ENVIRONMENTAL HYDRAULICS: POLLUTANTS, EMISSIONS AND GLOBAL WARMING

01 - Climate Change and Hydraulics

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Climate Change - Definitions

Climate System → The global system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system changes in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, orbital forcing, and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

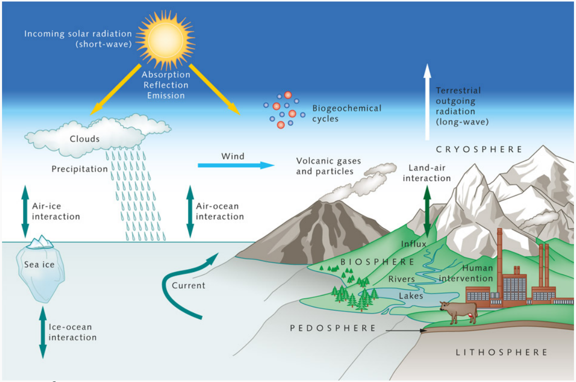


Figure 1: Image taken from:https://worldoceanreview.com/en/wor-1/climate-system/earth-climate-system/

Climate → In a narrow sense, climate is usually defined as the average weather or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. (A-Tropical, B-Dry,C-Temperate,D-Continental,E-Polar)

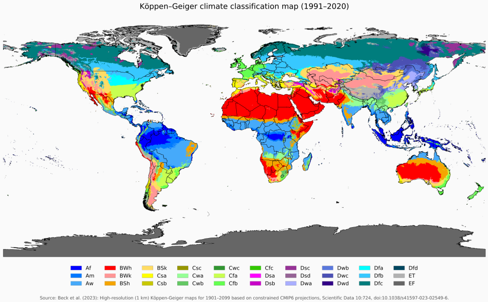


Figure 2: Image taken from:https://doi.org/10.1038/s41597-023-02549-6

Additional information:The Intergovernmental Panel on Climate Change (IPCC https://www.ipcc.ch/)

The definition of climate follow a statistical approach, therefore we need measurement of different variables. For example: temperature, precipitation.

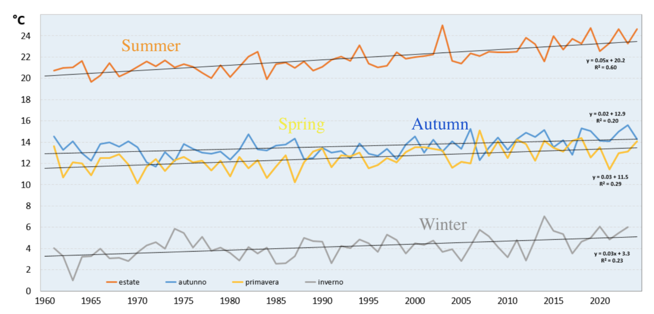


Figure 3: Image taken from: "Il Friuli Venezia Giulia nel cambiamento climatico" - ARPA FVG

Climate Change - Definitions - Measurement

The definition of climate follow a statistical approach, therefore we need measurement of different variables. For example: temperature, precipitation.

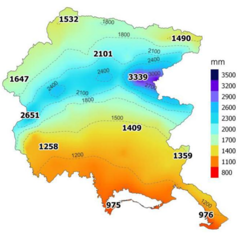


Figure 4: Image taken from:"Il Friuli Venezia Giulia nel cambiamento climatico" - ARPA FVG

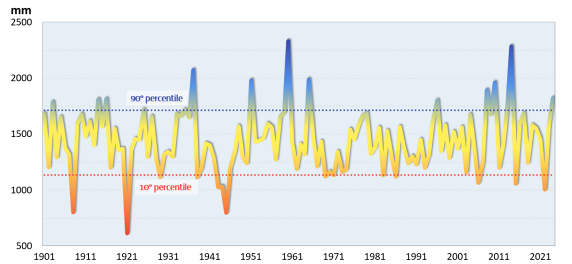
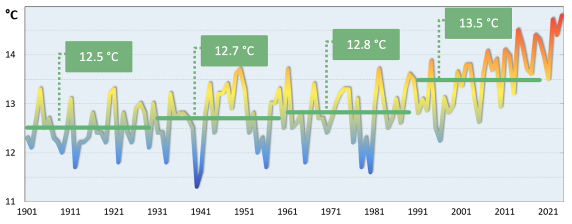


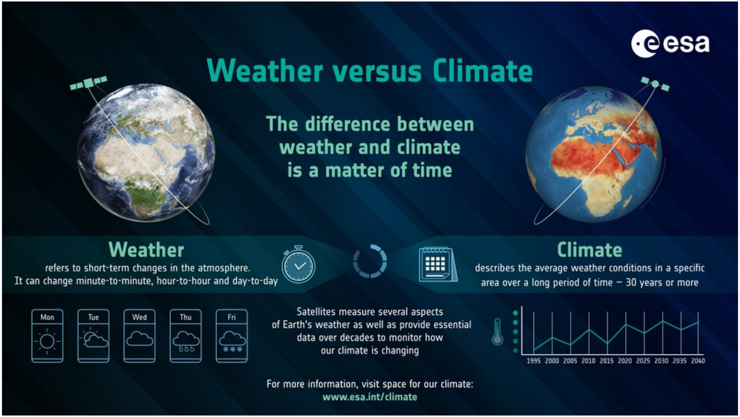
Figure 5: Image taken from:"Il Friuli Venezia Giulia nel cambiamento climatico" - ARPA FVG

