https://www.noaa.gov/news/its-official-july-2021-was-earths-hottest-month-on-record

Climate Change

ISAE, September 27, 2021

https://www.edf.org/climate/why-fighting-climate-change-so-urgent

By Ludovic Bouilloud, David Pollack and Catherine Freydier,

METEO-FRANCE

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https://www.noaa.gov/news/its-official-july-2021-was-earths-hottest-month-on-record

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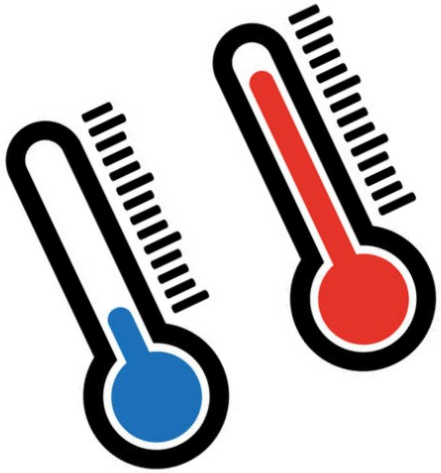
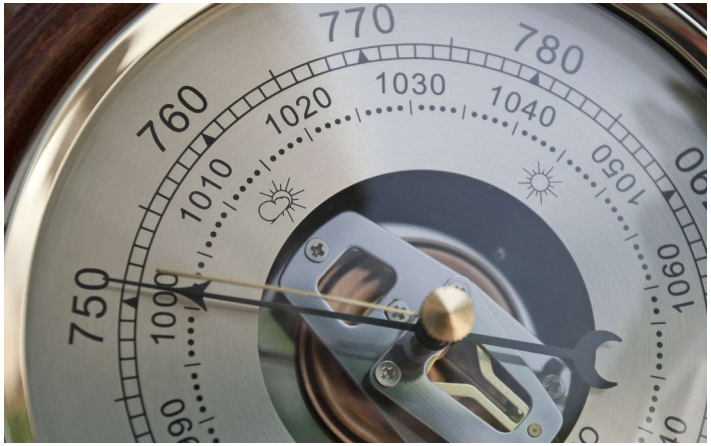
Weather vs climate



The **meteorologist**, who is interested in the weather and its changes, and the **climatologist**, whose area of expertise is the climate and its changes, both handle data on temperature, humidity, precipitation, etc.



https://www.futura-sciences.com/sciences/definitions/physique-barometre-15917/

Weather

https://commons.wikimedia.org/wiki/File:Rain_on_the_field.jpg

When you look out your window, at a given time, what you are seeing is what the weather is like at that time.

https://pixabay.com/fr/photos/sauter-le-brouillard-jardin-vert-3565308/

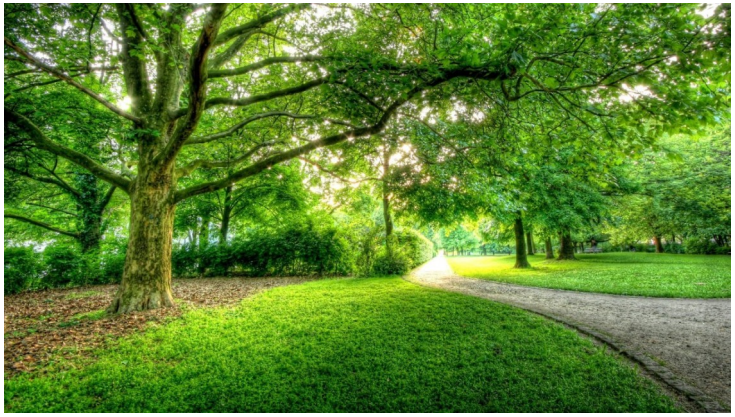


Image courtesy of Riverside Park

Weather is a snapshot of what's happening **right here, right now**.

The ever-changing weather

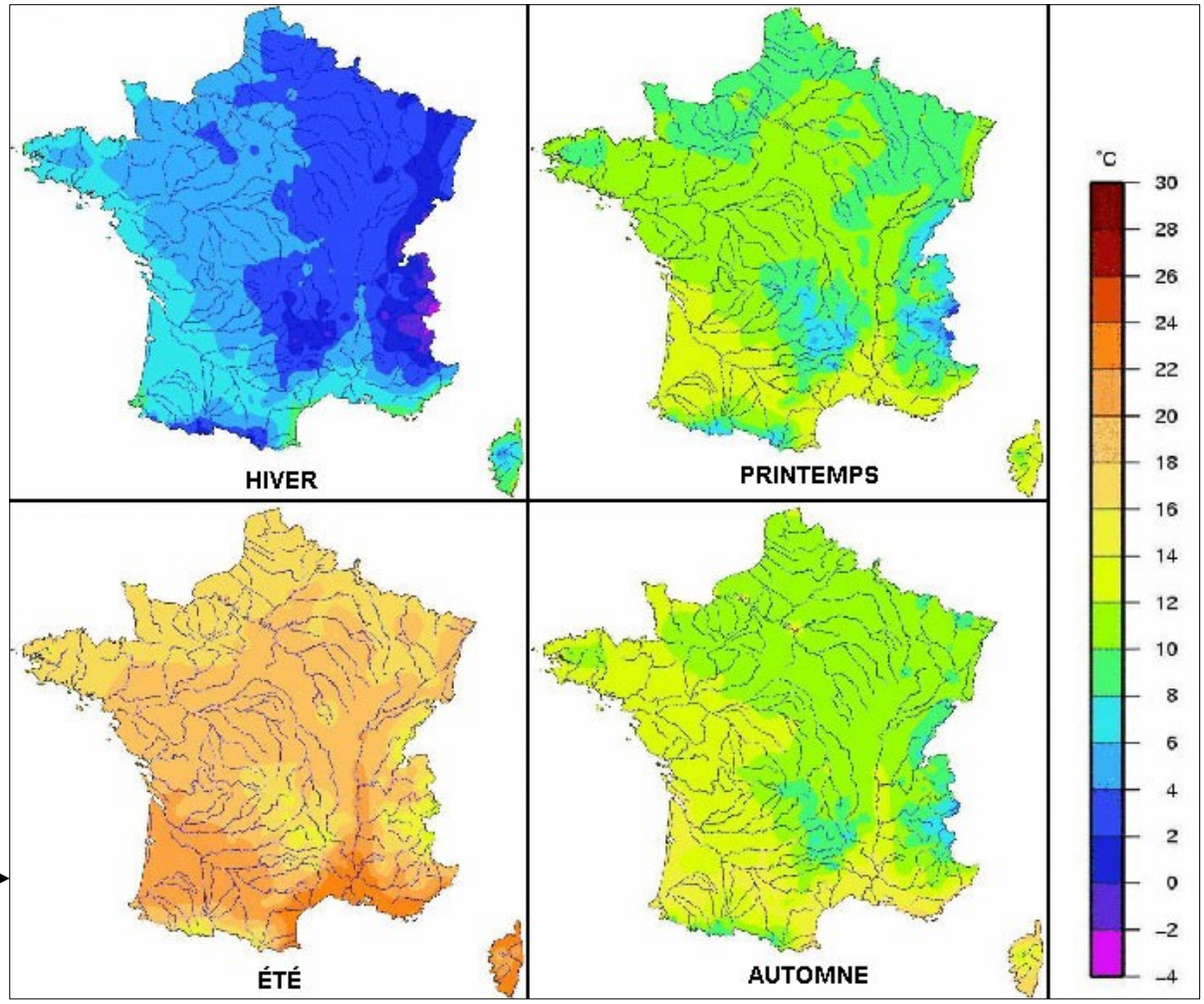
Weather **changes** over days, hours, even minutes …

Climate

Climate is the weather of a specific region **averaged over a long period of time :** 30 years or more.

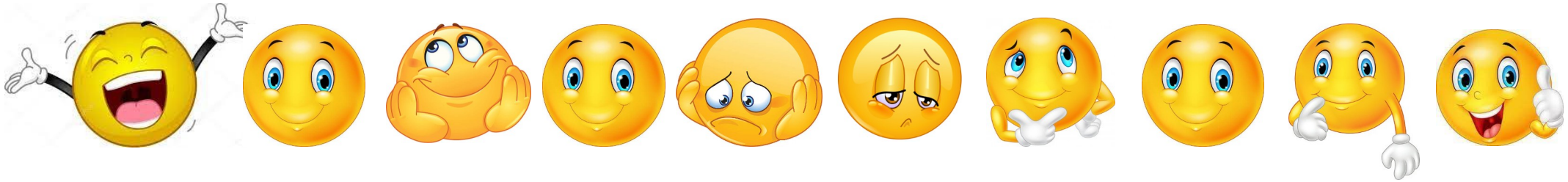
It's an average pattern of weather for a particular region.

Normal seasonal temperature (°C) over France, for the 1981-2010 period.



METEO FRANCE

Weather vs climate : an analogy



time

On average

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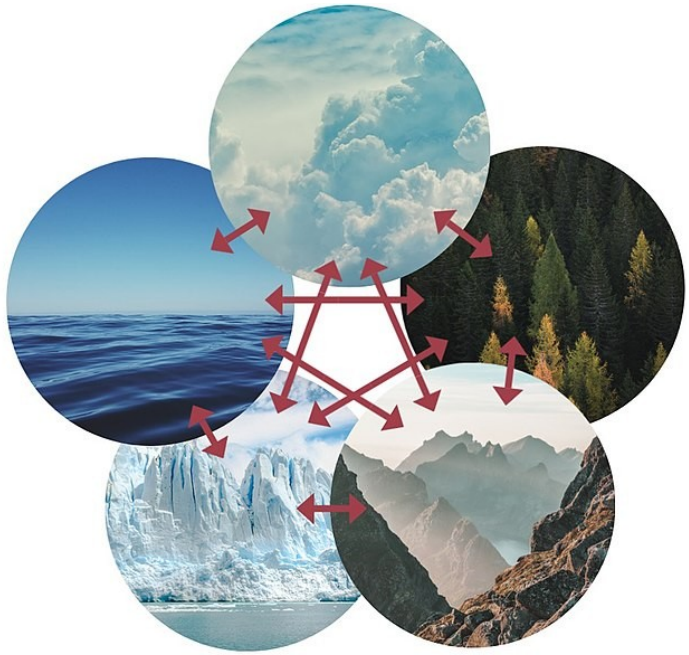
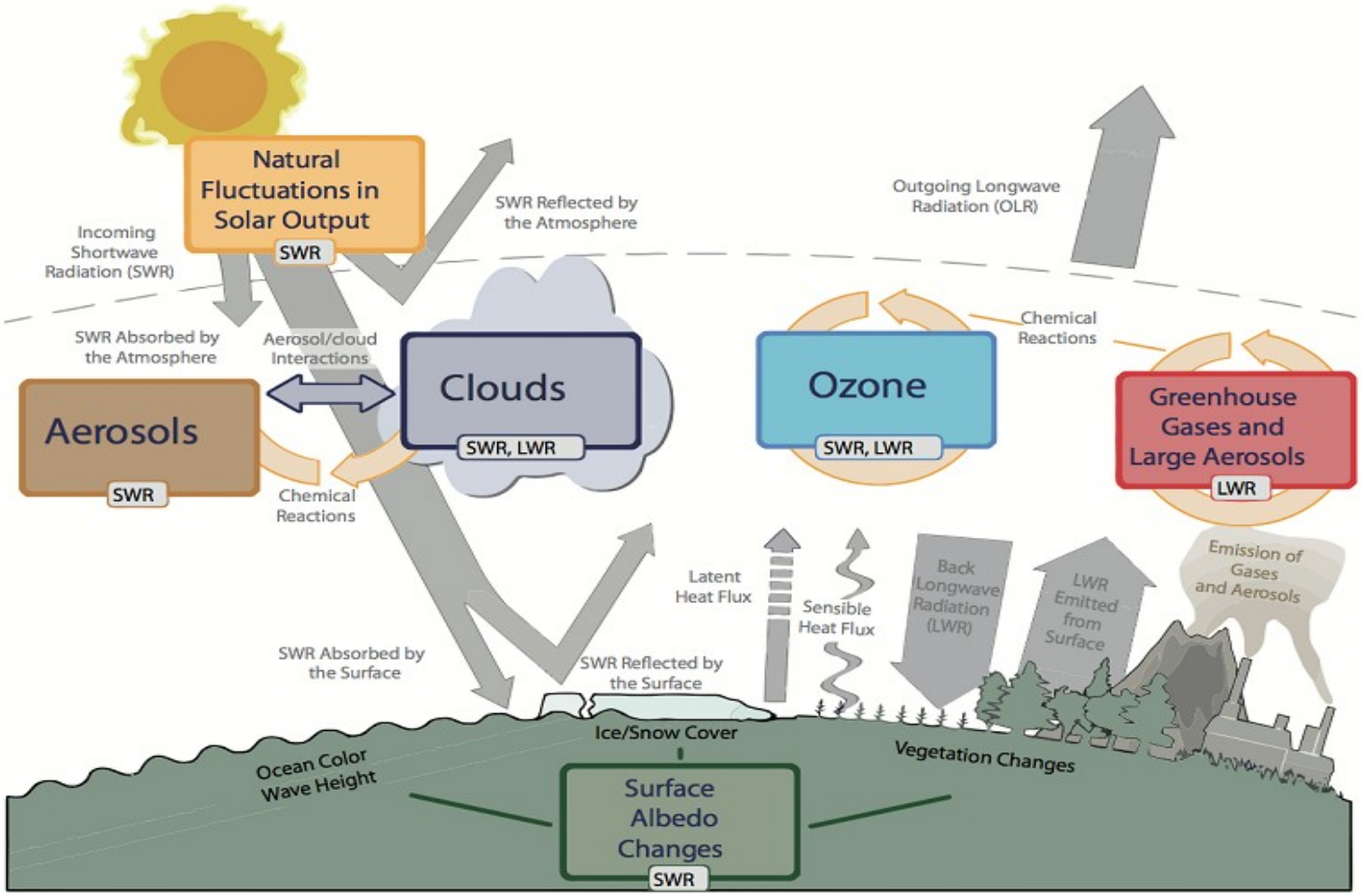


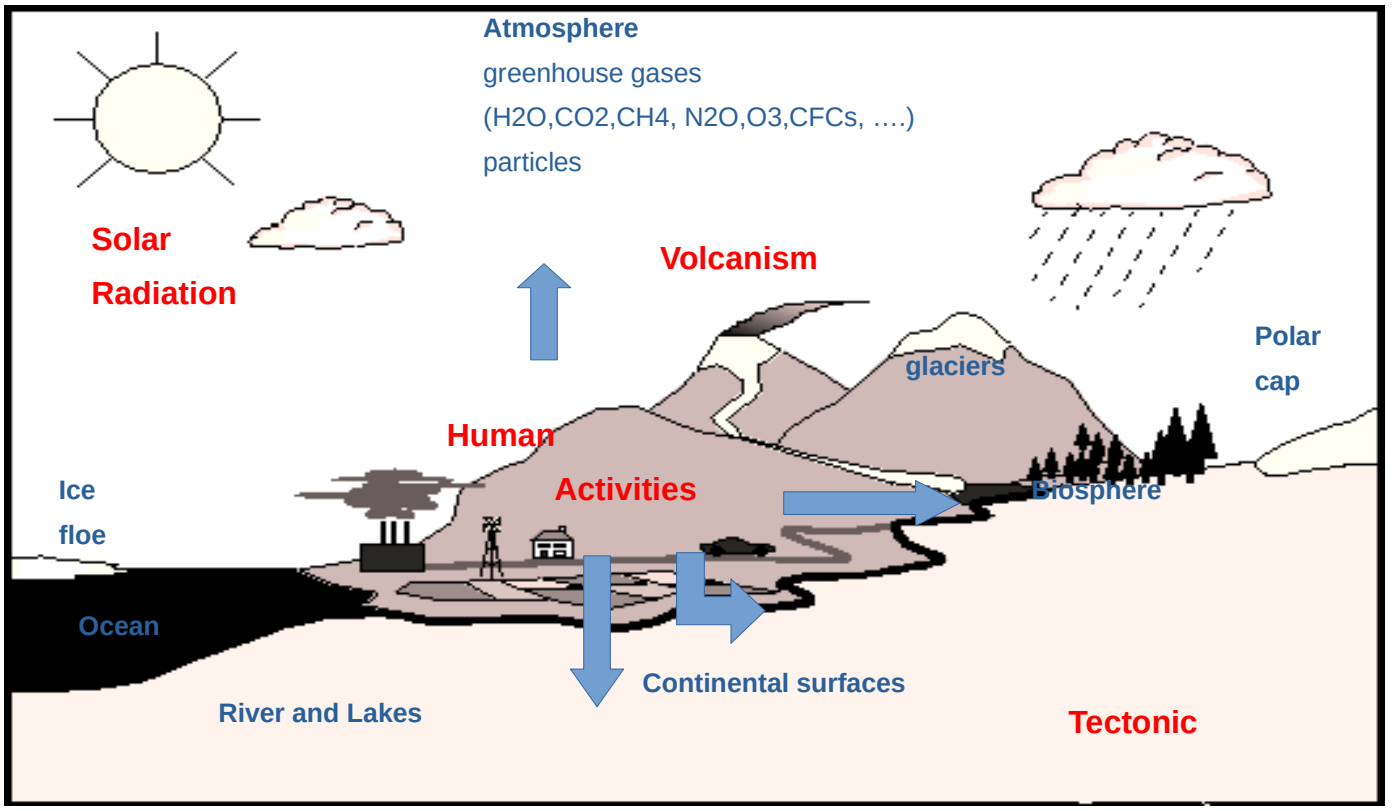
https://commons.wikimedia.org/wiki/File:Climate-system.jpg

The climate system



source IPCC 2013

The components and the major forcing factors of the climate system

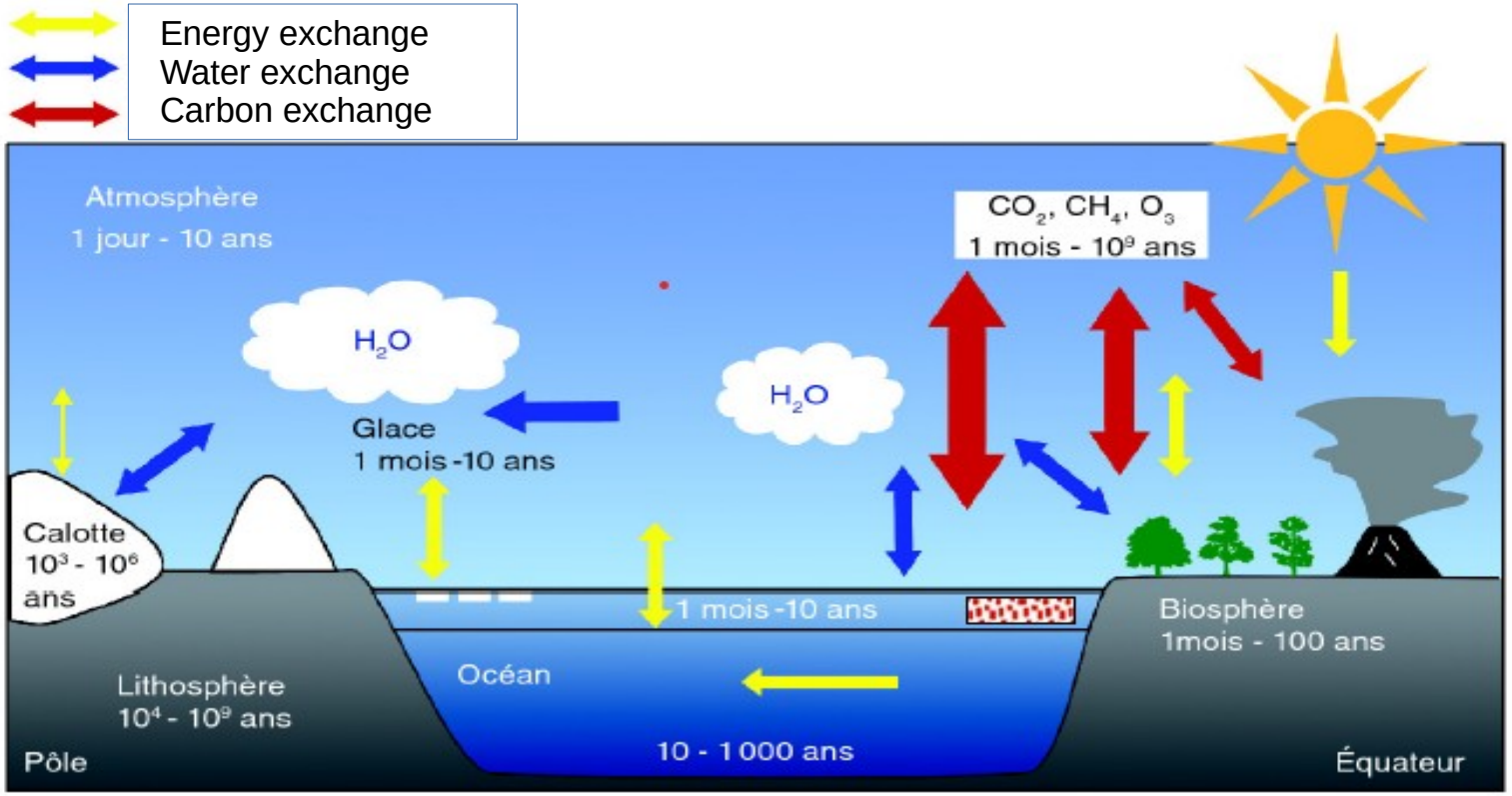


Source Serge Planton
Meteo France

The Climate system is composed of several components (blue in the slide) that interact with each other and that have different time scales.

The major forcing factors (red in the slide) influence directly the climate system.

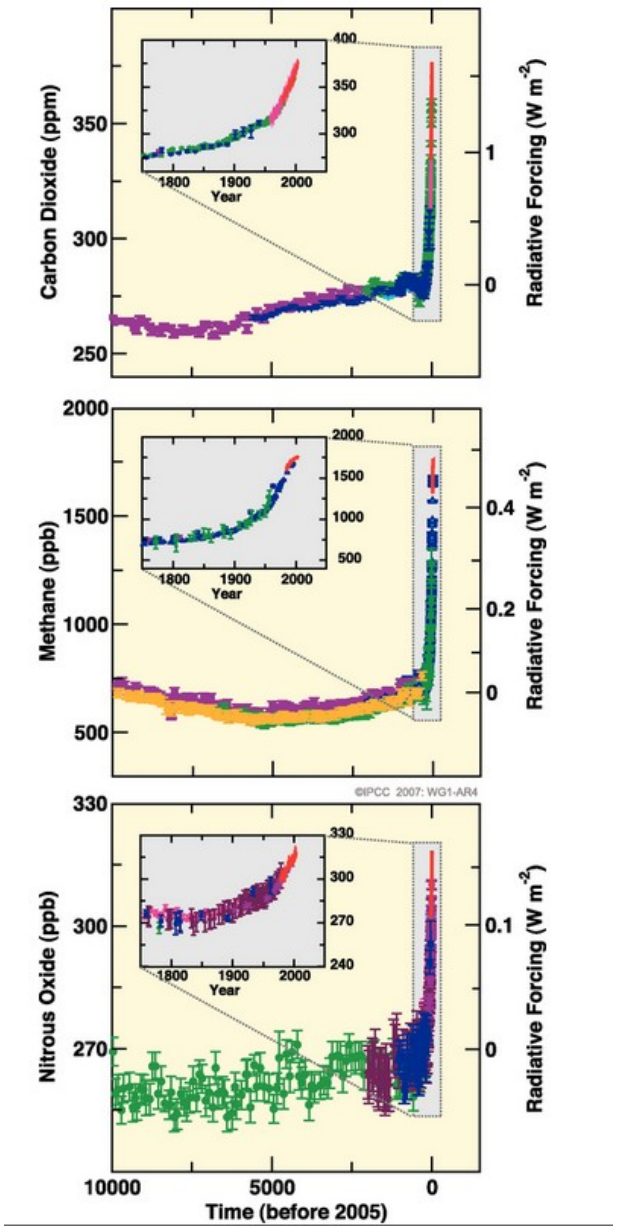
Climate system and the associated timescales of exchanges



Source Serge Planton Meteo France

These different components are closely linked and exchange energy, mass, water or carbon at different time scales (from seconds to millions of years).

Climate system and human activities

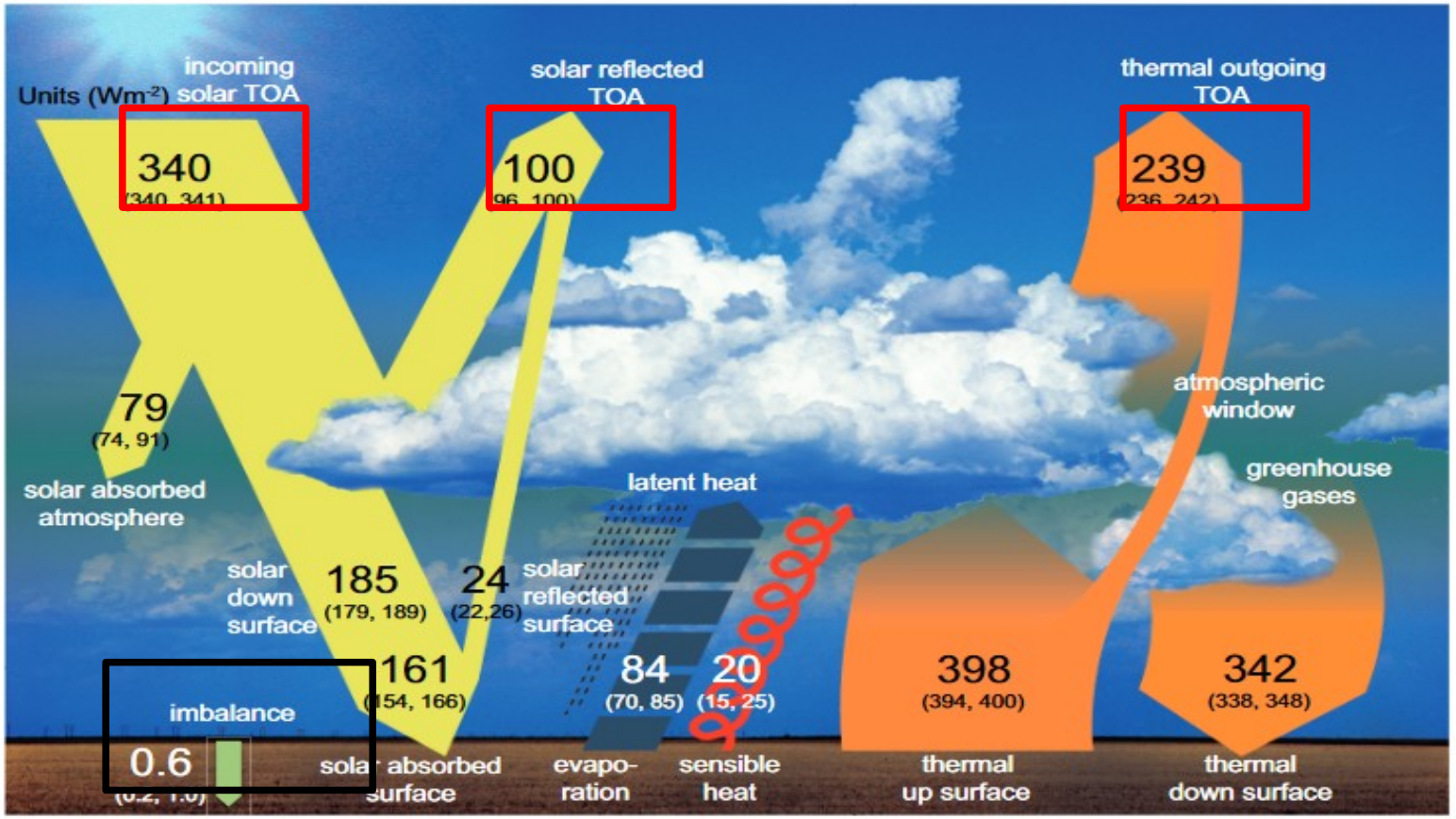


Evolution of the forcings due to the three main greenhouse gases (CO_2, CH_4, N_2O).

- 10000 years of stability.
- An exponential growth since 1850, especially after the second world war due to the industrial revolution.

source IPCC 2013

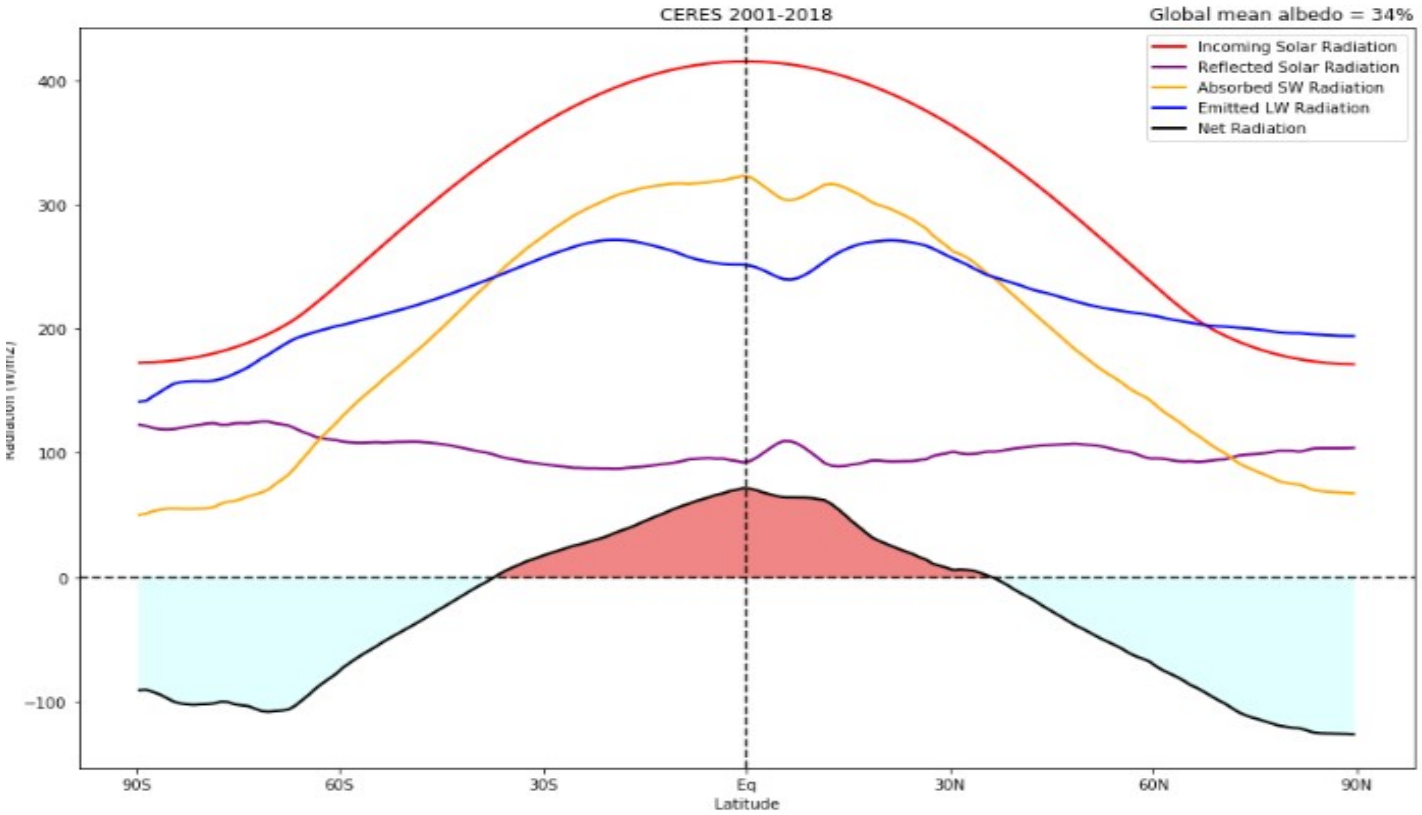
Energy budget on a global scale



source IPCC 2013

At the top of the atmosphere and on a global scale, incoming solar radiation nearly **balances** outgoing longwave radiation, except for the imbalance (0,6 W/m²) due to human activities.

Top of atmosphere radiative budget zonal and annual mean



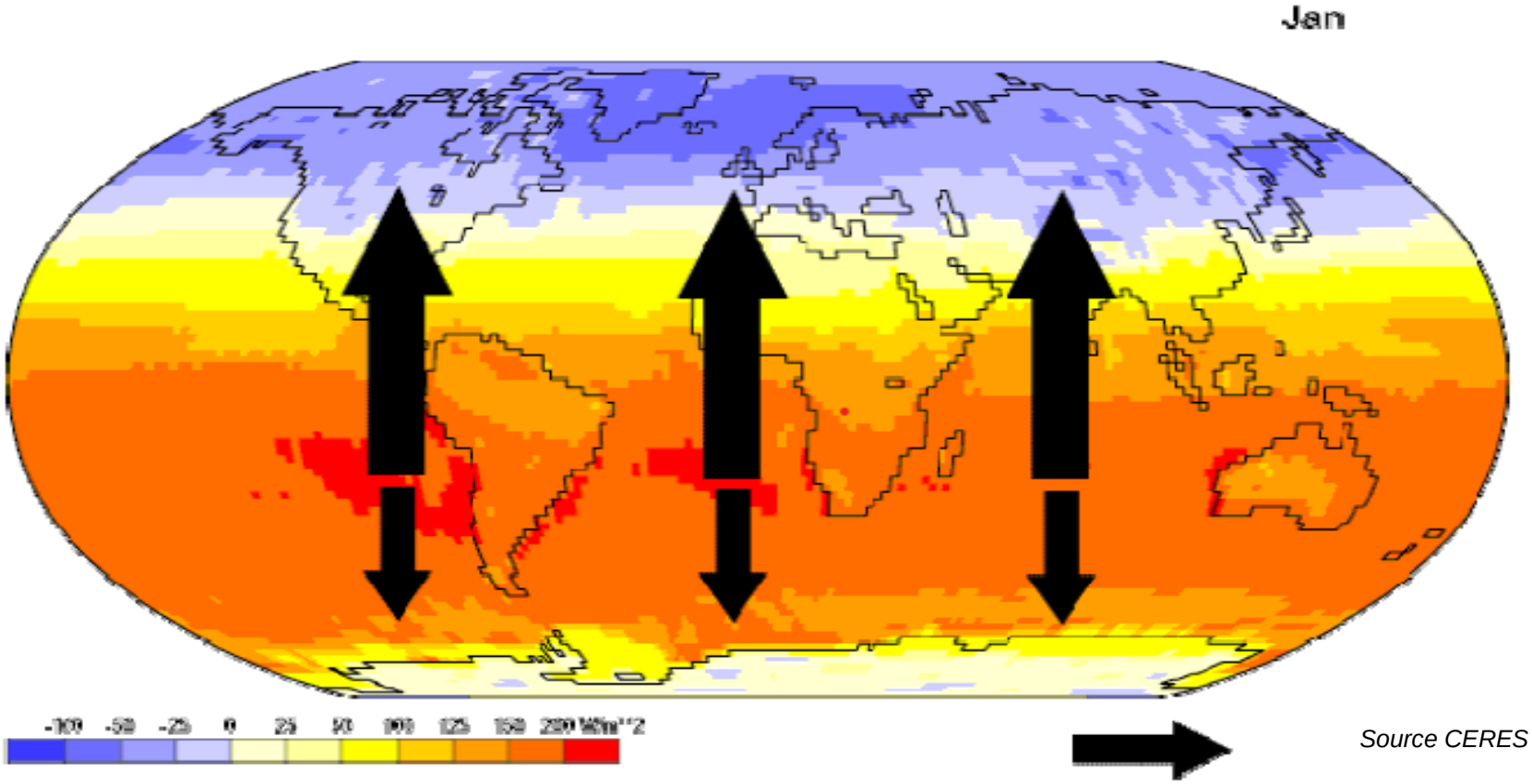
Source CERES

The radiative budget in equatorial regions is strongly positive while it is strongly negative in polar regions

–>

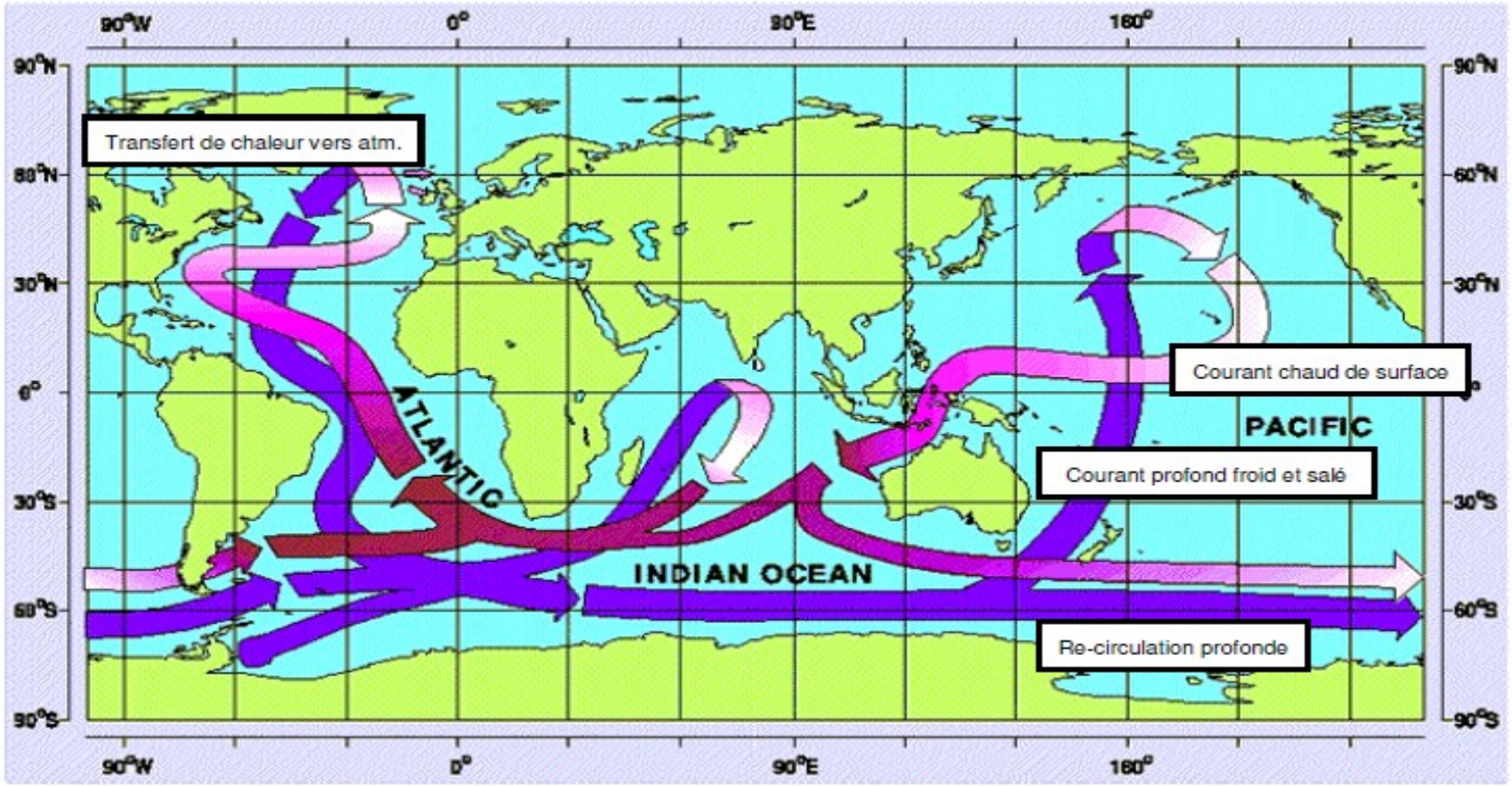
Strong **meridional imbalance** between polar and equatorials regions.

Energy transport in the atmosphere



Source CERES

Energy transport in the ocean



Source Meteo-France

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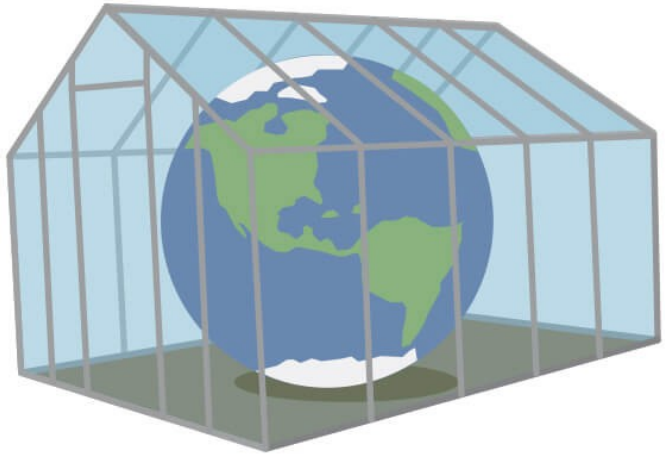


Credit: NASA/JPL-Caltech

Our cosy planet

By Malene Thyssen - Own work, CC BY-SA 3.0

Earth is a truly wonderful planet !

First, it has a breathable atmosphere ; and second, its average surface temperature is neither too cold, nor too hot …

The average surface temperature on Earth is a **cosy 15°C**.

An icy desert

The reason why our planet enjoys such a comfortable average temperature is the **greenhouse effect**.

Whitout the greenhouse effect, the Earth would be an icy desert.

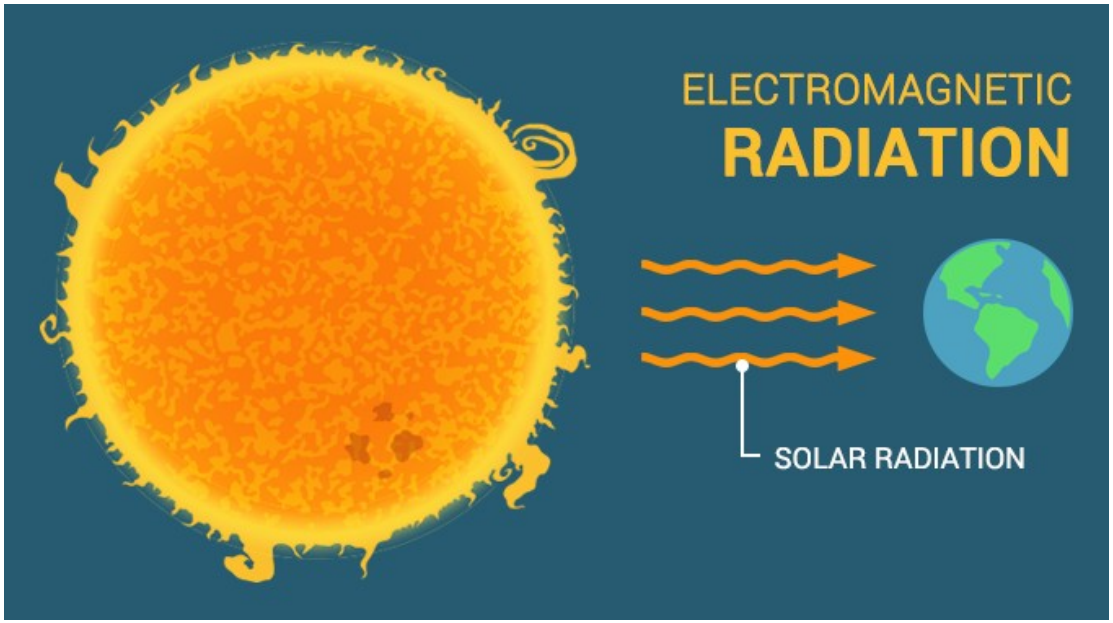
© Shutterstock.com/Anton Balazh

The greenhouse effect : how does it work ?

