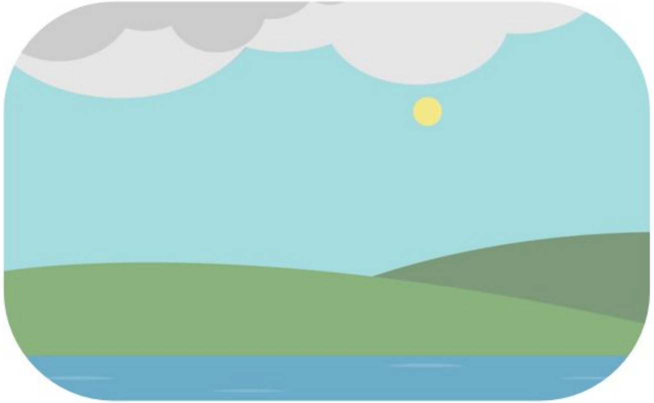
The climate system and climate modelling

Resources:
- Global physical climatology: chapter 1
- Global warming science: chapter 2

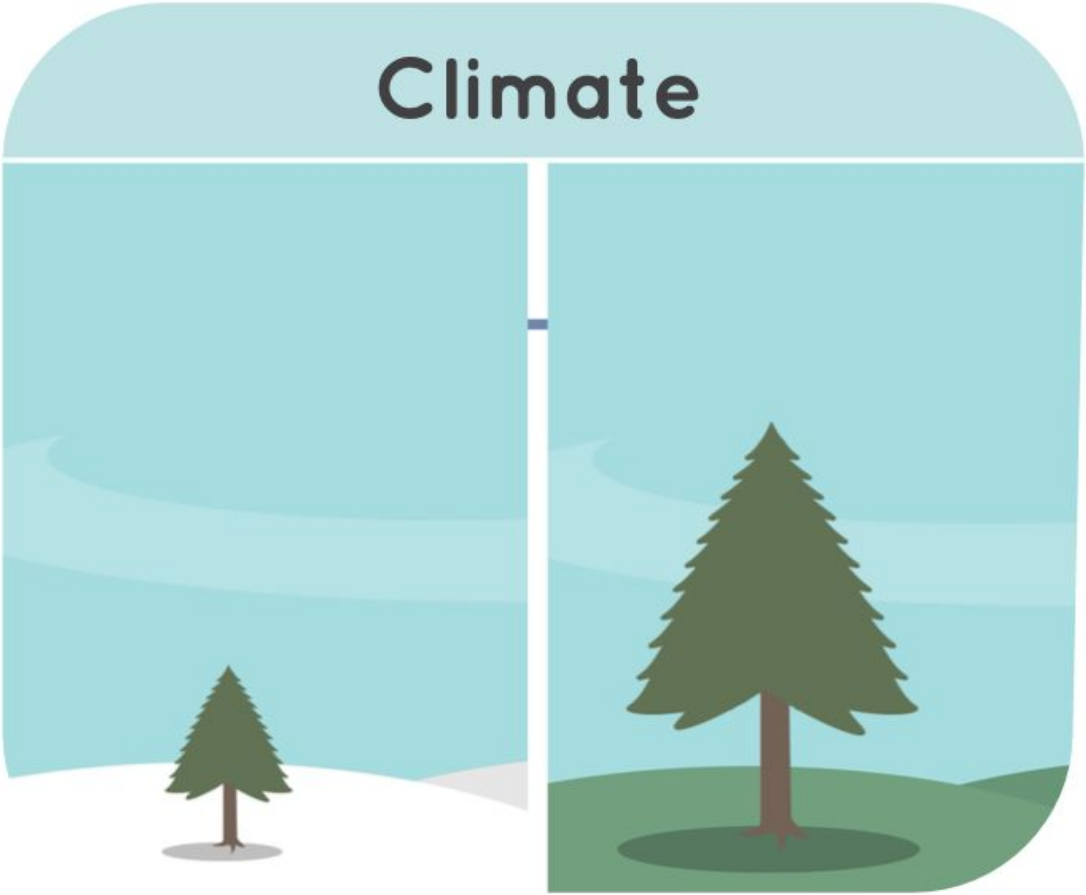
What’s the difference between weather and climate?

Take a look outside your window. Is it hot and sunny? Is it cloudy and rainy? Is there snow on the ground?
When you look out the window, you're seeing what the weather is like today.



Weather is only temporary. For example, a blizzard can turn into a flood after just a few warm spring days.

Climate, on the other hand, is more than just a few warm or cool days. Climate describes the typical weather conditions in an entire region for a very long time—30 years or more.



Weather

Weather shows the way the atmosphere behaves and can change from minute-to-minute, hour-to-hour and day-to-day. There are many components to weather, which include temperature, rain, wind, hail, snow, humidity, flooding, thunderstorms, heatwaves and more. When you look outside your window on any given day, what you see is weather.

Climate

Climate, on the other hand, is the weather in a specific area over a long period of time – usually 30 years of more. When scientists talk about climate, they look for trends or cycles of variability, such as changes in temperature, humidity, precipitation, ocean-surface temperature and other weather phenomena that occur over longer periods of time in a specific location.

WEATHER vs CLIMATE

WEATHER

WHAT YOU GET

CONDITIONS OF THE ATMOSPHERE OVER A SHORT PERIOD OF TIME

CAN CHANGE WITHIN MINUTES OR HOURS

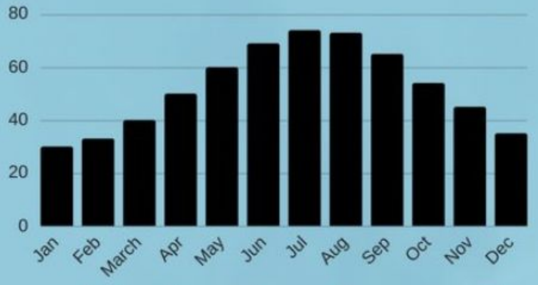
Saturday Sunday

CLIMATE

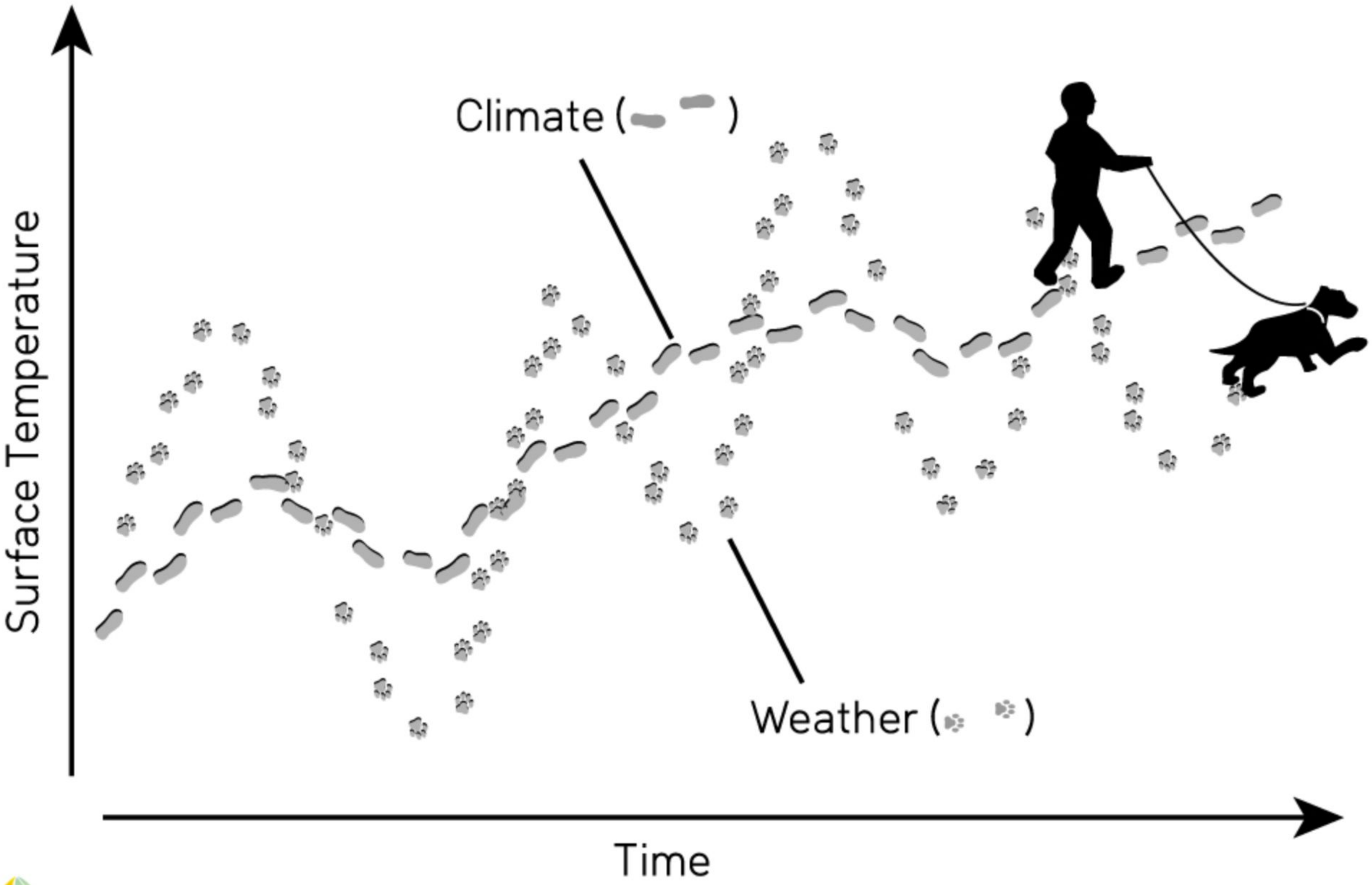
WHAT YOU EXPECT

HOW THE ATMOSPHERE BEHAVES OVER A LONG PERIOD OF TIME AND SPACE

AVERAGE REGIONAL WEATHER PATTERN OVER DECADES



30 Year Normal Average Temperature (F)



sks.to/jg Redrawn from TeddyTVNorge, https://www.youtube.com/watch?v=e0vj-0imOLw

The climate of the Earth is defined in terms of **measurable weather elements**. The weather elements of most interest are temperature (units of °C or K) and precipitation (units of mm/day or kg/m2/s) at the surface. Just these two elements determine the species of plants and animals that survive and prosper in a particular location.

Other important variables are:

- **Humidity**: amount of water vapor in the air, which depends on temperature and precipitation (units of g/kg)

- **Wind speed** (units of m/s) **and direction** (angle)

- **Cloudiness** (units of %)

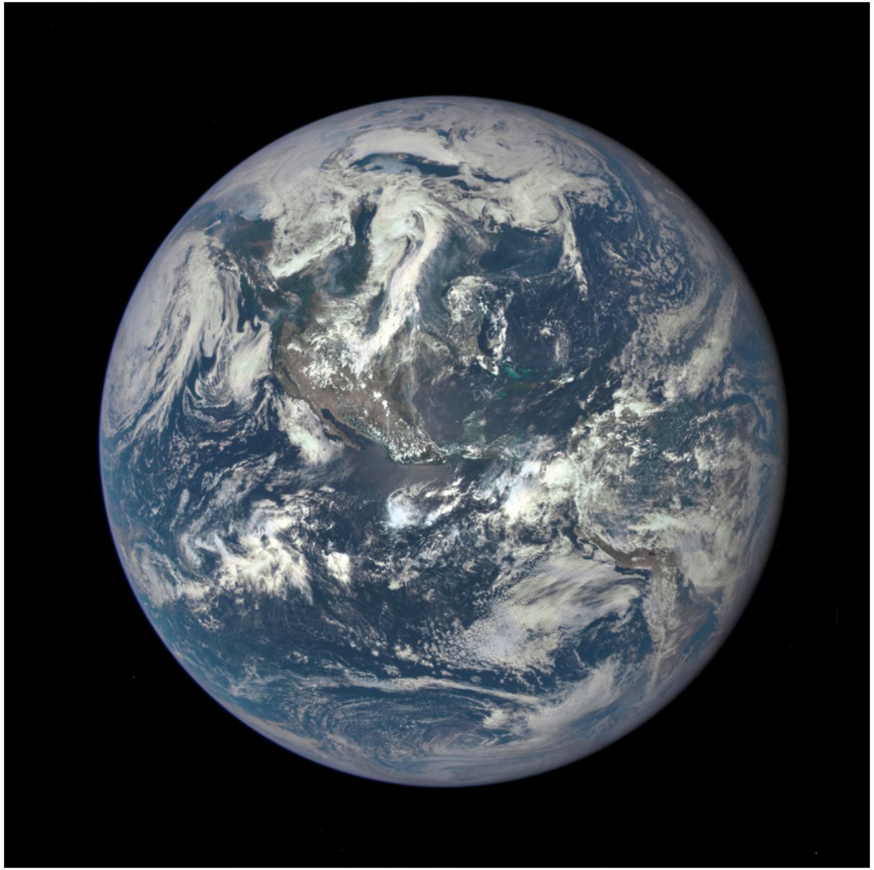


FIGURE 1.1 Earth as seen on July 6, 2015 by the NASA Earth Polychromatic Imaging Camera aboard the NOAA Deep Space Climate Observatory spacecraft one million miles from Earth.

