



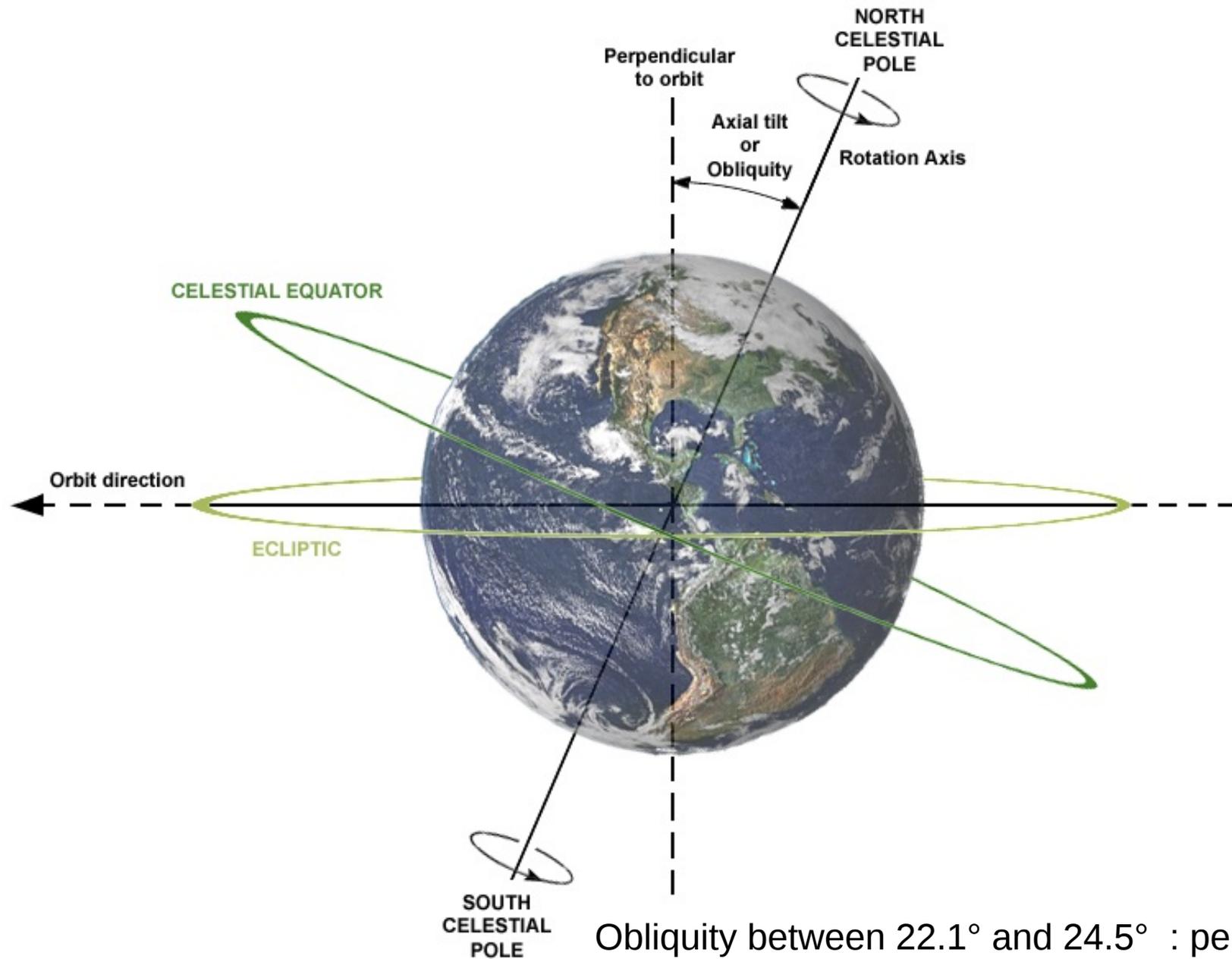
**CLIM0026:
Global warming
and natural risks**

Plan

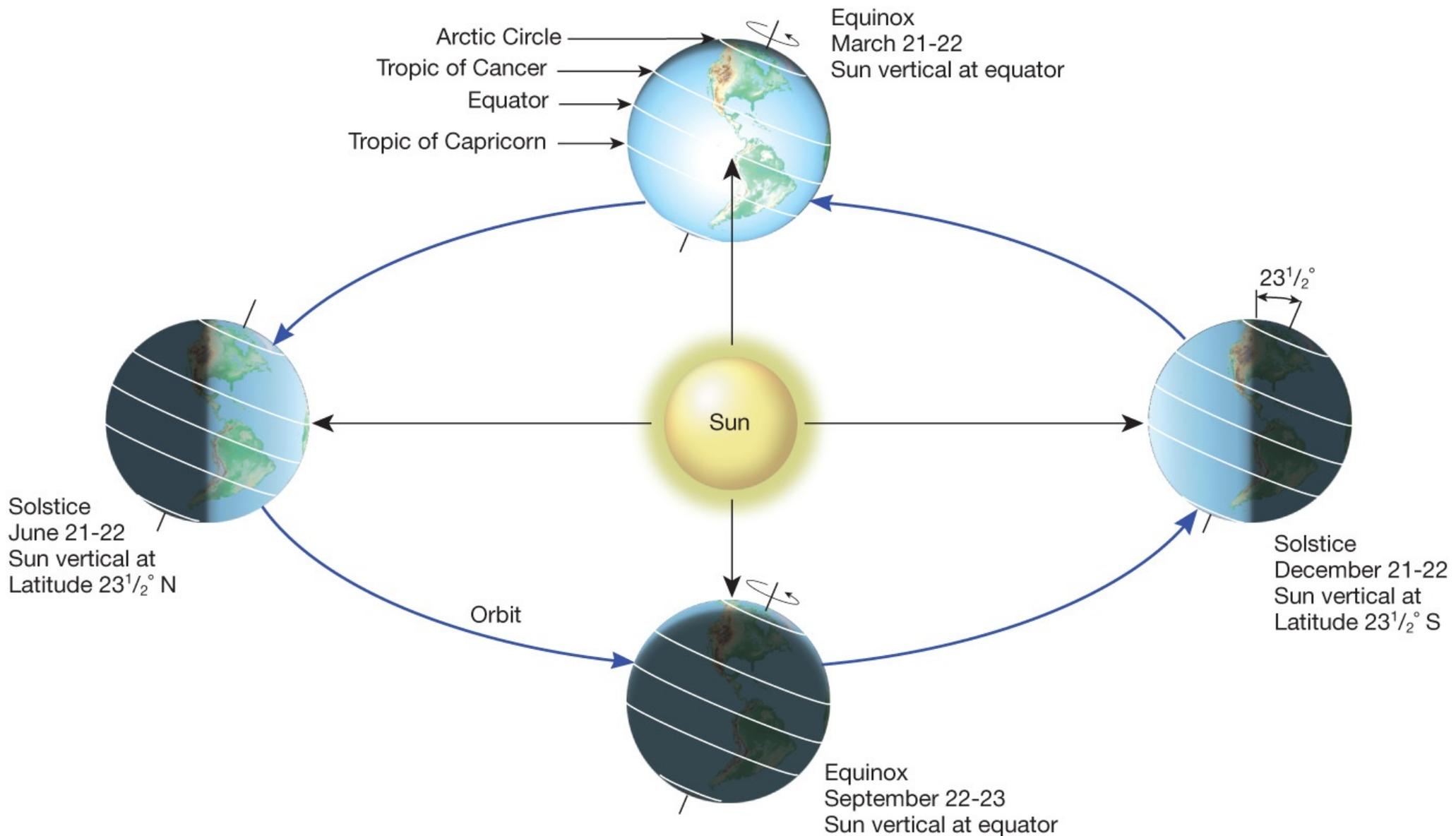
- Natural climate variability and impact from human activities
- Climate modelling, future scenarios and global climate change
- Sea level rise and ice sheets
- Floods and changes in the type and frequency of precipitation
- Droughts, water reserves and heat waves as well as the problem of urban heat islands amplifying warm waves in our cities
- Development of solar and wind potential
- Evolution of extreme events such as hurricanes, medicanes, tornadoes...
- **Exam:** Oral exam + 2 group works:
 - discussing the need of taking into account climate change in their own interest fields
 - tackling climate sceptics

Reference: [IPCC's AR6 WG1](#)

1. Milankovitch cycles



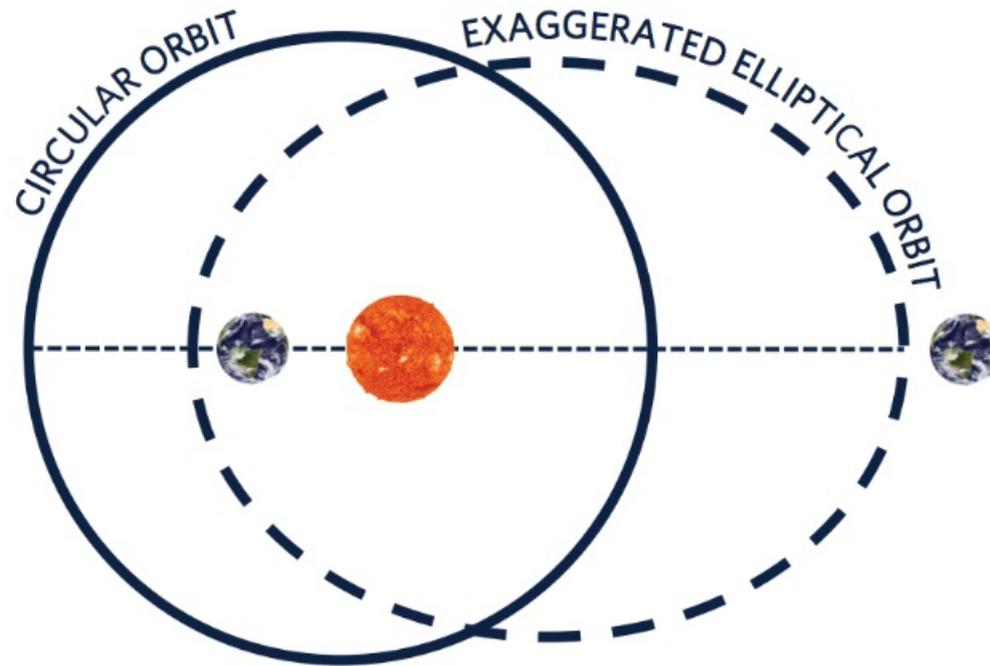
1. Milankovitch cycles



© 2013 Pearson Education, Inc.

