	Percentage of atmosphere (%)
Nitrogen (N_2)	78.084
Oxygen (N_2)	20.946
Argon (Ar)	0.9340
Carbon Dioxide (CO_2)	0.0417

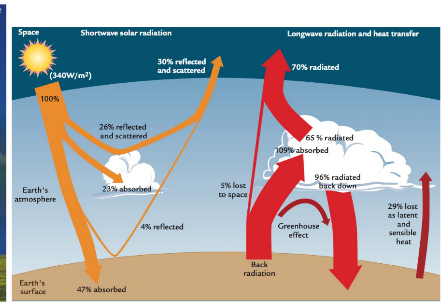
4.1 Trace gases

Gas	In ppm
Neon (Ne)	18.18
Helium (He)	5.24
Methane (CH_4)	1.87
Krypton (Kr)	1.14
Hydrogen (H_2)	0.55
Nitrous Oxide (N_2O)	0.50
Xenon (Xe)	0.09
Ozone (O_3)	0.07
Nitrogen Dioxide (NO_2)	0.02
Iodine (I)	0.01
Water Vapour (H_2O)	0 - 30,000 (0% - 3% of the atmosphere)

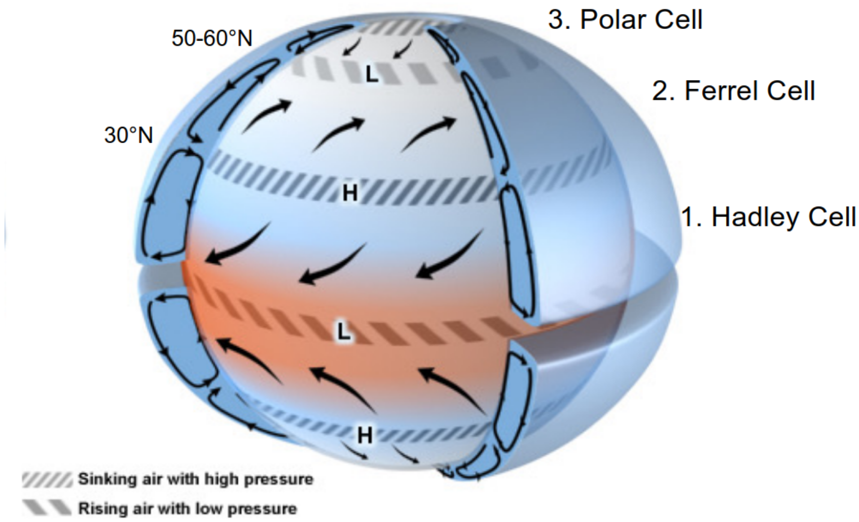
The greenhouse gases are methane (CH_4), Nitrous Oxide (N_2O), Ozone (O_3), Nitrogen Dioxide (NO_2) and water vapour (H_2O).

5 Global mean energy budget of the Earth





6 Global atmospheric conditions



7 The climate system

- The atmosphere - the air surrounding the Earth; the most variable part of the climate system.
- The hydrosphere - the part of the Earth's surface where water is in liquid form, including oceans, lakes and rivers, etc.
- The cryosphere - the part of the Earth's surface where water is in solid form, including glaciers, ice sheets and frozen ground, etc.
- The geosphere - the solid parts of the Earth (land).
- The biosphere - all living things on the Earth (ecosystem)
- The anthroposphere (people)

8 Atmospheric mass distribution

$$\frac{dp}{dz} = -\rho g = -\frac{p}{RT}g \qquad \frac{dp}{p} = -\frac{g}{RT}\,dz$$

- Pressure in the atmosphere falls roughly **exponentially** with height.
- From the ideal gas law, the atmospheric density also falls roughly **exponentially** with height (when the temperature is roughly constant).
- **Pressure** and **density** falls roughly by a factor of $e \approx 2.718$ for every ascent of h in height in the atmosphere.

$$H = \frac{RT}{g}$$

- Assuming that $T = 250\,\mathrm{K}$ on average,

$$H = \frac{\left(287\,\mathrm{J\,K^{-1}\,kg^{-1}}\right)(250\,\mathrm{K})}{9.8\,\mathrm{m\,s^{-2}}} = 7300\,\mathrm{m} = 7.3\,\mathrm{km}$$

- Hence, another equation is:

$$p = p_0 e^{\left(-\frac{z}{H}\right)}$$

8.1 Equations

$$\frac{dp}{dz} = -\rho g = -\frac{p}{RT}g$$

$$\frac{dp}{p} = -\frac{g}{RT}\,dz$$

$$p = p_0 e^{\left(-\frac{z}{H}\right)}$$

9 Energetics of atmospheric and oceanic motion

As hydrostatic balance is dominant at large scales, horizontal motion is large and vertical motion is small in the atmosphere and oceans.