Measurable weather elements:

Temperature: [K] or [°C]

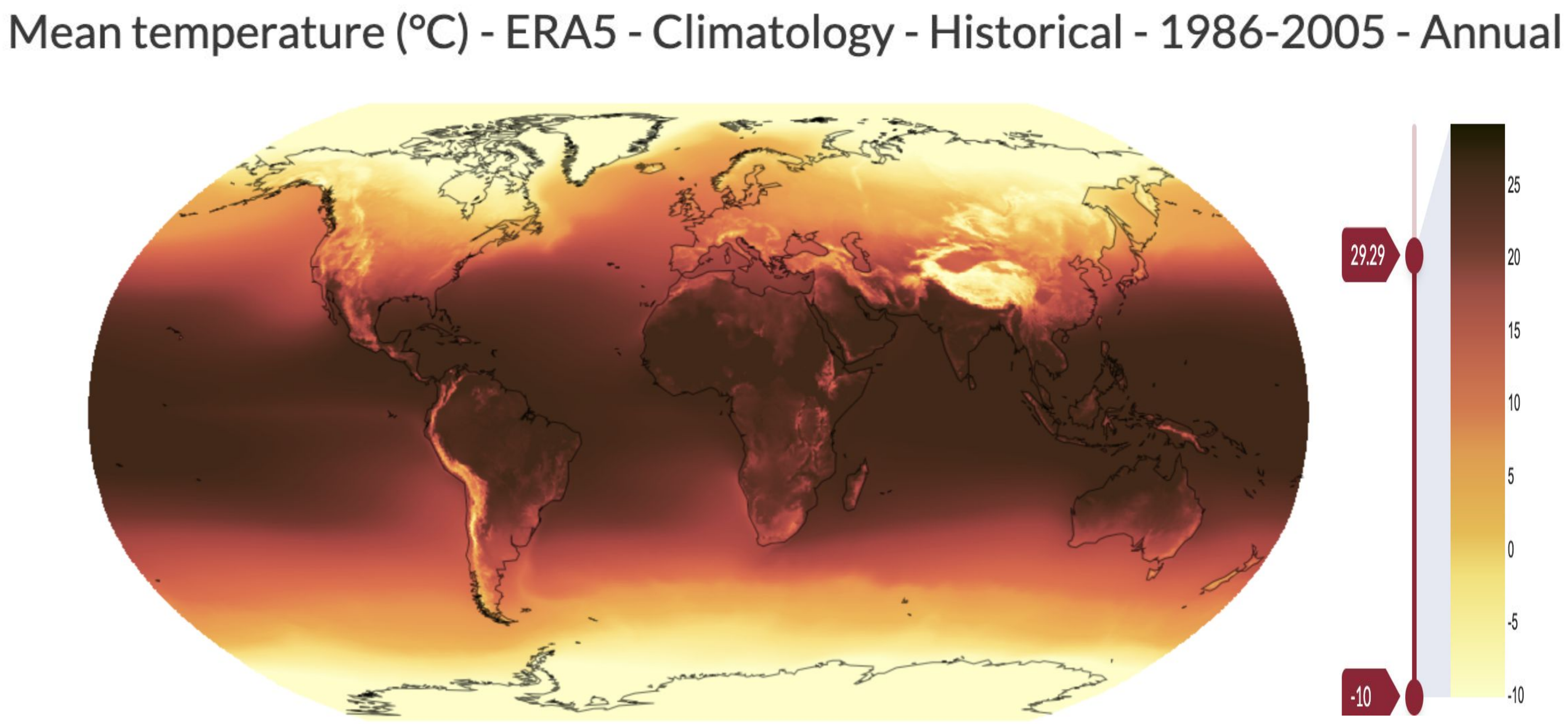
Precipitation: [mm/day]

Humidity: [g/kg]

Wind speed and direction: [m/s]

Cloudiness: [%]

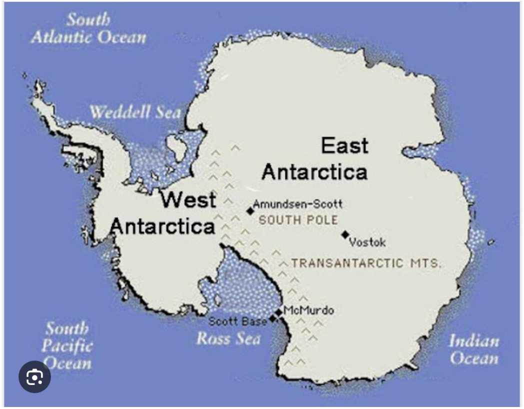
Atmospheric temperature



Atmospheric temperature

The global average temperature at the surface of the Earth is about 288K (15°C). The range of temperatures at the surface is favorable for the life forms that have developed on Earth. The **extremes** of recorded surface temperature range from the coldest temperature of -89.2°C at Vostok, Antarctica to the warmest temperature of 56.7°C at Furnace Creek Ranch in Death Valley, California.

Temperatures are warmer in the tropics and colder in the polar regions, depending on solar insolation. Temperatures also depend on altitude (height above sea level). Death Valley is below sea level while Vostok is at 3450m.



Lapse rate: Rate of temperature change with elevation

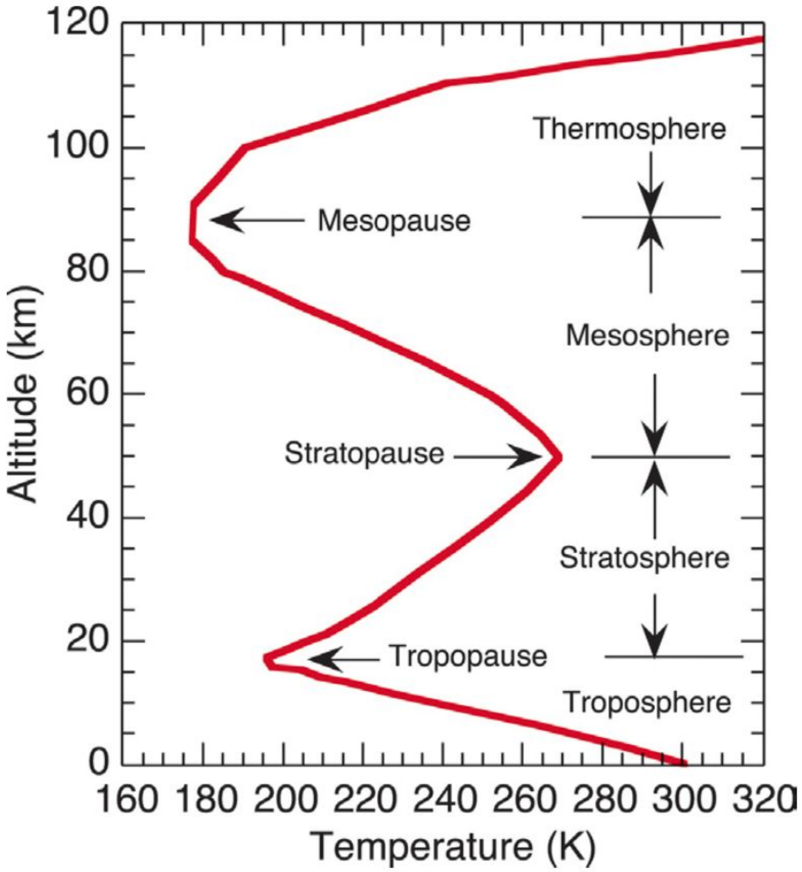
$$\Gamma \equiv -\frac{\partial T}{\partial z}$$

$\Gamma > 0$: temperature decreases with height
$\Gamma < 0$: temperature increases with height

The global average sign of the lapse rate in the annual mean depends on altitude. At each location the lapse rate varies with altitude, season and latitude.

A region of negative lapse rate is called a ***temperature inversion***.

FIGURE 1.2 **The main zones of the atmosphere defined according to the temperature profile of the standard atmosphere profile at 15°N for annual-mean conditions.** *Data from U.S. Standard Atmosphere Supplements (1966).*



Temperature dependence on **altitude**

The global mean tropospheric lapse rate is about **6.5K/km**.

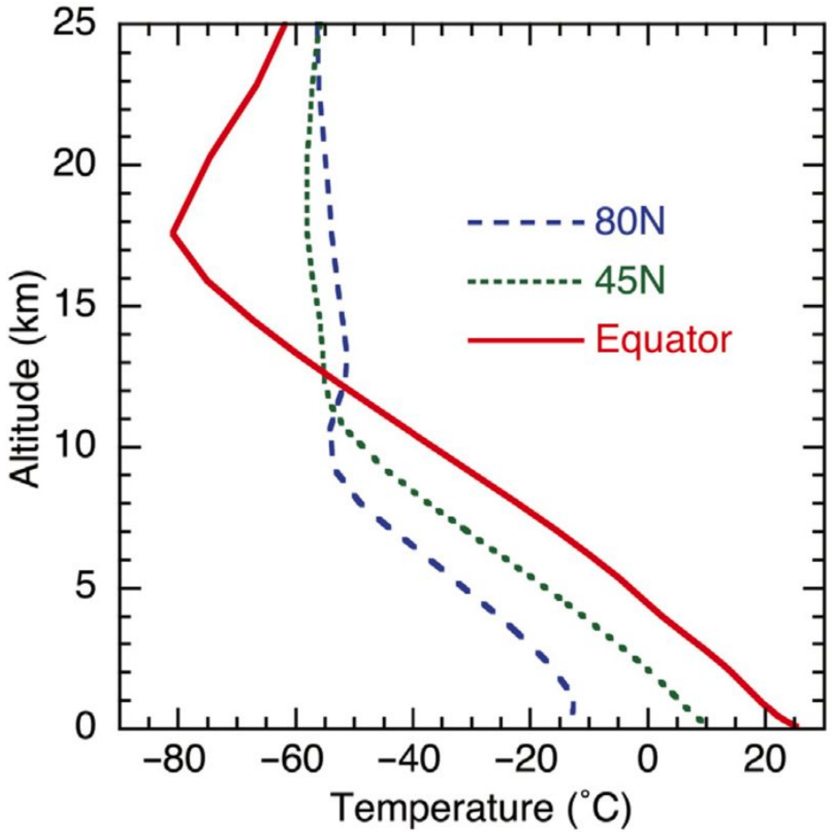
In the upper **stratosphere**, the temperature increases with height to about 50 km. In this layer, the temperature increase with height is caused by solar radiation absorption by ozone.

Above the stratosphere, the temperature begins to decrease with height in the **mesosphere**.

Above 100 km the temperature increases rapidly because of heating produced by absorption of UV radiation from the sun in the **thermosphere**.

FIGURE 1.3 **Annual mean temperature profiles for the lowest 25 km of the atmosphere in three latitude bands.** *Data from ERA-Interim.*

Temperature dependence on **latitude**



At the equator the temperature decreases with altitude up to ~17 km. In the mid-latitudes (45N) and high latitudes (80N) up to ~11 km and ~8 km, respectively.

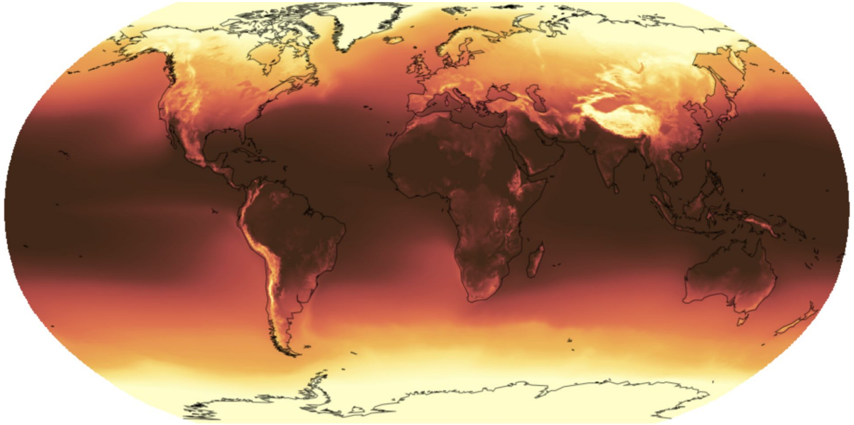
The tropospheric lapse rate (steepness of the curve) is smaller outside the tropics.

The **tropical tropopause** is thus the coldest part of the lowest 20 km of the global atmosphere in the annual mean.