Climate Change - Definitions

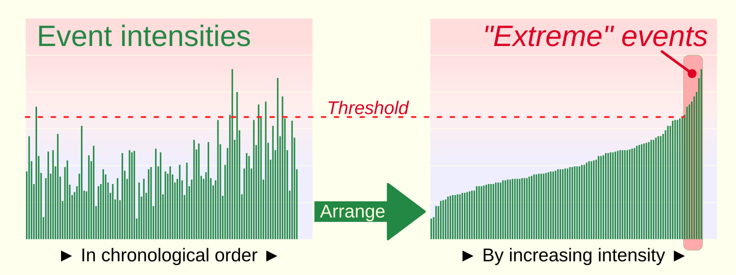
Climate Change → a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (**extended period of time → statistics**). Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. (Atmosphere -Temperature, Biosphere - Plant species)



Weather → is the state of the atmosphere at a particular time (**specific time → observation**), as defined by the various meteorological elements, including temperature, precipitation, atmospheric pressure, wind and humidity.


esa
Weather versus Climate
The difference between weather and climate is a matter of time
Weather
refers to short-term changes in the atmosphere.
It can change minute-to-minute, hour-to-hour and day-to-day
Climate
describes the average weather conditions in a specific area over a long period of time – 30 years or more
Mon
Tue
Wed
Thu
Fri
Satellites measure several aspects of Earth's weather as well as provide essential data over decades to monitor how our climate is changing
1995 2000 2005 2010 2015 2020 2025 2030 2035 2040
For more information, visit space for our climate:
www.esa.int/climate

Extreme weather events → are rare events that happen at a particular place and time of year, with unusual characteristics in terms of magnitude, location, timing, or extent. The characteristics of what is called extreme weather may vary from place to place in an absolute sense.



Extreme events registered in Europe

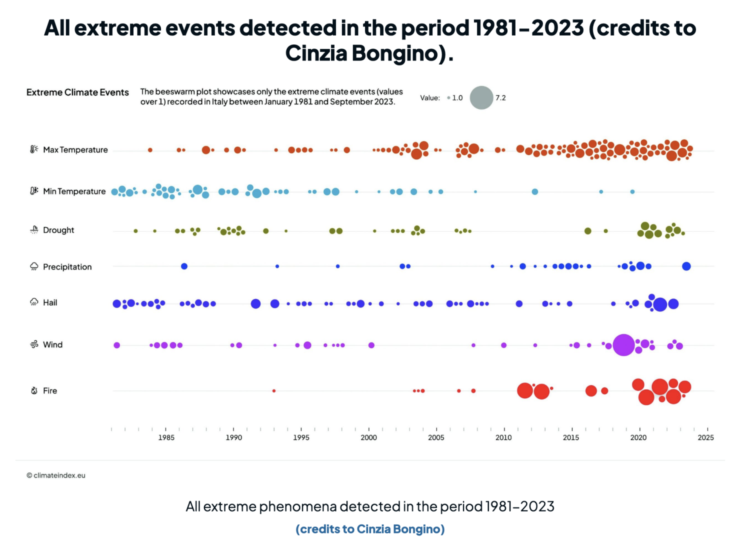


Figure 6: Interactive Map of Extreme Events (https://climateindex.eu/en/)

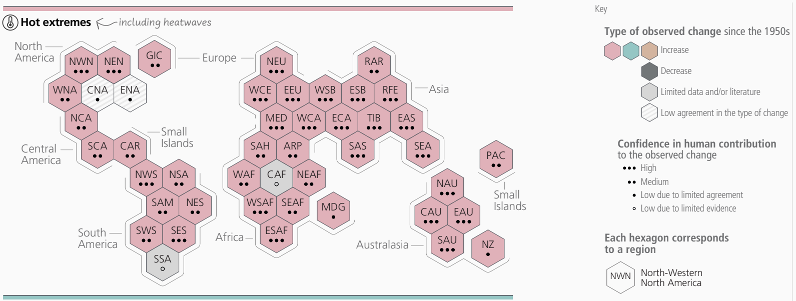
Climate Change - A Global Problem

Climate change is a global problem because its causes and impacts cross national boundaries.

- Greenhouse gas emissions from one region affect the entire planet, altering climate systems worldwide.
- Rising sea levels, extreme weather events, and biodiversity loss do not stop at borders.
- While some countries contribute more to emissions and others are more vulnerable, no nation is immune.

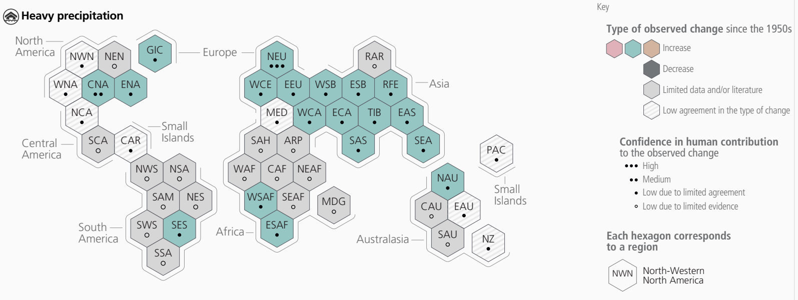
Addressing climate change requires international cooperation and shared responsibility, as only collective action can reduce risks and build resilience for future generations.

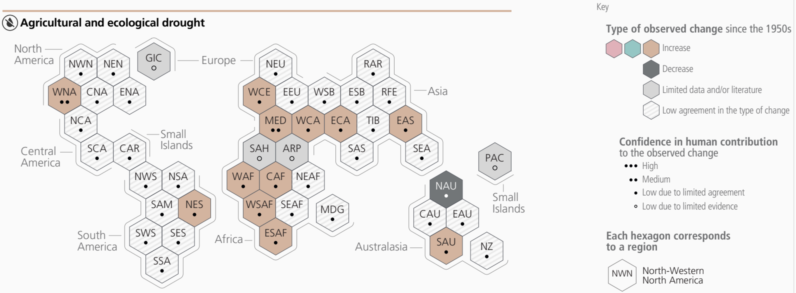
Climate Change - World - Hot Extremes



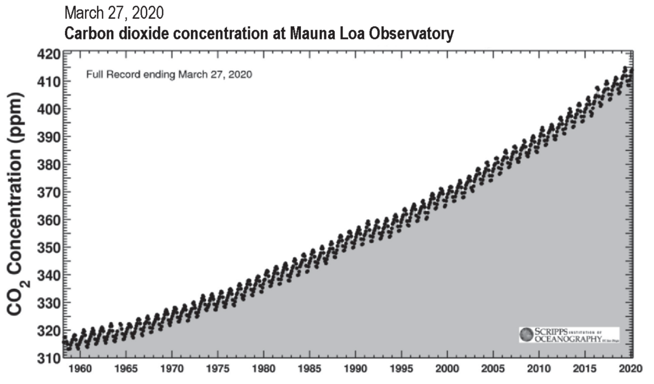
Uncertainties → Butterfly effects → Complex chaotic system

