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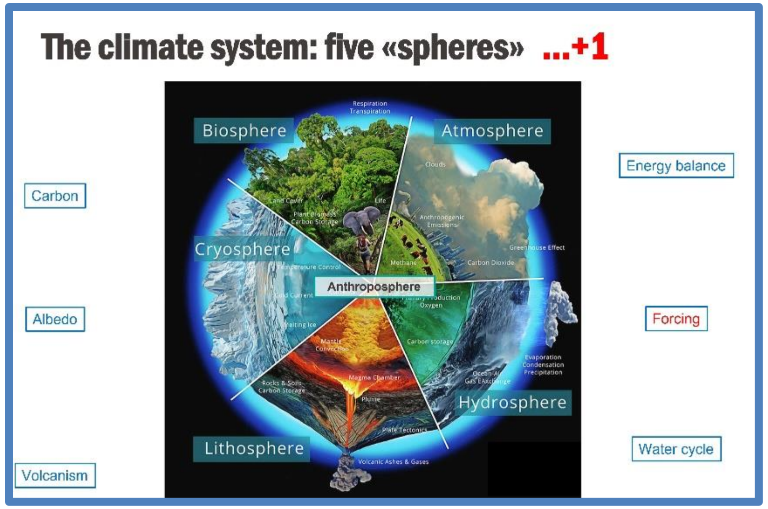
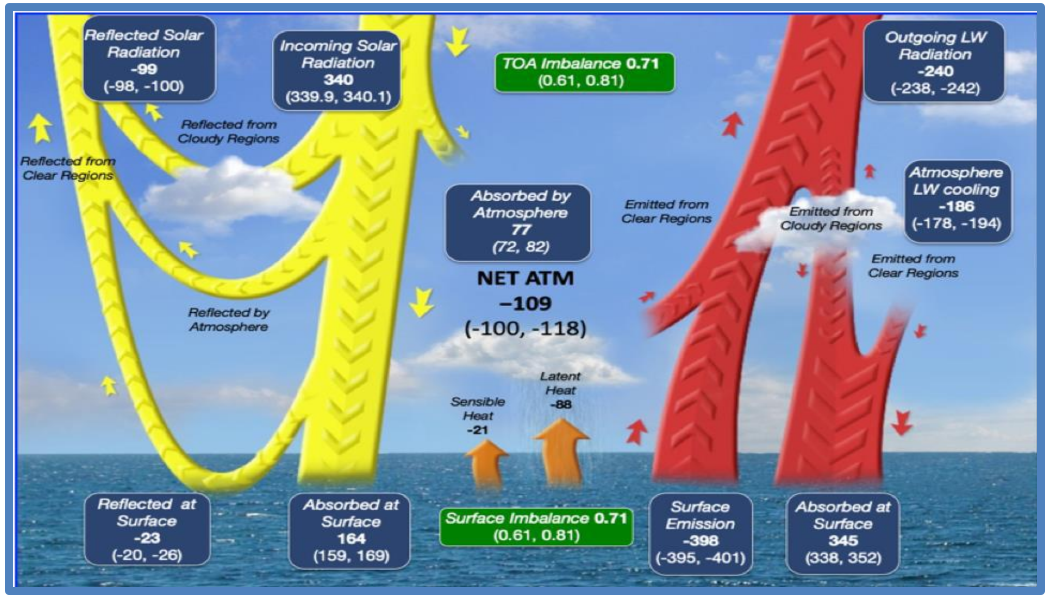
Sustainability, climate and energy

ENV-421
Jérôme Chappellaz, Jonas Schnidrig

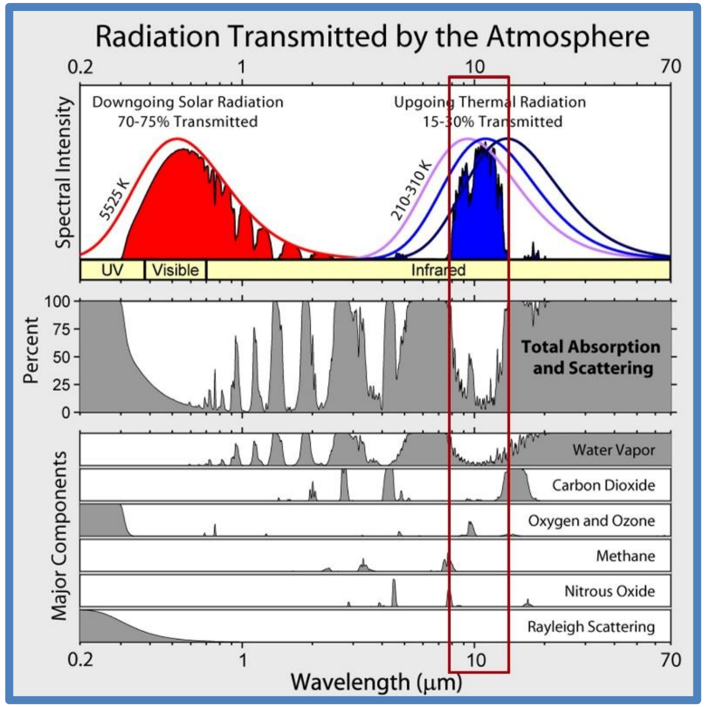
Recap from previous lecture



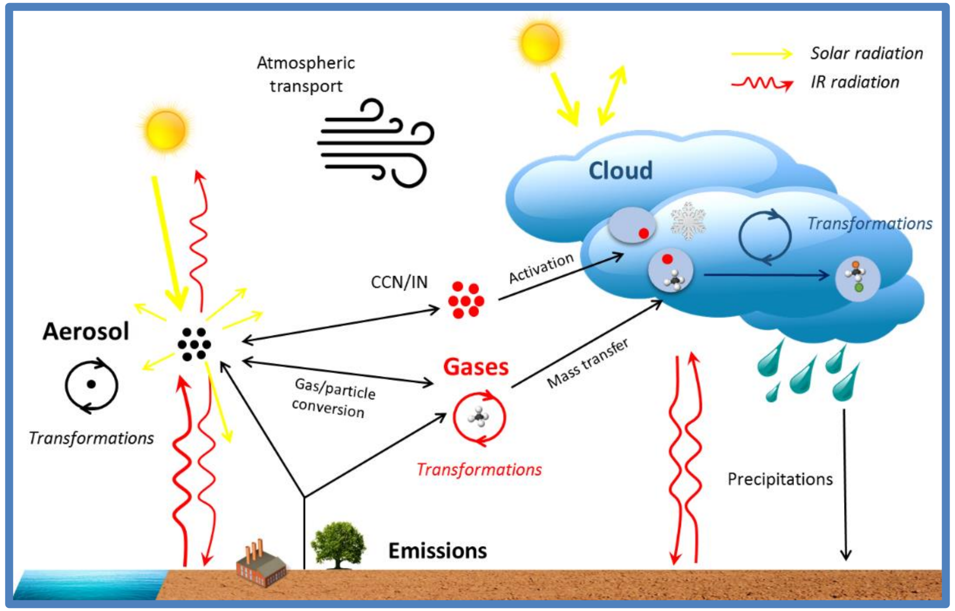
Climate system



Earth energy balance



Greenhouse gases

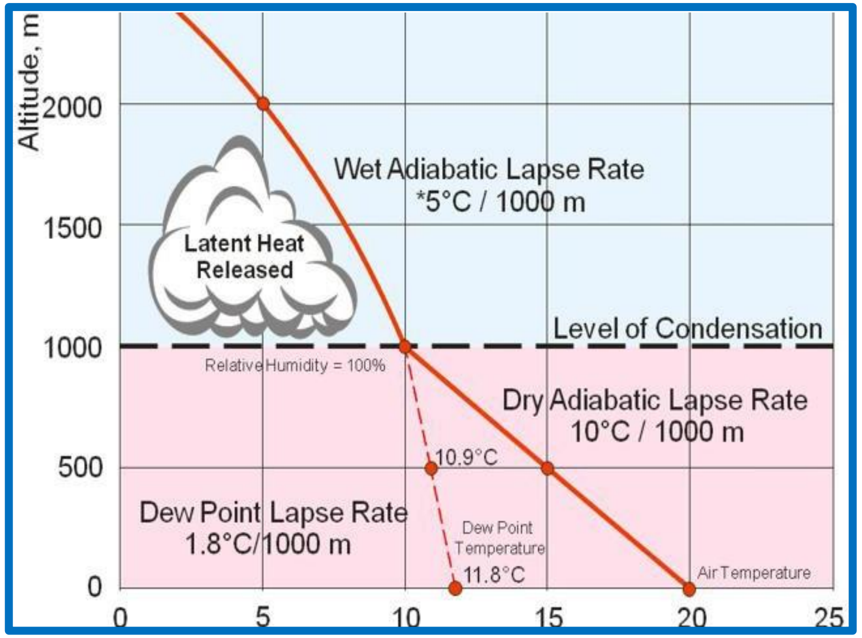


Aerosols

Summary: Climate system, Earth energy balance, greenhouse gases and aerosols

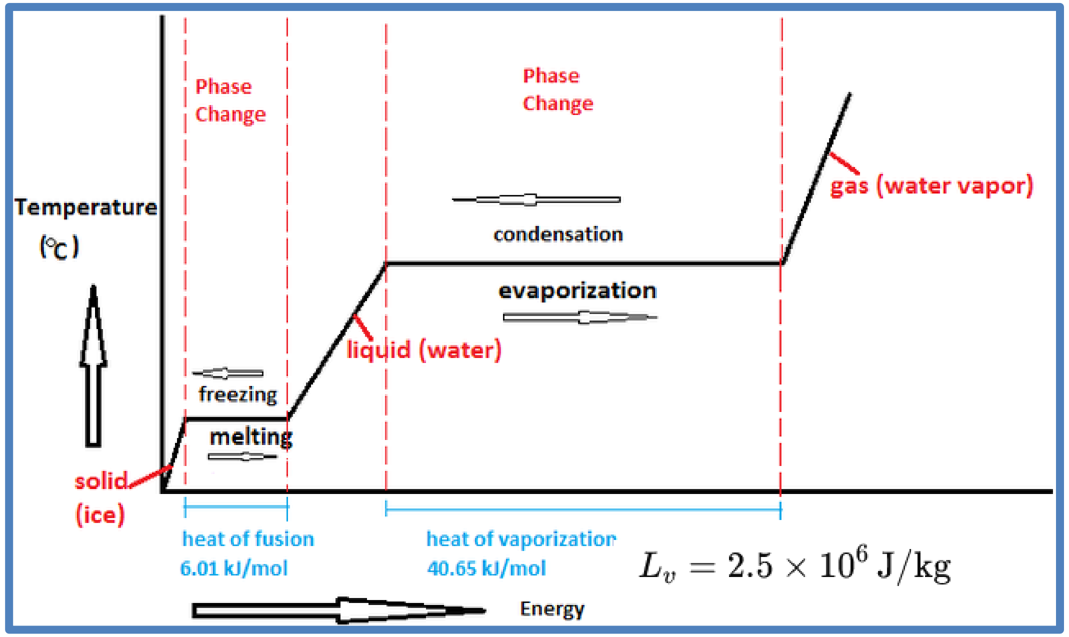
- The climate system can be described as **“spheres”**, having their own dynamics and interacting between each other. The anthropogenic impacts add another sphere.
- The Earth’s climate system is driven by the **sun**.
- The atmosphere mediates the flow of energy from the sun to the Earth and back to space (**effects of greenhouse gases, aerosols and clouds**).
- **Convection and latent heat transfer** are important physical phenomena transferring heat from the surface to higher altitudes.
- In addition to energy transfer, **water and carbon** are important molecules flowing between the spheres.
- The greenhouse effect is a **natural phenomenon**. Human activities increase it, in particular by affecting the **atmospheric window** of longwave radiation centered at 10 µm.
- Aerosols impact the radiative balance both on **shortwave and longwave radiations**. Major control on **clouds**.
- The spatial and temporal patterns of **energy distribution between latitudes** (and altitudes) drive atmospheric and oceanic circulations.

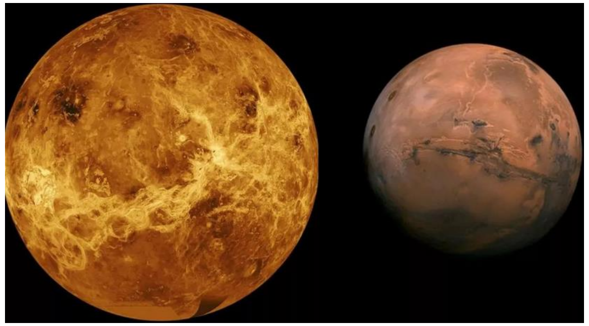
Recap from previous exercises



Lapse rate

Latent and sensible heat



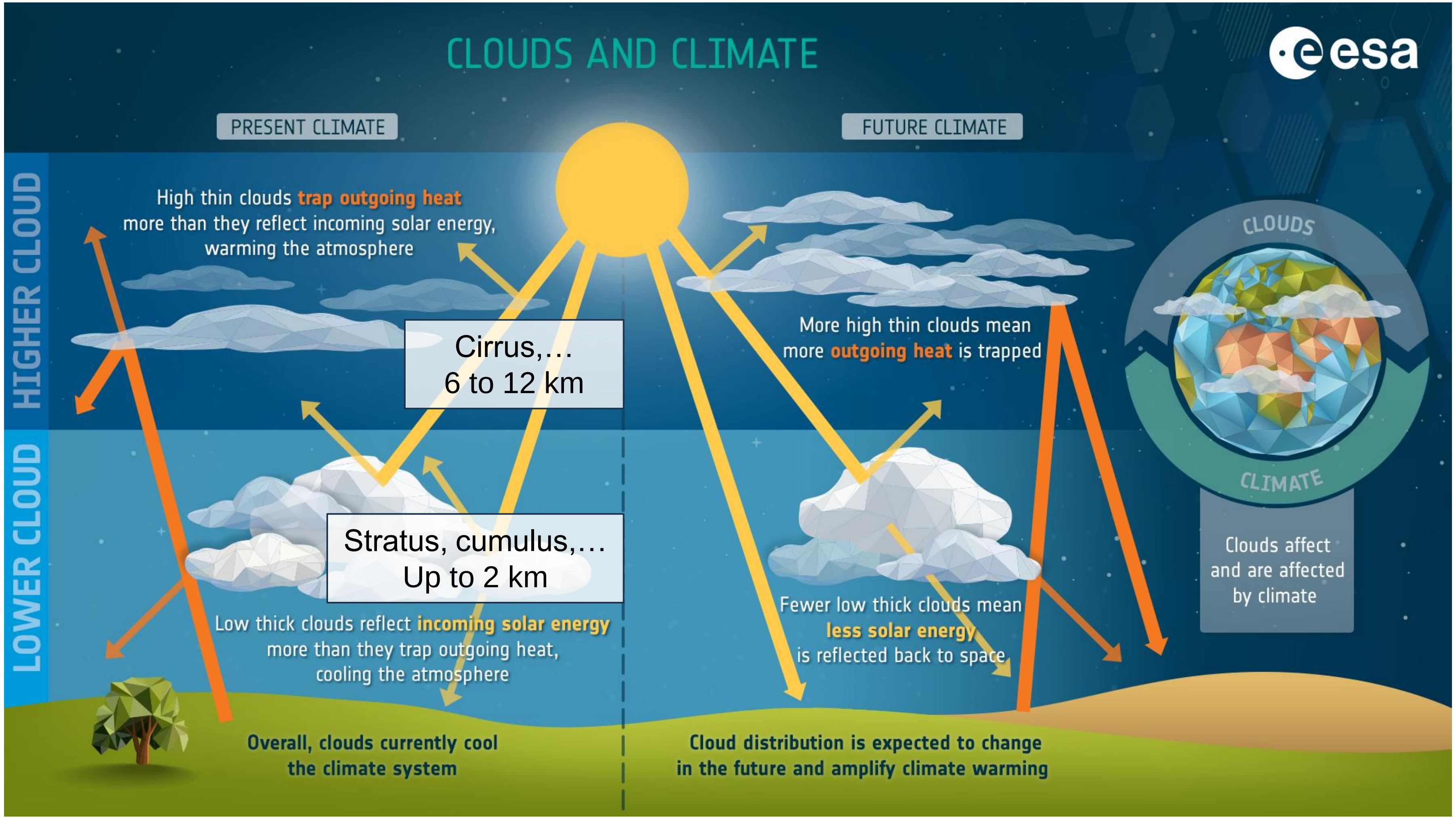


Greenhouse gases:

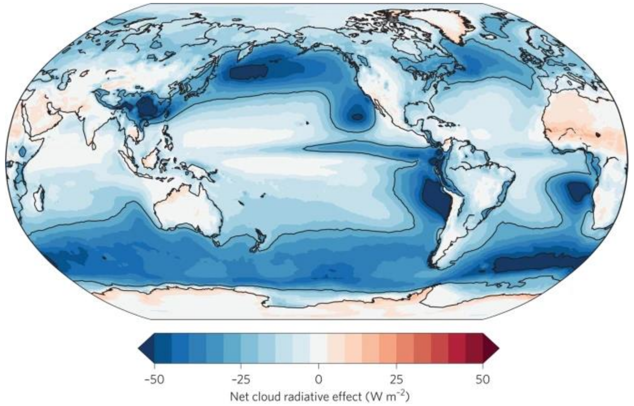
- Without them and the atmosphere, the Earth' surface would be - 18°C
- Venus would be at - 42°C (reality : + 462°C)
- Mars would be at - 64°C (reality : - 55°C)
- Major effect of atmospheric pressure on Venus (92 bar, with 95% of CO_2)

Cooling or heating by clouds

Cloud effect on the Earth's radiative balance depends on cloud amount, cloud altitude and cloud opacity



Source: *Zelinka et al., Nature 2017*

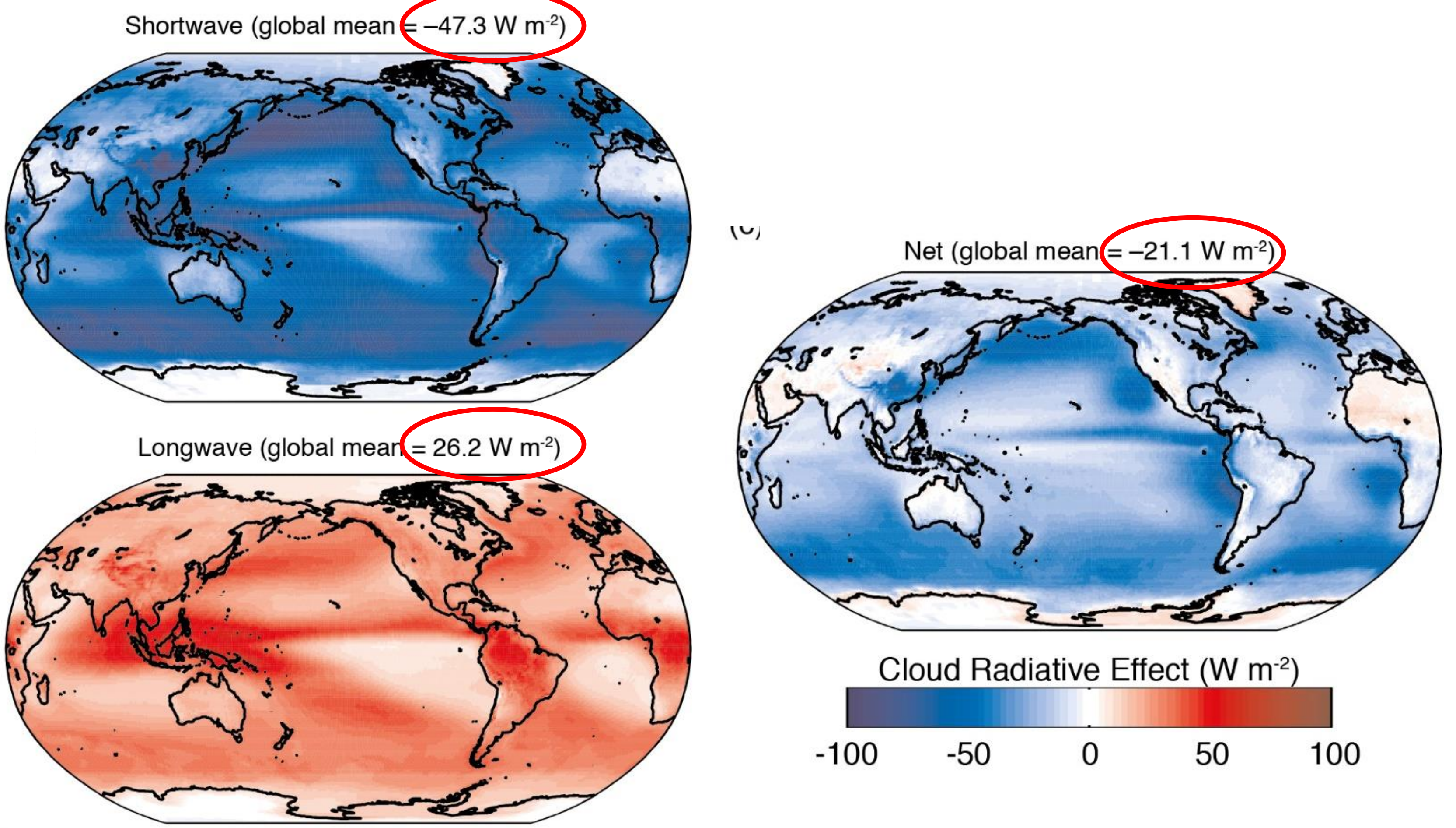


- All-sky versus clear-sky net radiative flux 2001-2016, based on satellite observations and modelling.
- Annual global mean: reduce the radiative input by 18 $W.m^{-2}$.
- Future scenarios could change the sign of the cloud impact.

- *Source: European Space Agency*

Cooling or heating by clouds

Based on CERES satellite observations averaged over the period 2001 to 2011.

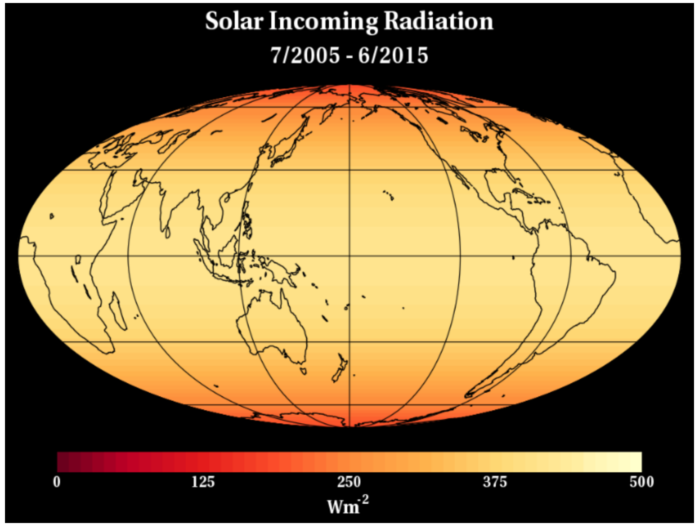


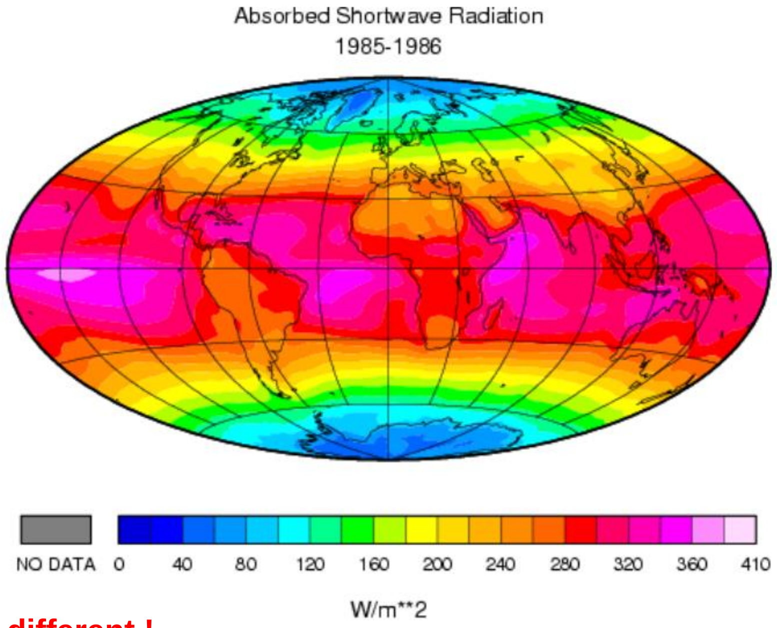
- Shortwave cooling is stronger than longwave heating, averaged over a year.
- High-altitude clouds (heating effect) are common in the Tropics (deep convection) and along the jet streams at mid-latitudes.
- Low-altitude clouds (cooling effect) are more ubiquitous over land and oceans.
- Note that satellite observations provide a stronger net negative radiative flux of clouds (21 $W.m^{-2}$) than modelling experiments (previous slide: 18 $W.m^{-2}$).
  → **Limits of models.**

Source: IPCC AR5 Chapter 7 Fig. 7.7

Earth's energy balance

Incoming solar shortwave radiation at top of the atmosphere. CERES-EOS satellite data.





Annual mean net downward shortwave radiation. NASA/ERBS satellite data

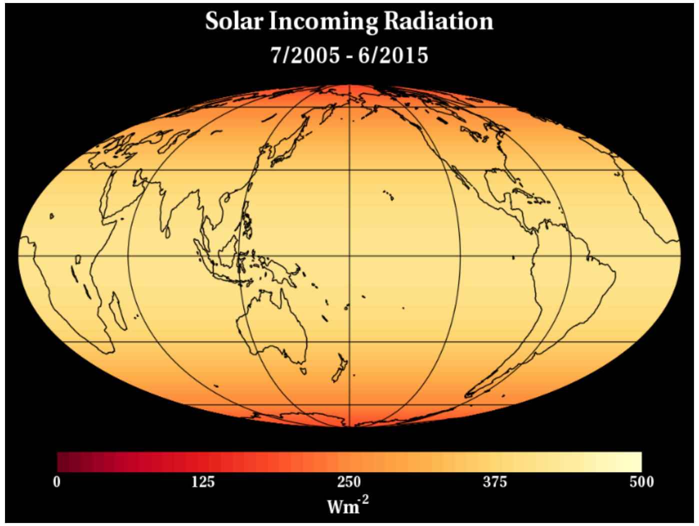
- High albedo of deserts and high latitudes
- Cloud cover
- Low solar radiation at high latitudes

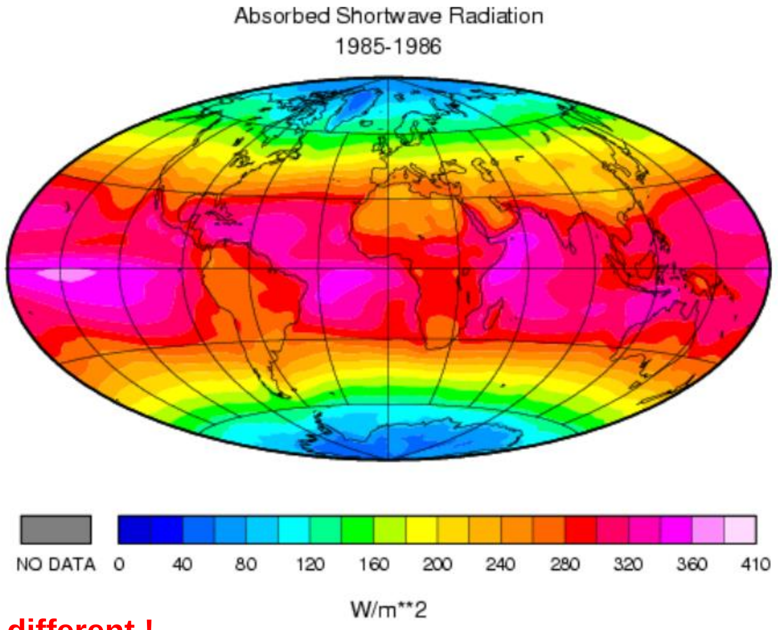
Scales are different !