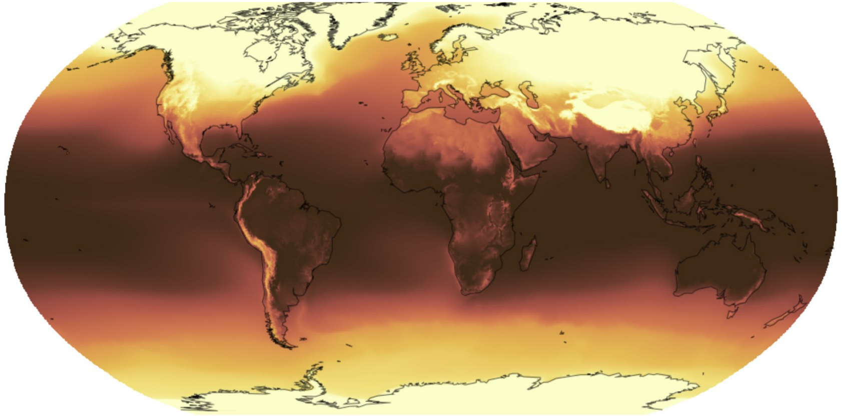
At the equator there is a temperature inversion in the stratosphere. At the mid- and high-latitudes the temperature in the lower stratosphere is almost independent of height.

Horizontal temperature dependence on **latitude** and **season**

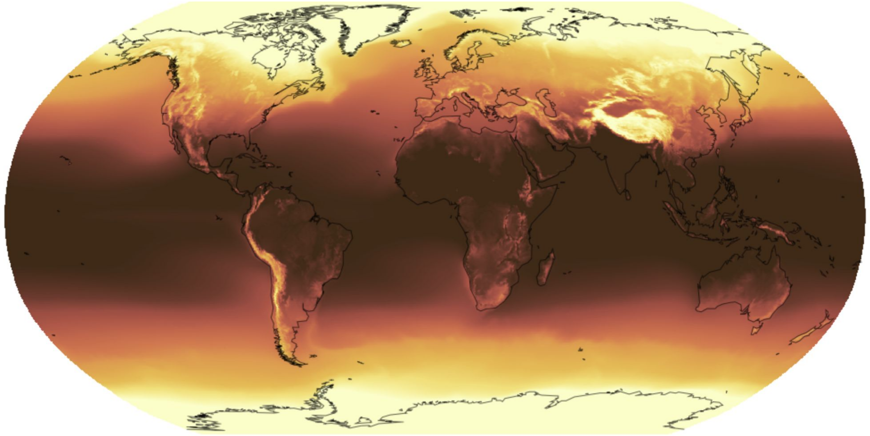
Mean temperature (°C) - ERA5 - Climatology - Historical - 1986-2005 - Autumn (SON)



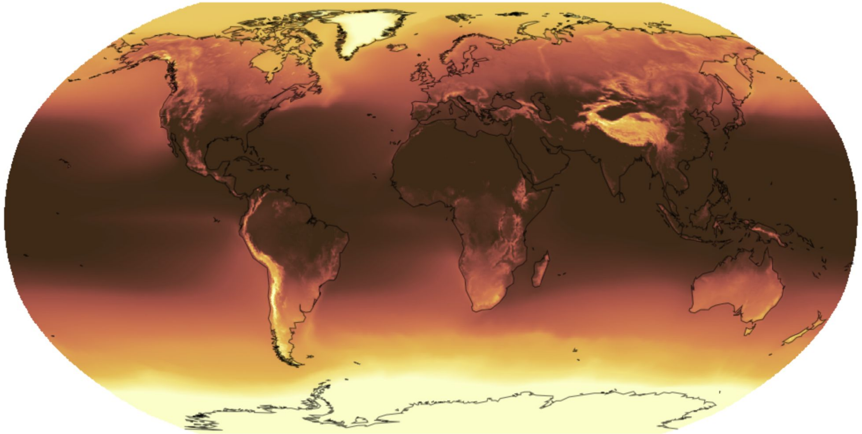
Mean temperature (°C) - ERA5 - Climatology - Historical - 1986-2005 - Winter (DJF)

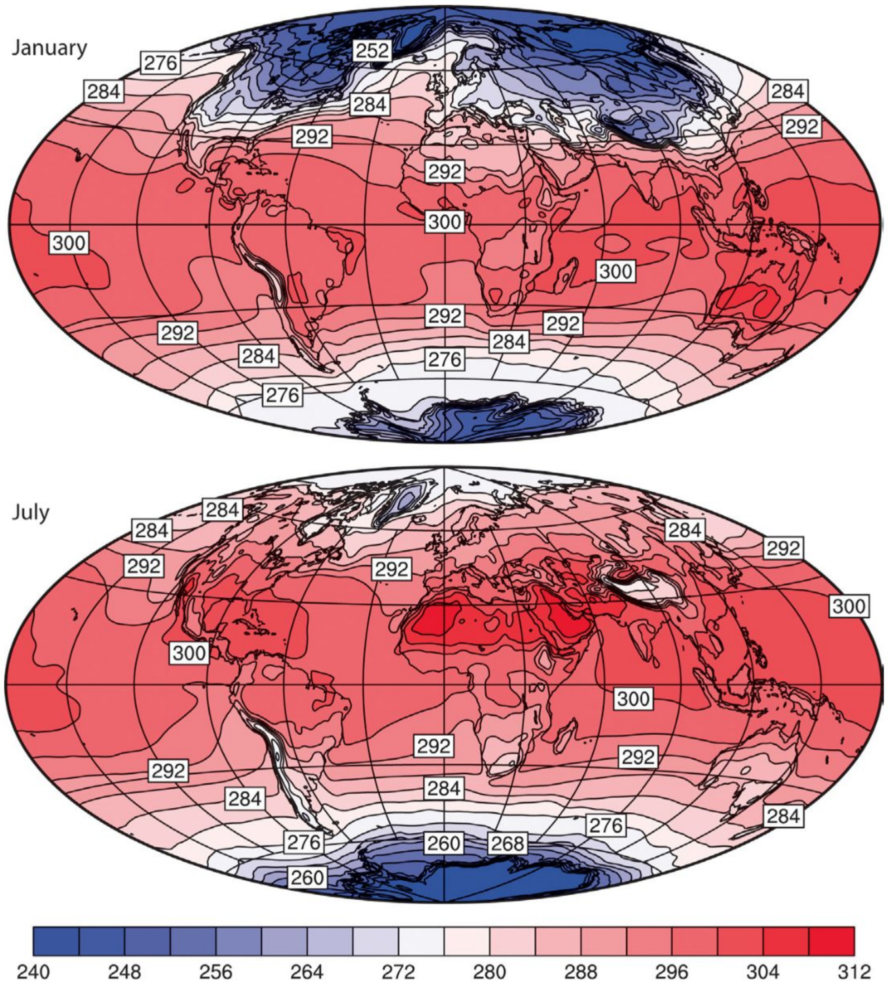


Mean temperature (°C) - ERA5 - Climatology - Historical - 1986-2005 - Spring (MAM)



Mean temperature (°C) - ERA5 - Climatology - Historical - 1986-2005 - Summer (JJA)





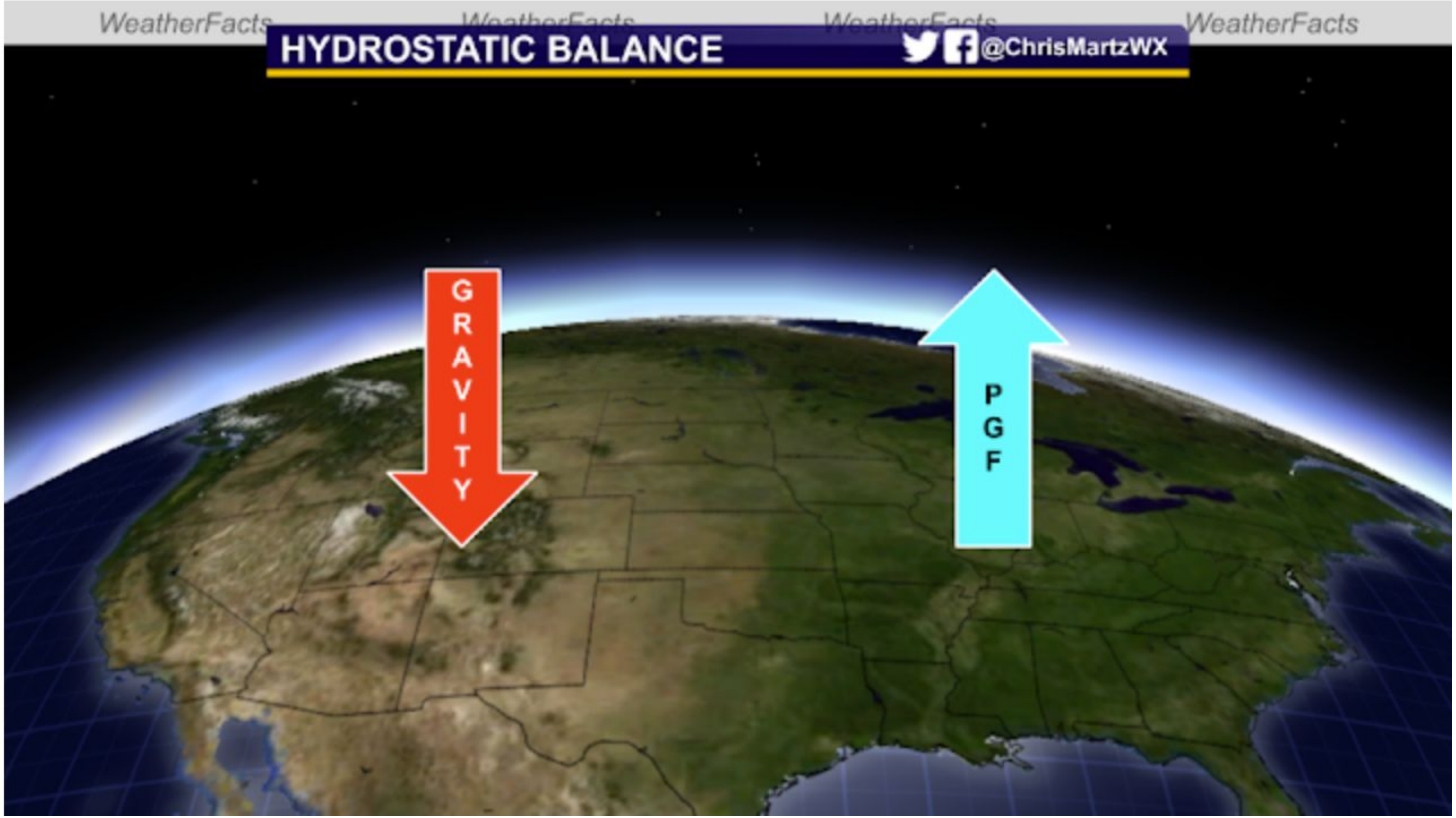
Temperature is greatest near the equator where it exceeds 23°C in all seasons.

Surface temperatures decrease steadily towards the poles. The northern continents become very cold during boreal winter, but they are warmer than oceans at the same latitudes over summer.

Seasonal variations of surface temperatures in the interiors of North America and Eurasia are very large compared to Southern Hemisphere were they are smaller because of the greater fraction of the surface covered by ocean.

Ocean stores heat very effectively because of the higher heat capacity of water. In contrast, land areas heat up and cold down more quickly because of the lower heat capacity of soil.

Hydrostatic balance



Hydrostatic balance

The atmosphere is composed of gases held close to the surface of the planet by gravity. The vertical forces acting on the atmosphere are in balance meaning that on average the **gravity force** is in balance with the **pressure gradient force.**

$$g = -\frac{1}{\rho}\frac{dp}{dz}$$

For an ideal gas, pressure (p), density (ρ), and temperature (T) are related by the formula

$$p = \rho RT \tag{1.3}$$

where R is the gas constant. After some rearrangement, (1.2) and (1.3) yield

$$\frac{dp}{p} = -\frac{dz}{H} \tag{1.4}$$

where

$$H = \frac{RT}{g} = \text{scale height.} \tag{1.5}$$

If the atmosphere is *isothermal* (i.e., temperature does not change with height) and T = ~260K then the temperature and scale height are constant and we can integrate the hydrostatic equation from the surface to an arbitrary height *z*.

Pressure at the surface

$$p = p_s = 1.01325 \times 10^5 \text{ Pa}$$

We obtain an expression for the distribution of pressure with height:

$$p = p_s e^{-z/H}$$

Pressure decreases **exponentially** away from the surface decline by a factor 1/e=0.368 every *scale height H*. The scale height for the mean temperature of Earth's temperature is about 7.6 km.