Precession: period 26kyr

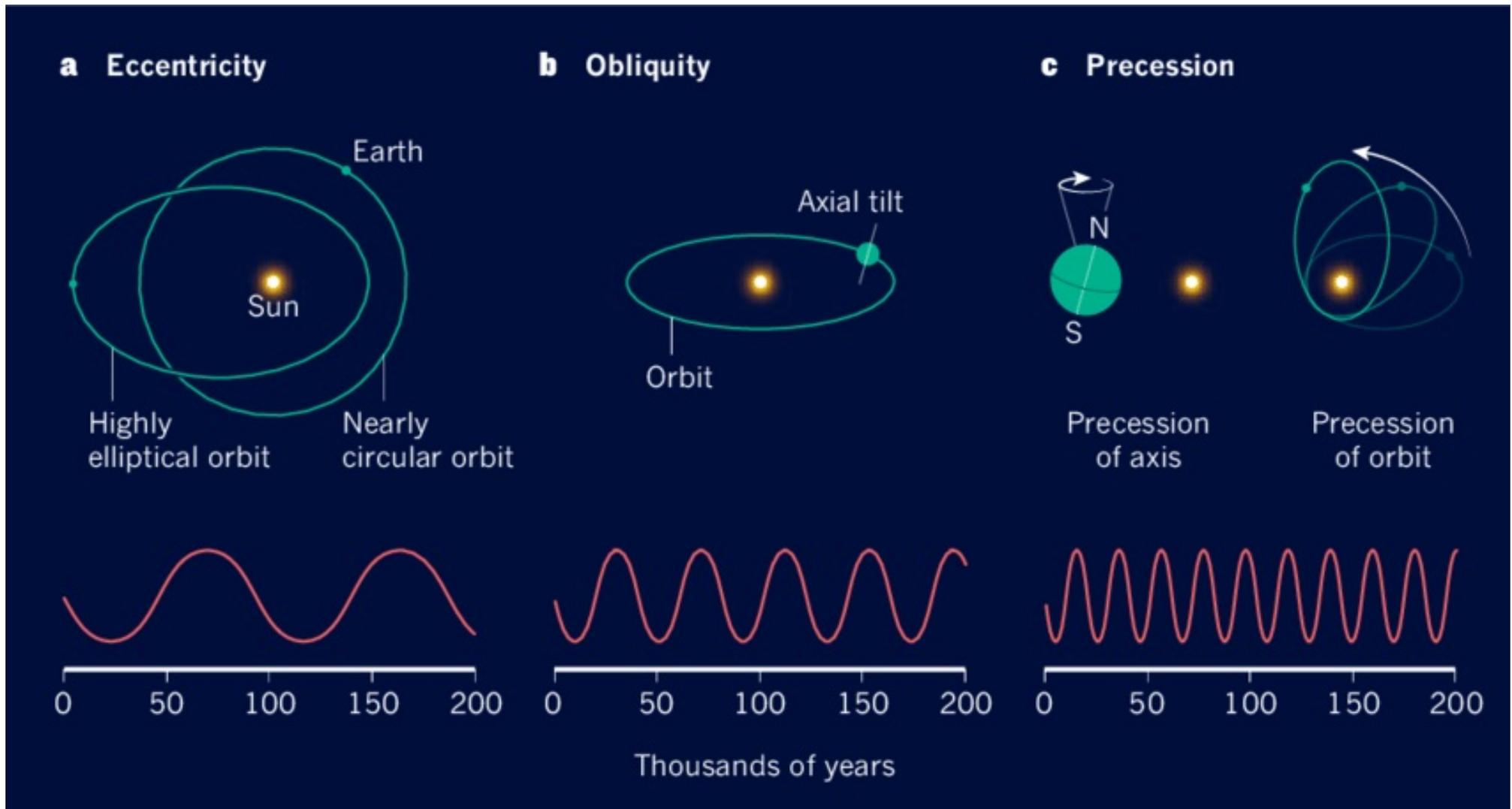
1. Milankovitch cycles



Eccentricity

Eccentricity: period
100kyr

1. Milankovitch cycles



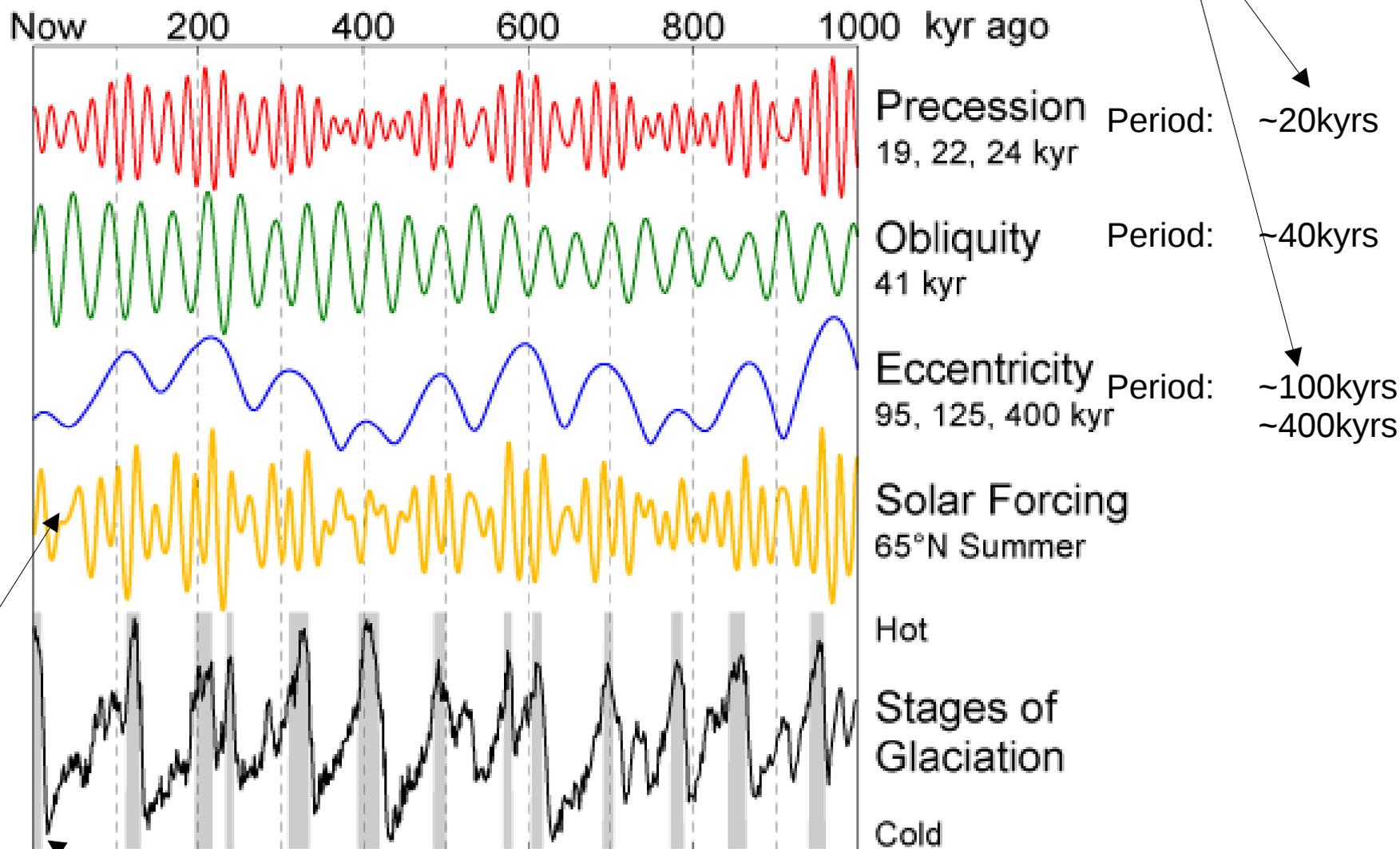
Period: 100ky

41ky

26ky

1. Milankovitch cycles

Impacted by the distance Earth-Moon

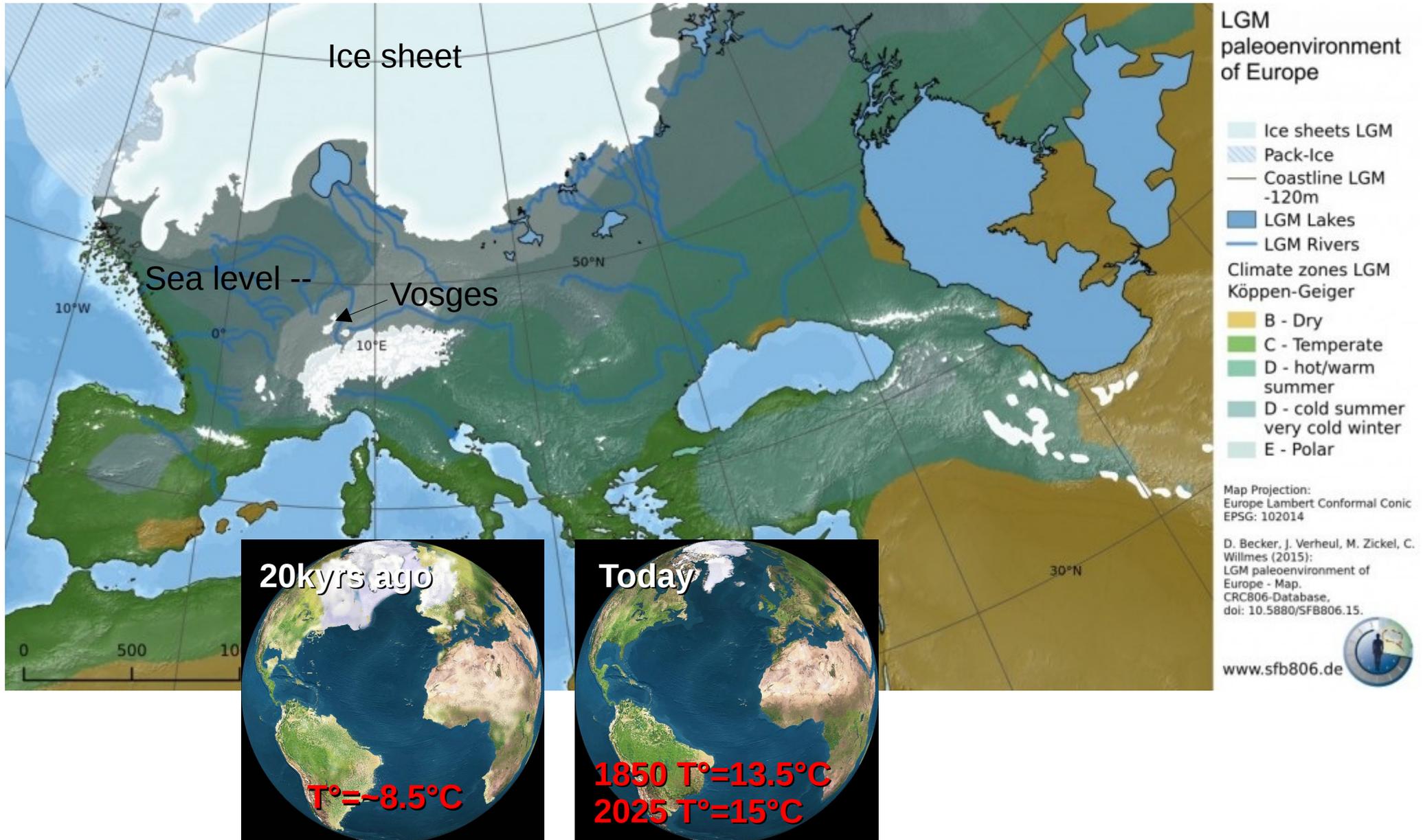


The North Hemisphere drives climate variability

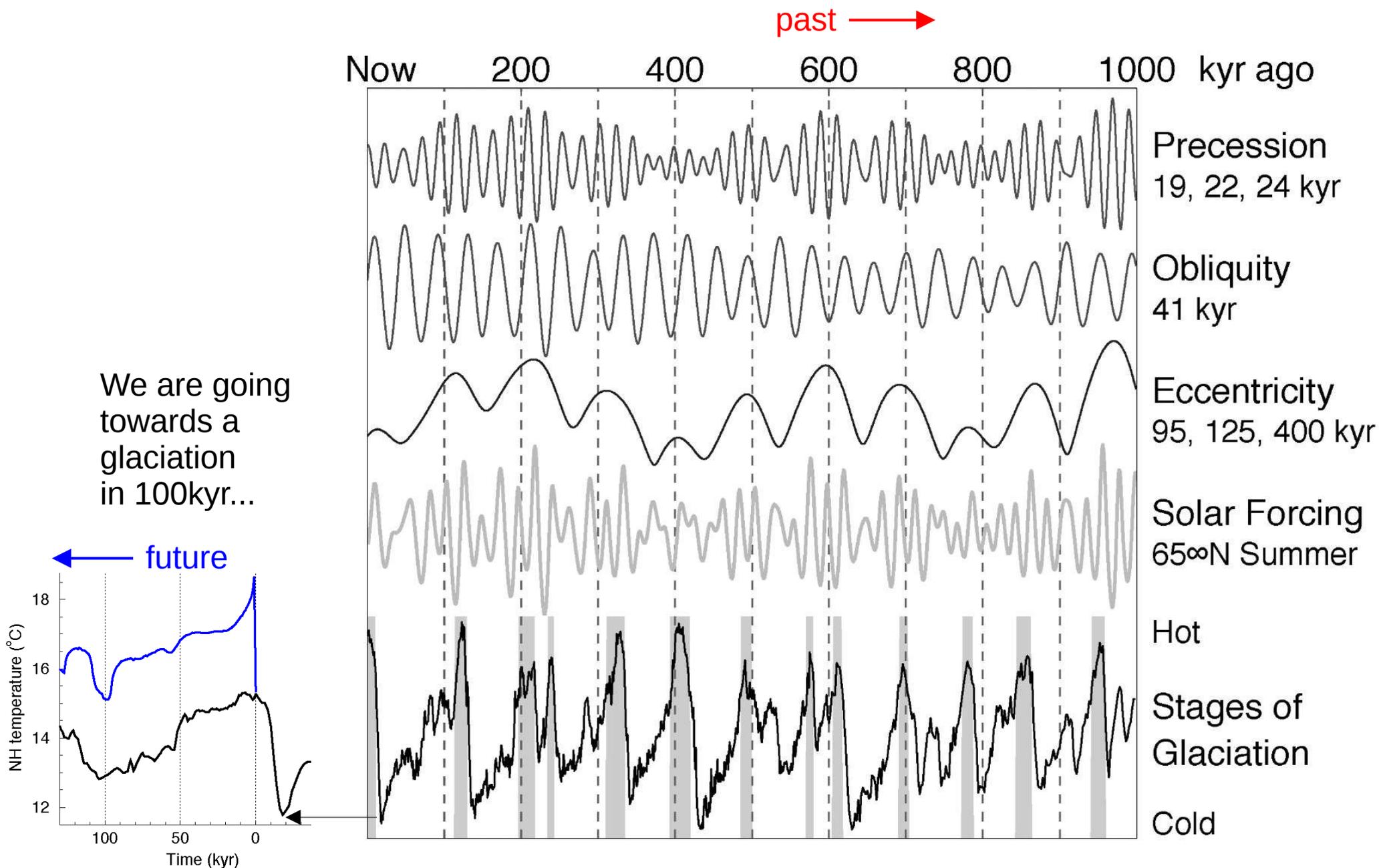
Last Glacial Maximum (LGM): 20kyrs ago

1. Milankovitch cycles

20000 years ago ...