Sources: NASA CERES Project and NASA/ERBE Project

Earth's energy balance

Incoming solar shortwave radiation at top of the atmosphere. CERES-EOS satellite data.





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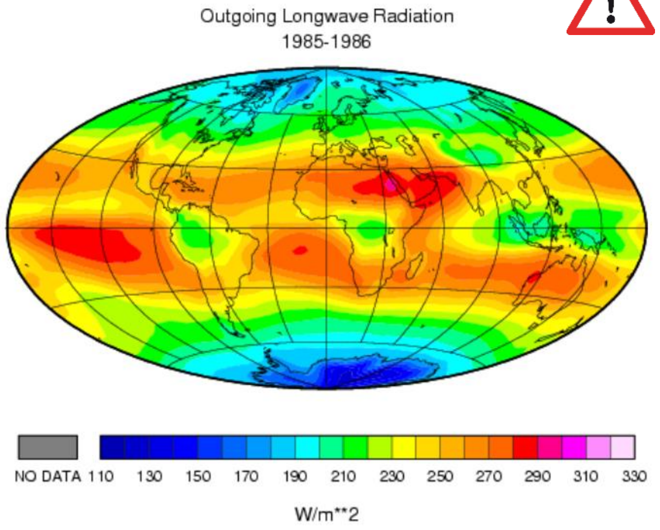
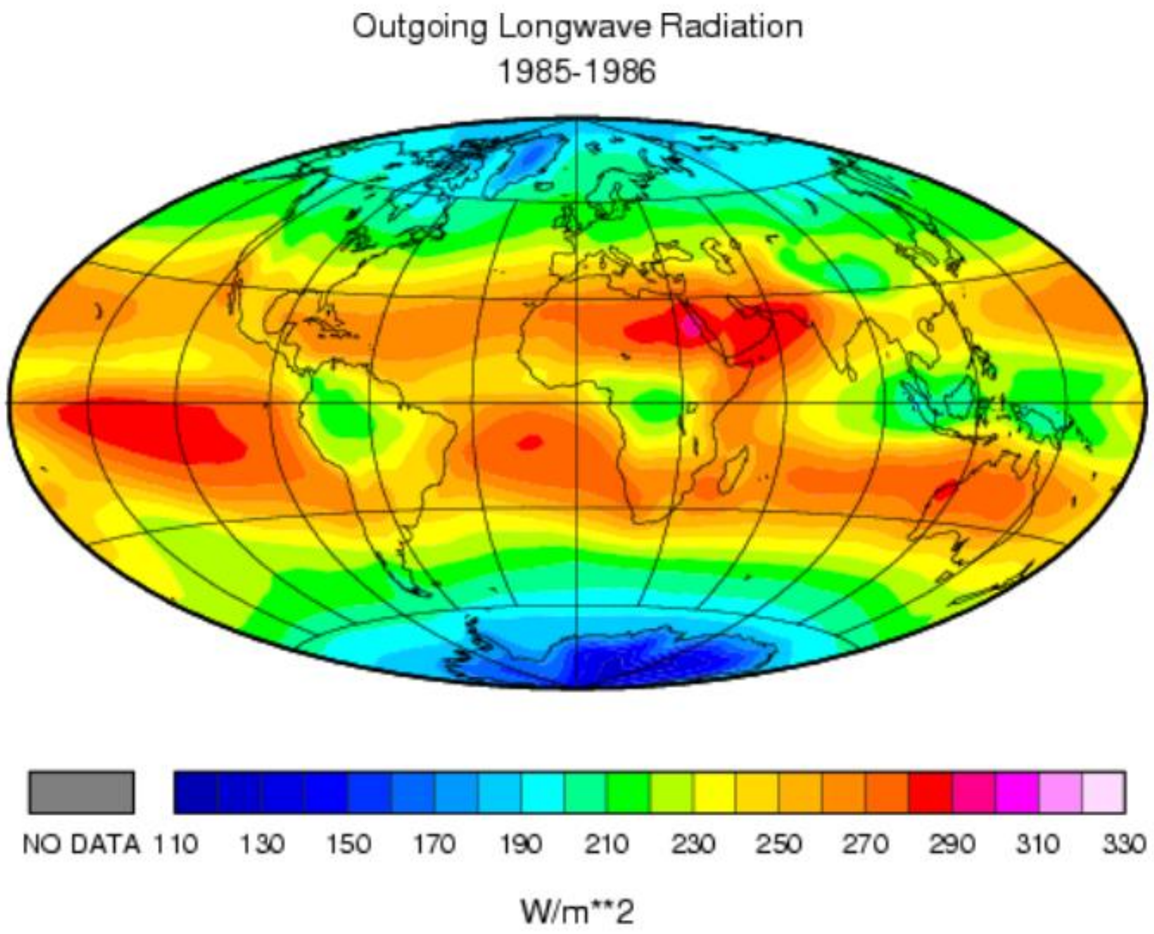


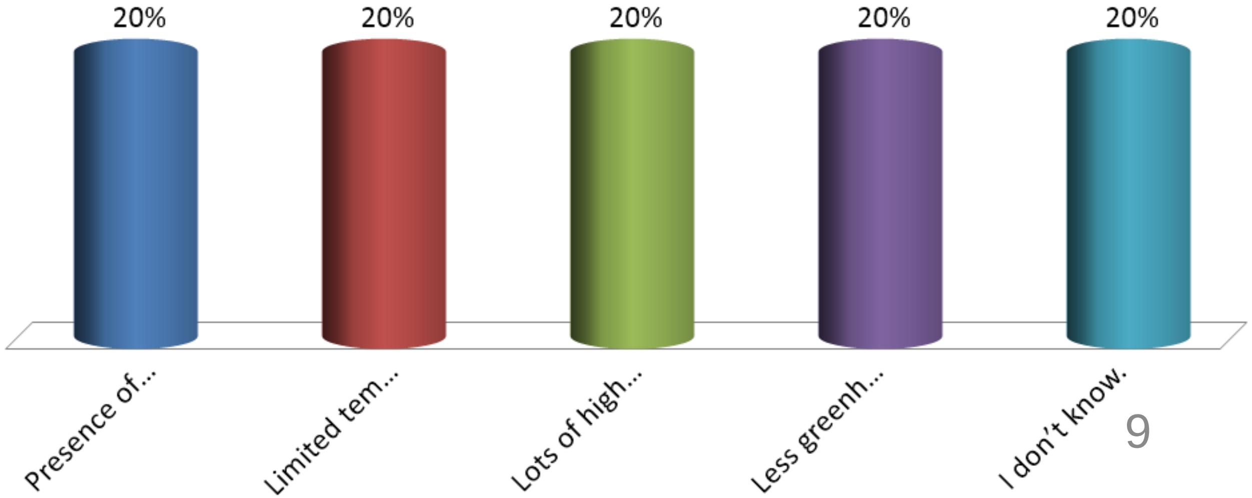
Annual mean net outgoing longwave radiation. NASA/ERBS satellite data

Sources: NASA CERES Project and NASA/ERBE Project

How do you interpret the green areas along the equator ?



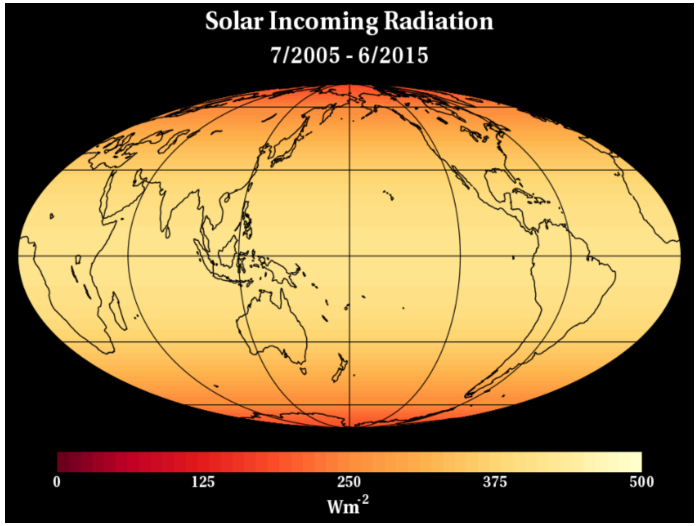
A. Presence of rainforests.
B. Limited temperature variations.
✓ C. Lots of high-altitude clouds.
D. Less greenhouse gases in these areas.
E. I don’t know.

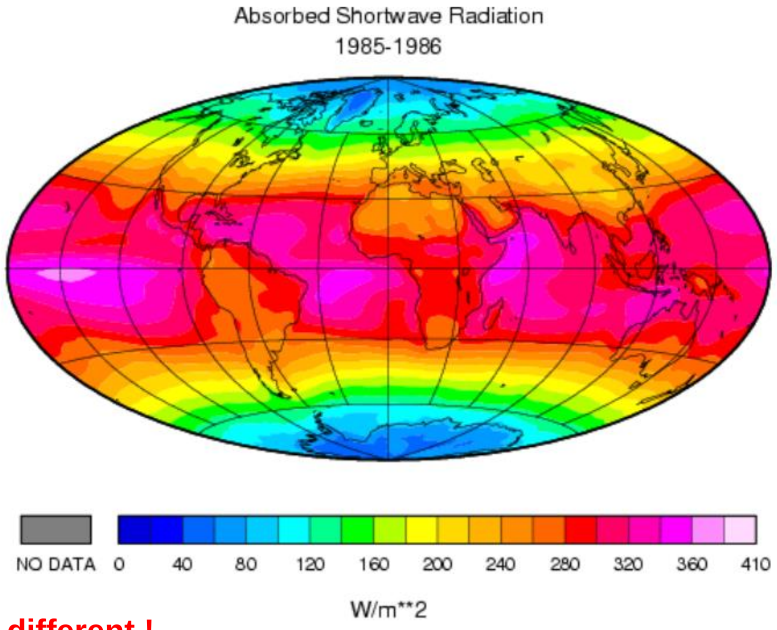


Sources: NASA CERES Project and NASA/ERBE Project

Earth's energy balance

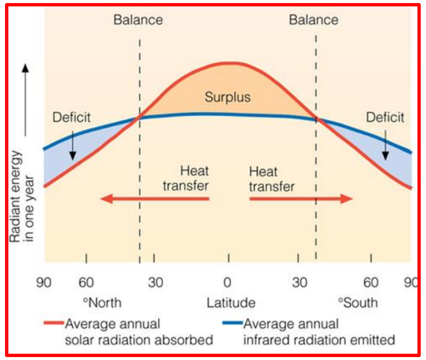
Incoming solar shortwave radiation at top of the atmosphere. CERES-EOS satellite data.





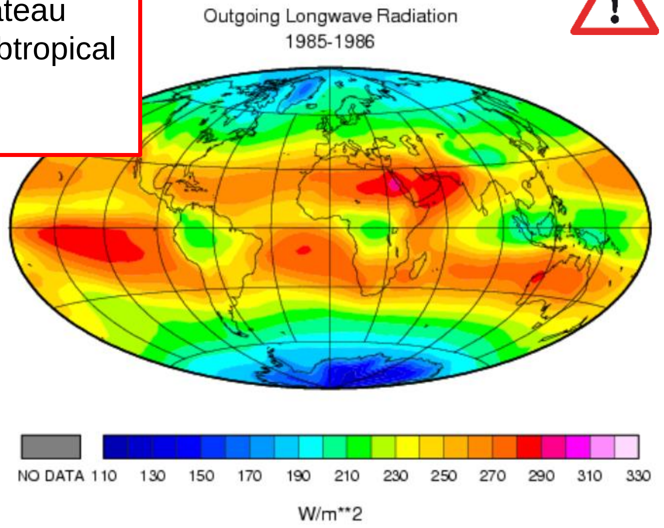
Annual mean net downward shortwave radiation. NASA/ERBS satellite data

- High albedo of deserts and high latitudes
- Cloud cover
- Low solar radiation at high latitudes

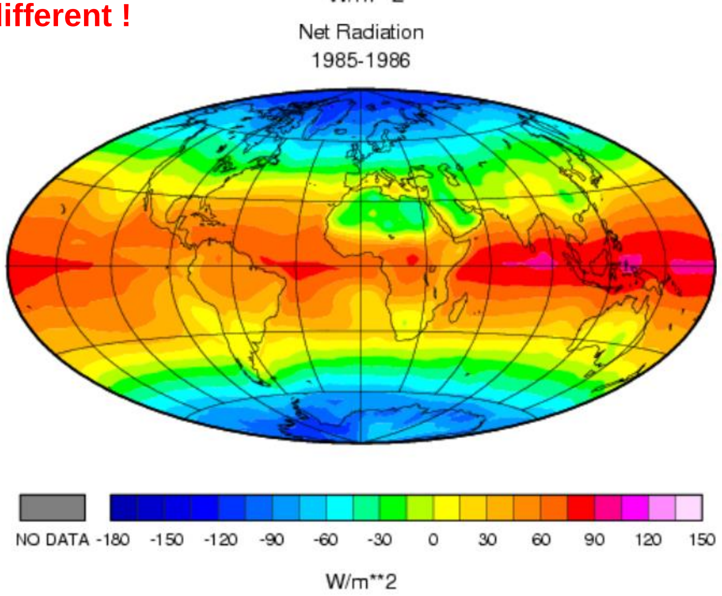


- High clouds along the equator
- Altitude of Tibetan Plateau
- Warm deserts and subtropical oceans
- Cold polar regions

Scales are different !



Annual mean net outgoing longwave radiation. NASA/ERBS satellite data



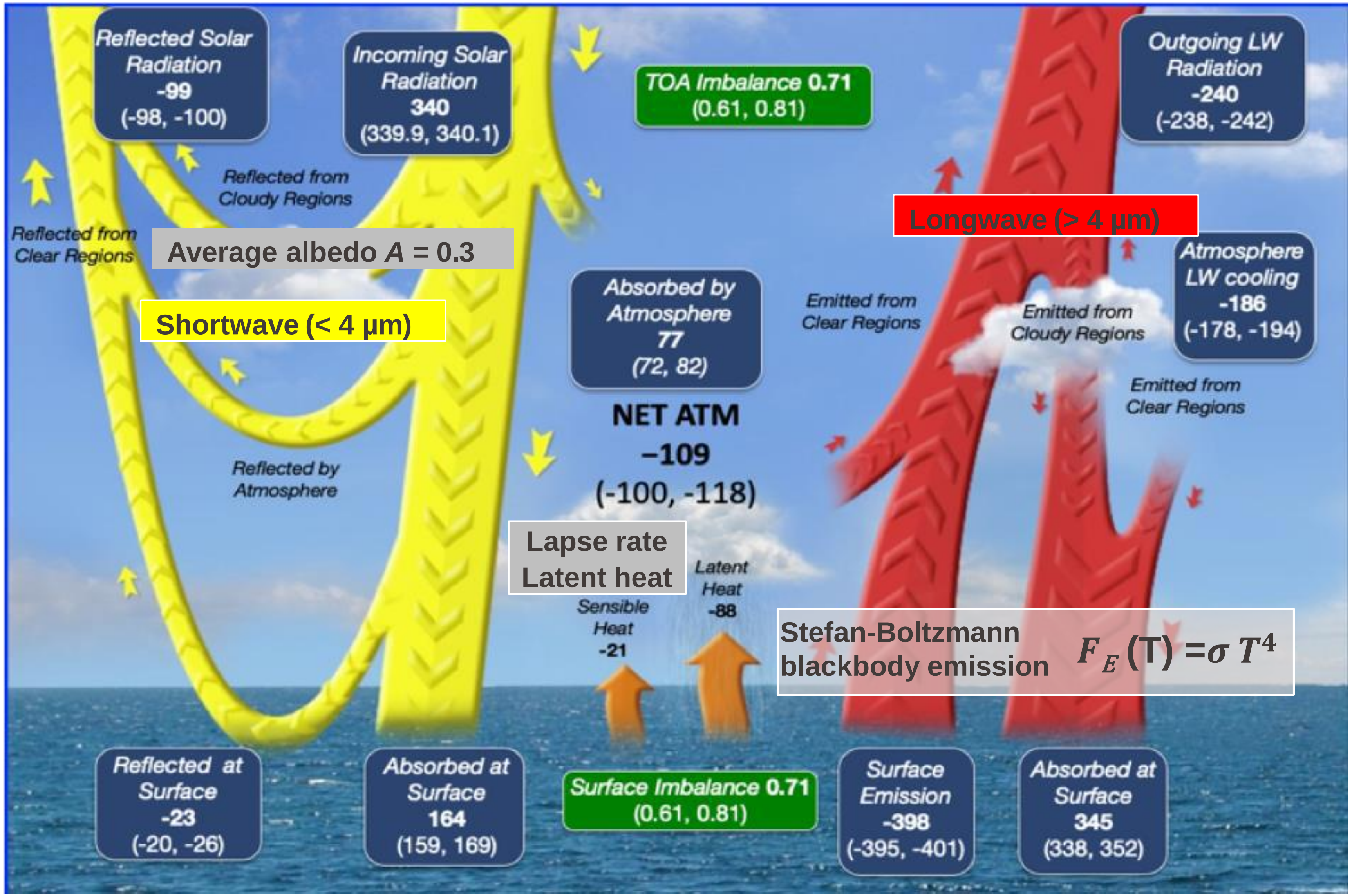
Net radiation: outgoing longwave minus net downward shortwave

The motor of latitudinal transport of energy by the atmosphere and the oceans from the equator to the pôles !

Sources: NASA CERES Project and NASA/ERBE Project

Earth's energy balance

$$\frac{(A \cdot F_s)}{4} \qquad \frac{F_s}{4}$$



Source: https://ceres.larc.nasa.gov/science/

In one dimension

- Incoming solar radiation corrected for Earth's albedo (shortwave) is balanced by outgoing Earth's radiation (longwave).
- Greenhouse gases (H_2O, CO_2,…) absorb/re-emit longwave radiation and heat the surface. Warming by 32°C compared with the absence of atmosphere.
- Energy deficit between atmosphere (-) and surface (+) is compensated by energy transfer (sensible and latent heat)

In 3 dimensions

- Spatial variability of incoming solar radiation, albedo, cloud type and cover, surface temperature, aerosols.
- Transfer of heat from low to high latitudes

General outline

No.	Date	Topics	Remarks
1.	18.02.2025	Introduction to the climate system. Earth energy balance. Greenhouse gases and aerosols	
2.	25.02.2025	Introduction to energy systems. Energy balance fundamentals	
3.	04.03.2025	**Radiative forcing. Feedback mechanisms. Climate sensitivity**	
4.	11.03.2025	Overview of energy technologies	
5.	18.03.2025	Climate archives: geological to millennial time scales	Conf. Michael Sigl + QCM evaluation (graded)
6.	25.03.2025	Climate variability. Climate change scenarios. Carbon cycle feedbacks.	
7.	01.04.2025	Technologies' impacts	Conf. Alexis Quentin
8.	08.04.2025	Tipping points. Extreme events. Regional climate change	
9.	15.04.2025	Climate change impacts on renewable energy systems. Impact of RES on climate	J. Castella (Watted) : PowerPlay game
10.	29.04.2025	Field visit : floating solar platform + dam (Romande Energie)	
11.	06.05.2025	Intro to systemic approach on local scale climate/energy engineering	Start of group work
12.	13.05.2025	Group work on chosen case study	
13.	20.05.2025	Group work on chosen case study	
14.	27.05.2025	Presentation of group reports	Reports are graded

Basics (1–9)

Applications (10–14)

Exam session between 16.06.2025 and 05.07.2025

Radiative forcing

Radiative forcing, feedback and sensivity are connected !

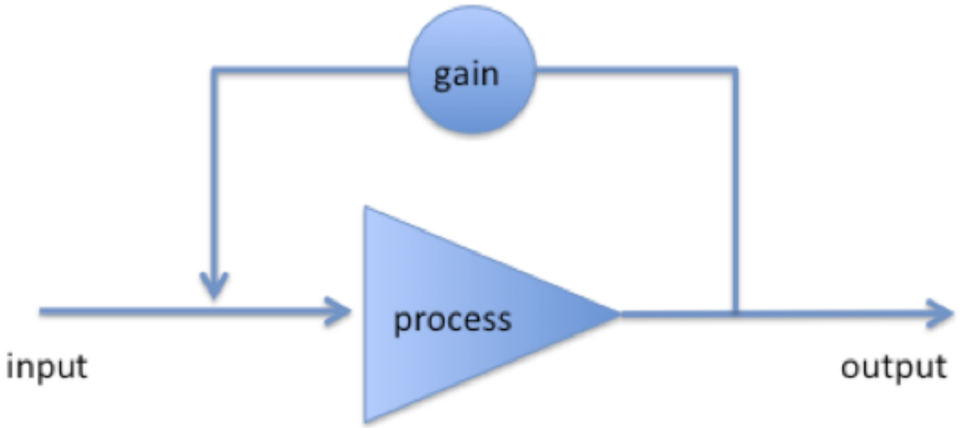
Three fundamental aspects of climate science !

- Radiative forcing in climate science: Change in the Earth's energy balance due to external and internal forcing factors (sun, volcanoes, tectonics, greenhouse gases, aerosols, land use). **Unit: W.m^{-2}.**

- Feedback: Process amplifying or dampening the effects of radiative forcing. Analogy with electrical engineering: amplifier. A portion of the output from the action of a system is added to the input and thus alters the output. **Unit: W.m^{-2}.°C^{-1}.**

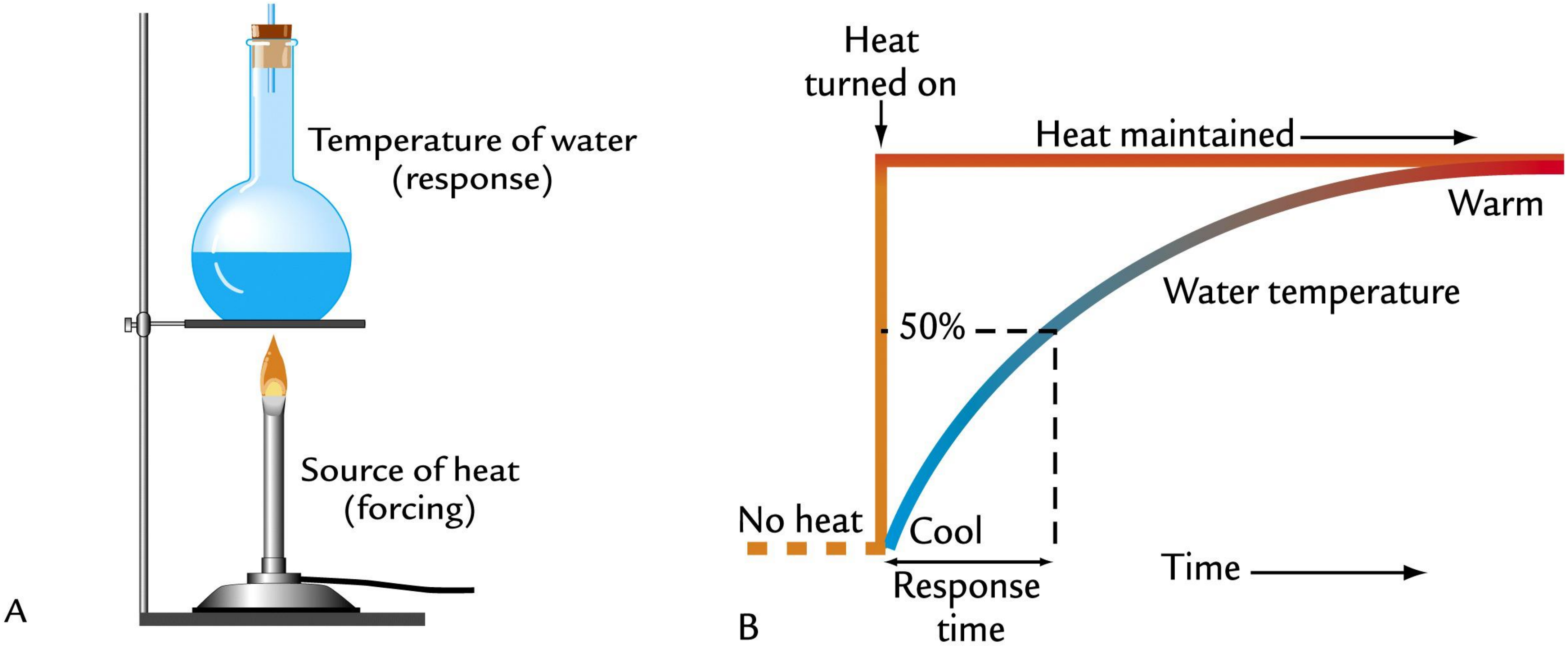
- Sensitivity: The measure of how much the average Earth's temperature will increase due to a doubling of atmospheric CO_2. **Unit: °C.**

- Anthropogenic greenhouse gases and aerosols alter the longwave radiative flux at the top of the atmosphere, inducing radiative forcing. **It is usually calculated with respect to preindustrial times** (atmosphere "without disturbance").