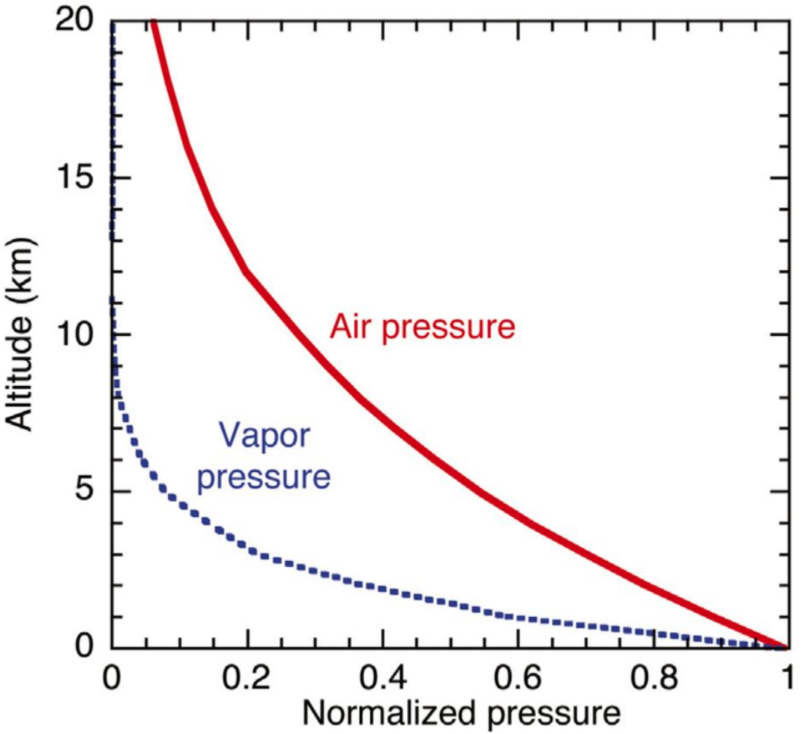


FIGURE 1.7 Vertical distributions of air pressure and partial pressure of water vapor as functions of altitude for globally and annually averaged conditions. Values have been normalized by dividing by the surface values of 1013.25 and 17.5 hPa, respectively.

Atmospheric humidity

Atmospheric humidity is the amount of water vapor carried in the air. It can be measured as **vapor pressure**, **mixing ratio** or **specific humidity.**

$$\text{Specific humidity [g/kg]} = \frac{\text{Water vapor mass}}{\text{Total air mass}}$$

$$\text{Mixing ratio [g/kg]} = \frac{\text{Water vapor mass}}{\text{Dry air mass}}$$

Atmospheric water vapor decreases very rapidly with altitude. The partial pressure of water vapor is less than 10% of its surface value at 5 km above the surface. The amount of water vapor at the equator is 10x that at the poles.

Atmospheric humidity

Water vapor is one of the most important atmospheric constituents:

- The atmosphere carries away the water evaporated from the surface and supplies water to regions of rainfall

- Water that flows from the land to the oceans through rivers was brought to the land areas by transport in the atmosphere as water vapor

- Atmospheric water vapor is also the **most important greenhouse gas** in the atmosphere

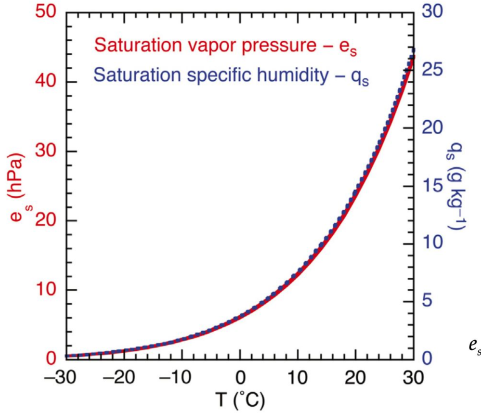
- Water vapor condenses to form **clouds**, which can release rainfall and are also very important in both reflecting solar radiation and reducing infrared radiation from Earth

Atmospheric water vapor decreases very rapidly with altitude. The partial pressure of water vapor is less than 10% of its surface value at 5 km above the surface. The amount of water vapor at the equator is 10x that at the poles.

"Warm air can hold more water vapor/humidity"

The temperature dependence of saturation pressure of water vapor over a water surface is governed by the **Clausius-Clapeyron relationship**.

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}$$

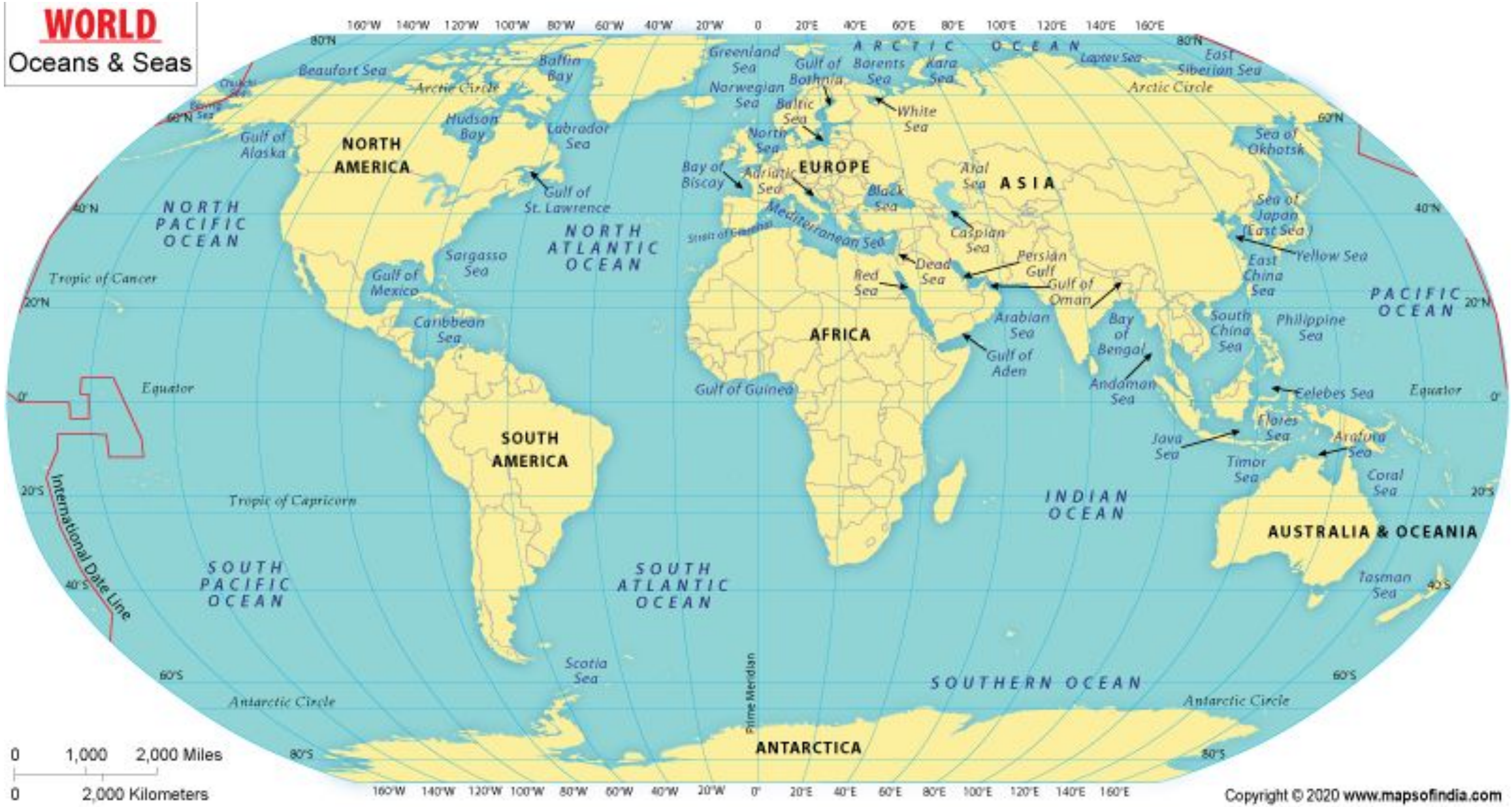


$$e_s \cong 6.11 \bullet \exp\left\{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)\right\}$$

FIGURE 1.9 **Saturation vapor pressure and specific humidity as functions of temperature at standard pressure.**

The World Ocean

Covers 71% of the Earth's surface
Average depth of 3730 m



Why is the ocean important?

- The ocean can store and release heat and chemicals on time scales of seasons to centuries, modulating climate variability and change

- The world ocean is the reservoir of water that supplies atmospheric water vapor for rain and snowfall over land

- The ocean plays a key role in determining the composition of the atmosphere through the exchange of gases and particles across the air-sea interface

- The ocean removes carbon dioxide from the atmosphere and produces molecular oxygen

On Earth there are 1.35×10^9 km^3 of water,

TABLE 1.2 Water on Earth

Water reservoir	Depth if spread over the entire surface of Earth (m)	Total (%)
Oceans	2650	97
Icecaps and glaciers	60	2.2
Groundwater	20	0.7
Lakes and streams	0.35	0.013
Soil moisture	0.12	0.013
Atmosphere	0.025	0.0009
Total	2730	100

The Cryosphere

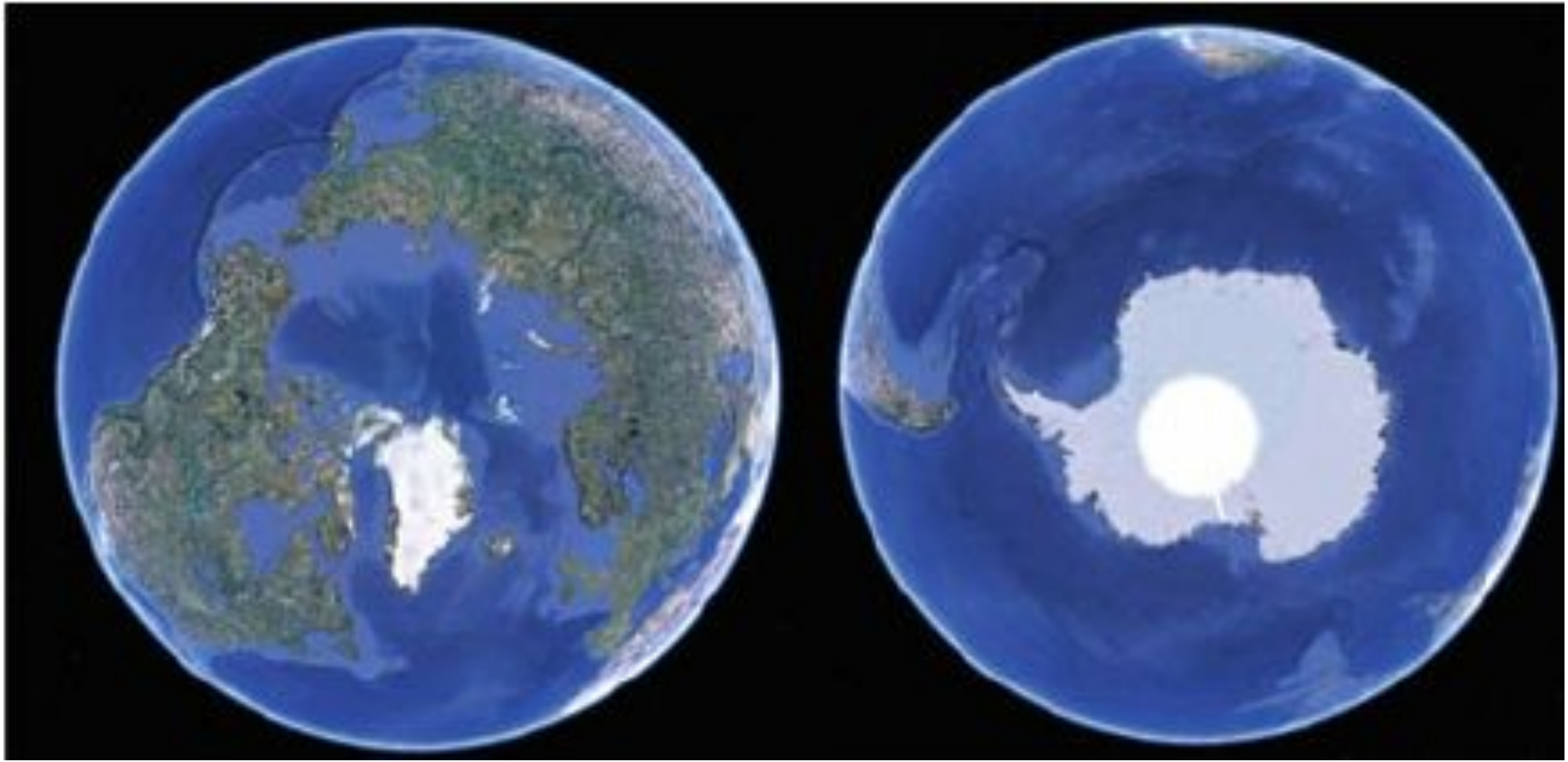
- All of the ice near the surface of the Earth constitutes the *cryosphere*

- About 2% of water on Earth is frozen and this frozen water makes up 80% of the freshwater.

- Most of the mass of ice is contained in the ice sheets of Antartica (89%) and Greenland (8.6%).

- For climate it’s not the mass of ice that is important, but rather the area covered by ice of any depth. This is because of the “albedo”.

- Currently, perennial ice covers 11% of the land are and 7% of the world ocean.