The greenhouse effect results from the interaction of the Earth's atmosphere with the **electromagnetic waves** passing through it.

https://www.nasa.gov/content/earths-atmospheric-layers

Electromagnetic waves



https://earthhow.com/solar-radiation-electromagnetic/

Electromagnetic waves do not carry matter.
They carry energy.

Electromagnetic waves do not require a medium to propagate.

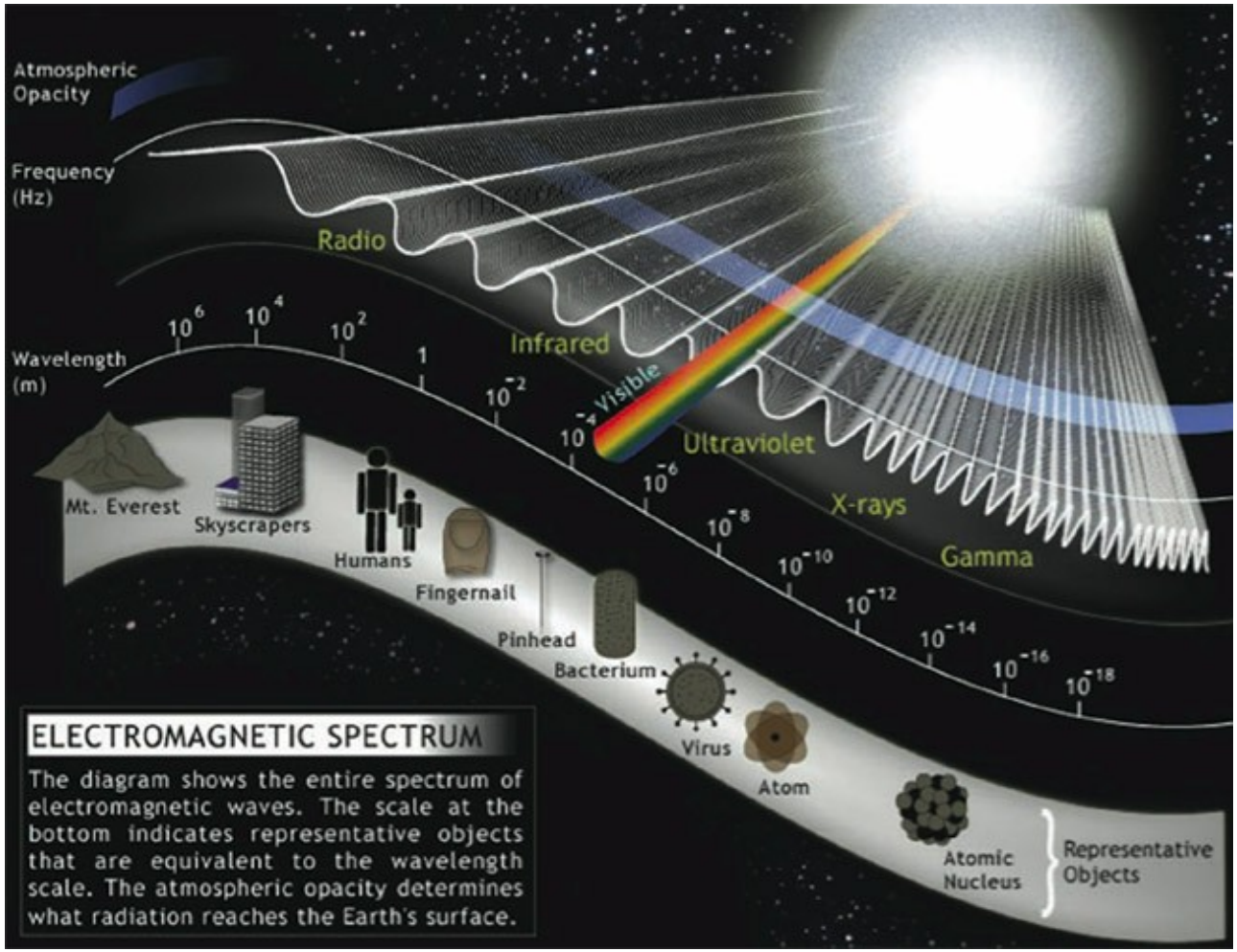
They can travel not only through air and solid materials, but also **through the vacuum of space**.

So electromagnetic waves can travel between the Sun and the Earth and transfer energy to the Earth.

Solar radiation

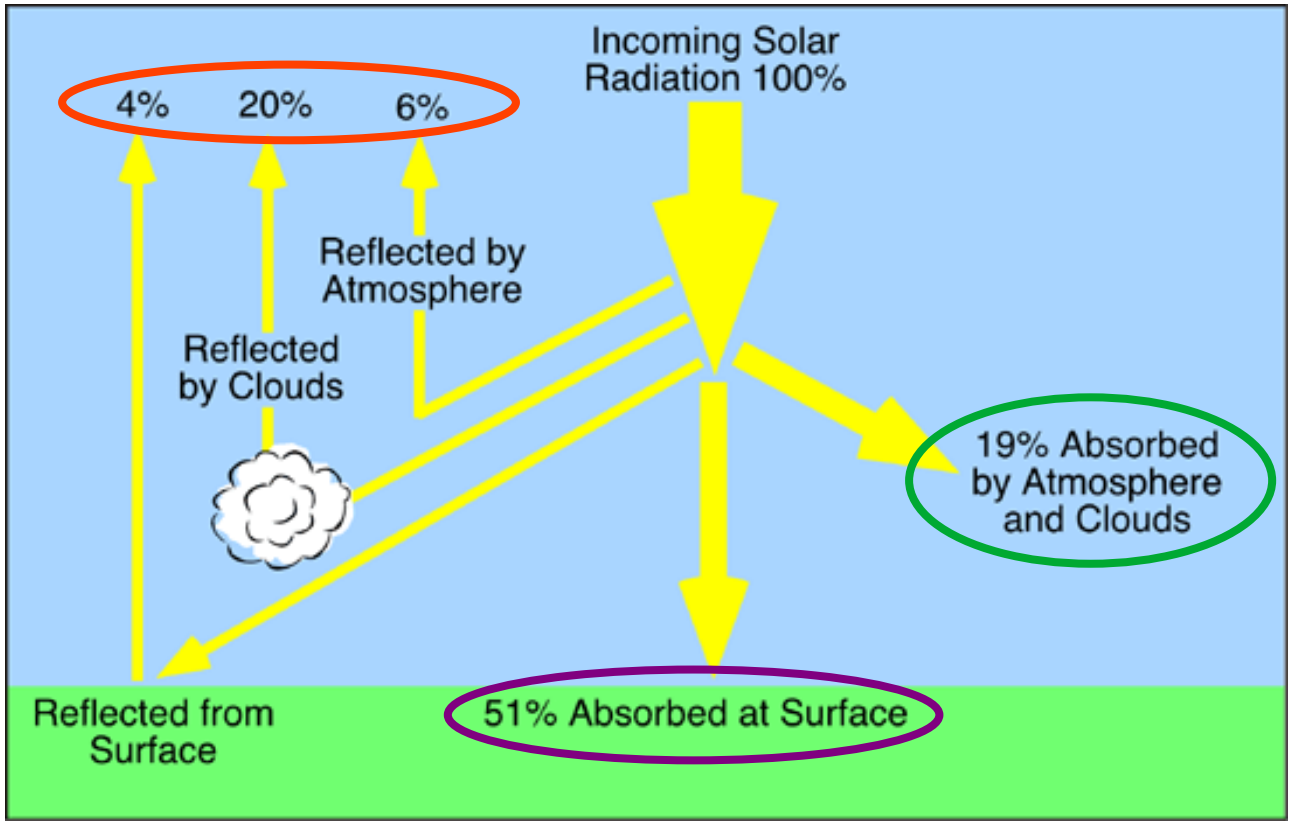
The Sun emits electromagnetic waves in a **wide range of wavelengths** :

- X-rays,
- ultraviolet radiation,
- visible light (of course!),
- infrared radiation,
- and even radio waves.



https://www.windows2universe.org/sun/spectrum/multispectral_sun_overview.html

What happens to solar radiation ?

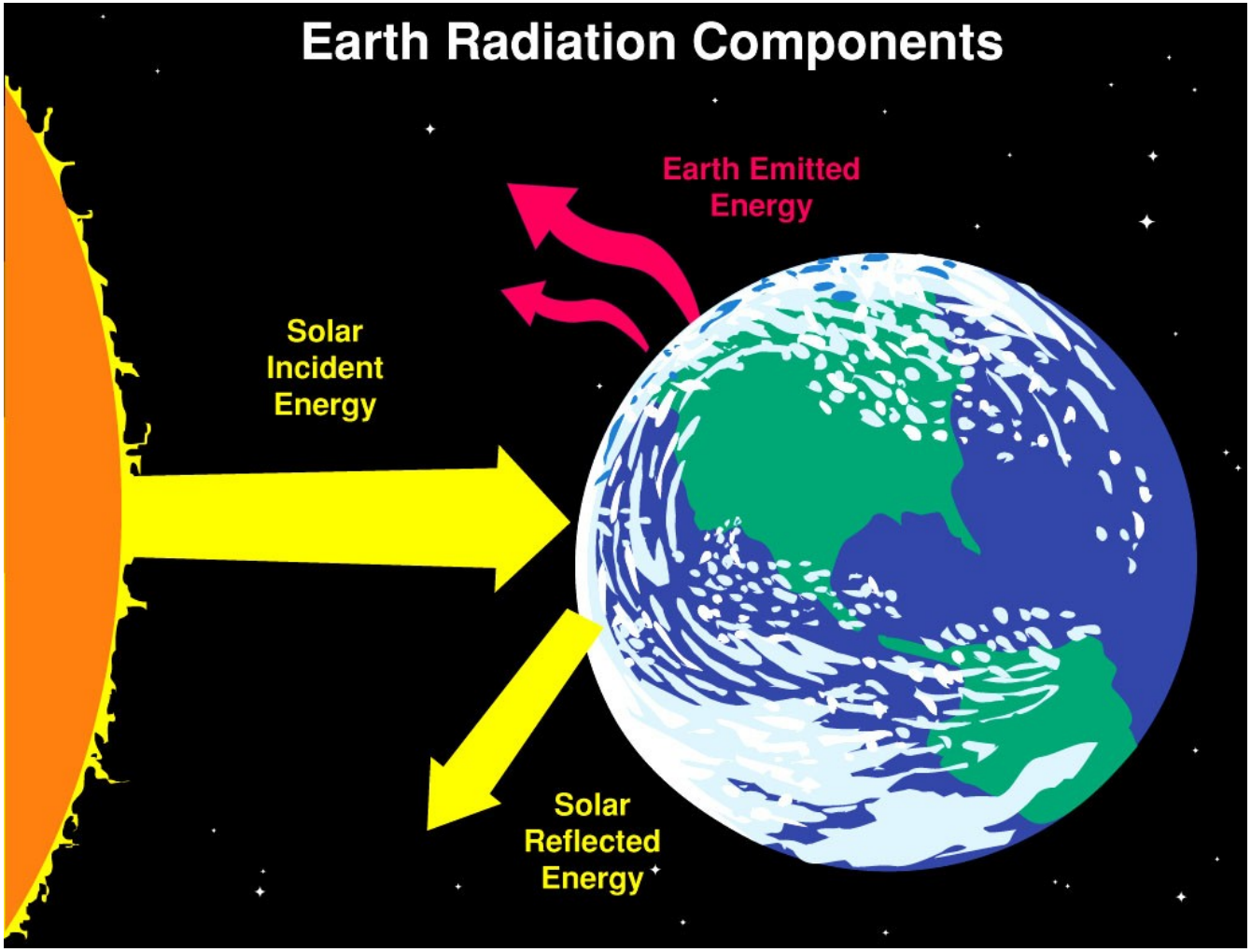


Source: Pidwirny (2006).

- Of all the incoming solar radiation, **51%** is absorbed by the Earth's surface.
- Of the other 49%, **30%** is scattered or reflected to space.
- **Only 19%** is absorbed by atmospheric gases and clouds.

The gases that make up the Earth's atmosphere absorb only a small fraction (19%) of the incoming solar radiation.

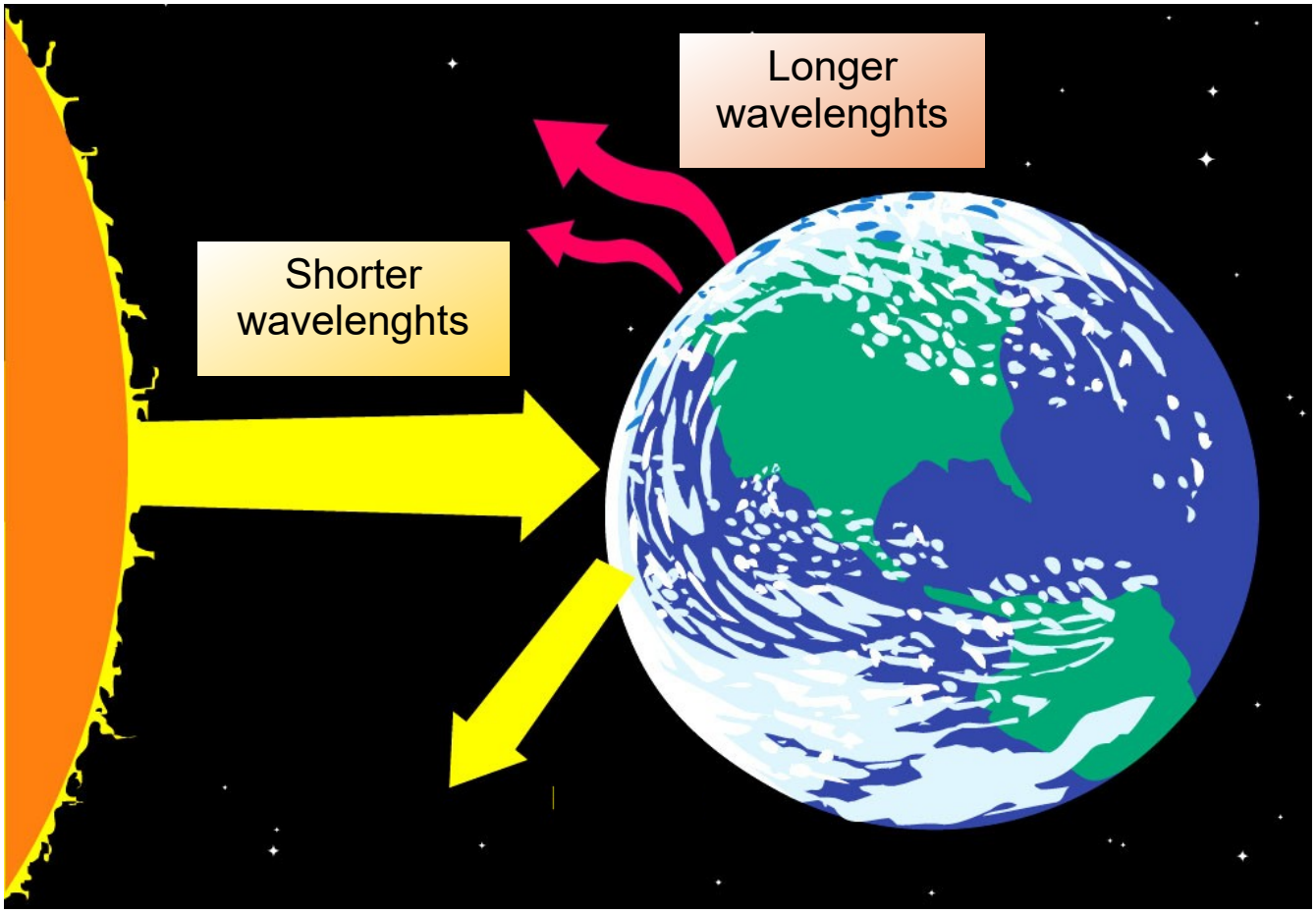
Energy in, energy out



https://visibleearth.nasa.gov/images/54217/earth-radiation-components/54218l

The Earth's surface and atmosphere also **emit infrared electromagnetic radiation** to space.

Different wavelength ranges

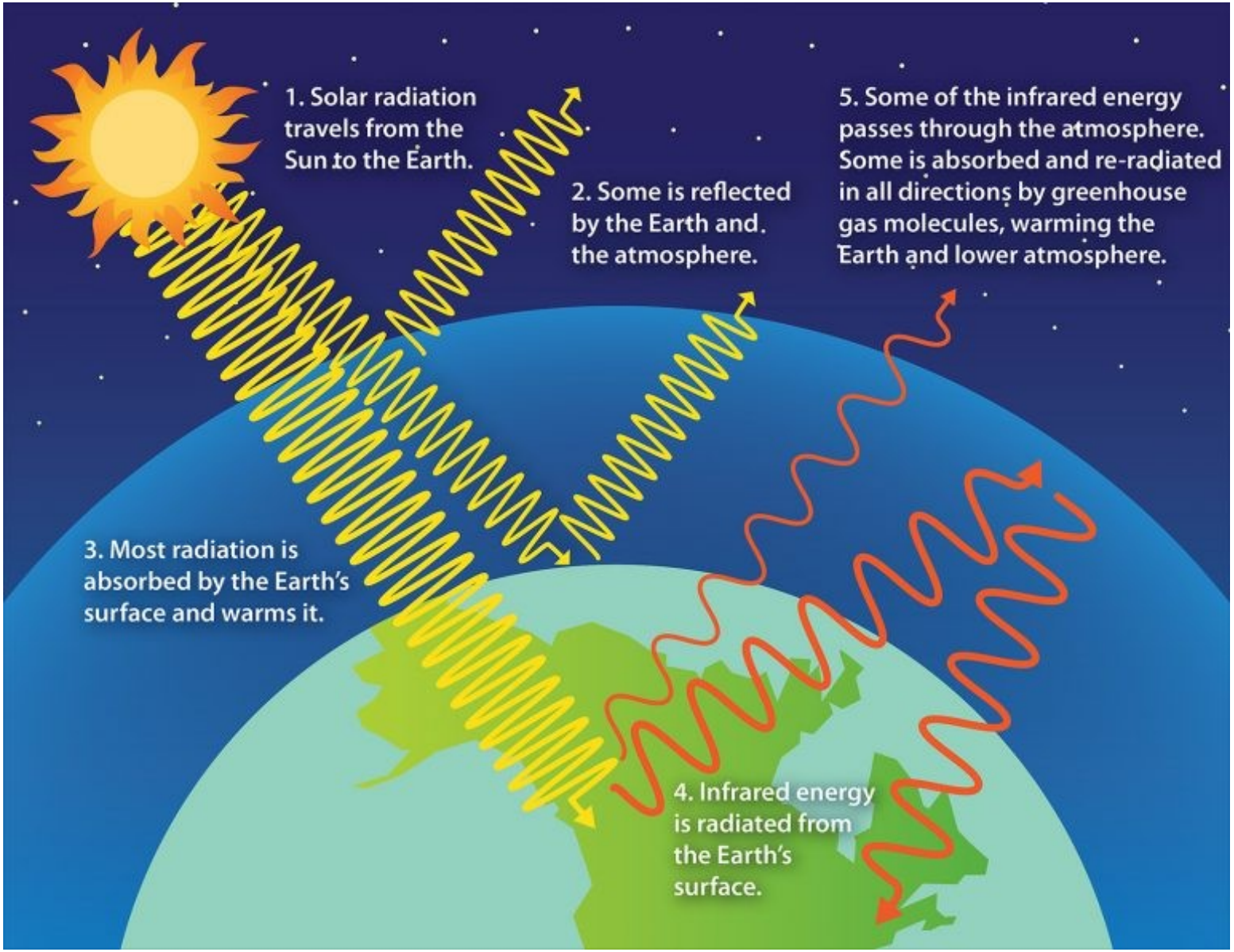


Adapted from https://visibleearth.nasa.gov/images/54217/earth-radiation-components/54218l

Radiation from the Sun and radiation from the Earth are in **very different** wavelength ranges.

This difference results in a very different behaviour of the atmosphere with respect to solar radiation and Earth's radiation.

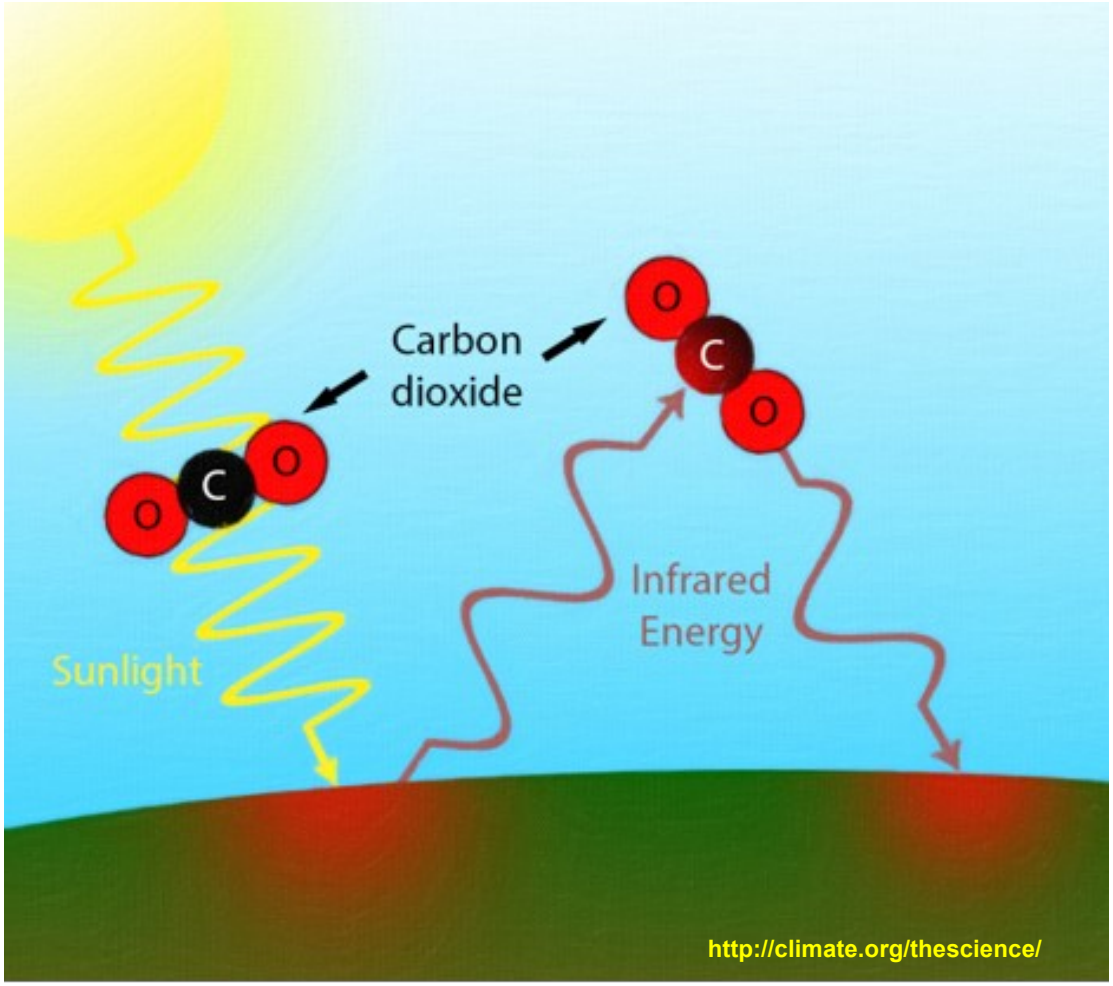
Earth's outgoing infrared radiation is largely absorbed



Most of the **infrared radiation** coming from Earth's surface is absorbed by greenhouse gases and then re-radiated in all directions, including towards Earth's surface

https://ugc.berkeley.edu/background-content/greenhouse-effect/

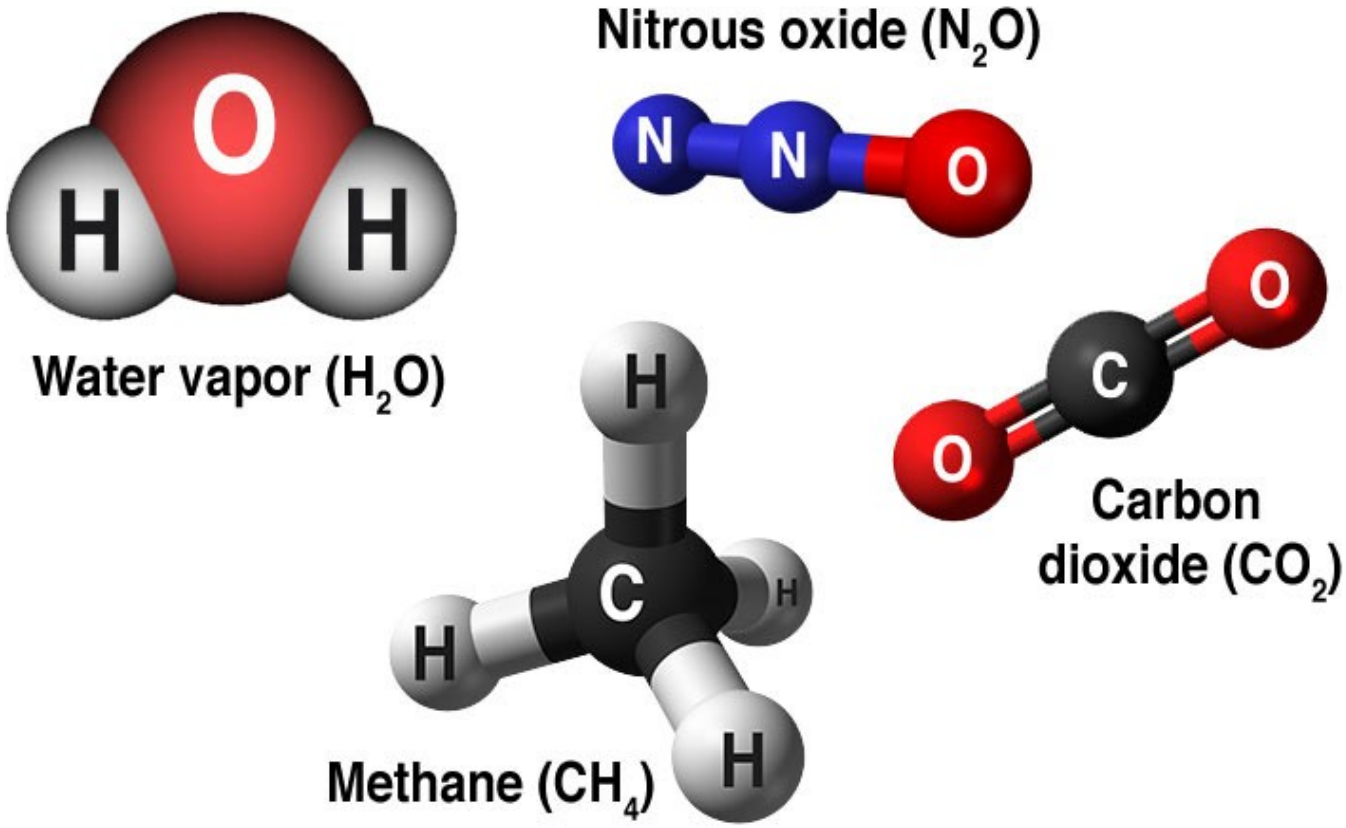
A well known greenhouse gas



CARBON DIOXIDE DOES NOT INTERACT WITH VISIBLE LIGHT, BUT ABSORBS AND REEMITS INFRARED ENERGY.

The ability to absorb and re-emit infrared energy is what makes carbon dioxide an effective heat-trapping **greenhouse gas**.

The main greenhouse gases



https://climate.nasa.gov/causes/

The main greenhouse gases are **water vapor**, carbone dioxide, methane, and nitrous oxide.

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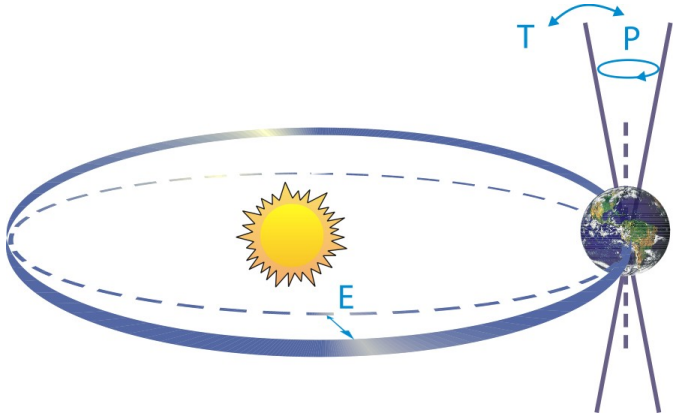
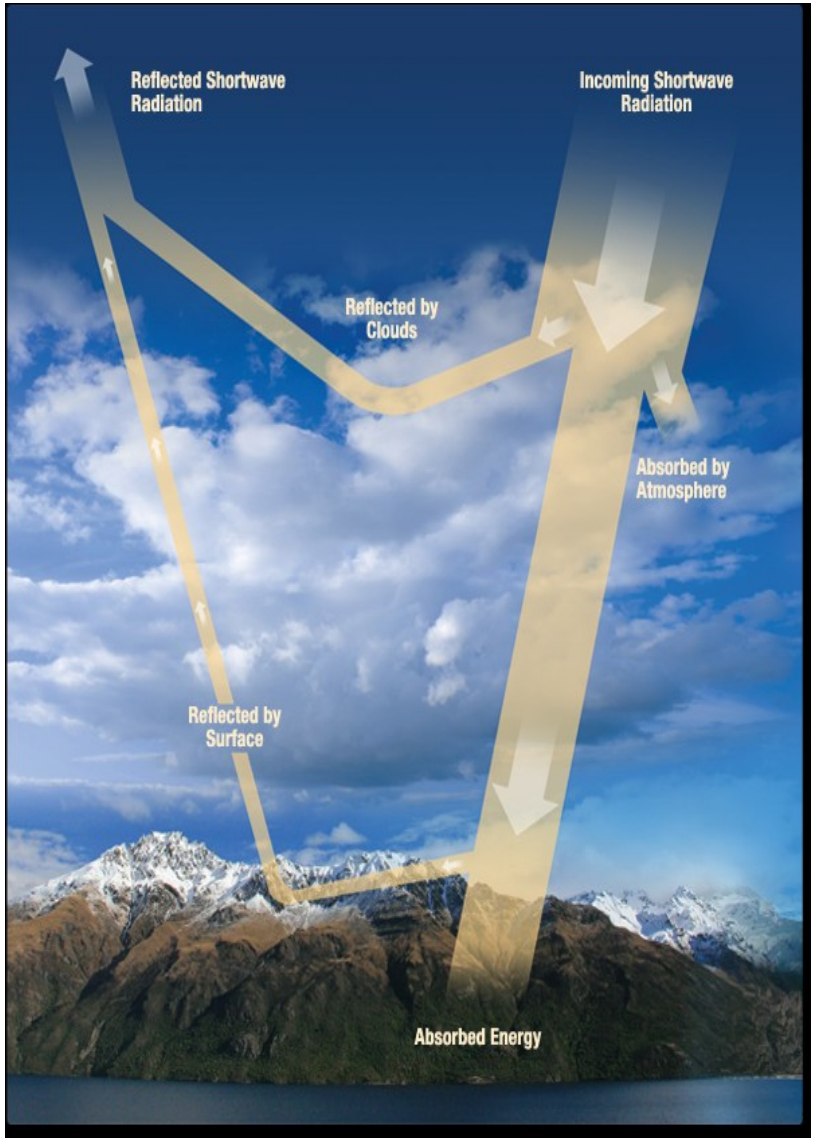
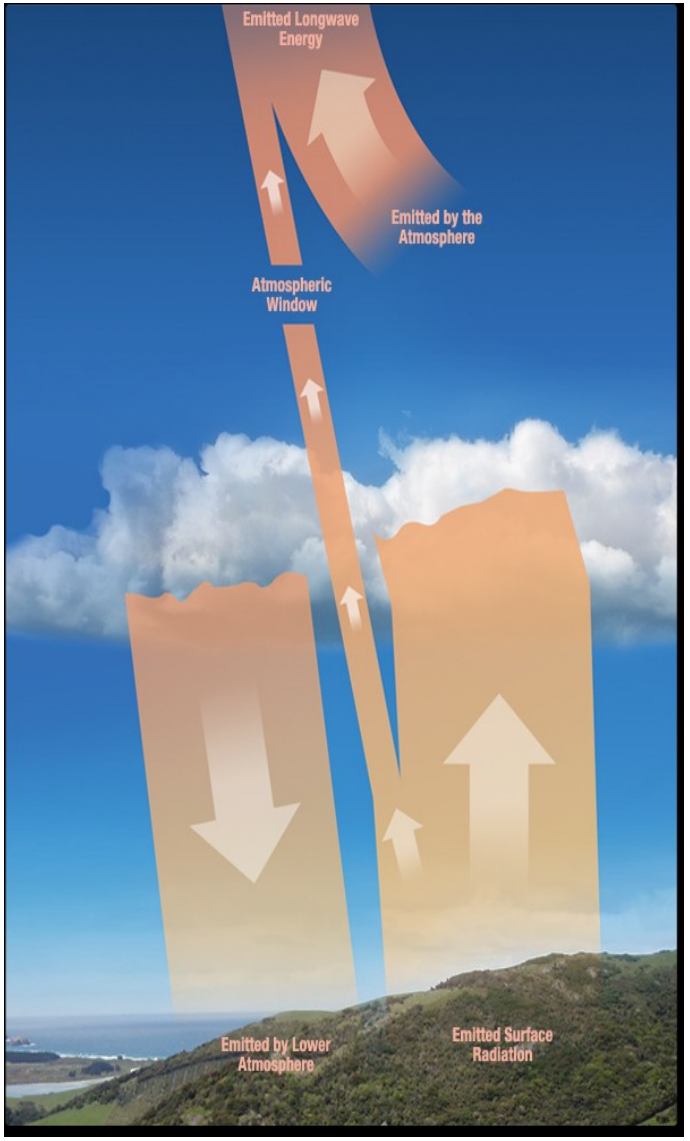


http://ipcc-wg1.ucar.edu/wg1/FAQ/fig/FAQ-6.1_Fig-1.png

Let’s define what a forcing is





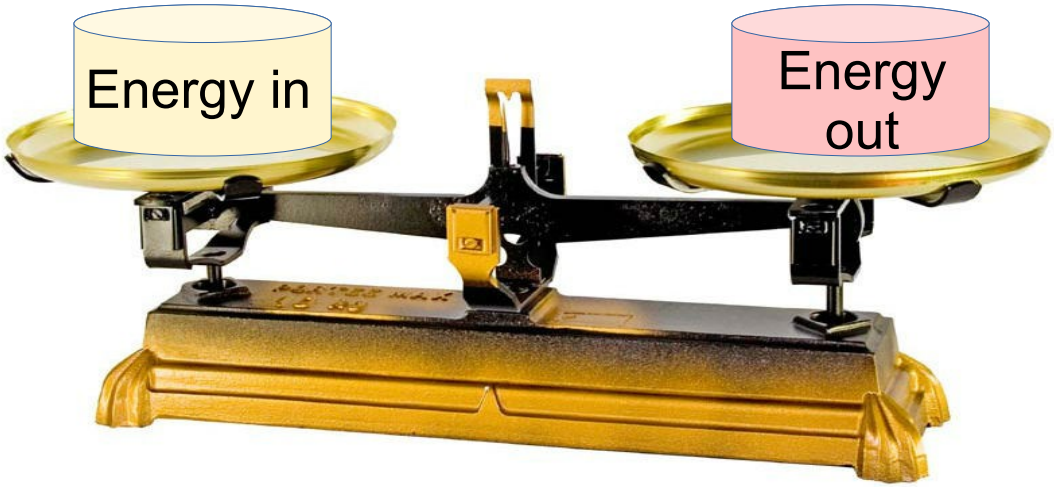
Earth and its atmosphere continually **receive** energy from the sun.

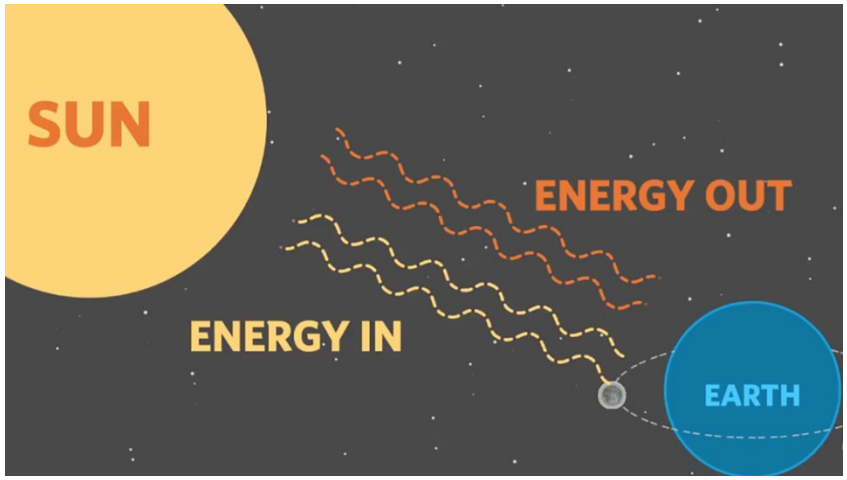
Earth and the atmosphere also **emit** energy into space.

http://gsp.humboldt.edu/olm_2016/courses/GSP_216_Online/lesson8-1/overview.html

Let’s define what a forcing is

In accordance with the basic laws of thermodynamics, as Earth absorbs energy from the sun, it must eventually emit **an equal amount** of energy to space.





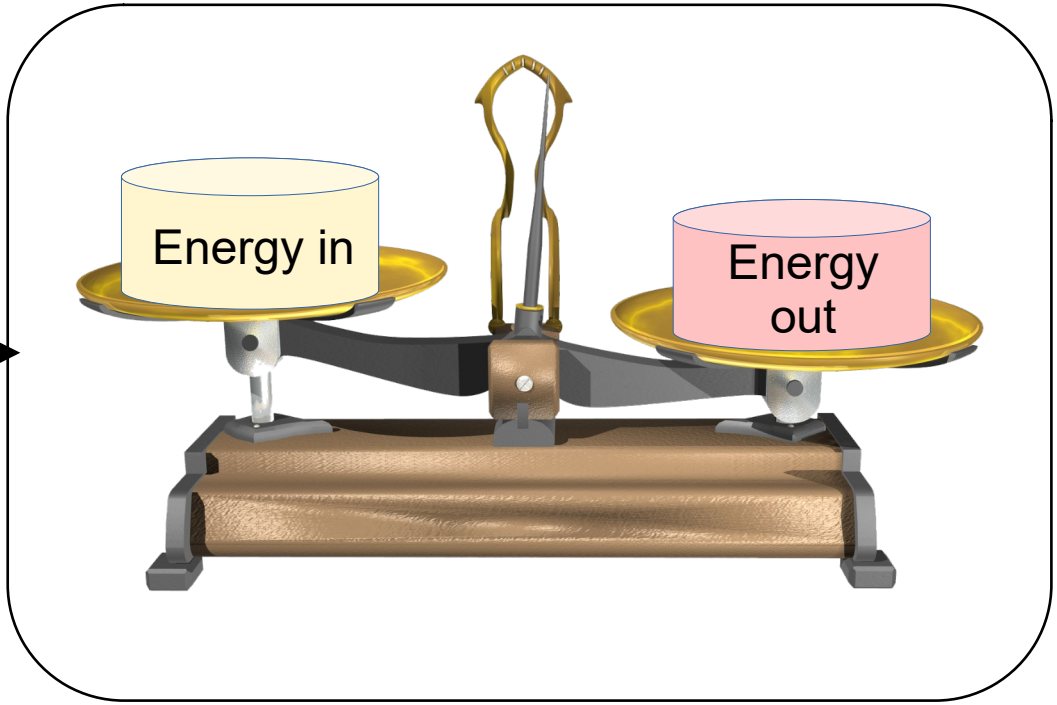
https://www.calacademy.org/educators/earths-delicate-energy-balance

Let’s define what a forcing is

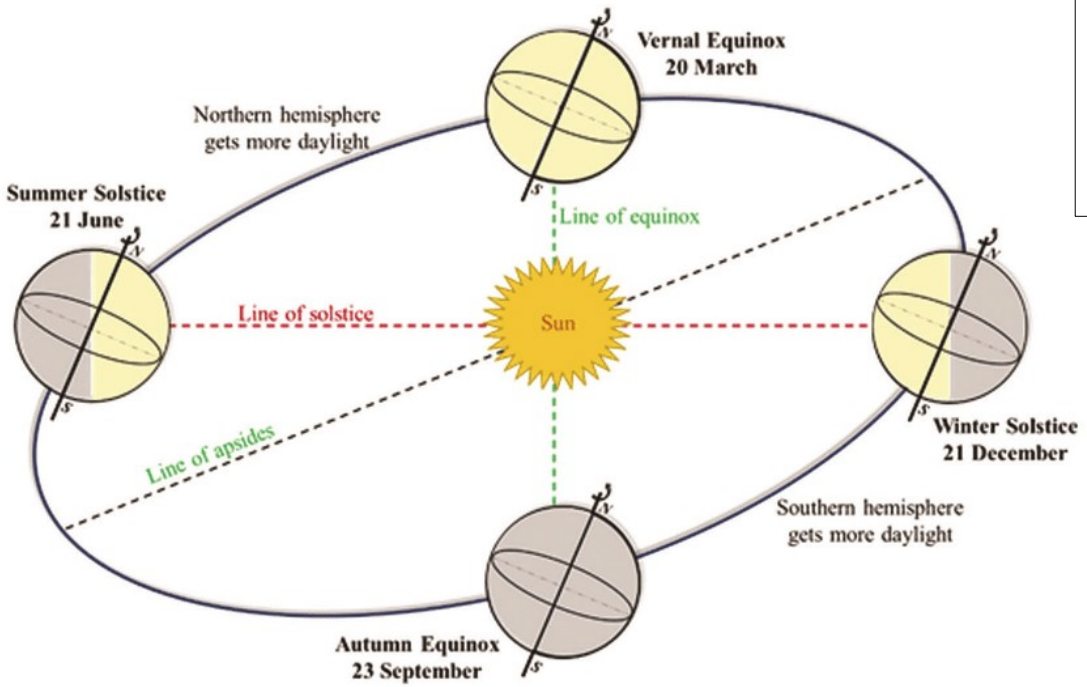
The difference between incoming and outgoing radiation is known as a **radiative forcing.**

It **forces the temperature** of the planet to adjust to the forcing.

- When the incoming energy is greater than the outgoing energy, the planet will warm.
- Conversely, if the outgoing energy is greater than the incoming energy, the planet will cool.