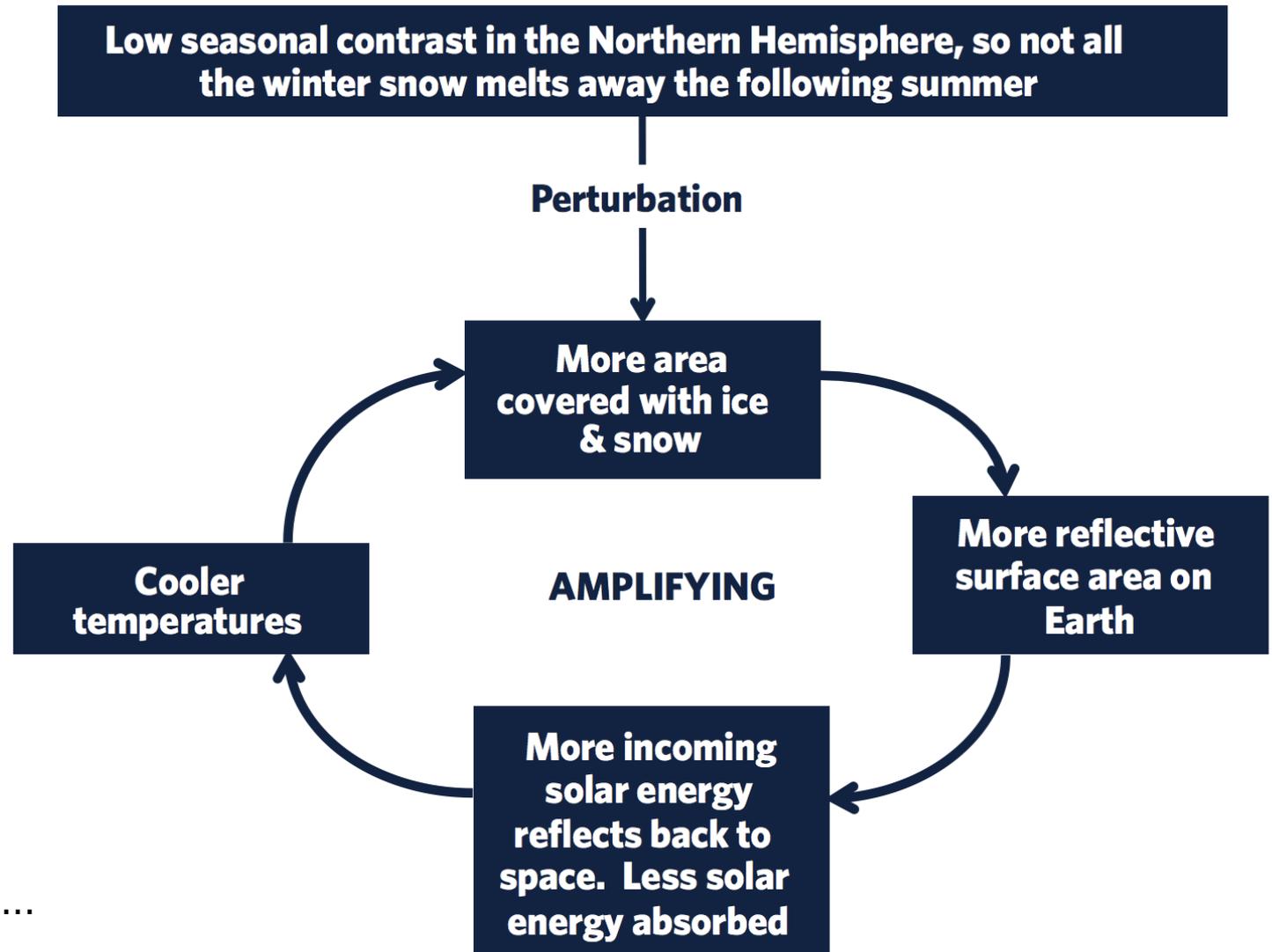


1. Milankovitch cycles



1. Milankovitch cycles

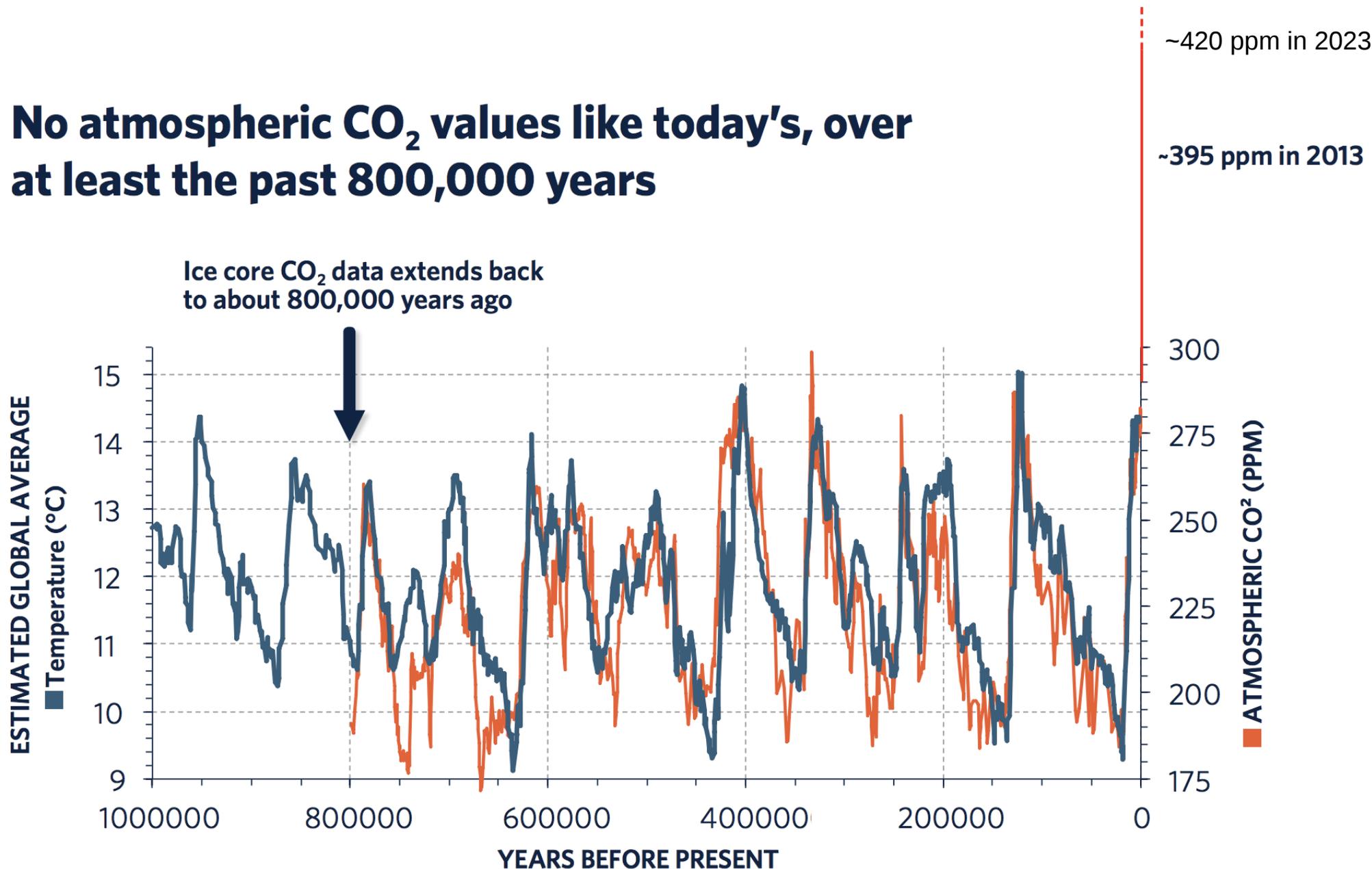
Growing an ice sheet with the ice-albedo feedback



Towards a glaciation ...

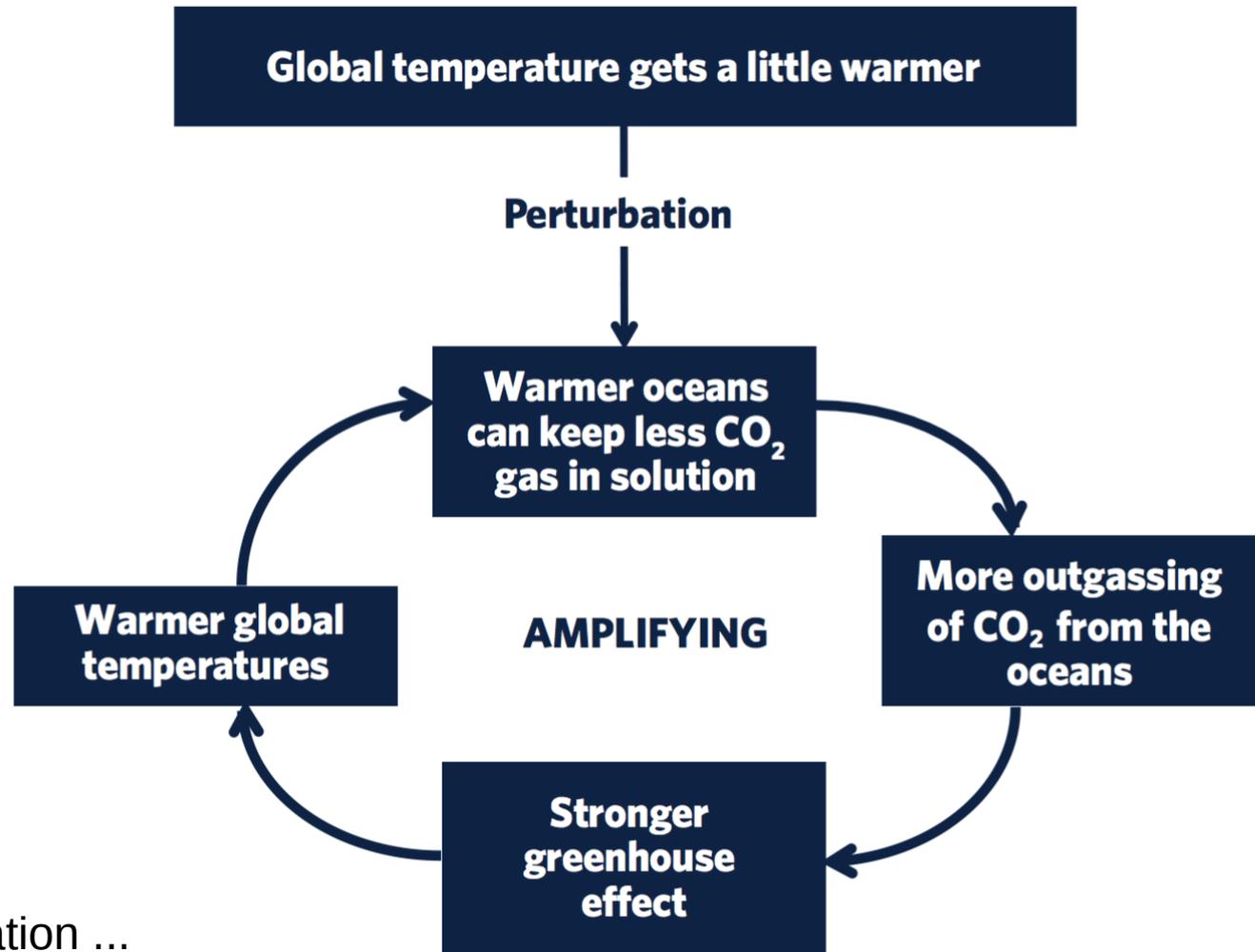
1. Milankovitch cycles

No atmospheric CO₂ values like today's, over at least the past 800,000 years



1. Milankovitch cycles

Temperature and CO₂ — another amplifying feedback



Towards a deglaciation ...

2. Energy balance

Main driver of anthropogenic variability

Global energy balance on Earth (after Wild et al. 2012)

Based on solar constant 1360.8 Wm^{-2}

The diagram is considered to represent present day climate, with the underlying data emphasizing the climatological conditions at the beginning of the twenty first century.

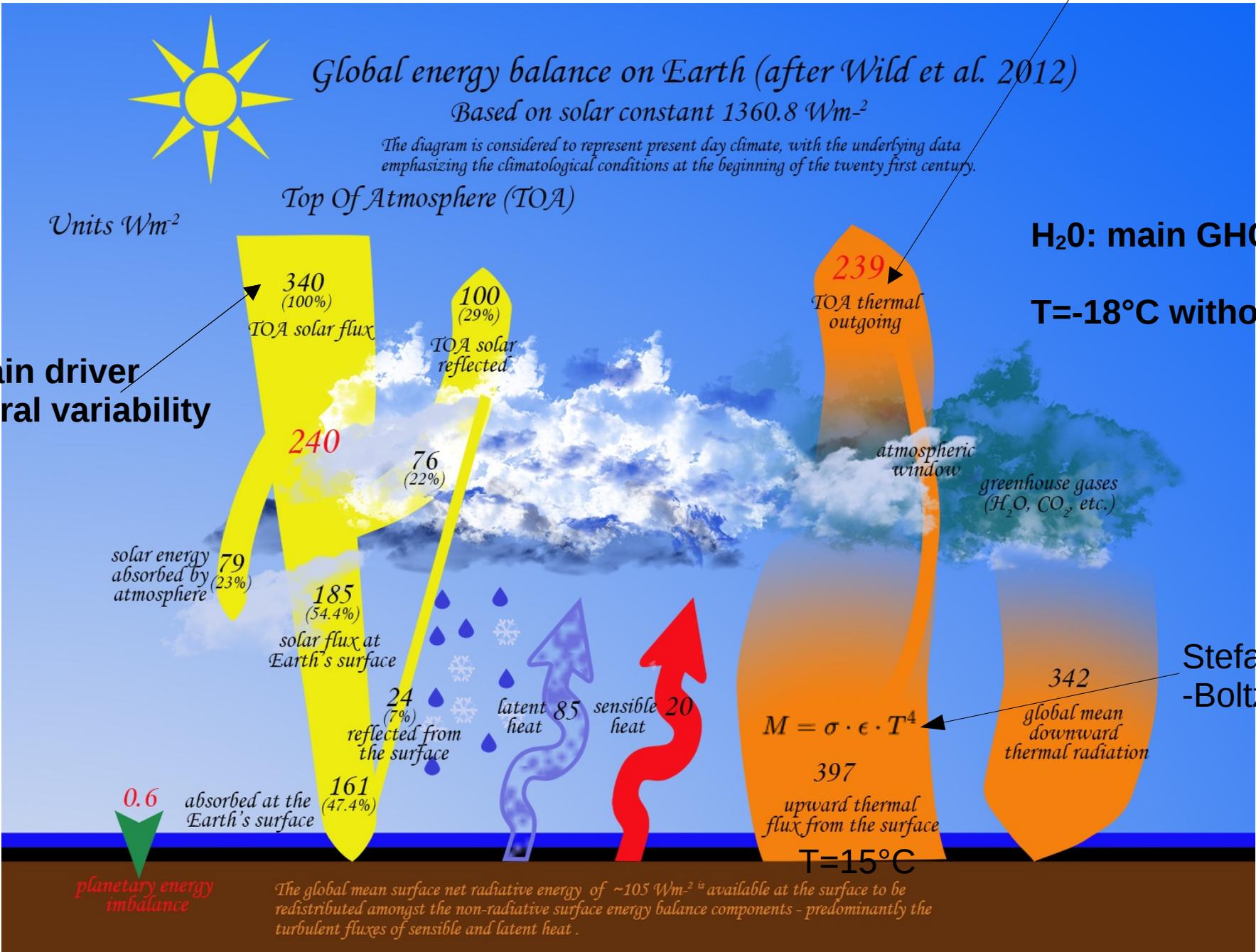
Top Of Atmosphere (TOA)