The Land Surface

- Covers only 29% of Earth, but climate over land is extremely important to humans

- Over land, temperature and soil moisture are key determinants of natural vegetation and the agricultural potential of a given area.

- The distribution of land and ocean areas plays a role in determining global climate. The arrangement of land and ocean varies on time scales of millions of years with continental drift. At present time, 68% of land is in the Northern Hemisphere, which creates important inter-hemispheric differences in climate and climate change.

- The Northern hemisphere has bigger zonal (east-west) variations in continental topography (e.g., Himalaya, Rocky mountains), which influences the global climate.

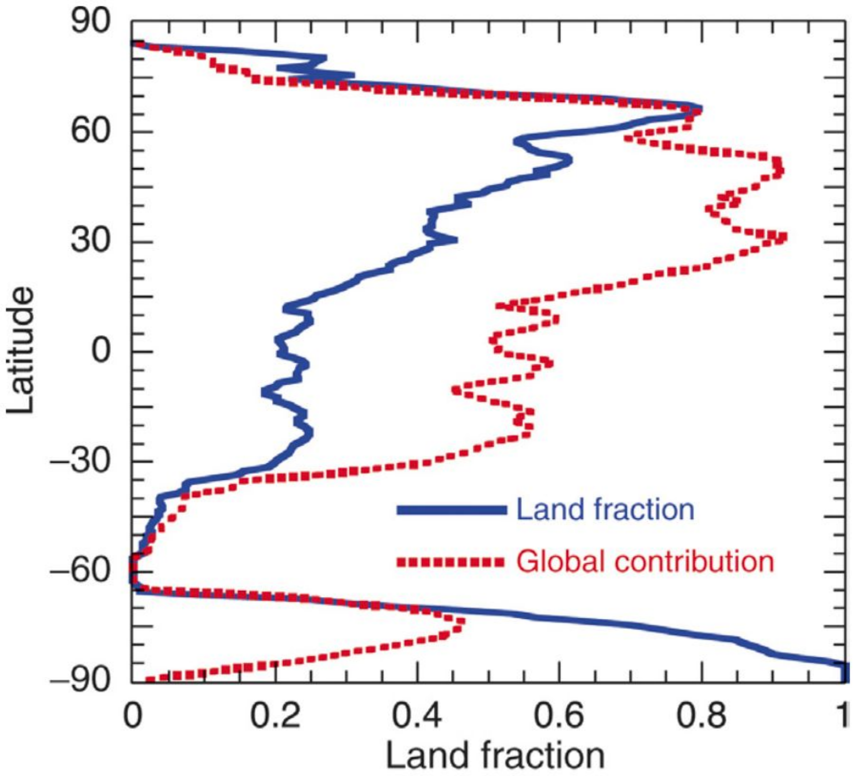


FIGURE 1.13 Fraction of surface area covered by land as a function of latitude (solid line) and contribution of each latitude belt to the global land surface area (dashed line).

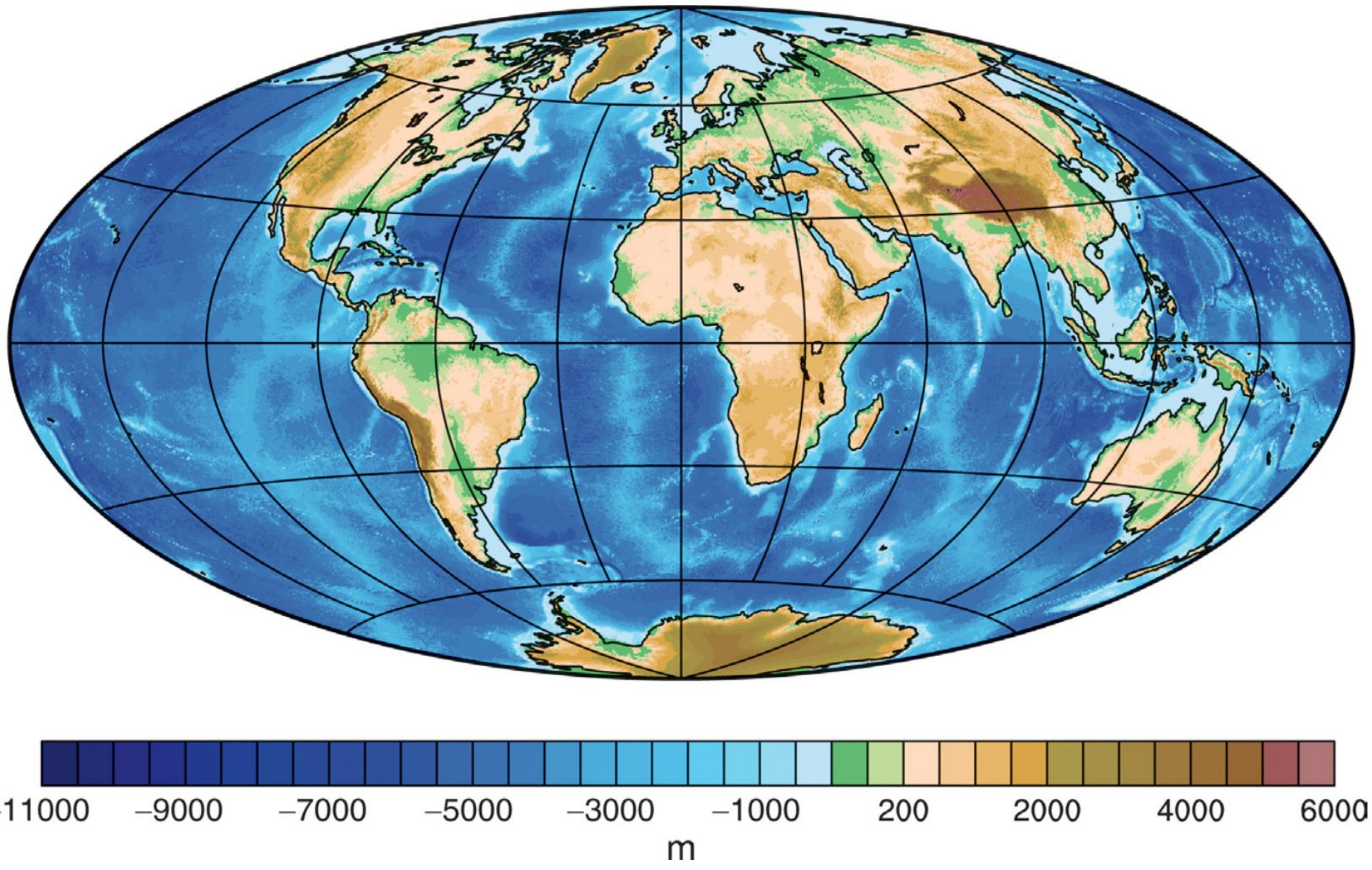
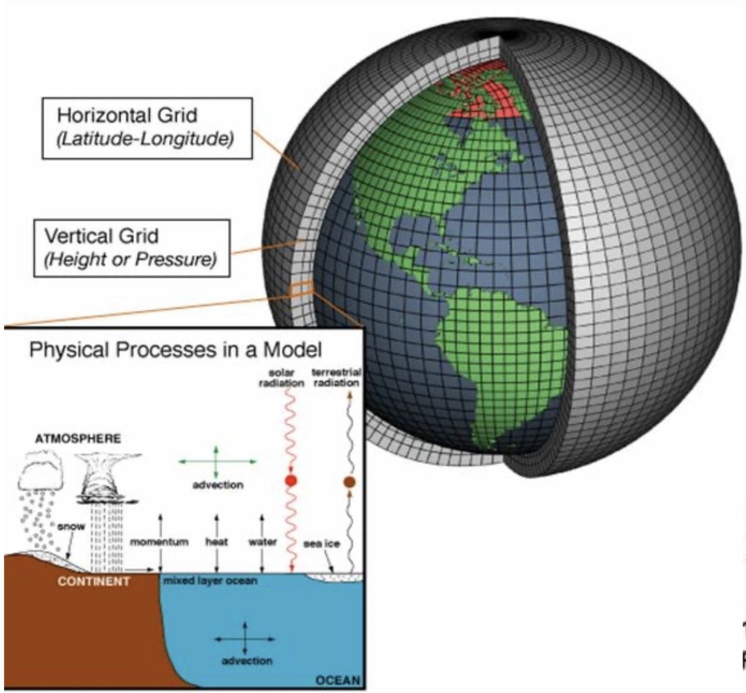
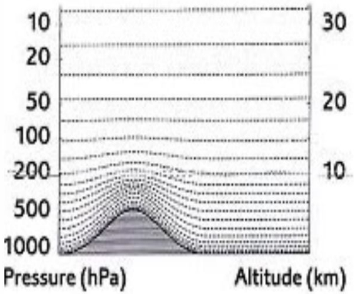


FIGURE 1.14 Color contour plot of the topography of Earth relative to sea level. Scale is in meters.

Climate models

Numerical circulation models





Mathematical equations that represent the physical characteristics and processes are entered for each box

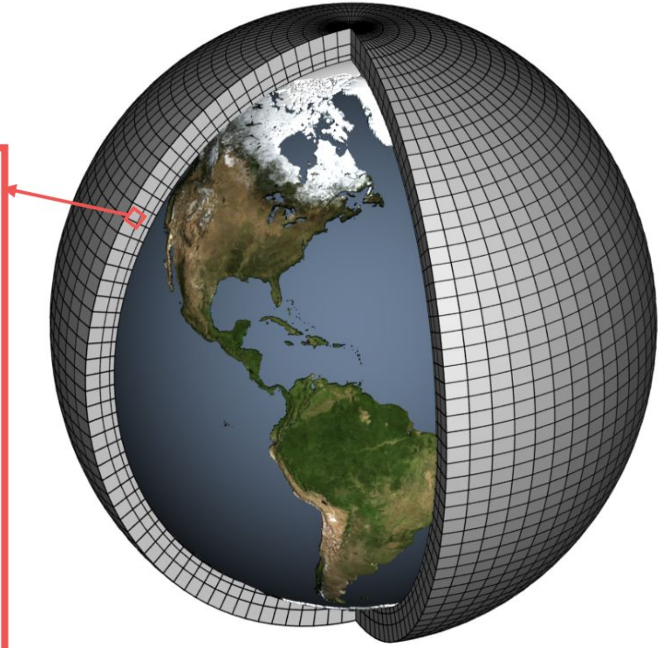
$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p\theta\frac{\partial \pi}{\partial x} - z\frac{\partial u}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial x}$$

$$\frac{\partial v}{\partial t} = -\eta\frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p\theta\frac{\partial \pi}{\partial y} - z\frac{\partial v}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial y}$$

$$\frac{\delta T}{\partial t} = \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}$$

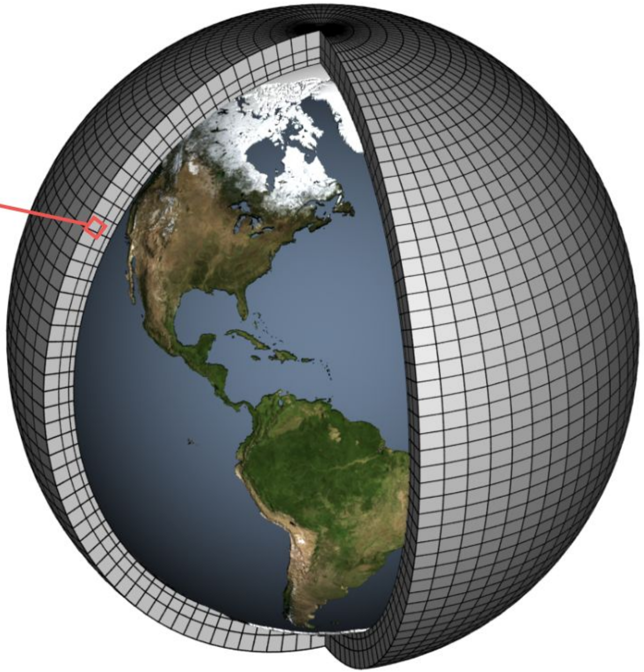
$$\frac{\delta W}{\partial t} = u\frac{\partial W}{\partial x} + v\frac{\partial W}{\partial y} + w\frac{\partial W}{\partial z}$$

$$\frac{\partial}{\partial t}\frac{\partial p}{\partial \sigma} = u\frac{\partial}{\partial x}x\frac{\partial p}{\partial \sigma} + v\frac{\partial}{\partial y}y\frac{\partial p}{\partial \sigma} + w\frac{\partial}{\partial z}z\frac{\partial p}{\partial \sigma}$$