1. Unequal heating of the atmosphere and oceans generates gradients in potential energy.
2. Potential energy can be converted into kinetic energy by the movement of air and ocean water.
3. Kinetic energy is then dissipated by friction.

10 General circulation of the atmosphere

Differential solar radiative heating causes a temperature gradient across the surface from the equator to the poles.

The north-south (meridional) circulation of the troposphere transport part of the heat from the equatorial zone to the polar regions. The tropical circulation is **dominated by the Hadley circulation**. There is a Hadley cell on either side of the intertropical convergence zone, located close to the equator.

Rising air in the intertropical convergence zone is replaced by **inflowing air (convergence)** at the surface. **Outflowing air (divergence)** in the upper troposphere sinks about $30°N$ and $30°S$, completing the circulation.

10.1 Hadley cell

Hot air rises in the intertropical convergence zone (ITCZ) due to shortwave absorption and sensible and latent heating. The hot air spreads polewards and cools by longwave emission.

10.2 Ferrel cell

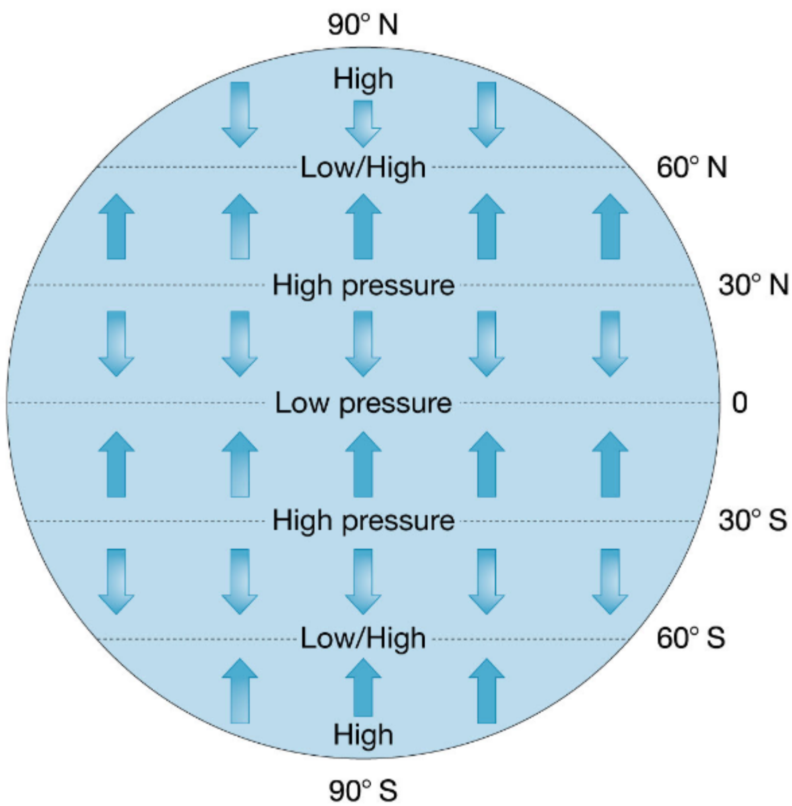
Warm subtropical air moves polewards and rises over the cold polar air at the polar front and recirculates towards the equator in the upper atmosphere.

10.3 Polar cell

Weak surface cold-air outbreaks.