Climate Change - World - Heavy Precipitation




Agricultural and ecological drought
North America
NWN
NEN
GIC
Europe
NEU
RAR
WNA
CNA
ENA
WCE
EEU
WSB
ESB
RFE
Asia
NCA
MED
WCA
ECA
TIB
EAS
Small Islands
Central America
SCA
CAR
SAH
ARP
SAS
SEA
PAC
NWS
NSA
WAF
CAF
NEAF
NAU
Small Islands
SAM
NES
WSAF
SEAF
MDG
CAU
EAU
South America
SWS
SES
Africa
ESAF
Australasia
SAU
NZ
SSA
Key
Type of observed change since the 1950s
Increase
Decrease
Limited data and/or literature
Low agreement in the type of change
Confidence in human contribution to the observed change
High
Medium
Low due to limited agreement
Low due to limited evidence
Each hexagon corresponds to a region
NWN
North-Western North America

Climate Change - Physics

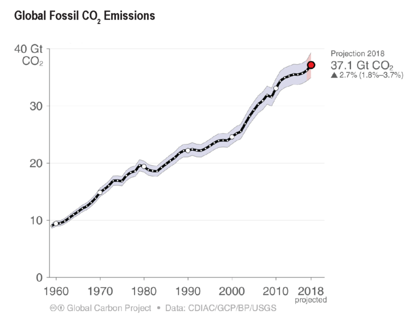


The Keeling Curve, which describe the average value of the CO_2 concentration in the atmosphere at Mauna Loa (Why?).

https://www.youtube.com/watch?v=x1SgmFa0r04

We observe a monotonic rise with superimpose a sinusoidal variation. Seasonal changes in the Northern Hemisphere's atmosphere are linked to photosynthesis, where plants absorb CO_2 and release $=_2$.

Climate Change - Physics - CO_2



CO_2 emissions have increased by a factor of five since 1960, while the slope of the Keeling curve has not increased by a similar factor.

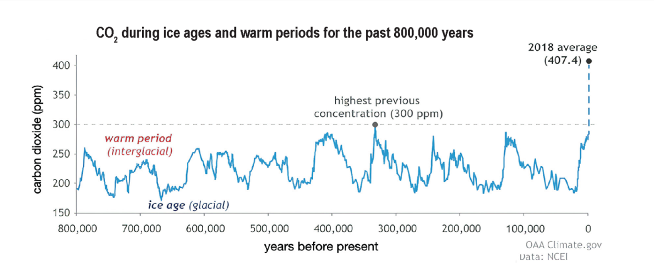
Not all human-produced CO_2 stays in the atmosphere, a portion dissolves in oceans, therefore this natural uptake by oceans reduces the direct rise of atmospheric CO_2 levels.

Correlation does not imply causation

Maybe we can explore longer-term variations.

[1]

[1] https://www.tylervigen.com/spurious/correlation/2965_associates-degrees-awarded-in-science-technologiestechnicians_correlates-with_google-searches-for-avocado-toast



Geological variations in the CO2 concentration have occurred, but at much smaller levels and over much longer timescales than the recently observed rise correlated also with temperature variation.
The variation in the last century is comparable with global fossil fuel consumption by human industrial activity.

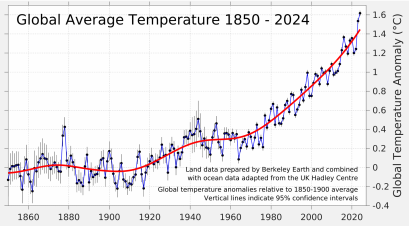
Why we discuss about CO_2?

First law of thermodynamics is the principle of energy conservation, stating that energy cannot be created or destroyed, only transformed from one form to another or transferred between systems.

If we consider a closed system and a quantity X, we can define the conservation of the quantity X as

$$\frac{\partial X}{\partial t} = I - O$$

where I is the input and O is the output.



Now, if the average temperature of the Earth is increasing in time, it means that there is an imbalance between Input and Output of Energy .

But where is this energy coming from?

If we take the Earth as an example, it receives energy continuously from the Sun. We can assume that the Earth system is in equilibrium and that it radiates into space as much energy as it receives from the Sun. Otherwise, it would continue to heat up infinitely.

$$\frac{\partial \text{Energy}}{\partial t} = I - O = 0$$

Now, on average the Earth receives $1361(W/m^2)$, the solar irradiance (average over time and space).
Earth also directly reflects some fraction, a (about 30 percent , a is also defined as **albedo**), of the sun's radiation.
So the total rate of energy flowing into Earth from the sun (Input) is given by

$$I = P_{solar} = 1361(W/m^2) \times (1-a)\pi R^2 \approx 10^{17} W$$

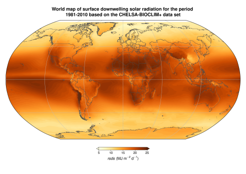


Figure 7: https://en.wikipedia.org/wiki/Solar_irradiance

Now, we need to define the Output → Black Body Theory

We know that a black body emits a total power equal to:

$$O = P_{emitted} = S \times kT^4, \quad \text{(Stefan–Boltzmann law)}$$

where S is the surface of the Earth, k is the Stefan- Boltzmann constant and T is the temperature of the Earth.

$$\frac{\partial \text{Power}}{\partial t} = I - O = 0 \rightarrow 10^{17}W = S \times kT^4$$

Now if we solve this equation for T we get that $T = -18°$;

However average global surface temperature of the Earth is $T_{surface} = 15°$.