Units Wm^{-2}

Main driver of natural variability

H_2O : main GHG

$T = -18^\circ\text{C}$ without GHG

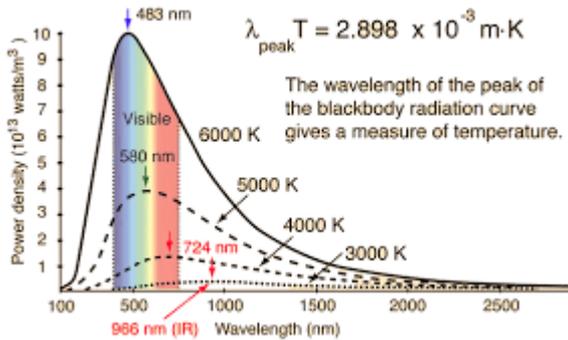


$$M = \sigma \cdot \epsilon \cdot T^4$$

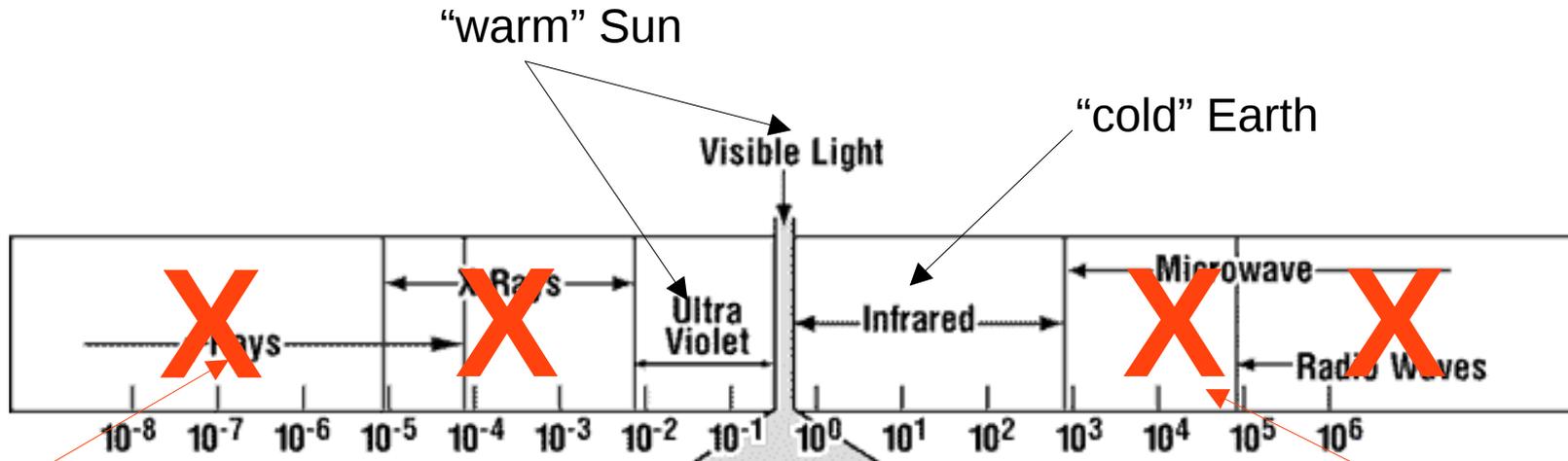
Stefan-Boltzmann

The global mean surface net radiative energy of $\sim 105 \text{ Wm}^{-2}$ is available at the surface to be redistributed amongst the non-radiative surface energy balance components - predominantly the turbulent fluxes of sensible and latent heat.

2. Energy balance

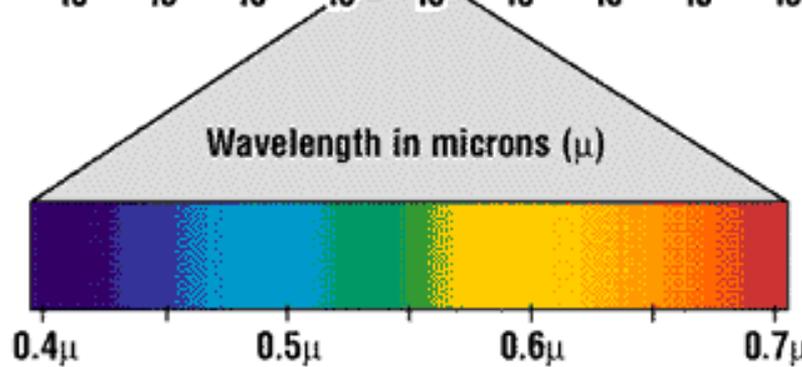


Wien's law: $\lambda_{\text{max}} = \frac{2,898 \cdot 10^{-3}}{T}$



No impact on weather but very dangerous (nuclear emission)

Used by satellite to detect meltwater or snow-height



2. Energy balance

Wien's law

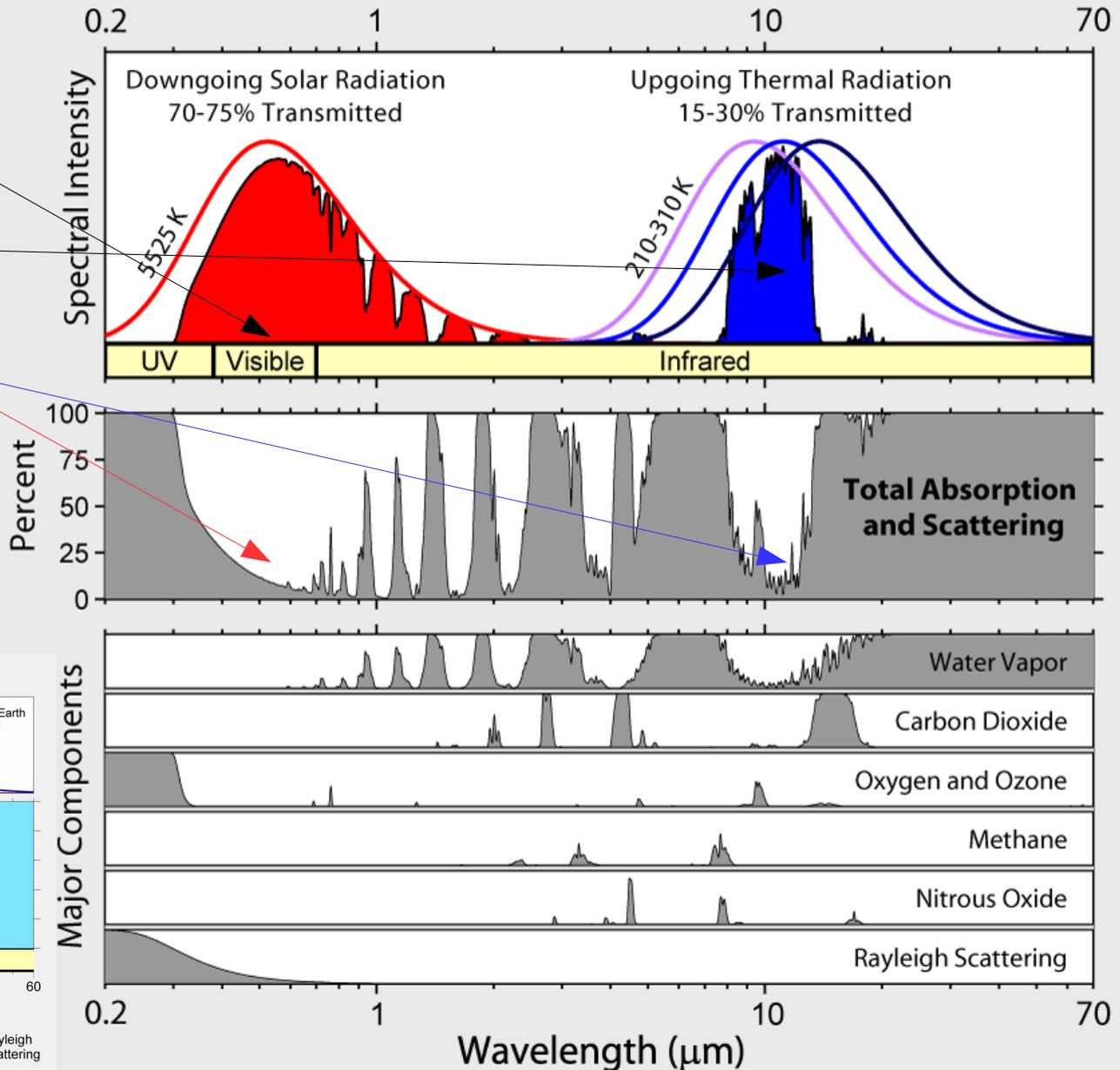
$$\lambda_{\max} = \frac{2,898 \cdot 10^{-3}}{T}$$