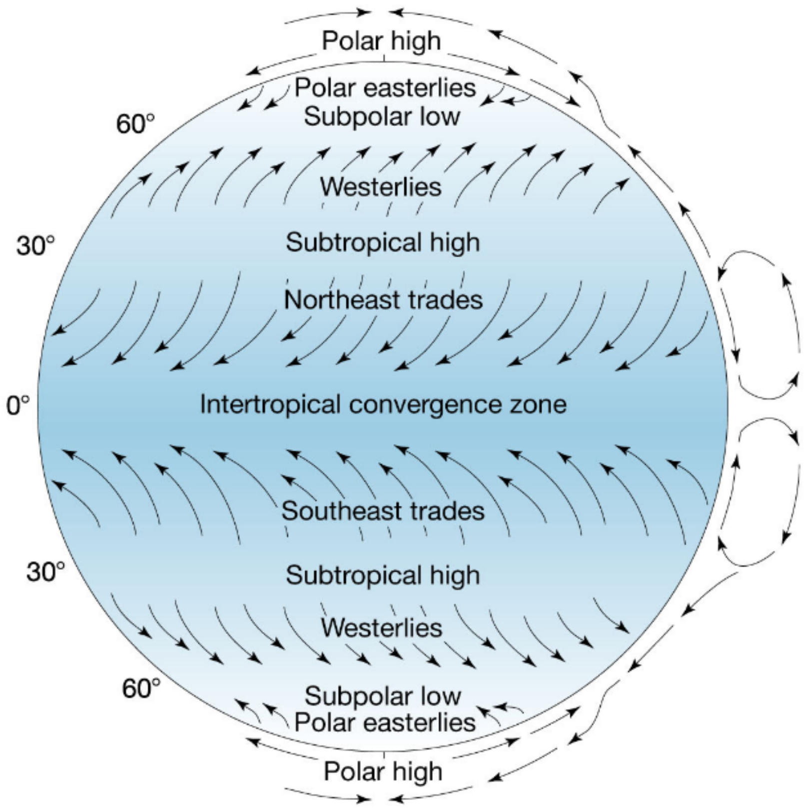
11 Distribution of surface winds

11.1 No Coriolis effect



Surface winds blow out of the **high-pressure zones at the poles and at** $30°N$ **and** $30°S$, and blows towards the **low-pressure zones at the equator and in the mid-latitudes**.

11.2 Coriolis effect



The winds are deflected to the **right** in the **Northern Hemisphere** and are deflected to the **left** in the **Southern Hemisphere**.

12 Unstable polar front

The polar front is unstable and only lasts for a few days. In the process, anticyclones (*high-pressure* systems at the surface) are usually formed upstream, and extratropical cyclones (*low-pressure* systems at the surface) in the downstream.

13 Wind-driven currents

- Apart from the two tides that happen daily as a result of the **gravitational pull** of the Moon and the Sun, ocean currents are driven almost entirely by **surface wind drag**.
- Trade winds create warm easterly equatorial currents.
- Warm currents flow polewards along western boundaries, and are indirectly created by westerly winds. (**Gulf Stream** and **Kuroshio**).
- Deeper cold currents on the eastern boundaries close the circulation. (**California** and **Canary** currents).

14 Possible conditions for condensation

1. Cooling at constant specific humidity and pressure. Vapour pressure e is constant while saturated vapour pressure $e_s(T)$ falls as temperature T falls. Eventually, vapour pressure $e >$ saturated vapour pressure e_s.
2. Mixing of unsaturated air. This can sometimes result in supersaturation because saturated vapour pressure e_s decreases exponentially as temperature T falls, but internal energy (temperature T) and water vapour (vapour pressure e) mix linearly.
3. Adiabatic ascent of moist air. Adiabatic means that there is no net input of heat. As air ascends, temperature T falls due to adiabatic expansion. Vapour pressure e does not change much, but saturated vapour pressure e_s decreases exponentially. Eventually, vapour pressure $e >$ saturated vapour pressure e_s.

15 Precipitation

- Clouds are water droplets or ice crystals suspended in air currents.
- They can evaporate or sublimate with time.
- When the particles become too massive, they fall under gravity leading to "precipitation".

15.1 Types of precipitation

15.1.1 Rain

Falling water droplets.

15.1.2 Snow

Falling ice crystals (order-six symmetry; fluffy clumps).

15.1.3 Graupel

Ice frozen onto falling snow forming soft pellets.

15.1.4 Sleet

Mixture of rain and snow.

15.2 Characterisation of rainfall or snowfall

- Intensity ($\mathrm{mm\,h^{-1}}$))
- Area coverage ($\mathrm{km^{-2}}$)
- Duration (h)
- Frequency (days per month)

16 Rainy regions

Rainy regions have **converging air**.

16.1 Examples

- Intertropical convergence zone.
- Mid-latitude storm tracks where activity is high.
- **Windward slopes** of mountains, like the Himalayan foothills during the southwest monsoon.

17 Deserts

Deserts have **diverging air**.

17.1 Examples

- Subtropical zones, especially on the western side of continents where there are cold currents offshore.
- **High-latitude or high-altitude regions**, as cold air has less moisture. Some examples include Siberia, Tibet and Antarctica.