We are missing something?

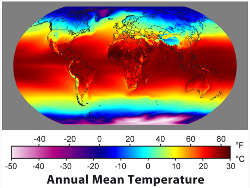


Figure 8: https://commons.wikimedia.org/wiki/File:Annual_Average_Temperature_Map.jpg

The wavelength of radiation emitted by hot bodies depends on their temperature. An object with the average temperature of the Earth's surface (about 15°C) radiates in the infrared band, with wavelengths longer than visible light. Instead the wavelengths of light from the sun are centered in the visible band.

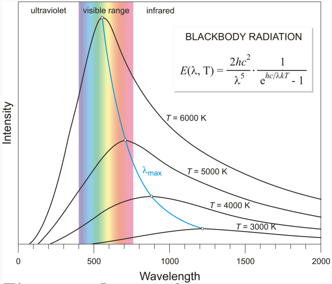


Figure 9: Image taken from:https://www.periodni.com/gallery/blackbody_radiation.png

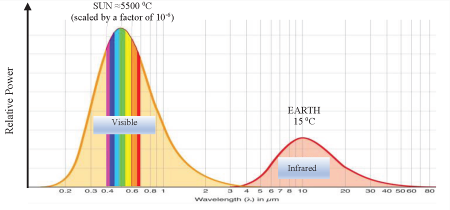


Figure 10: Image taken from: The physics of climate change-LM Krauss

The figure suggests that the atmosphere behaviour depends on the wavelength of the radiation.

In general atmosphere is transparent to visible light. (We can see things)

In general atmosphere is not transparent to infrared radiation (or absorption).

Now we return to our simple model and we factor in the presence of the atmosphere.

At equilibrium, we have that P_{solar} (input) is equal to the sum of $P_{Earth} + P_{atm}$ (output), since also the atmosphere at a fixed temperature is emitting radiation. However, part of energy radiated by the Earth is captured by the Atmosphere **(b)**, therefore, we have:

$$(1 - b)P_{Earth} + P_{atm} = P_{solar},$$

The atmosphere is transparent to visible light; therefore, almost all of the sun's radiation reaches Earth, and part of the energy emitted by the Earth is absorbed by the atmosphere.

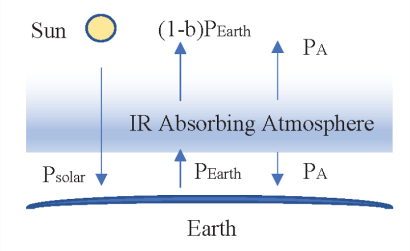
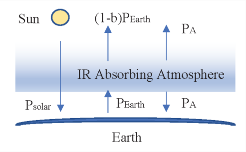


Figure 11: Image taken from: The physics of climate change-LM Krauss



$$(1-b)P_{Earth} + P_{atm} = P_{solar}$$

For the atmosphere to remain in equilibrium with the radiation it receives from the Earth, the total energy it emits, both back toward the Earth and out into space, must balance the energy it absorbs. This absorbed energy corresponds to a fraction **b** of the radiation emitted by the Earth.

$$\frac{\partial P_{atm}}{\partial t} = 0 = I - O = bP_{Earth} - 2P_{atm} \qquad \rightarrow \qquad bP_{Earth} = 2P_{atm}$$

Inserting P_A in the previous equation we have

$$\left(1 - \frac{b}{2}\right) P_{Earth} = P_{solar}$$

since $(1 - b/2) < 1$, this means the power radiated at the surface of the Earth would have to be greater than it would be if b were 0.

And that the temperature of the Earth needs to be higher, since the emitted power is a function of the temperature.

Role of the atmosphere in keeping the Earth livable (Greenhouse effect).

In reality the process are more complex than the simple model presented; the complete relation between Earth, Sun and the atmosphere Energy Balance is the following:

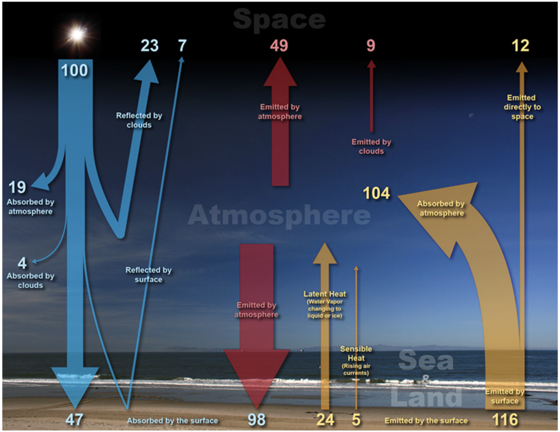


Figure 12: Image taken from: https://www.noaa.gov/jetstream/atmosphere/energy

Why part of the energy is able to reach the surface, or reflected back at the surface, etc. ?

If we take as an example the solar radiation spectrum we observe that not all the spectrum of electromagnetic waves is able to reach the surface.