Forcing and response time

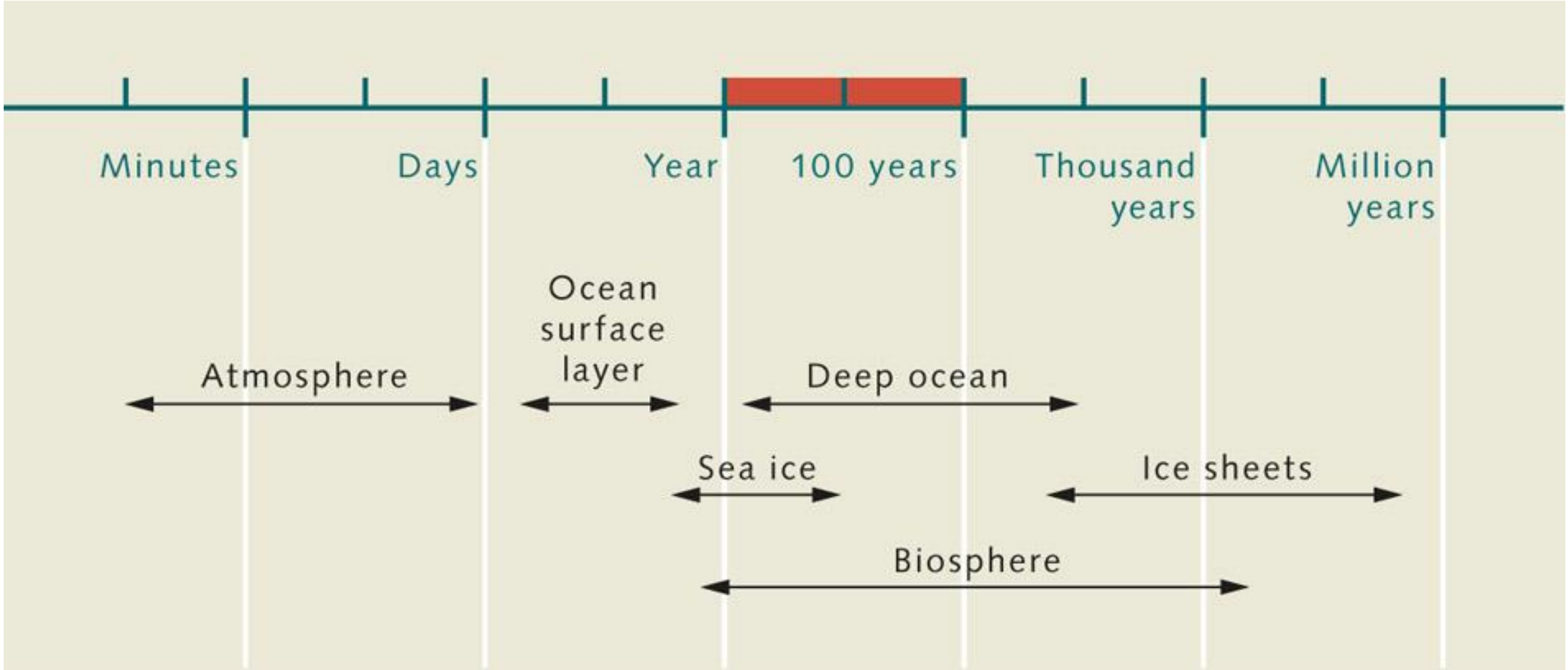
Think about a Bunsen burner heating a beaker of water !
Response time: time required by the system to reach half of the final response.



Source: [Ruddiman, Earth's climate, past and future]

Forcing and response time

Typical response times in the climate system



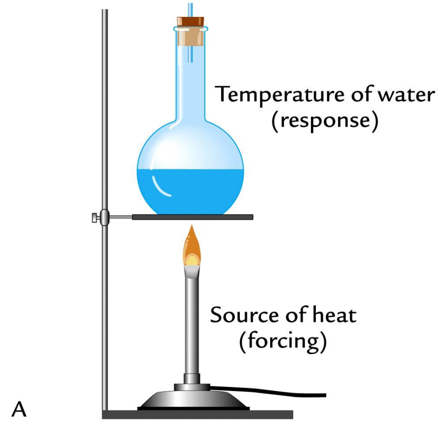
Note : The lithosphere works on even longer time scales (tectonics)

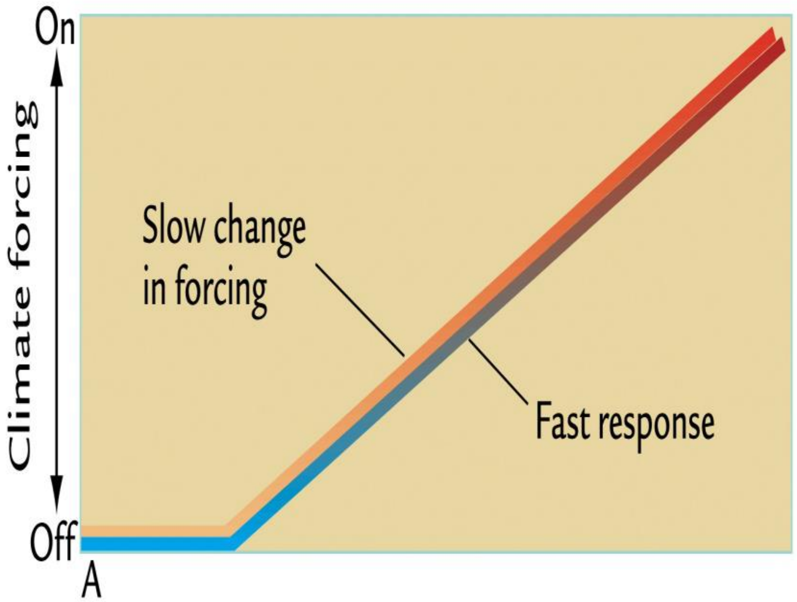
Source : Meincke, J.; Latif, M., Geographische Rundschau 47(2): 90-96, 1995

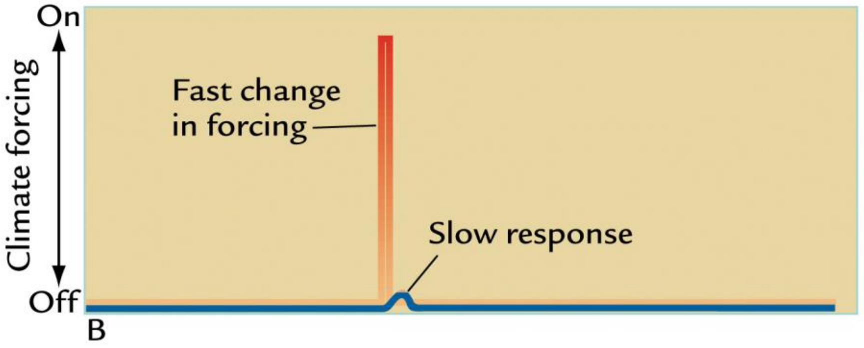
Forcing and response time

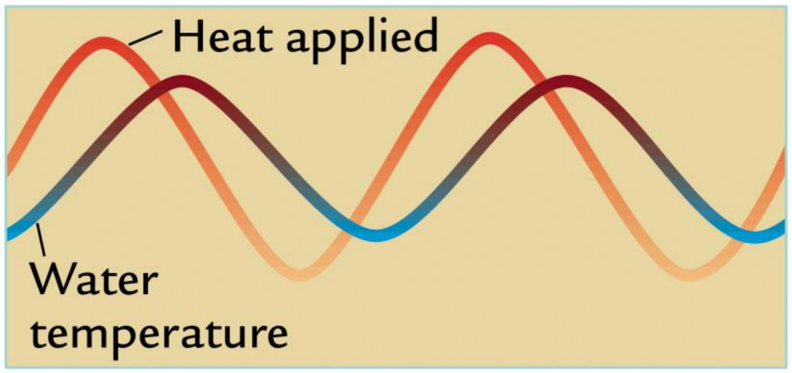
Different types of response time.

Source: Ruddiman, Earth's climate, past and future









C

Example A: tectonics. Average surface temperature has time to adjust to slow continental drift.

Example B: a volcanic eruption. Affects regional/global temperature over a few months.

Example C: Orbital-scale climate change. But also seasonal-scale or daily-scale temperature changes ! Phase shift between the forcing and the response.

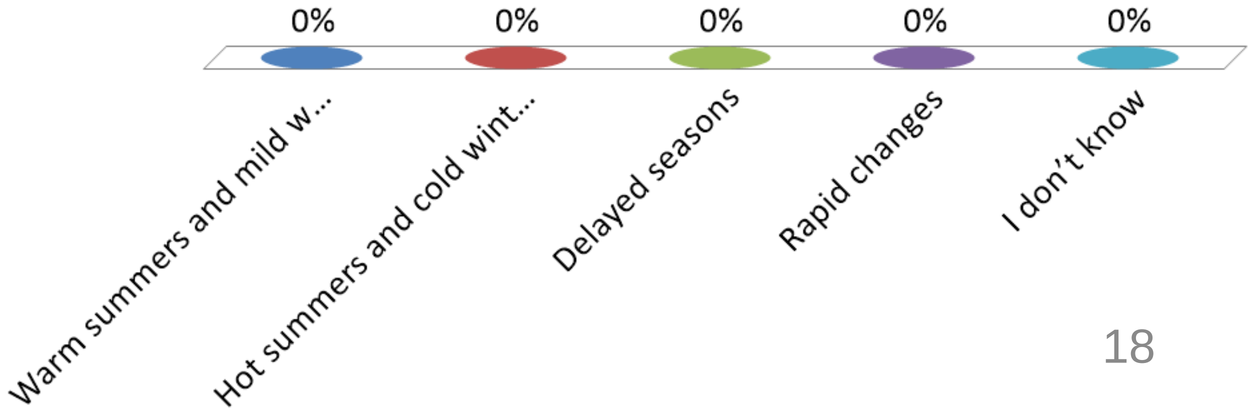
Future climate change will be a combination of anthropogenic forcing (until e.g. all fossil fuel resources are burnt) and response of the climate system with different time scales: very short for the atmosphere (days-months), intermediate for the oceans and the biosphere (10s to 1000s of years), long for the cryosphere (1000s+ years).

Analogy with seasons: let's take a coastal environment !

Interface between the ocean and land.

What is the main seasonal characteristic of a coastal environment compared to a neighboring continental environment ?

A. Warm summers and mild winters
B. Hot summers and cold winters
C. Delayed seasons
D. Rapid changes
E. I don't know

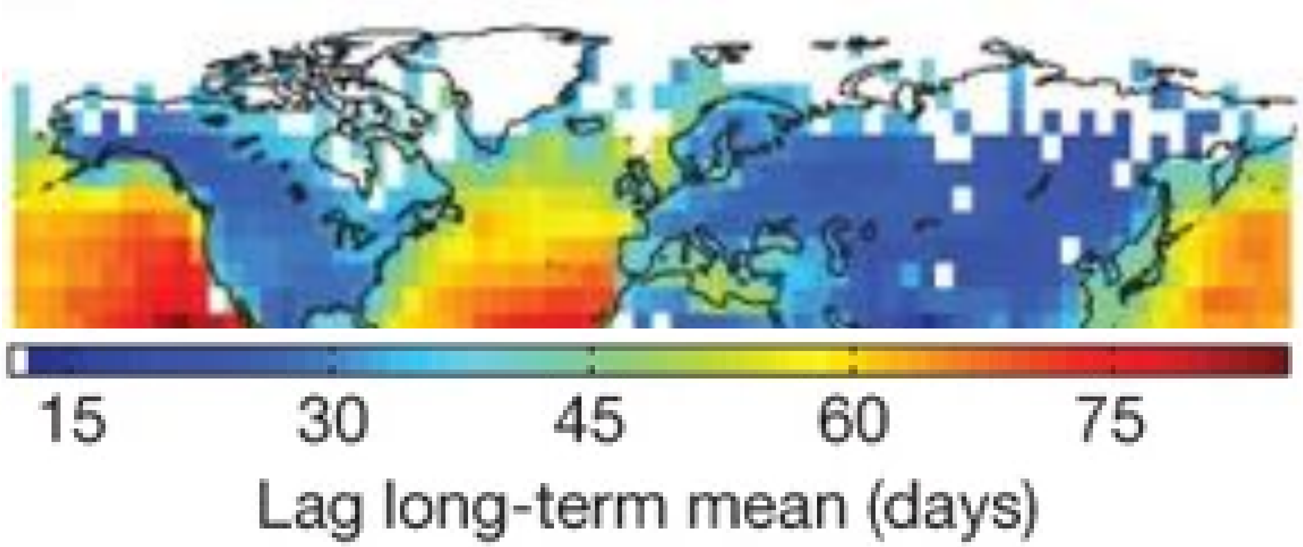


Analogy with seasons: let's take a coastal environment !

Interface between the ocean and land.

What is the main seasonal characteristic of a coastal environment compared to a neighboring continental environment ?

Difference between the temperature and local insolation phases



A. Warm summers and mild winters
B. Hot summers and cold winters
C. ✓ Delayed seasons
D. Rapid changes
E. I don't know

Source: Stine et al., Nature 2009

- Large ocean thermal mass
- Small land thermal mass

Natural external forcing factors: Earth's orbit

Source: NASA science

Eccentricity: mostly influenced by gravitational anomalies generated by Jupiter, Saturn and Venus.

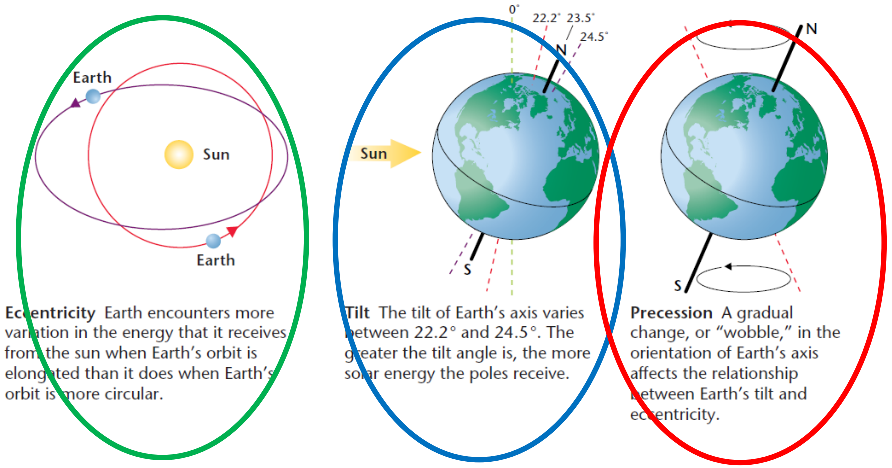
Tilt: effects mostly of Jupiter and Venus. The Moon acts as a stabilizer.

Precession: again Jupiter and Venus, with additional effects from the Moon (torque).

- *Source: http://gulfcoastcommentary.blogspot.com/2013/11/what-causes-ice-ages.html*

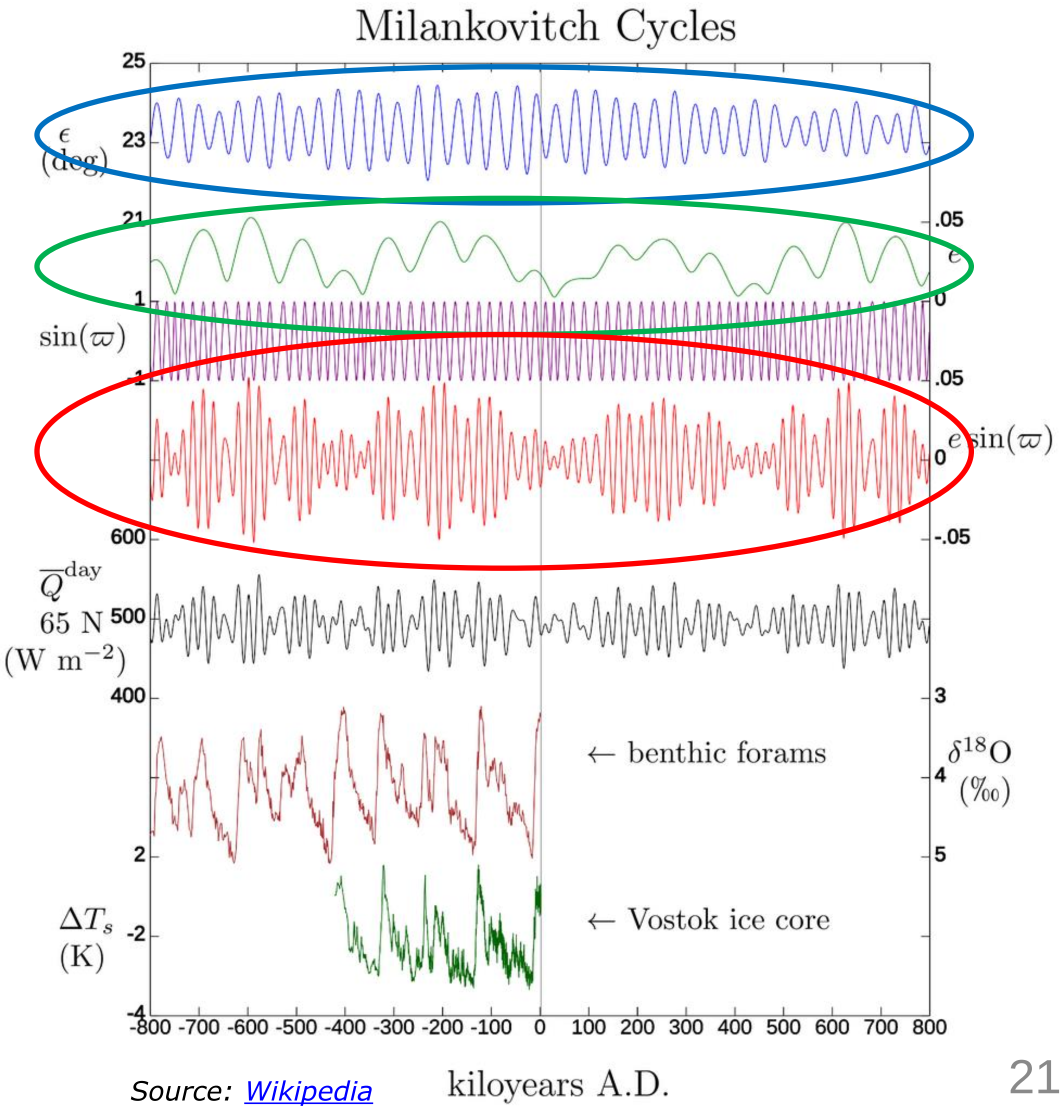
Natural external forcing factors: Earth’s orbit

Change of solar radiation on top of the atmosphere, as a function of latitude and seasons, can be computed using the equations of celestial mechanics (Kepler’s laws)



Periodicities:	100,000 yr 400,000 yr	41,000 yr	19,000 yr 23,000 yr

Illustration with insolation changes at the top of the atmosphere on June 21st (summer solstice) at 65°N.



Important: Changes of the Earth’s orbit do not affect the global annually averaged incoming solar radiation. They modify the seasonal and latitudinal distribution.

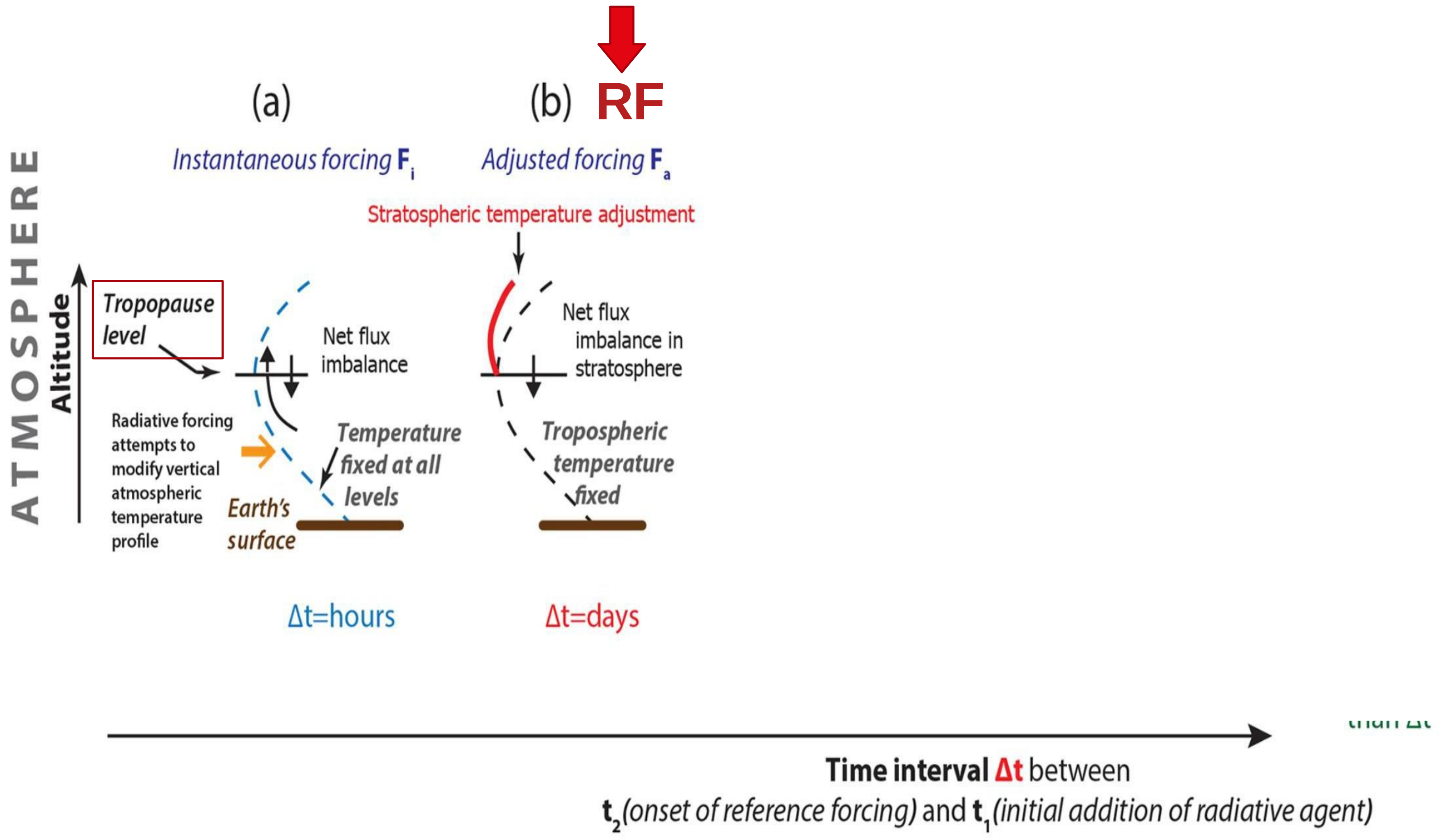
Source: http://gulfcoastcommentary.blogspot.com/2013/11/what-causes-ice-ages.html

Source: Wikipedia

Short-term radiative forcing: taking into account physical adjustments

RF = Radiative Forcing
ERF = Effective Radiative Forcing

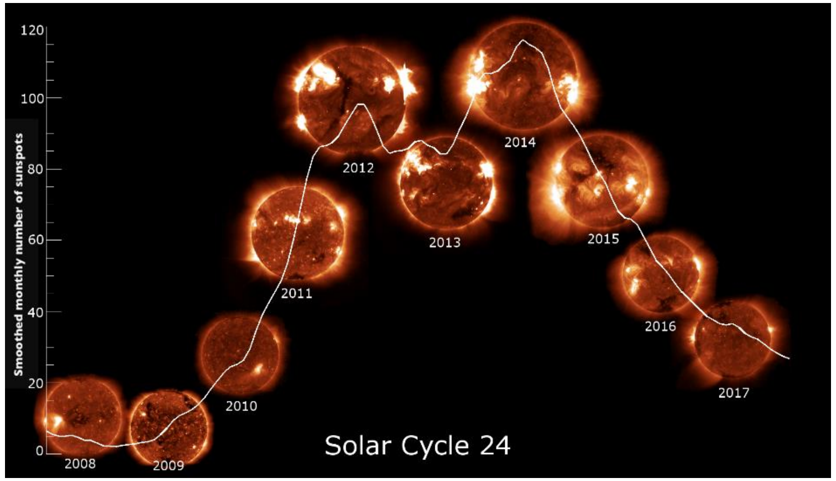
- ERF = Radiative forcing when all rapid adjustments for temperature (incl. the stratosphere), water vapor, surface albedo (snow, vegetation) and clouds are included in the response to a change in a forcing agent.
- Sea surface temperatures and sea ice cover are fixed.
- ERF = Effects of the forcing agent + of the rapid adjustments.



Source: Heinze et al., ESD, 2019

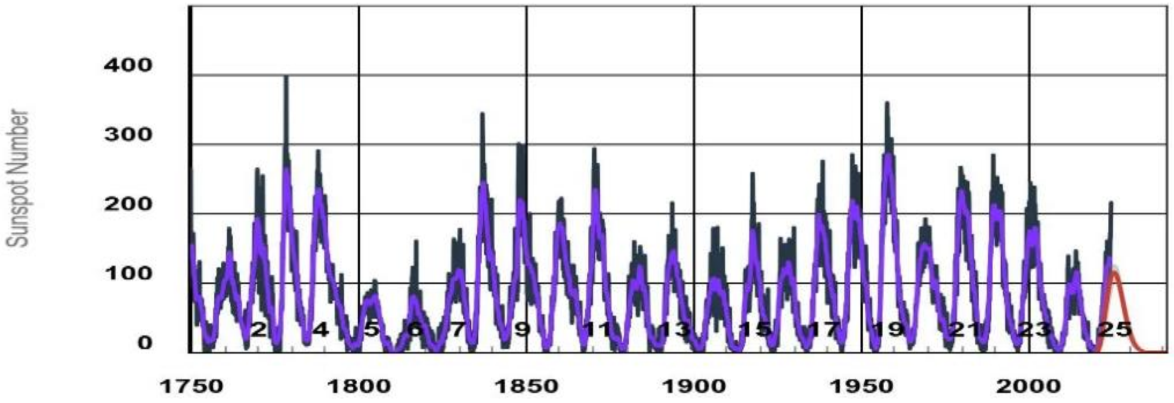
Natural external forcing factors: solar cycles

The Sun magnetic field flips completely between the north and south poles, every 11 years or so.
Illustration with the last cycle, number 24.



Warning: the images show active regions of the sun, not sunspots or flocculae

Source: [XRT satellite observations]

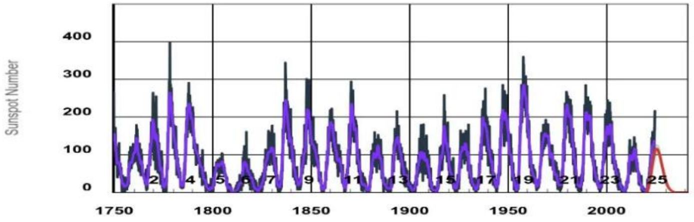


Source: [NOAA Space Weather Prediction Center]

It shows up as changes in the number of sunspots.

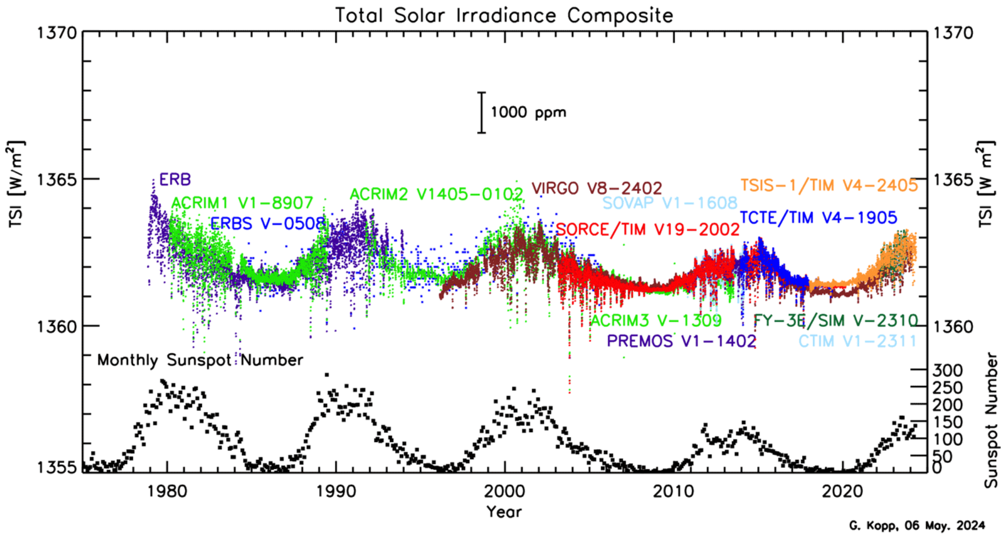
Largest number of sunspots:
- Maximum solar activity.
- Maximum of the «solar constant».