18 Collision of India with Asia

- The Tibetan plateau has an area of 2 million km^2, with an average elevation of above 5 km.
- Subduction processes do no cause "sudden" changes in global high terrain but continent-continent collisions do (such as the collision between India and Asia over the last 50 million years).

19 Ocean gateway hypothesis

- The opening of Drake's Passage between South America and Antarctica about 35 million years ago may have decreased oceanic poleward heat transport.
- After opening, a strong Antarctic circumpolar current started which might have enhanced the glaciation in the Antarctic continent.
- The closure of Isthmus of Panama about 3 million years ago caused increased poleward heat transport.
- It might have provided more moisture to the North Atlantic region.
- This increase in moisture may have helped start the major Northern Hemisphere glaciations around 2.5 million years ago.

20 Eons

20.1 Precambrian

4.54 billion years ago - 541 million years ago.

20.1.1 Hadean era

4.54 billion years ago - 4.0 billion years ago.

20.1.2 Archean era

2.5 billion years ago - 4.0 billion years ago.

20.1.3 Proterozoic era

2.5 billion years ago - 541 million years ago.

20.2 Phanerozoic

541 million years ago - present time.

21 Global warming

21.1 What causes stratospheric cooling to occur more rapidly than surface warming?

- The stratosphere is thinner and has a low density of air molecules.
- The troposphere contains 75% of the mass of the atmosphere but only a small fraction of its volume.
- More greenhouse gases in the troposphere traps more heat.
- More greenhouse gases in the stratosphere results in molecules emitting more heat. However, the low density of air molecules result in the heat not transferring to other air molecules in the stratosphere. Instead, the heat emitted is lost to space.
- As a result, the presence of more greenhouse gases means that more heat is lost to space.

21.2 Why does land, despite its substantial mass, store relatively little of the excess heat?

- Sunlight penetrates and heats the upper tens of meters of the ocean, especially in the tropics, where the Sun's radiation arrives from a high angle. Winds blowing across the ocean's surface stir the upper layers and mix solar heat as deep as 100 meters.
- In contrast, even though tropical and subtropical landmasses generally become very hot under the strong sunlight, they are not capable of storing much heat because heat is conducted down into soil or rock at very slow rates.

21.3 Heat stored in the ocean causes its water expand

- Thermal expansion of the oceans causes thermosteric sea level rise.
- If an object is heated, its atoms vibrate faster and spread out, causing the object to expand. When it cools, the atoms slow down and the object shrinks.
- Steric sea-level changes = Thermosteric changes due to changes in ocean's temperature + Halosteric changes due to variations in salt content (or salinity) of seawater.
- Global mean sea-level rise was $3.0\,\mathrm{mm\,yr^{-1}}$ from 1993 to 2016.

21.4 Possible causes of global warming

21.4.1 Solar forcing: changes in the solar energy (not the cause)

- The Sun can influence Earth's climate, but it isn't responsible for global warming.
- There has been no upward trend in the amount of solar energy reaching Earth.
- If the Sun were responsible for global warming, we would expect to see warming throughout all layers of the atmosphere. But what we see is warming at the surface and cooling in the stratosphere.

21.4.2 Orbital forcing: changes in the Earth's orbit (not the cause)

- Milankovitch (orbital) cycles are the collective effect of three periodic variations in the Earth's orbit (obliquity, eccentricity and axial precession) on the Earth's climate. They are the driving force behind glacial-interglacial cycles.
- Milankovitch cycles operate on long time scales, ranging from tens of thousands to hundreds of thousands of years, and they have not significantly changed the amount of solar energy absorbed by Earth over the last 150 years.
- If there were no human influences on climate, Earth's current orbital positions within the Milankovitch cycles predict our planet should be cooling, not warming, continuing a long-term cooling trend that began 6,000 years ago.

21.4.3 Increasing CO_2 levels

- Direct measurements by NOAA at Mauna Lao Observatory in Hawaii from 1958 to present.
- The annual rise and fall of CO_2 levels is caused by seasonal cycles in photosynthesis on a massive scale.
- Despite these small seasonal fluctuations, the overall trend shows that CO_2 is increasing at a roughly linear rate in the atmosphere.
- The atmosphere's CO_2 content has increased by 50% in less than 200 years.
- The Earth once had higher CO_2 than now.