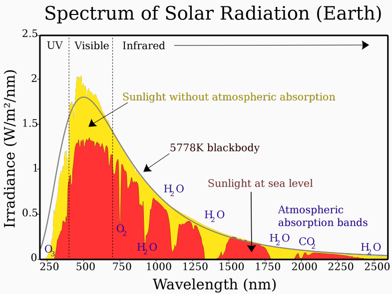


Figure 13: Image taken from: https://en.wikipedia.org/wiki/Solar_irradiance

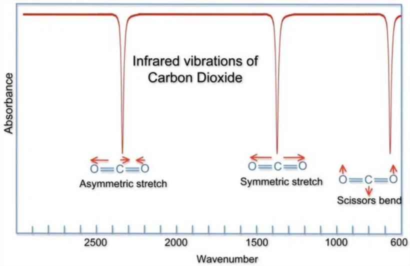
The atmosphere absorbs and scatters solar radiation at specific wavelengths:

- Ultraviolet (UV): absorbed mainly by the ozone layer (O_3).
- Infrared (IR): absorbed by greenhouse gases (H_2O, CO_2, O_2).
- Visible light: mostly transmitted, making sunlight bright at the surface.

The atmosphere acts as a filter, so only parts of the solar spectrum reach the ground. Why?

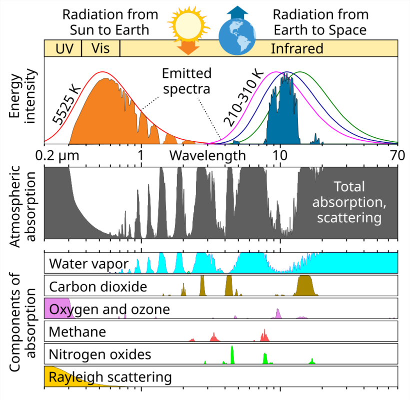
Absorption and emission of radiation are linked to the **vibrational and rotational capacities** of molecules. Photons carry just enough energy to cause molecules to vibrate at characteristic frequencies, determined by:

- The type and strength of chemical bonds.
- The molecular geometry.



- These modes resonate at **specific frequencies**, corresponding to distinct regions of the electromagnetic spectrum (CO_2 spectrum).
- Greenhouse gases such as H_2O, CO_2, and CH_4 absorb strongly in the infrared region, where vibrational transitions dominate.
- Selective absorption and emission are fundamental to the **greenhouse effect** and the regulation of Earth's energy balance.

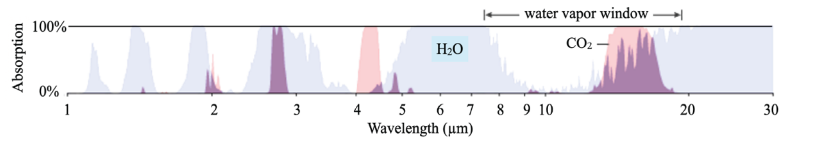
If we look at the whole spectrum (Earth and Sun), we can see which molecules regulates the absorption and emission of electromagnetic waves.



Greenhouse effect: the infrared radiative effect of all infrared absorbing constituents in the atmosphere. Greenhouse gases (GHGs), clouds, and some aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere.

Climate Change - Physics - CO_2 vs H_2O overlap

Back to the start: Why CO_2 is important?



- Overlap of absorption: CO_2 absorption overlaps with H_2O absorption and fills gaps between H_2O peaks.
- **H_2O vs CO_2 distribution:** Water vapor decreases sharply with altitude, while CO_2 remains well mixed throughout the atmosphere.
- Implication: Even when H_2O absorption is saturated in the lower atmosphere, CO_2 continues to enhance absorption, especially at higher altitudes where radiation escapes to space.

Increased CO_2 → More energy is stored and emitted by the atmosphere
→ we have an imbalance of energy → Earth heats up
New equilibrium: Eventually, a higher global temperature is reached, restoring the balance between incoming and outgoing radiation.

How do we quantify a change to the balance of energy in the atmosphere?

$$\frac{\partial P}{\partial t} = I - O \neq 0$$

Any change in the Earth's energy balance is driven by different factors, such as the greenhouse effect, which is defined as a Radiative Forcing, since it effects the amount of emitted by the Earth system.

The radiative forcing is defined as a radiative flux and it is expressed in W$/m^2$.

A change in the radiative balance at the top-of-the-atmosphere will cause:

- warming if the forcing is positive (more absorbed solar radiation or less emitted terrestrial radiation),
- cooling if the forcing is negative (less absorbed solar or more emitted terrestrial to space).

The radiative forcing of the CO_2 is

$$\Delta F = 5.35[Wm^{-2}]ln(C/C_0)$$

where C is the CO_2 concentration and C_0 is the CO_2 concentration of a reference state (e.g. the pre-industrial).

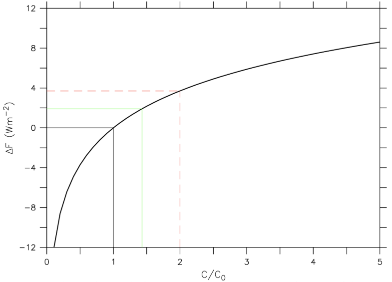


Figure 9: Radiative forcing (ΔF) in watts per square meter as a function of the atmospheric CO_2 concentration (C) relative to a reference value (C_0) according to eq. (2; black thick line). The black straight lines indicate the reference state $C = C_0$ ($\Delta F = 0$). The green and red dashed lines indicate the current (2016) state relative to the pre-industrial C/C_0 = 400 ppm / 280 ppm = 1.4 (ΔF = 1.9 Wm^{-2}) and that for a doubling of CO_2 (ΔF_{2x} = 3.7 Wm^{-2}) respectively.

Figure 14: Image taken from: $https://doi.org/10.1175/AMSMONOGRAPHS-D-19-0001.1$

This means that the radiative effect of adding a certain amount of CO_2 to the atmosphere will be smaller the more CO_2 is already in the atmosphere. The reason for this is the saturation of peaks in the absorption spectrum.