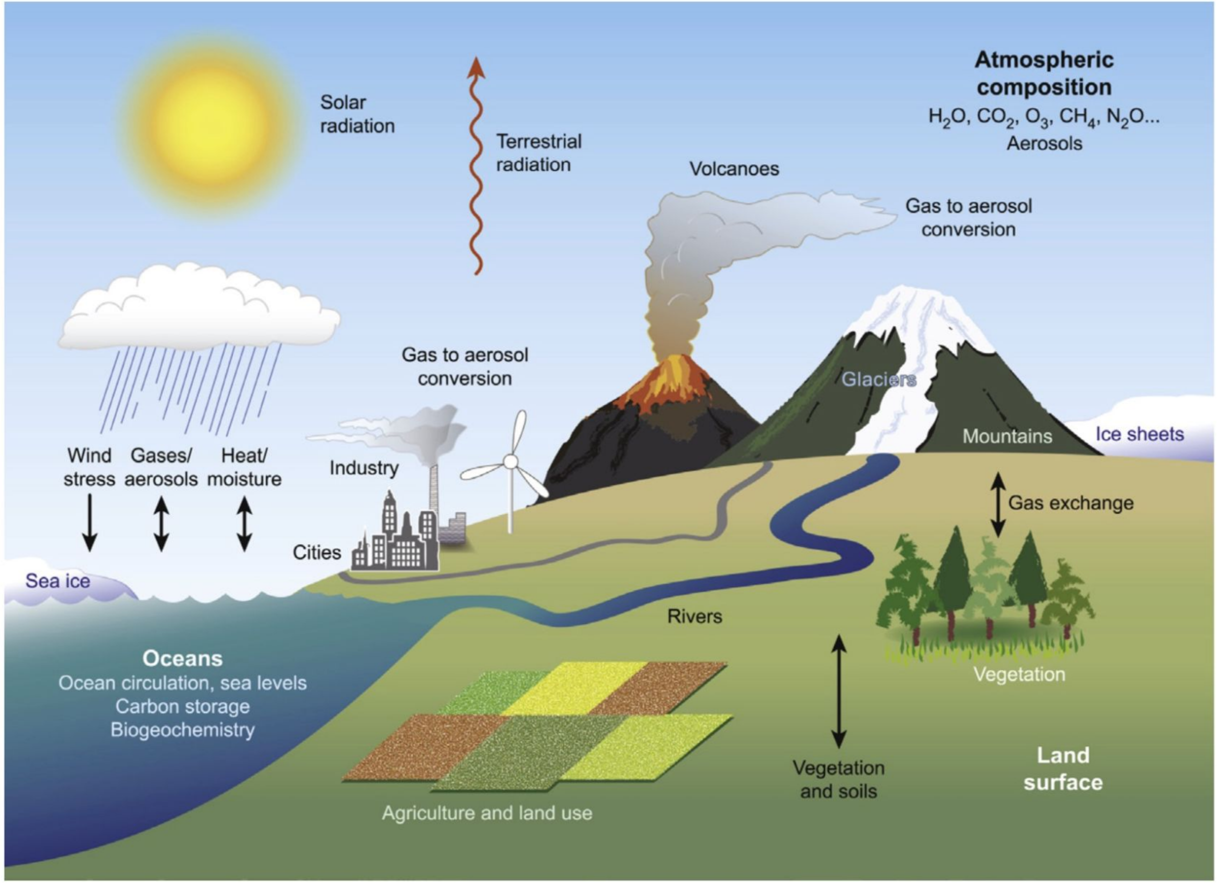


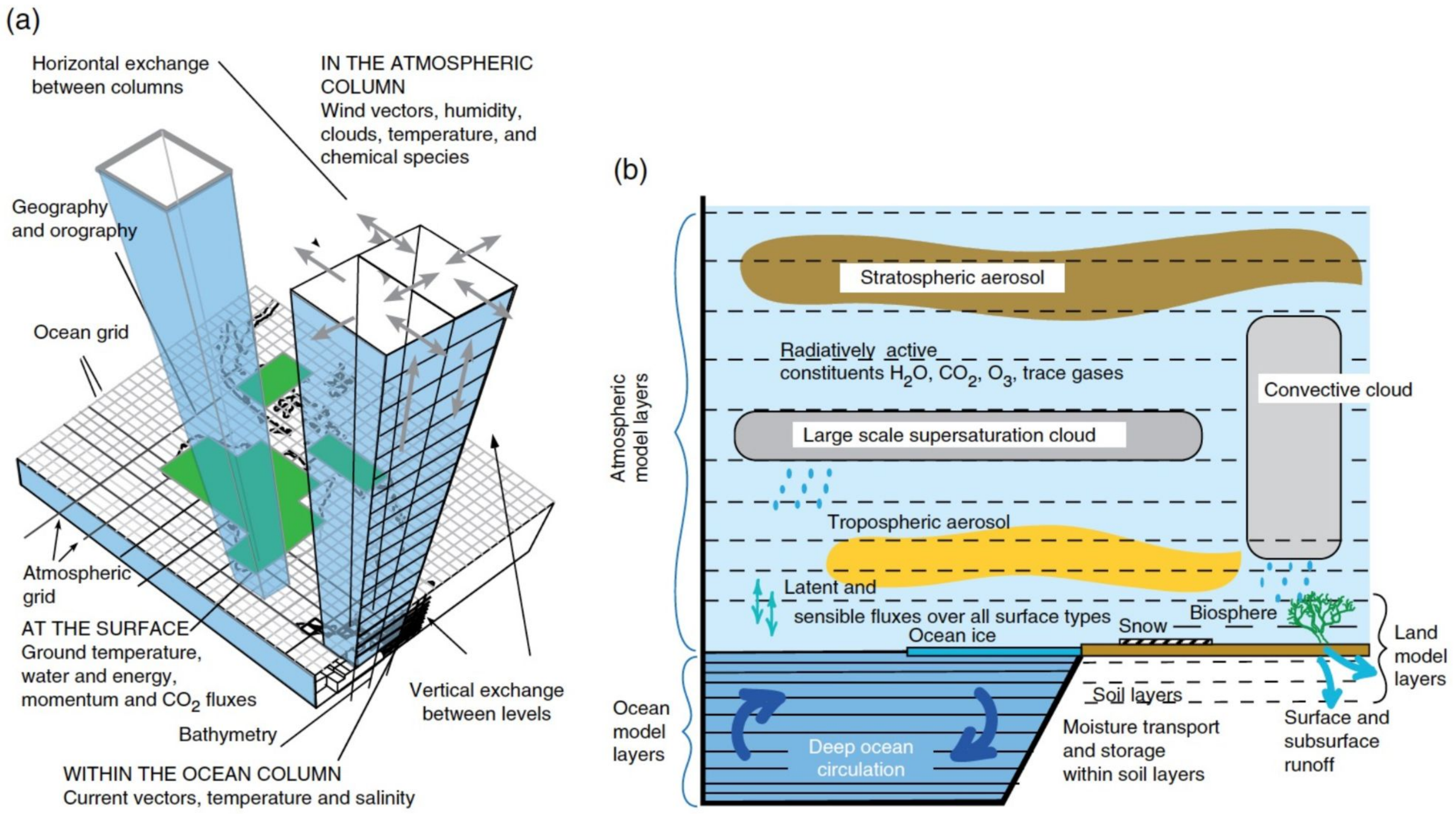
Equations are converted to computer code and climate variables are set

```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxcel(k))
      do 1480 i=2,imtm1
        boxfx            = fx*dxt(i)*fm(i,k,jc)
        sddt             = (ta(i,k,m)-t(i,k,jc,nm,m))*boxfx
        svar             = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                           *boxfx
        n                = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)      = tvar(k,m,n)     + svar
        n      = nhreg*(mskvr(k)-1) + mskhr(i,j)
        if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
          termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
          tvar(k,m,n)      = tvar(k,m,n)     + svar
```



Main components of a global earth-system model




(a)
Horizontal exchange between columns
IN THE ATMOSPHERIC COLUMN
Wind vectors, humidity, clouds, temperature, and chemical species
Geography and orography
Ocean grid
Atmospheric grid
AT THE SURFACE
Ground temperature, water and energy, momentum and CO_2 fluxes
Vertical exchange between levels
Bathymetry
WITHIN THE OCEAN COLUMN
Current vectors, temperature and salinity
(b)
Atmospheric model layers
Stratospheric aerosol
Radiatively active constituents H_2O, CO_2, O_3, trace gases
Convective cloud
Large scale supersaturation cloud
Tropospheric aerosol
Latent and sensible fluxes over all surface types
Biosphere
Snow
Ocean ice
Land model layers
Soil layers
Ocean model layers
Deep ocean circulation
Moisture transport and storage within soil layers
Surface and subsurface runoff

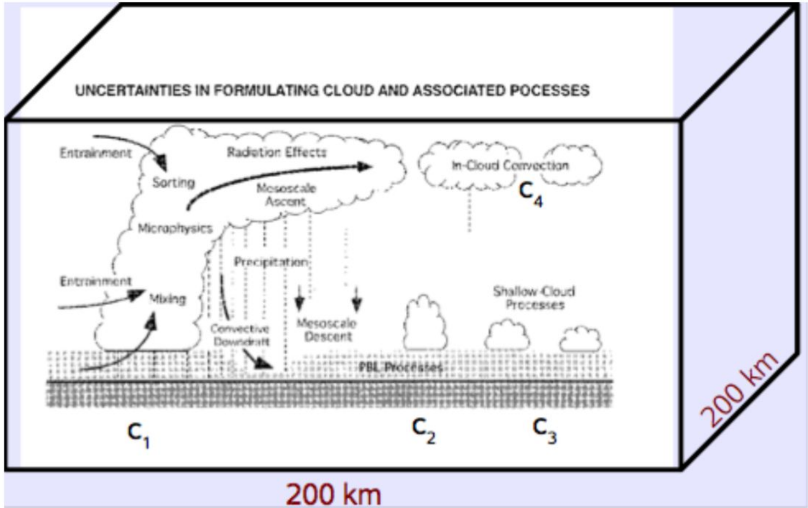
Parameterizations

A mathematical representation of processes acting at sub-grid scale.

Typically bulk formulas are used (mathematical statistical expressions function of the average quantities (temperature, humidity etc) over a grid cell)

Examples are parameterizations for:

- Microphysical cloud processes
- Radiative transfer
- Convection
- Soil processes



How does a climate model work?
https://www.youtube.com/watch?v=UIFUljuaUQo

What’s the IPCC?
https://www.youtube.com/watch?v=eEIIBDK22Us
https://www.youtube.com/watch?v=NCEGcXs_lt4