21.4.4 Volcanic activities: part of tectonic forcing (not the cause)

- Volcanoes emit CO_2 through eruptions and degassing.
- Volcanoes are a major source for restoring CO_2 lost from the atmosphere and oceans by silicate weathering, carbonate deposition, and organic carbon burial.
- Volcanoes can have a cooling effect.
- Volcanic eruptions often produce volcanic ash and aerosol particles. Volcanic aerosols reflect sunlight back into space, blocking solar radiation.
- The catastrophic eruption of Mount Pinatubo in 1991 ejected enormous amount of aerosol particles, which reflected so much incoming sunlight that global surface temperatures cooled off for two years.

21.4.5 Anthropogenic activities (the cause)

CO_2 emitters	Billion tons per year ($\mathrm{Gt\,yr^{-1}}$)
Global volcanic emissions (highest preferred estimate)	0.3 (Gerlach Eos, 2011) 0.6 (Burton et al., 2013)
Human activities (fossil fuels and land use change)	Roughly 40

- Annually, human activities produce roughly 100 times the carbon dioxide of Earth's volcanic eruptions.
- Human influence has warmed the climate at an unprecedented rate in at least the last 2000 years.

22 Uplift of high mountains and their effect

- Mountains and plateaus have steep slopes.
- Mass wasting processes, including rock slides, falls, and water-saturated debris flows, can move rock and expose fresh bedrock.
- Mountain glaciers grind against underlying rock, creating smaller rock grains with larger surface areas for further chemical interactions.
- Steep slopes also serve as precipitation hotspots on the upwind side, promoting chemical weathering.
- Hence, the uplift of high mountains such as the Himalayas enhanced chemical weathering and removed more atmospheric CO_2.

22.1 Uplift of high mountains is not the cause of global cooling

- The rate of CO_2 consumption decreased by 50% between roughly 16 and 5.3 million years ago, especially in the Indus system.
- Falling chemical weathering fluxes during a period of global cooling refutes the idea that the Himalayan-Tibetan Plateau uplift drove the Neogene global cooling.

23 Excess CO_2

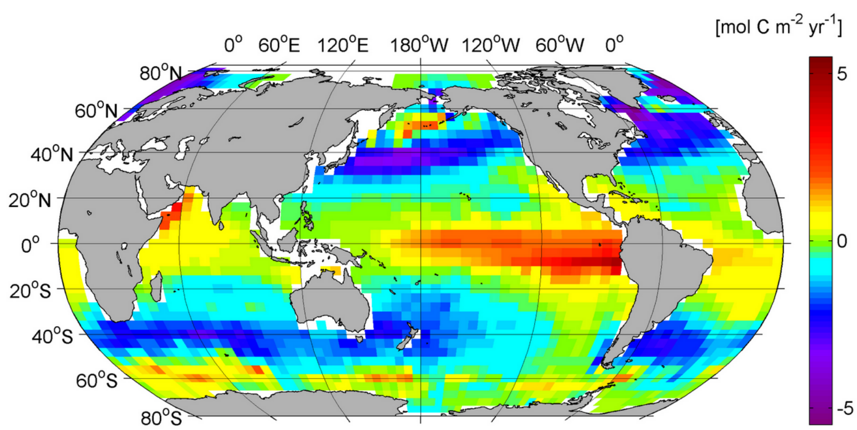
- CO_2 remains in the atmosphere long after emissions.
- Without the sequestration of carbon by the land and ocean, the level of CO_2 in the atmosphere would now be around 600 parts per million, with an associated warming about double the current level.

24 CO_2 and the oceans

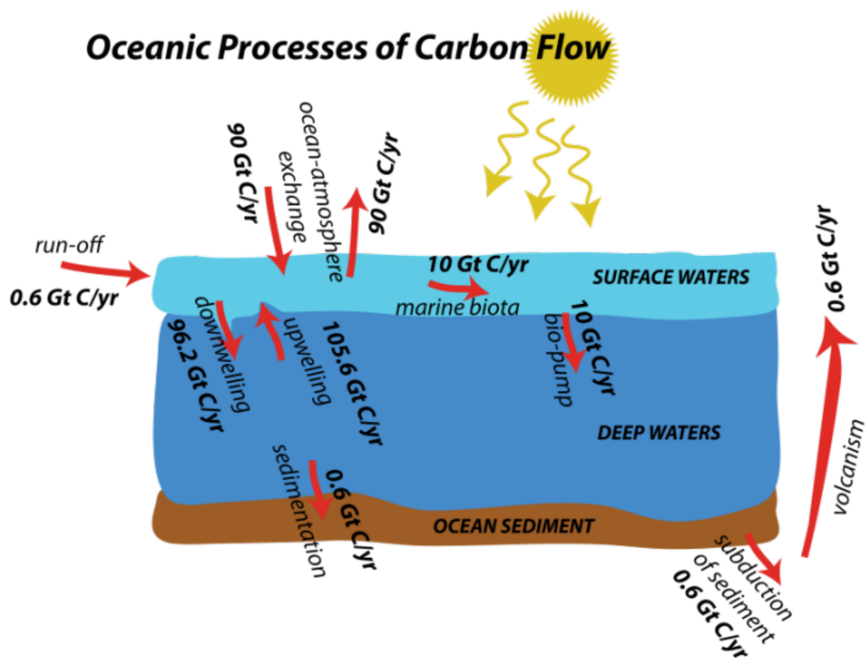
- CO_2 can be dissolved in seawater, like how it dissolves in a can of soda.
- CO_2 can also be released from seawater, much like the way CO_2 is released when soda fizzes.
- CO_2 emissions acidify the Earth's oceans.