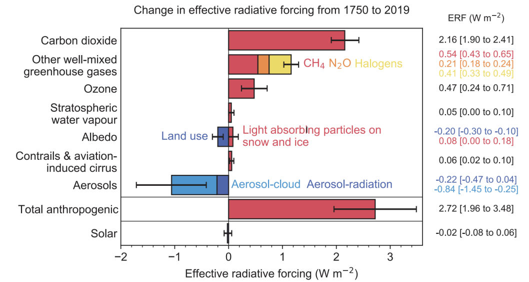


Figure 7.6 | Change in effective radiative forcing (ERF) from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, anthropogenic total, and solar). Solid bars represent best estimates, and *very likely* (5–95%) ranges are given by error bars. Non-CO_2 WMGHGs are further broken down into contributions from methane (CH_4), nitrous oxide (N_2O) and halogenated compounds. Surface albedo is broken down into land-use changes and light-absorbing particles on snow and ice. Aerosols are broken down into contributions from aerosol–cloud interactions (ERFaci) and aerosol–radiation interactions (ERFari). For aerosols and solar, the 2019 single-year values are given (Table 7.8), which differ from the headline assessments in both cases. Volcanic forcing is not shown due to the episodic nature of volcanic eruptions. Further details on data sources and processing are available in the chapter data table (Table 7.SM.14).

Figure 15: Image taken from: $https://doi.org/10.5194/essd-15-2295-2023$

Greenhouse Gases (GHGs)

- CO_2, CH_4, N_2O, O_3 increase infrared absorption ⇒ **Positive forcing (warming)**

Aerosols

- Scattering aerosols (sulfates, nitrates) ⇒ reflect sunlight ⇒ **Negative forcing (cooling)**
- Reduce pollution problem

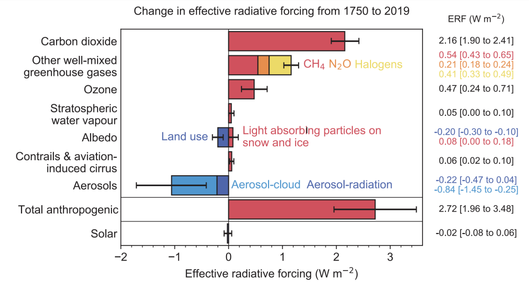


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Figure 16: Image taken from: $https://doi.org/10.5194/essd-15-2295-2023$

Land Use and Surface Albedo

- Deforestation, urbanization, ice/snow melt change surface reflectivity
- Lower albedo ⇒ **Positive forcing (warming)**

Solar Irradiance

- Variations in Sun's output directly affect energy balance

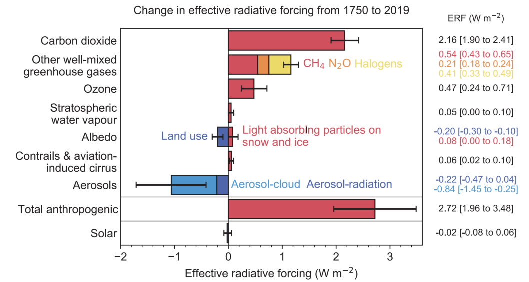


Figure 7.6 | Change in effective radiative forcing (ERF) from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, anthropogenic total, and solar). Solid bars represent best estimates, and *very likely* (5–95%) ranges are given by error bars. Non-CO_2 WMGHGs are further broken down into contributions from methane (CH_4), nitrous oxide (N_2O) and halogenated compounds. Surface albedo is broken down into land-use changes and light-absorbing particles on snow and ice. Aerosols are broken down into contributions from aerosol–cloud interactions (ERFaci) and aerosol–radiation interactions (ERFari). For aerosols and solar, the 2019 single-year values are given (Table 7.8), which differ from the headline assessments in both cases. Volcanic forcing is not shown due to the episodic nature of volcanic eruptions. Further details on data sources and processing are available in the chapter data table (Table 7.SM.14).

Figure 17: Image taken from: $https://doi.org/10.5194/essd-15-2295-2023$

Cloud - Contrails - Forcing

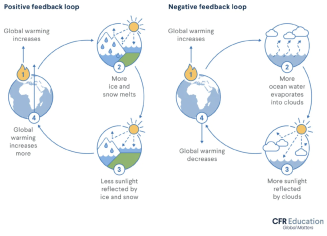
- Reflect shortwave radiation (cooling)
- Trap longwave radiation (warming)
- Net effect depends on type, altitude, thickness

Stratospheric Ozone

- Ozone depletion reduces UV absorption
- Causes stratospheric cooling and circulation changes

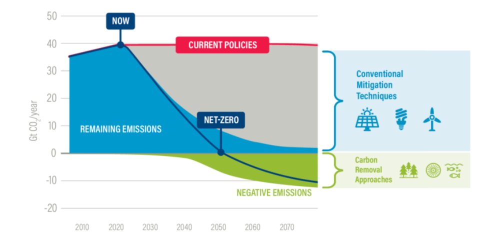
A feedback process is a modifier of climate change. It can be defined as a process that can amplify (positive feedback) or dampen (negative feedback the response to the initial radiative forcing through a feedback loop.

Example:
As a response to increasing CO2 concentrations surface temperatures will warm, which will cause more evaporation and increased water vapor in the atmosphere. Since most of Earth is covered in oceans there is no lack of water available for evaporation. Therefore, it is likely that warmer air temperatures will lead to more water vapor in the atmosphere. Because water vapor is a strong greenhouse gas this will lead to an additional reduction in the amount of outgoing longwave radiation and therefore to more warming.
Thus, the water vapor feedback is positive.