Natural external forcing factors: solar cycles

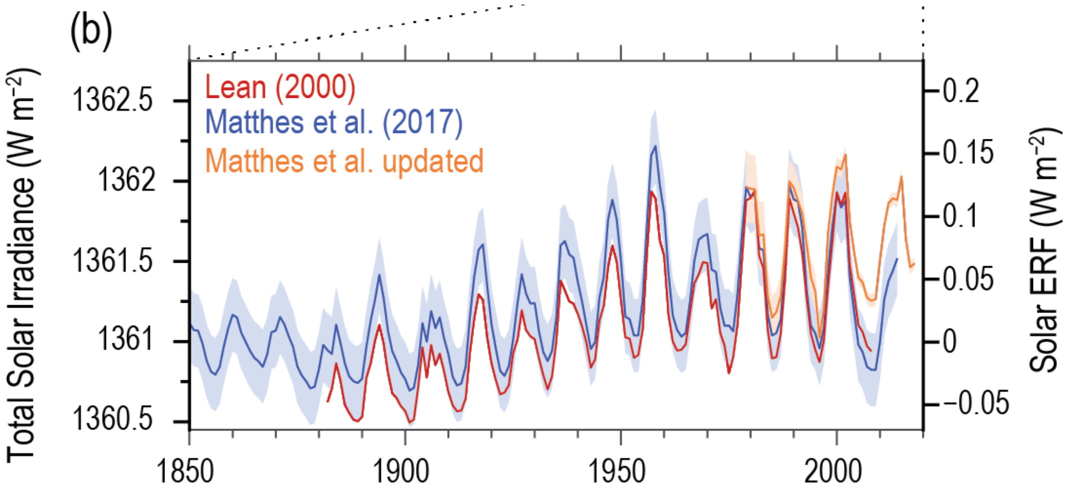


Source: NOAA Space Weather Prediction Center

- The effects of the 11-year solar cycle on solar irradiance on top of the atmosphere can be measured by satellites since 1978.
- Calibration issues to come up with correct absolute values.
- Relative changes of solar irradiance of 0.1%.
- Resulting changes of solar ERF: **0.15 W.m^{-2}**.



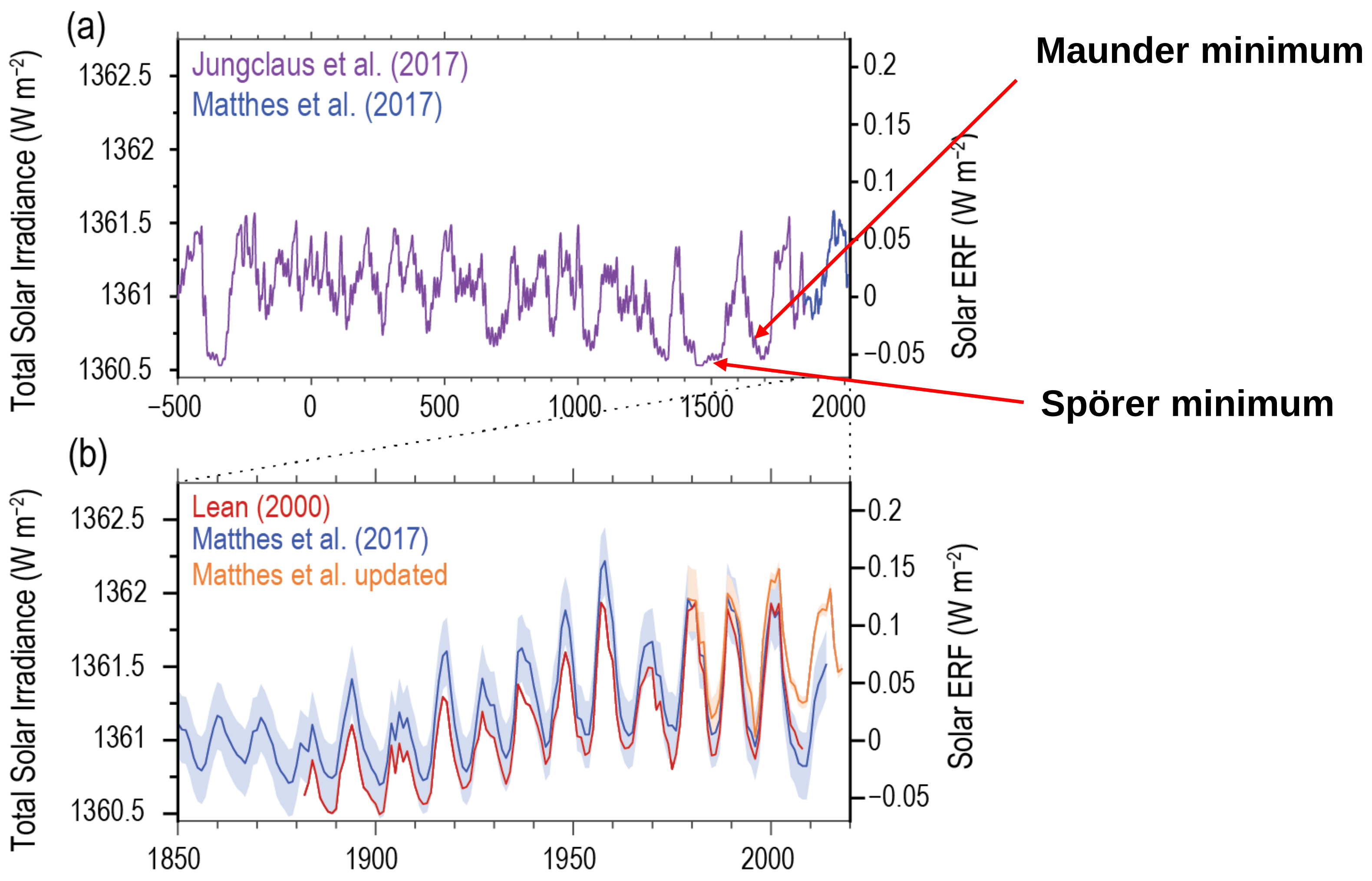
Source: Greg Kopp, Laboratory for Atmospheric and Space Physics (LASP)/University of Colorado (UC).



Source: IPCC AR6 Fig. 2.2.

Natural external forcing factors: solar cycles

Longer term perspective. Periods of time when solar activity was largely reduced (almost no sunspots).



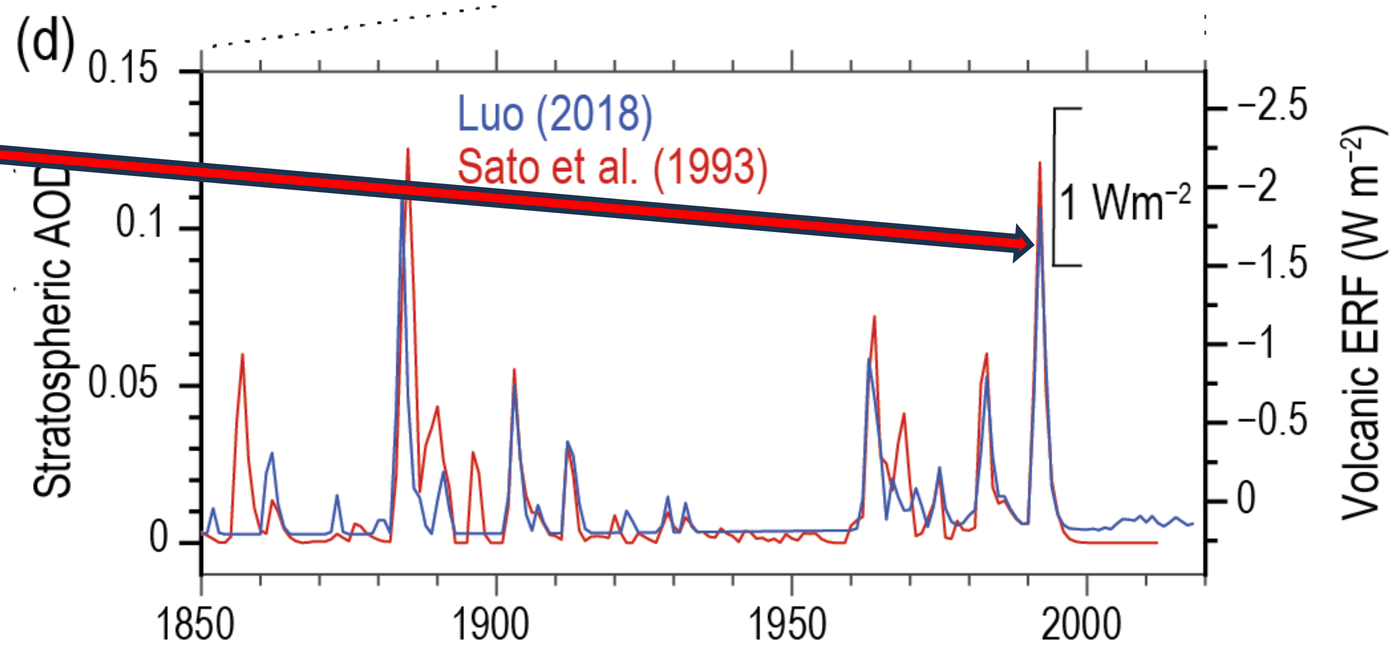
Source: *IPCC AR6 Fig. 2.2.*

Natural external forcing factors: volcanic eruptions

- Fast change in forcing.
- Large impact when vast amounts of SO_2 (and ash) is injected in the stratosphere (cooling effect by scattering of incoming solar radiation).
- Strong ERF, but lasting only one to three years.

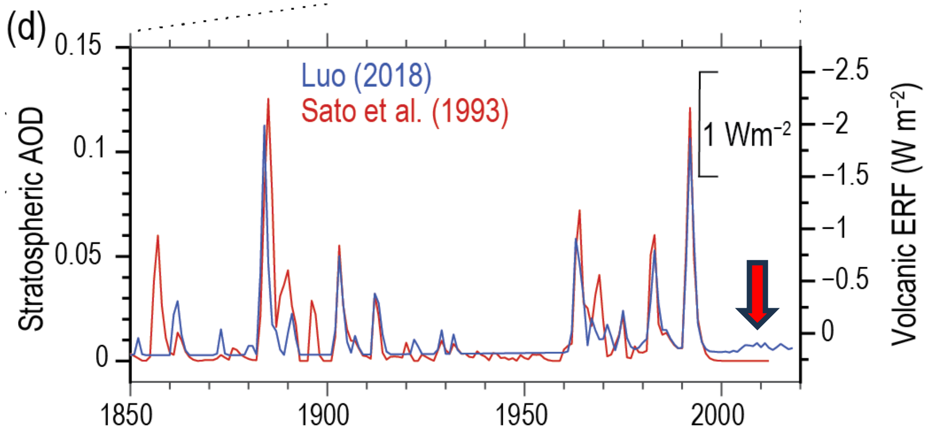
Mount Pinatubo eruption, Philippines, April-Sept. 1991

Source: USGS/Cascades Volcano Observatory



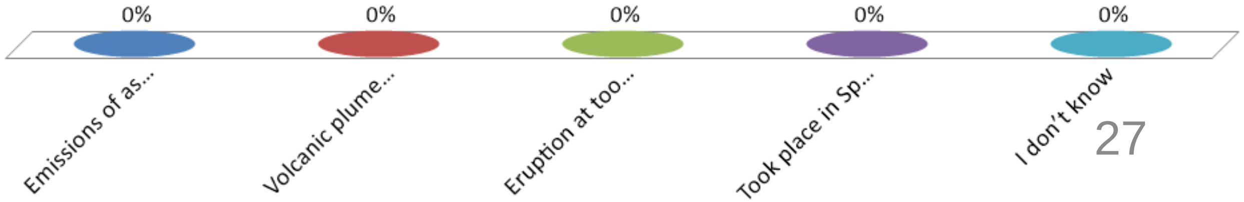
Source: IPCC AR6 Fig. 2.2.

Why the Eyjafjallajökull eruption in 2010 does not show up ?



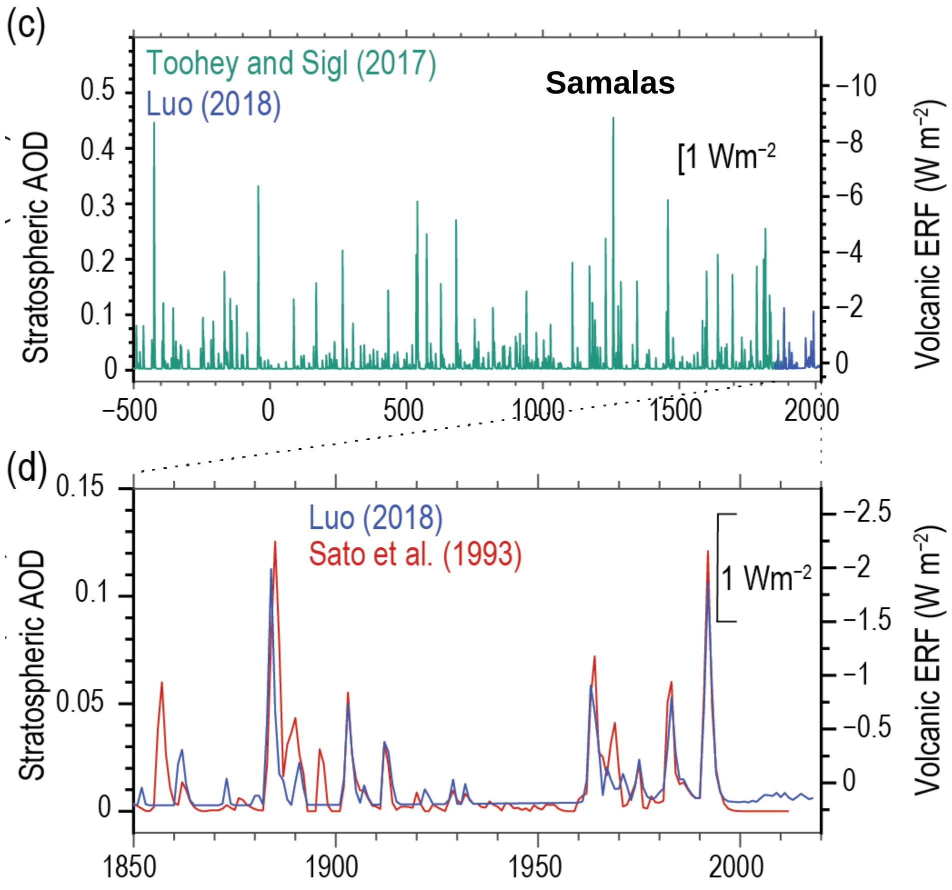
Source: Boaworm, Wikipedia

A. Emissions of ash in addition to SO_2
B. Volcanic plume not high enough ✓
C. Eruption at too high latitude
D. Took place in Spring time
E. I don’t know

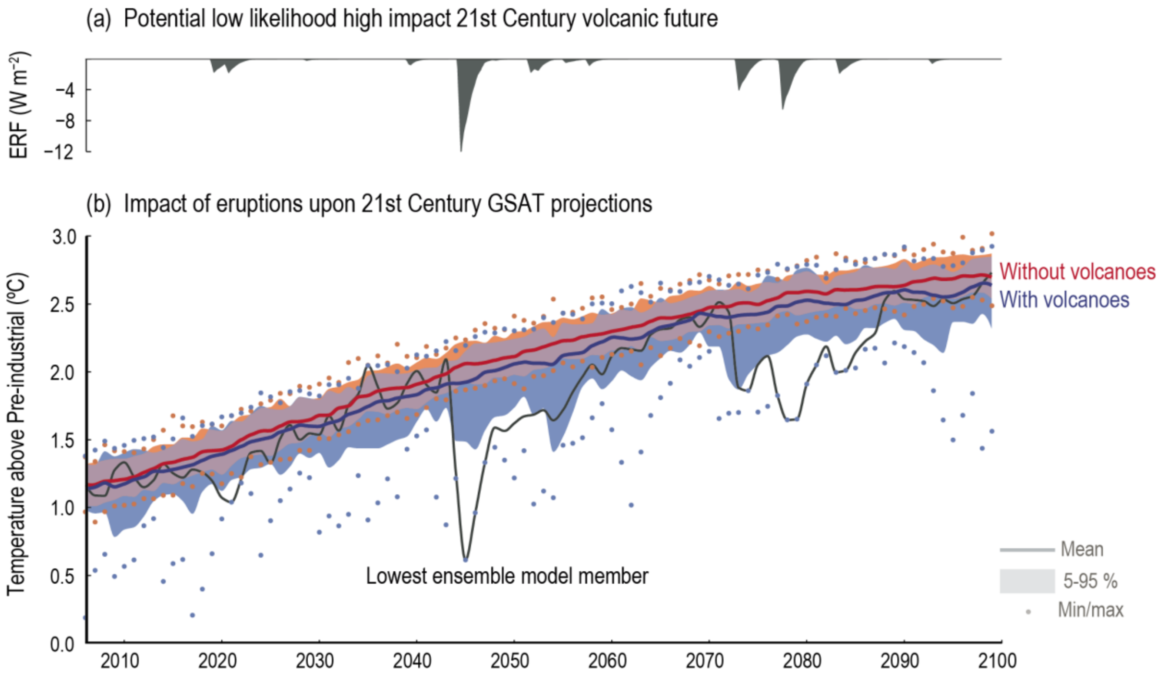


Natural external forcing factors: volcanic eruptions

Longer term perspective. Even stronger events during the last two millennia. What about the future ?



Source: [IPCC AR6 Fig. 2.2.]

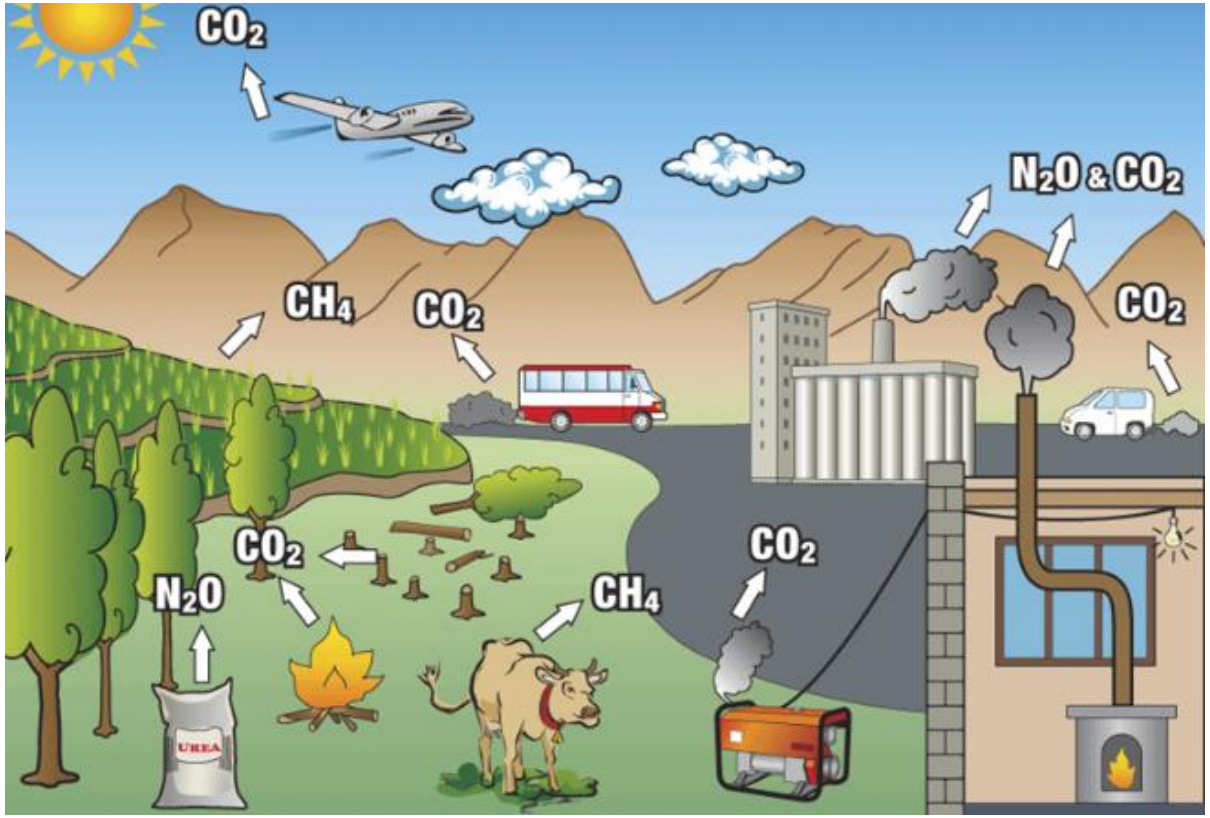


Source: [IPCC AR6, cross-chapter Box 4.1, Figure 1]

See conference by Michael Sigl on March 18th !

Anthropogenic greenhouse effect: the main contributor today

- The intensification of the greenhouse effect by human activities results from:
  - an increase in greenhouse gases,
  - changes of the aerosol concentrations,
  - change of aerosol composition.



Source: Climate Emergency Institute

Main anthropogenic greenhouse gases

Greenhouse gas	Chemical formula	Major sources	Atmospheric lifetime (years)
Carbon Dioxide	CO_2	Fossil fuel combustion. Deforestation. Cement production	100 (not univoque)
Methane	CH_4	Fossil fuel production. Agriculture. Landfills. Biomass burning.	12
Nitrous Oxide	N_2O	Fertilizer application. Fossil fuel and biomass combustion. Industrial processes.	121
Chlorofluorocarbon-12 (CFC-12)	CCl_2F_2	Refrigerants	100
Hydrofluorocarbon-23 (HFC-23)	CHF_3	Refrigerants	222
Sulfur Hexafluoride	SF_6	Electricity transmission	3,200
Nitrogen Trifluoride	NF_3	Semiconductor manufacturing	500

Exchanges with C reservoirs (Carbon Dioxide)

Destruction in the atmosphere (Methane to Nitrogen Trifluoride)

- *Source: IPCC AR5, and https://gml.noaa.gov/*

Anthropogenic greenhouse gases: different global warming potential (GWP)

- Definition of Global Warming Potential (GWP): « *A measure of how much energy the emissions of 1 ton of a GHG will absorb over a given period of time, relative to the emissions of 1 ton of CO_2* ».

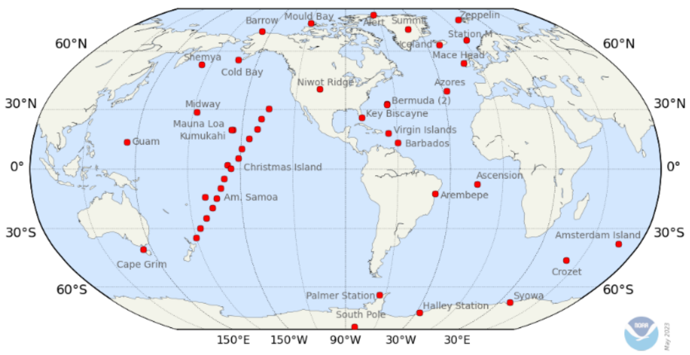
- It's a practical metric to homogenize the impact of different GHG. Important for policymakers.

- It depends on:
  - The radiative properties of the molecule.
  - The atmospheric lifetime of the molecule.

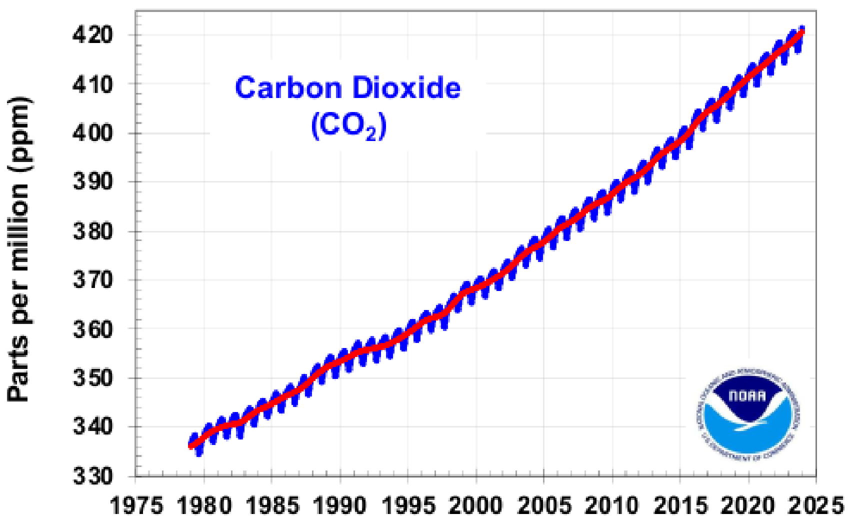
- Due to its relatively short lifetime, the GWP of methane becomes only 30 over 100 years. And 10 over 500 years.