The orbital forcing of climate



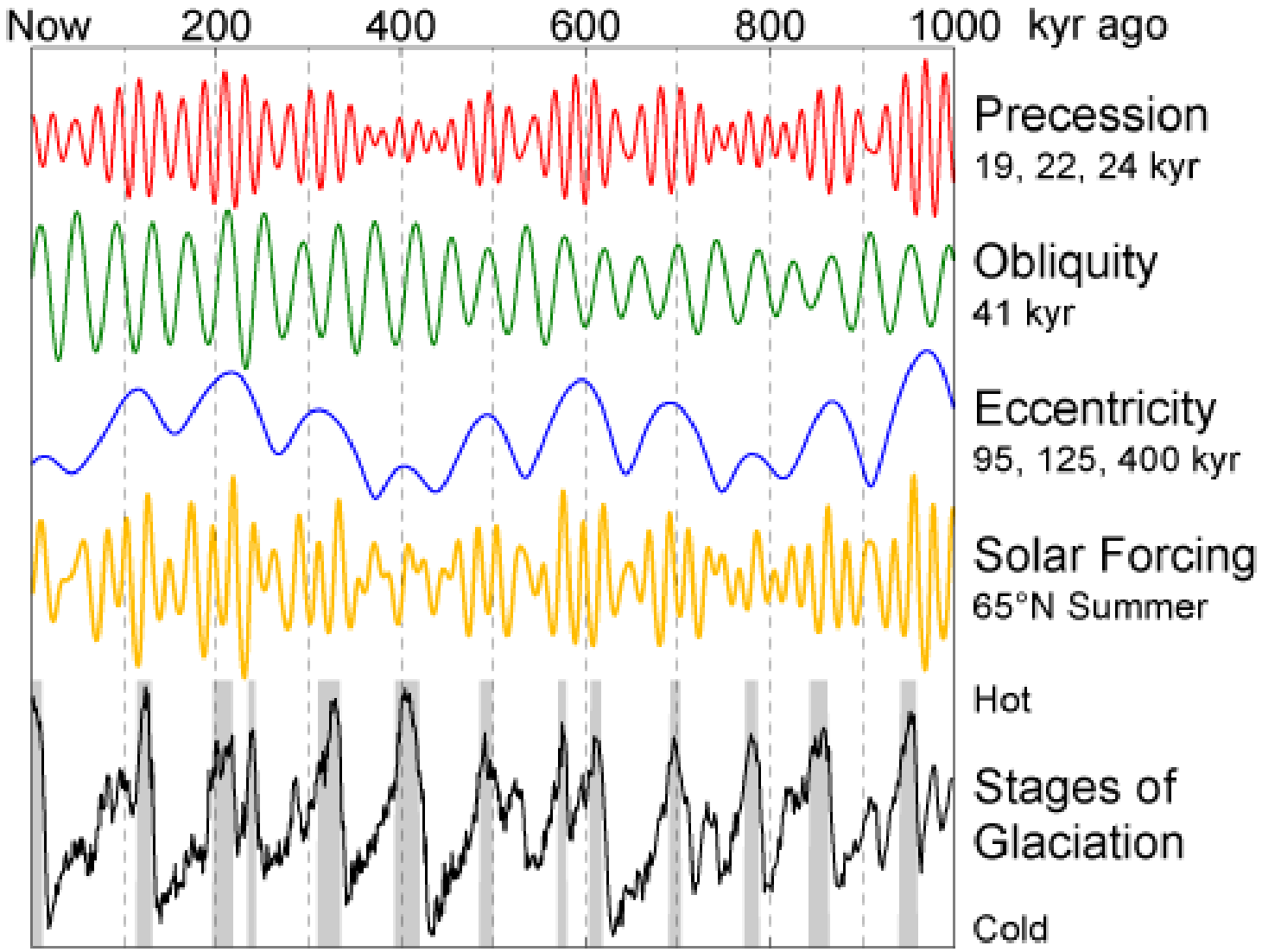
https://www.researchgate.net/figure/Rotation-of-Earth-about-its-own-axis-and-its-revolution-around-the-Sun-resulting-into_fig3_328491205

In the 1920s, Milanković hypothesized that **cyclical variations in the parameters of the Earth's orbit** around the sun are a major radiative forcing.

© 1943 Paja Jovanovic (Vasko Milankovitch).

Milutin Milanković was a Serbian geophysicist and astronomer.

The orbital forcing of climate



https://commons.wikimedia.org/wiki/File%3AMilankovitch_Variations.png

The primary driver of glacial-interglacial cycles lies in the fluctuations of seasonal and latitudinal **distribution of incoming solar energy**, driven by long-term changes in the geometry of the Earth's orbit around the Sun (« orbital forcing »).

Other natural forcings of climate

Orbital forcing is the primary driver of glacial-interglacial cycles.

But it's not the only one. Other natural forcings significantly impact climate.

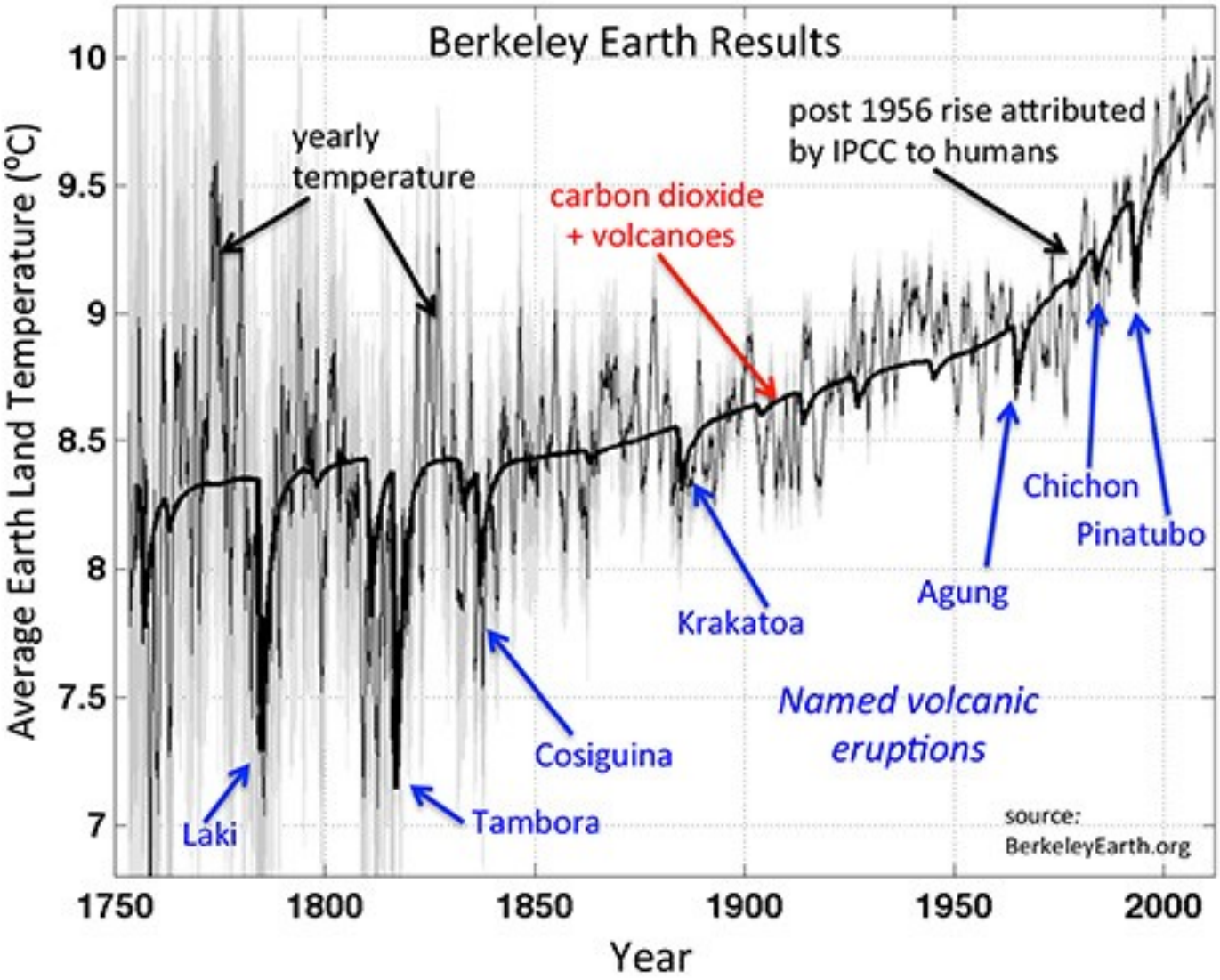
For instance : volcanic eruptions

Volcanic eruptions inject both mineral particles and sulphate aerosol precursor gases (predominantly SO_2) into the atmosphere.

- It is the sulphate aerosols, which because of their small size are effective **scatterers of sunlight** and have long lifetimes, that are responsible for Radiative Forcing important for climate.

Par John, CC BY-SA 2.0, https://commons.wikimedia.org/

Big volcanic eruptions

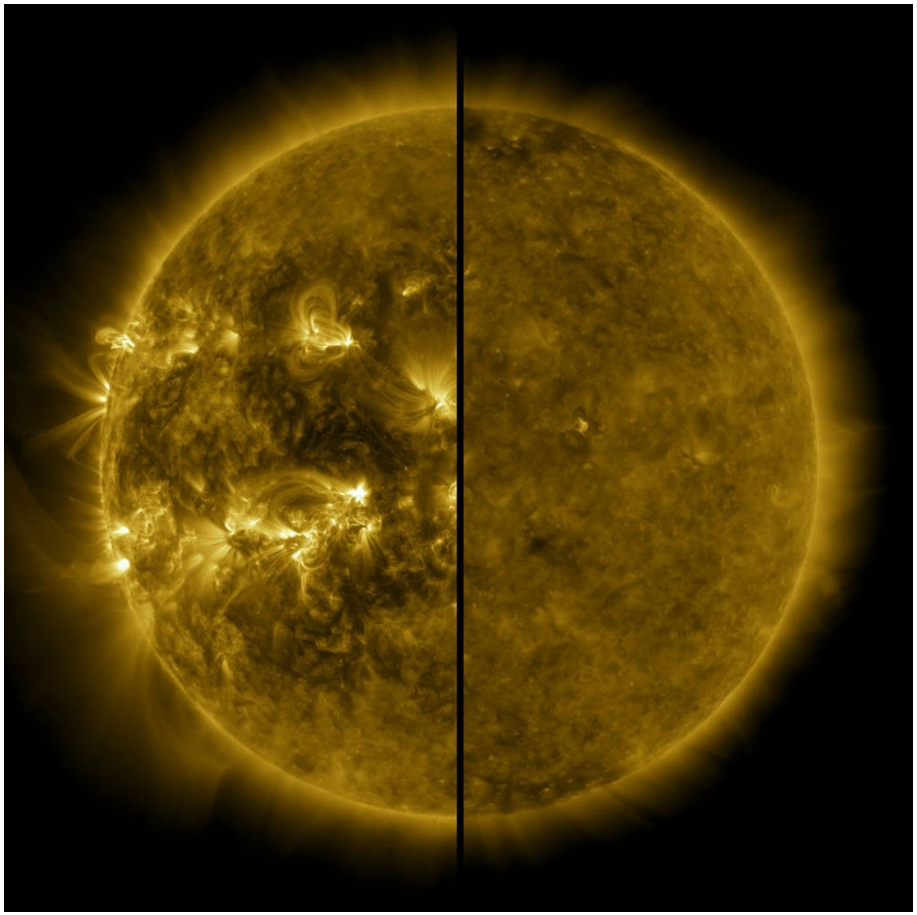


http://berkeleyearth.org/volcanoes/

Abrupt dips in the temperature pattern match the emissions of known explosive volcanic eruptions.

The aerosols from such events reflect sunlight and cool the Earth's surface for a few years.

Another natural climate forcing : fluctuations in solar activity



https://www.nasa.gov/press-release/solar-cycle-25-is-here-nasa-noaa-scientists-explain-what-that-means

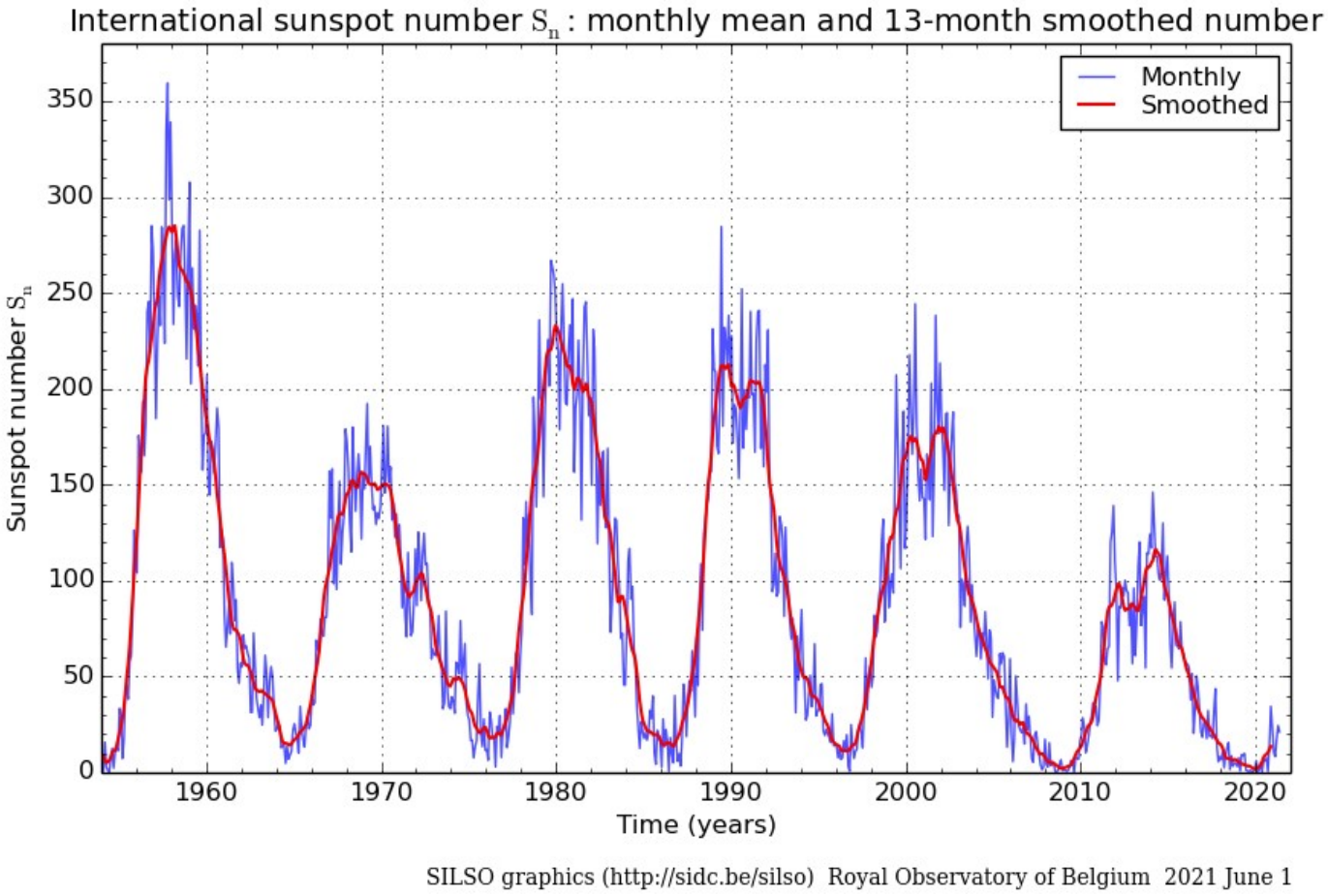
The number of sunspots **increases and decreases** over time in a regular, approximately 11-year cycle, called the sunspot cycle.

The Sun's apparent surface, the photosphere, radiates more actively when there are more sunspots.

The split image shows the difference between an active Sun during solar maximum (on the left, captured in April 2014) and a quiet Sun during solar minimum (on the right, captured in December 2019)

Fluctuations in solar activity

The highest number of sunspots in any given cycle is designated "solar maximum," while the lowest number is designated "solar minimum."



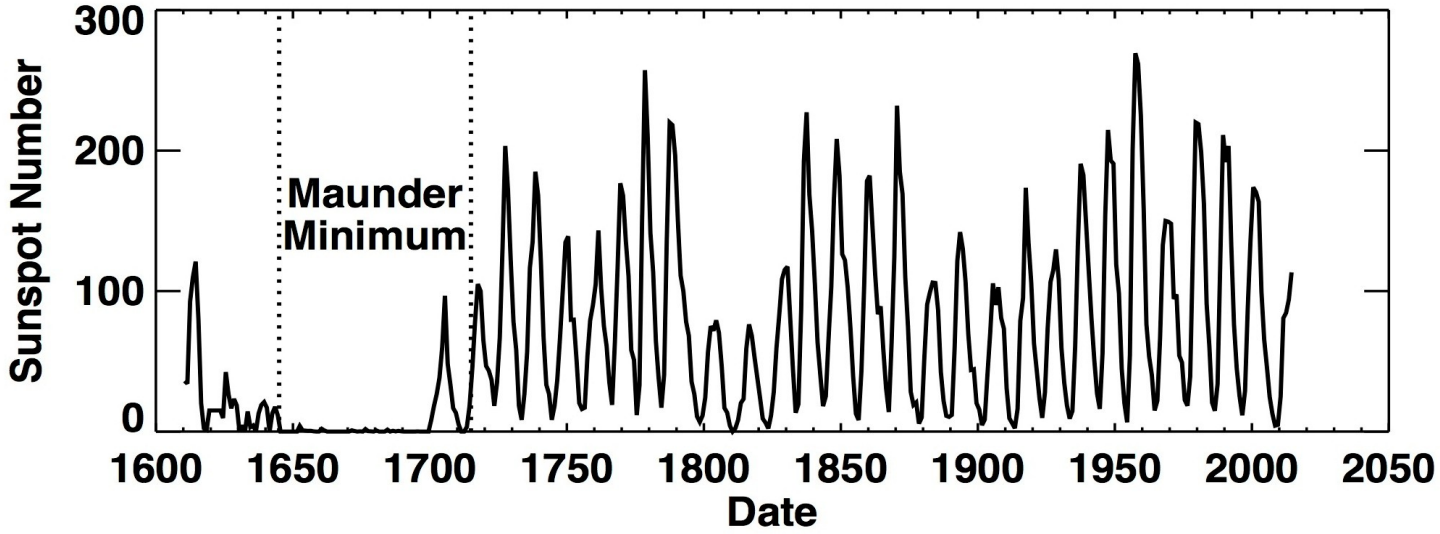
- The previous solar minimum occurred in December 2019 ;
- the next solar maximum is predicted for 2025.

Long-term variations of solar activity

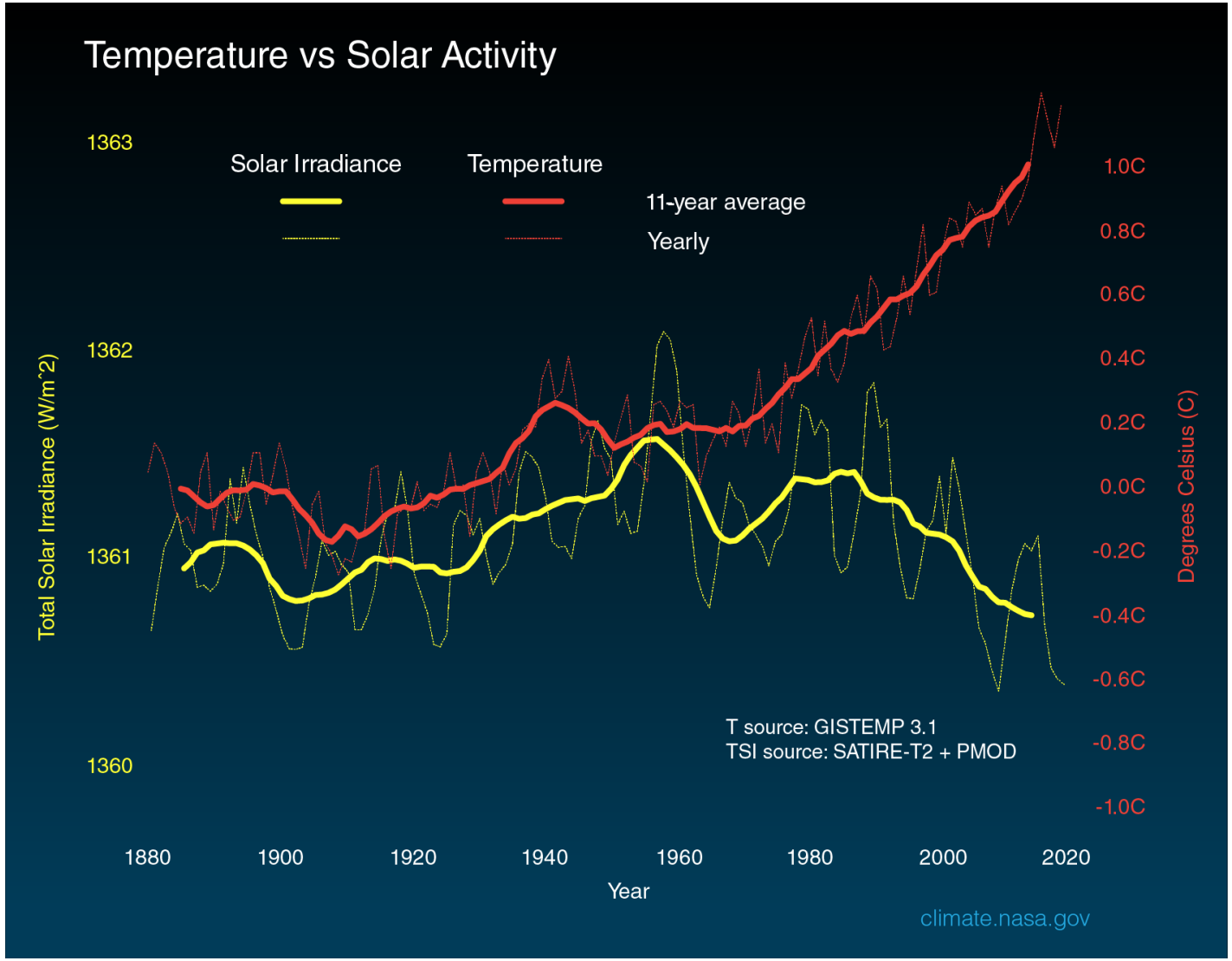
Each cycle varies dramatically in intensity.

The 11-year cycle of solar activity is modulated by a **long-term cycle**.

During the second half of the 17th century (1645-1715), the Sun exhibited a long period of very low activity, called the **Maunder Minimum.**



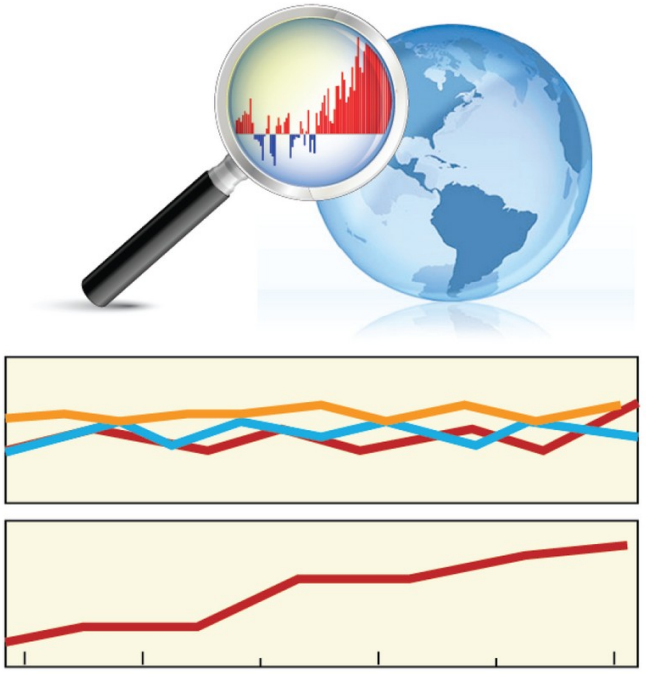
Fluctuations in solar activity and climate



https://climate.nasa.gov/climate_resources/189/graphic-temperature-vs-solar-activity/

It is **extremely unlikely** that the Sun has caused the observed global temperature warming trend over the past half-century.

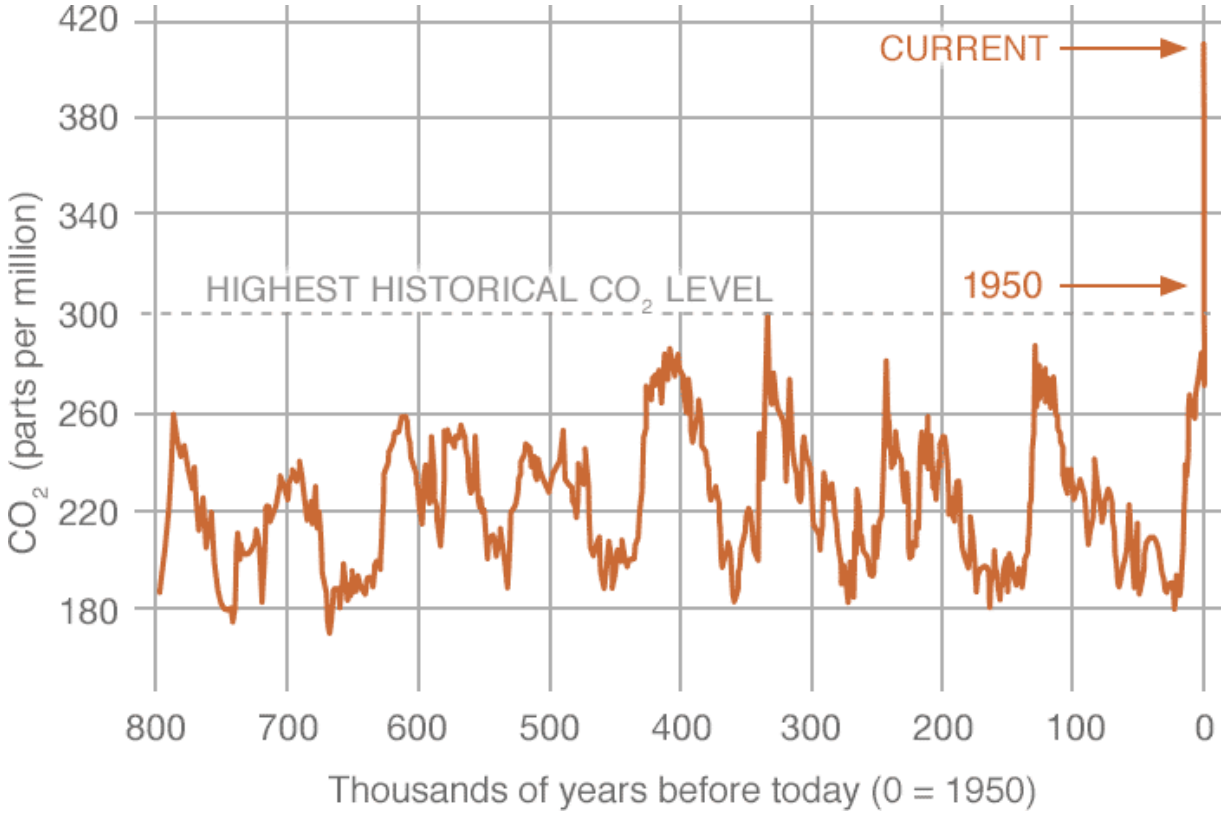
Contents



By NOAA NCDC [Public domain], via Wikimedia Commons

The ever-changing climate

Evolution of carbon dioxide concentration in the atmosphere, in ppm, over the last **800,000** years.



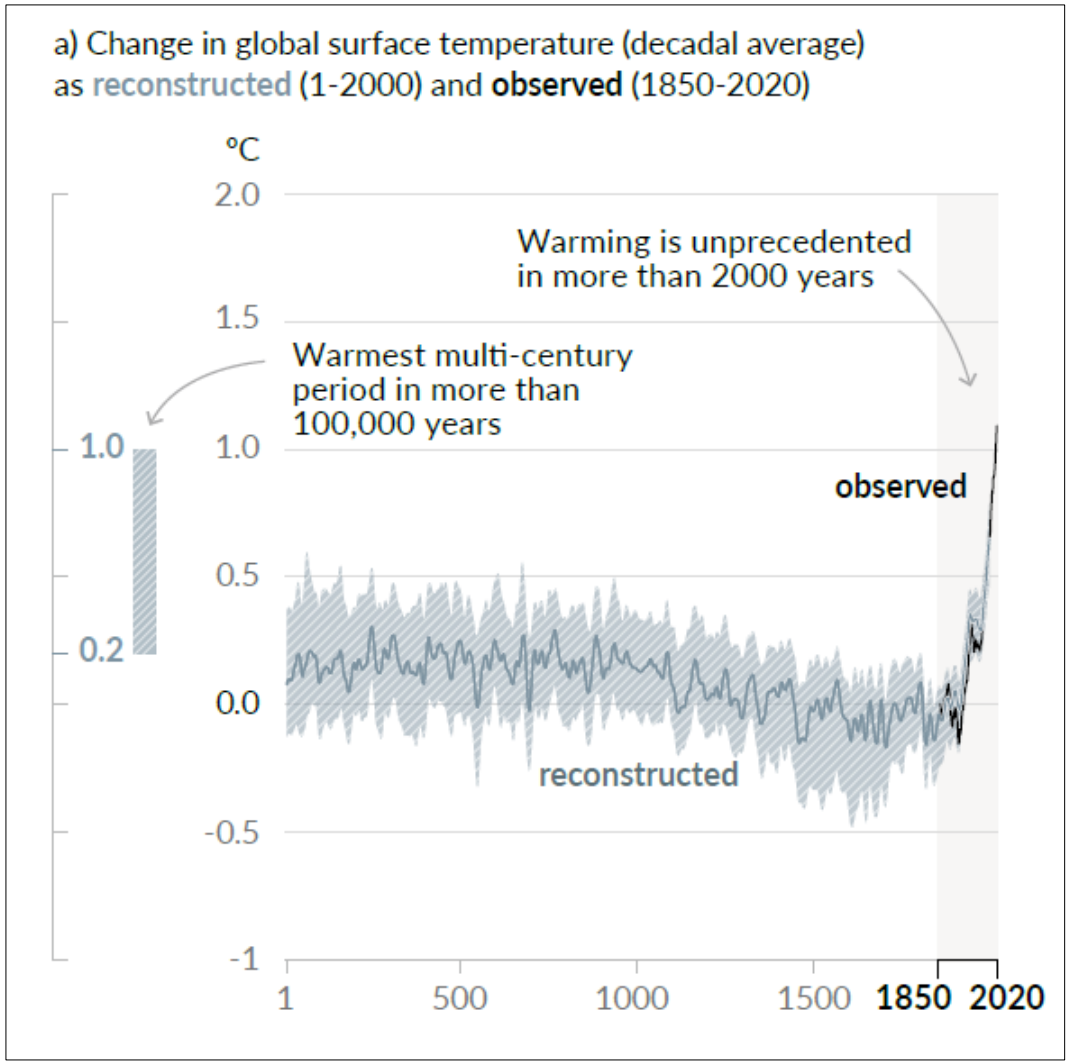
https://climate.nasa.gov/vital-signs/carbon-dioxide/

By May 2021 : 416 ppm

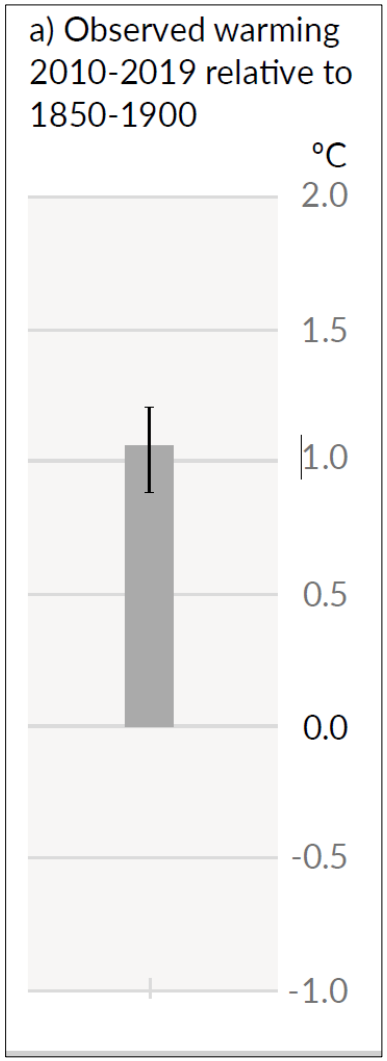
The cycle of natural variations, driven by fluctuations in the Earth's orbital parameters, **has clearly been broken**.

Changes in global surface temperature

Changes in global surface temperature relative to 1850-1900

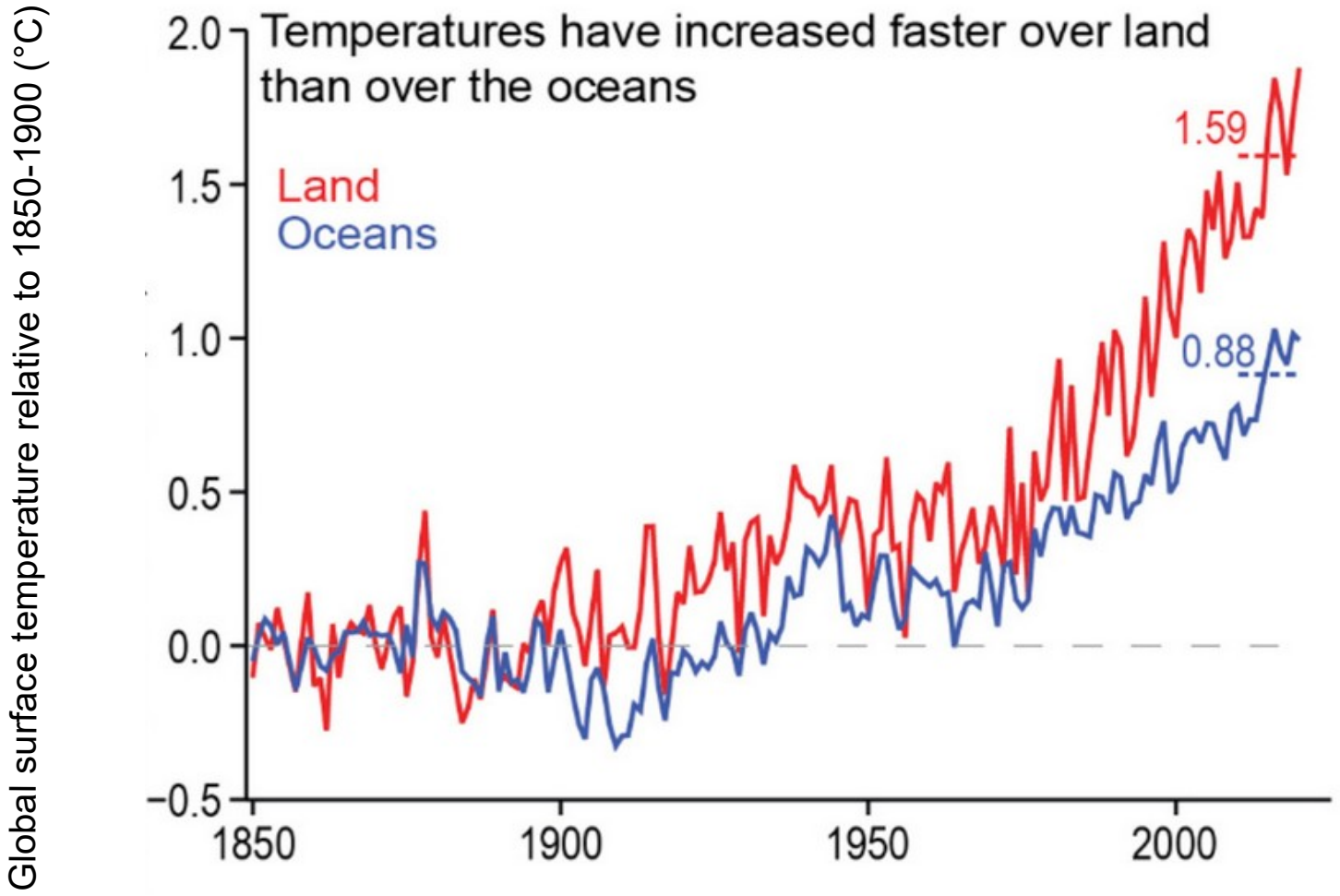


IPCC 2021 (WG1 AR6 « Summary for Polycymakers »)



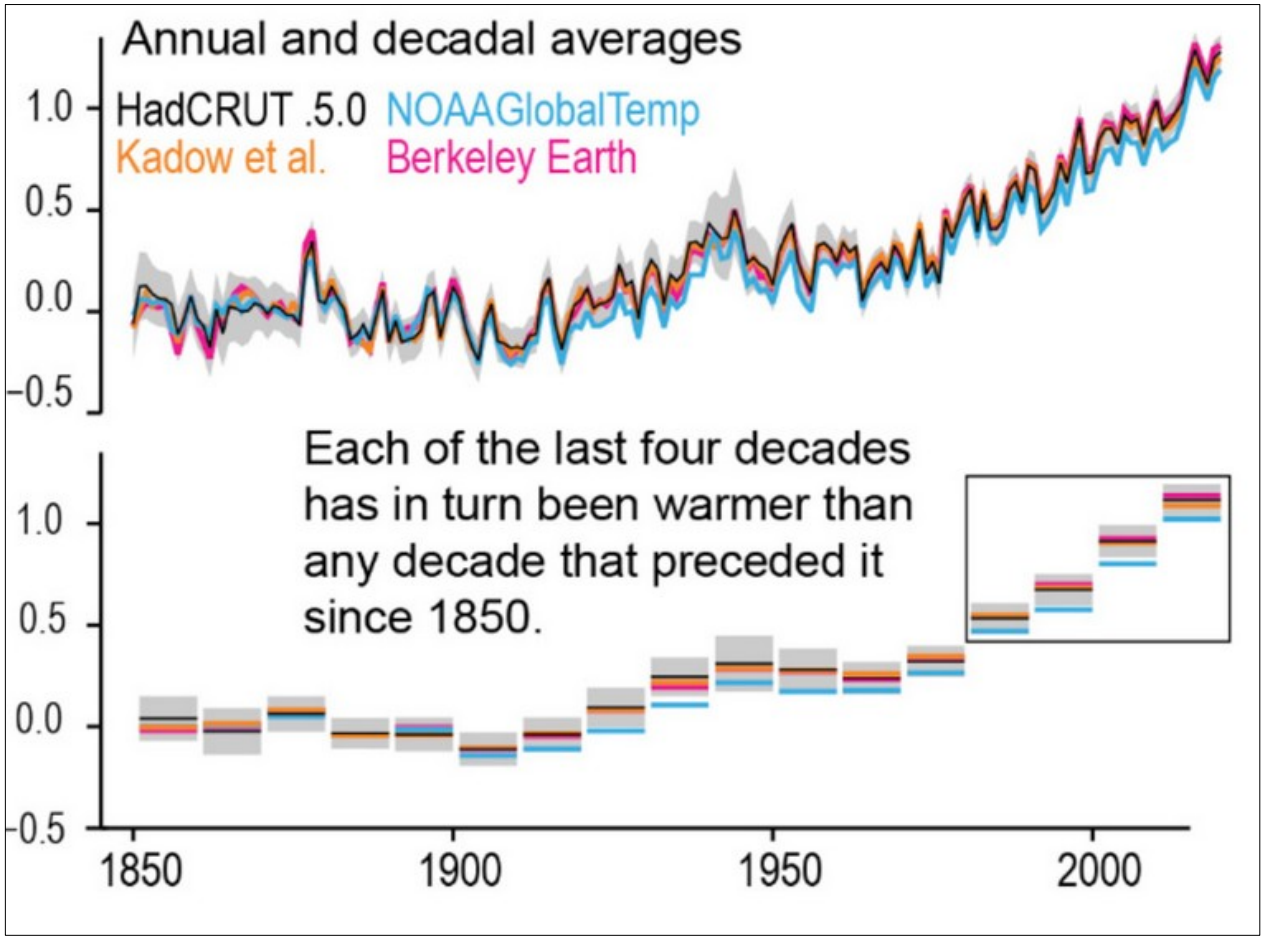
IPCC 2021 (WG1 AR6 « Summary for Polycymakers »)

Changes in global surface temperature



https://www.carbonbrief.org/in-depth-qa-the-ipccs-sixth-assessment-report-on-climate-science
Source: IPCC (2021) Figure 2.11c

Changes in global surface temperature

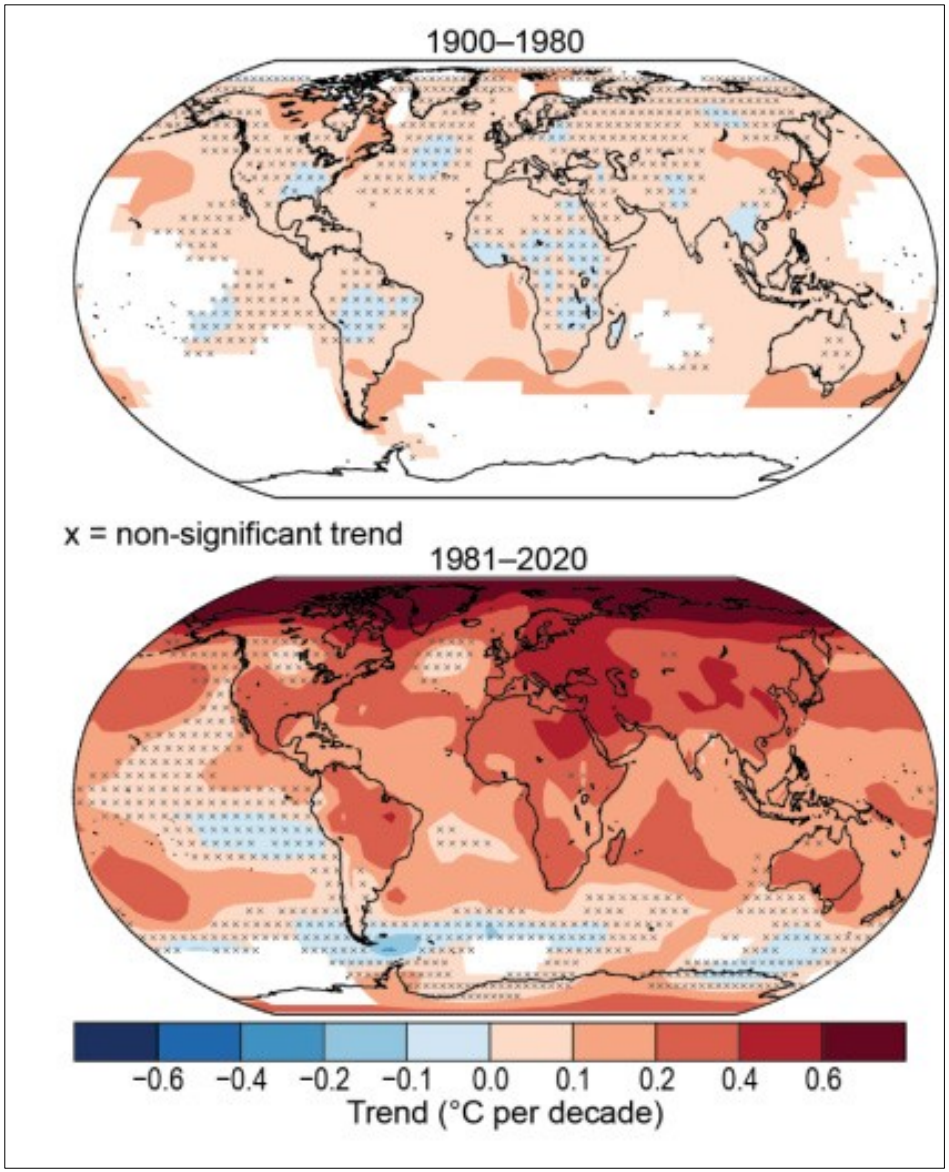


https://www.carbonbrief.org/in-depth-qa-the-ipccs-sixth-assessment-report-on-climate-science

« Each of **the last four decades** has been successively warmer than any decade that preceded it since 1850. »

IPCC 2021 (WG1 AR6 « Summary for Polycymakers »)

An **accelerating** climate warming

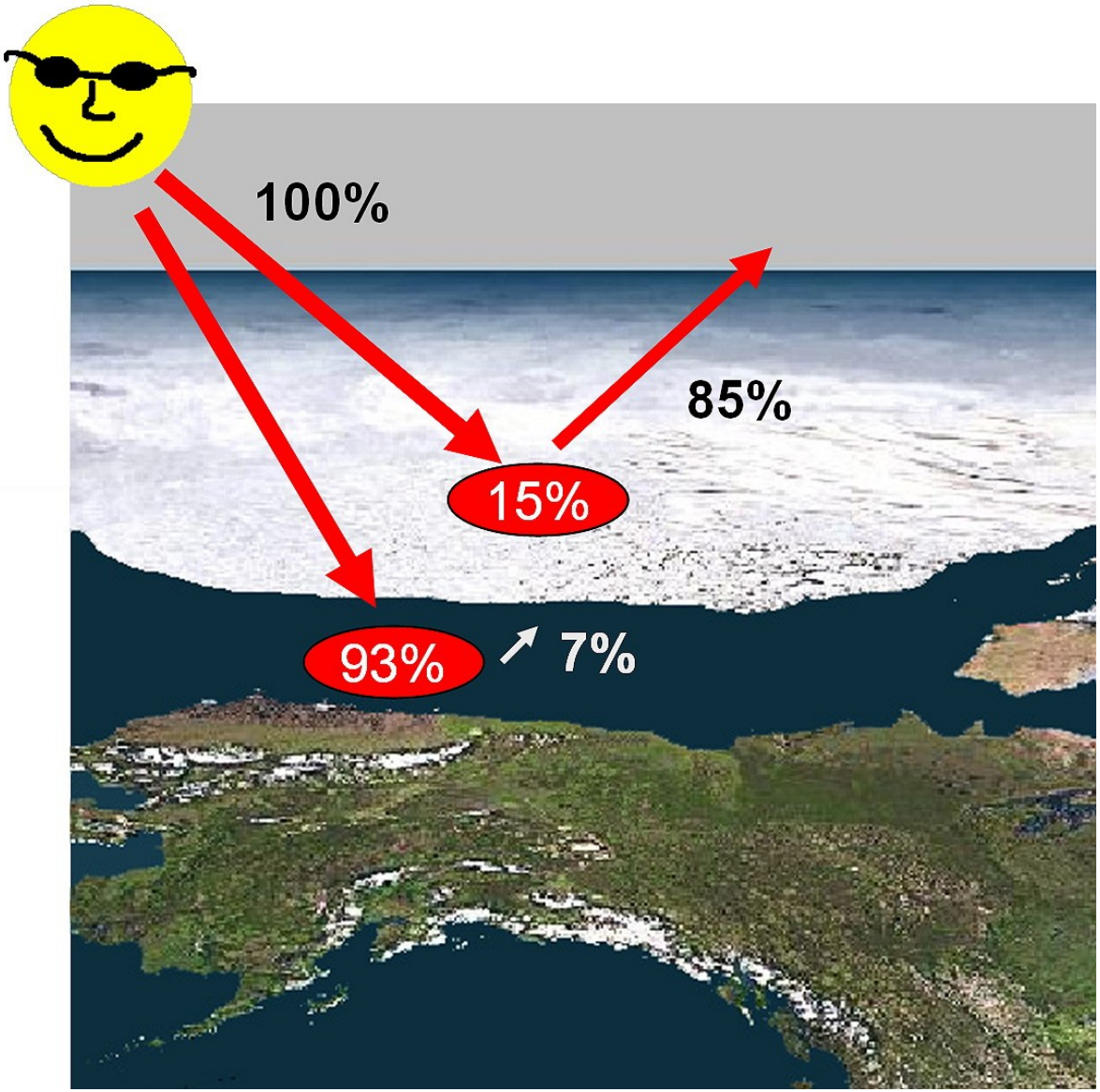


Trends in surface temperature (degrees °C per decade) for the periods

- 1900-1980 (upper map)
- 1981-2020 (lower map).