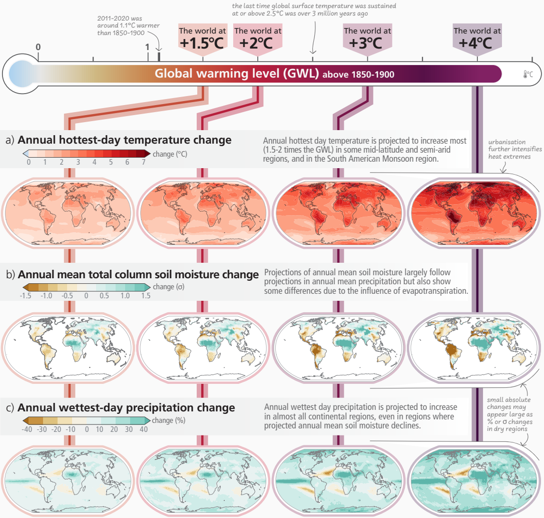
- **Carbon Dioxide (CO_2):** Stays in the atmosphere from decades up to thousands of years; removal is slow due to ocean and rock uptake processes.
- **Methane (CH_4):** Atmospheric lifetime 12 years; removed primarily via reaction with hydroxyl radicals (OH).
- **Nitrous Oxide (N_2O):** Lifetime 114 years; removed mainly through photolysis in the stratosphere.
- **Fluorinated Gases (CFCs, HFCs, SF_6):** Lifetimes range from decades to thousands of years depending on the compound; often very long-lived and potent.

Long-lived GHGs accumulate in the atmosphere, sustaining their warming effect even after emissions cease. Net Zero Inertia Problem

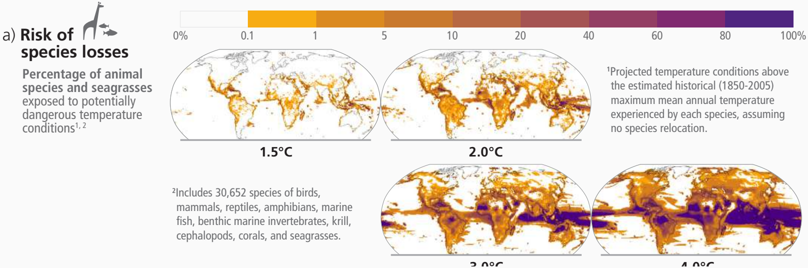


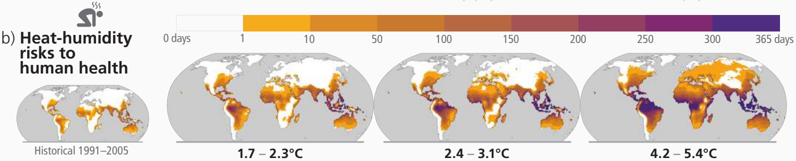
Climate Change - Future Projections and Models

Future Scenario



Future Scenario - Species



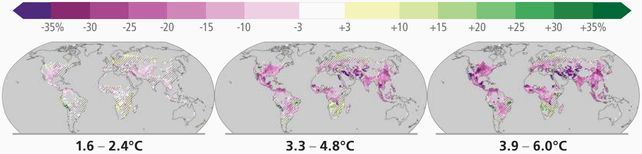


Days per year where combined temperature and humidity conditions pose a risk of mortality to individuals[3]

[3]Projected regional impacts utilize a global threshold beyond which daily mean surface air temperature and relative humidity may induce hyperthermia that poses a risk of mortality. The duration and intensity of heatwaves are not presented here. Heat-related health outcomes vary by location and are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability. The threshold used in these maps is based on a single study that synthesized data from 783 cases to determine the relationship between heat-humidity conditions and mortality drawn largely from observations in temperate climates.

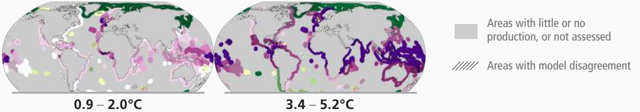
c) Food production impacts

c1) Maize yield[4]
Changes (%) in yield



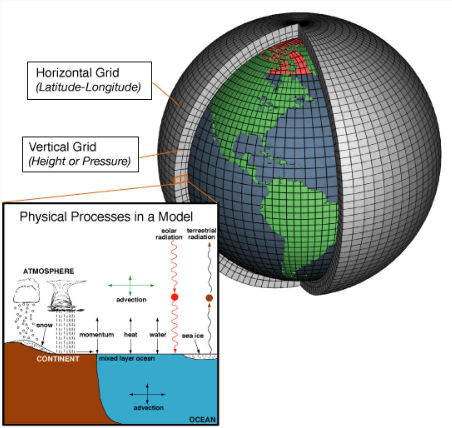
[4]Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO_2 enhancement of growth and water retention in currently cultivated areas. Models assume that irrigated areas are not water-limited. Models do not represent pests, diseases, future agro-technological changes and some extreme climate responses.

c2) Fisheries yield[5]
Changes (%) in maximum catch potential



[5]Projected regional impacts reflect fisheries and marine ecosystem responses to ocean physical and biogeochemical conditions such as temperature, oxygen level and net primary production. Models do not represent changes in fishing activities and some extreme climatic conditions. Projected changes in the Arctic regions have low confidence due to uncertainties associated with modelling multiple interacting drivers and ecosystem responses.

Future Scenario - Climate Model



Climate Model

- A climate model is a computer simulation of the Earth's climate system
- Climate models calculate many different properties of the climate, including atmospheric temperature, pressure, wind, and humidity.
- Data Input problem.
- Physics is modelled.
- Ensemble average.