24.1 CO_2 flux across the air-sea interface in 2000

- Colder oceans absorb CO_2 and warmer oceans release CO_2 into the atmosphere because CO_2 is more soluble in colder water



24.2 Marine carbon cycle



24.3 Why can't oceans be an immediate CO_2 sink?

- If the atmospheric concentration changes by 10%, the concentration in solution in the water changes by only one-tenth of this, which is 1%.
- This change will occur quite rapidly in the upper waters of the ocean, which is the top 100 m or so.
- Absorption in the lower levels in the ocean takes longer.
- The mixing of surface water with water at lower levels takes up several hundred years, or for the deep ocean, over a thousand years.

25 Hazards around Singapore

- Seismic and tsunami hazard
- Volcanic hazard
- Typhoon and cyclone hazard
- Sea level rise

26 Sea-level driving processes

Sea level varies in time and in space.

26.1 Global driving processes

26.1.1 Volume problem

An increase in ocean temperatures result in an increase in the volume of ocean water, which contributes 40% of the global sea level rise.

26.1.2 Mass problem

- An increase in global temperatures result in the melting of ice sheets, which increase the mass of water in the oceans and hence the volume of water in the ocean, which contributes 30% of the global sea level rise.

- Greenland will completely be free of ice if global temperatures reach 2 °C above pre-industrial levels.

26.2 Regional driving processes

26.2.1 Pro-glacial forebulge

- A pro-glacial forebulge is formed due to the weight of an ice sheet pressing down on the earth, lifting the surrounding land around the ice sheet up.

- The melting of the ice sheet will result in the forebulge sinking due to the reduction of mass pressing down on the earth, which results in the earth under the ice sheet rising, and the forebulge sinking.

- This makes the sea level rise much quicker in the area as the land is sinking as well when the sea level is rising.

26.2.2 Gravitational attraction of ice sheets

- The density of ice sheets are much larger than that of the earth, which results in stronger gravitational attraction in areas with ice sheets.
- Thus, the water is pulled towards the ice sheet.
- When the ice sheet beside the ocean melts, there is a fall in sea levels in the area due to the reduction in the gravitational attraction of the area.

26.3 Local driving processes

26.3.1 Subsidence

- The land near the coastline in some areas may have groundwater, which results in the land sinking.
- This results in a greater sea level rise in the area as the land is sinking when the sea level is rising.

26.3.2 Tectonic uplift

- The oceanic plate in some coastlines subduct under the continental plate the land sits on, which results in the continental plate rising and hence the land rises.
- This results in a lower sea level rise in the area as the land is rising while the sea level is rising.

26.3.3 Ocean dynamics

The ocean winds can shift create larger waves in certain areas, which result in a greater sea level rise in some areas as compared to others.

27 Sea levels

27.1 Last Glacial Maximum - Present day

- At the Last Glacial Maximum, Northern Europe and America were covered by vast ice sheets is roughly 3 km thick.
- As a result of the water being locked up, global sea levels were roughly 130 m below present.
- Adjustment of the land to the unloading of ice and redistribution of meltwater caused spatially variable sea-level changes that continue to this day.
- Due to the melting of the large ice sheets since the Last Glacial Maximum, the Glacial Isostatic Adjustment process causes highly spatially variable sea-level histories across the globe.

27.2 Holocene

Holocene sea levels in Singapore rose from roughly -20.7 m 9.5 thousand years ago to 4 m high 5.2 thousand years ago before falling thereafter.

27.3 Common Era sea levels

It is very likely that the rates of sea-level rise emerged above pre-industrial rates by 1863, which is similar in timing to evidence for early ocean warming and glacier melt.