Stefan-Boltzmann's law

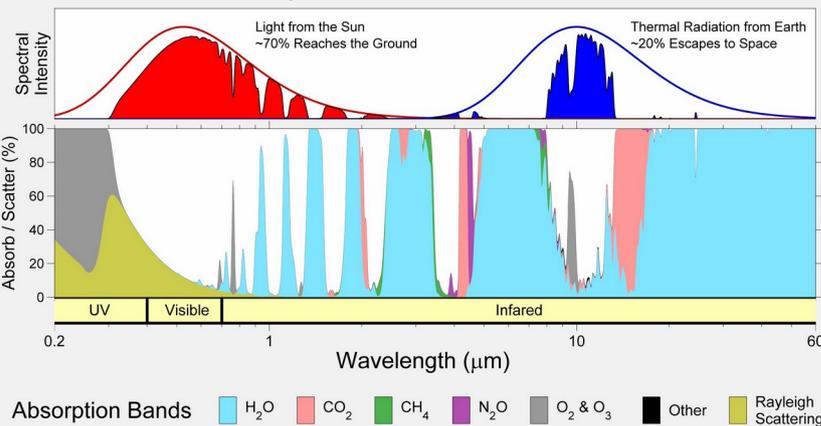
$$LW_{up} = \sigma T^4$$

Atmospheric windows

Radiation Transmitted by the Atmosphere

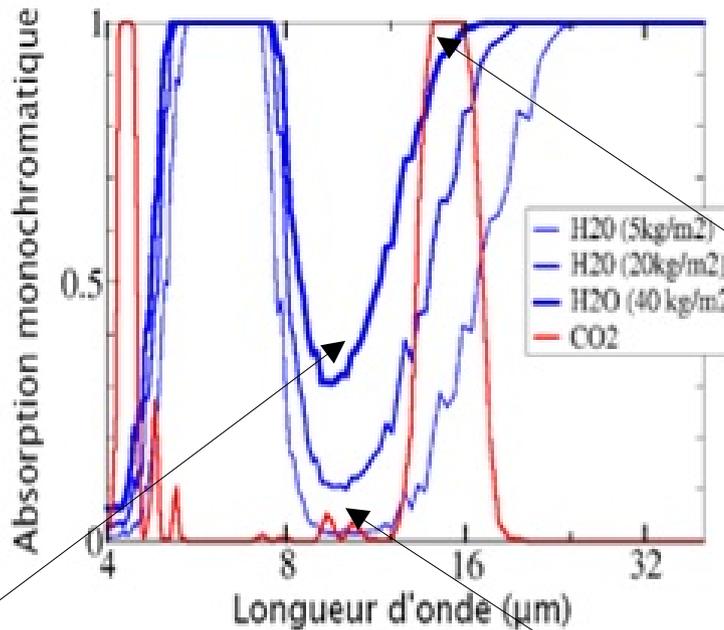


Clear-Sky Atmospheric Transmission

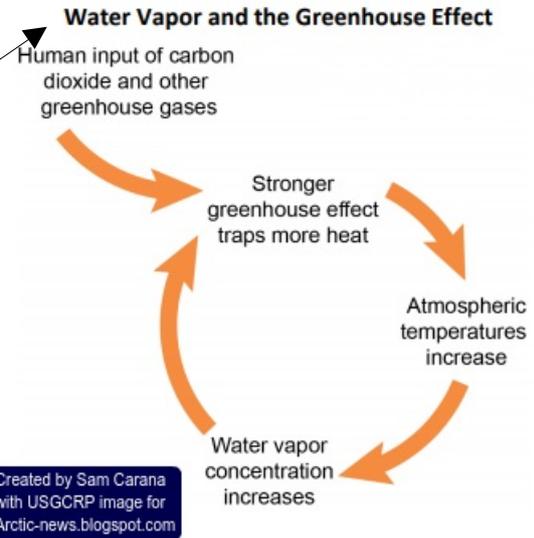


2. Energy balance

In the polar regions

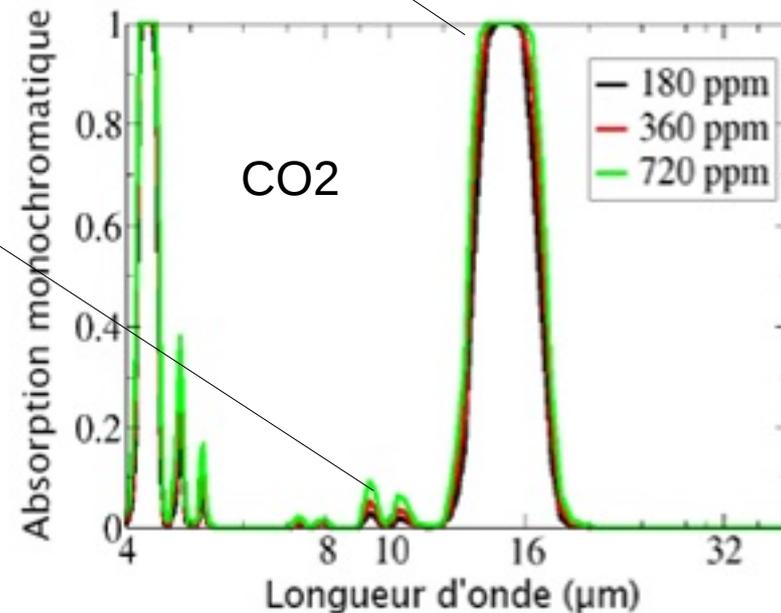


Polar area
Temperate area
Tropical area



Atmospheric windows where IR is not absorbed by water

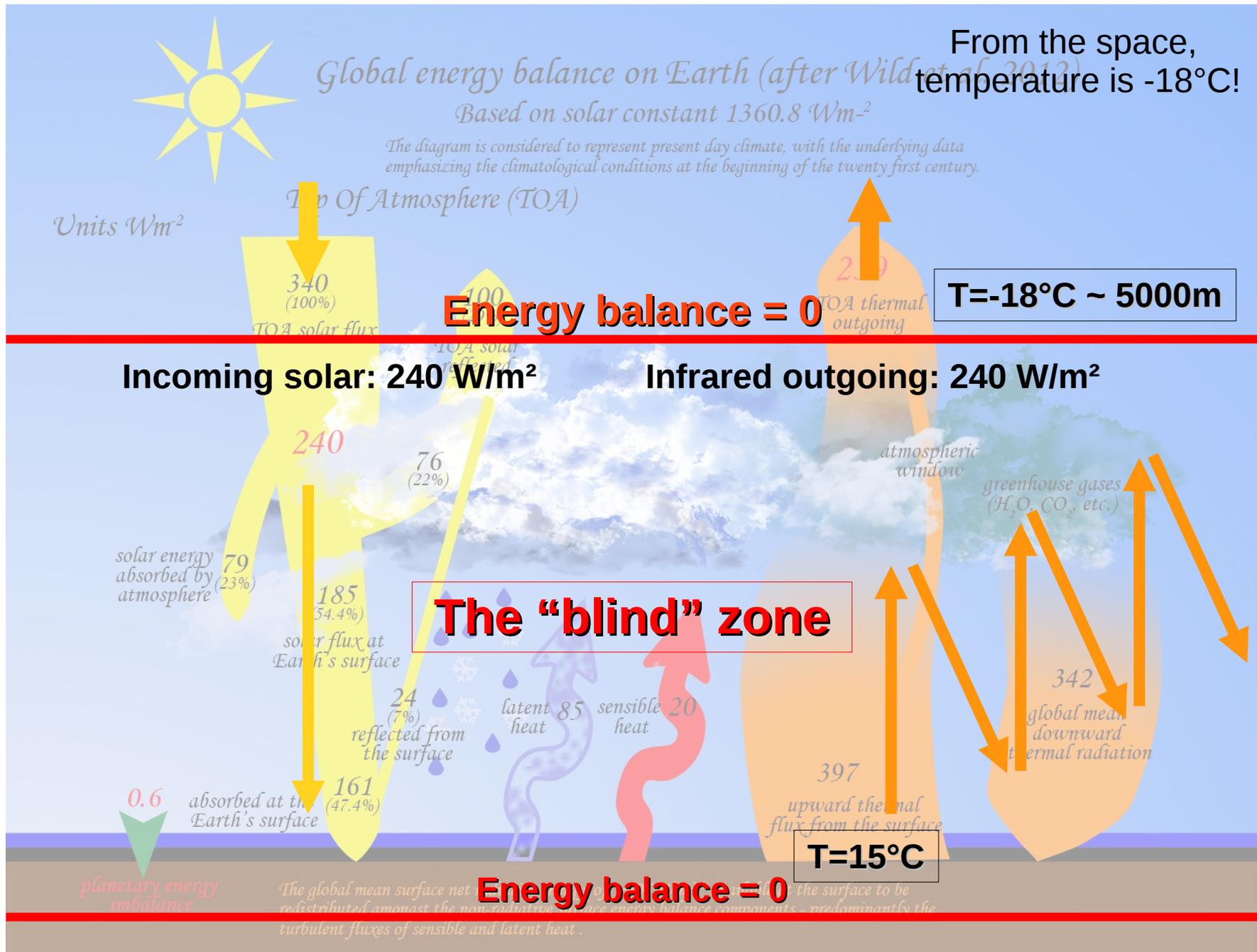
- CO2 absorption more efficacy:
1. in polar regions
 2. in high troposphere



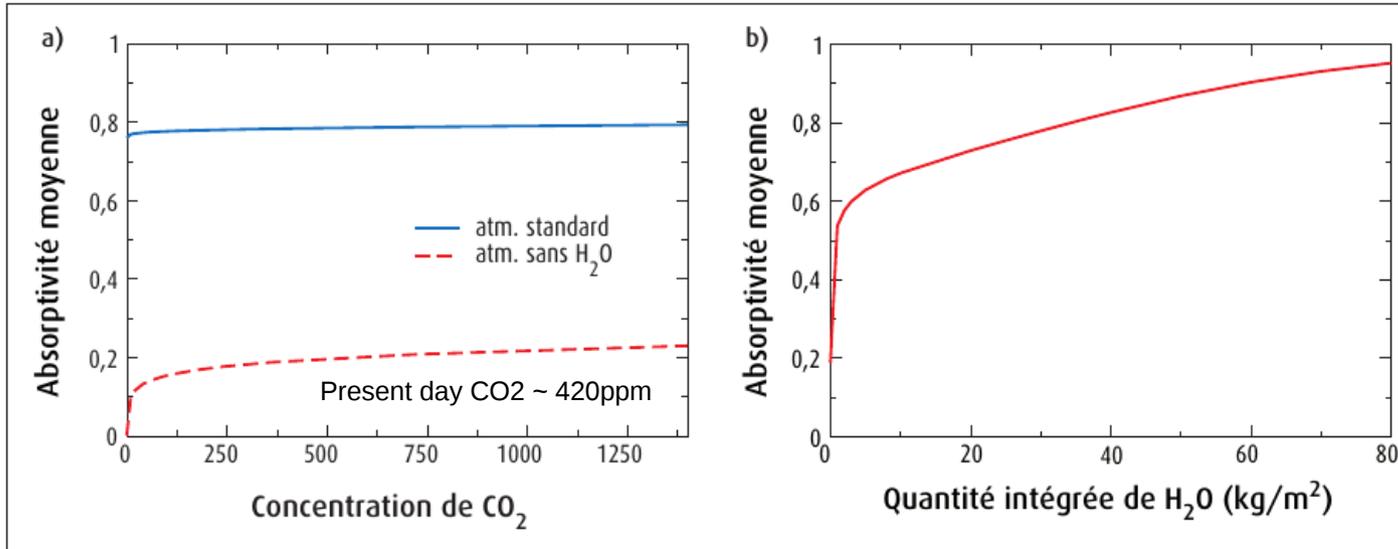
2022:
420ppm

Polar regions become faster warmer thanks to the melt-albedo, lapse rate and water vapour feedbacks.

2. Energy balance

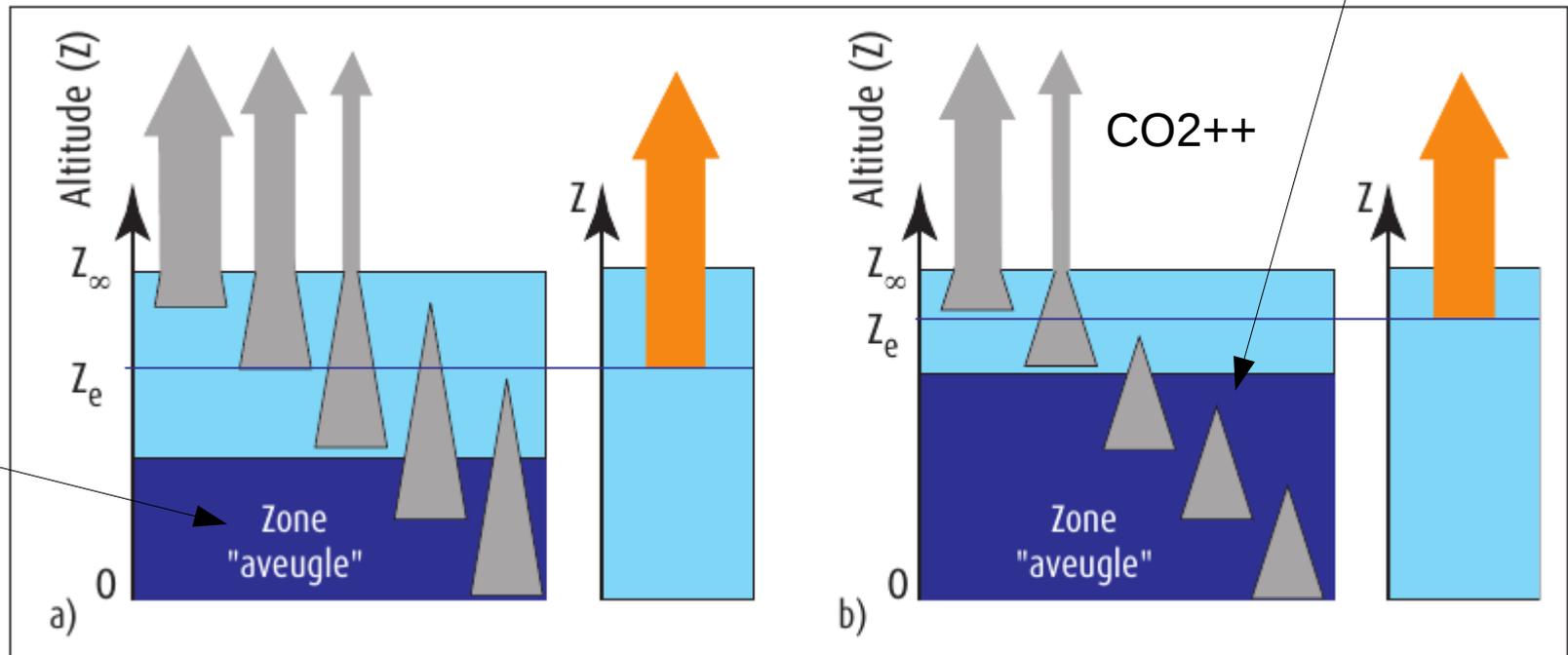


2. Energy balance



The "blind" zone reached higher altitudes with less H₂O

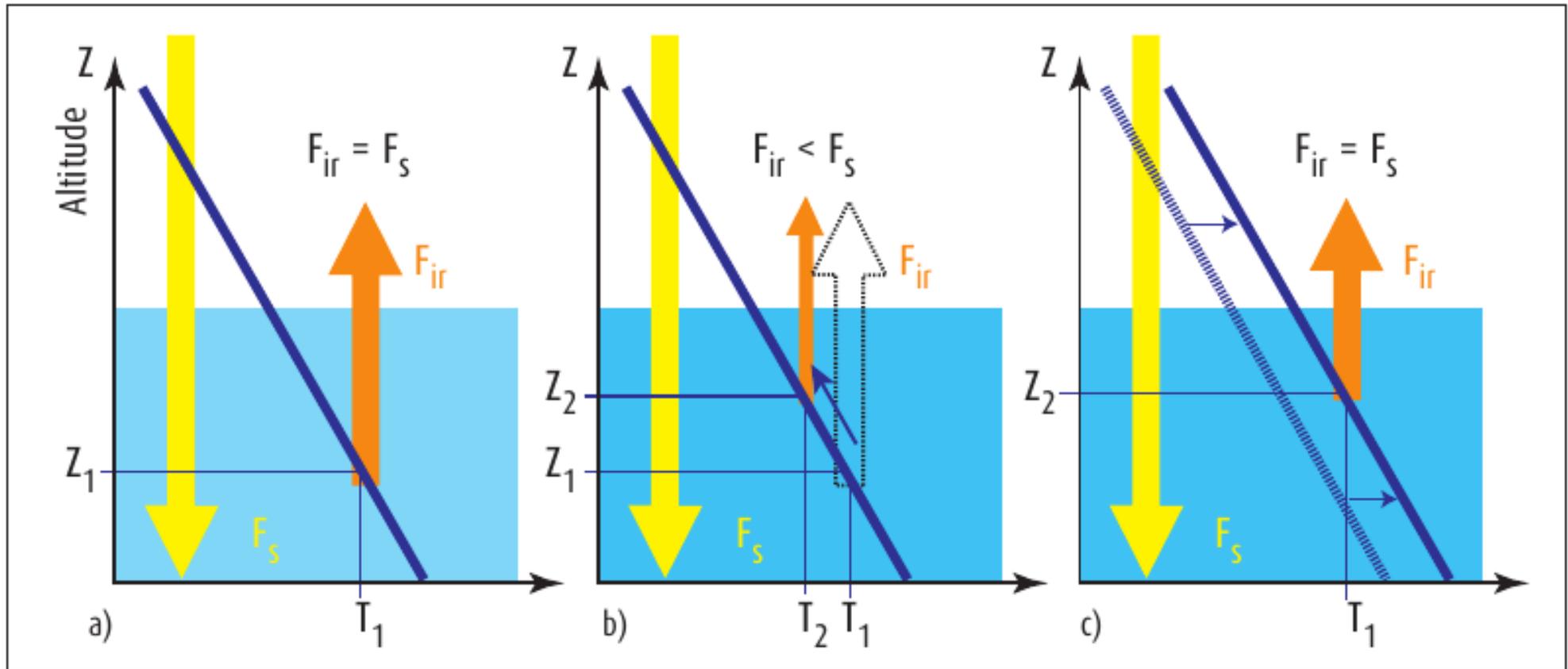
Atmospheric levels where infrared absorption is saturated



2. Energy balance

1. Increase 1st in altitude
2. Increase after in surface due to the lapse rate

High troposphere is expected to warm larger than surface!