IPCC slides

BY THE NUMBERS

Author Team

234 authors from **65** countries

28% women, **72%** men

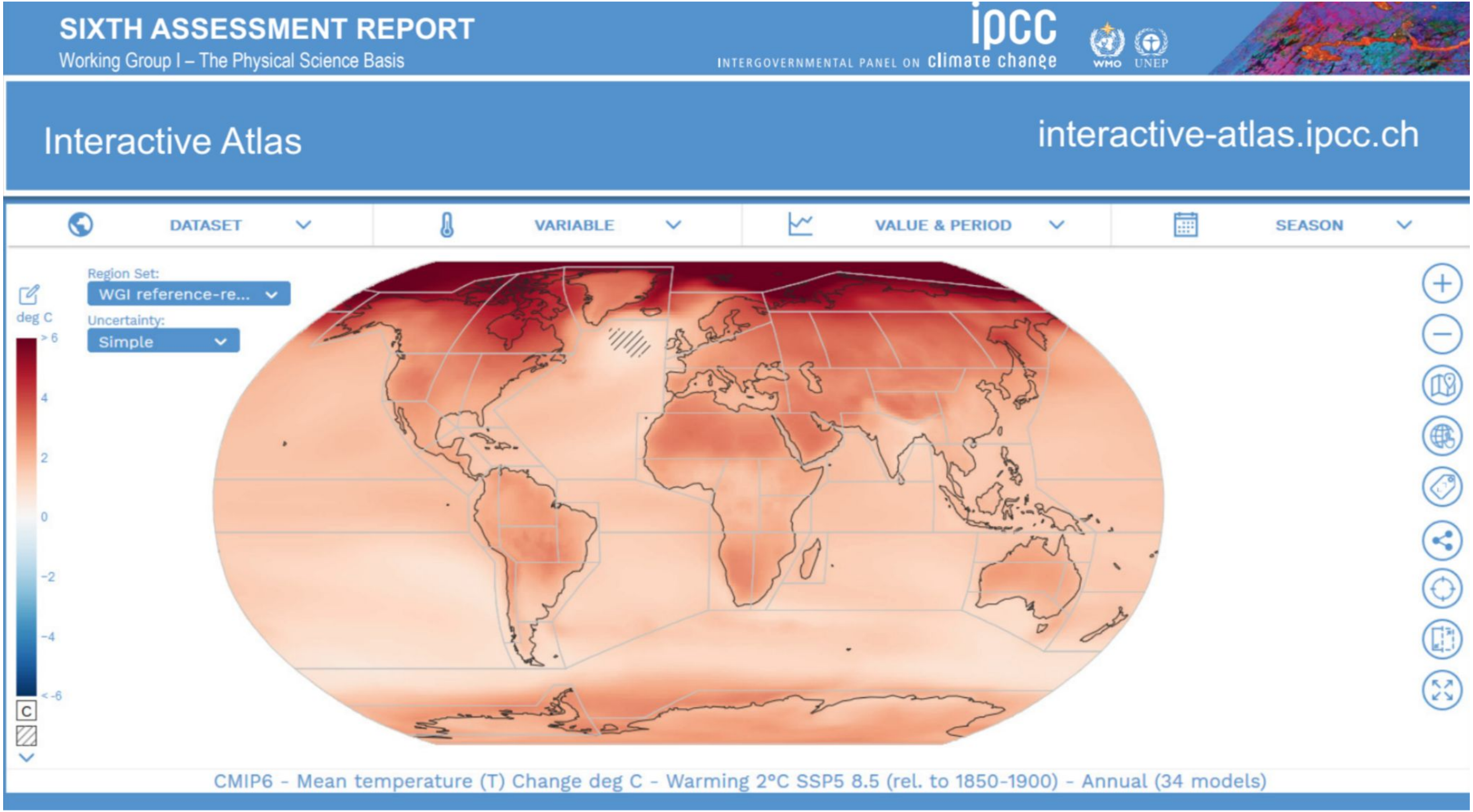
30% new to the **IPCC**

Review Process

14,000 scientific publications assessed

78,000+ review comments

46 countries commented on Final Government Distribution


SIXTH ASSESSMENT REPORT
Working Group I – The Physical Science Basis
ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO
UNEP
Interactive Atlas
interactive-atlas.ipcc.ch
DATASET
VARIABLE
VALUE & PERIOD
SEASON
Region Set:
WGI reference-re...
Uncertainty:
Simple
deg C
> 6
4
2
0
-2
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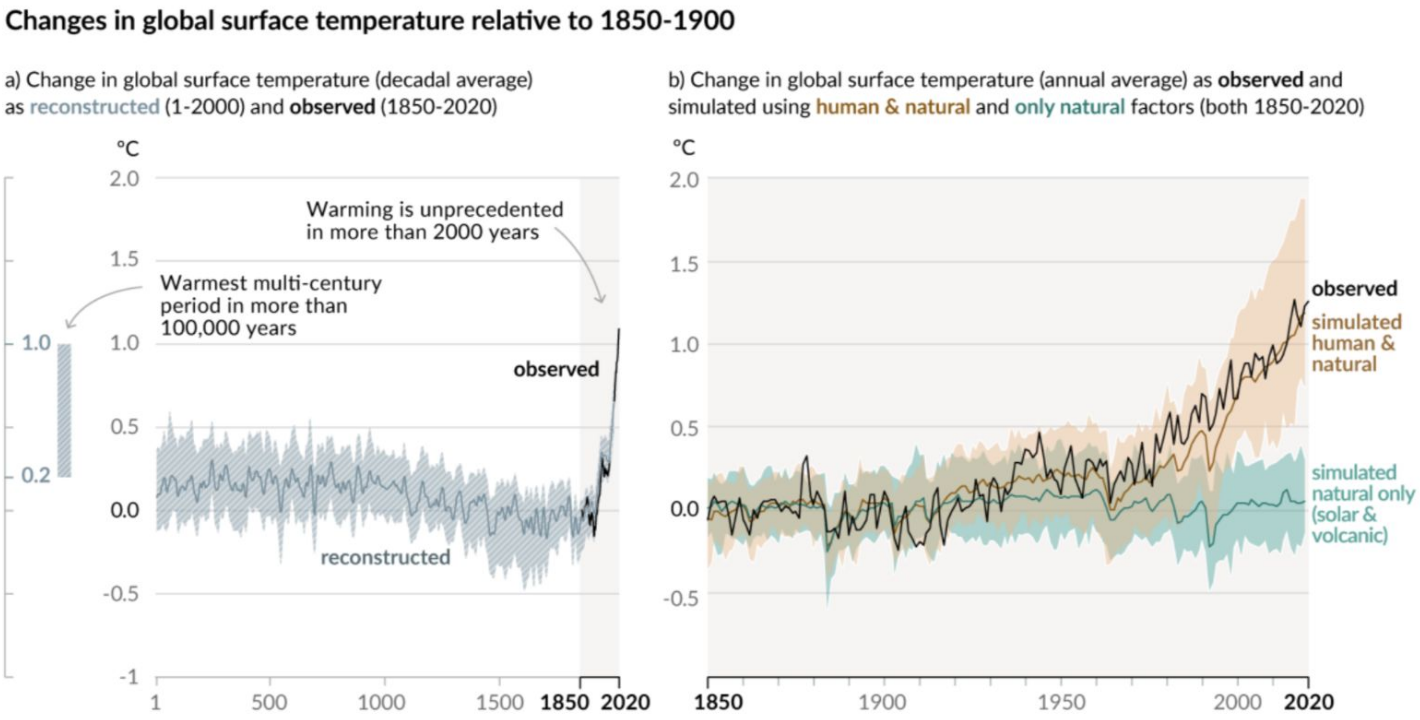
C
CMIP6 - Mean temperature (T) Change deg C - Warming 2°C SSP5 8.5 (rel. to 1850-1900) - Annual (34 models)

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

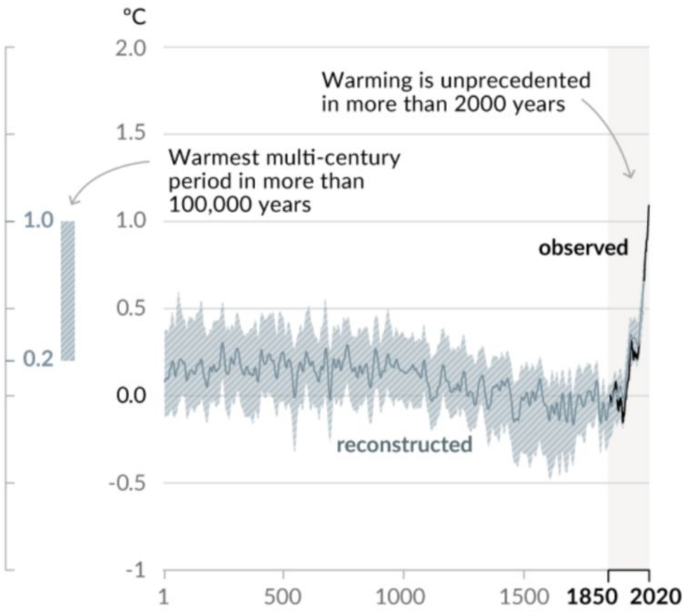
Figure SPM.1



Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

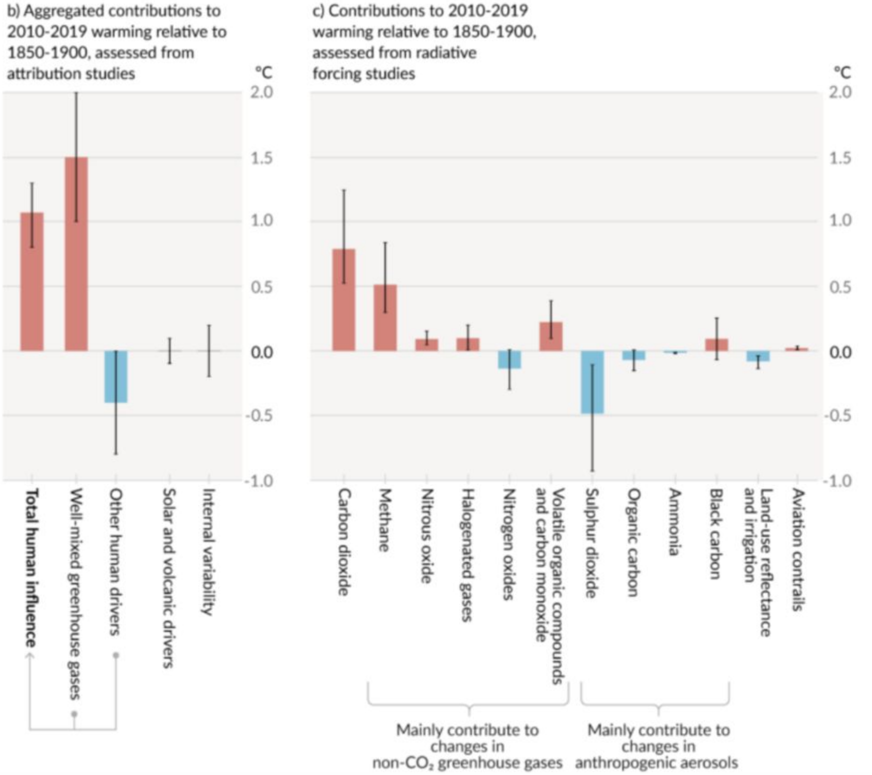
Figure SPM.1

a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and observed (1850-2020)



Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

Figure SPM.2



"SSP" stands for **Shared Socioeconomic Pathways**.

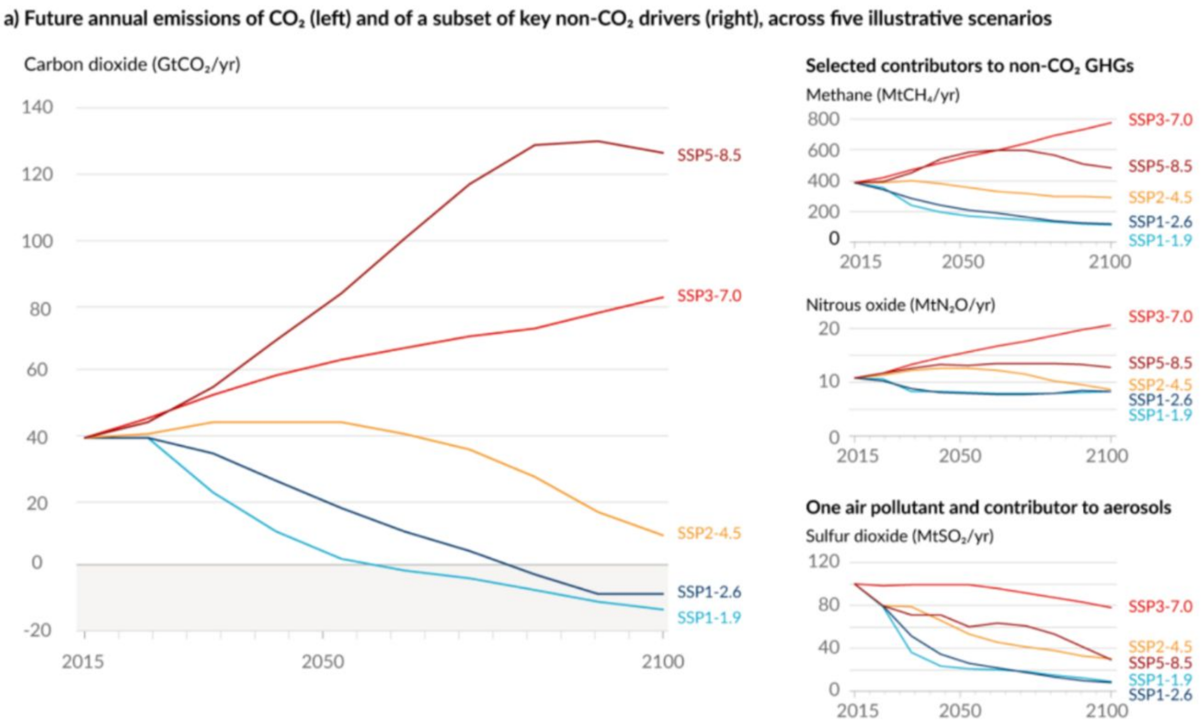
These are scenarios used in climate change research to explore how different socio-economic developments might affect greenhouse gas emissions, climate impacts, and adaptation efforts. The SSPs are a set of five possible pathways that describe different future global development scenarios, ranging from highly sustainable to more fragmented and unequal pathways.