27.4 Present sea levels

- Global mean sea level increased by 0.20 m between 1901 and 2018.
- The rate of sea level rise is **accelerating**.
- The rate was $1.3\,\mathrm{mm\,yr^{-1}}$ between 1901 - 1971, $1.9\,\mathrm{mm\,yr^{-1}}$, between 1971 - 2006, and was $1.9\,\mathrm{mm\,yr^{-1}}$ between 2006 - 2018.

27.5 Future sea levels

- Sea-level projections are provided for 5 Shared Socioeconomic Pathway (SSP) scenarios that consider driving processes for which we have at least medium confidence.

- It is presented as likely ranges representing 17^{th} - 83^{rd} percentile representing a probability of at least 66%.

27.5.1 SSP1-1.9

- Globally averaged surface air temperature over the period 1081 - 2100 is very likely (at least 90% probability) to be higher by $1.0\,^{\circ}\text{C} - 1.8\,^{\circ}\text{C}$ compared to 1850 - 1900.

- Net-zero CO_2 emissions around the middle of the century.

27.5.2 SSP5-8.5

- Globally averaged surface air temperature over the period 2081 - 2100 is very likely to be higher by $3.3\,^{\circ}\text{C} - 5.7\,^{\circ}\text{C}$ compared to 1850 - 1900.

- High reference scenario with no additional climate policy.

- Emission levels as high as SSP 5 - SSP 8.5 are not obtained by Integrated Assessment Models (IAMs) under any of the SSPs other than the fossil fuelled SSP5 economic development pathway.

27.5.3 SSP5-8.5 (low confidence)

- Globally averaged surface air temperature over the period 2081 - 2100 is very likely to be higher by $3.3\,^{\circ}\text{C} - 5.7\,^{\circ}\text{C}$ compared to 1850 - 1900.

- High reference scenario with no additional climate policy.

- Emission levels as high as SSP 5 - SSP 8.5 are not obtained by Integrated Assessment Models (IAMs) under any of the SSPs other than the fossil fuelled SSP5 economic development pathway.

- Integrates information from the Structured Expert Judgement and results from a simulation study that incorporates Greenland and Antarctica ice sheet processes for which we have low confidence.

27.5.4 High impact processes

Higher amounts of sea-level rise before 2100 could be caused by earlier-than-projected disintegration of Antarctica through the abrupt, widespread onset of Marine Ice Sheet Instability and Marine Ice Cliff Instability.

27.5.5 Projected exposure of coastal ecosystems to sea-level rise

- Nearly all the world's mangrove forests and coral reefs and 40% of tidal marshes will be subjected to rising sea level rates of $7\,\mathrm{mm\,yr^{-1}}$ by 2100 under a global mean warming scenario of $3\,^{\circ}\mathrm{C}$ above the 1850 - 1900 baseline (SSP2 - SSP 4.5).
- Once these tipping points are reached, there is little prospect of reversal during the following century, and ecological and socio-economic consequences will be profound.

27.6 Driving human migration

- In Southeast Asia, rising sea levels flooded the Sunda Shelf and reduced land area by over 50%, resulting in segregation of local human populations.
- Integrated paleogeographic and population genomic analysis demonstrates the earliest instance of forced human migration driven by sea-level rise.
- Spikes in human population displacement coincides with occurrences of rapid sea-level rise.

27.7 Sea-level tendency

27.7.1 Transgressive contacts (Positive tendency)

A change from a marsh to a mudflat deposit (marsh retreat).

27.7.2 Regressive contacts (Negative tendency)

Replacement of mudflat by a marsh deposit (marsh expansion).

27.8 Summary

1. Past and present records of sea level have varied in response to a wide range of boundary conditions and climate forcing and can serve as a valuable guide to projecting future sea-level rise and its uncertainty.

2. Ice mass loss from glaciers, Greenland and Antarctica is accelerating and will continue to lose mass throughout the 21st century under all considered SSP scenarios.

3. Sea level will continue to rise through 2100.

4. Higher amounts of sea-level rise before 2100 could be caused by Marine Ice Sheet Instability and Marine Ice Cliff Instability. Such processes could contribute more than one additional meter of sea level rise by 2100.

28 Extremes

28.1 How does climate change affect temperature extremes?

1. A small shift of the mean by itself greatly enhances the probability of one extreme and greatly reduces the probability of the other extreme.