As the t° gradient is fixed $\sim 1^\circ C / 100m$ if dry (or $0.5^\circ C / 100m$ if wet), the temperature rise in altitude is reflected towards the surface even if the layer is "blind".

surface warming \approx elevation of emission altitude \times thermal gradient

2. Energy balance

At radiative equilibrium:

$$(1 - \alpha) \frac{S_0}{4} = \sigma T_e^4 \quad \longrightarrow \quad T_e \approx 255 \text{ K} = -18^\circ\text{C}$$

Where:

- $S_0 \approx 1361 \text{ W m}^{-2}$ is the solar constant
- the factor $1/4$ accounts for Earth's spherical geometry
- $\alpha \approx 0.30$ is Earth's planetary albedo
- σ is the Stefan-Boltzmann constant
- T_e is Earth's **effective radiating temperature**

Introduce an **effective emission altitude** z_e :

$$T_s \approx T_e + \Gamma z_e$$

Where:

- T_s = surface temperature
- $\Gamma \approx 6.5 \text{ K km}^{-1}$ is the tropospheric lapse rate
- $z_e \approx 5 \text{ km}$ is the effective infrared emission altitude

Then:

$$T_s \approx 255 + 6.5 \times 5 \approx 288 \text{ K}$$

→ $\approx +15^\circ\text{C}$

→ **Natural greenhouse effect $\approx 33^\circ\text{C}$**

If greenhouse gases increase:

$$\Delta T_s \approx \Gamma \Delta z_e$$

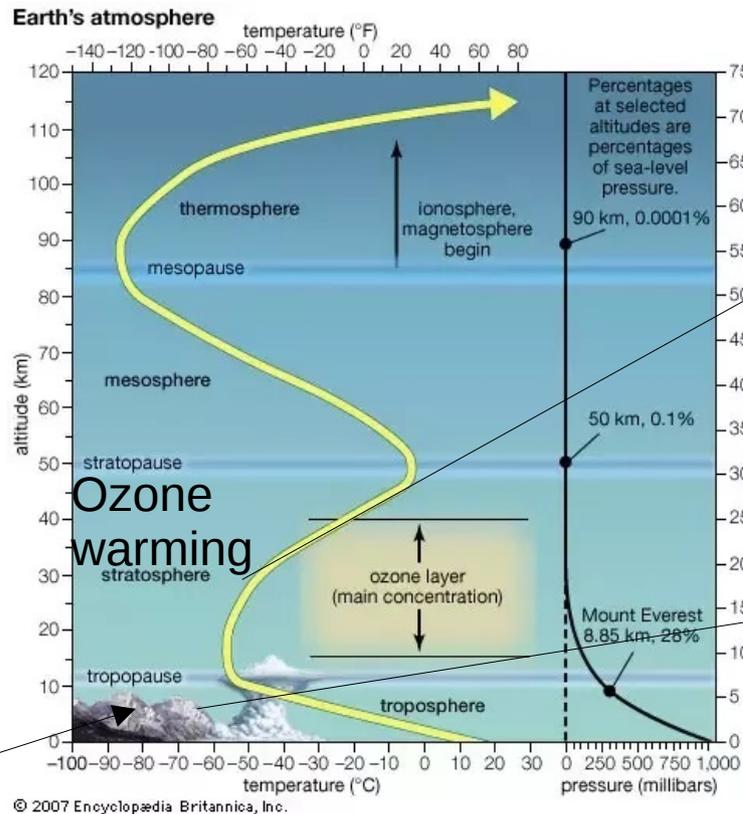
Example:

- $\Delta z_e = +150 \text{ m}$
- $\Gamma = 6.5 \text{ K km}^{-1}$

$$\Delta T_s \approx +1^\circ\text{C}$$

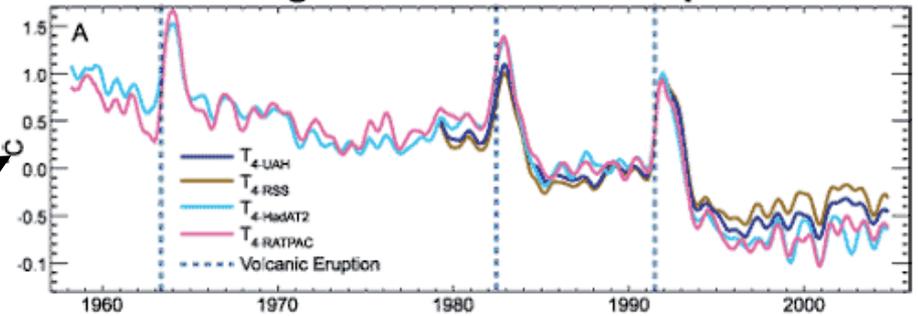
2. Energy balance

Tropospheric warming vs stratospheric cooling

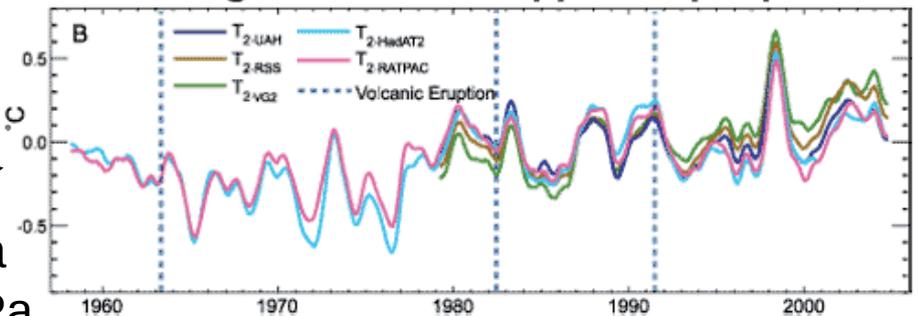


Ideal gas law
 $PV \sim T$

Cooling in the lower stratosphere



Warming in the Mid to Upper Troposphere



Stable CO₂ absorbs IR => becomes excited => releases IR by becoming stable again

Stratosphere: no dense (captured IR no more absorbed), less ozone (ozone hole) (absorbing UV) and warmer above (IR goes up)

Troposphere: dense (=> reabsorbed), warmer below (IR goes down) + absorbed most of IR emissions that do no more reach stratosphere

2. Energy balance - feedbacks

List of feedbacks:

Increasing upward longwave radiation (it is the result in fact)

There are still uncertainties about this

Negative feedbacks

-CO₂ (into plants, ocean)

More CO₂ absorbed
since more is in the air

-Heat (emitted to space)

More heat radiated
from a warmer planet

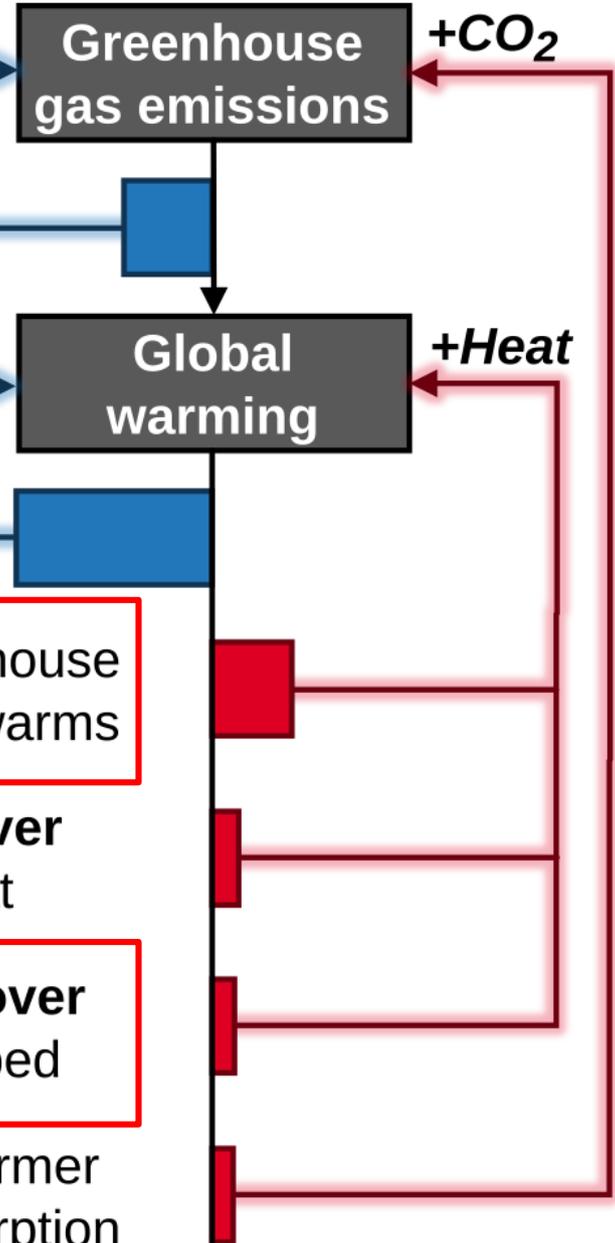
Positive feedbacks

Water vapor (a greenhouse gas) increases as air warms

Changes to cloud cover
trap more radiated heat

Less snow and ice cover
= more sunlight absorbed

Lost plant life and warmer oceans limit CO₂ absorption



2. Energy balance - feedbacks

Feedback	Symbol	Typical value ($\text{W m}^{-2} \text{K}^{-1}$)	Sign	Notes
Planck (thermal IR emission)	λ_p	+3.1 to +3.3	negative	Fundamental radiative stabilization
Water vapor	λ_v	-1.5 to -2.0	positive	Dominant amplifying feedback
Lapse rate	λ_{LR}	+0.6 to +1.0	negative	Strong in the tropics
Water vapor + lapse rate	λ_v+LR	-0.8 to -1.2	positive	Net positive
Surface albedo (snow-ice)	λ_a	-0.3 to -0.5	positive	Polar amplification
Clouds (net)	λ_c	-0.2 to -1.0	likely positive	Largest uncertainty

$$\Delta T = \frac{F_{2 \times CO_2}}{\lambda_{\text{total}}}$$

Where:

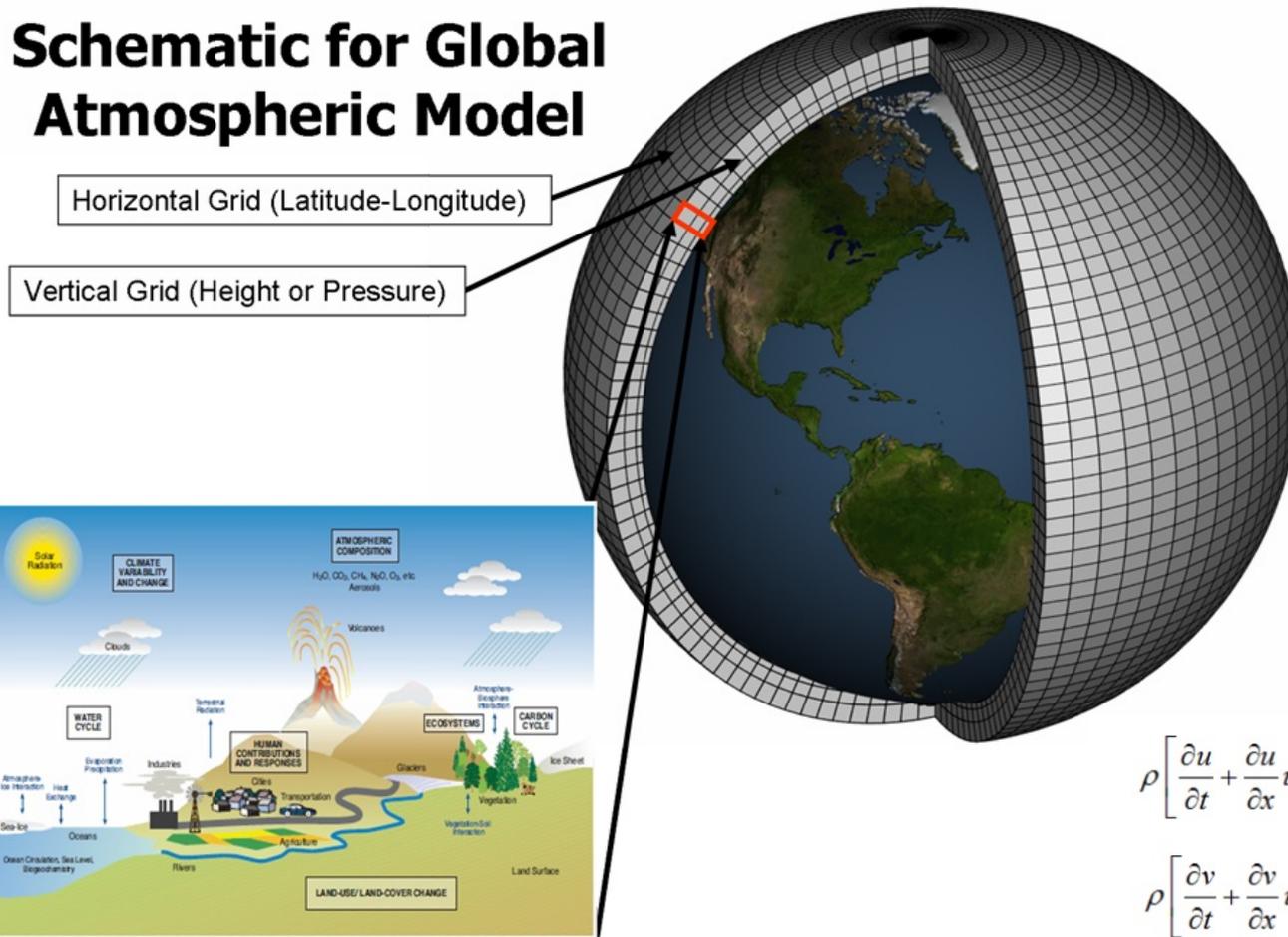
- $F_{2 \times CO_2} \approx 3.7 \text{ W m}^{-2}$
- $\lambda_{\text{total}} \approx 1.0\text{--}1.5 \text{ W m}^{-2} \text{K}^{-1}$

👉 ECS $\approx 2.5\text{--}4 \text{ }^\circ\text{C}$, consistent with IPCC AR6.

Equilibrium Climate Sensitivity (ECS)

3. Climate models and human activities

Schematic for Global Atmospheric Model



The impact of the sub-grid processes are parametrised but not resolved.