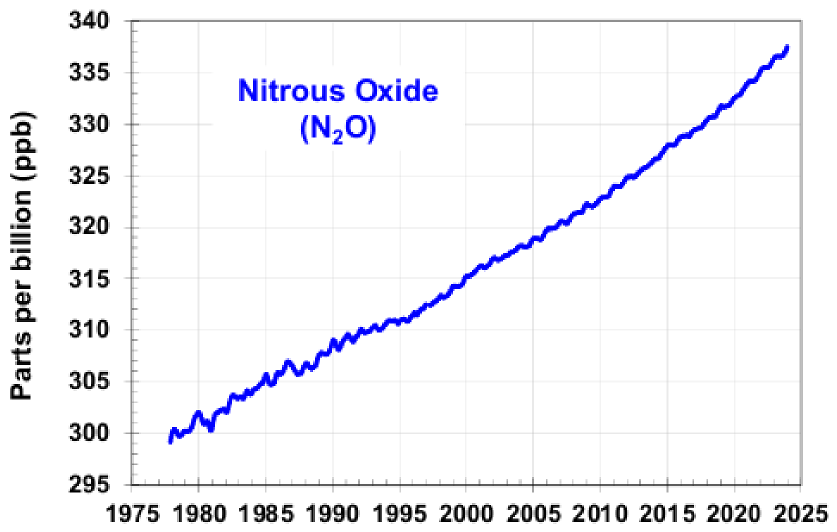
Greenhouse gas	Chemical formula	Atmospheric lifetime (years)	Global Warming Potential on 20 years
Carbon Dioxide	CO_2	100 (not univoque)	1
Methane	CH_4	12	83
Nitrous Oxide	N_2O	121	273
Chlorofluorocarbon-12 (CFC-12)	CCl_2F_2	100	10,800
Hydrofluorocarbon-23 (HFC-23)	CHF_3	222	12,400
Sulfur Hexafluoride	SF_6	3,200	17,500
Nitrogen Trifluoride	NF_3	500	12,800

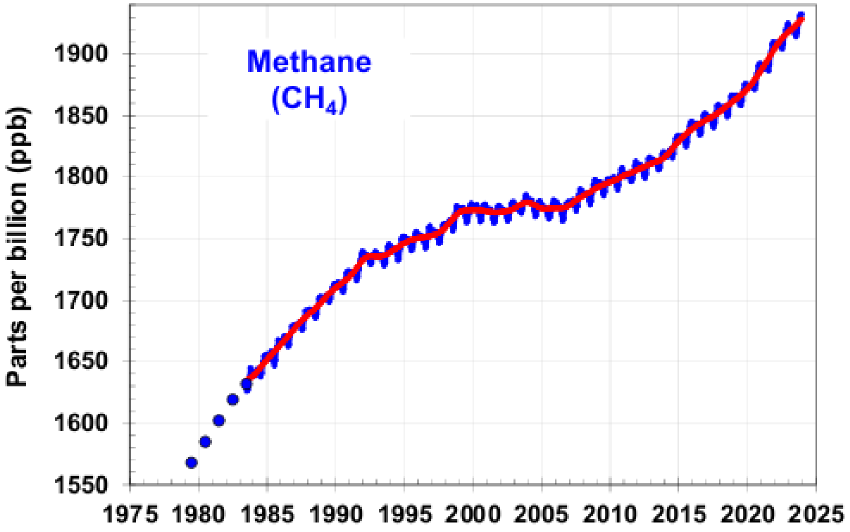
Anthropogenic greenhouse gas evolution

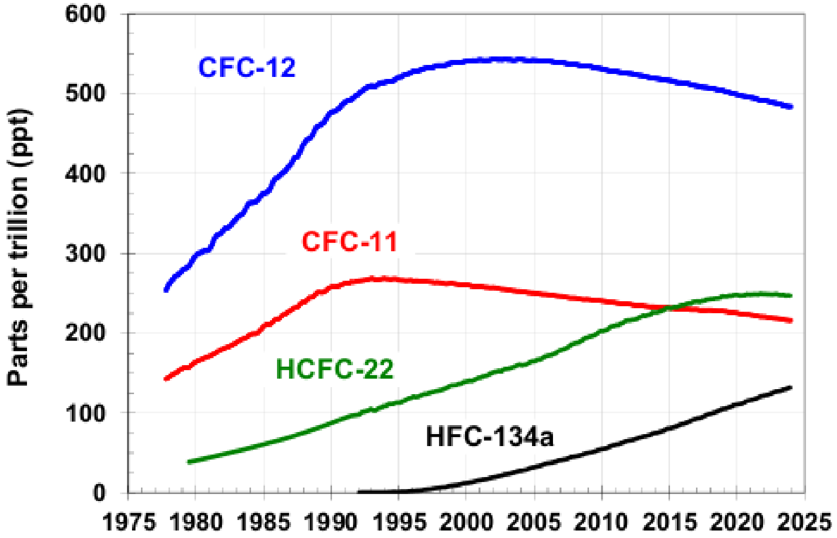


- Direct measurements in the atmosphere from the NOAA Global Greenhouse Gas Reference Network.
- Annual cycles due seasonal changes of sources / sinks.
- Slight acceleration of CO_2 and N_2O rates of increase. Temporary slowdown of the CH_4 increase during the years ~1998 to 2007.
- Montreal Protocol in 1989 (reduction of the ozone hole): replacement of CFCs by HFCs and other halogenated compounds.



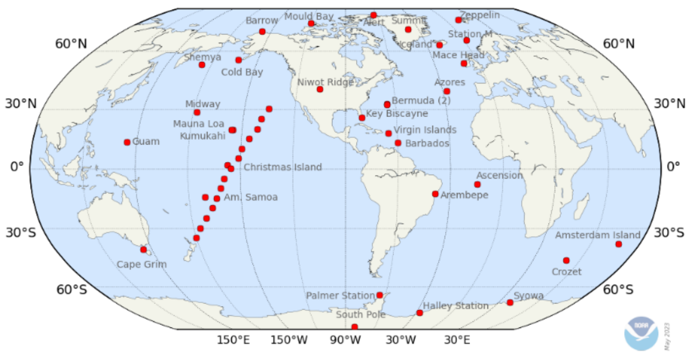




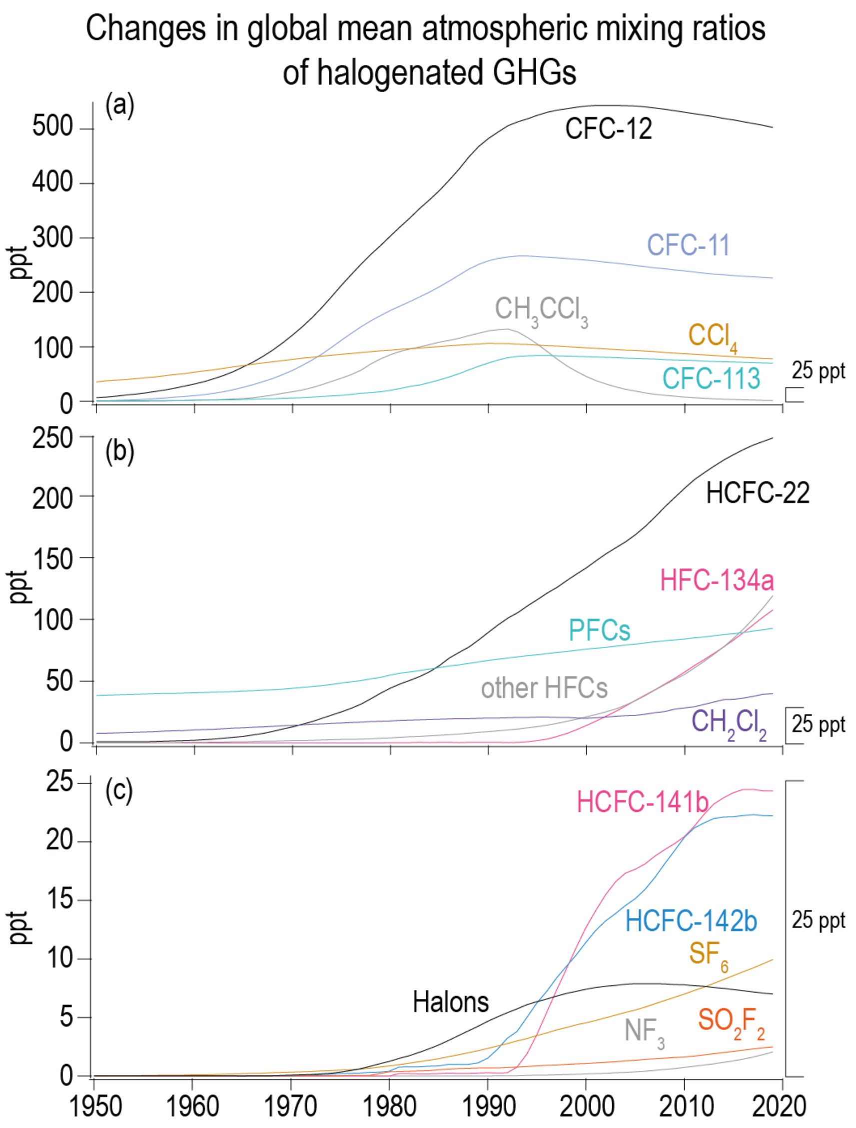


Source: NOAA GML

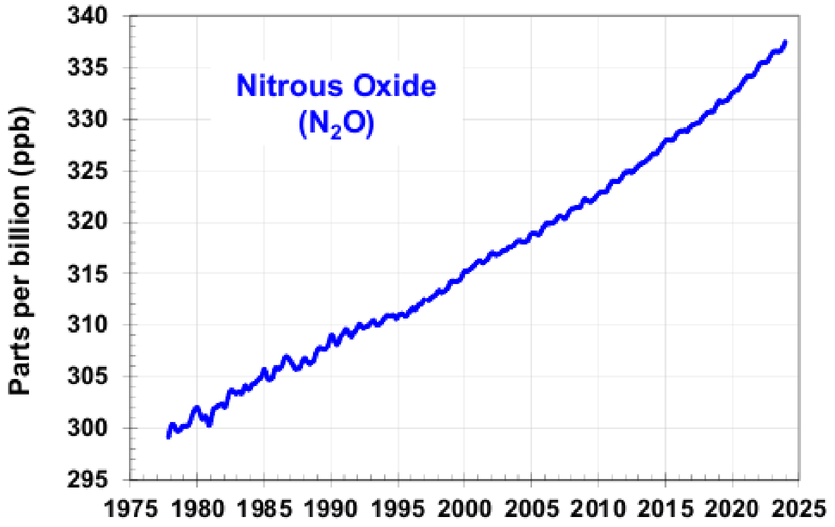
Anthropogenic greenhouse gas evolution

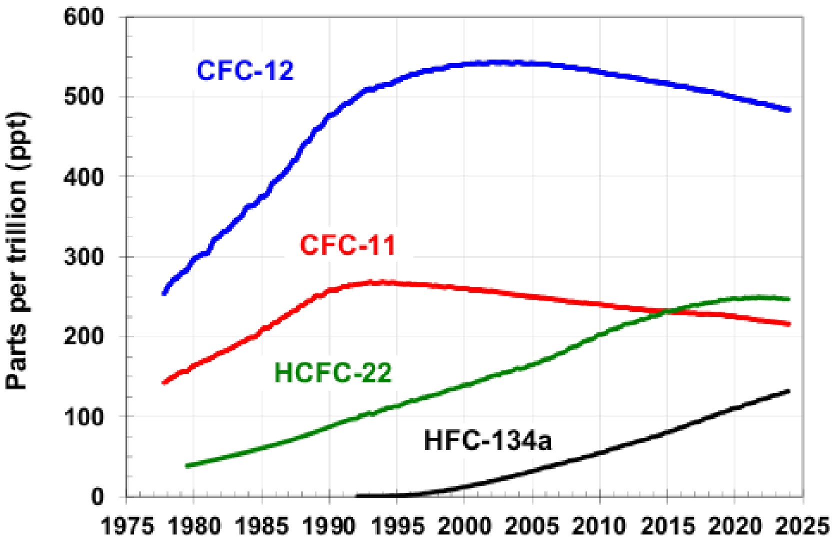


- Montreal Protocol in 1989 (reduction of the ozone hole): replacement of CFCs by HFCs and other halogenated compounds.
- Be careful at the concentration scale:
  - **10^{-12}** instead of 10^{-9} for CH_4 and N_2O and 10^{-6} for CO_2 !



Source: IPCC AR6 Fig. 2.6

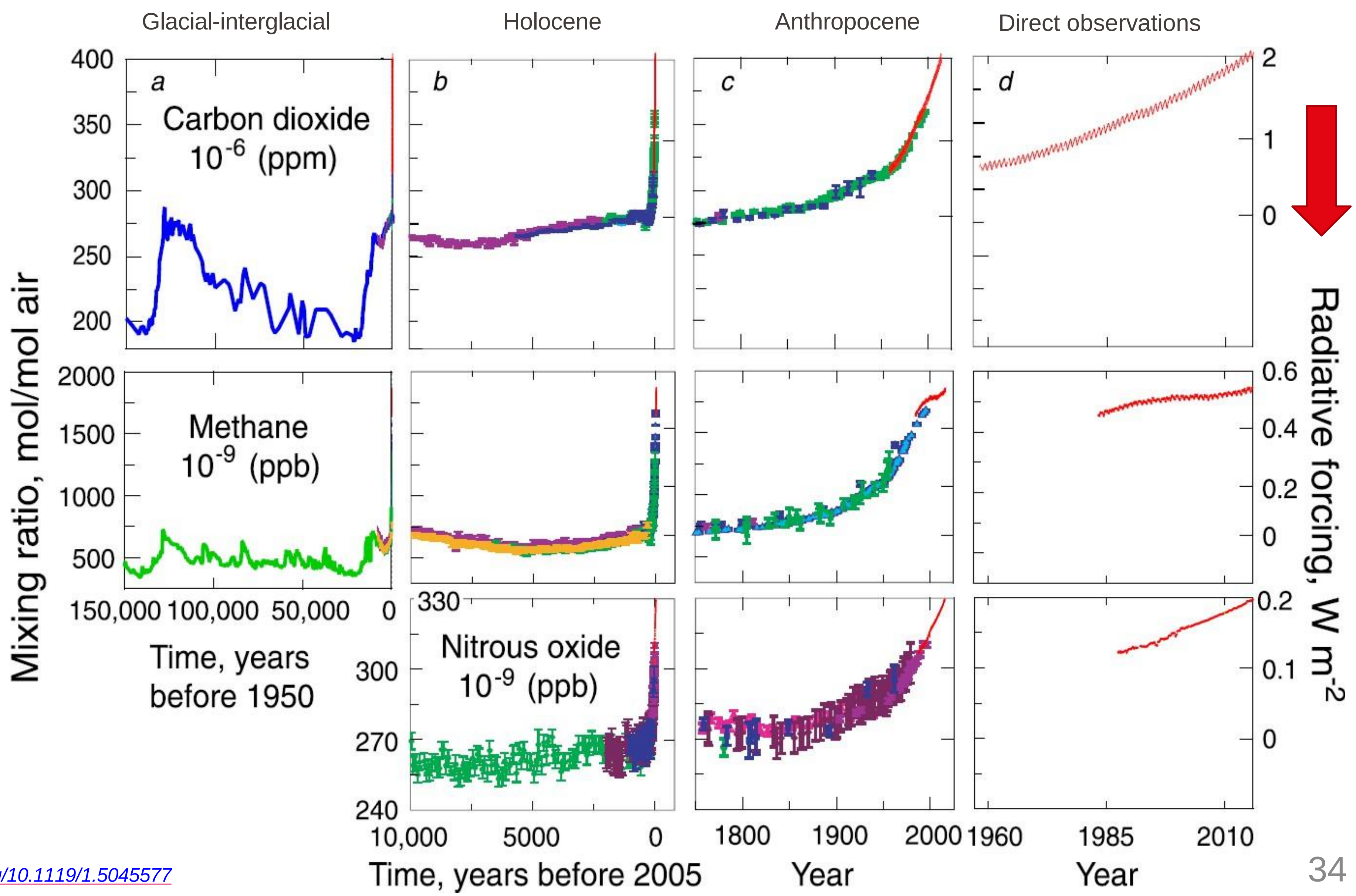




Source: NOAA GML

Anthropogenic greenhouse gas evolution

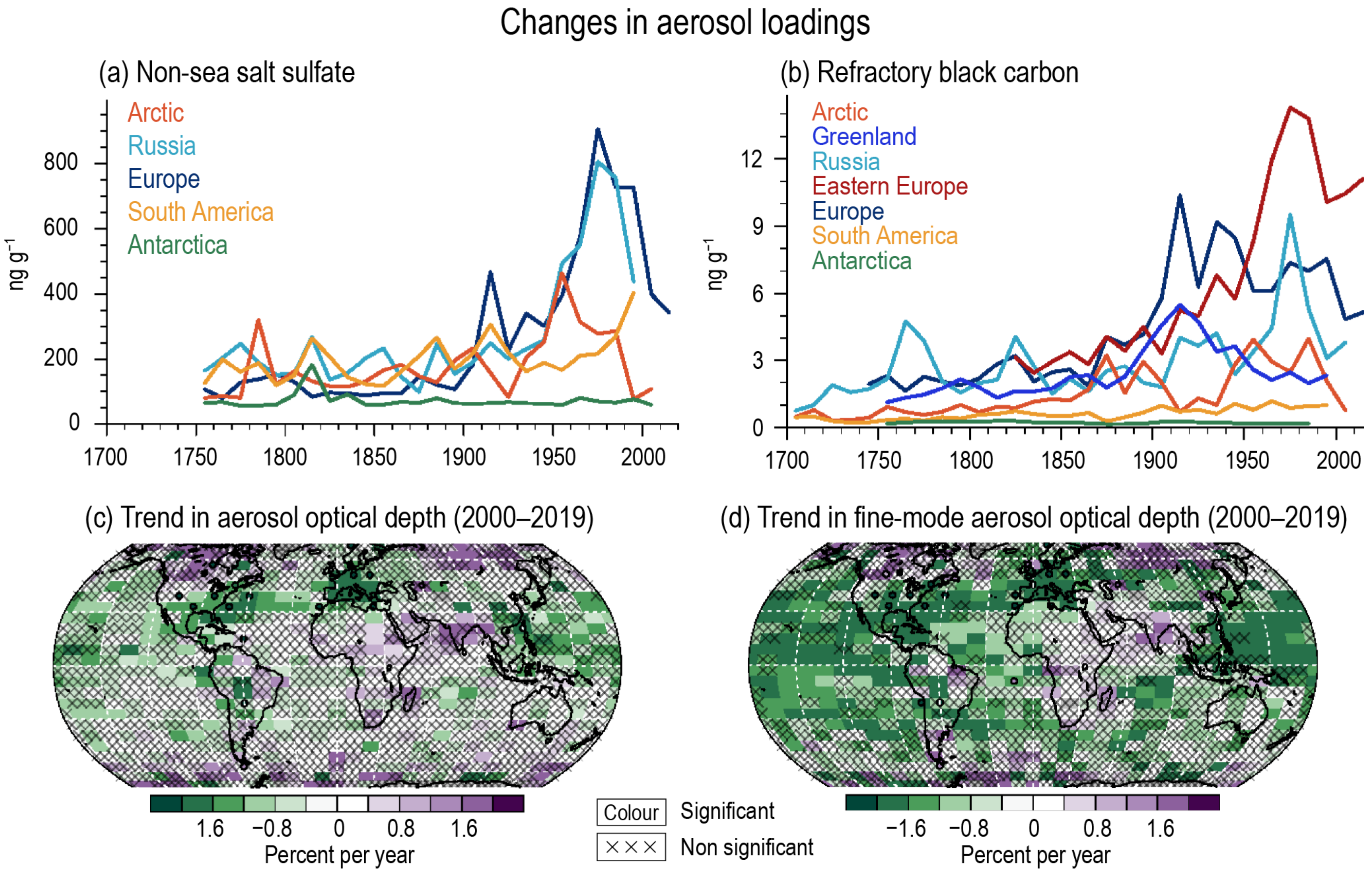
- CO_2 radiative forcing RF since pre-industrial times: **+2 W.m^{-2}**.



Source: Schwartz 2018 https://doi.org/10.1119/1.5045577

Anthropogenic aerosol evolution

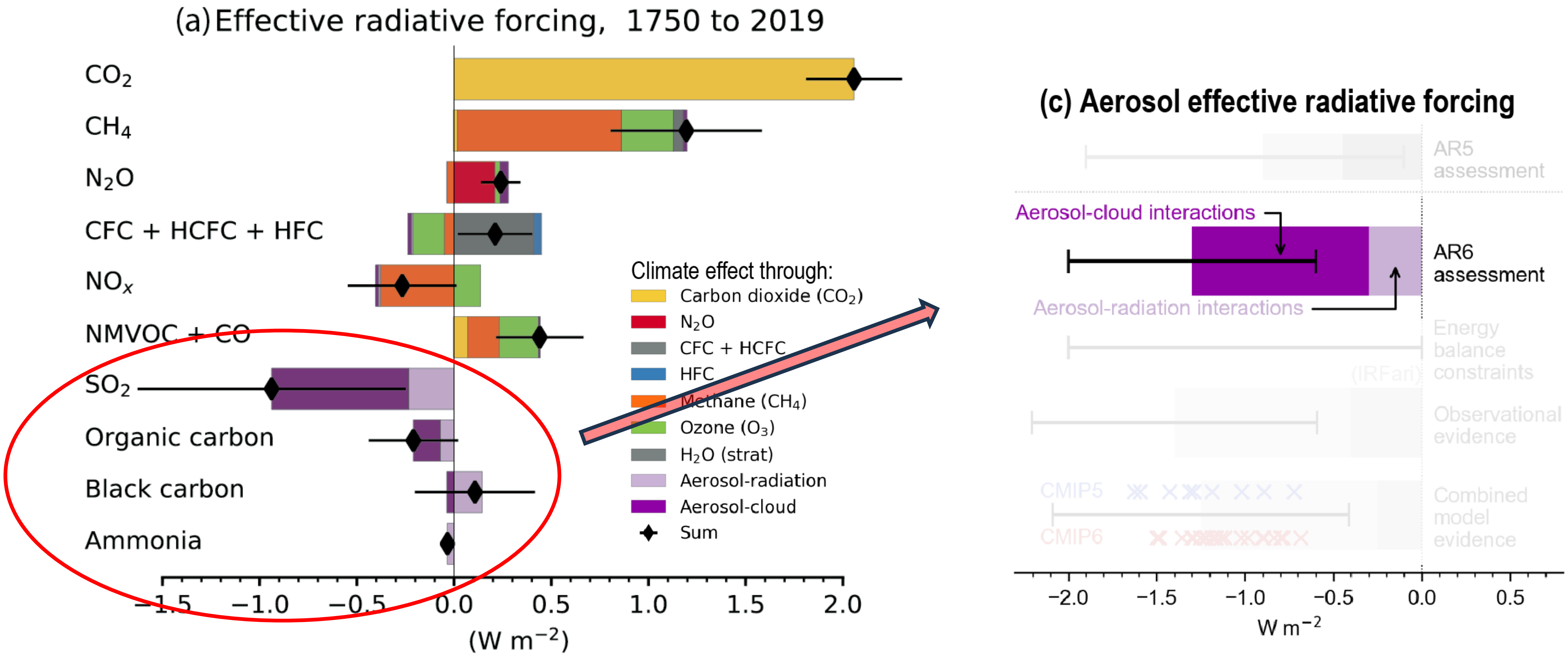
- Aerosol lifetimes much shorter (hours to days) than GHG, as they are removed by precipitation and gravitational settling.
- Long-term trends deduced from ice core analyses from different mountain ranges.
- Short-term trends from satellite measurements of aerosol optical depth.
- Large spatial differences due to distance to the sources and to air-quality policies.
- The 1970s-1980s have been times of highest anthropogenic aerosol loading.



Source: [IPCC AR6 Fig. 2.9]

ERF of each contributor

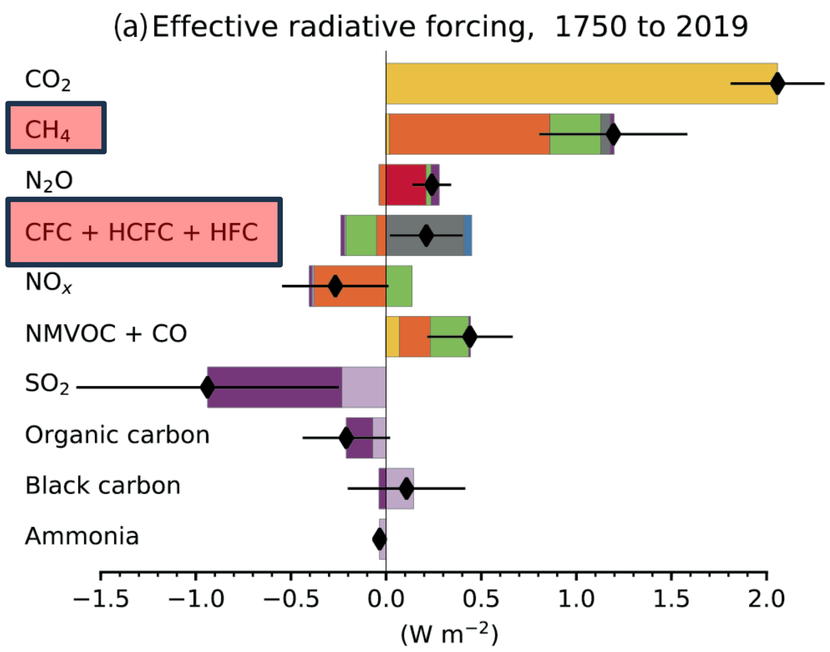
- Anthropogenic emissions of GHG contributed a total ERF of **3.84 W m^{-2}** *(3.46 – 4.22)* since 1750.
- Reminder: TOA outgoing longwave radiation is -240 W m^{-2}.
- Largest uncertainty: aerosols and clouds.



Negative leads to temperature decrease | Positive forcing leads to temperature increase

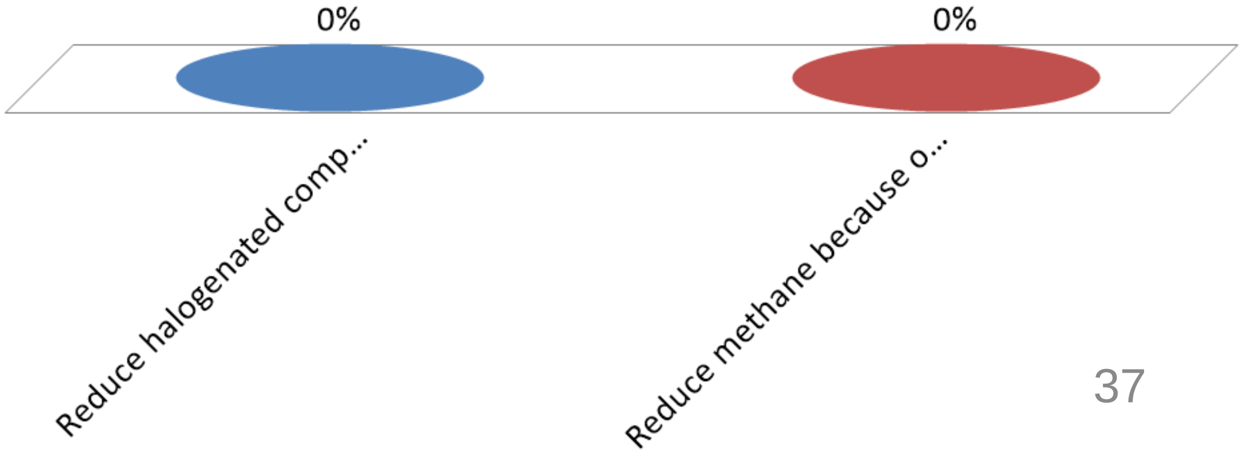
Source: [IPCC AR6 Fig. TS.15]

Which priority in reducing GHG emissions ?