2. A small increase in the variance by itself results in huge enhancements in the probabilities of both extremes.

3. The symmetry of the probability distribution can also be altered such that only one extreme is adversely affected.

28.2 Why does climate change cause more frequent and intense rainfall?

- At the global scale, column-integrated water vapour content increases roughly following the **Clausius-Clapeyron (C-C) relation**, with an increase of approximately **7% per** 1 °C of global warming.

- The intensification of heavy precipitation will follow the rate of increase in the maximum amount of moisture that the atmosphere can hold as it warms (high confidence), of about **7% per** 1 °C of global warming.

- Global mean precipitation and evaporation increase with global warming, but the estimated rate is model-dependent (very likely range of **1 − 3% per** 1 °C).

- The increase in water vapour leads to robust increases in precipitation extremes everywhere, with a magnitude that varies between 4% and 8% per 1 °C of surface warming (thermodynamic contribution).

28.3 Climate change and extreme events

- Future changes in **temperature** averages and extremes will be **similar**, while the future changes in **precipitation** averages and extremes can be **very different**.

- Scientists cannot answer directly whether a particular event was caused by climate change, as extremes do occur naturally, and any specific weather and climate event is the result of a complex mix of human and natural factors. Instead, scientists quantify the relative importance of human and natural influences on the magnitude and probability of specific extreme weather events.

- **Attribution** is done by estimating and comparing the probability or magnitude of the same type of event between the current climate, like the increases in greenhouse gas concentrations and other human influences, and an alternate world where the atmospheric greenhouse gases remained at pre-industrial levels.

- Strong increases in probability and magnitude, attributable to human influence, have been found for many heatwaves and hot extremes around the world.

- Attributable increases have also been found for some extreme precipitation events, including hurricane rainfall events, but these results can vary among events. In some cases, large natural variations in the climate system prevent attributing changes in the probability or magnitude of a specific extreme to human influence.

- As the climate continues to warm, larger changes in probability and magnitude are expected and, as a result, it will be possible to attribute future temperature and precipitation extremes in many locations to human influences. Attributable changes may emerge for other types of extremes as the warming signal increases.

- Human-caused climate change increases wildfire by intensifying its principal driving factor, heat. The heat of climate change dries out vegetation and accelerates burning. Non-climate factors also cause wildfires.

- Evidence shows that human-caused climate change has driven increases in the area burned by wildfire in the forests of western North America. Across this region, the higher temperatures of human-caused climate change doubled burned area from 1984 to 2015, compared with what would have burned without climate change.

- In other regions, wildfires are also burning wider areas and occurring more often. This is consistent with climate change, but analyses have not yet shown if climate change is more important than other factors. In Indonesia, intentional burning of rainforests for oil palm plantations and El Niño seem to be more important than long-term climate change.

- 90 percent of the world's population, both rich and poor countries alike, will be exposed to one or more threats arising from global warming.

- Far more people (about 600 million people) are seeing heavier precipitation than lighter precipitation (80 million).

29 Climate models

29.1 Nobel Laureates in climate science (2021)

1. Syukuro Manabe
2. Klaus Hasselmann

29.2 How it works

- The Earth is divided into grid boxes.
- The governing equations are then calculated for every grid box.
- The influence of vegetation and terrain is included in the calculation.
- The atmosphere is divided into cubes, each with its own local climate.
- The air in grid boxes interacts horizontally and vertically with other boxes.
- Oceanic grid boxes model currents, temperature, and salinity.
- Water in oceanic grid boxes interacts horizontally and vertically with other boxes.

29.3 Ocean models vs atmosphere models

Property	**Ocean models**	**Atmosphere models**
Heating	From top	From bottom
Memory	Long	Short (except stratosphere)
Density variations	Small	Large
Density profile	Increases with depth	Decreases with altitude
Obstruction	Yes, strong boundary currents	No

29.4 Challenges

- Unknown future greenhouse gas concentration
- Natural variability of the climate, and hence there is a lack of long data records
- Limitation in understanding the full climate system
- High-resolution global climate modelling is computationally expensive
- Stubborn mean-state biases

29.5 Model bias

$$\text{Model bias} = \text{model simulation} - \text{observations}$$

- Substantial deviations from observed climate on regional and local scales are possible
- Climate models are a simplification of the climate system, and the large-scale grid cells may not represent processes that happen on a smaller scale than the area of grid cells.

29.5.1 Sources of bias

- Low horizontal resolution of the model
- Inappropriate model physics
- Error in the input data or the lack of observations
- Model structure
- Error in the initial condition for weather forecasting
- Unknown future conditions (for climate change projections)