Eg: convection, turbulence, ...

$$\rho \left[\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} u + \frac{\partial u}{\partial y} v + \frac{\partial u}{\partial z} w \right] = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho g_x$$

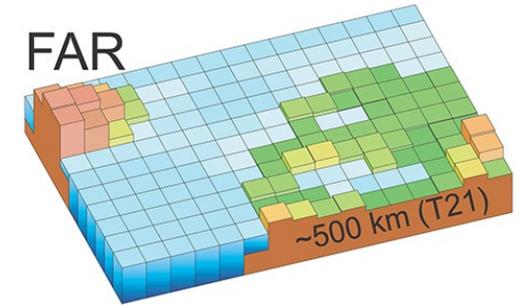
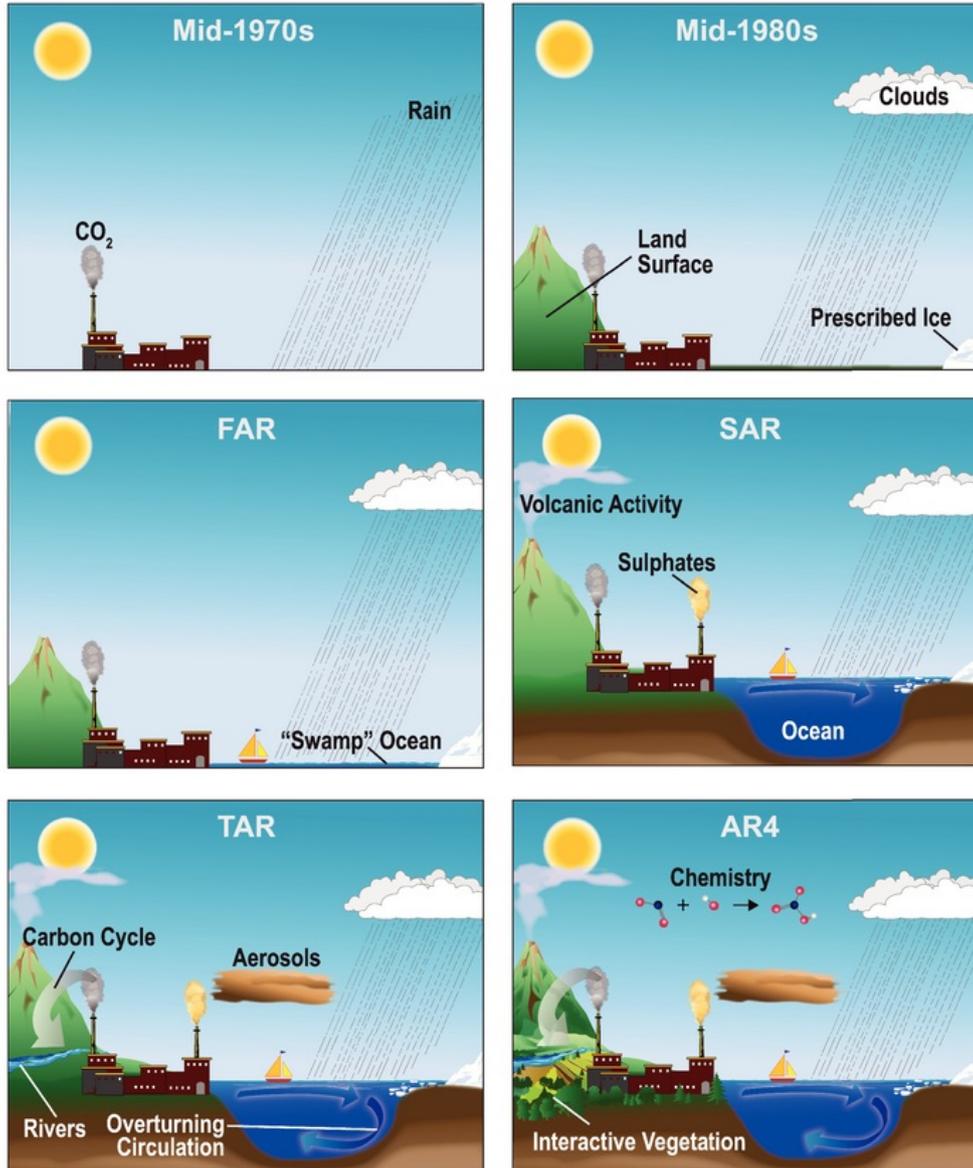
$$\rho \left[\frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} u + \frac{\partial v}{\partial y} v + \frac{\partial v}{\partial z} w \right] = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho g_y$$

$$\rho \left[\frac{\partial w}{\partial t} + \frac{\partial w}{\partial x} u + \frac{\partial w}{\partial y} v + \frac{\partial w}{\partial z} w \right] = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho g_z$$

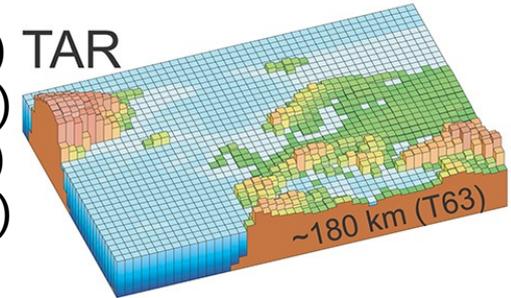
fluid (atmosphere + ocean) motion are explicitly simulated by numerically resolving/approximating the Navier-Stokes equations in Fortran or C

3. Climate models and human activities

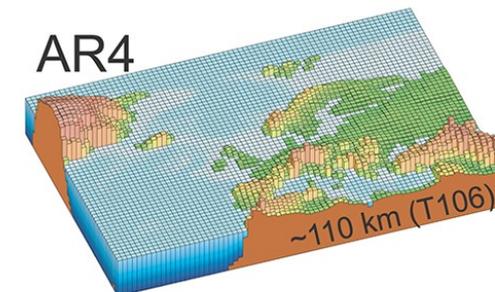
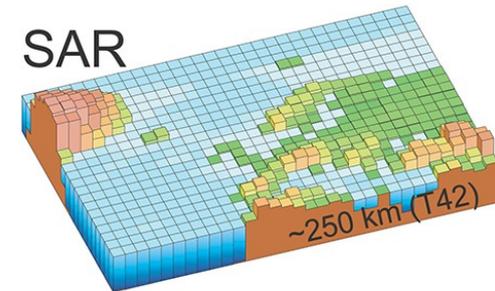
Improvements of the climate models ...



FAR = AR1 (1990)
SAR = AR2 (1995)
TAR = AR3 (2001)
AR4 (2007)



AR =
assessment report
from IPCC



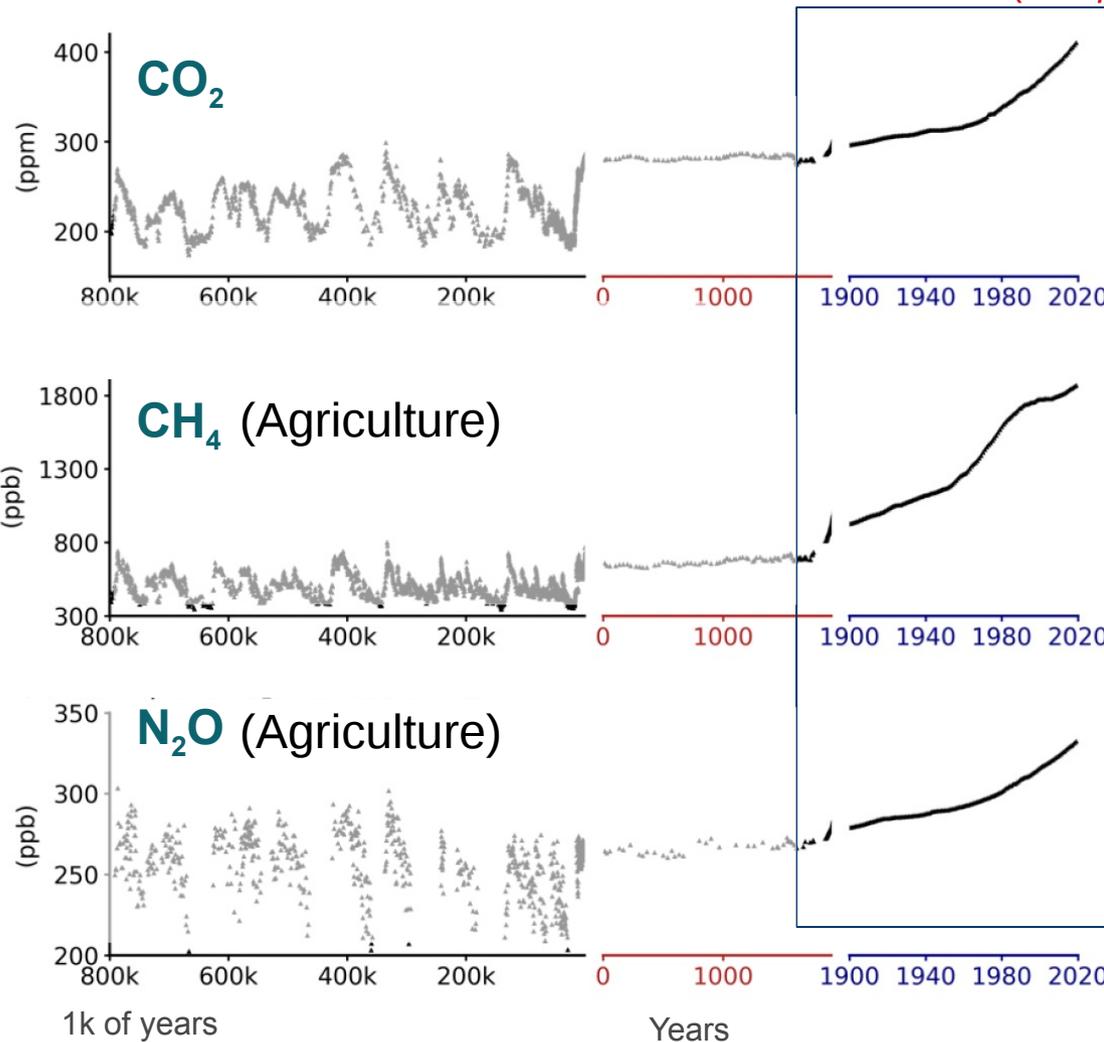
3. Climate models and human activities

H₂O = 1/1000 of air

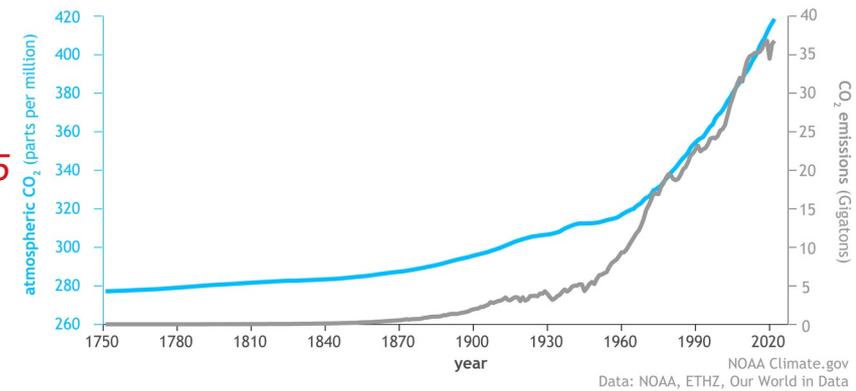
ppm = parts per million of air

ppb = parts per billion

Atmospheric concentration



Global atmospheric carbon dioxide compared to annual emissions (1751-2022)