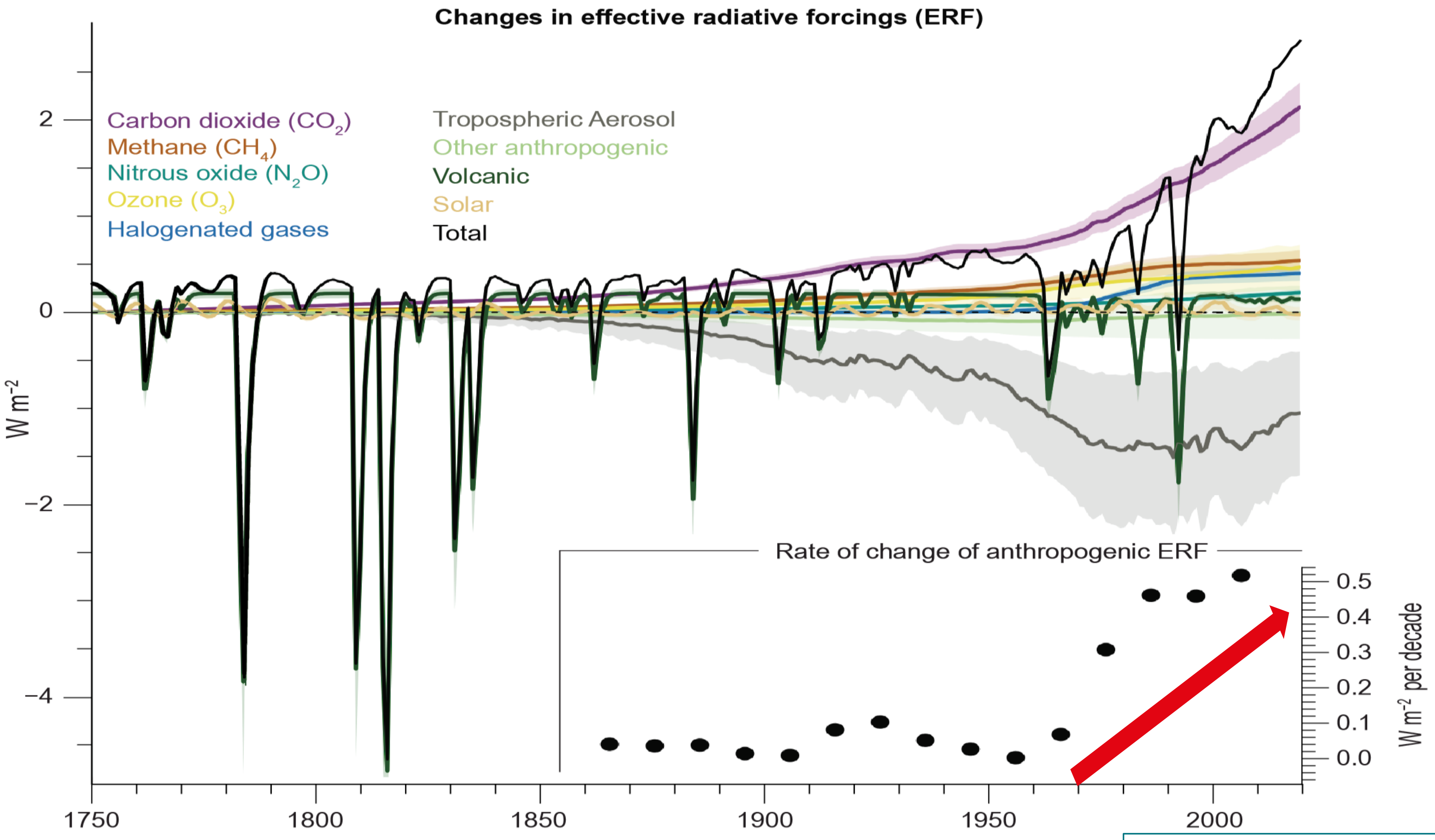
A. Reduce halogenated compounds because of their very long lifetime and very large global warming potential GWP.

B. Reduce methane because of its relatively short lifetime and large global warming potential GWP.



Total ERF of different forcings

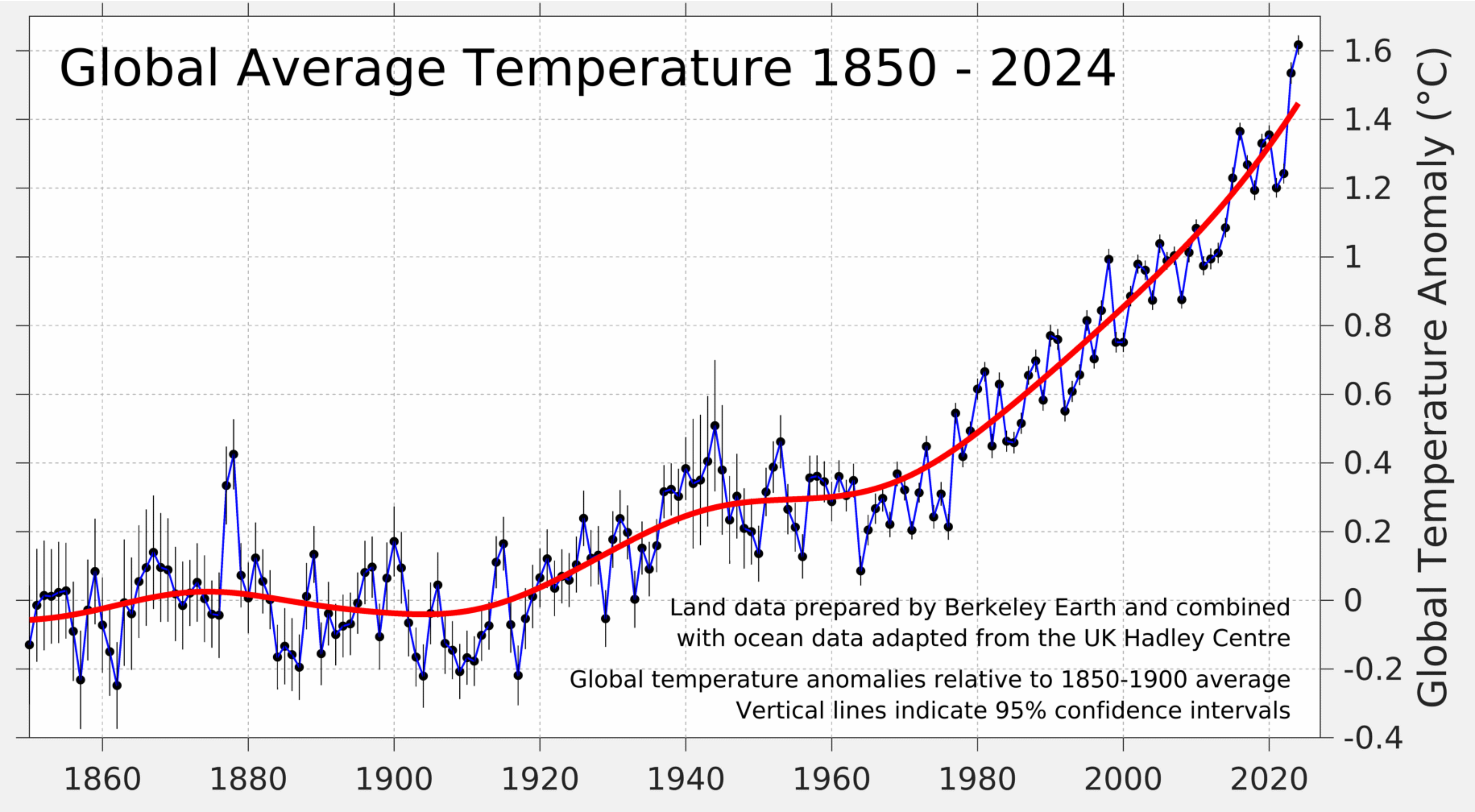
Total ERF in 2020: **2.72 W.m^{-2}** since 1750.



Rate of forcing is increasing as well!

Source: IPCC AR6, Fig. 2.10

What about global mean surface temperature (GMST) changes ?

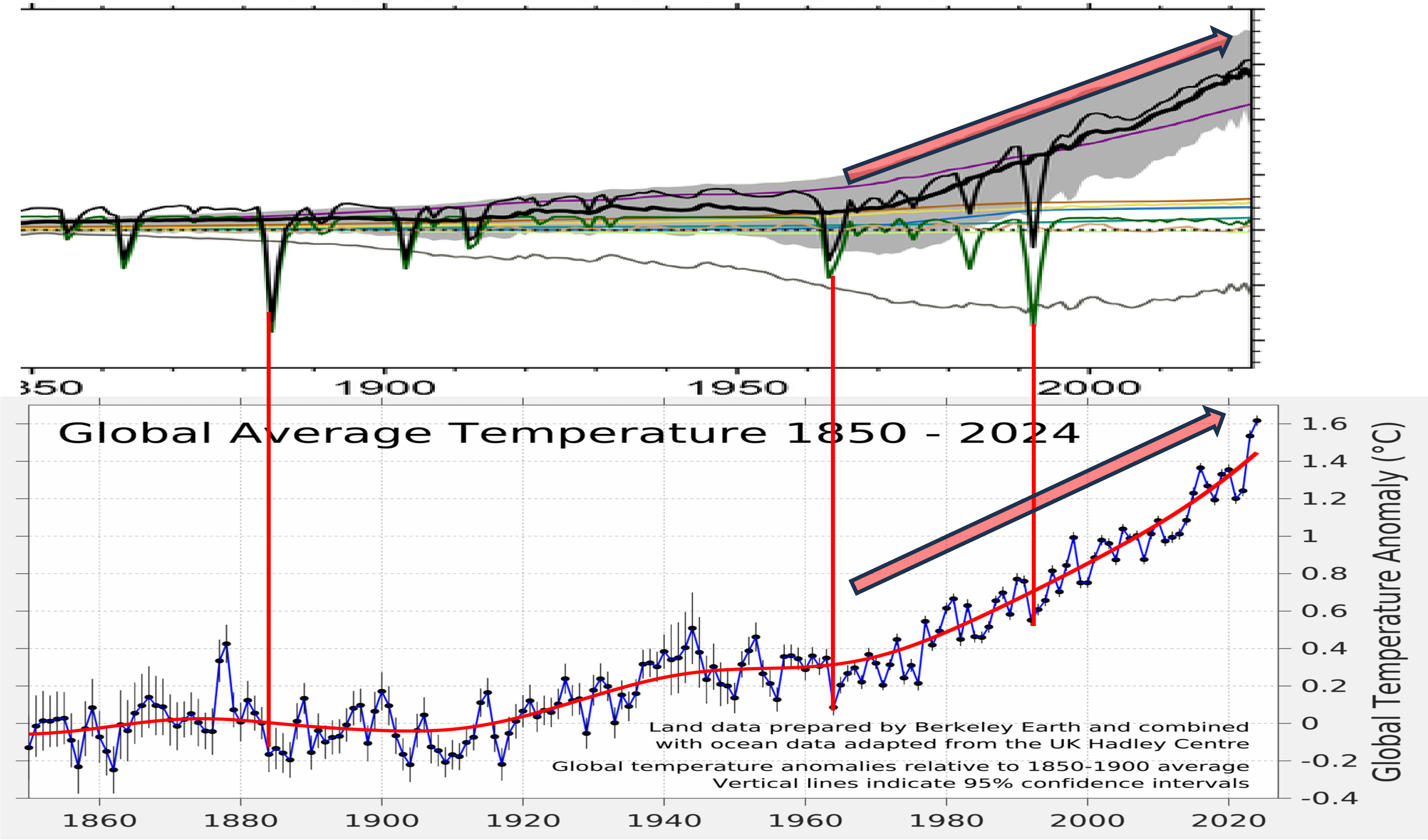


Global annual average for **2024** is **+1.62°C** compared with the average period 1850-1900.

IPCC: *Likely* range of total anthropogenic increase of global surface temperature between 1850– 1900 and 2010–2019 is +0.8°C to +1.3°C.
Best estimate of +1.07°C.

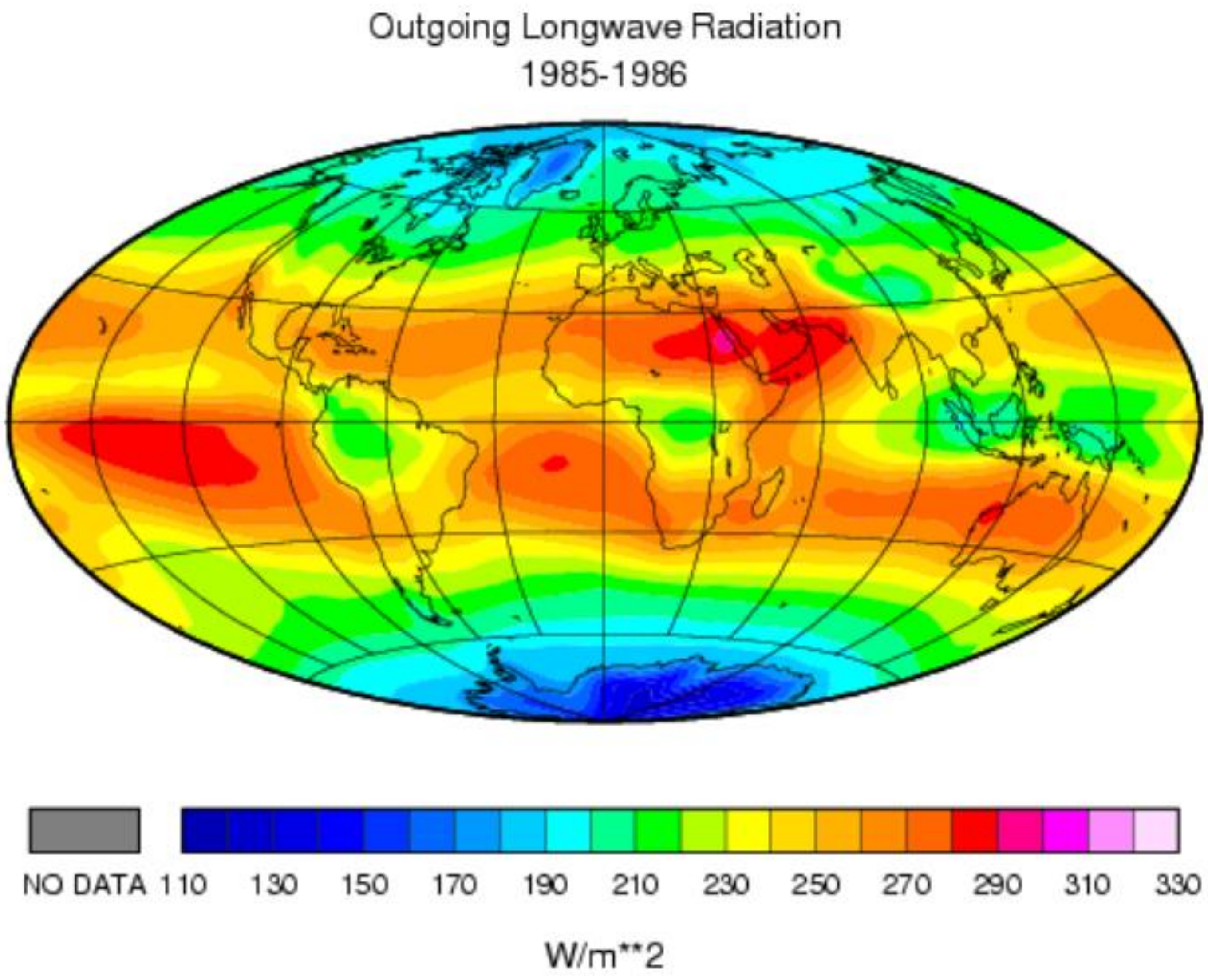
- *Source: Berkeley annual temperature report for 2024*

How do GMST and ERF compare ?



- *Source: [Berkeley annual temperature report for 2024]*

GHG ERF cannot be measured



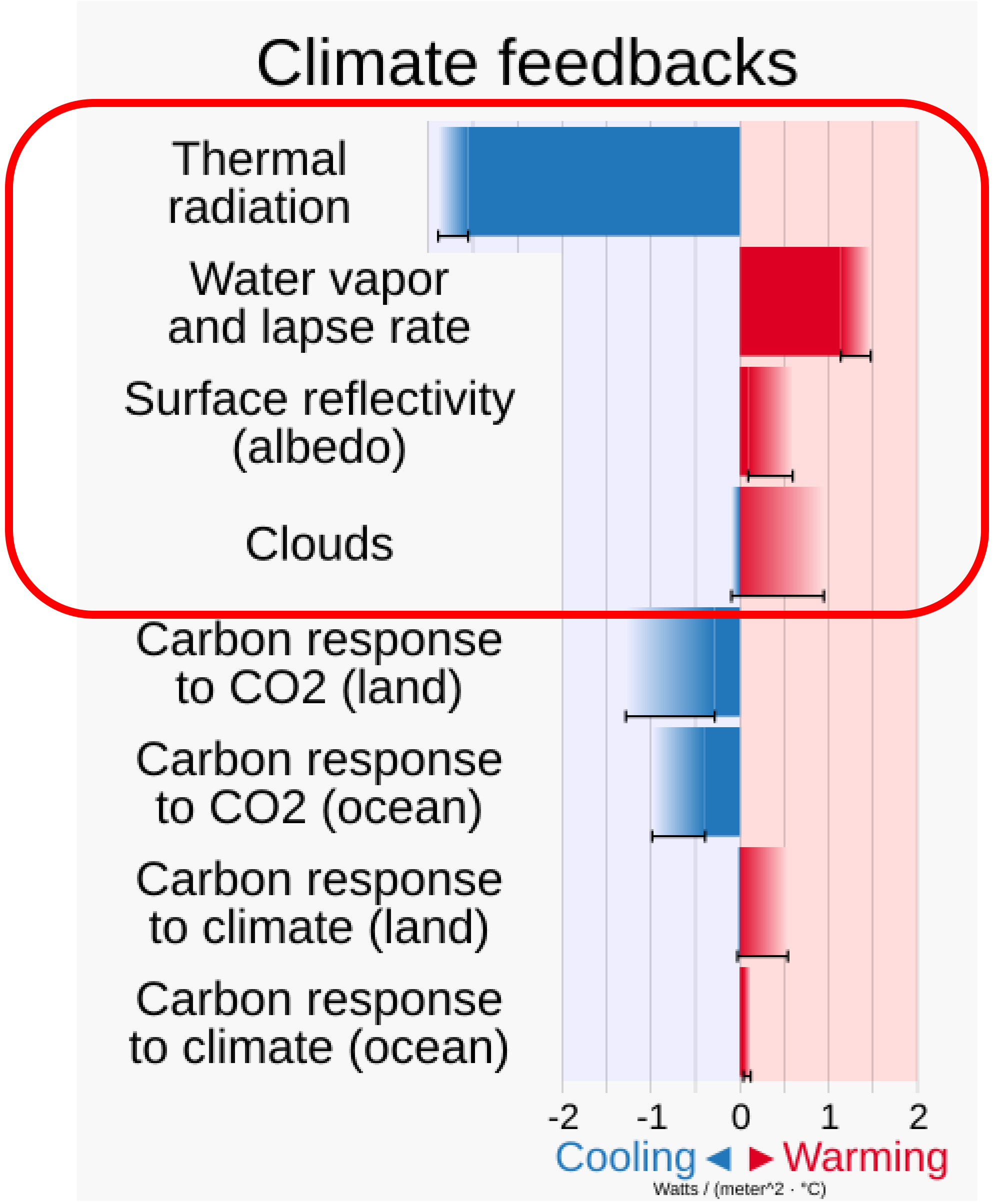
- GHG ERF since 1750 is **3.84 W m^{-2}**
- Net anthropogenic ERF is **2.72 W m^{-2}**
- Annual global average outgoing longwave radiation is **240 W m^{-2}**
- GHG ERF cannot be measured directly, but only calculated.
- Calculations depend on the realism of models (water vapor, clouds).


Feedbacks

Climate feedbacks

- Feedback: Process amplifying **(positive feedback)** or dampening **(negative feedback)** the effects of radiative forcing. Analogy with electrical engineering: amplifier. A portion of the output from the action of a system is added to the input and thus alters the output. **Unit: $W.m^{-2}.°C^{-1}$.**

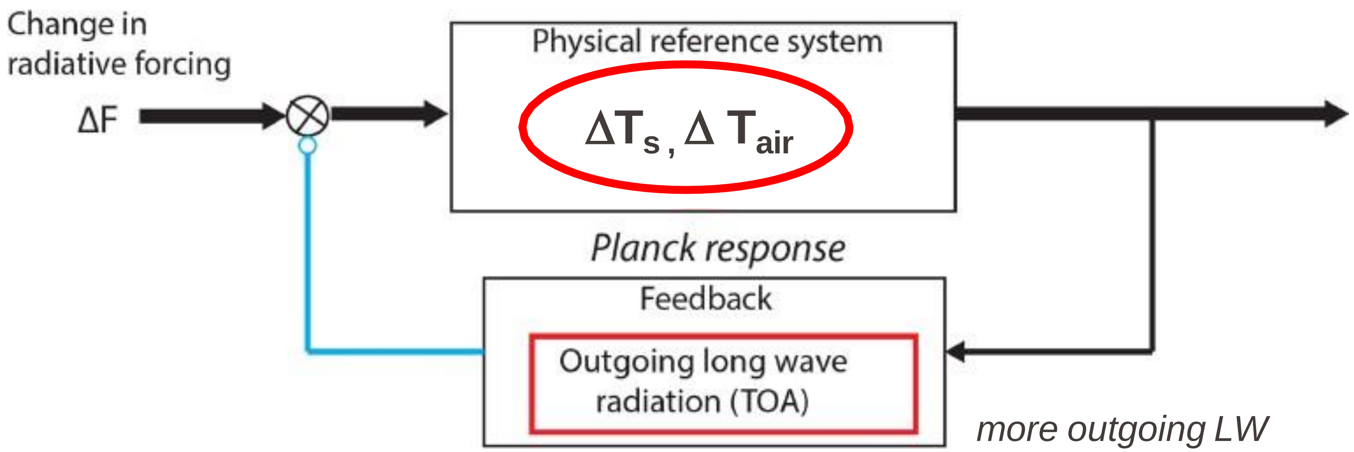
- We will focus on the fast physical ones, which are important to evaluate the climate sensitivity in the context of the 21st century warming.



Source: Wikimedia

Planck response

ΔT_s change in surface temperature
ΔT_{air} change in air temperature



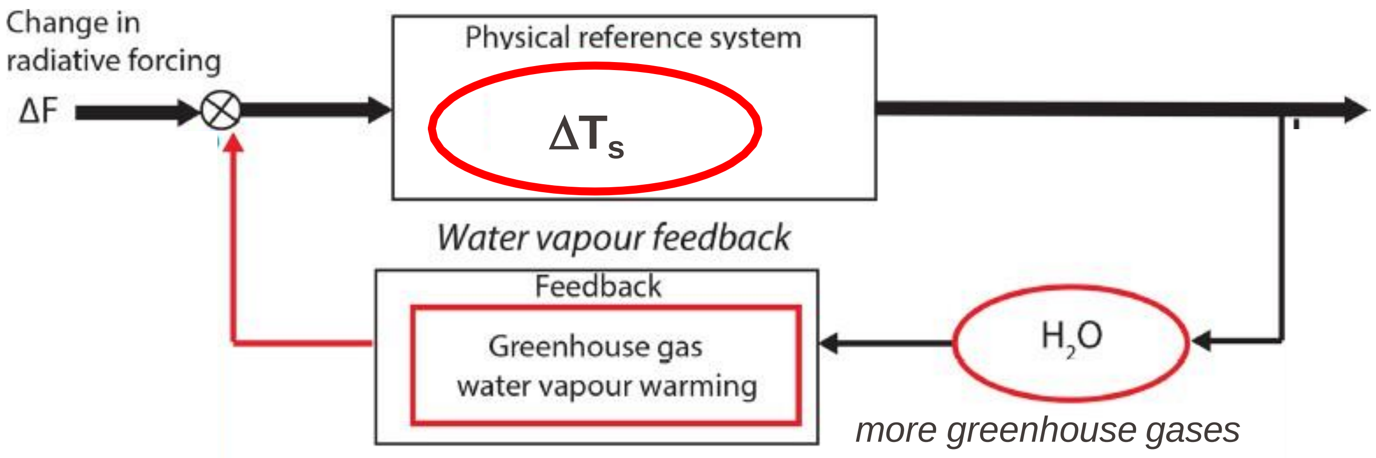
$$F_B = \sigma T^4$$

λ = -3.8 W.m^{-2}.°C^{-1}

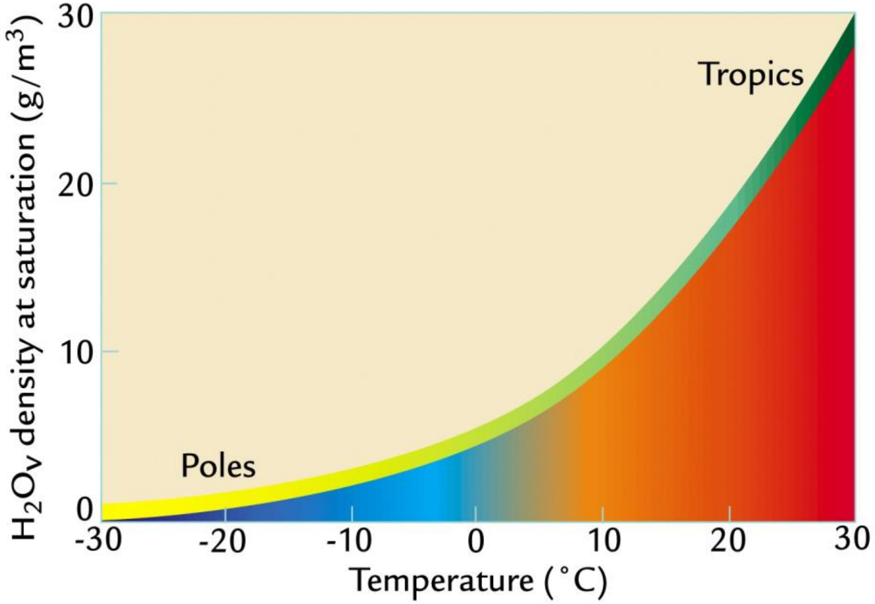
- **Single largest negative feedback** in the climate system.
- According to Stefan-Boltzmann law, surface and air warming leads to increased longwave radiation towards space.
- It is the main feedback tempering the effect of increased radiative forcing.

Source: *[Heinze et al., ESD, 2019]*

Water vapour and lapse rate feedbacks



λ = 1.8 W.m^{-2}.°C^{-1}



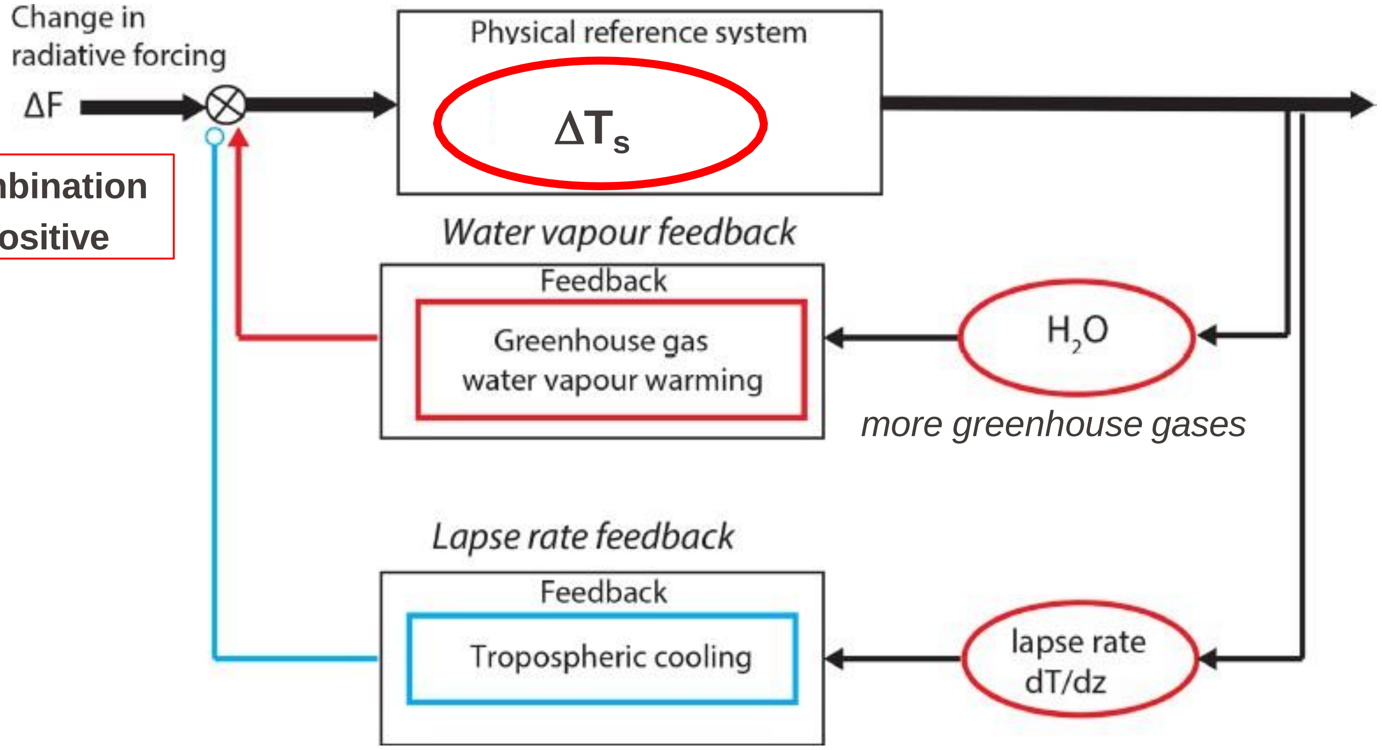
Water vapour feedback:

- The warmer the atmosphere, the more water vapor it can hold.
- Water vapor is a greenhouse gas with a RF ~proportional to the logarithm of its concentration.
- Weak effect at the poles because of low moisture content. Strong effect in the Tropics where warm air can hold lots of moisture.