Temperature data from HadCRUTv5. Source: IPCC (2021)

Arctic amplification



https://www.pmel.noaa.gov/arctic-zone/images/icealbedo.jpg

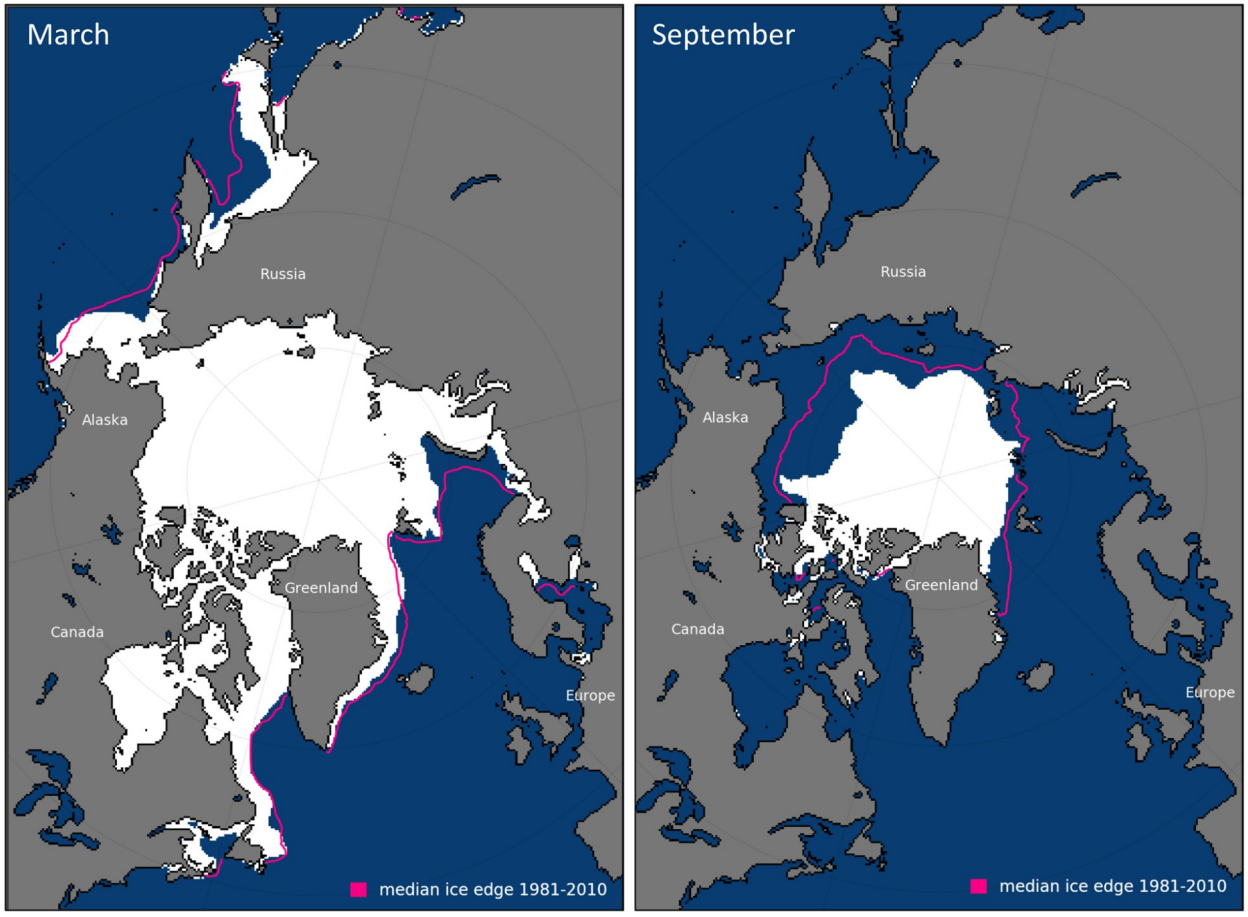
Credit NASA

A rapidly melting arctic ice pack

https://www.noaa.gov/media-release/arctic-saw-2nd-warmest-year-smallest-winter-sea-ice-coverage-on-record-in-2017

The accelerated warming in the Arctic is associated with a **rapid melting** of the Arctic sea ice.

A rapidly melting arctic ice pack



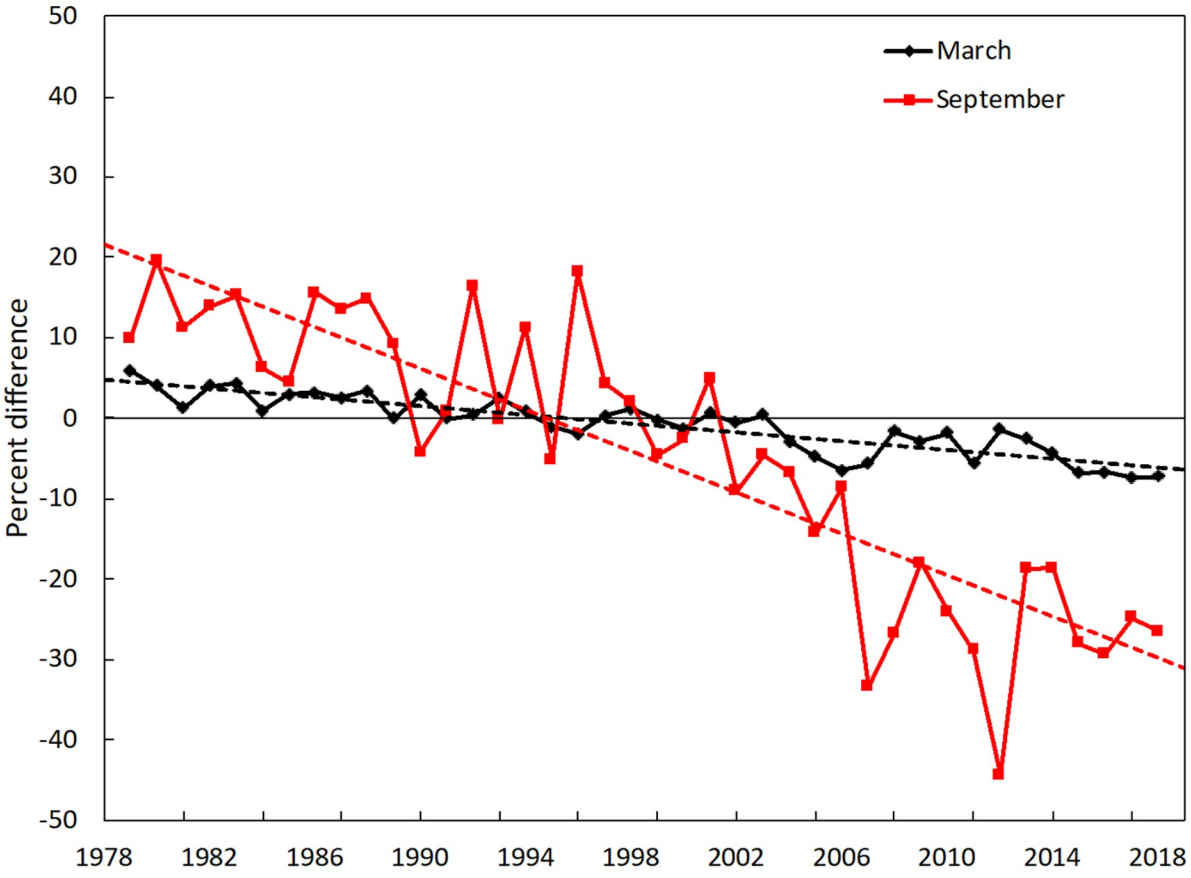
https://arctic.noaa.gov/Report-Card/Report-Card-2017/ArtMID/7798/ArticleID/699/Sea-Ice

Average monthly sea ice extent in

- March 2017 (on the left)
- September 2017 (on the right).

- *The month of maximum extent of the arctic sea ice is March,*
- *the month of minimum extent is September.*

A rapidly melting arctic ice pack



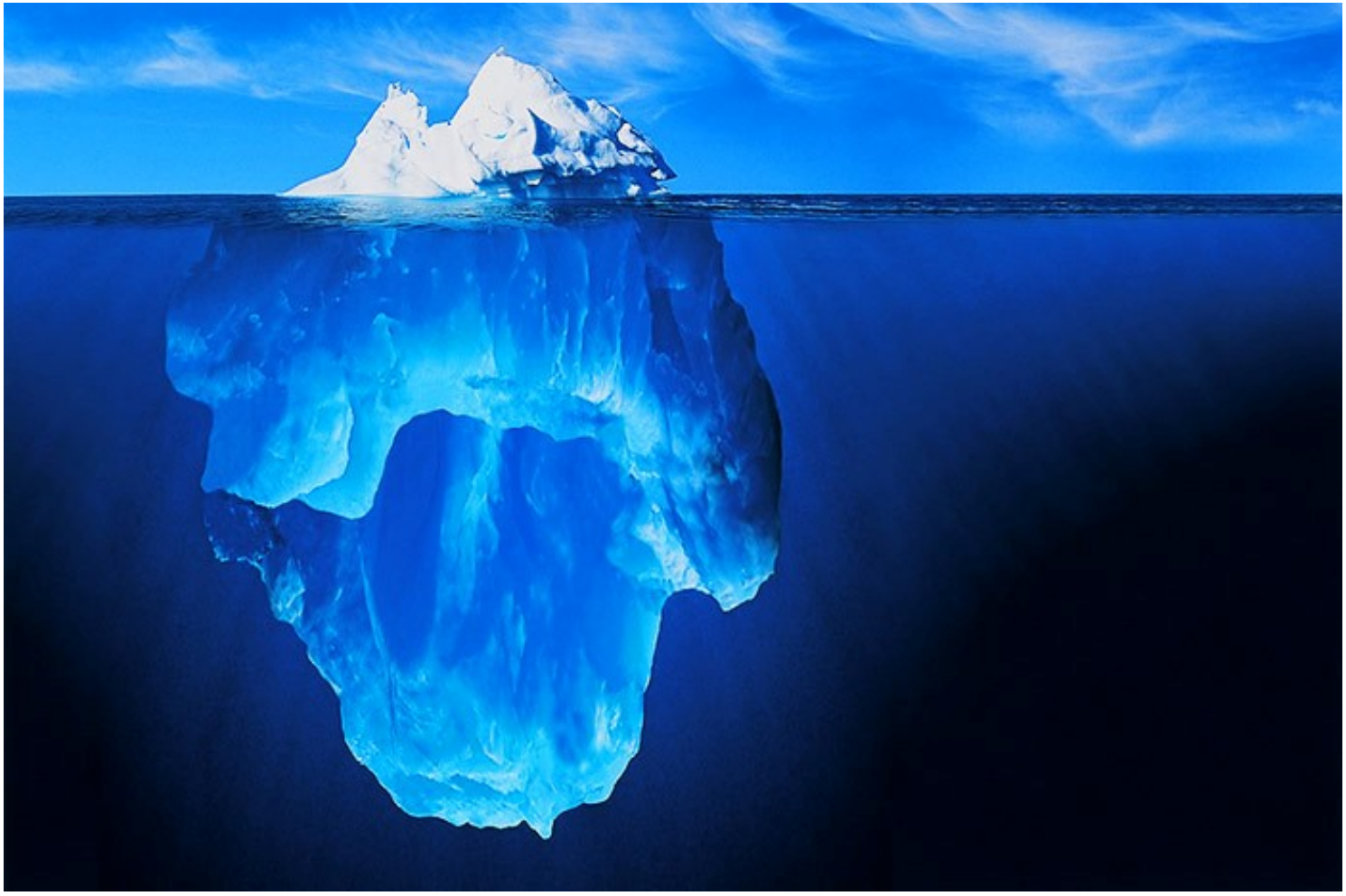
https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/780/SeanbspIce

Evolution of the Arctic sea ice extent anomaly[1]

- in March (black curve)
- in September (red curve).

[1] : *The anomaly, expressed as a percentage, is calculated in relation to the average value for the period* ***1981-2010***.

A rapidly melting arctic ice pack



https://www.espace-sciences.org/multimedia/blogs/49221/billet/les-icebergs

The melting of the arctic ice pack does **not** raise sea levels at all !

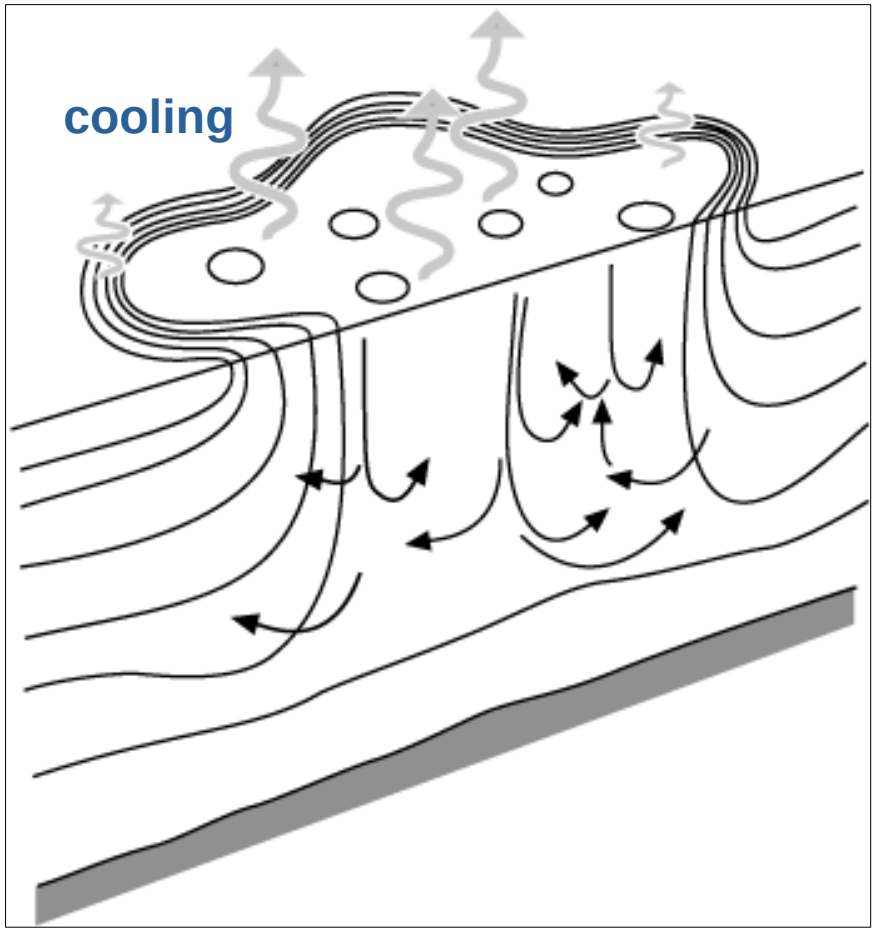
A rapidly melting arctic ice pack

The melting of the Arctic ice pack has very important consequences, and not only for polar bears !

Photograph ©2008 fruchtzwerg's world

The melting of the Arctic ice pack provides an inflow of **fresh water** to the surface of the North Atlantic Ocean/Labrador Sea.

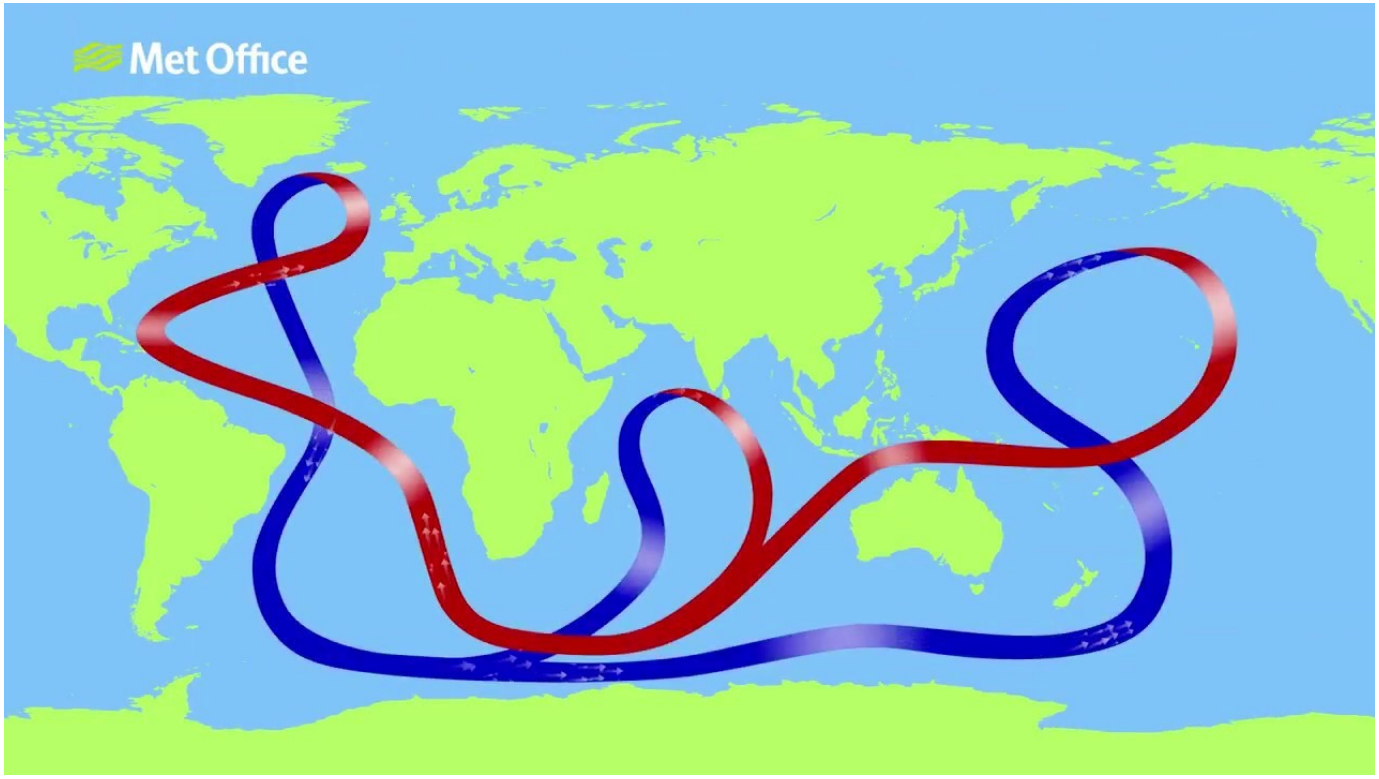
A rapidly melting arctic ice pack



http://puddle.mit.edu/~helen/oodc.html

The decrease in surface water **density** is of particular concern.

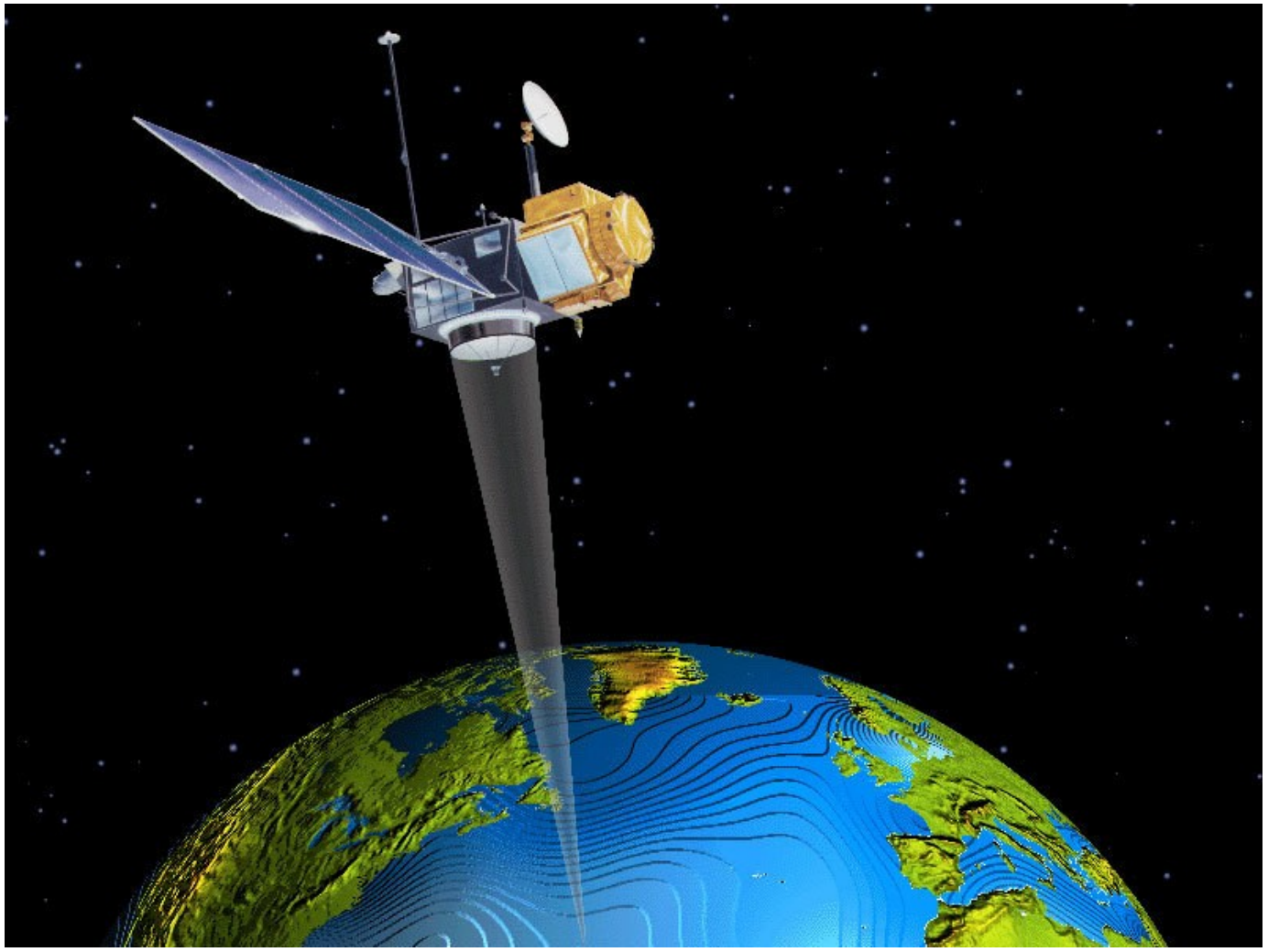
The Atlantic Meridional Overturning Circulation



https://www.metoffice.gov.uk/weather/learn-about/weather/oceans/amoc

The AMOC is currently at its weakest in more than a millennium, probably in response to a freshening of the surface water of the North Atlantic.

Sea level

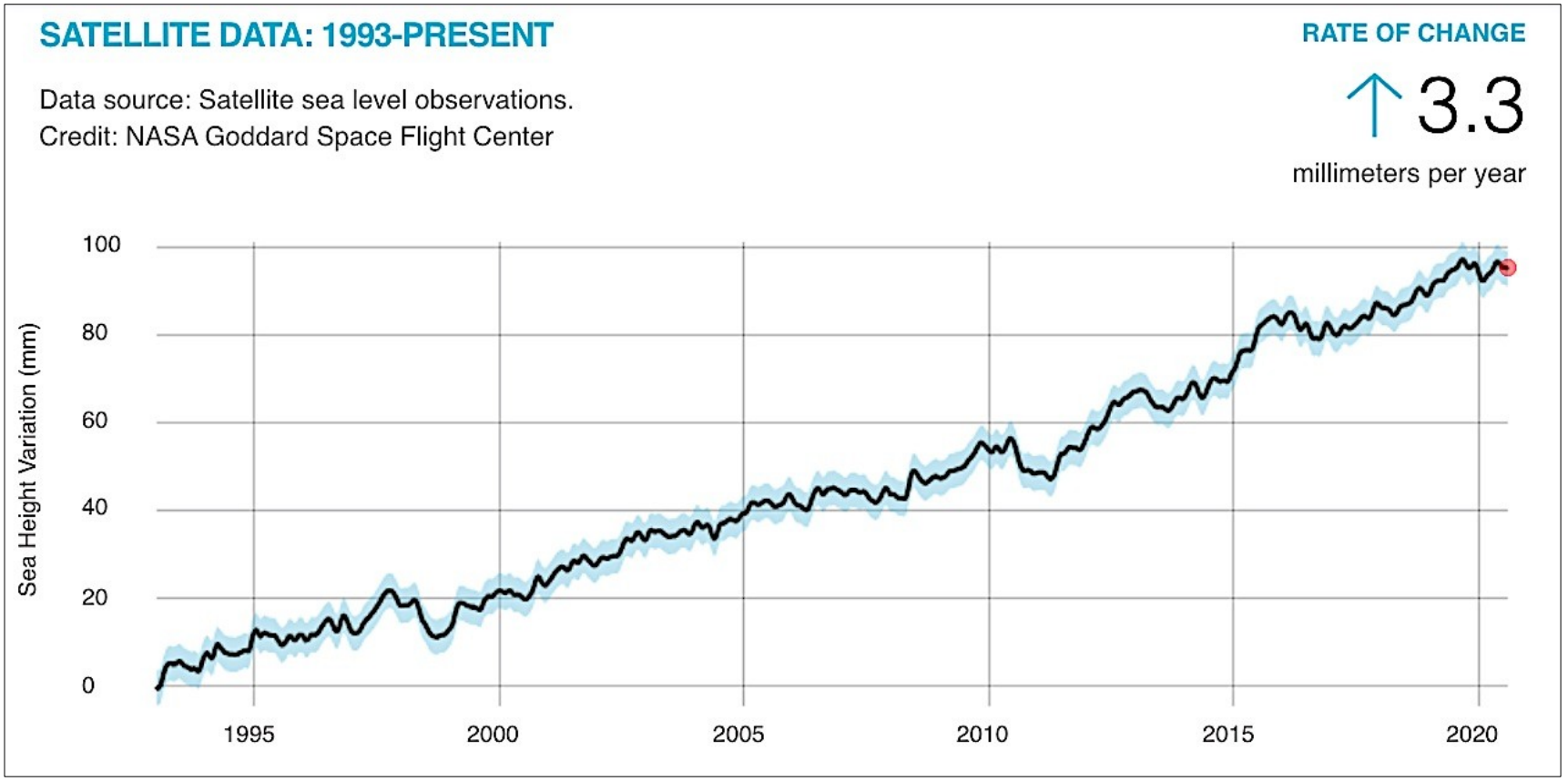


https://sealevel.nasa.gov/missions/topex-poseidon

Another aspect of climate change to watch out for is the **rise** in the average sea level.

The average sea level has risen since 1850, as evidenced by tide gauge measurements, and by satellite measurements since 1993.

Global Mean Sea Level : the recent trend



Currently, sea levels rise an average of **3.3 millimeters per year,** more than twice the rate at the start of the 20th century.

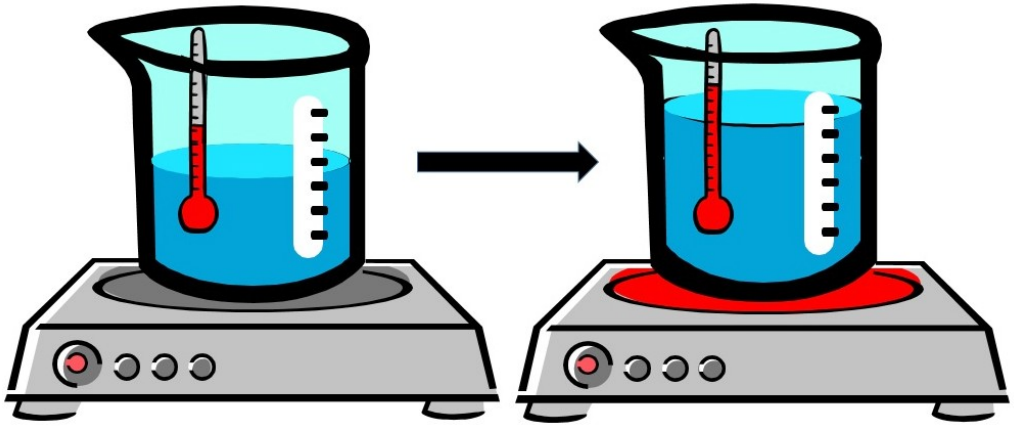
Sea level rise : two factors

https://www.bbc.com/news/science-environment-36029753

Sea level rise : two factors

Svalbard, Norway .Credit: Art Wolfe Getty Images

Transfer to the ocean of water currently stored on land, particularly from melting glaciers and ice sheets.



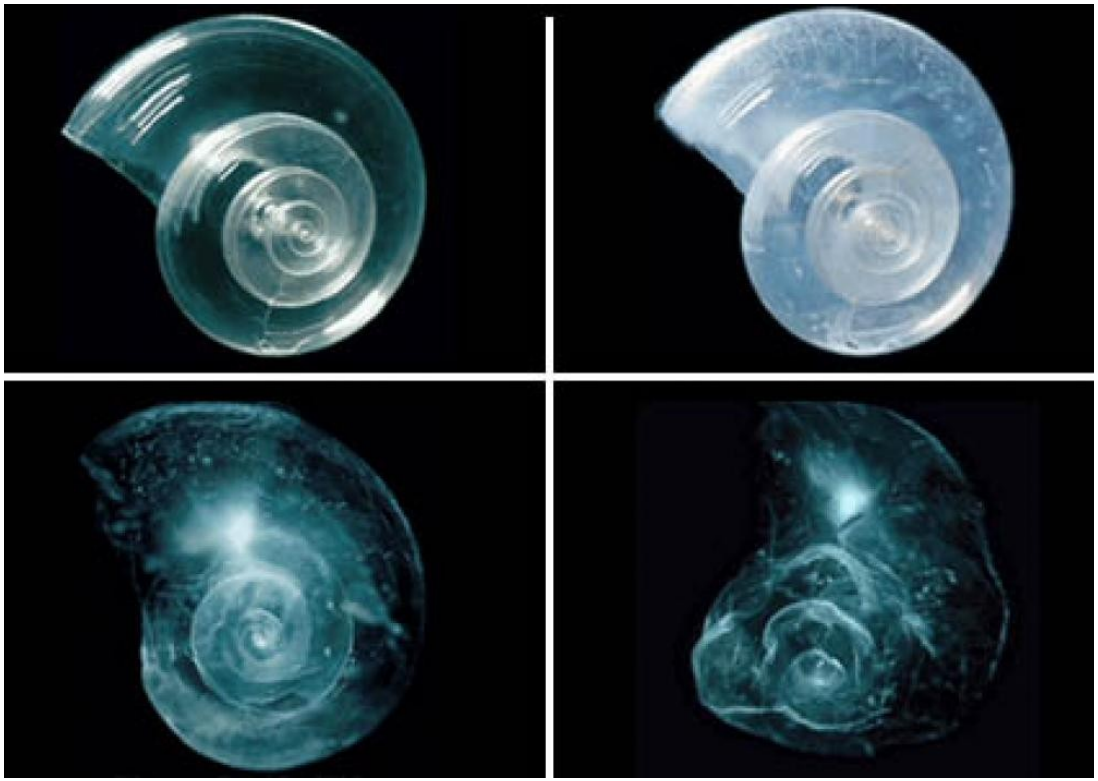
http://www.ces.fau.edu/nasa/impacts/rising-seas/index.php

Thermal expansion of seawater as it warms.

Last not least

Ocean **acidification**

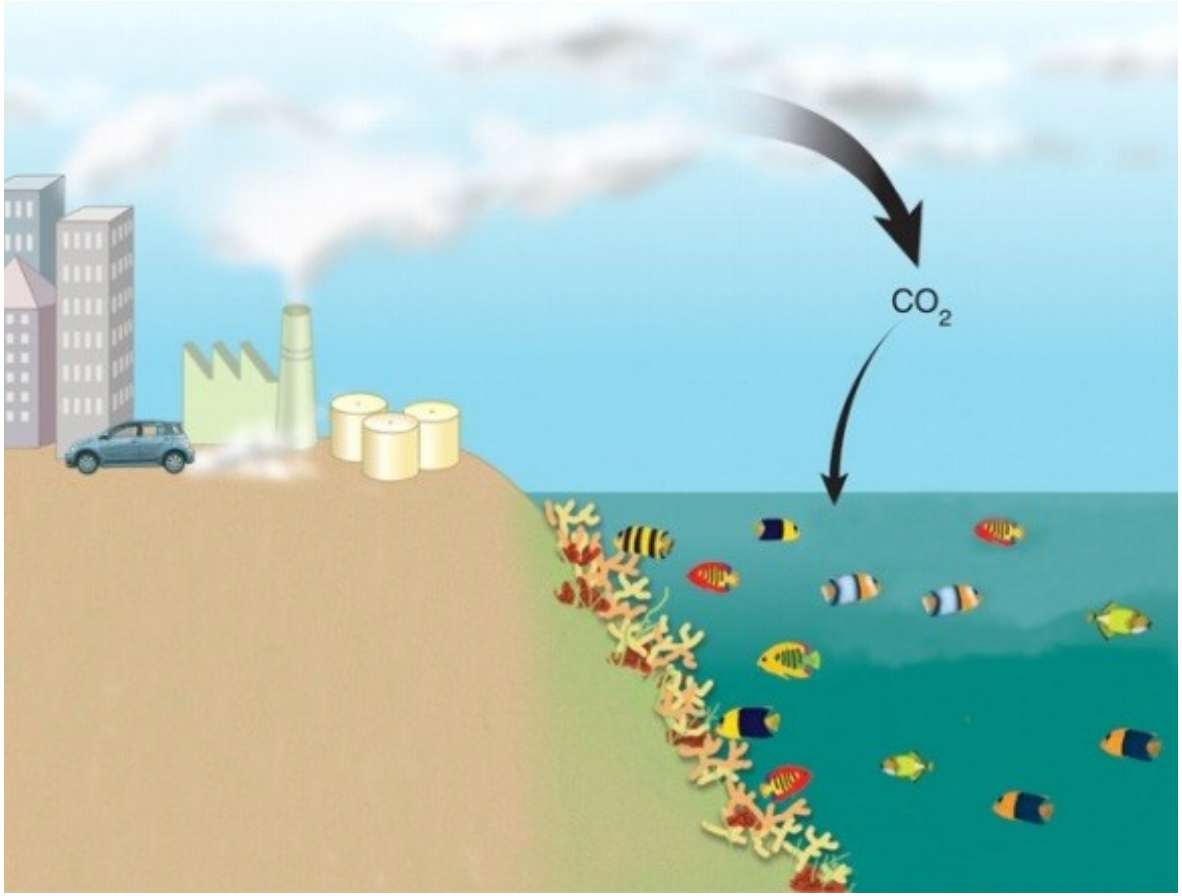
https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification



https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification

A serious threat to many marine species, such as corals and sea snails.

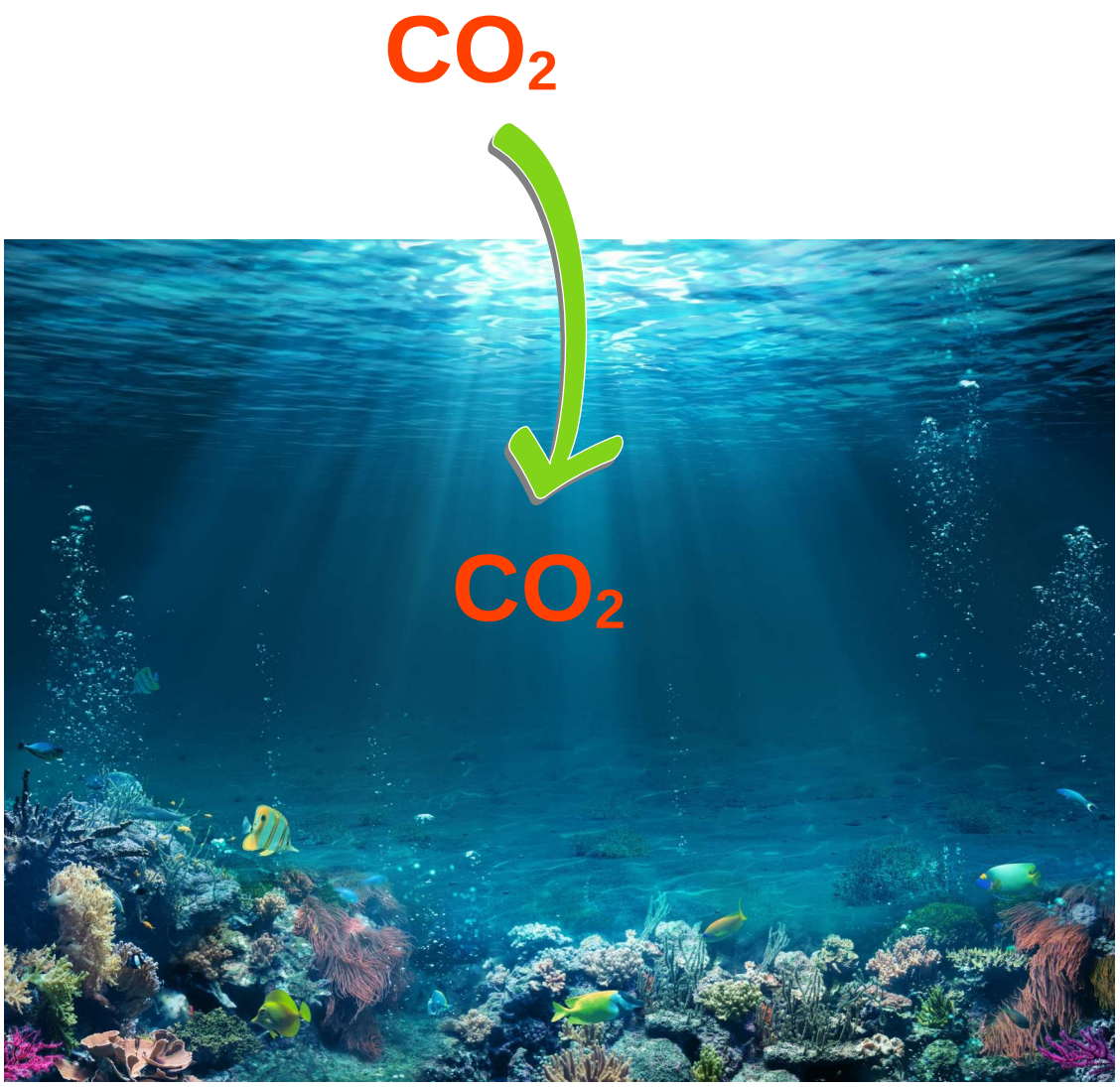
From the atmosphere to the ocean



https://www.dolphinaris.com/learn-about-5-scary-consequences-to-ocean-acidification/

If we look at the fate of anthropogenic carbon dioxide molecules released into the atmosphere during the period 2010-2019, **23 % has been transferred to the ocean**.