Further reading:
https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/

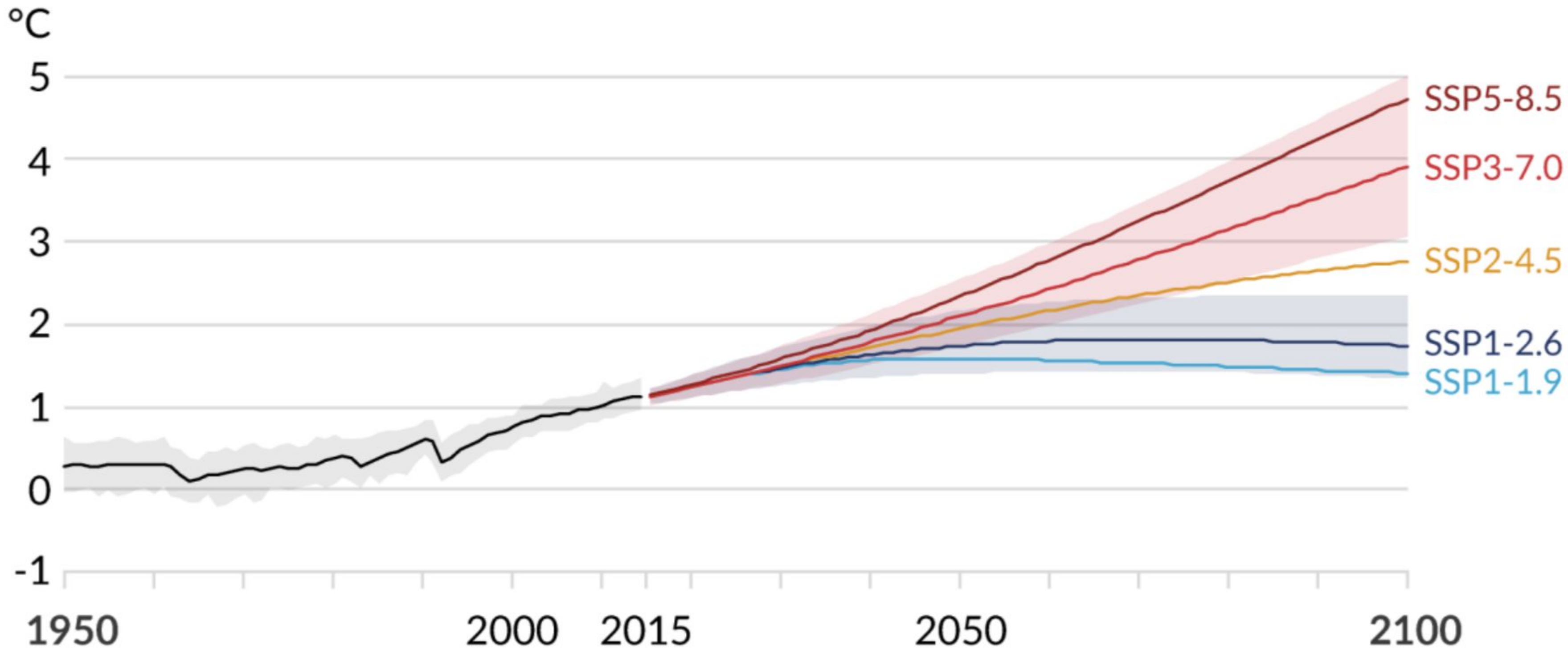
SSPs

Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions

Figure SPM.4



a) Global surface temperature change relative to 1850-1900



Radiative forcing (RF)

RF is the net increase in the energy input to the climate system due to greenhouse gas increase, in watts/m^2.

More specifically: (IPCC AR5, 2013)
RF: the change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures, and water vapor and cloud cover, fixed at the unperturbed values.

Observed radiative forcing increases

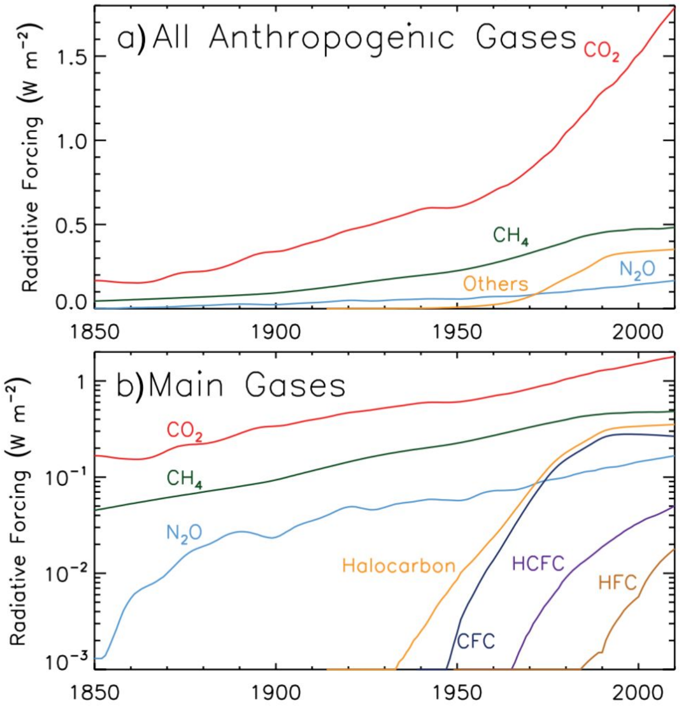
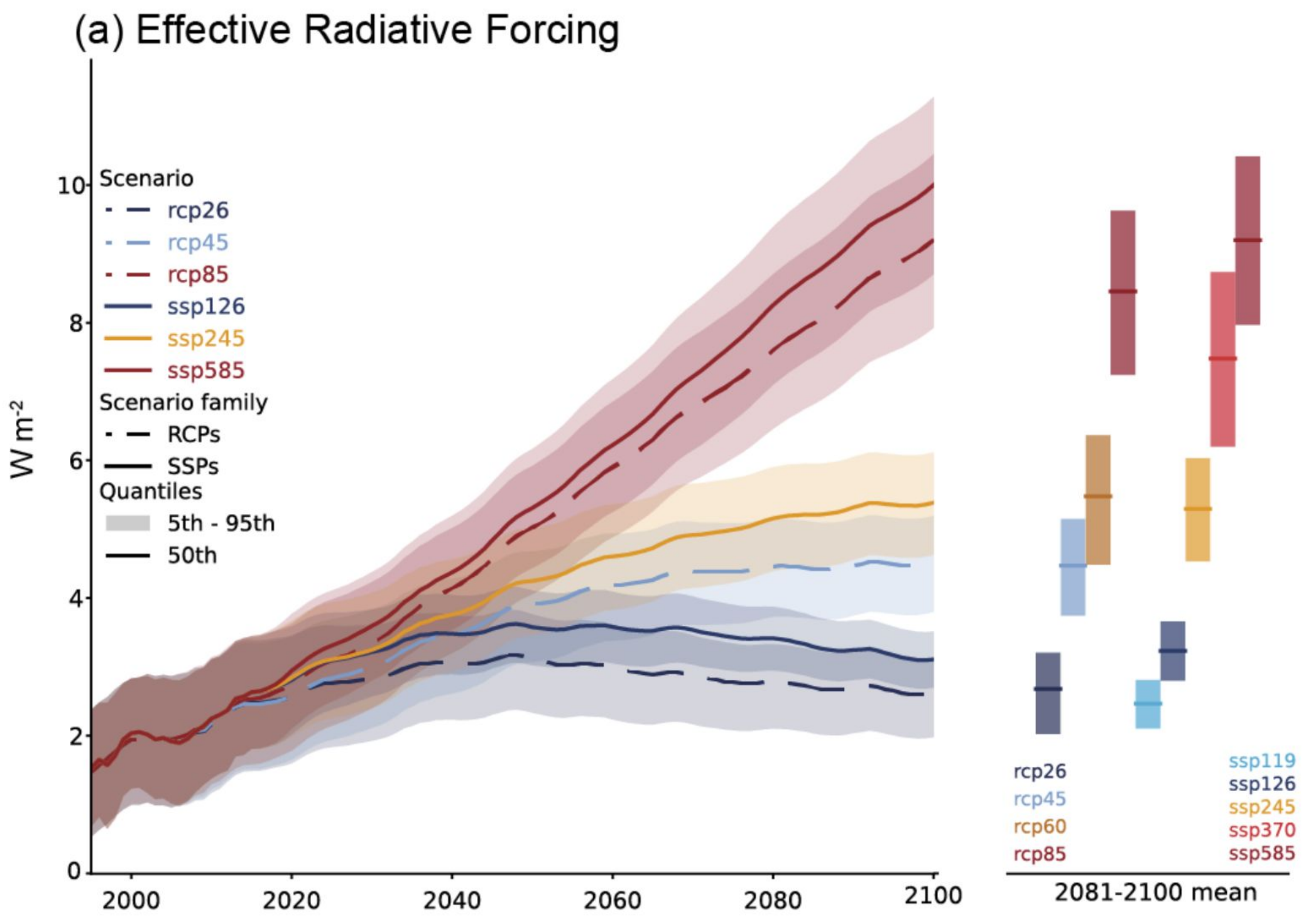
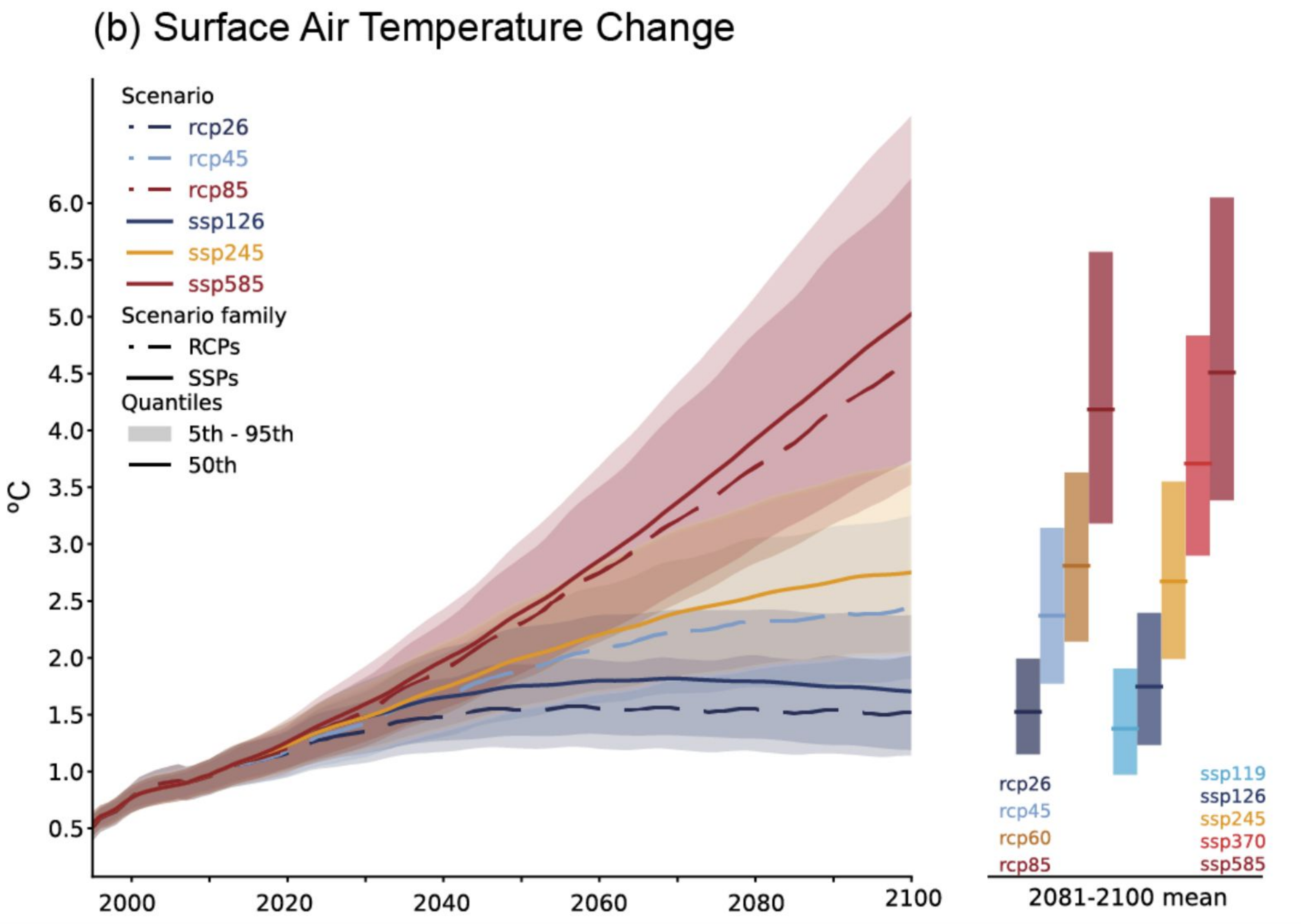


Figure 8.6 | (a) Radiative forcing (RF) from the major well-mixed greenhouse gases (WMGHGs) and groups of halocarbons, 1850-2011, (b) as (a) but with a log scale.

(IPCC AR5, 2013)


(a) Effective Radiative Forcing
W m-2
Scenario
rcp26
rcp45
rcp85
ssp126
ssp245
ssp585
Scenario family
RCPs
SSPs
Quantiles
5th - 95th
50th
0
2
4
6
8
10
2000
2020
2040
2060
2080
2100
rcp26
rcp45
rcp60
rcp85
ssp119
ssp126
ssp245
ssp370
ssp585
2081-2100 mean



(b) Surface Air Temperature Change
Scenario
rcp26
rcp45
rcp85
ssp126
ssp245
ssp585
Scenario family
RCPs
SSPs
Quantiles
5th - 95th
50th
°C
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2000
2020
2040
2060
2080
2100
rcp26
rcp45
rcp60
rcp85
ssp119
ssp126
ssp245
ssp370
ssp585
2081-2100 mean

Google Colab

https://www.youtube.com/watch?v=rsBiVxzmhG0

Notebook: “greenhouse1.ipynb”