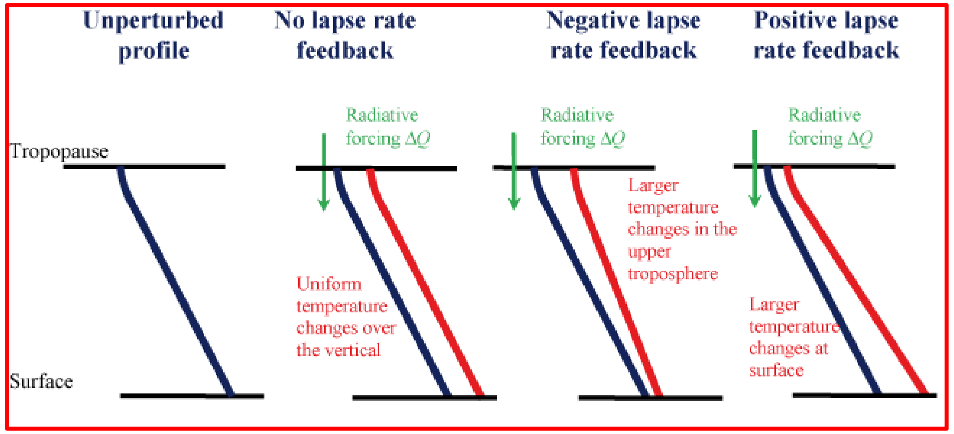
- *Source: Heinze et al., ESD, 2019*

Water vapour and lapse rate feedbacks

Combination is positive



$\lambda = -0.8\ W.m^{-2}.°C^{-1}$



Source: Université catholique de Louvain

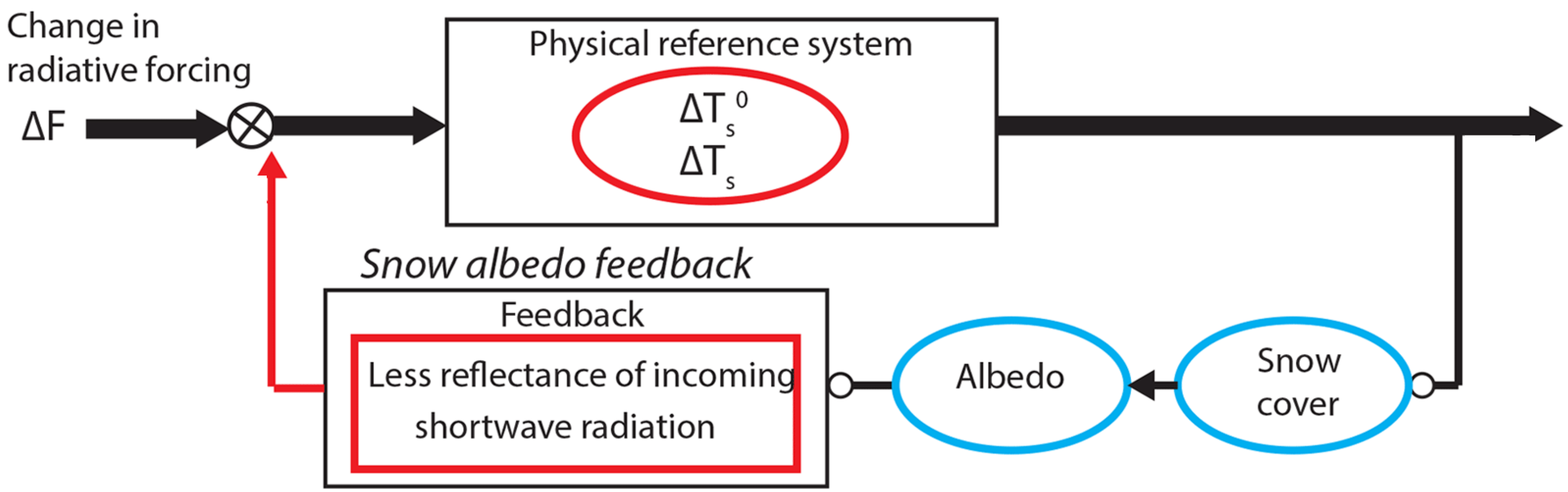
Lapse rate feedback:

- In particular in the Tropics, more convection due to RF leads to warming of the upper troposphere.
- This weakens the lapse rate.
- The upper troposphere then emits more longwave radiation towards space than without this feedback.
- It's generally a negative feedback *(except in the Arctic where the surface warms more than the upper troposphere)*.

Source: Heinze et al., ESD, 2019

Surface albedo feedback

ΔT_s change in surface temperature
ΔT_{air} change in air temperature



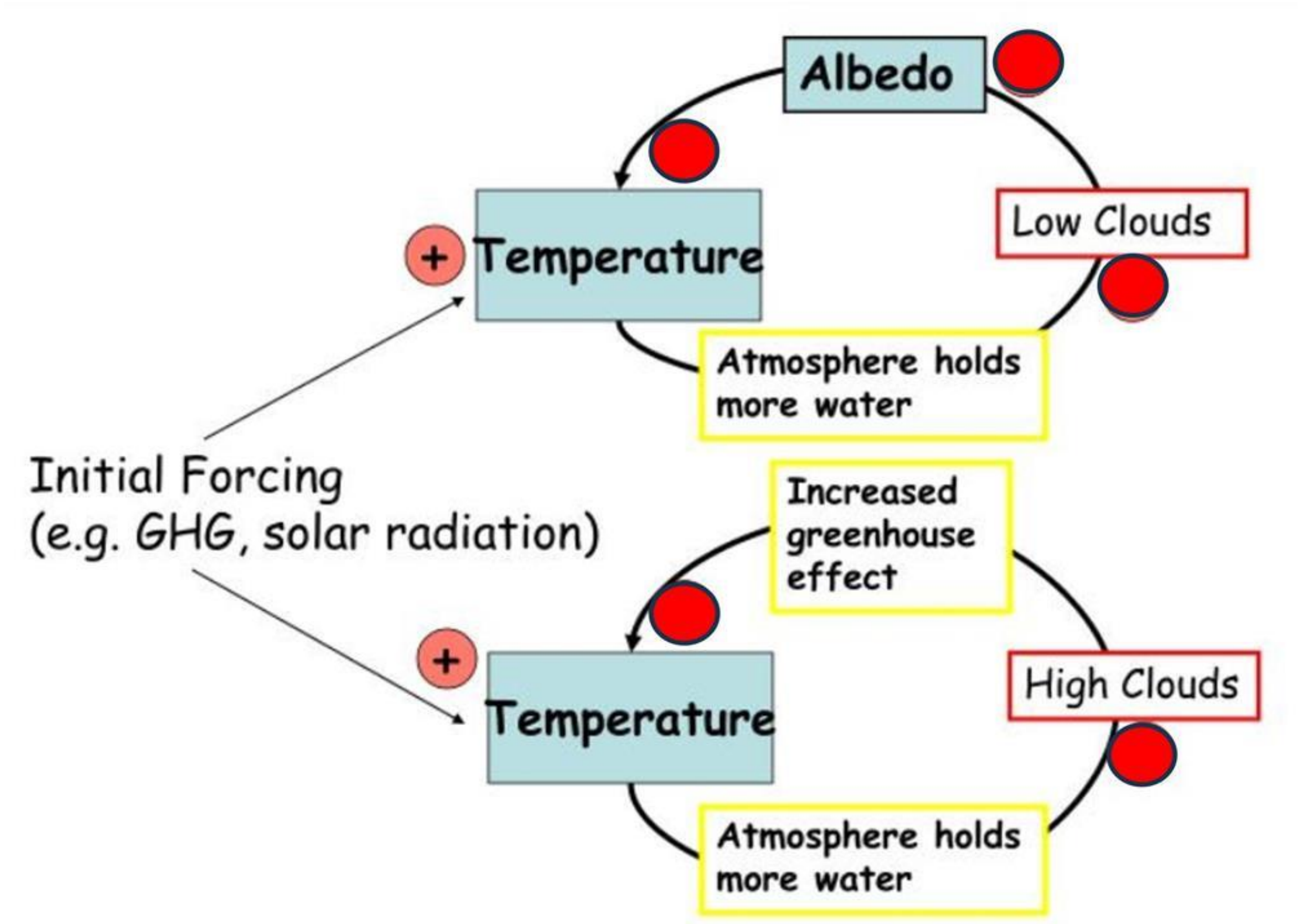
- **Snow albedo feedback** is an important fast land surface feedback.
- Surface and atmospheric warming leads to decreased snow cover and less reflective snow.
- This decreases the surface albedo. Less incoming shortwave radiation is reflected.
- It's a positive feedback.

$\lambda = 0.08\ W.m^{-2}.°C^{-1}$

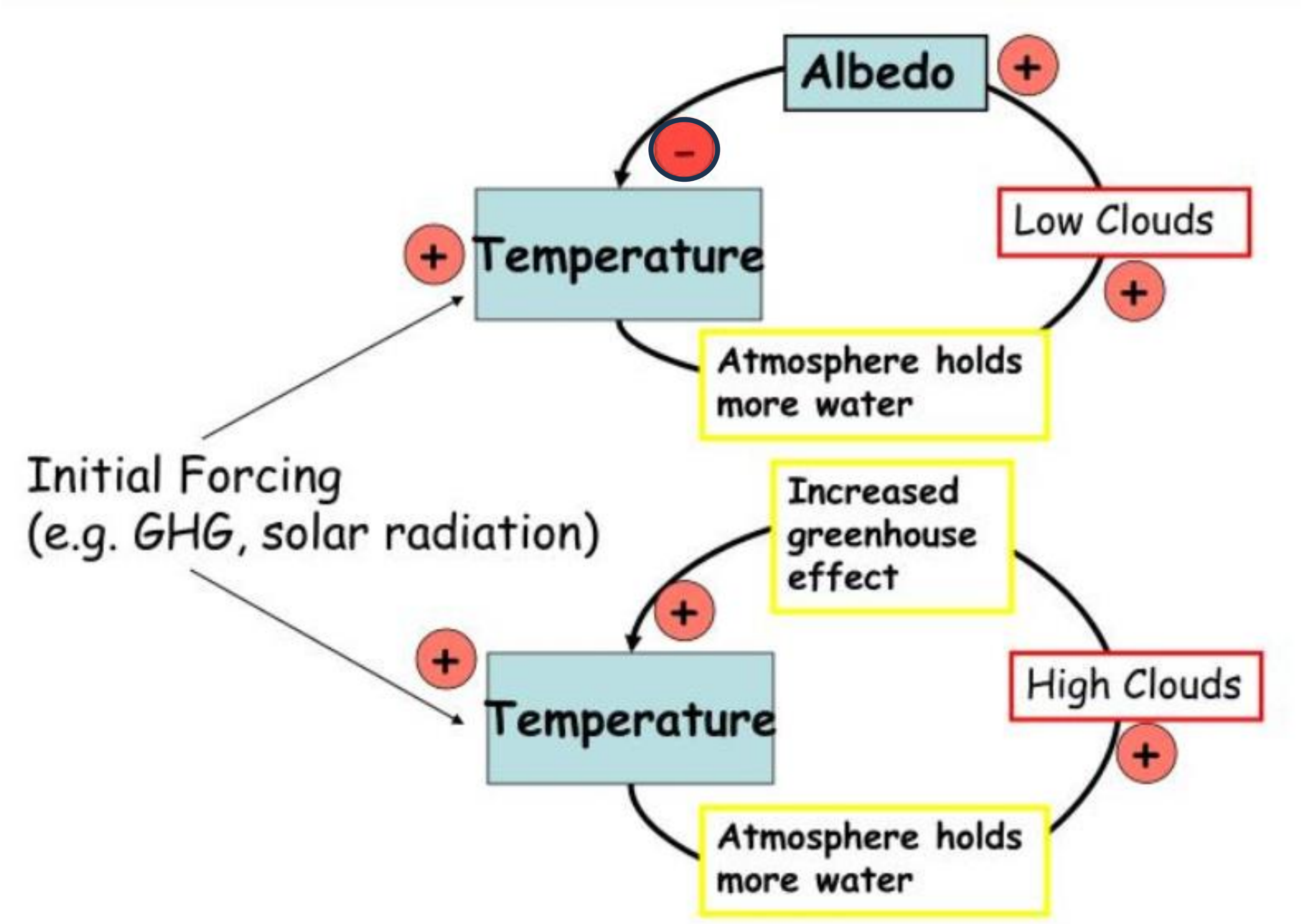
With other albedo feedbacks (sea-ice, vegetation) $\lambda = 0.26\ W.m^{-2}.°C^{-1}$

Source: *[Heinze et al., ESD, 2019]*

Cloud feedback: where is it negative ?



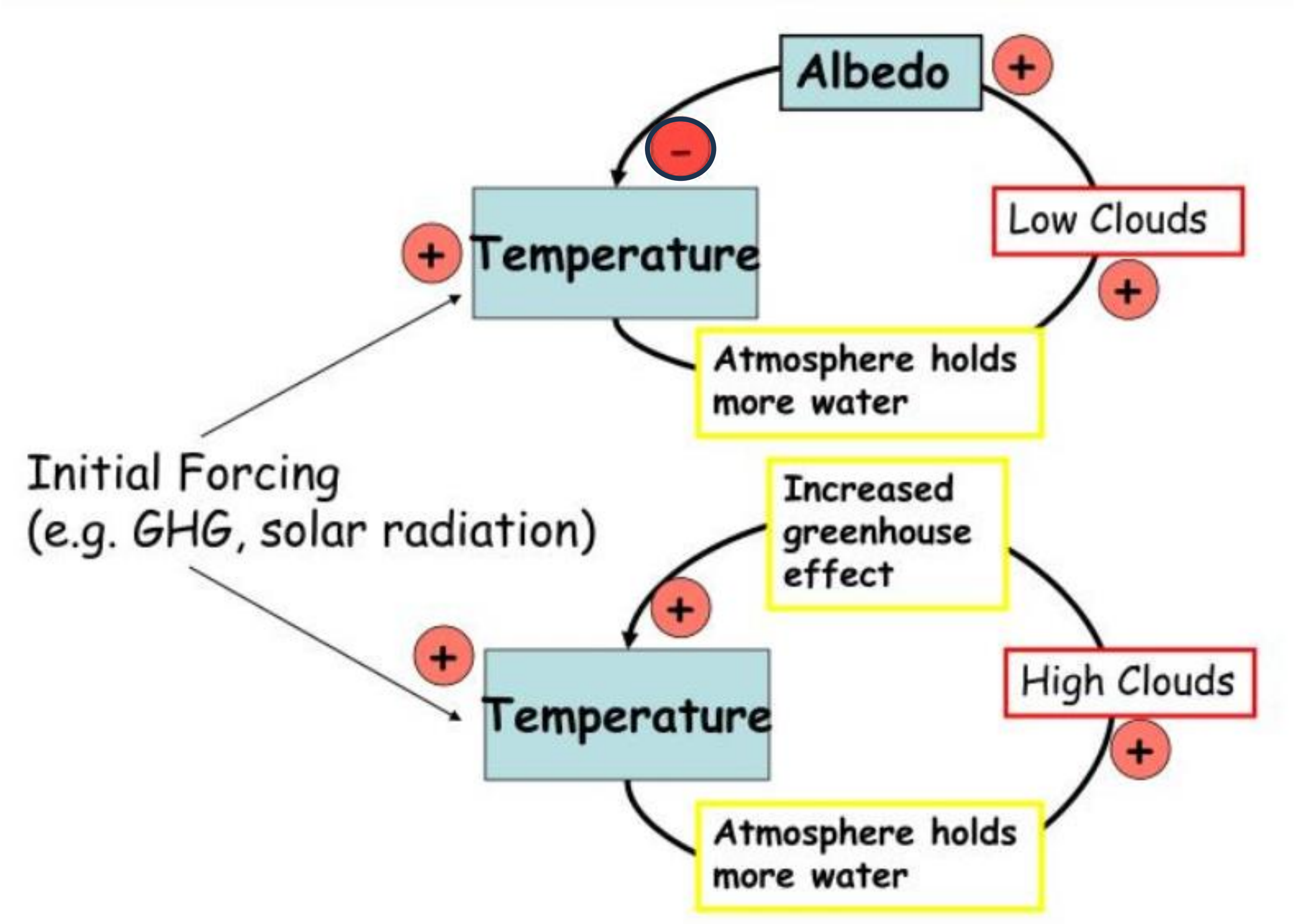
Cloud feedback: where is it negative ?

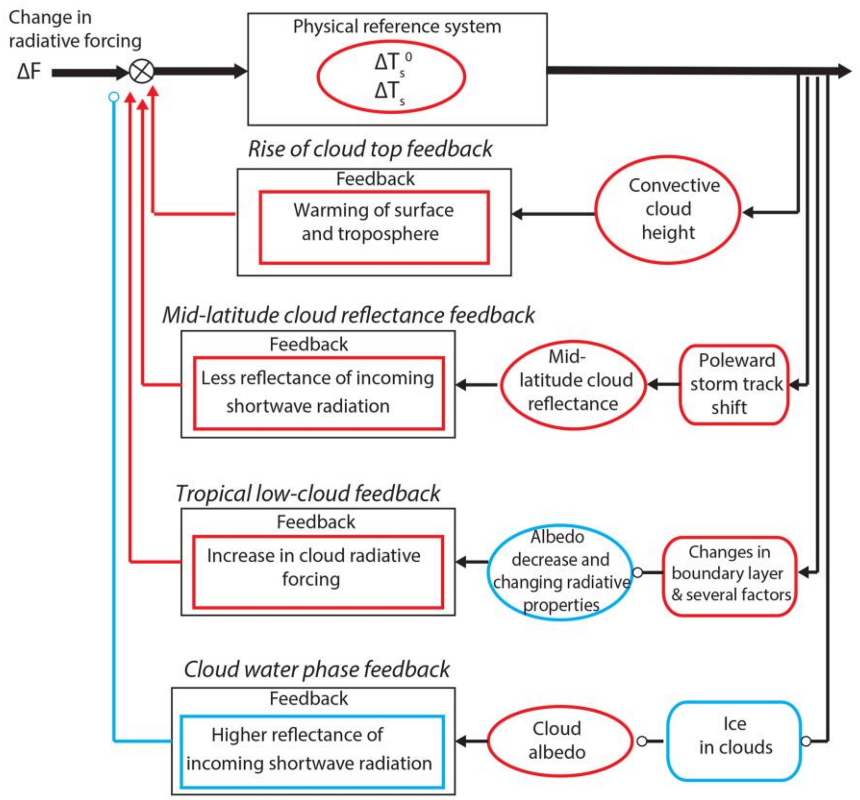


Cloud feedback: positive but uncertain

λ = 0.6 W.m^{-2}.°C^{-1}

But large range of uncertainty: -0.2 to 1.3 W.m^{-2}.°C^{-1} !!

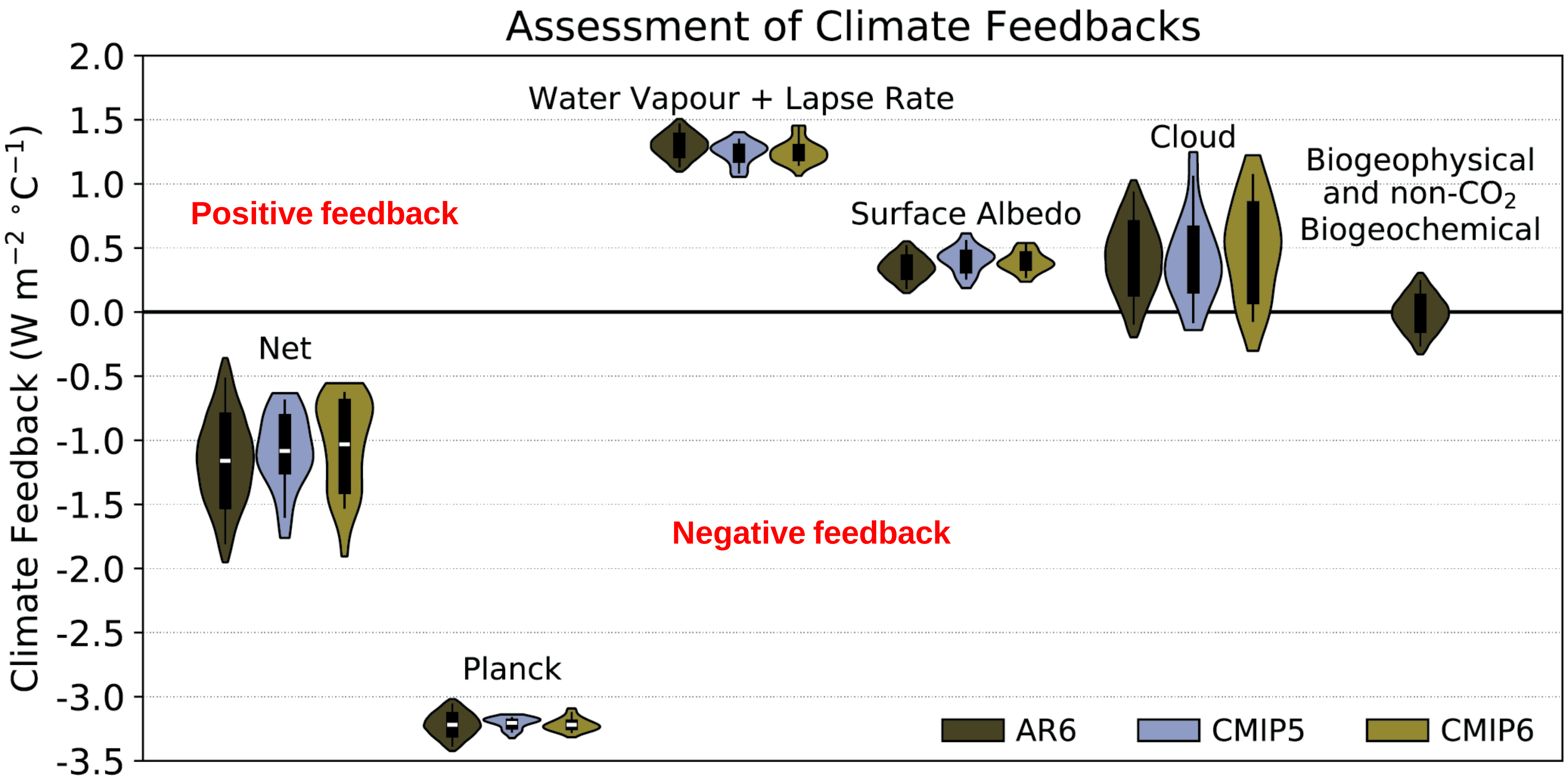




Source: Heinze et al., ESD, 2019

Synthesis of fast physical feedbacks

$$\lambda = \lambda_0 + \lambda_1 + \lambda_2 + \ldots = \sum_{i=0}^{n} \lambda_i$$



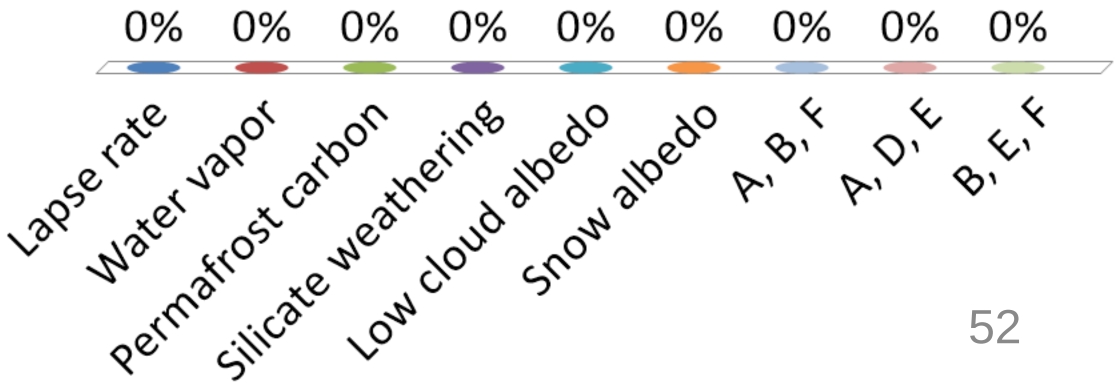
Assessment made with simulations of abrupt 4xCO_2 radiative forcing

CMIP5 simulations: 40 global climate models run in the 2010s.
CMIP6 simulations: 100 global climate models run in 2019+ (higher resolution).
AR6: final IPCC assessment combining CMIP5 and CMIP6 simulations.