The ocean slowed global warming

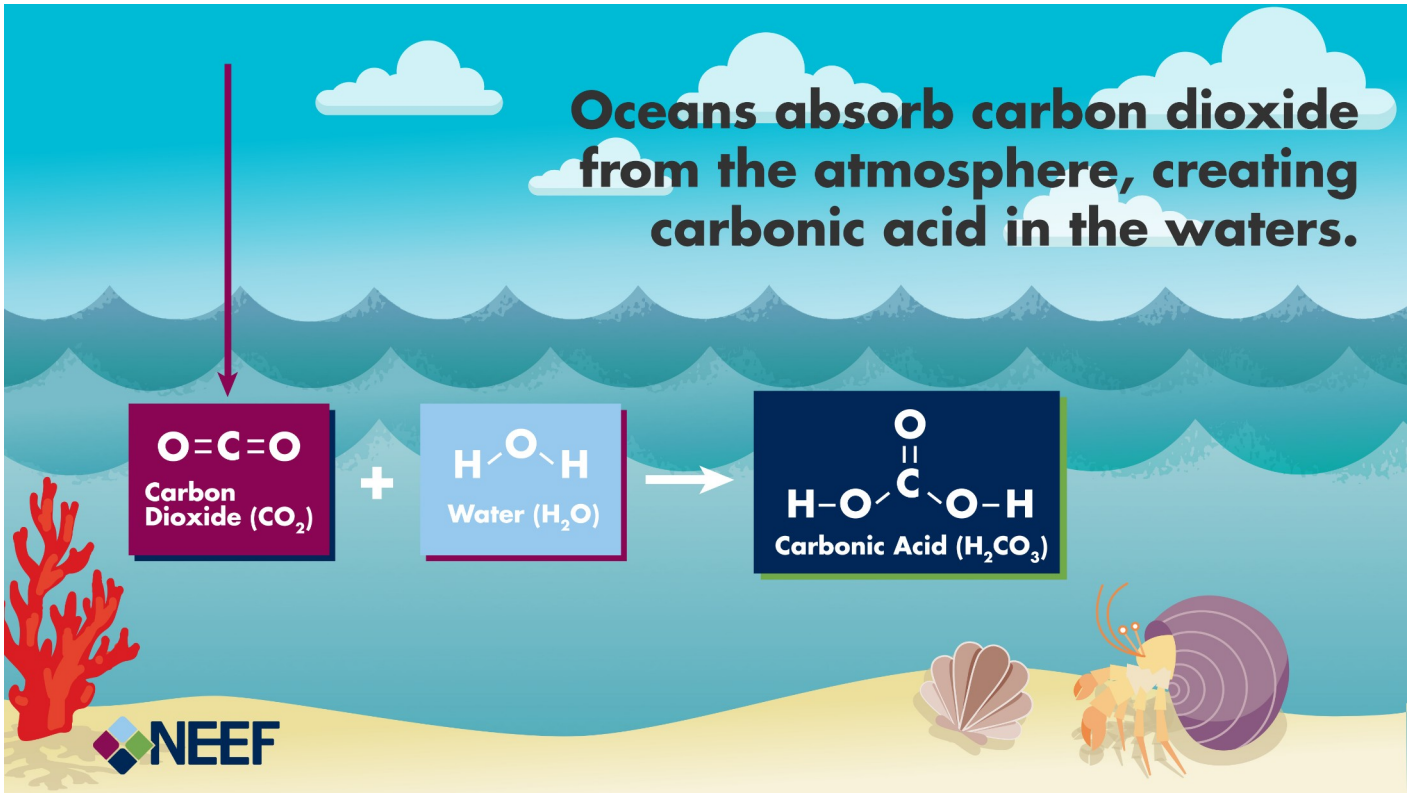


https://cdn.futura-sciences.com/buildsv6/images/largeoriginal/5/c/a/5cac543f48_50151060_ocean-coraux.jpg

Less carbon dioxide in the atmosphere.

If not for the ocean, the global warming would be much worse.

Ocean acidification

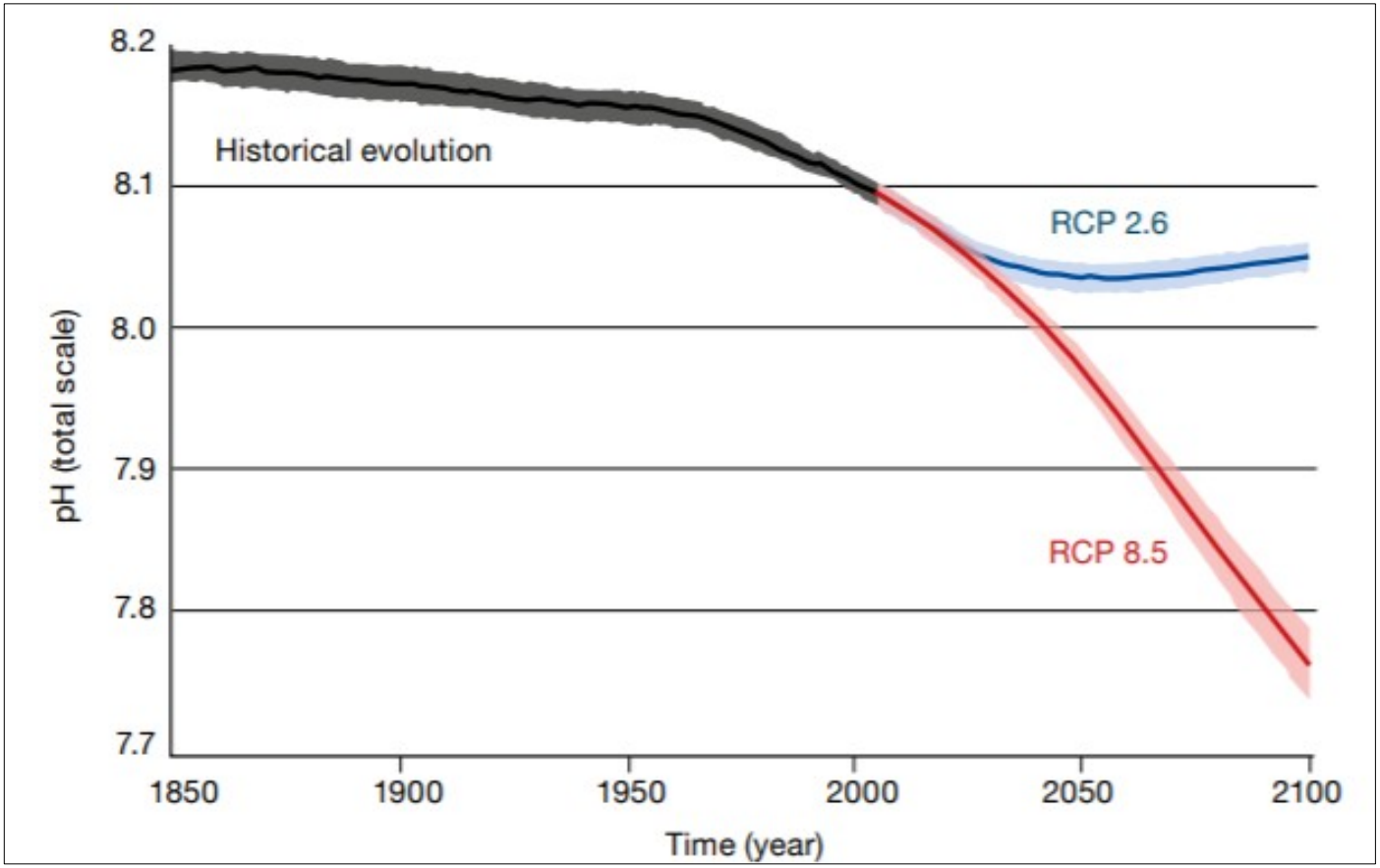


https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification
Graphic developed by the National Environmental Education Foundation (NEEF).

But this slowed warming has come at the cost of **changing the ocean's chemistry**.

When water and carbon dioxide mix, they combine to form carbonic acid.

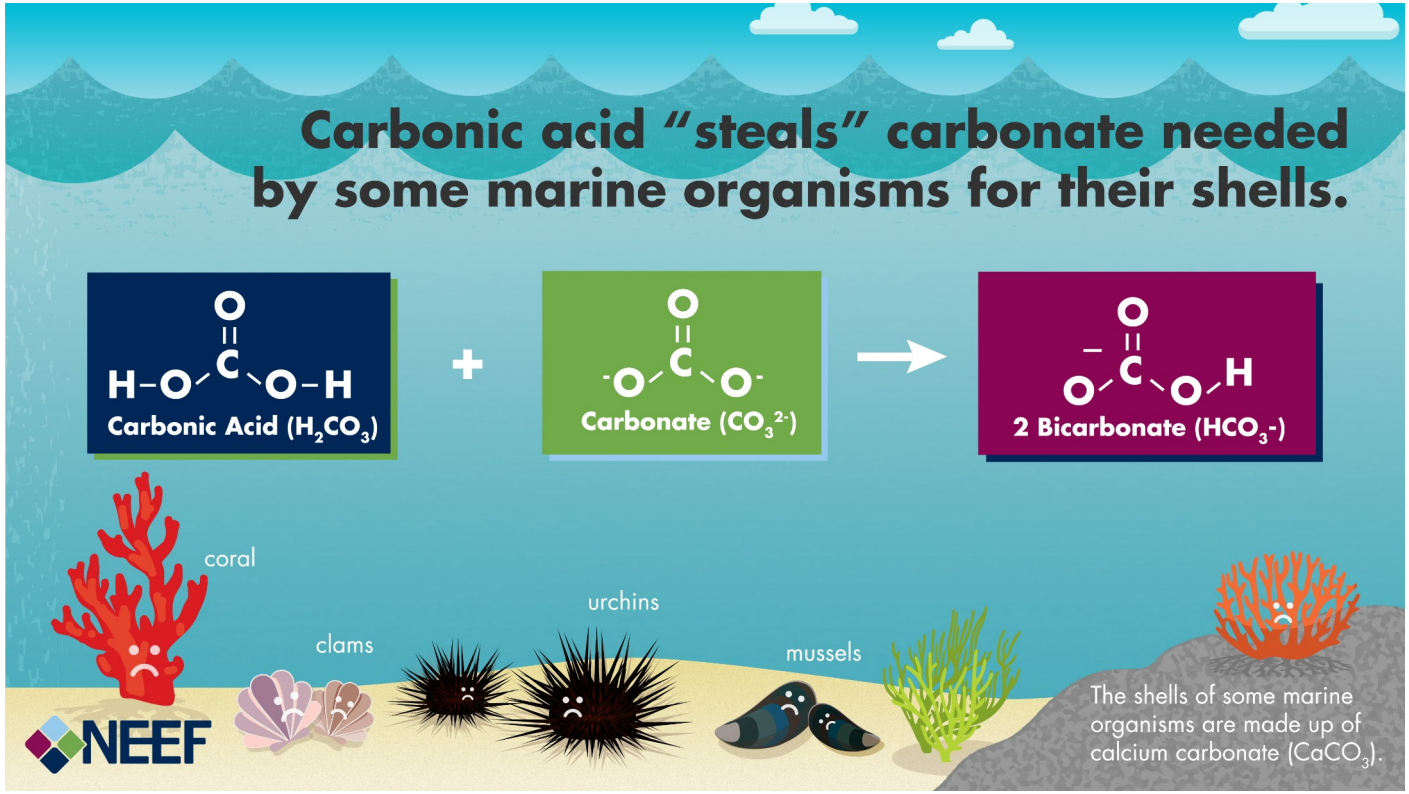
Ocean acidification



https://upload.wikimedia.org/wikipedia/commons/5/5a/Ocean_Acidification_under_Low_and_High_Carbon_Emission_Scenarios.png

So far, the pH of the ocean has dropped **from 8.2 to 8.1**

Why does ocean acidification matter?



https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification
Graphic developed by the National Environmental Education Foundation (NEEF).

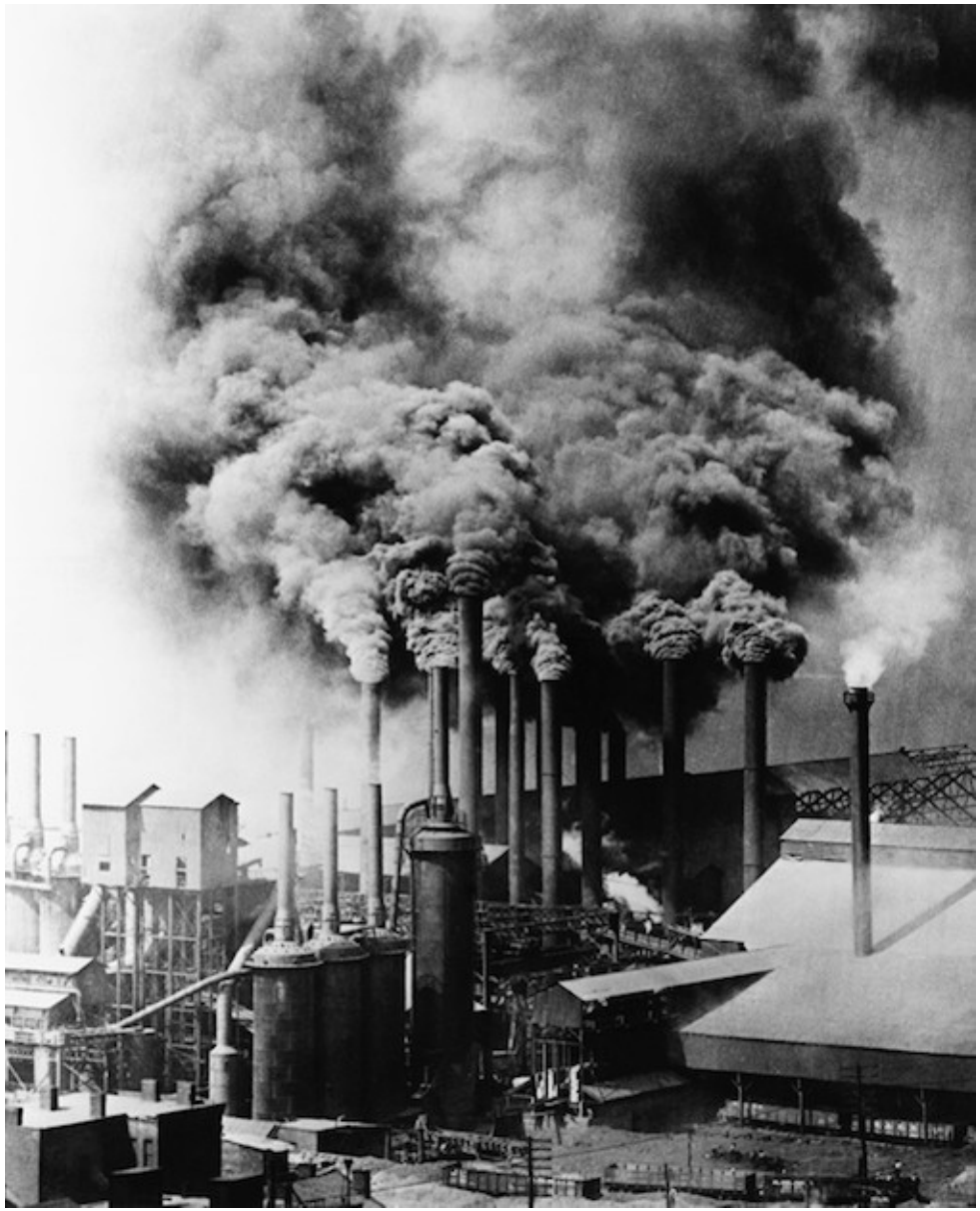
Ocean acidification is already **negatively impacting** many ocean species, especially organisms like oysters and corals that make **hard shells and skeletons** by combining calcium and carbonate from seawater.

https://oceanacidification.noaa.gov/WhatWeDo/BiologicalResponse/TabId/2990/PID/14746/evl/0/TagID/655/TagName/pteropods/Default.aspx

Contents

Image source: Billy Wilson / Flickr

The industrial revolution



Smokestacks in Pittsburgh, Pennsylvania, 1890s © Bettmann/CORBIS

The industrial revolution brought a rapid increase in the **burning of fossil fuels**, releasing huge amounts of carbon dioxide and methane into the atmosphere.

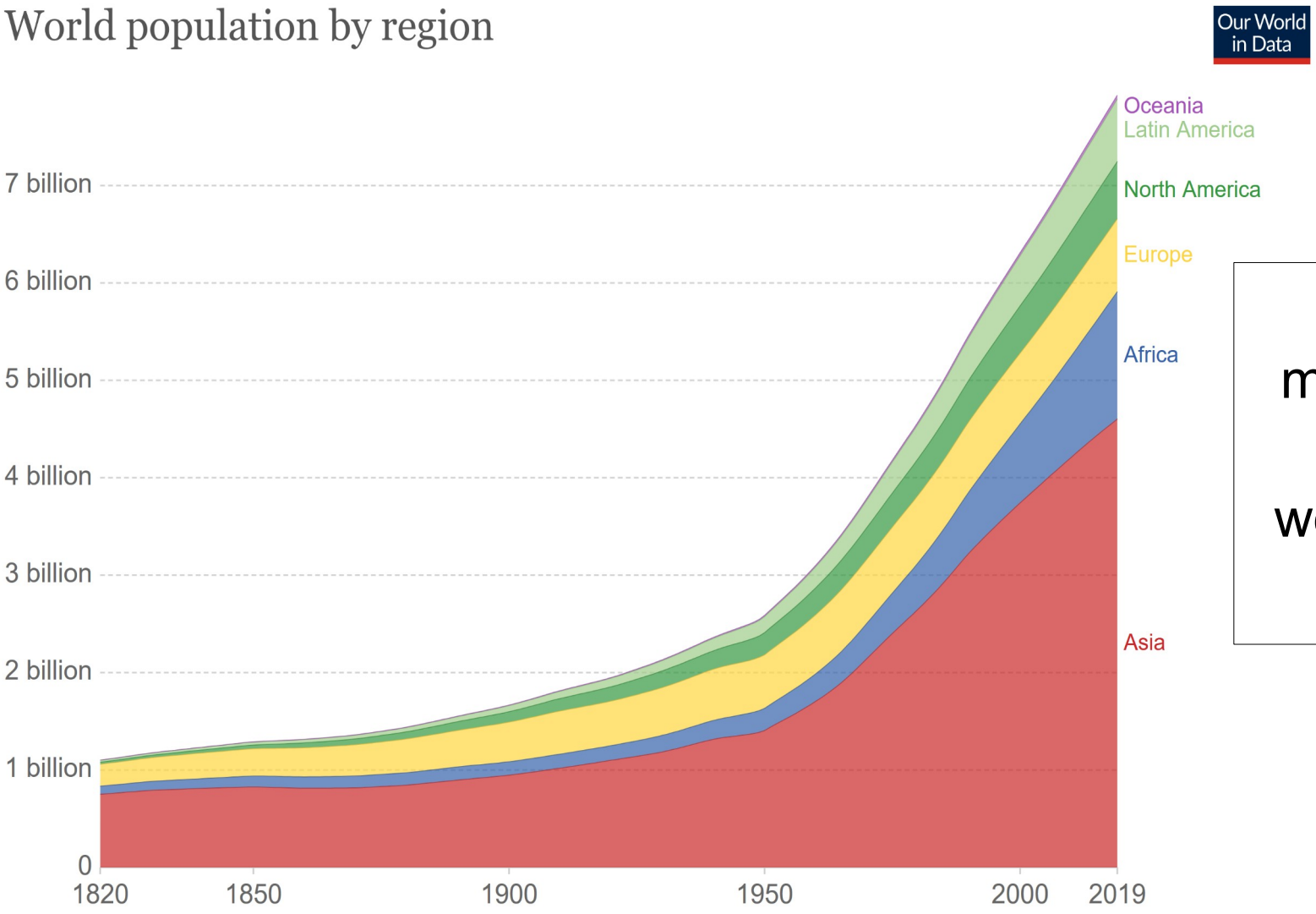
The industrial revolution

https://geneticliteracyproject.org/2018/10/01/sustainability-advantage-high-yield-intensive-agriculture-outpaces-organic-farming-large-study-shows/

The industrial revolution also led to the rise of a more intensive agriculture and livestock breeding, which has led to a change in land use.

https://www.consoglobe.com/en-finir-avec-lelevage-intensif-200-personnalites-co-signent-une-tribune-cg

A growing population



Finally, we can mention the rapid increase in the world's population since 1850.

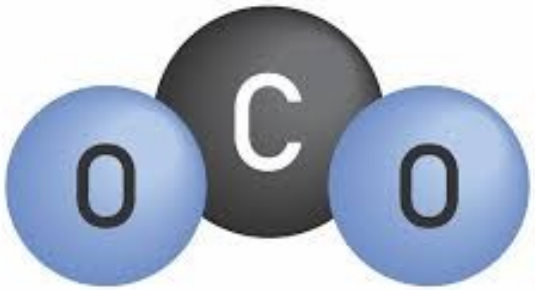
https://ourworldindata.org/world-population-growth

Greenhouse gases released into the atmosphere

https://www.worldatlas.com/articles/countries-who-contribute-the-least-greenhouse-gasses.html

All these changes together have led to the **emission** of significant amounts of greenhouse gases into the atmosphere.

Greenhouse gases released into the atmosphere

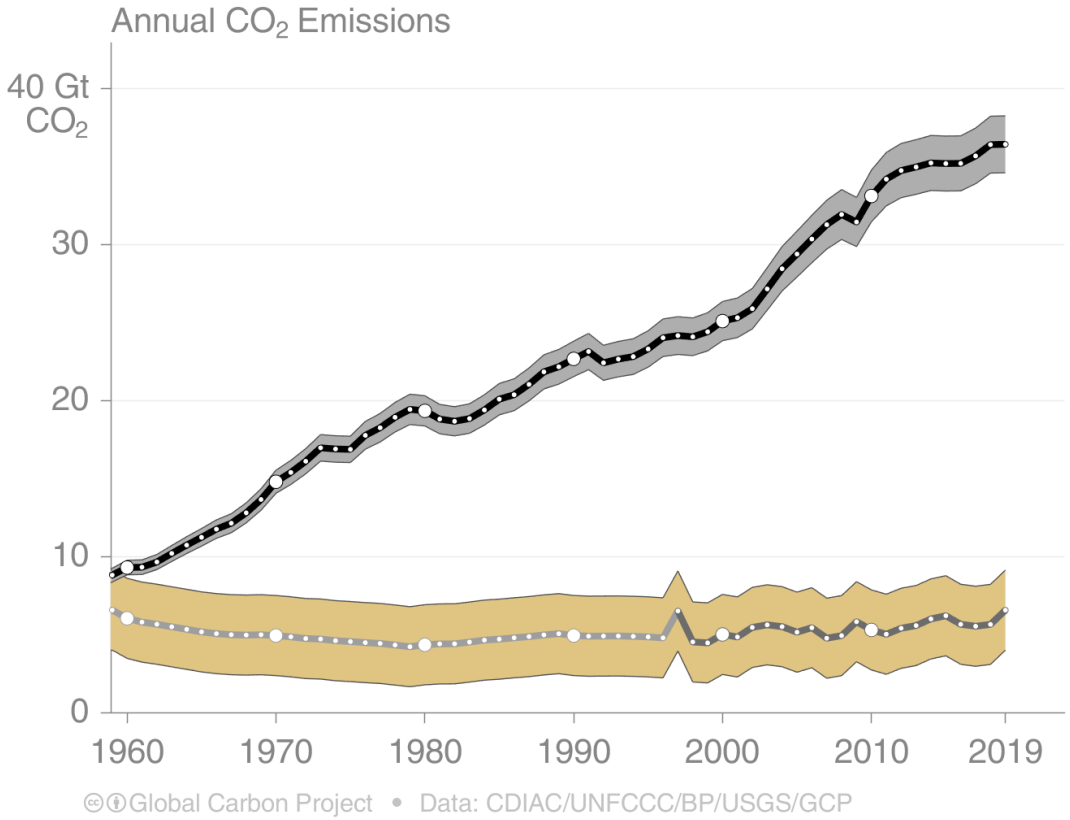


The emissions that have contributed most strongly to the increase of the greenhouse effect are those of **carbon dioxide**.

https://www.online-sciences.com/tag/physical-properties-of-carbon-dioxide-gas/

Global carbon dioxide emissions

Total global emissions: 43.0 ± 3.3 $GtCO_2$ in 2019, 56% over 1990
Percentage land-use change: 39% in 1960, 14% averaged 2010–2019

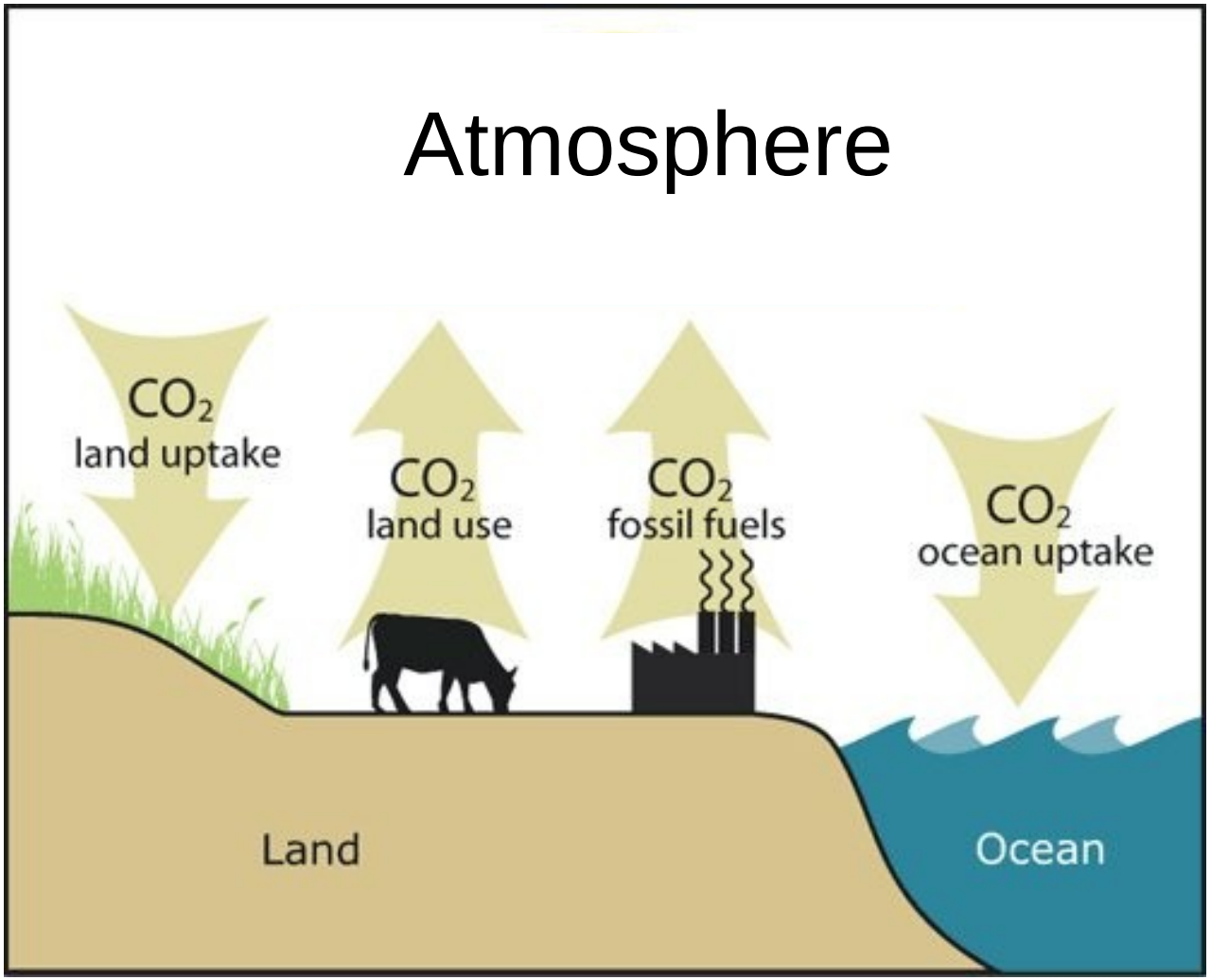


The CO_2 emission is shown in billion tonnes of CO_2 ($GtCO_2$).

1 Gigatonne (Gt) = 1 billion tonnes

 +  = Global carbon dioxide emissions

Fate of anthropogenic CO_2 emissions



Adapted from https://twitter.com/urban_herbco/status/1009450903362064384

Not all carbon dioxide released into the atmosphere remains in the atmosphere.

Indeed, carbon emissions **are partitioned** among the atmosphere and carbon sinks.

Fate of anthropogenic CO_2 emissions

(2010–2019)

Anthropogenic CO_2 emissions

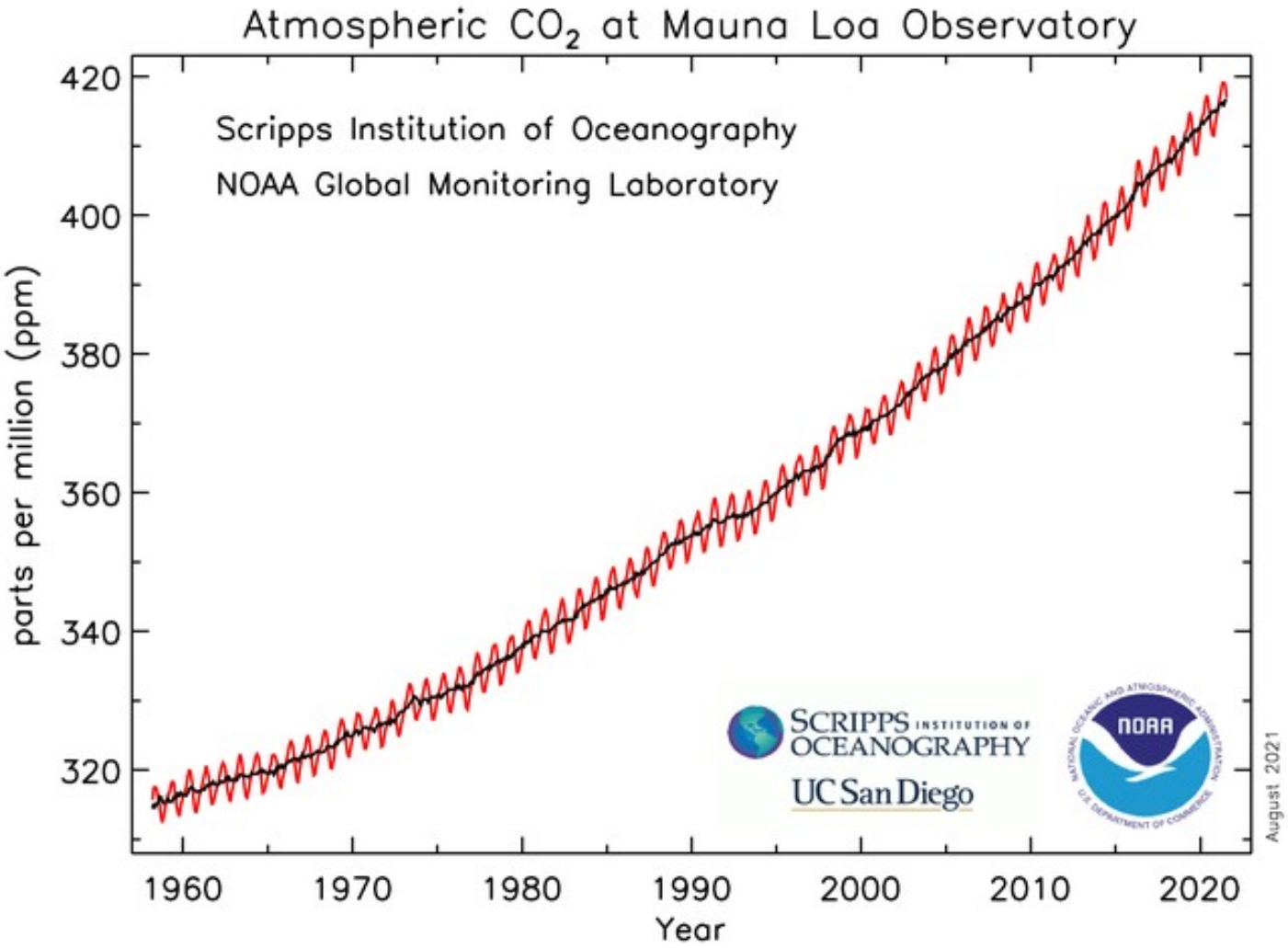
46%

31%

23%

Adapted from ; Global Carbon Budget 2020

Carbon dioxide in the atmosphere

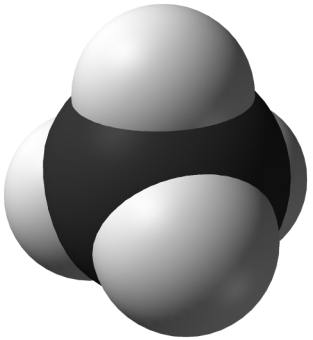


- About 315 ppm in 1958 ;
- 416.96 ppm in July 2021.

The **red line** represents the monthly mean values, centered on the middle of each month.

Methane

(LightRocket/Getty/Kyodo)

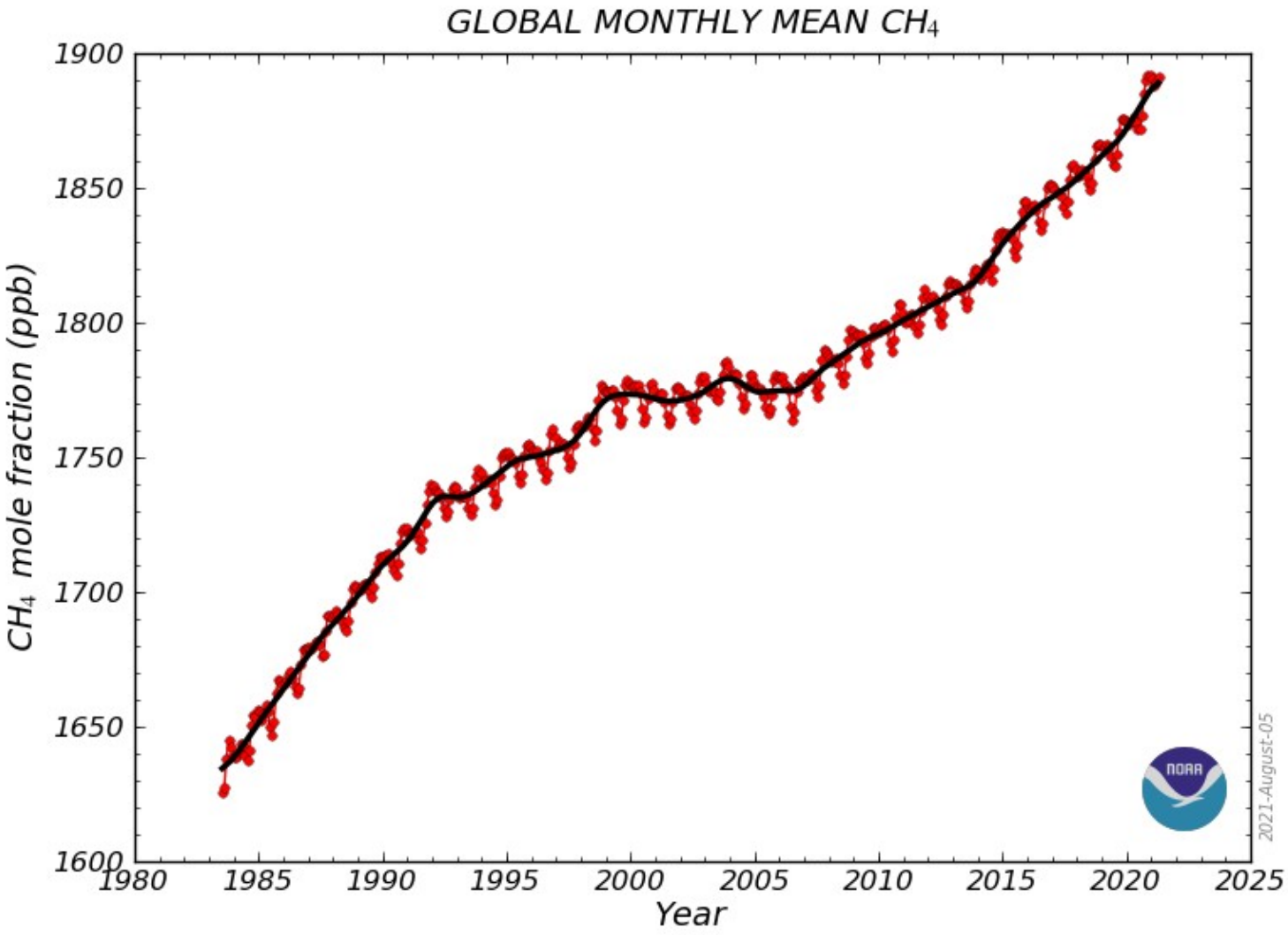


Benjah-bmm27, Public domain, via Wikimedia Commons

Methane : one carbon atom and four hydrogen atoms.

The major sources of methane being released into the atmosphere are the use of fossil fuel , intensive cattle breeding, agriculture, and landfills.

Methane in the atmosphere



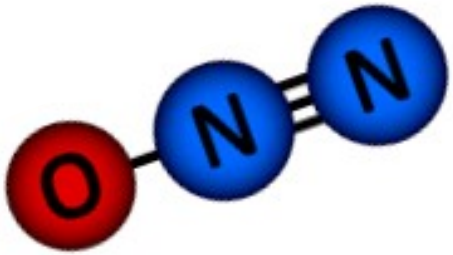
The concentration of methane in the atmosphere is 150% above pre-industrial levels.

https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/

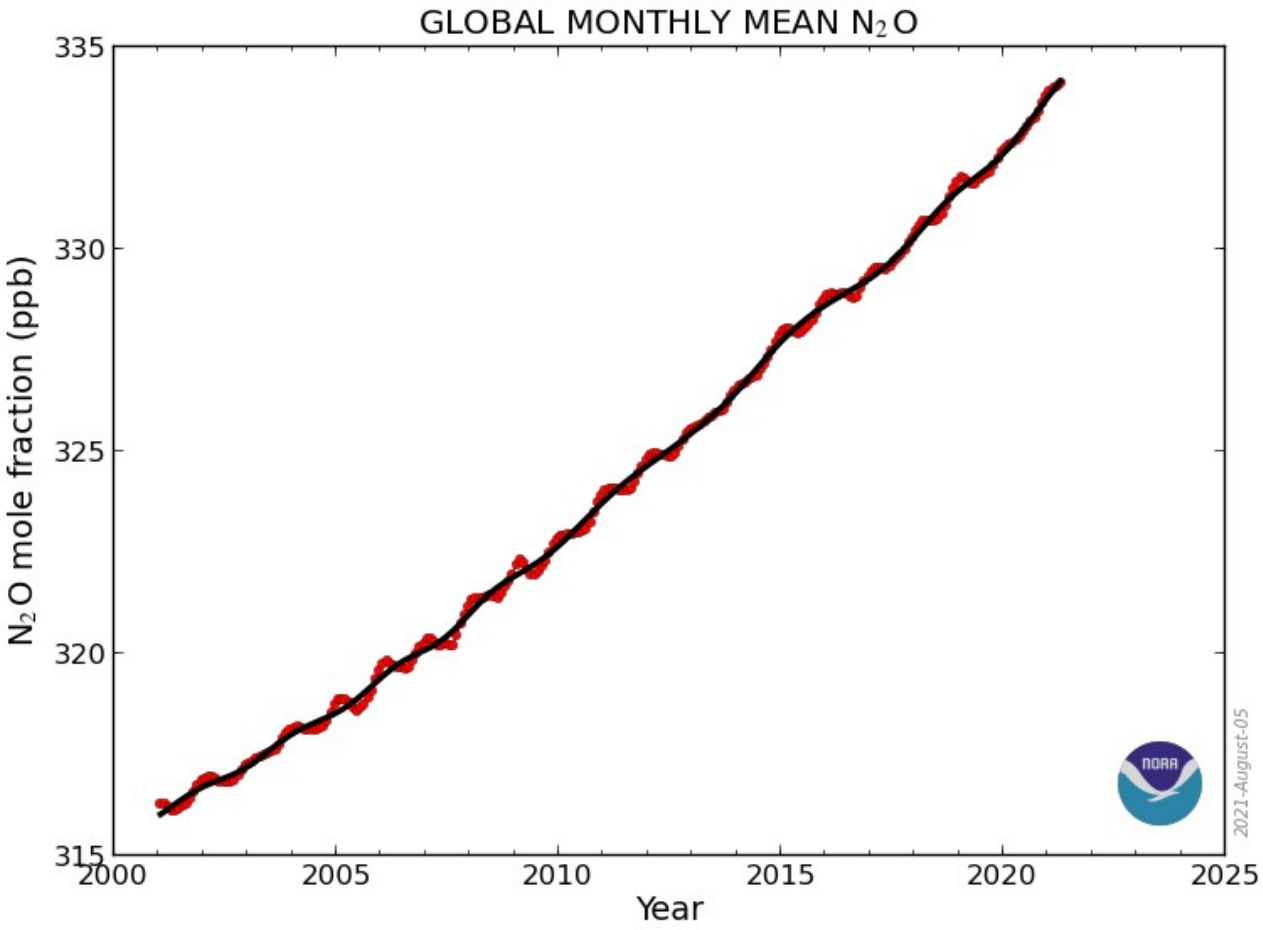
Nitrous oxide

https://www.agric.wa.gov.au/climate-change/reducing-nitrous-oxide-emissions-agricultural-soils-western-australia

A third gas that has played a significant role in enhancing the greenhouse effect is **nitrous oxide**, commonly known as laughing gas.



Nitrous oxide



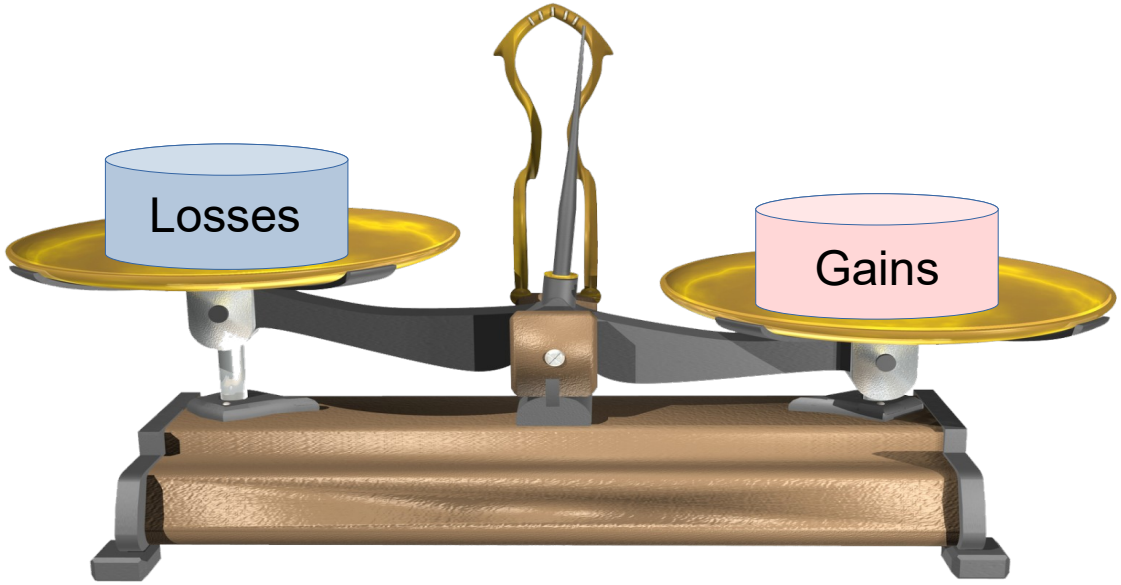
The **red line** of the graph shows globally-averaged, monthly mean atmospheric nitrous oxide abundance.

The black line represents the same, after correction for the average seasonal cycle.