Interactive Map

https://meteohub.mistralportal.it/app/maps/observations

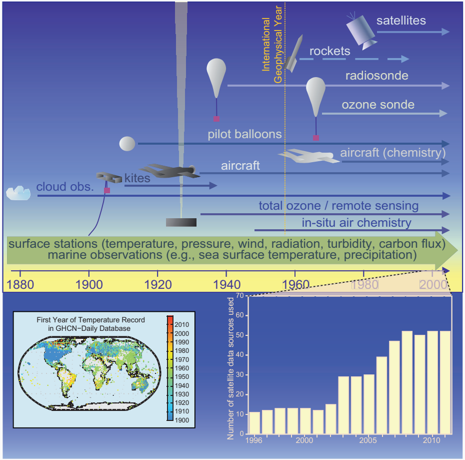
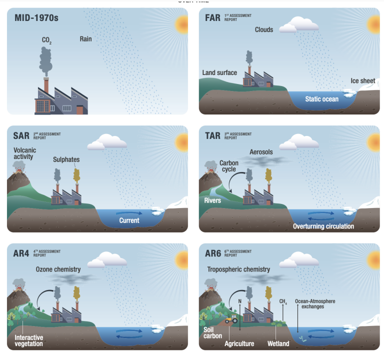


Figure 1.12 | Development of capabilities of observations. Top: Changes in the mix and increasing diversity of observations over time create challenges for a consistent climate record (adapted from Brönnimann et al., 2008). Bottom left: First year of temperature data in Global Historical Climatology Network (GHCN) daily database (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/; Menne et al., 2012). Bottom right: Number of satellite instruments from which data have been assimilated in the European Centre for Medium-Range Weather Forecasts production streams for each year from 1996 to 2010. This figure is used as an example to demonstrate the fivefold increase in the usage of satellite data over this time period.

Climate models are increasing the parameters taken into account and also the interaction between different physical processes, to keep pace with the increasing amount of data at our disposal and the computational resources.



Source: 2007, adapted from Figures 1.2 and 1.4, IPCC AR4, The Physical Science Basis, available on the IPCC website (https://www.ipcc.ch/report/ar4/wg1/).

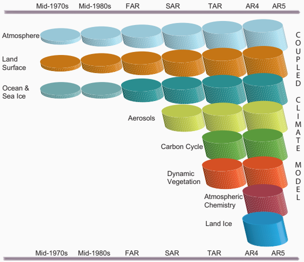


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard.

Future Scenario - Climate Model - Resolution

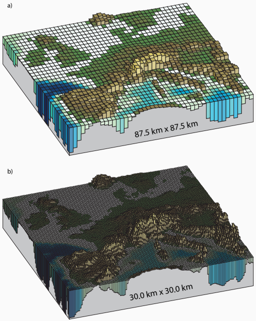


Figure 1.14 | Horizontal resolutions considered in today's higher resolution models and in the very high resolution models now being tested: (a) Illustration of the European topography at a resolution of 87.5 × 87.5 km; (b) same as (a) but for a resolution of 30.0 × 30.0 km.

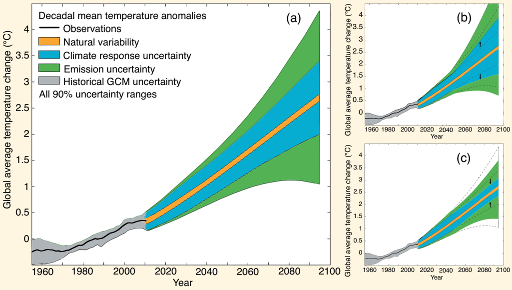
Why do we want higher resolution?

Allows for the explicit representation of smaller-scale processes like cloud formation, convection, and local land-surface hydrology, providing more detailed information on extreme events like hurricanes and floods.

At what cost?

Simply doubling the resolution in a 3D model multiplies the grid squares by eight (2^3), and the need to shorten the time step for stability can multiply the overall computational cost by 16 or more.

Global average temperature prediction Uncertainties from the ensemble average of different model.

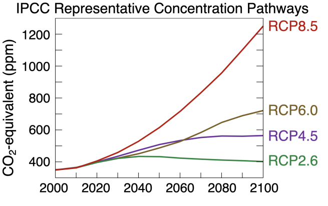


FAQ 1.1, Figure 1 | Schematic diagram showing the relative importance of different uncertainties, and their evolution in time. (a) Decadal mean surface temperature change (°C) from the historical record (black line), with climate model estimates of uncertainty for historical period (grey), along with future climate projections and uncertainty. Values are normalised by means from 1961 to 1980. Natural variability (orange) derives from model interannual variability, and is assumed constant with time. Emission uncertainty (green) is estimated as the model mean difference in projections from different scenarios. Climate response uncertainty (blue-solid) is based on climate model spread, along with added uncertainties from the carbon cycle, as well as rough estimates of additional uncertainty from poorly modelled processes. Based on Hawkins and Sutton (2011) and Huntingford et al. (2009). (b) Climate response uncertainty can appear to increase when a new process is discovered to be relevant, but such increases reflect a quantification of previously unmeasured uncertainty, or (c) can decrease with additional model improvements and observational constraints. The given uncertainty range of 90% means that the temperature is estimated to be in that range, with a probability of 90%.

An ensemble average is calculated by taking the mean or median of multiple model simulations. This reduces uncertainty by canceling out random errors from individual models or simulations.

Future Scenario - Climate Model - Representative Concentration Pathways (RCPs)

- **RCP2.6** — strong mitigation: radiative forcing peaks at $\approx 2.6\ \mathrm{W\,m^{-2}}$ by 2100 and declines. Compatible with ambitious emission cuts and likely to limit global warming close to 1.5–2°C (depending on carbon budgets and overshoot).
- **RCP4.5** — moderate mitigation: forcing stabilizes near $4.5\ \mathrm{W\,m^{-2}}$ by 2100. Requires sustained mitigation policies and widespread deployment of low-carbon technologies.
- **RCP6.0** — intermediate scenario: forcing stabilizes near $6.0\ \mathrm{W\,m^{-2}}$ after mid-century; represents slower mitigation.
- **RCP8.5** — high emissions / business-as-usual: forcing reaches $\approx 8.5\ \mathrm{W\,m^{-2}}$ by 2100. Yields the largest temperature and sea-level responses and the most severe impacts.



Source: IPCC assessment reports (e.g. AR5) — RCPs are pathways of greenhouse-gas

Future Scenario - Climate Model - Representative Concentration Pathways (RCPs)

The output are the main variables of interest as the temperature.