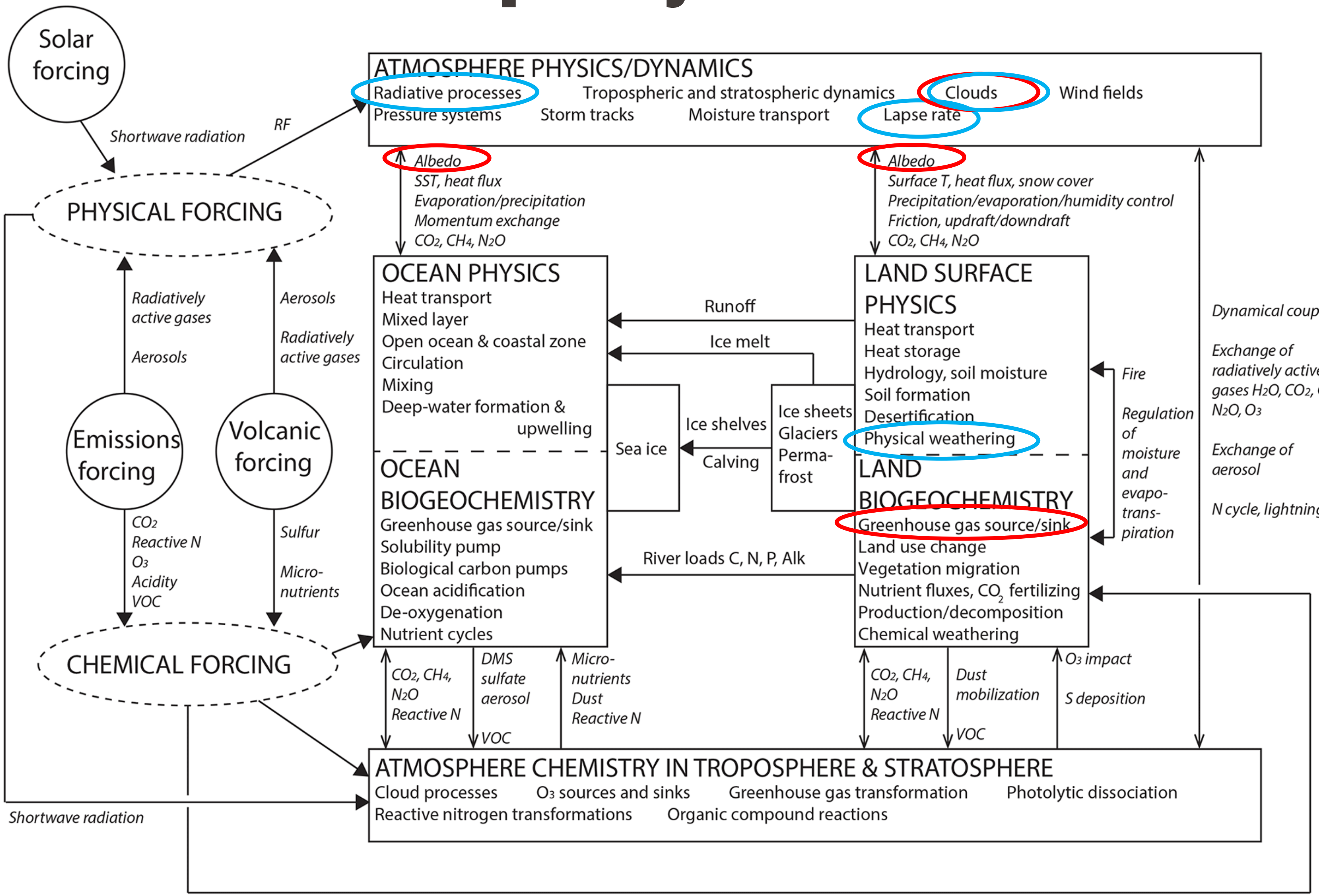
Source: *IPCC AR6 Fig. 7.10*

Which feedback is negative ?

A. Lapse rate
B. Water vapor
C. Permafrost carbon
D. Silicate weathering
E. Low cloud albedo
F. Snow albedo
G. A, B, F
✔ H. A, D, E
I. B, E, F



The whole complexity of feedbacks !



There are slow feedbacks:
- Deep ocean
- Ice sheets
- Weathering

There are biogeochemical feedbacks:
- Vegetation
- Oceans

There is atmospheric chemistry:
- Troposphere
- Stratosphere

Only the most recent complex climate models can combine a large part of them.

Source: Heinze et al., ESD, 2019

Climate sensitivity

Climate sensitivity

- **Climate sensitivity** = the amount of global mean surface warming occurring in response to a change of atmospheric CO_2 concentrations compared to preindustrial levels.
- It is usually determined with respect to a doubling of CO_2 from the preindustrial level of 280 ppm.
- The unit is a temperature (°C or K).
- Very important for policymakers, for humanity and for living organisms in general, as it defines what will be the trajectory of future climate change, in addition to the scenarios of anthropogenic GHG / aerosol emissions.
- But difficult to determine as it mostly relies on the performance of climate models.

See also: Knutti et al., 2017; https://www.nature.com/articles/ngeo3017?proof=t

Climate sensitivity in detail: three types

Centuries

- **Equilibrium climate sensitivity (ECS)**: it is the long-term warming after the climate system has «fully adjusted» to a doubling of CO_2.
- It includes fast feedbacks (water vapor, lapse rate, clouds change of surface albedo). As well as a «slab ocean» taking into account heat transfer.
- It does not include the biogeochemical feedbacks, nor the chemical ones, nor the slow feedbacks (deep ocean, ice sheets,…).
- It's the most commonly cited climate sensitivity in climate reports.
- IPCC AR6: **~2.5 to 4°C** per doubling of CO_2 (**best estimate: 3°C**)

70 years

- **Transient climate response (TCR)**: it is the global average warming at the time of CO_2 doubling, assuming a 1% per year increase of CO_2 concentration for 70 years.
- TCR provides a measure of the strength and rapidity of the climate response to greenhouse gas forcing. It is useful for 21st century projections.
- It is sensitive to the ocean heat uptake compared to the atmosphere, without reaching equilibrium.
- IPCC AR6: **1.4°C to 2.2°C** (less than ECS because ocean heat uptake is a slow process),

Thousands of years

- **Earth system sensitivity (ESS)**: it is the very long-term temperature change for a doubling of CO_2, including the slow feedbacks (ice sheets, vegetation changes, carbon cycle changes such as permafrost thaw).
- Computationally very costly and less relevant for 21st century policies. ESS could reach **4 to 8°C**.

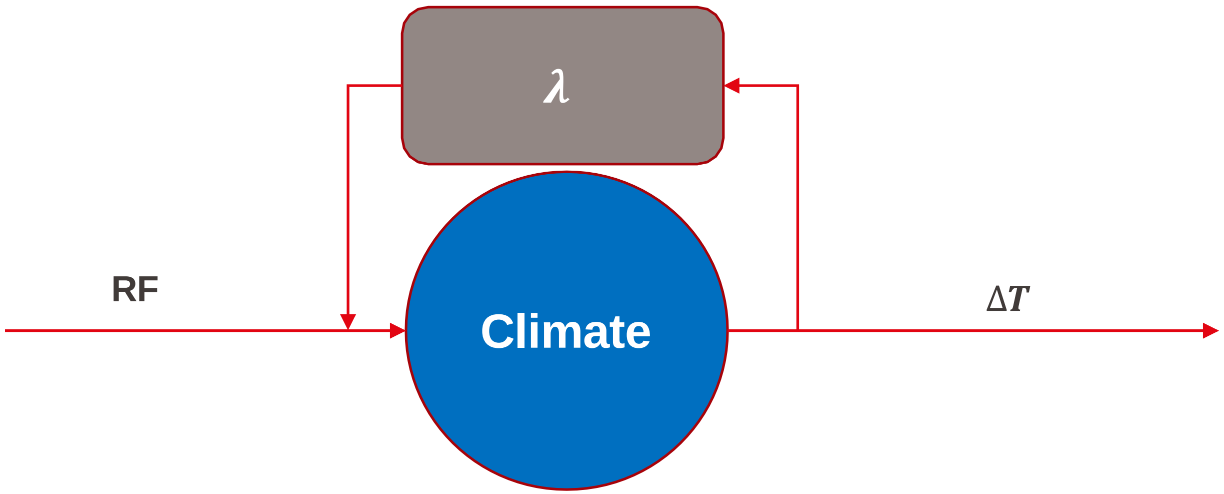
- *More info: Carbonbrief*

Forcing, climate sensitivity and feedback

$$N = RF + \lambda \Delta T$$

N: Top of atmosphere radiative imbalance (W/m^2)
RF: radiative forcing (W/m^2)
ΔT: global surface temperature response, climate sensitivity (°C)
λ : net climate feedback ($W / (m^2 * °C)$)

Positive feedback amplifies the response
Negative feedback dampens the response



- A doubling of atmospheric CO_2 leads to radiative forcing RF of **3.93 ± 0.47 $W.m^{-2}$**.
- At equilibrium ($N = 0$), we can calculate ΔT (or "equilibrium climate sensitivity" ECS).

$$\Delta T = \frac{RF}{\lambda}$$

- With a fast feedback factor $\lambda \approx 1$, the global surface temperature response is +3.9°C.

An alternative to calculate ECS: Gregory method

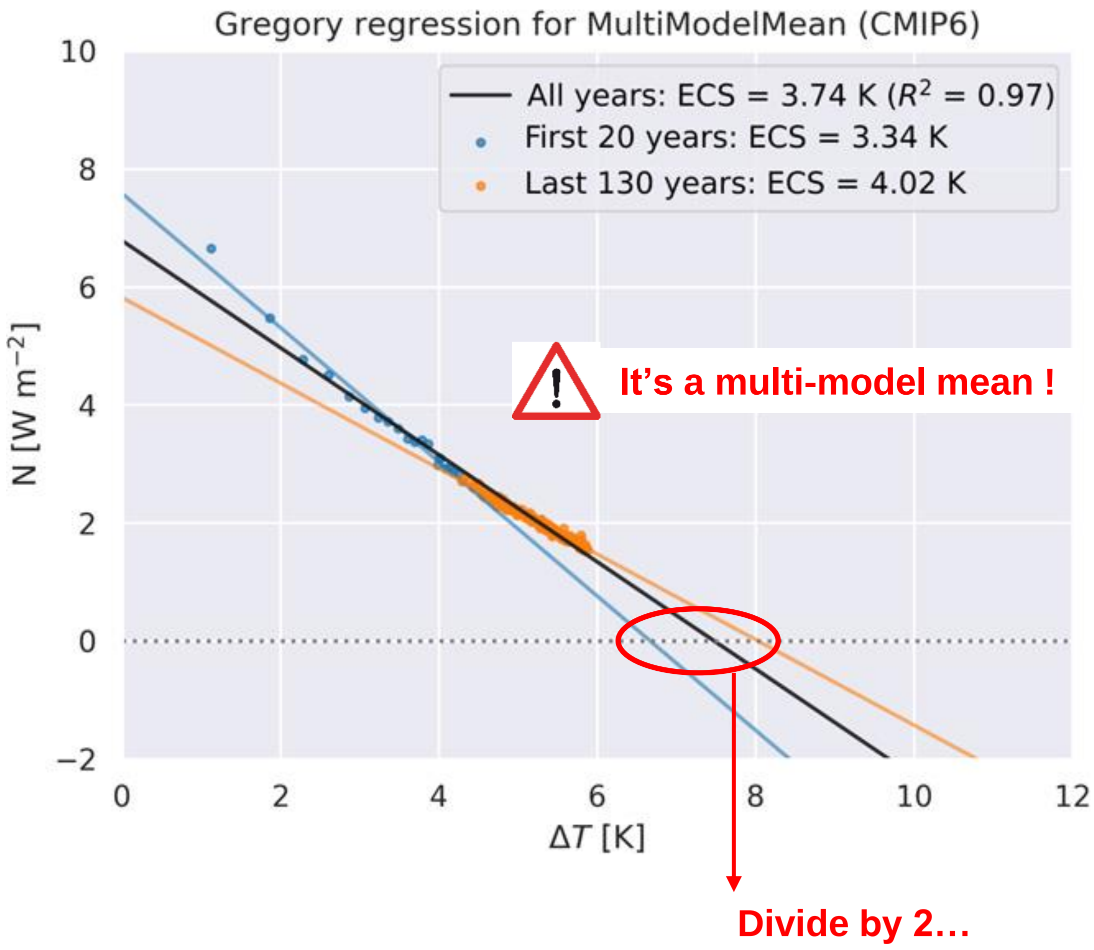
$$N = RF + \lambda\Delta T$$

N: Top of atmosphere radiative imbalance.
RF: radiative forcing.
ΔT: global surface temperature response.
λ : feedback factor.

- **Gregory method**:
  - Introduced by Jonathan Gregory in 2004.
  - **CO_2 is instantaneously quadrupled** in a fully coupled Earth system model and **run for 150 years**.
  - *N* is plotted as a function of *ΔT*.
  - The slope gives *λ* ; the x-intercept (*N* = 0) gives the ECS for 4xCO_2 ; dividing by 2 gives the final ECS.

- Pros:
  - Short simulations of 150 years
  - Captures fast feedbacks and some of the slow ones.

- Cons:
  - Assumes linear feedbacks, while e.g. possible tipping points in the climate system may lead to non-linearities.
  - May not apply to aerosol forcing.

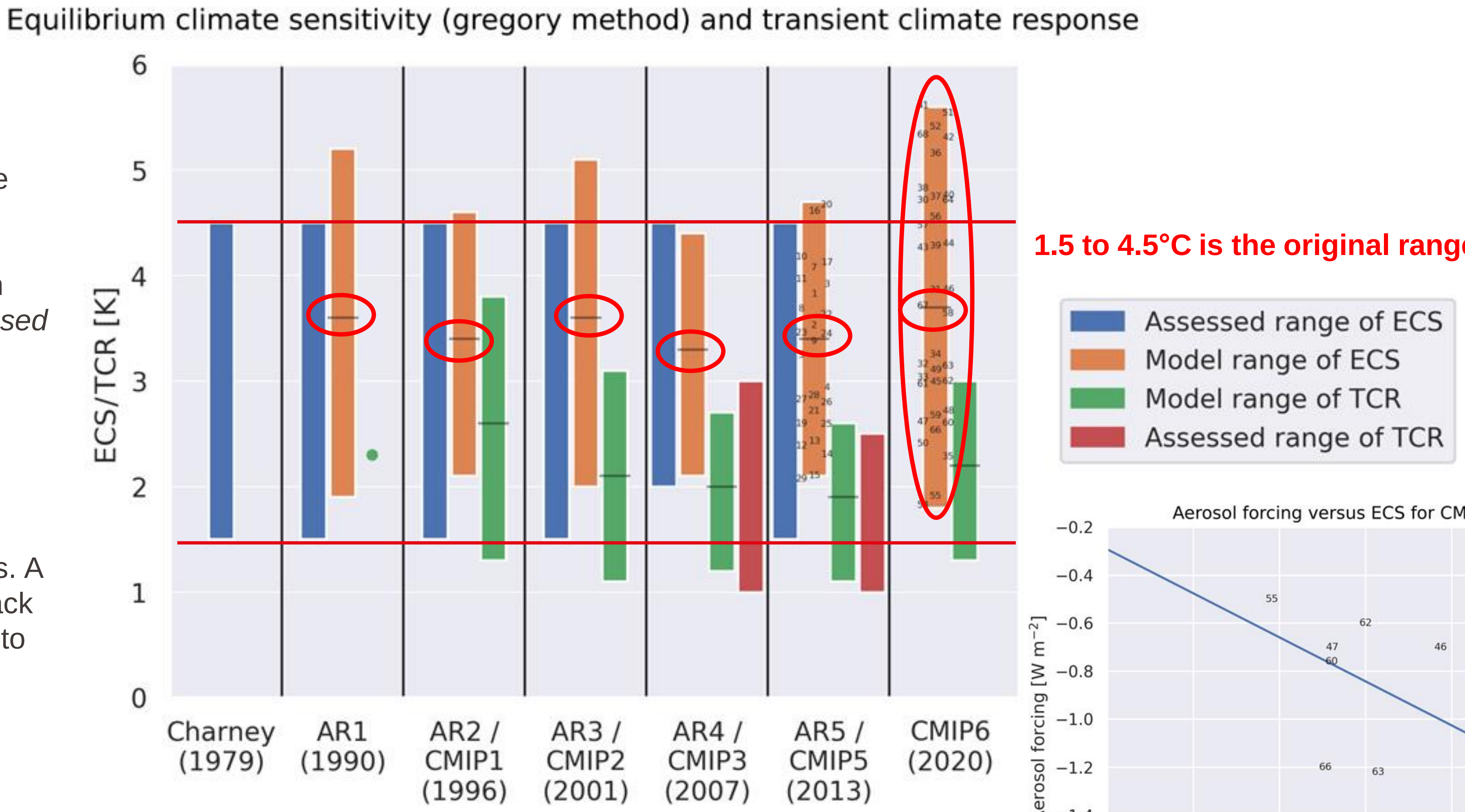


Note the time-varying ECS, implying different feedback strengths with time in the climate system.

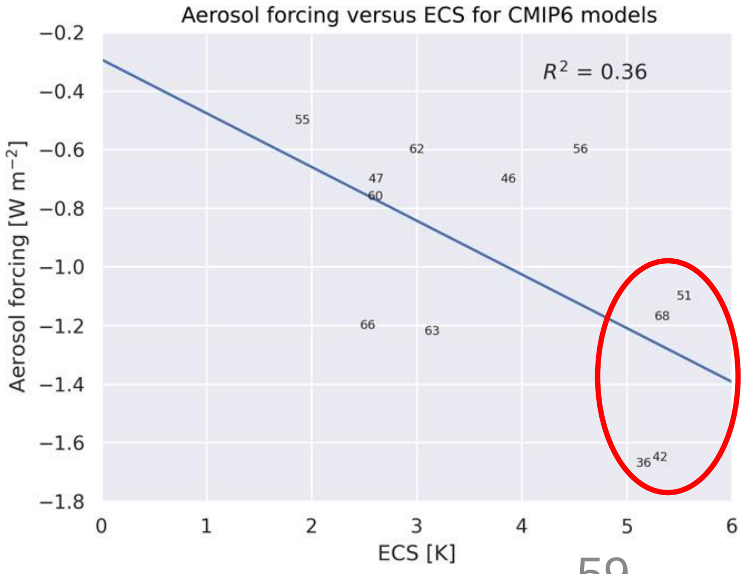
Source: Meehl et al., ScienceAdvances 2020

Climate sensitivity and evolution of climate models

- All mean ECS values are quite similar.
- But huge differences between models ! *(spread of the assessed range and model range)*
- Larger ECS range with the newest models (CMIP6).
- Probably related with a more complex treatment of aerosols. A more negative aerosol feedback leads to a stronger sensitivity to CO_2.



1.5 to 4.5°C is the original range.



Source: [Meehl et al., ScienceAdvances 2020]

Can we constrain climate sensitivity from observations?

- Changes of the climate system between equilibrium states with different radiative forcing provide in principle the best estimate of climate sensitivity.

- However, the mean climate state and the nature of the forcing (both affecting feedbacks) should be close to the current one.

- Examples: different positions of the continents, meteorite impacts, snowball Earth,… are not so pertinent for climate sensitivity of the next decades / centuries. They allow to test feedbacks under extreme conditions.

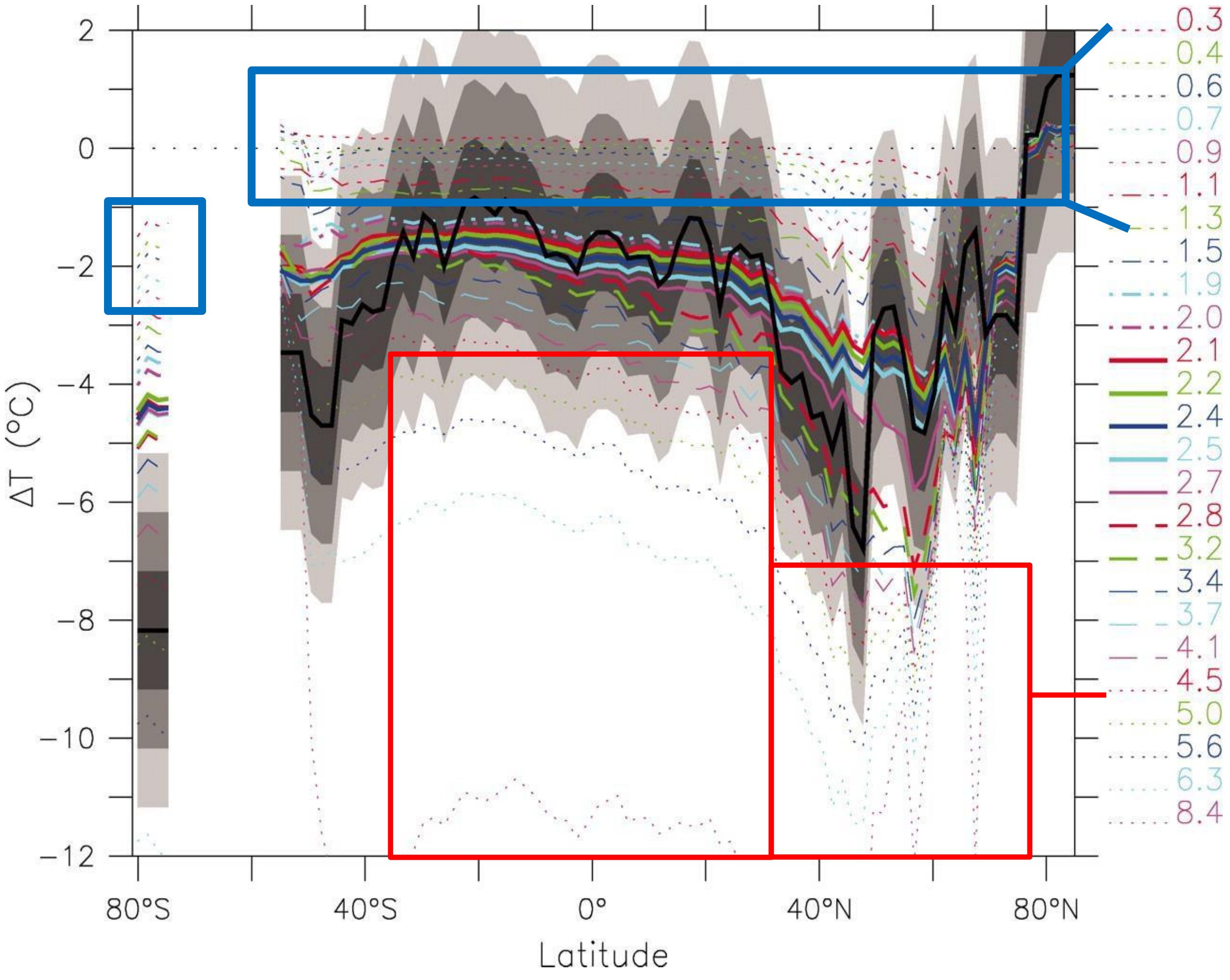
- Constraints from observations:
  - Observed warming over the instrumental record.
  - Process-understanding of feedbacks (e.g. satellite and reanalysis products for cloud and water vapor feedback).
  - Short-term climate response to volcanic eruptions (but does not include slow feedbacks).
  - Paleoclimate records, in particular the Last Glacial Maximum, 20,000 years ago (CO_2~ ≈ 185 ppm).
  - Observed trends in recent climate variations (emergent-constraint approach).

- *https://www.nature.com/articles/ngeo3017?proof=t*

Why the instrumental record is not the perfect option ?

- Short observational period (150 years). It does not include long-term feedbacks such as the evolution of ice sheets and the deep ocean warming.
- The aerosol forcing is highly uncertain because we do not know very well their concentration, chemical composition and spatial distribution during pre-industrial times.
- There could be new feedbacks starting to imprint the climate system under warmer future conditions.

Using the Last Glacial Maximum



- Zonally average surface temperature change between the Last Glacial Maximum (LGM) and preindustrial times.

- Black line = observations.
- Colored lines = different model simulations, with different climate sensitivity ECS.

- Models with ECS_{2xCO2} < 1.3°C underestimate the LGM cooling nearly everywhere, in particular at mid-latitudes and over Antarctica.

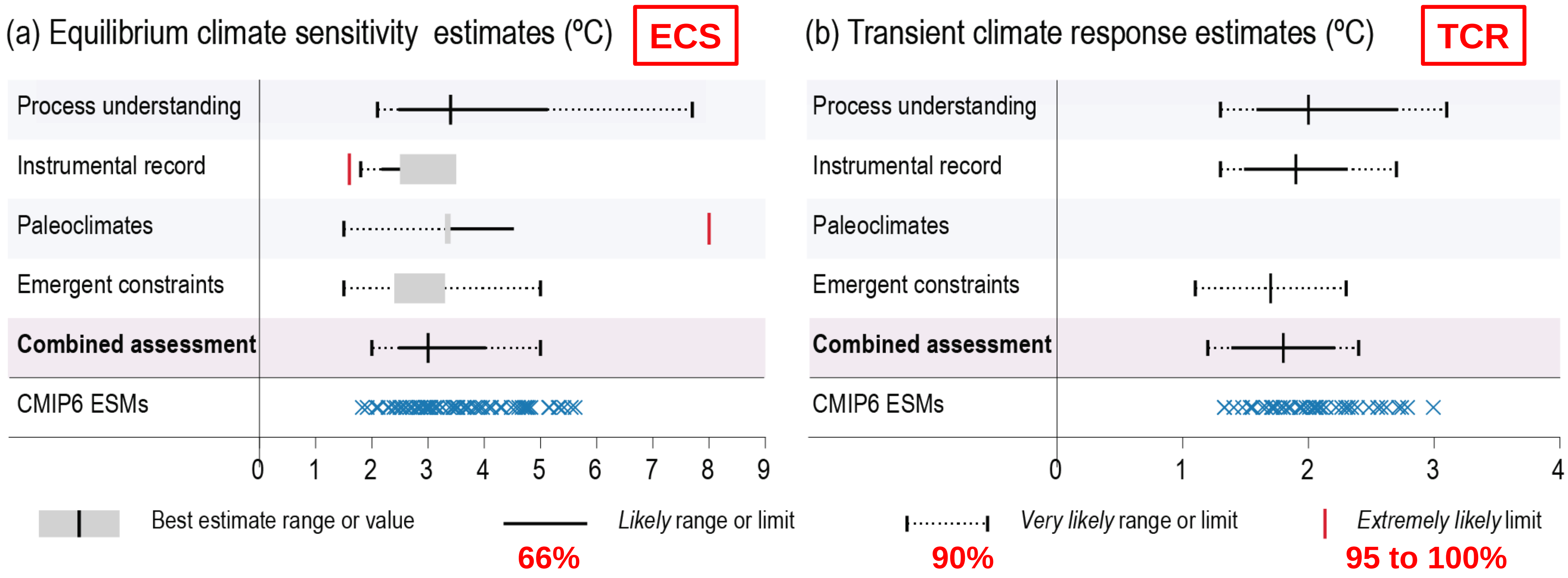
- Models with ECS_{2xCO2} > 4.5°C overestimate the cooling almost everywhere, in particular at low latitudes.

- 95% range: 1.4 to 2.8°C.

- IPCC AR6: new paleoclimatic data and improved models. Likely ECS range of **2.5 to 4.0°C**

Source: Schmittner et al., Science 2011

Current state of knowledge about ECS and TCR



Emergent constraints: statistical methods to narrow down the ECS from models and to rule out unrealistic ECS values.

See [Caltech Climate Dynamics Group for more explanation]

- IPCC AR6: **~2.5 to 4°C** per doubling of CO_2 (**best estimate: 3°C**)

- IPCC AR6: **1.4°C to 2.2°C** (less than ECS because ocean heat uptake is a slow process),

Source: [IPCC AR6, Fig. 7.18]

Summary: Radiative forcing, feedbacks, climate sensitivity

- They are three fundamental aspects of climate science. Usually referenced **with respect to pre-industrial state**.
- **Time matters !** There are different speeds among radiative forcing factors and different response time of the climate system.
- Solar forcing currently accounts for **0.15 $W.m^{-2}$**. Volcanic forcing can reach several $W.m^{-2}$ but is limited in time.
- The effective **radiative forcing** of greenhouse gases since 1750 amounts to **3.84 $W.m^{-2}$**.
- Strongly muted (but with large uncertainties) by aerosols (including impact on clouds). Total ERF of **2.72 $W.m^{-2}$** since 1750. Difficult to measure at top of the atmosphere…
- The **fast physical feedback factors** amount to **-1.16 $W.m^{-2}.°C^{-1}$**. Slow feedbacks (deep ocean, ice sheets,…) will add on over millennial time scales.
- **Climate sensitivity** is calculated based on a doubling of atmospheric CO_2. It depends on the time scale being considered, which impacts the involved feedbacks.
- For the 21st century, it ranges typically between **1.5 and 4°C**.
- **Our future climate depends on climate sensitivity. But even more on emission scenarios for greenhouse gases and aerosols !**