A stronger greenhouse effect

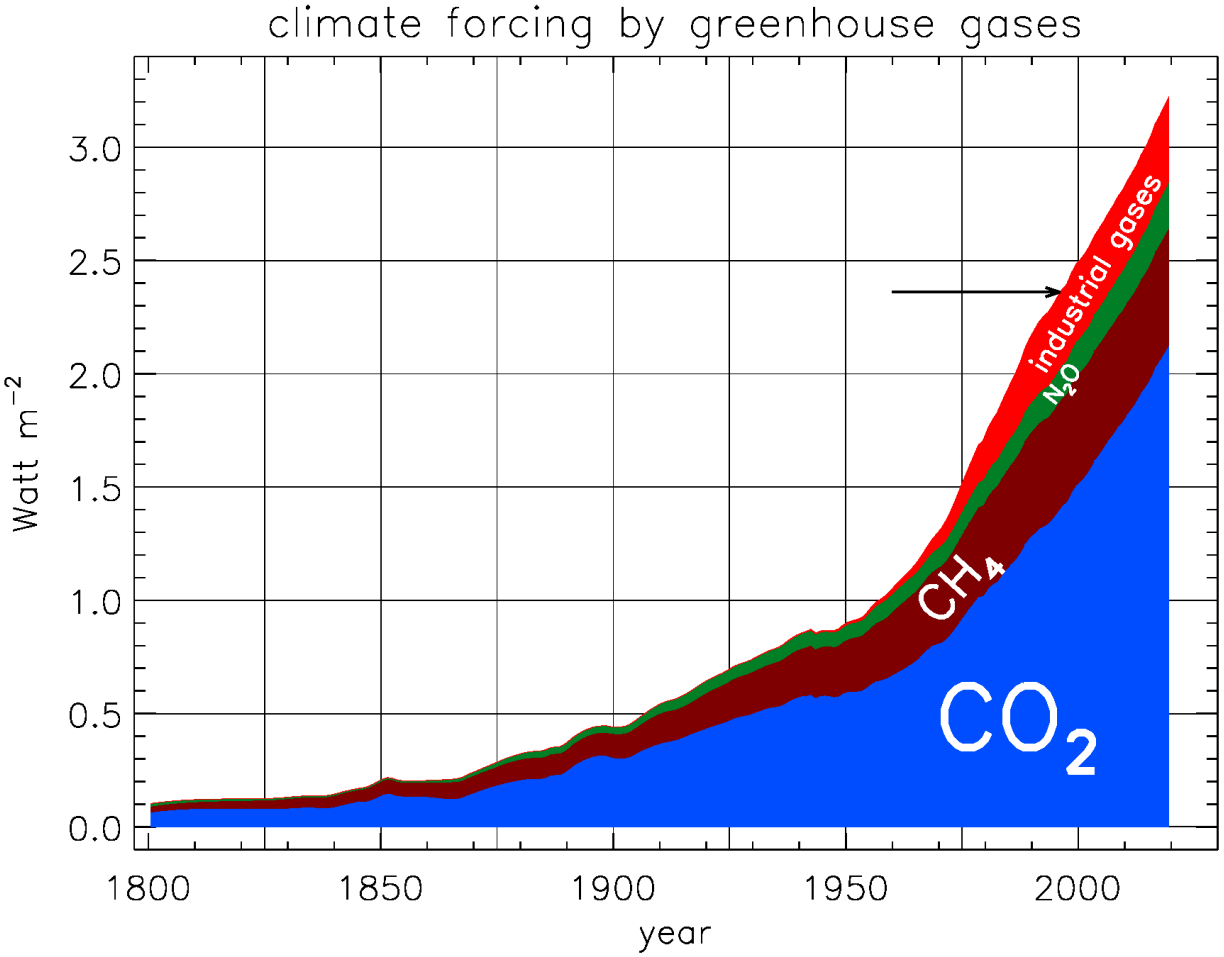
The Earth receives more energy than it used to because of the enhanced greenhouse effect.

The budget between energy gains and energy losses isn't balanced anymore.



A stronger greenhouse effect creates a **radiative forcing.**

Radiative climate forcing



https://gml.noaa.gov/ccgg/ghgpower/

As you can see, in 2019, the radiative forcing created by all greenhouse gases was about **3.2 W m^{-2}**.

The horizontal arrow on the graphic shows when climate forcing surpassed 1% of the mean power gained from the sun.

Contents

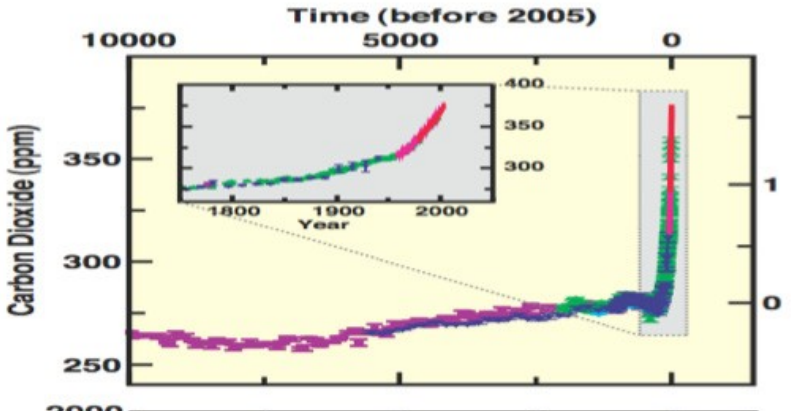
https://www.climatesignals.org/what-climate-change-detection-and-attribution

The causes of climate change

© KEYSTONE/EPA/SASCHA STEINBACH

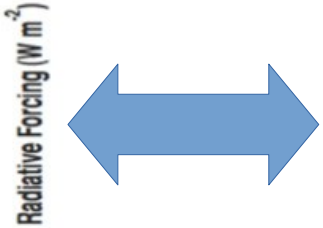
Causes of climate change : CO_2 and temperature

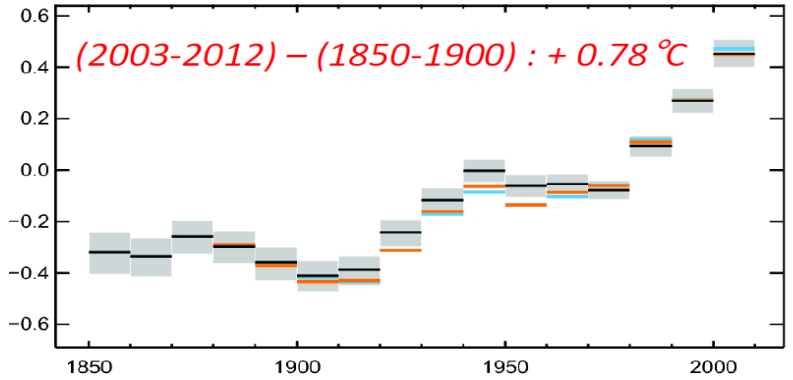
Human activities



© IPCC, 2013

ATTRIBUTION ?





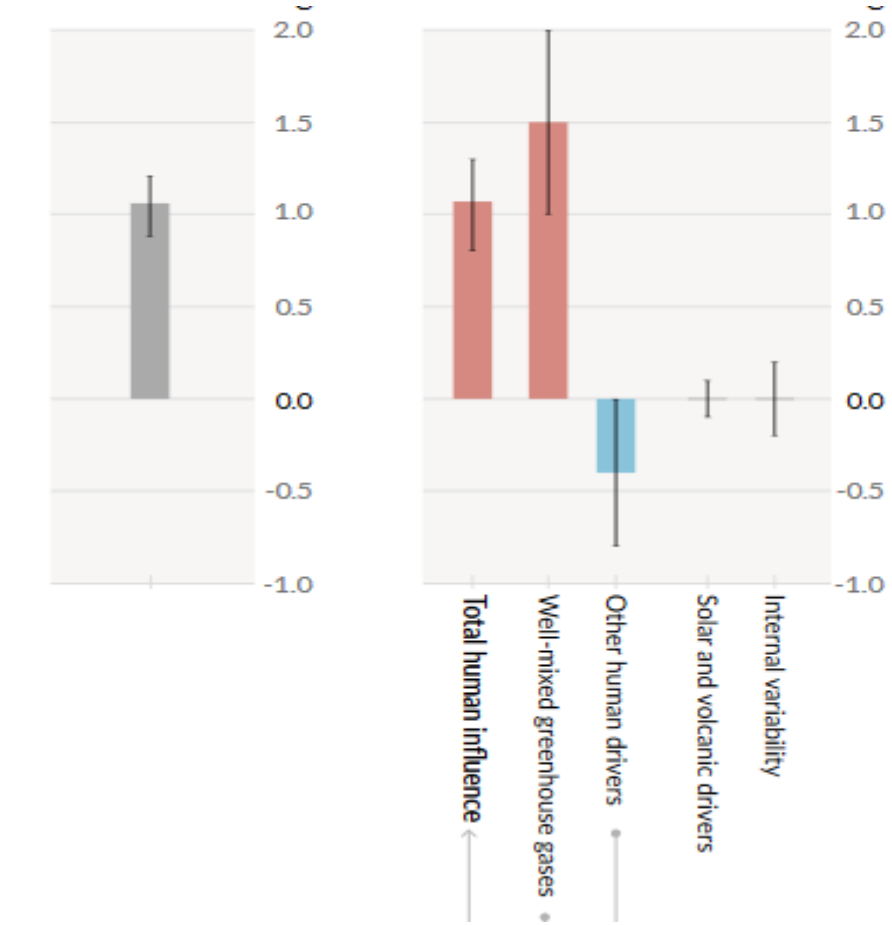
© IPCC, 2013

Human activity has led to an increase of greenhouse gases like carbon dioxide.

There is a strong correlation between carbon dioxide concentration and the increase of the global mean temperature.

The cause and effect relationship has been proven by modelling.

Contributions to observed surface temperature change relative to 1850-1900 period



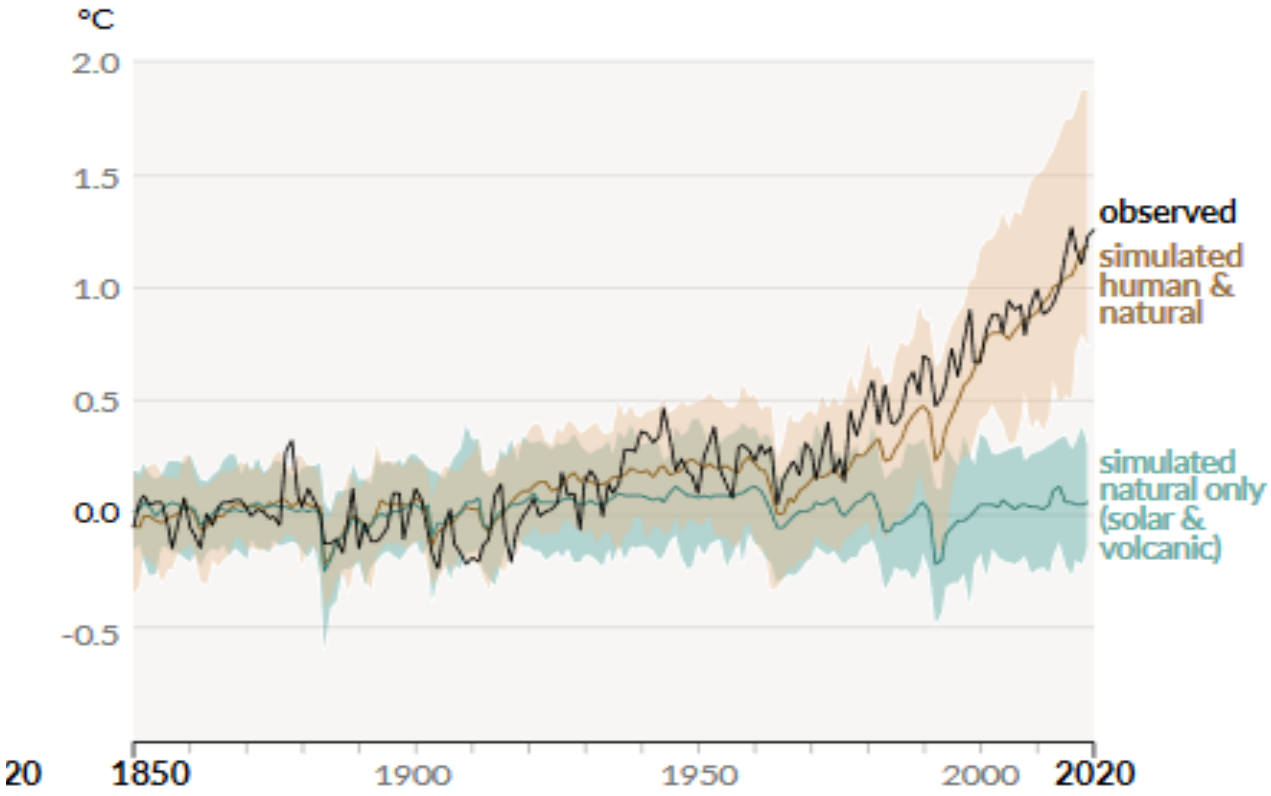
© *IPCC, 2021*

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era.

They have been detected throughout the climate system and **are extremely likely to have been the dominant cause** of the observed warming since the mid-20th century.

Comparison of observed and simulated change in temperatures

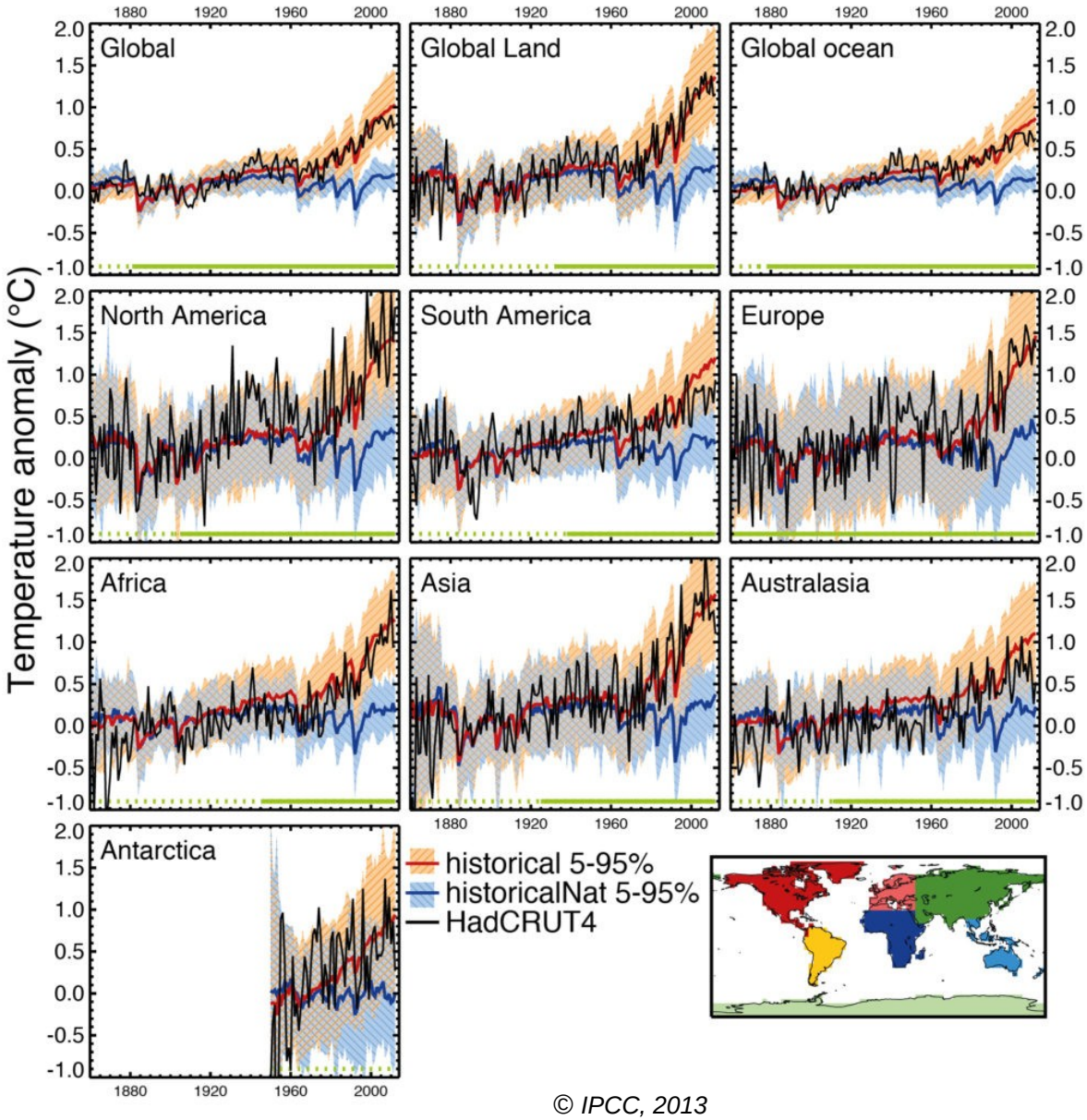
Change in global surface temperature (annual average) as observed and simulated using **human and natural** and **only natural** factors



© IPCC, 2021

- When the effects of anthropogenic and natural external forcings are included in the CMIP6 simulations, the spread of simulated global mean surface temperature (GMST) anomalies spans the observational estimates of températures anomaly in almost every year.
- **This is not the case** for simulations in which only natural forcings are included.

Comparison of observed and simulated change in temperatures



© *IPCC, 2013*

The conclusion of the IPCC (2013) :

it is likely that there has been a substantial **anthropogenic contribution** to surface **temperature increases in every continen**t.

Conclusion

Courtesy NOAA

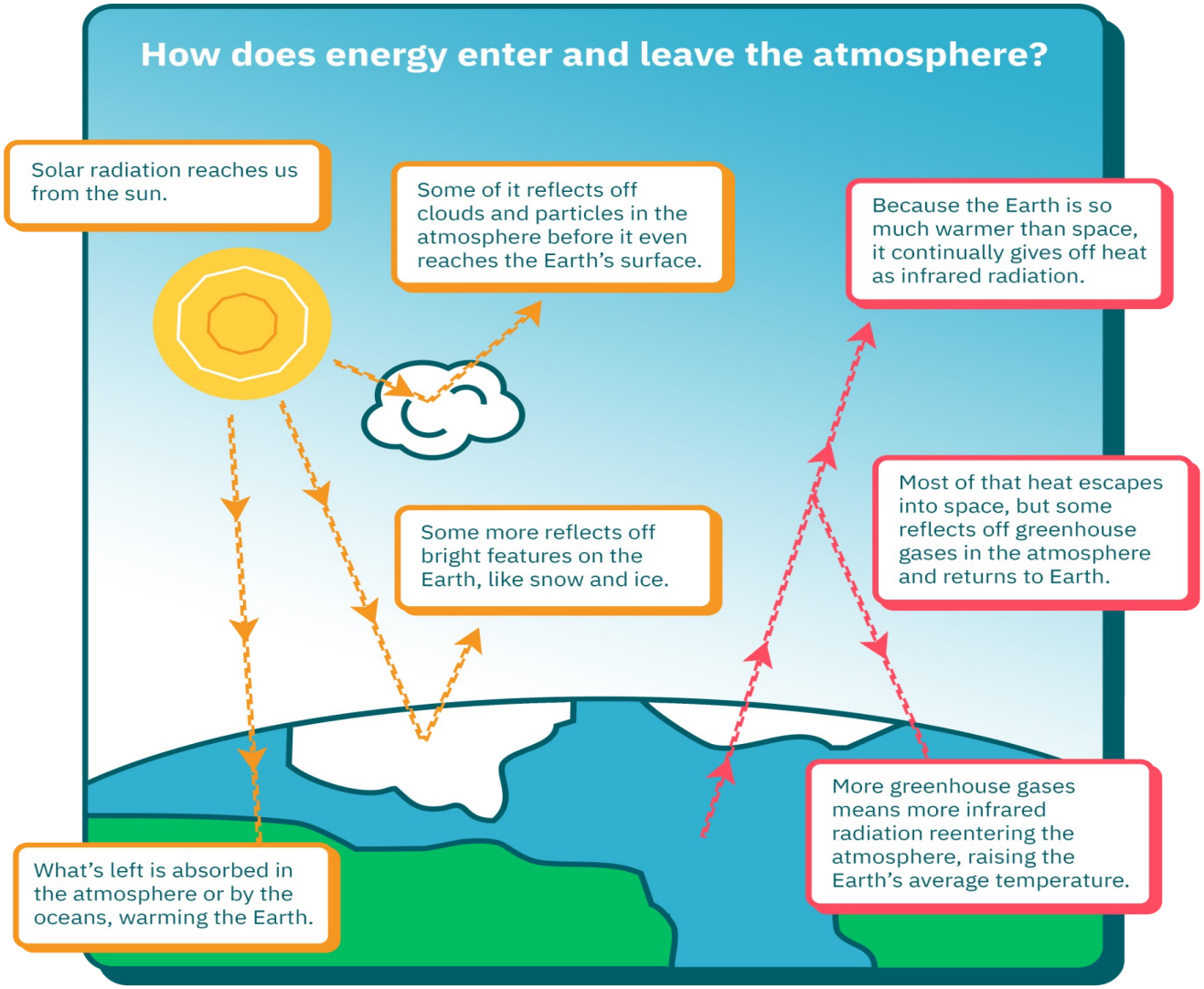
The effects of the anthropogenic forcing have been detected throughout the climate system and are **extremely likely** to have been the dominant cause of the observed warming since the mid-20th century.

Contents

https://www.arch2o.com/paris-smart-city-2050-vincent-callebaut/

REUTERS/Philippe Wojazer

The scenarios



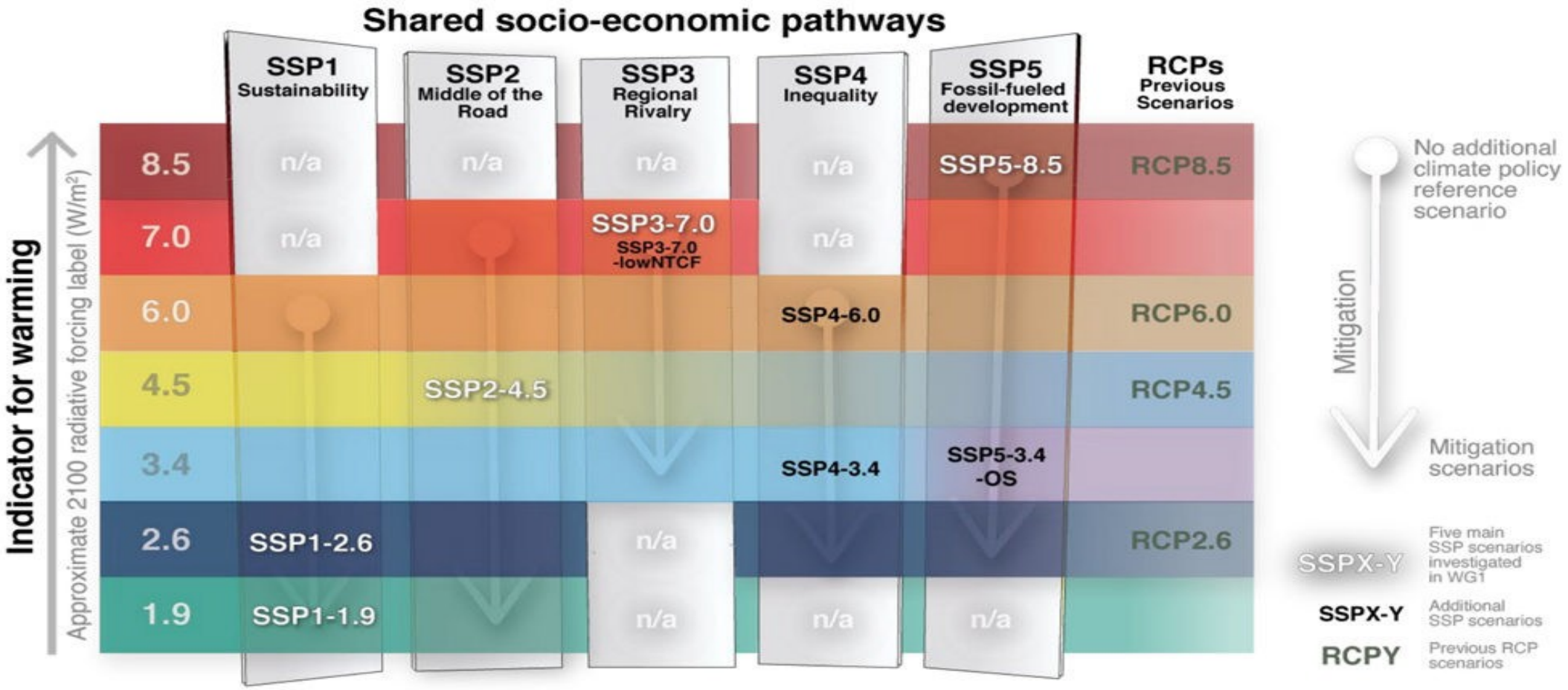
© *serc.carleton.edu*

The scenarios are based on assumptions about the evolution of radiative forcing.

What is radiative forcing ?

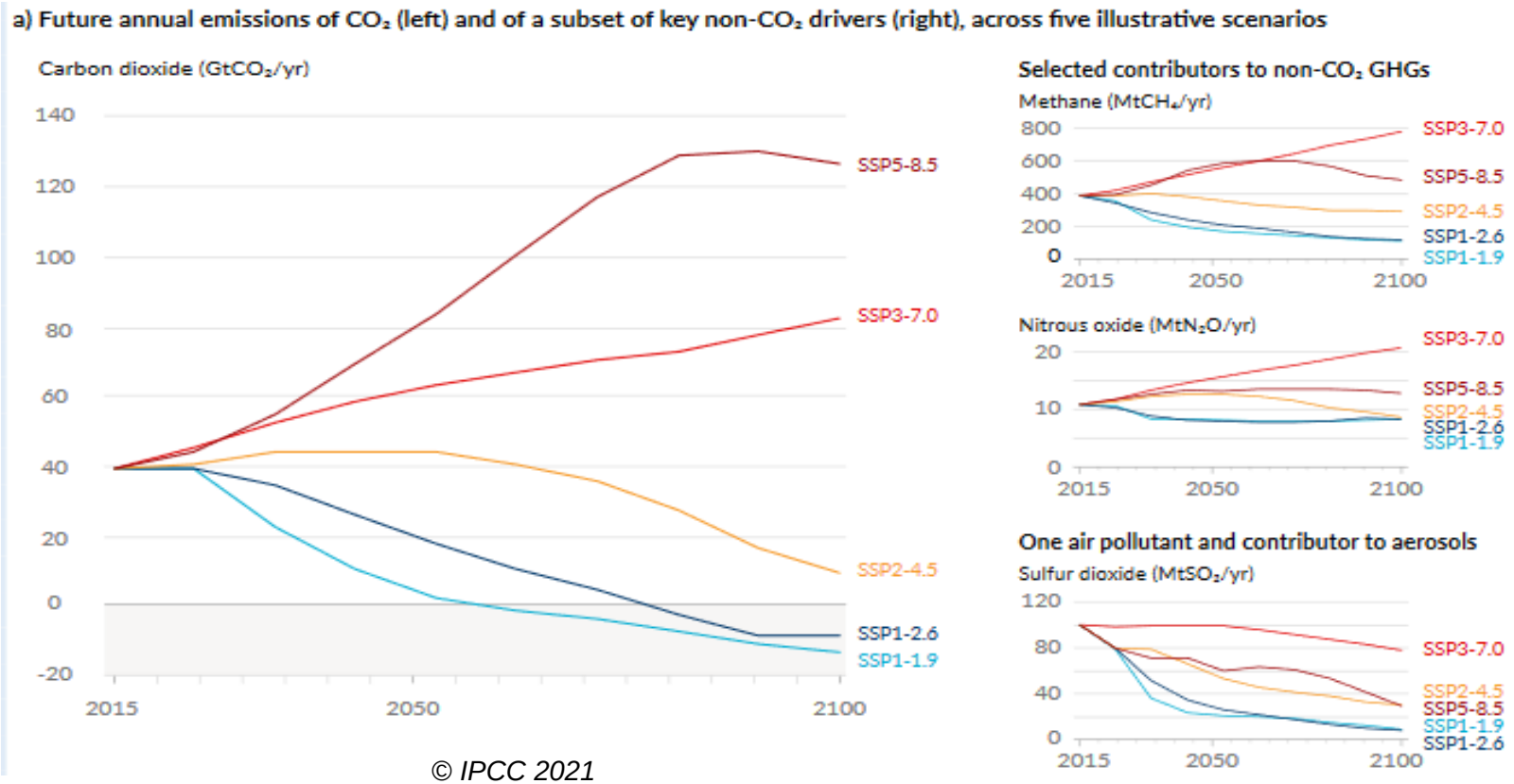
Expressed in W/m^2, a radiative forcing is a change in the radiative balance (the difference between the incoming radiation and outgoing radiation) at the top of the troposphere (between 10 and 16 km of altitude), due to a change in a factors of climate change - such as the concentration of the greenhouse gas.

The SSP scenarios



© IPCC 2021

The SSP scenarios

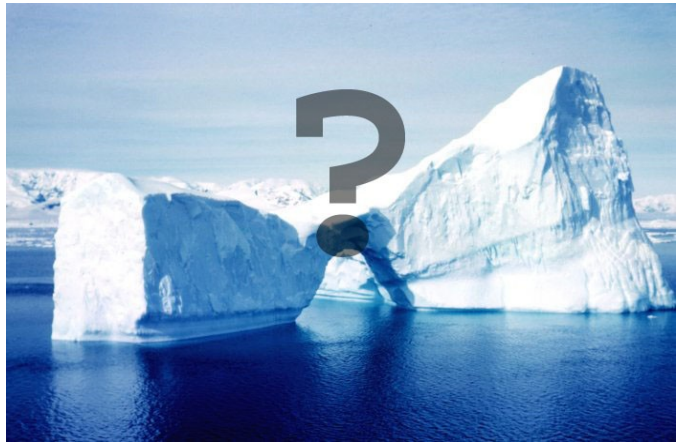


© *IPCC 2021*

The figure shows the annual emissions of CO_2 (left) and of a subset of key non-CO_2 drivers (right), under five illustrative scenarios.

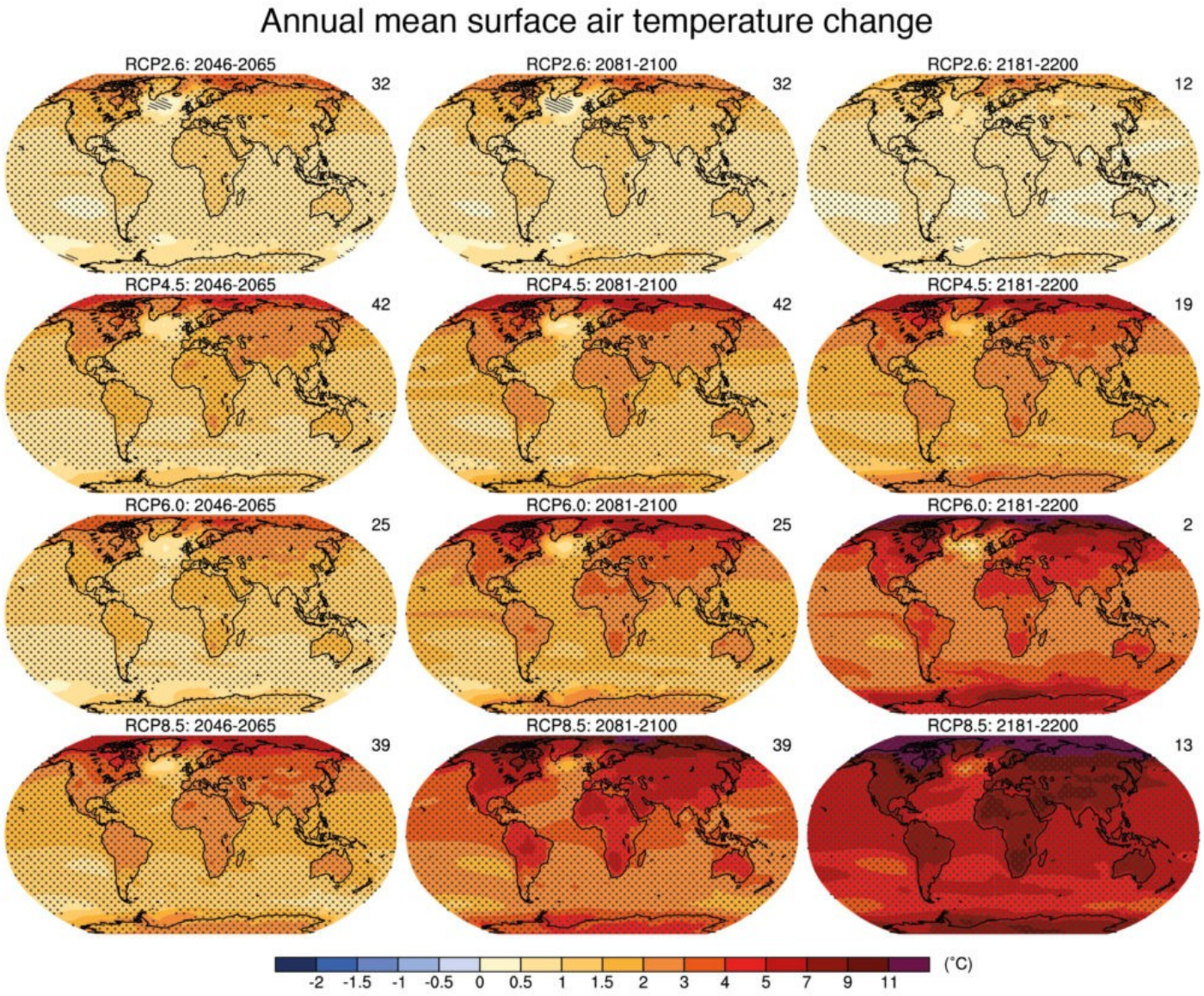
- The **most pessimistic** scenario corresponds to a forcing of 8,5 W/m² in 2100.
- The **most optimistic** scenario corresponds to a forcing of 1,9 W/m² in 2100.

Contents



NOAA Corps Collection, Image ID : Corp1417

The uncertainties of climate projections



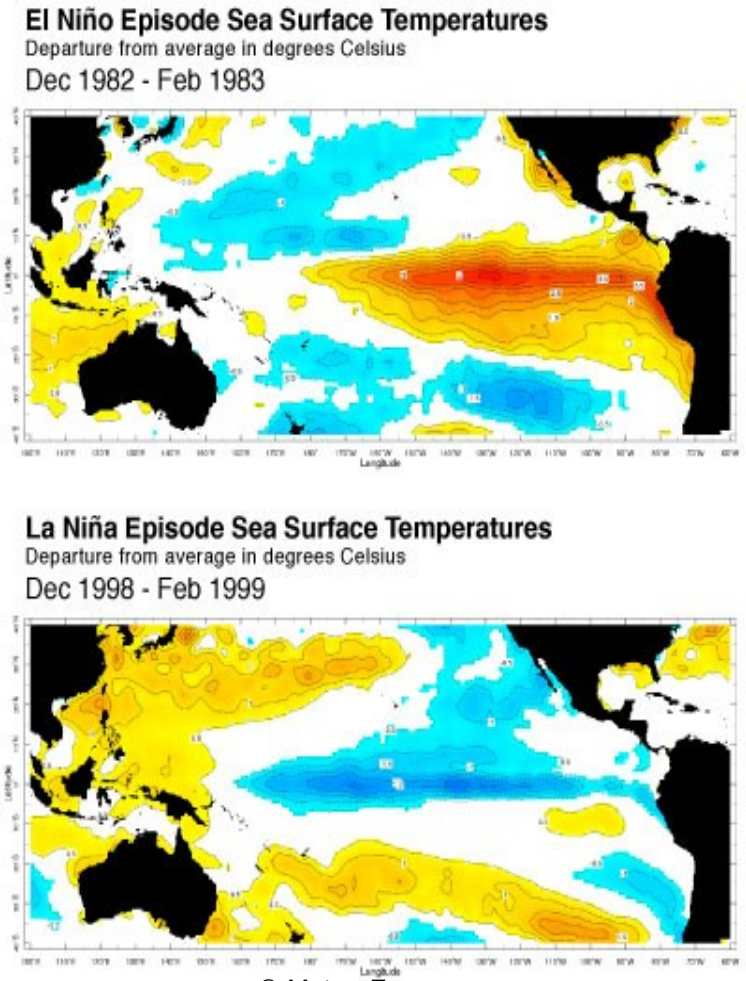
Which climate projection for 2100 is going to happen ?

? ? ?

© IPCC 2013

Internal variability

The **El Niño-Southern Oscillation** (ENSO) is one of the most famous example of internal variabitily.



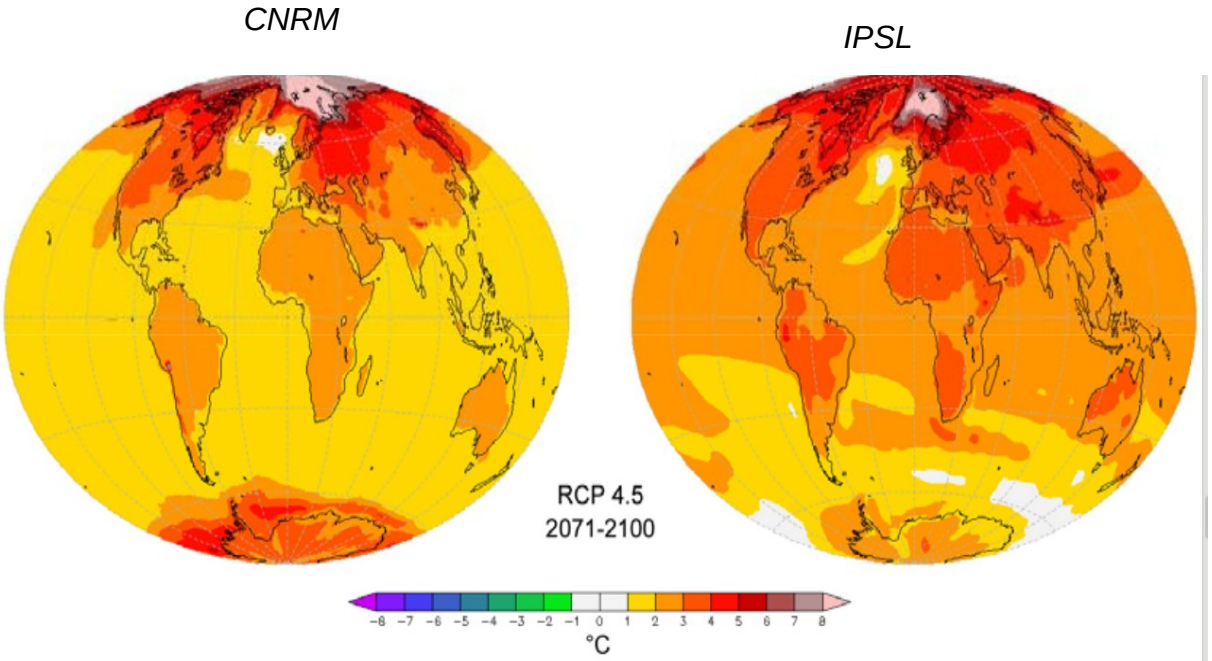
© *Meteo-France*

El Niño is involved in the large variations observed on a decadal scale.

The average period length of the oscillation is five years.

The climate can thus be rather warm or rather cold for a few years.

Uncertainties associated with numerical simulations



© Meteo-France

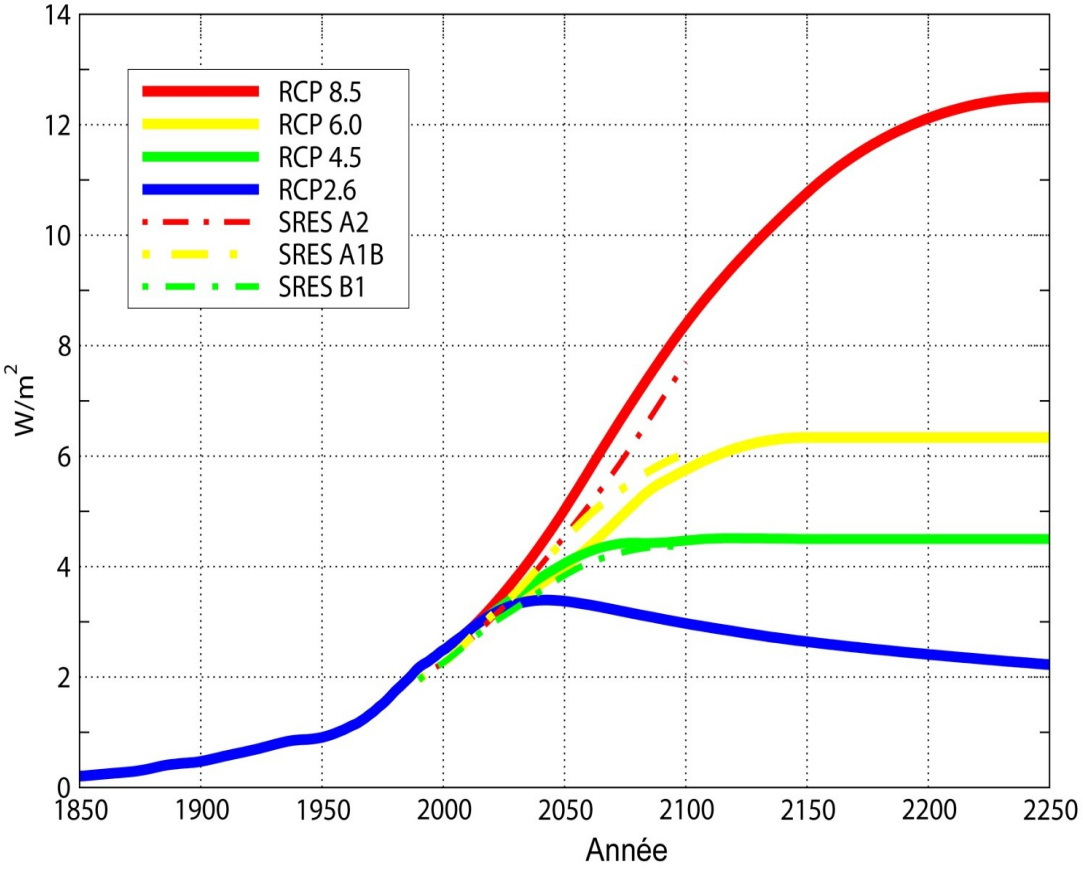
Changes in the Earth's surface temperature for the 2071-2100 period, compared to a reference period (1971-2000),

- *calculated by the CNRM-CERFACS model(left)*
- *and calculated by the IPSL model (right),*

both using the RCP4.5 medium scenario.

The results of numerical simulations can vary significantly from one model to another.

The variability between the different scenarios

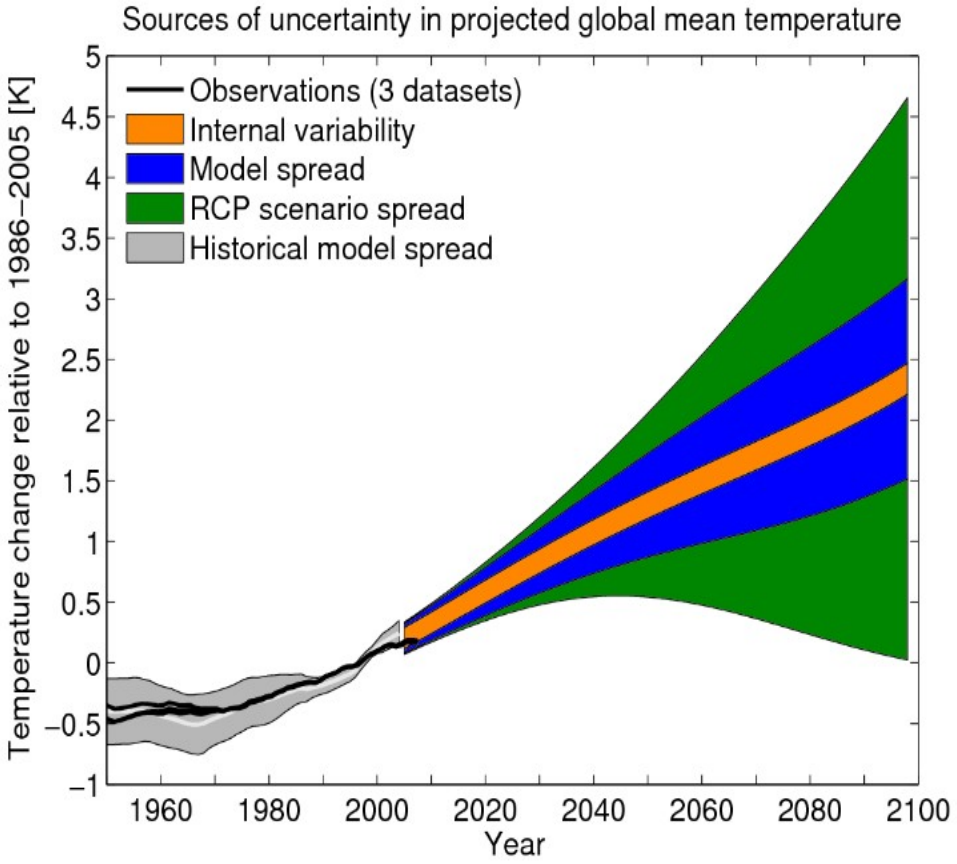


© *Stéphane Senesi (Météo-France)*

RCP scenarios are four reference scenarios of the evolution of **radiative forcing** over the period 2006-2300

A significant part of the uncertainty in the climate projections is related to the choice of the scenario.

Sources of uncertainty in projected global mean temperature



The different sources of uncertainty in global surface temperature projections up to 2100 :

- Internal variability
- Model spread
- RCP scenario spread

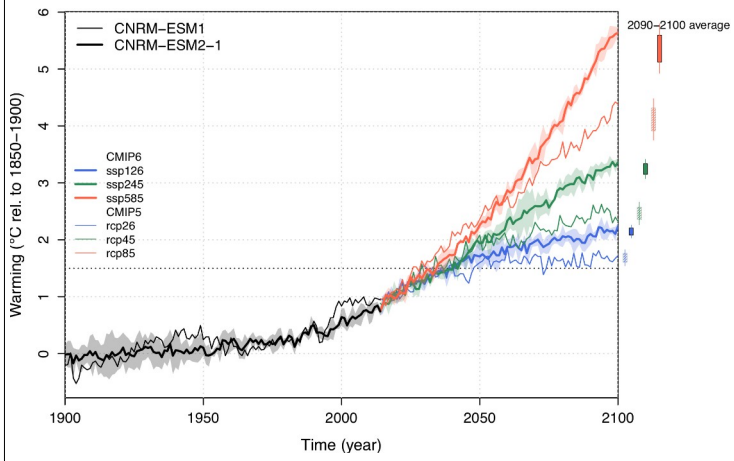
- **Internal variability** is the main source of uncertainty for **near term projections.**
- **RCP scenario spread** is the main source of uncertainty for **long term projections.**

Key points to remember

https://vimeo.com/85531490

© *Samuel Somot*
Meteo-France/CNRM

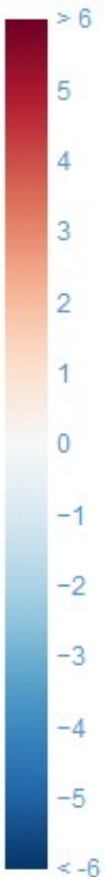
Contents

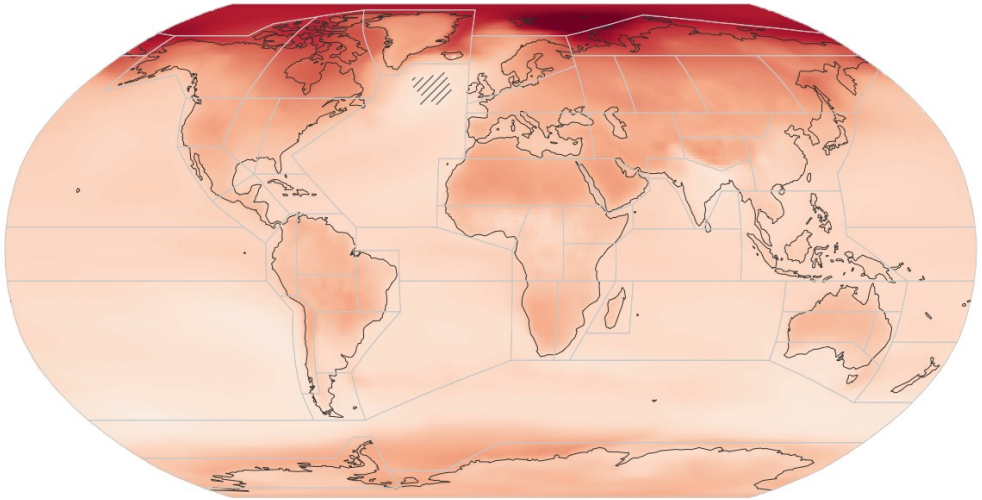


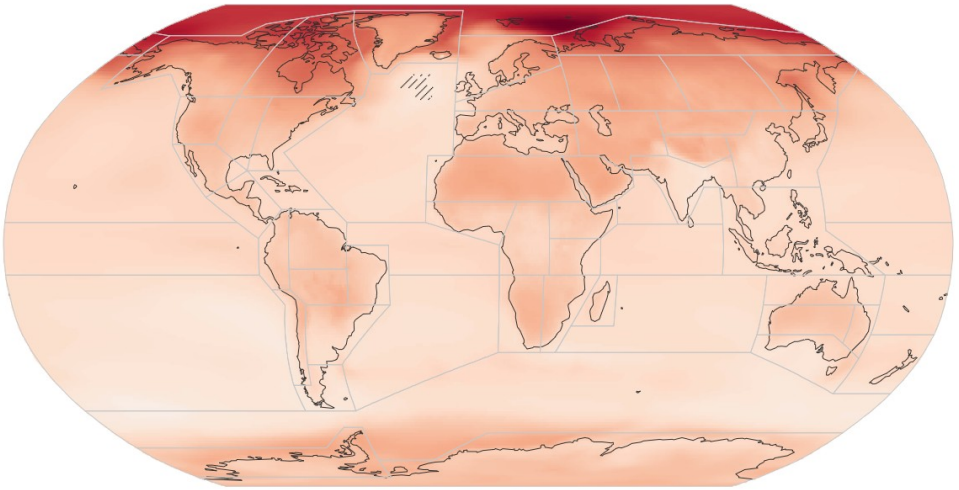
http://www.umr-cnrm.fr/cmip6/spip.php?article10

Global temperature projections

Near term projections (2021-2040), relative to 1850-1900







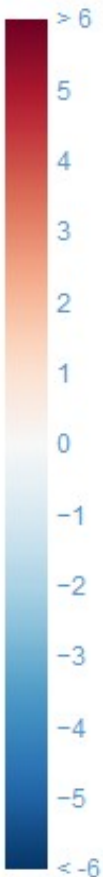
CMIP6 - Mean temperature change °C - Near Term (2021-2040) **SSP5 8.5** (rel. To 1850-1900)
Annual (34 models)

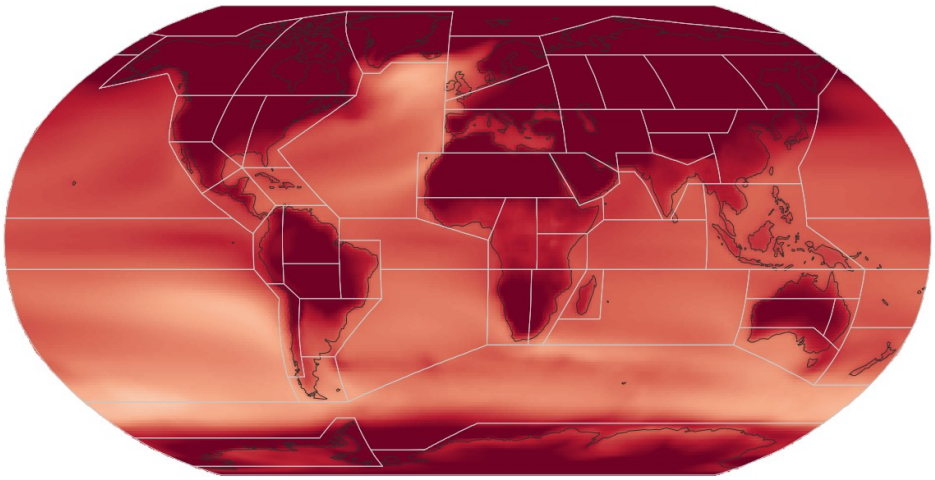
CMIP6 - Mean temperature change °C - Near Term (2021-2040) **SSP1 2.6** (rel. To 1850-1900)
Annual (32 models)

https://interactive-atlas.ipcc.ch/

Global temperature projections

Long term projections (2081-2100), relative to 1850-1900





CMIP6 - Mean temperature change °C - Long Term (2081-2100) **SSP5 8.5** (rel. To 1850-1900)
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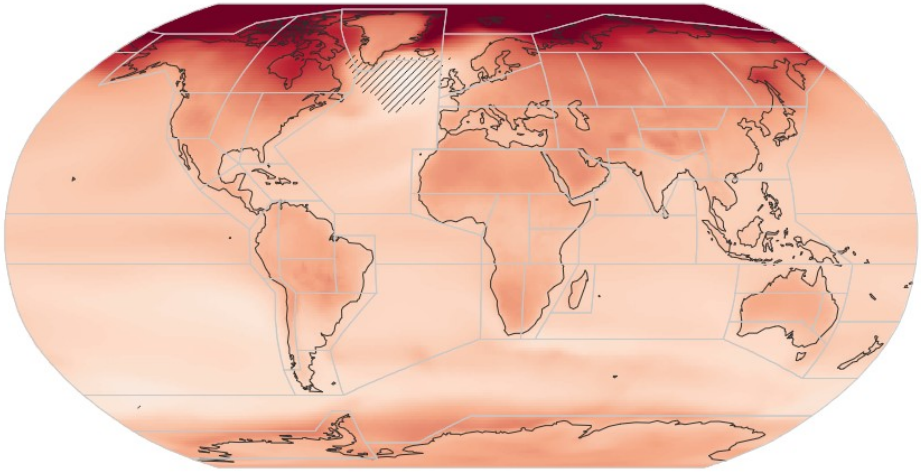
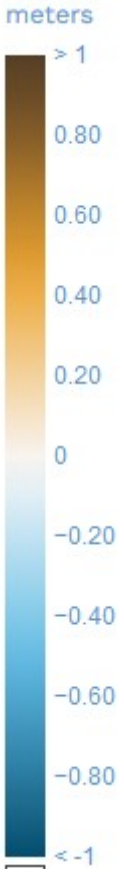


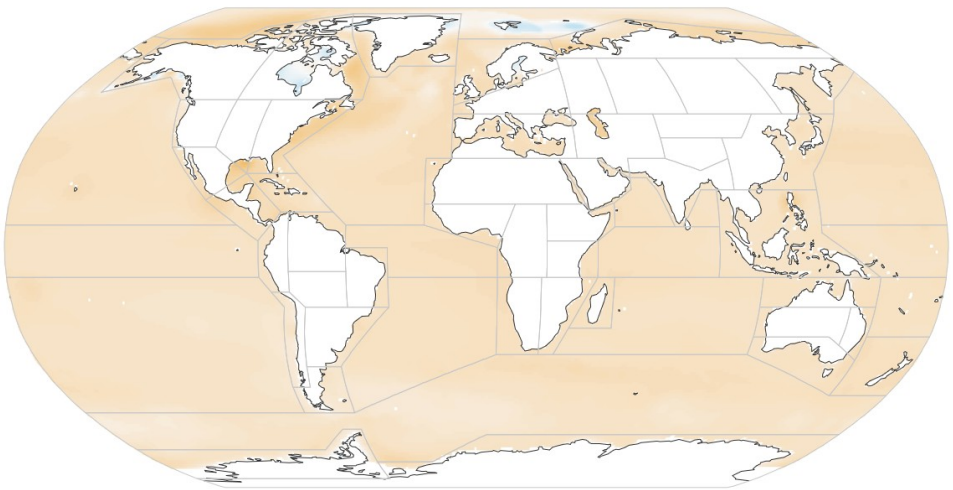
CMIP6 - Mean temperature change °C - Long Term (2081-2100) **SSP1 2.6** (rel. To 1850-1900)
Annual (32 models)

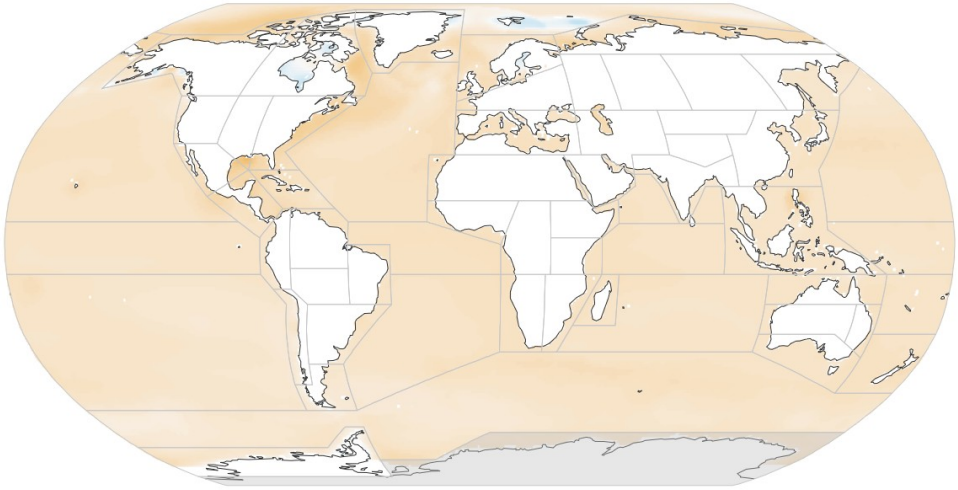
https://interactive-atlas.ipcc.ch/

Global sea level projections

Near term projections (2081-2100), relative to 1995-2014







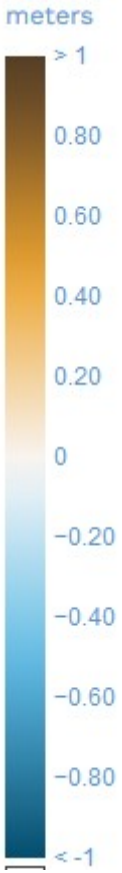
CMIP6 - Sea level rise (SLR)
Near Term (2021-2040)
SSP5 8.5 (rel. to 1995-2014) - Annual

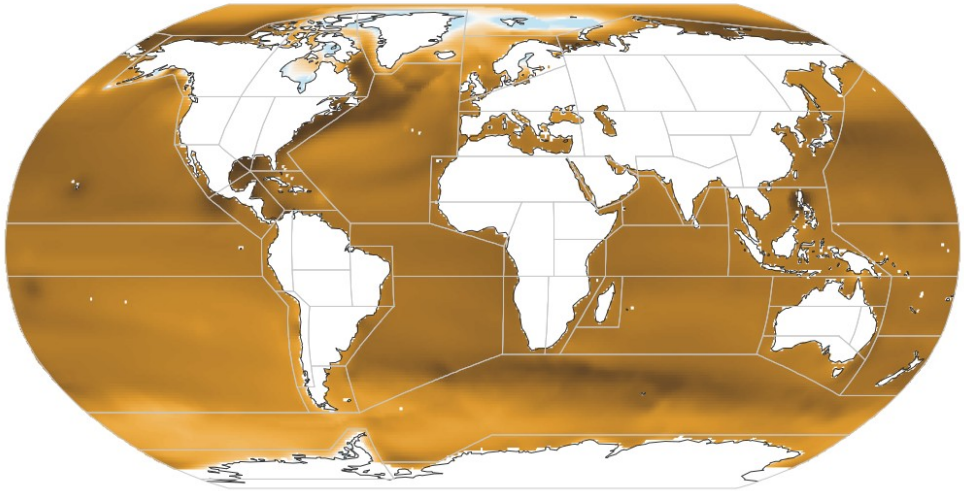
CMIP6 - Sea level rise (SLR)
Near Term (2021-2040)
SSP1 2.6 (rel. to 1995-2014) - Annual

https://interactive-atlas.ipcc.ch/

Global sea level projections

Long term projections (2081-2100), relative to 1995-2014





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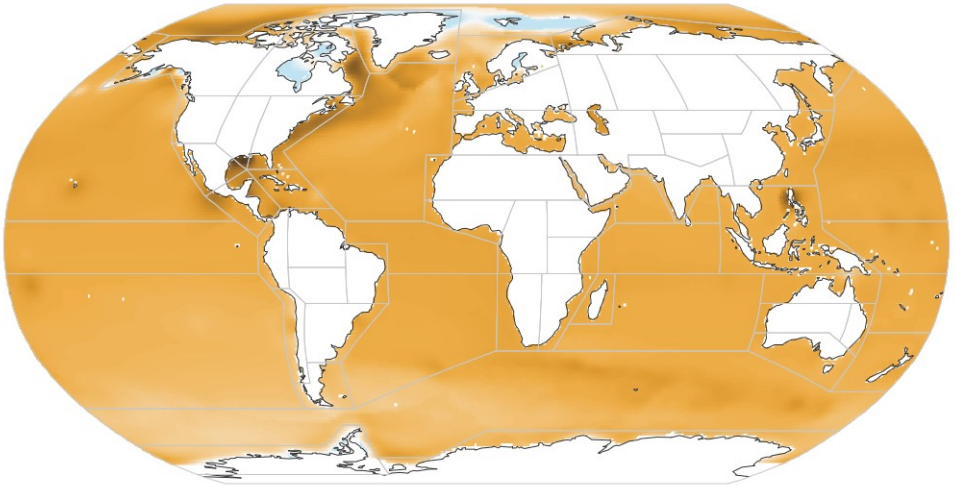
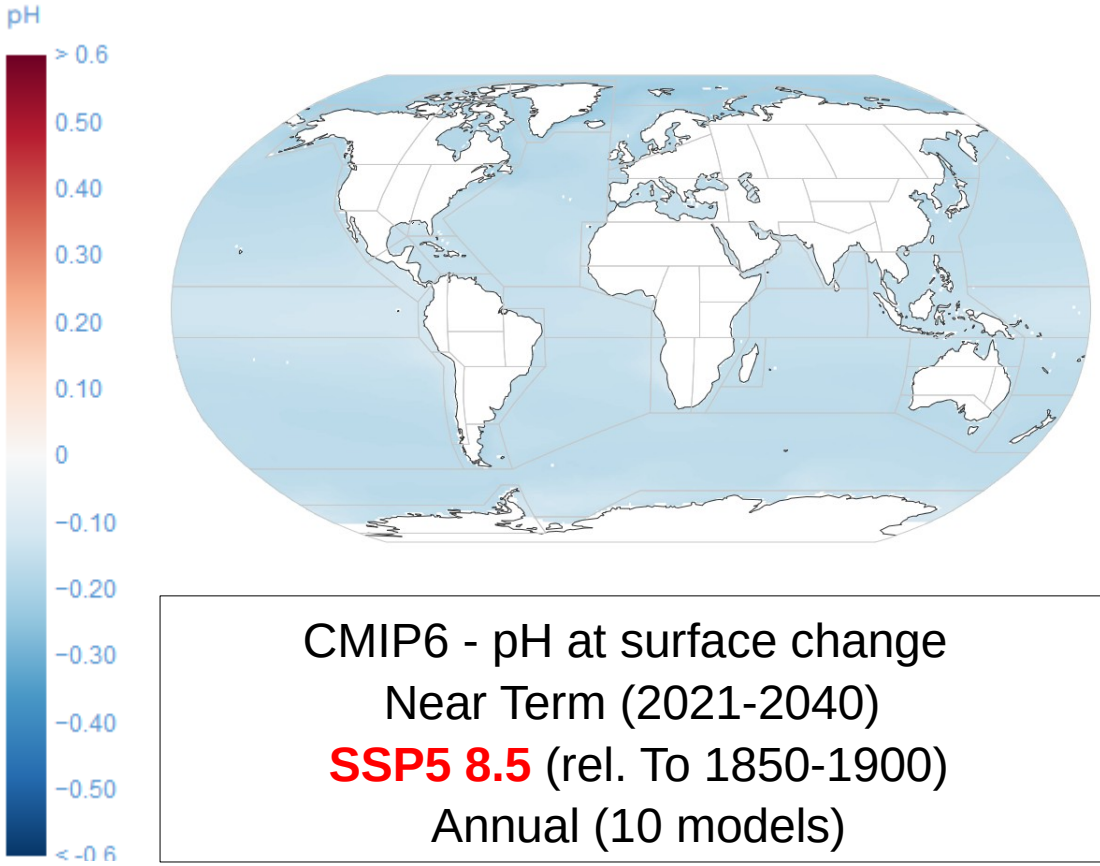


CMIP6 - Sea level rise (SLR)
Long Term (2081-2100)
SSP1 2.6 (rel. to 1995-2014) - Annual

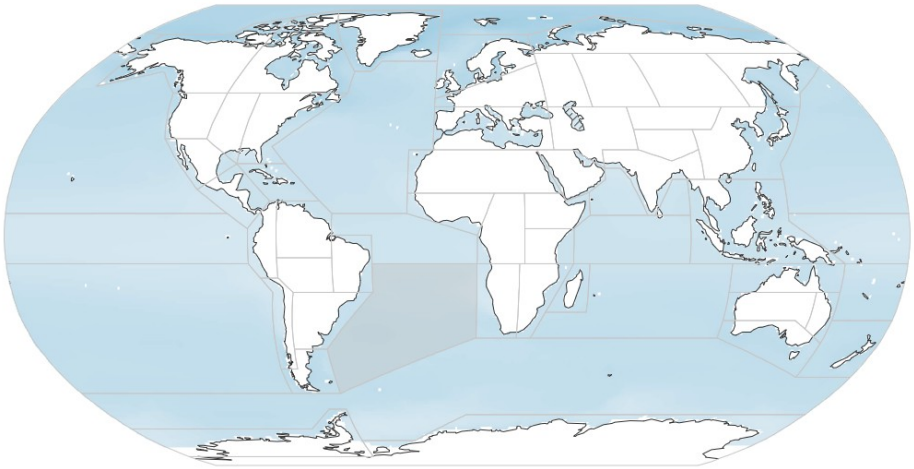
https://interactive-atlas.ipcc.ch/

pH change projections

Near term projections (2021-2040), relative to 1850-1900



CMIP6 - pH at surface change
Near Term (2021-2040)
SSP5 8.5 (rel. To 1850-1900)
Annual (10 models)

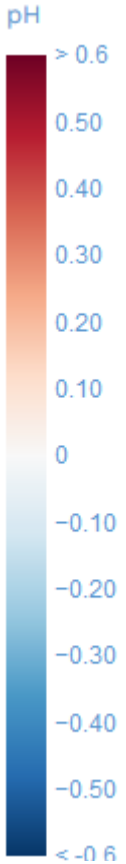


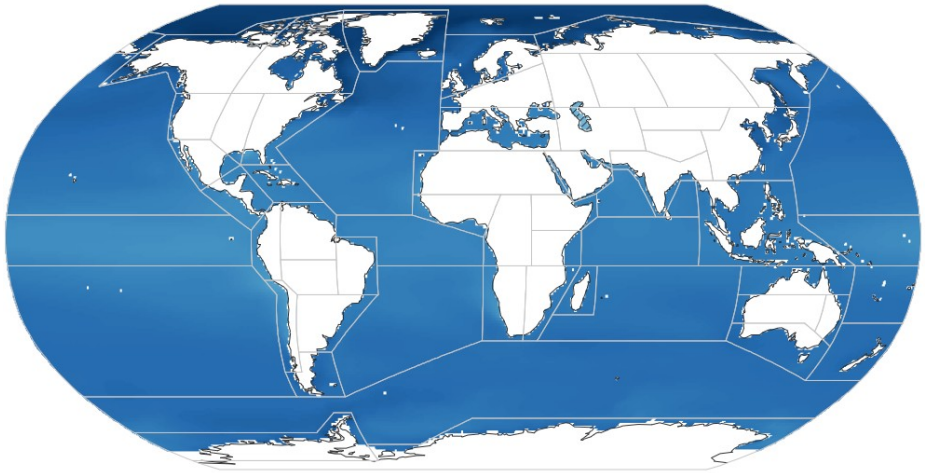
CMIP6 - pH at surface change
Near Term (2021-2040)
SSP1 2.6 (rel. To 1850-1900)
Annual (9 models)

https://interactive-atlas.ipcc.ch/

pH change projections

Long term projections (2081-2100), relative to 1850-1900





CMIP6 - pH at surface change
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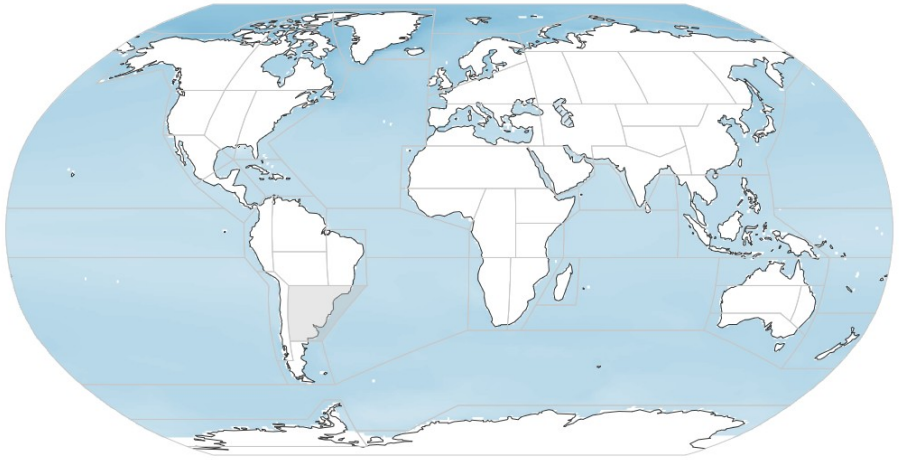


CMIP6 - pH at surface change
Long Term (2081-2100)
SSP1 2.6 (rel. To 1850-1900)
Annual (9 models)

https://interactive-atlas.ipcc.ch/

Contents

Climate services

Several definitions, one we like (from Allenvi)

Climate services refer to a set of information and services which allow :

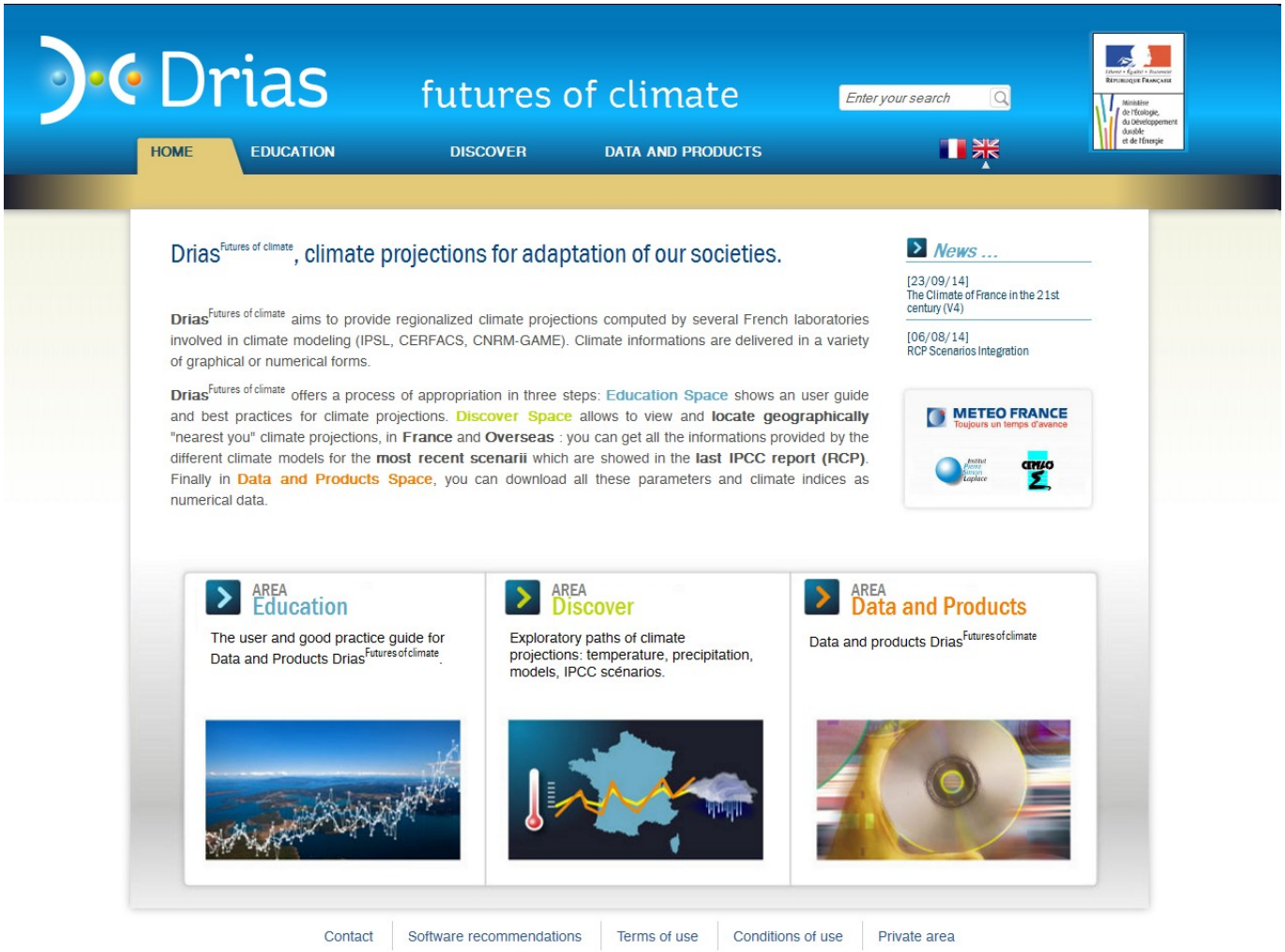
- to assess and qualify **passed, present and future climate**,
- to estimate the **impacts** of climate change on economic activity, society and the environment,
- to provide some input data to start mitigation and adaptation actions.

ClimatHD : general public information

- Free access : http://www.meteofrance.fr/climat-passe-et-futur/climathd
- ClimatHD, *climat d'hier et de demain* (climate 'high definition') allows a easy display, accessible for all users, and is a state of art for knowledge of climate change over France. Available only in french.
- An integreted approach for passed and future climate at national and regional (administrative) scale :
  - temperature (minimum, maximum, mean)
  - precipitation
  - different events :hot days, frost days, heat waves, cold waves, heavy rainfall
  - impacts : soil wetness, drought, snow cover.

DRIAS portal

An on-line climate service : http://drias-climat.fr



DRIAS portal

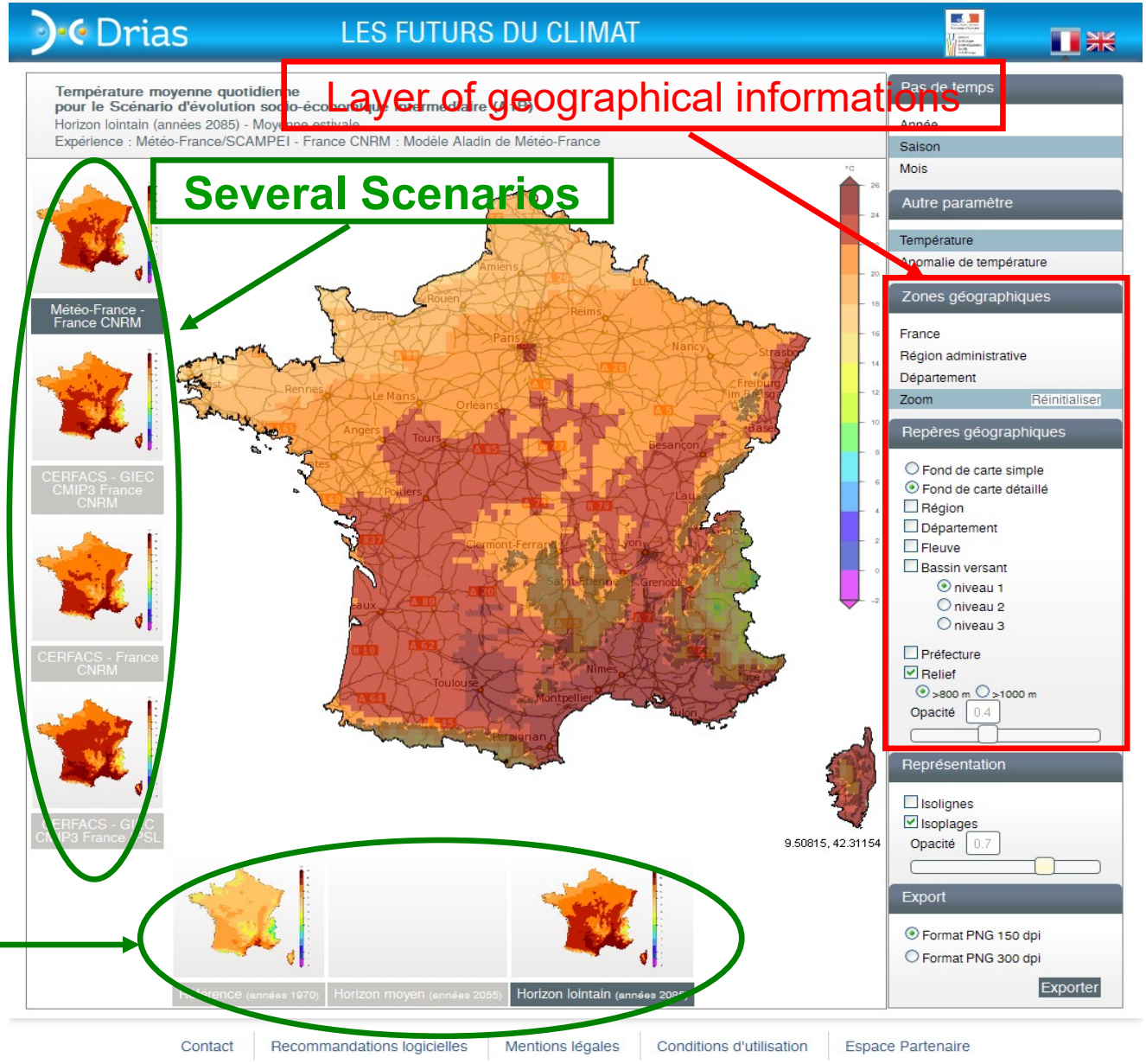
Drias: **Providing Access to French Regional Climate data and products for Impact and Adaptation of our Society and environment**

- One of the first french achievement as climate service.
- An ‘expert’ climate service
  - for a scientific public
  - content regionalised climate projections : Allow characterisation of climate change and its impacts (12 km resolution vs ~100 km for global projections)
- An open and **free service**
  - http://www.drias-climat.fr

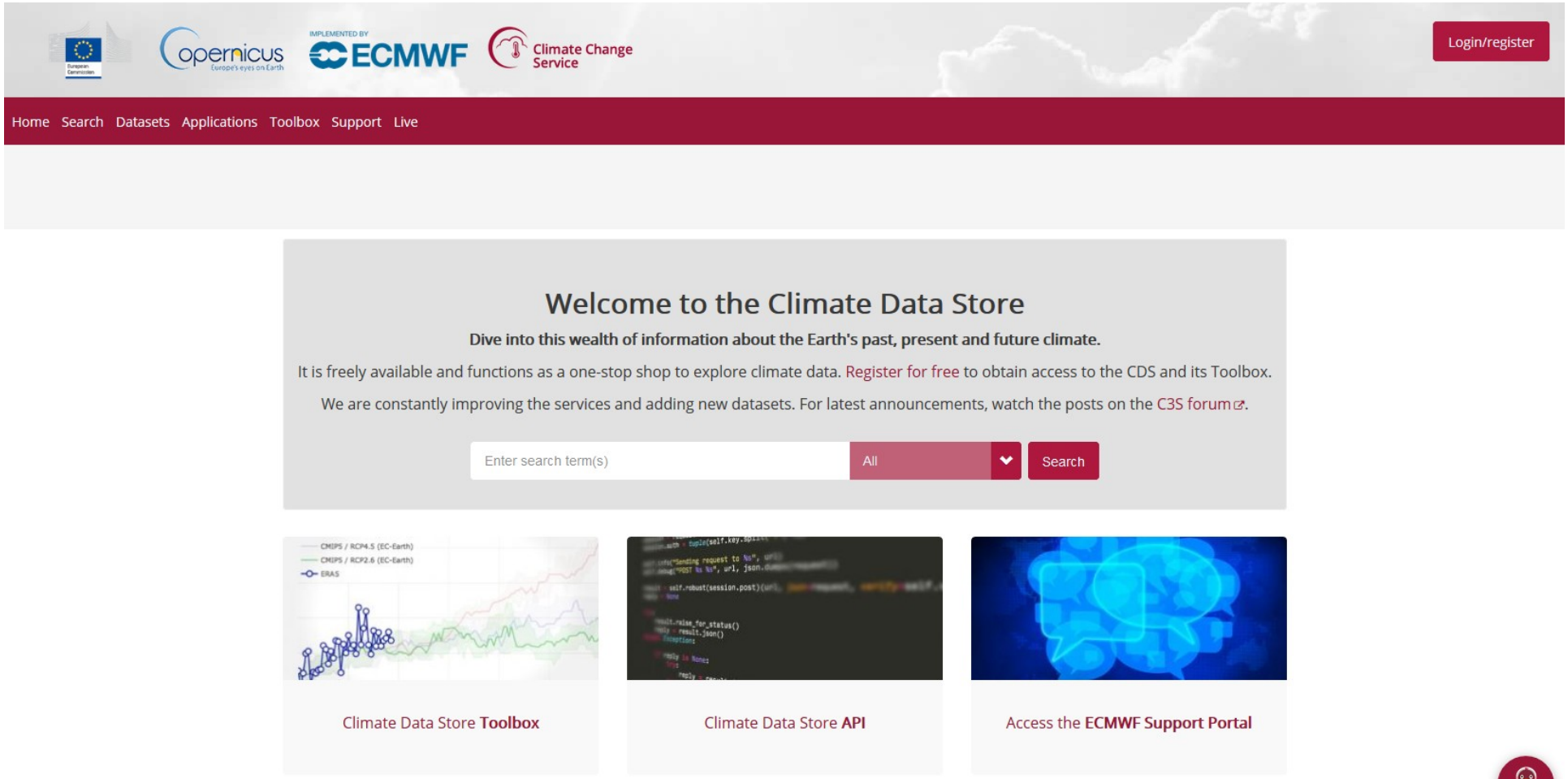
DRIAS portal

- Several hypothesis of emission, several models, allowing a first assessment of uncertainty

- Geographical tools
  - Zoom (up to the level of a French department)
  - Geographical layers (i.e. relief, cities, administrative areas, watershed…



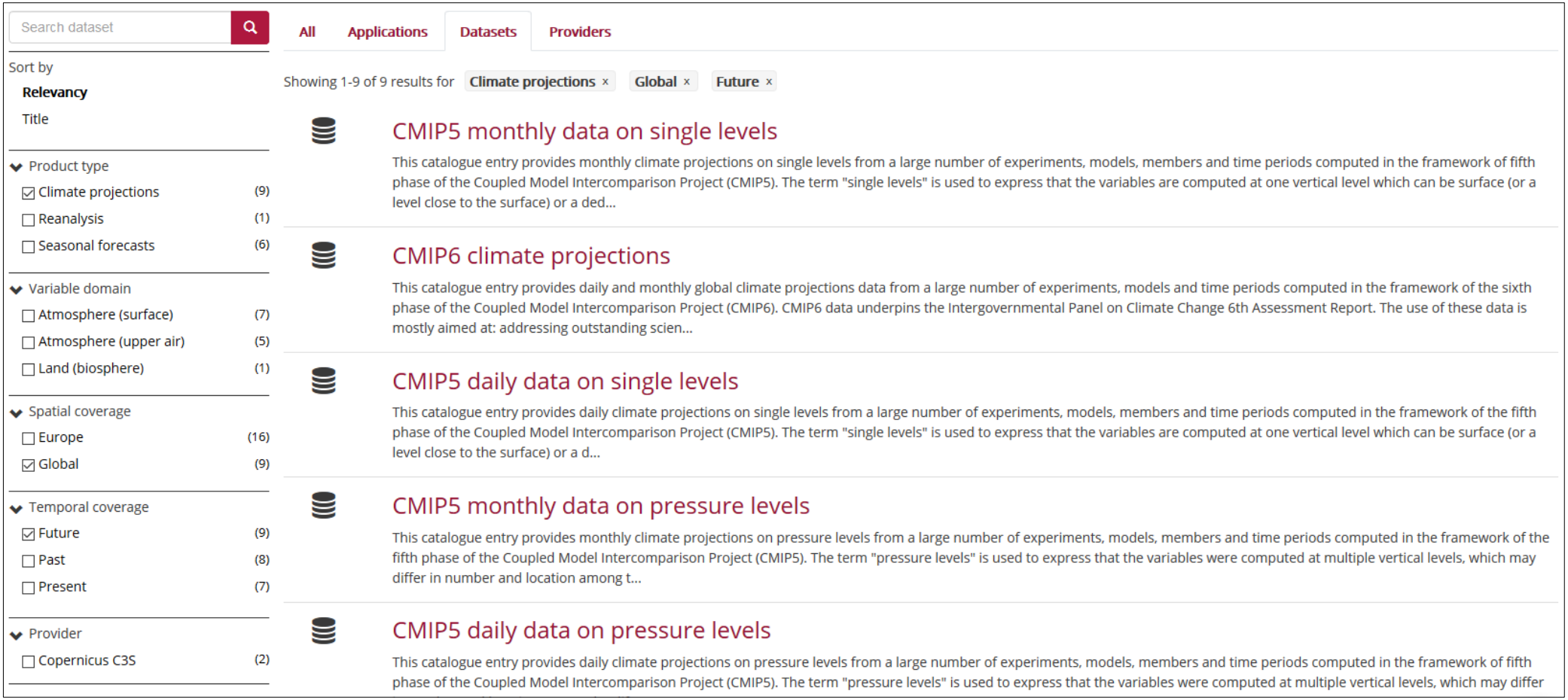
Copernicus climate data store



A portal with a very high amount of data (climate and other), free acces with HMI or API.

Copernicus climate data store

A comprehensive climate service at global and european scale, free of use



Appendix

http://en.people.cn/n3/2016/0122/c90000-9008125-10.html

Extreme events
in the context of
climate change

© Nasa/Earth Observations Laboratory

© Wikipedia

https://www.belfercenter.org/event/extreme-realities-link-between-severe-weather-climate-change-and-our-national-security

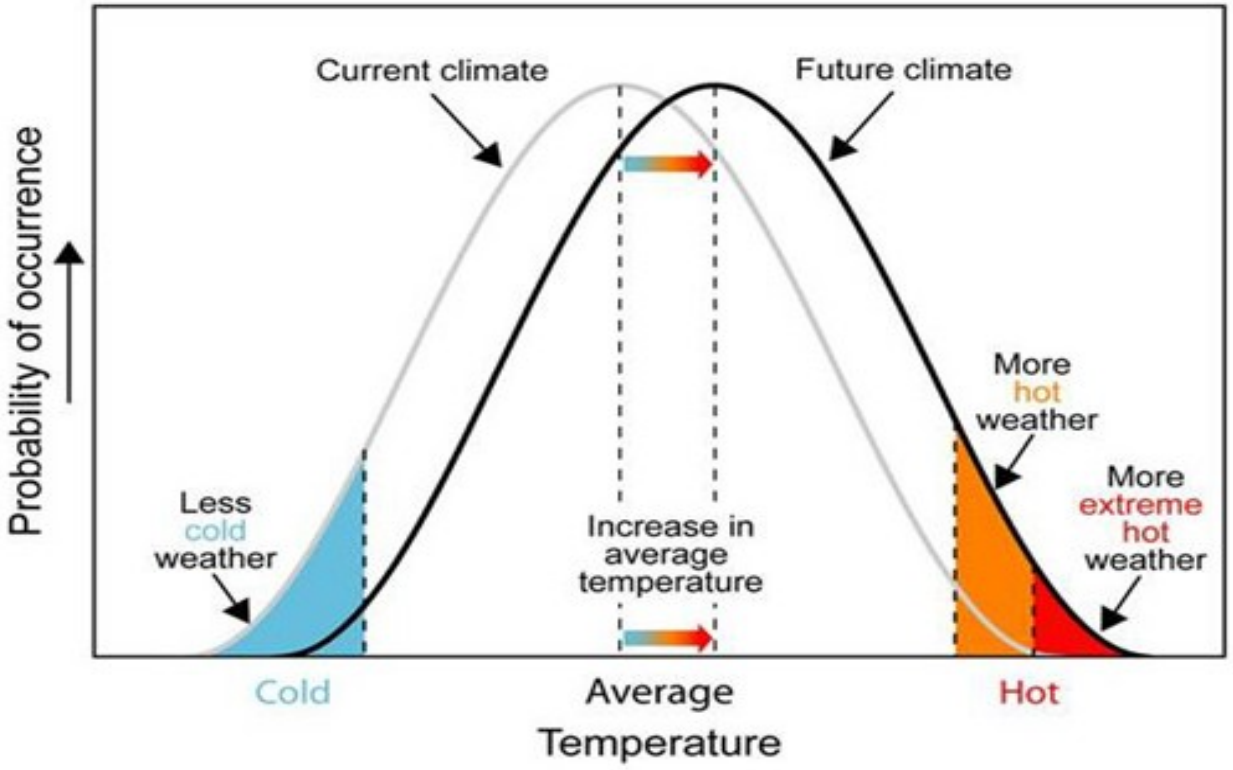
Weather Extremes and Climate Change

© Nasa/Earth Observations Laboratory

Reference article : CATTIAUX Julien, CHAUVIN Fabrice, DOUVILLE Hervé, RIBES Aurélien (2021), Weather Extremes and Climate Change, Encyclopedia of the Environment

Whether extreme : a definition

Temperature distribution : the effect of a simple shift



© Cattiaux

Climate events are classified as extreme when a weather or climate variable takes a value **above** (or **below**) a threshold close to the upper (or lower) limit of the range of observed values for that variable.

Extreme weather events: what are we talking about?

Heat waves

© *Wikipedia*

In France, heat waves are defined as periods of at least **five consecutive days** with a maximum temperature **5°C** above the 1976-2005 normal.

Extreme weather events: what are we talking about?

Cold waves

© Archives Sud ouest

A **cold weather episode** is characterised by its persistence, intensity and geographical extent.

For at least two days, temperatures reach values significantly lower (**by 5°C**) than a reference value for the region.

Extreme weather events: what are we talking about?

Drought

© *AFP*

- There are several definitions (meteorological, agricultural, hydrological, geotechnical) of a drought.
- We are interested in **meteorological droughts**.
- A meteorological drought corresponds to a **prolonged deficit of precipitation**.

Extreme weather events: what are we talking about?

Extreme rainfalls

© AFP

Extreme rainfalls are characterised by the intake of a large quantity of water over a short period of time (from 1 hour to one day).

This amount can equal the amount usually received in a month or even several months !

Extreme weather events: what are we talking about?

Extratropical cyclones

METEO FRANCE

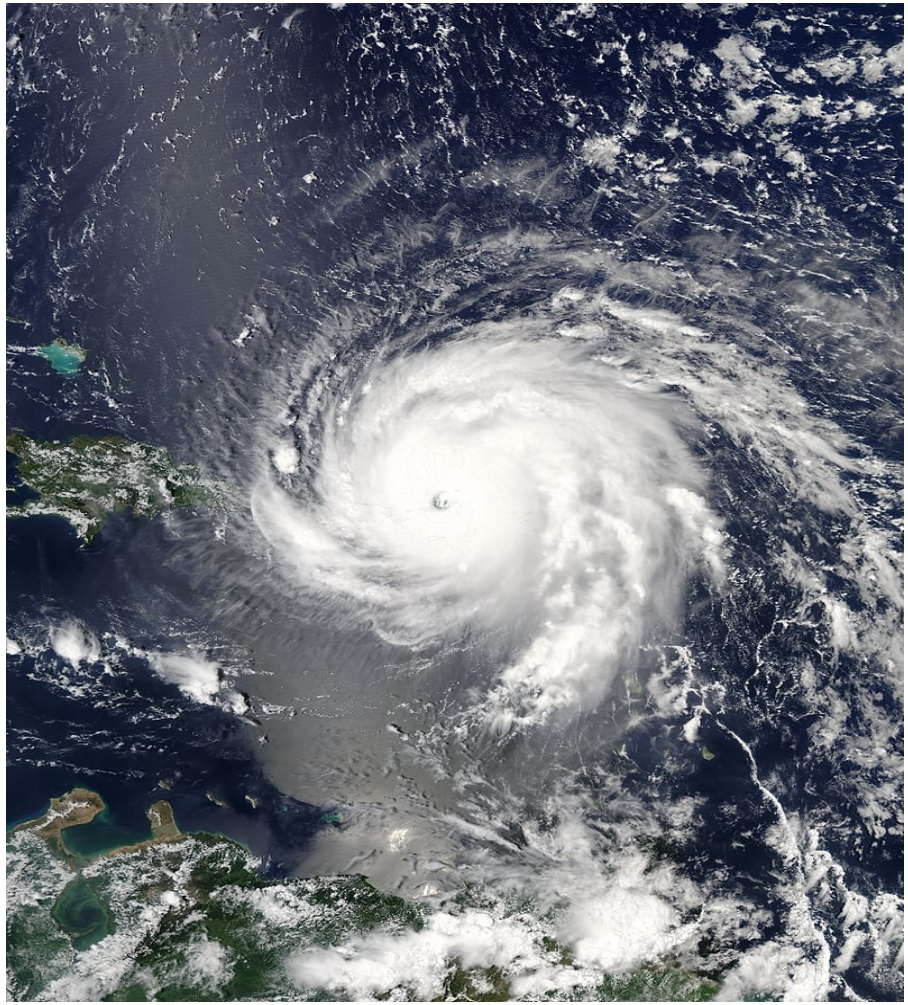
When the wind reaches **100 km/h inland** and **120 km/h** (or even 130 km/h) **on the coast**, the low-pressure system that generates these winds is called a "storm".

This term refers to both a large area of strong winds and the low-pressure system that generates them.

© *AFP*

Extreme weather events: what are we talking about?

Tropical cyclones

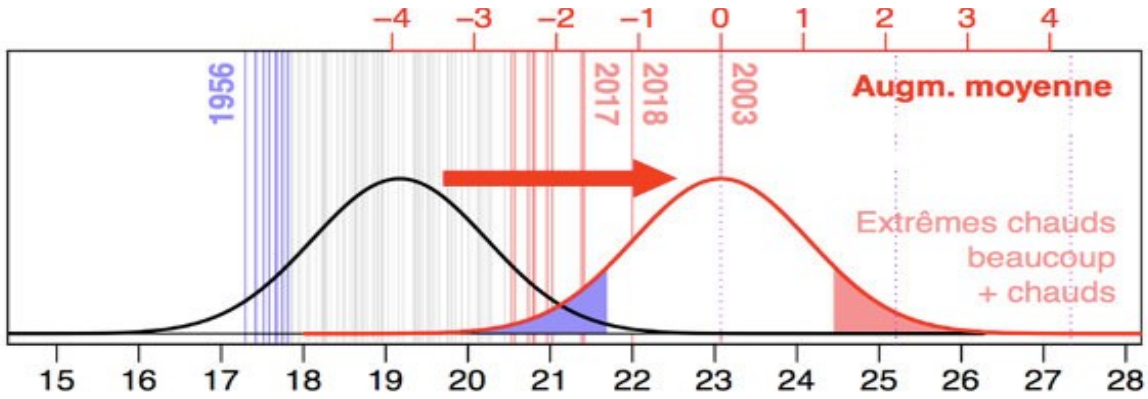


© *Météo-France*

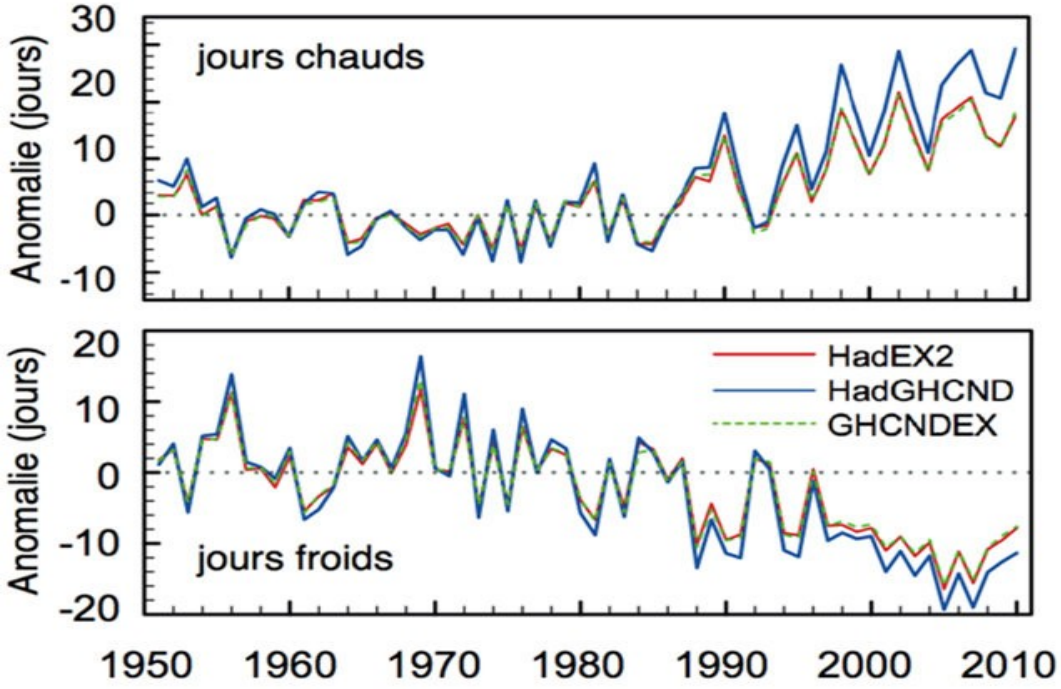
A "tropical storm" is a depression observed in tropical or subtropical latitudes, with average winds between **62 and 117 km/h**.

Above these values, the depression becomes a "tropical cyclone".

Extreme temperature (observations)



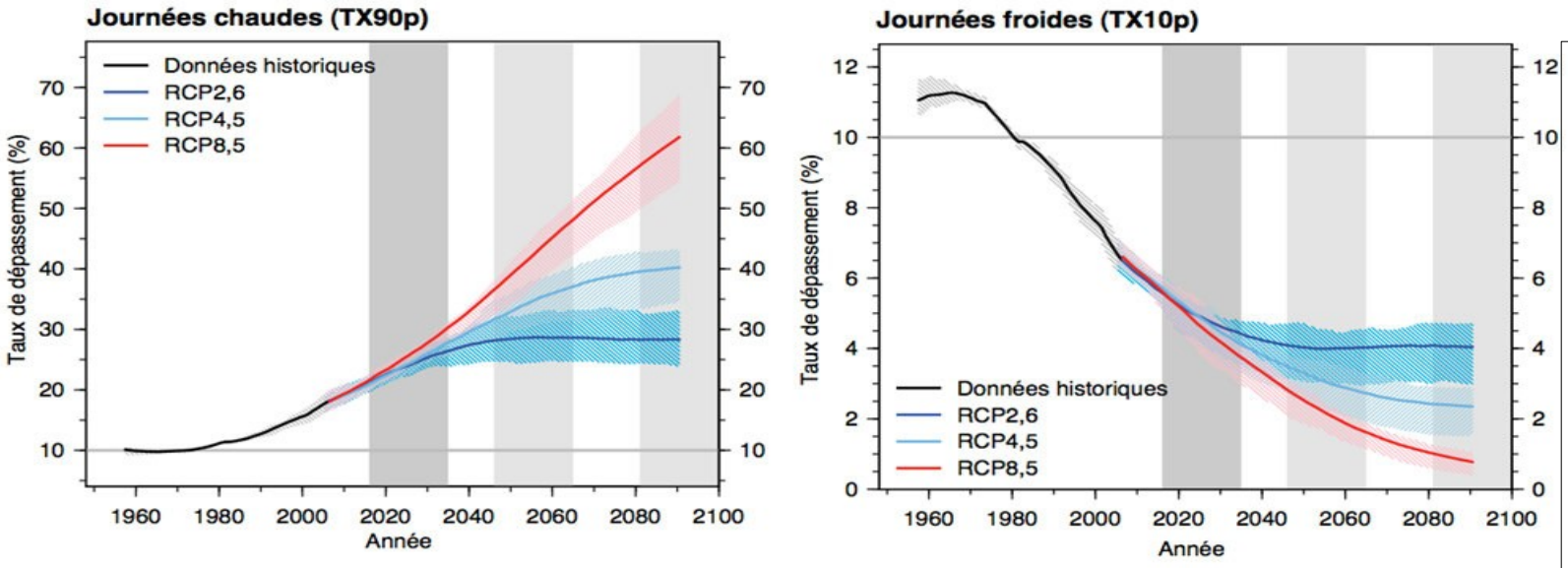
© *Cattiaux*



© *IPCC 2013*

Observed annual frequency of **unusually warm** (top) and **unusually cold** (bottom) days, on average over the globe (continents only).

Extreme temperature (simulations)



© IPCC 2013

Numerical projections of the annual frequency of

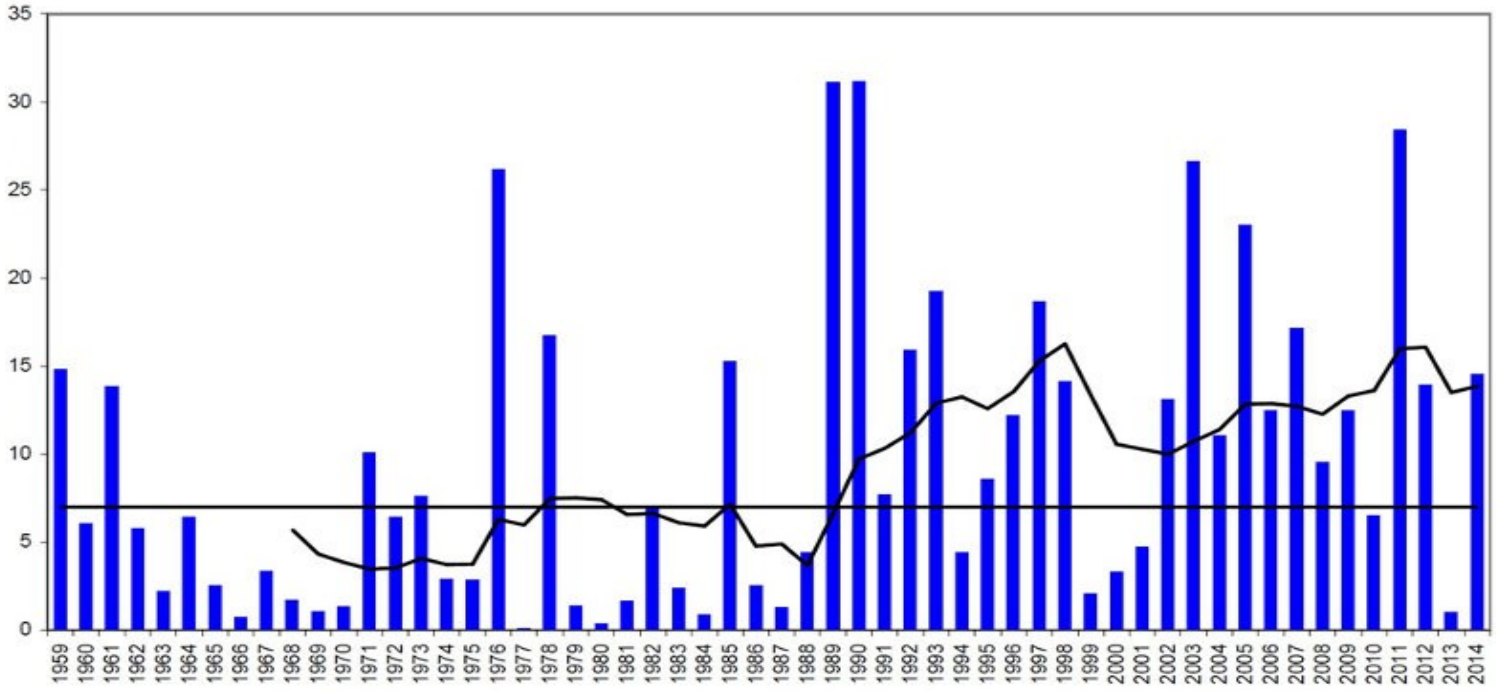
- **unusually warm days** (left),
- **unusually cold days** (right),

according to three scenarios.

According to climate projections:

- **hot extremes** will become increasingly frequent and intense,
- **cold extremes** will become increasingly rare and less marked.

Hydrological extremes

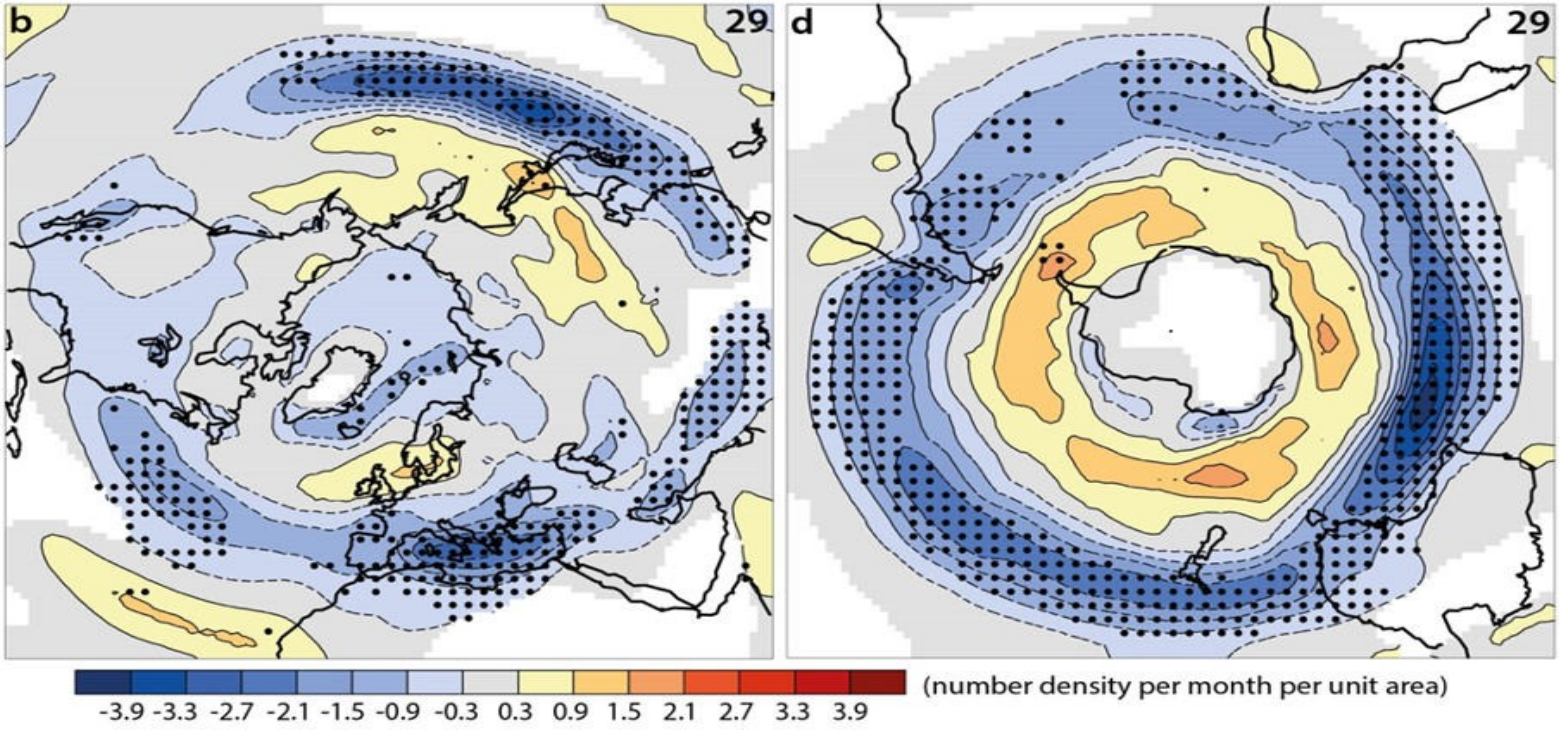


© Météo France

Percentage of the french metropolitan territory affected by agricultural drought each year.

The criterion used here is the first decile of soil moisture over the period 1961-1990, based on re-analysis data.

Extra-tropical storms



© Gwendal Rivière, LMD

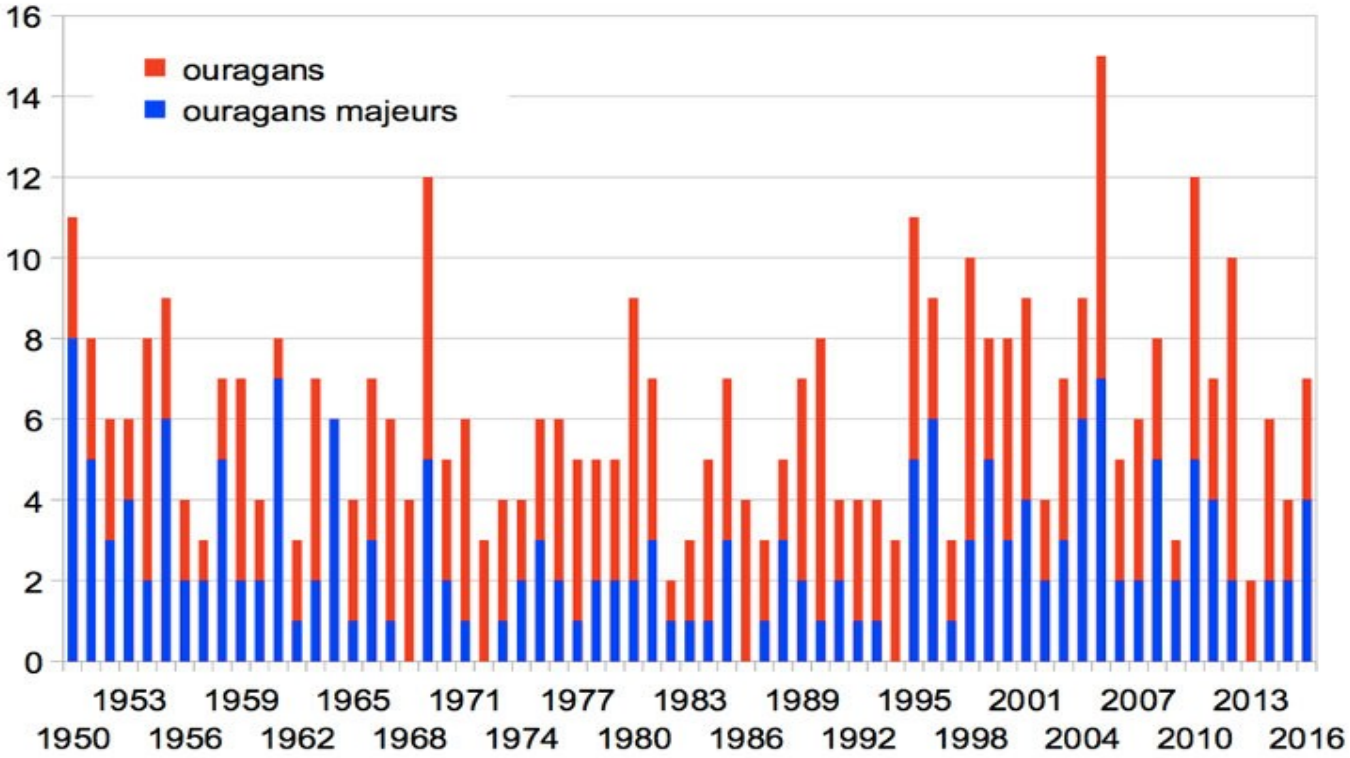
Projections of the change in frequency of winter storms

- in the northern hemisphere (left),

and southern hemisphere (right),

between the 1986-2005 climate, and the future (2081-2100) climate, under the RCP8.5 scenario.

Tropical Cyclones

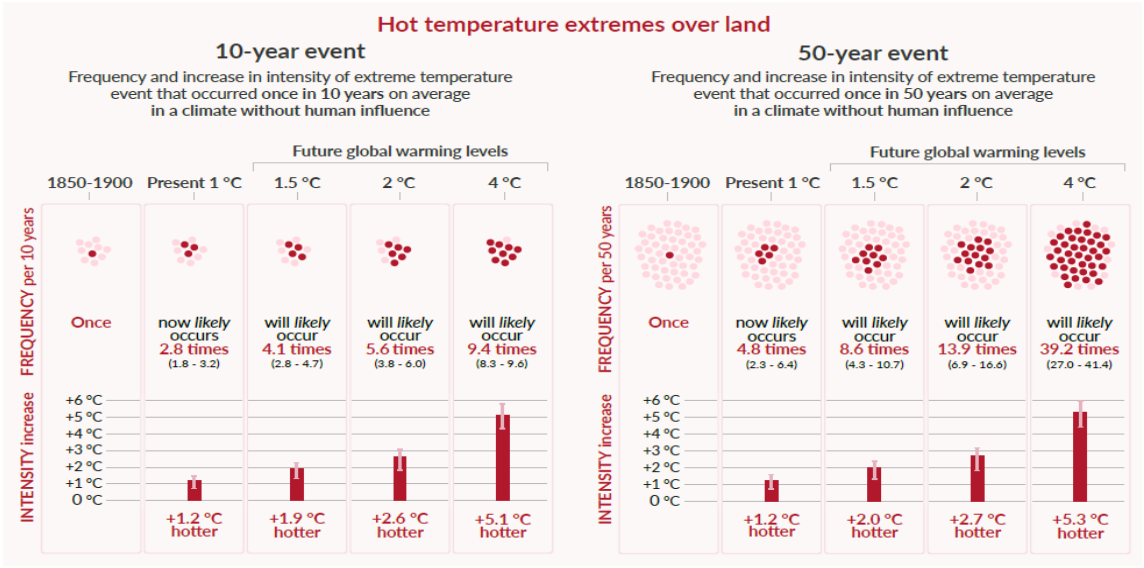


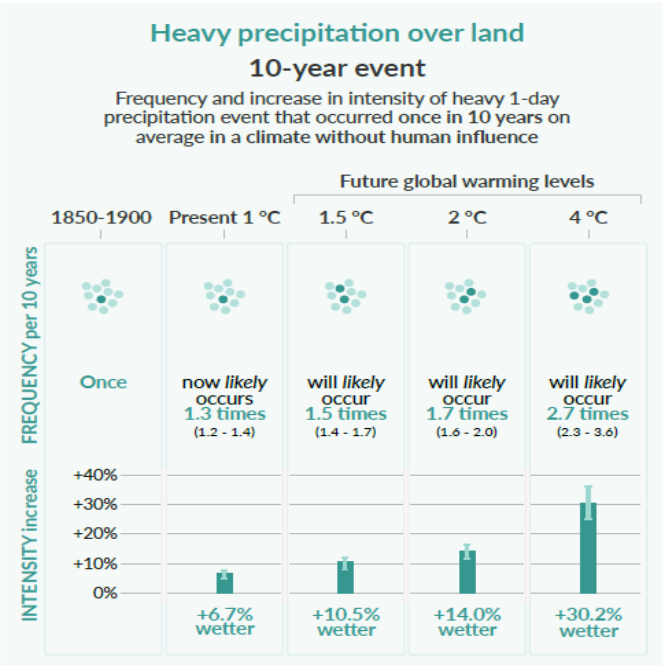
© Gilles Delaygue

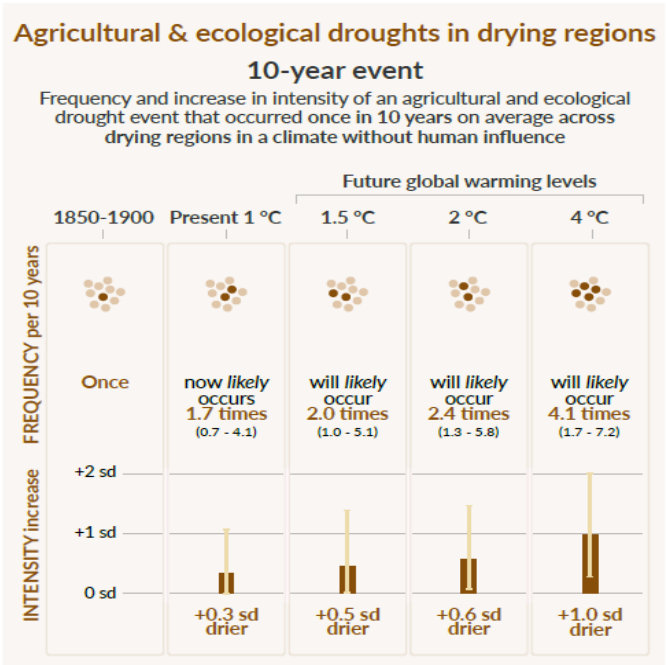
Annual number of

- **tropical cyclones or hurricanes** in the Atlantic (categories 1 to 5 on the Saffir-Simpson scale),
- and of the **strongest hurricanes only** (categories 3 to 5 on the same scale).

Projected changes in extremes are **larger in frequency and intensity** with every additional increment of global warming







Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to the reference period 1850-1900 (which represents a climate without human influence).

The figure depicts frequencies and increases in intensity of 10- or 50-year extreme events from the base period (1850-1900) under different global warming levels.

Conclusions

More frequent or intense extreme phenomena

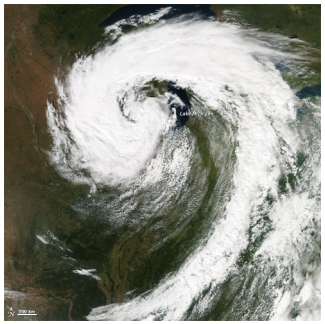
Global warming makes some extreme events **more frequent and/or intense :**

- heat waves
- intense rainfall episodes
- Droughts

Other extreme events become less likely (**cold waves**).

http://en.people.cn/n3/2016/0122/c90000-9008125-10.html

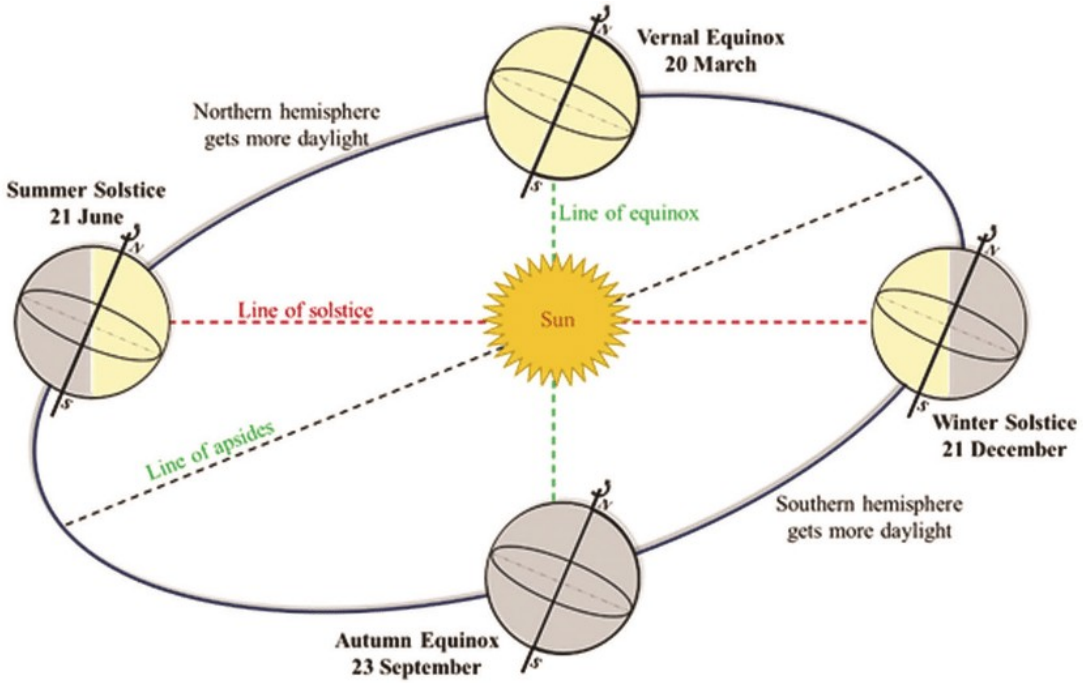
As for **mid-latitude storms**, their evolution with climate change remains largely uncertain.



NASA Earth Observatory

Concerning **tropical cyclones**, the state of knowledge suggests a slight decrease in the total number, but an increase in the number of cyclones of the strongest categories.

Appendix 2



https://www.researchgate.net/figure/Rotation-of-Earth-about-its-own-axis-and-its-revolution-around-the-Sun-resulting-into_fig3_328491205

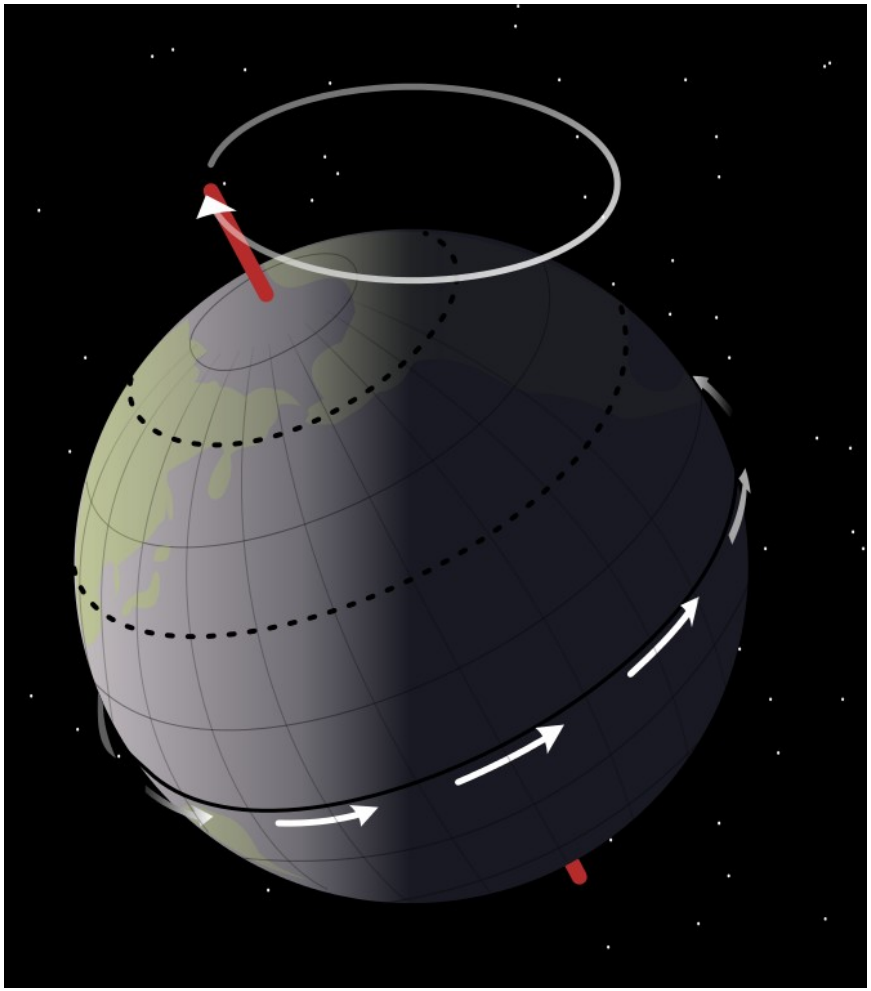
The orbital forcing of climate

Axial precession

www.amazon.com

The **Earth's axis rotates** just as a spinning top does.

The period of precession is about 26,000 years.

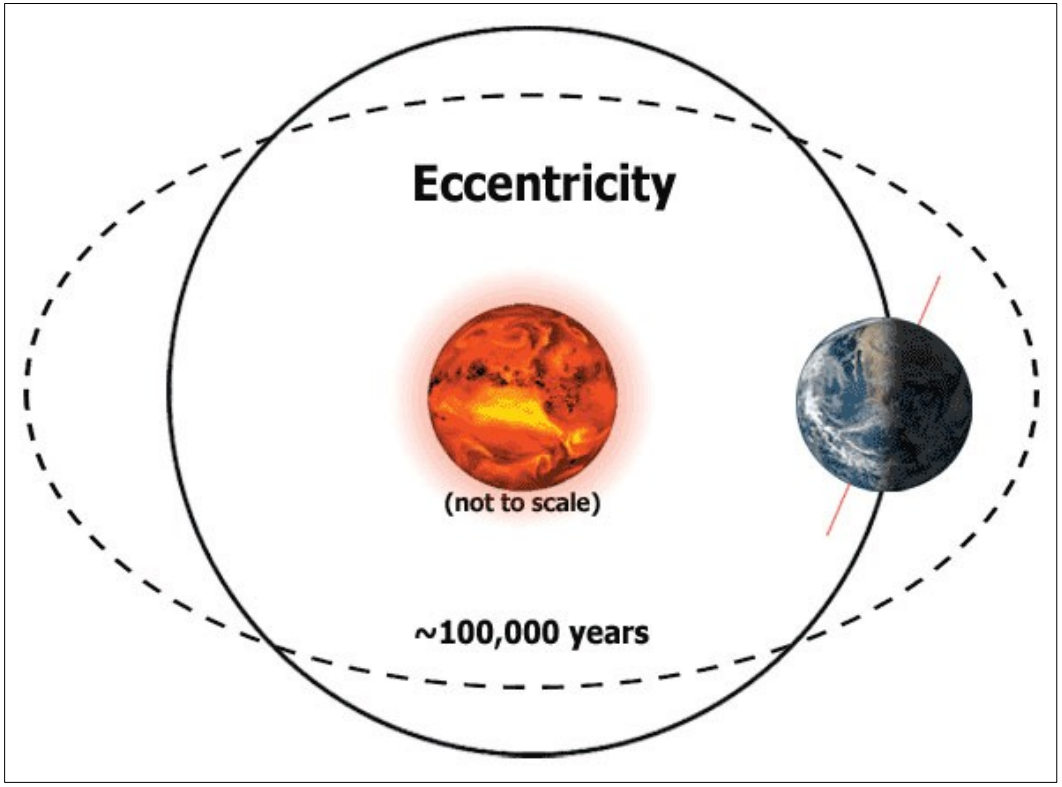


By NASA, Mysid [Public domain], via Wikimedia Commons

Precession is caused by the gravitational pull of the Sun and the Moon on the Earth.

Eccentricity

The Earth's orbit approximates an ellipse.
Eccentricity measures the departure of this ellipse from circularity.



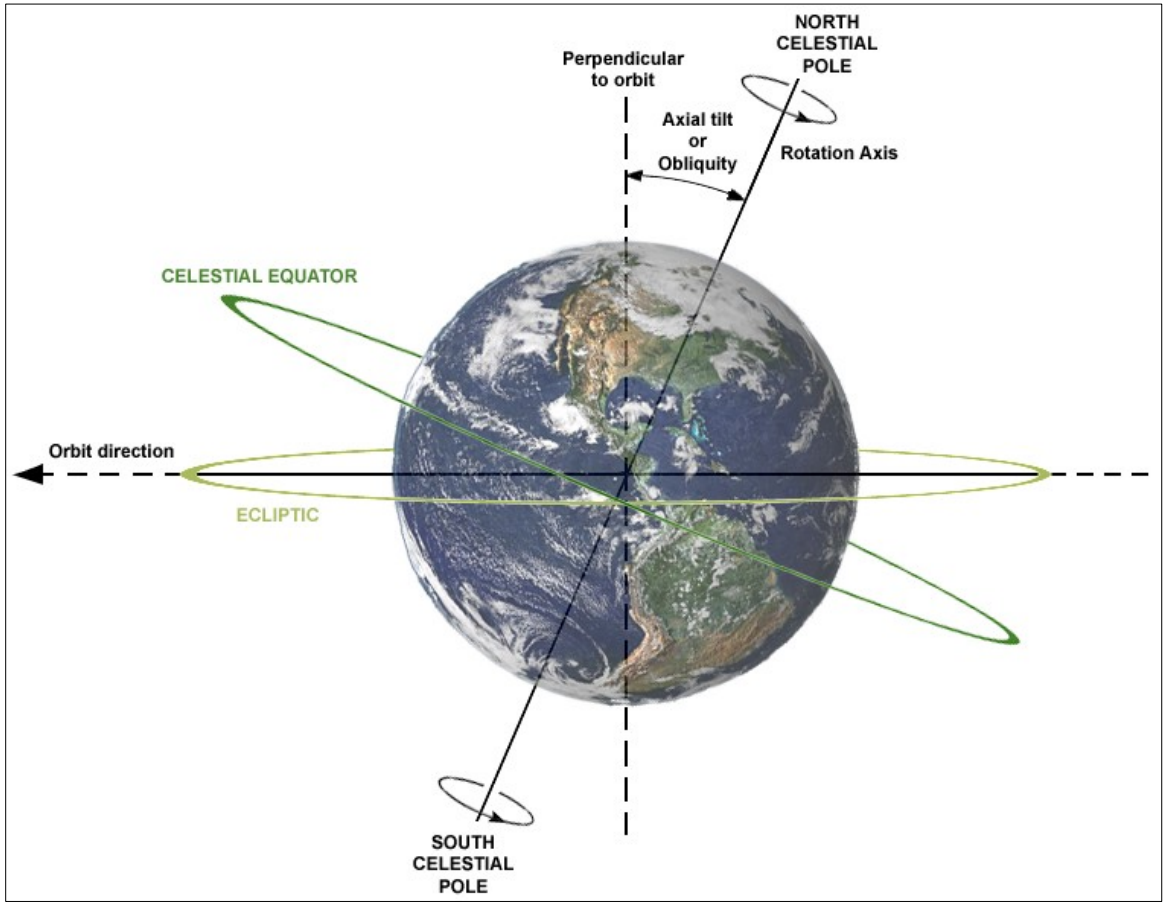
The shape of the Earth's orbit varies between **nearly circular** (with the lowest eccentricity of 0.000055) and **mildly elliptical** (highest eccentricity of 0.0679).

Eccentricity varies primarily due to the gravitational pull of Jupiter and Saturn.

http://www.ces.fau.edu/nasa/module-3/temperature-trend-changes/causes-glaciation.php

Obliquity (also called axial tilt)

Obliquity is the **angle** between the plane of the Earth's equator and the plane of the Earth's orbit around the Sun.



By I, Dennis Nilsson, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=3262268

For the past 5 million years, Earth's obliquity has varied between 22° 2′ 33″ and 24° 30′ 16″, with a mean period of 41,040 years.

Earth's current axial tilt of **23.44** degrees gives our planet its seasons and moderates the climate.