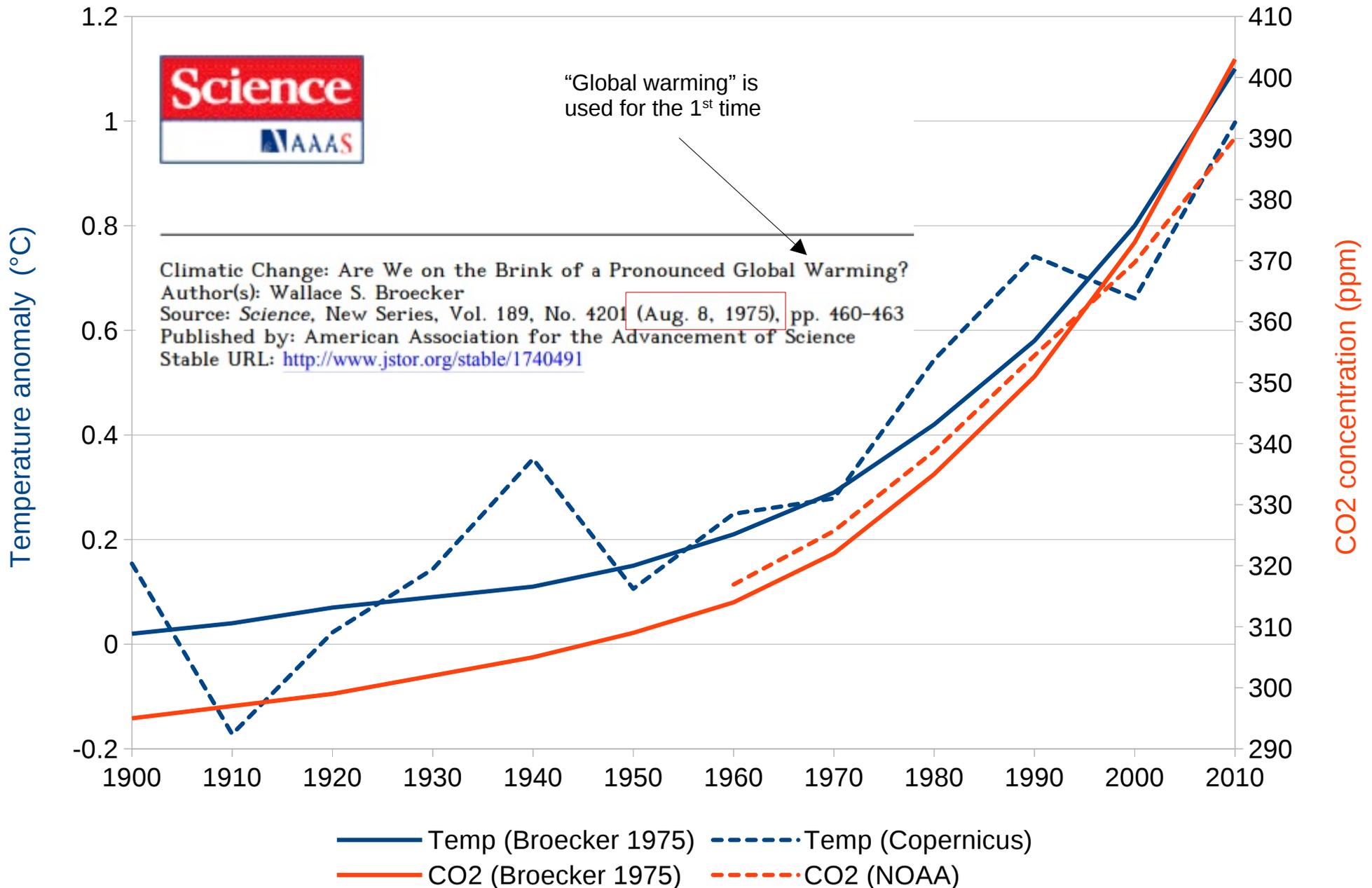


Residence time (half time live): ~100yrs

Residence time: ~10yrs
but 12 x stronger than CO₂

Residence time: ~120yrs
but 300 x stronger than CO₂

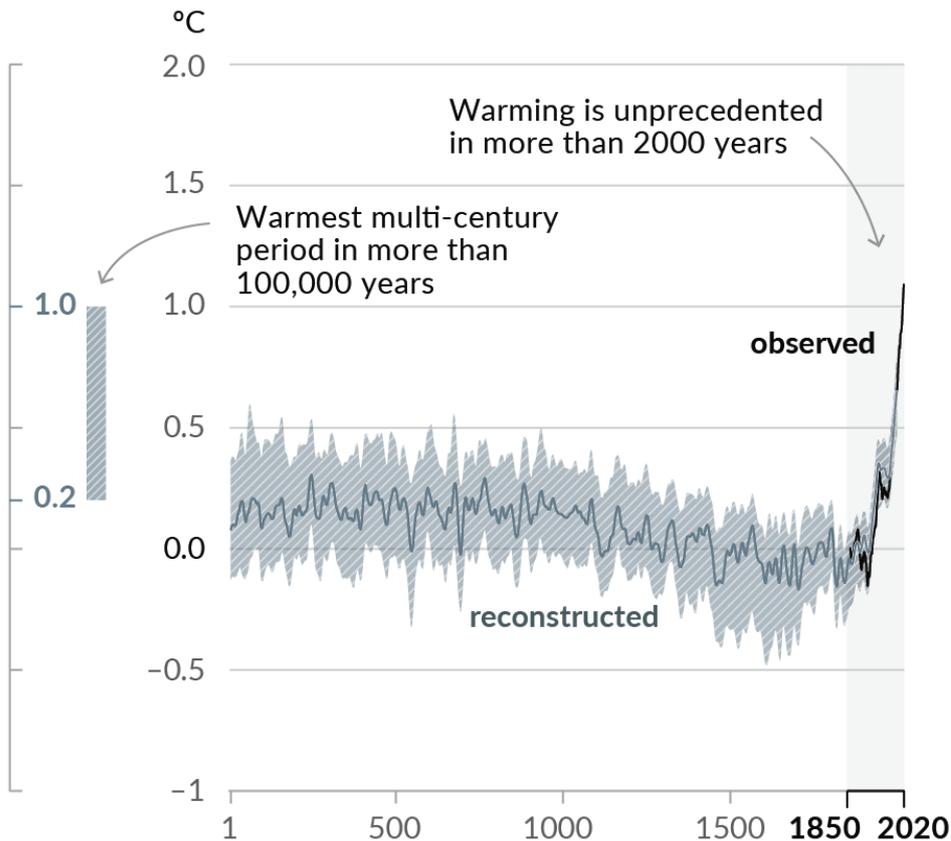
3. Climate models and human activities



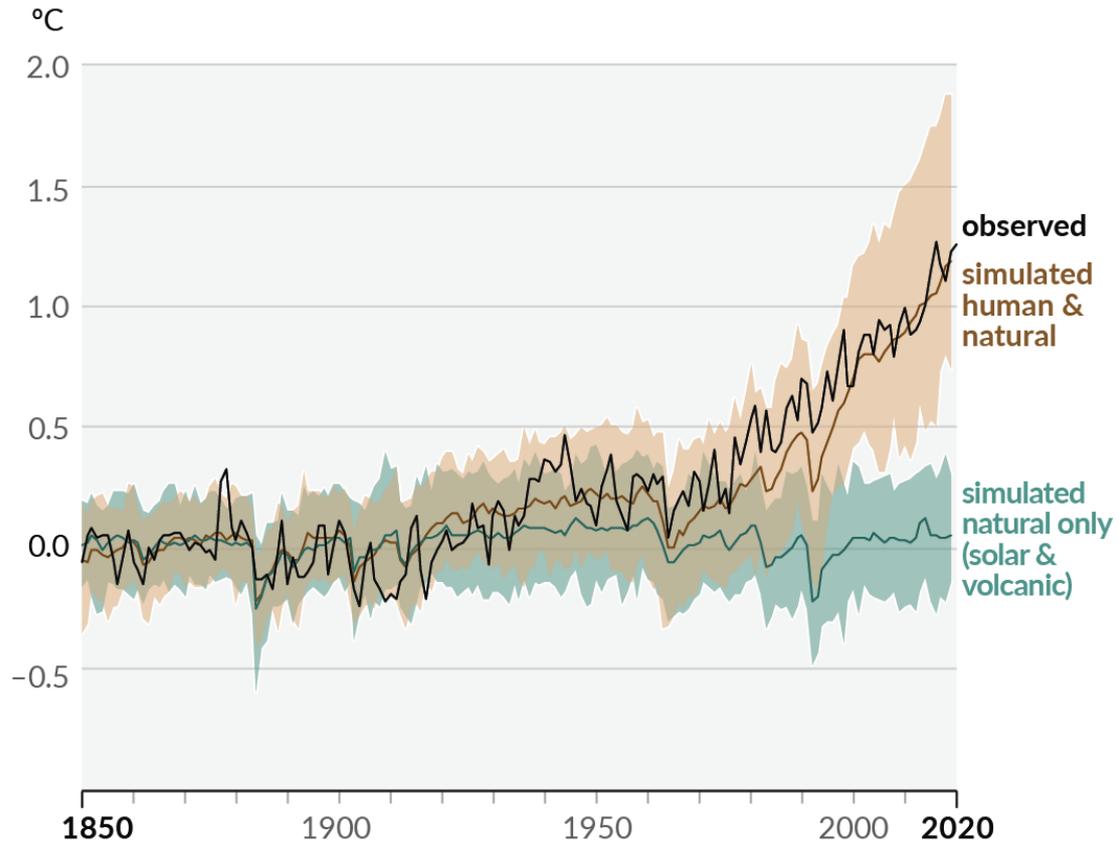
3. Climate models and human activities

Changes in global surface temperature relative to 1850–1900

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



(b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850–2020)

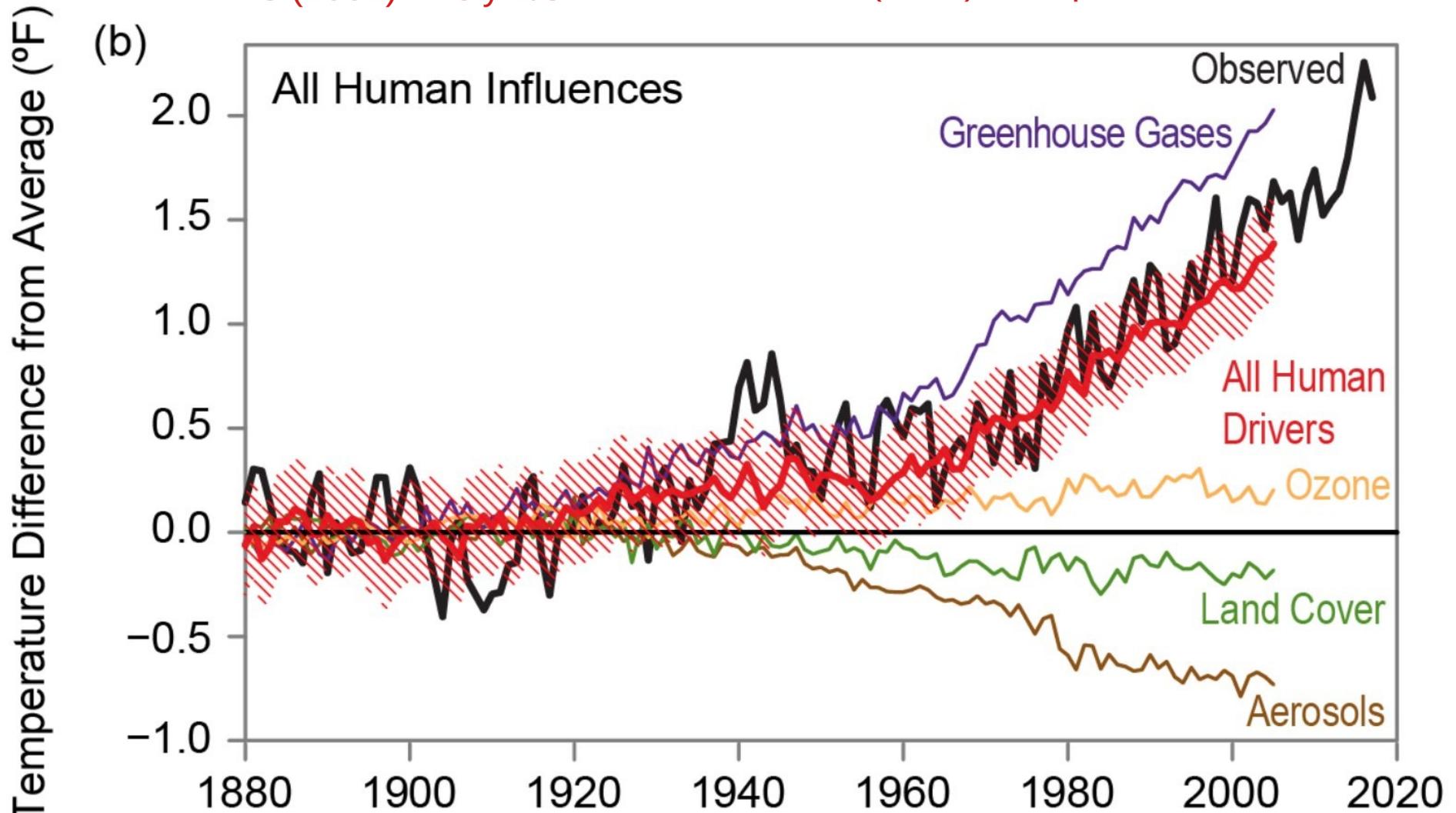


AR6 (2021) : **It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.**

3. Climate models and human activities

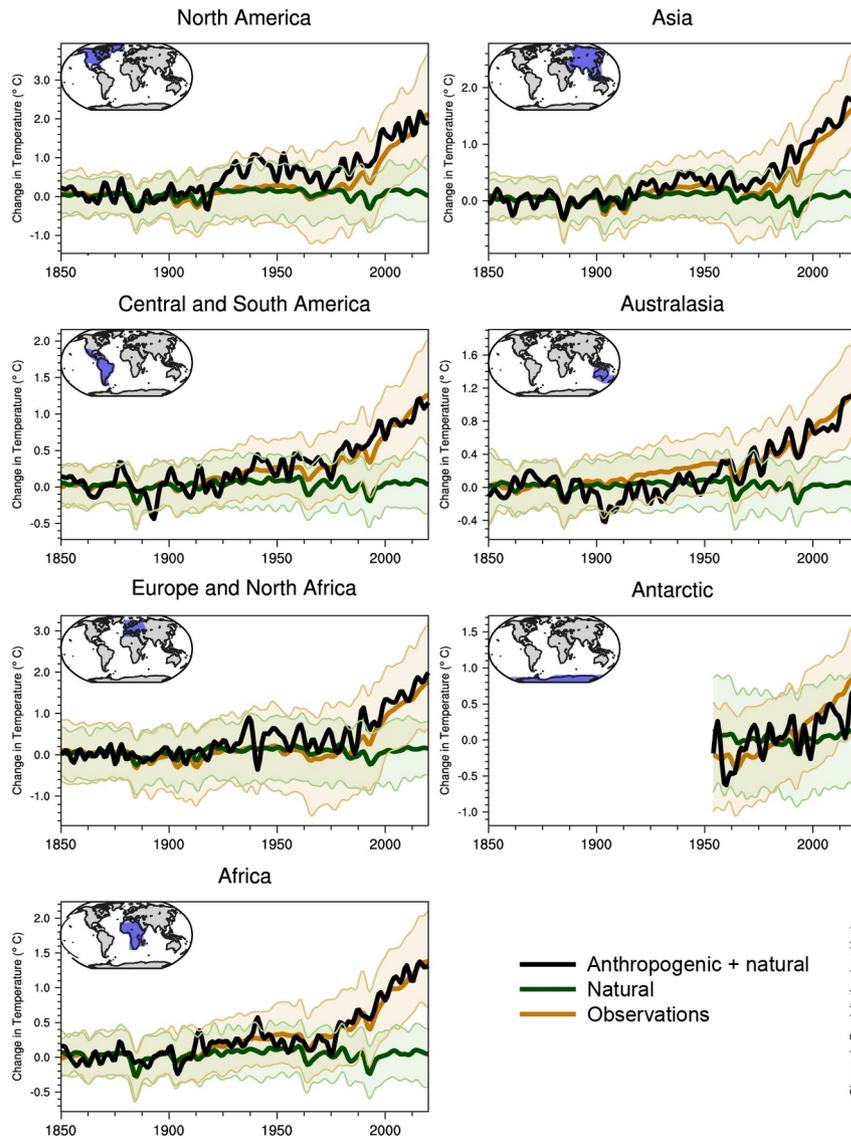
IPCC : Global warming is due to human activities ?

- AR1 (1990): nothing confirms it
- AR2 (1995): discernible
- AR3 (2001): likely 2/3
- AR4 (2007): very likely 9/10
- AR5 (2013): extremely likely 9.5 / 10
- AR6 (2021): unequivocal 10/10

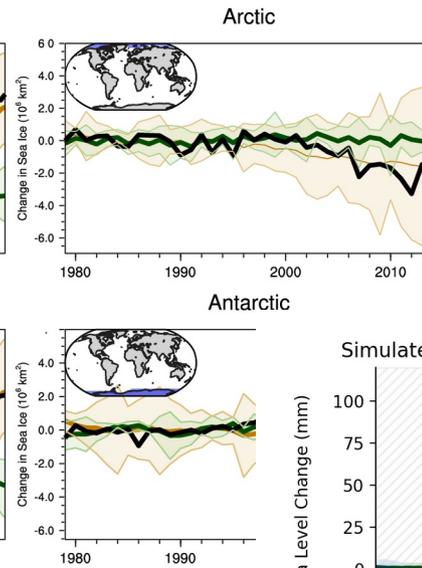


3. Climate models and human activities

Near-surface air temperature

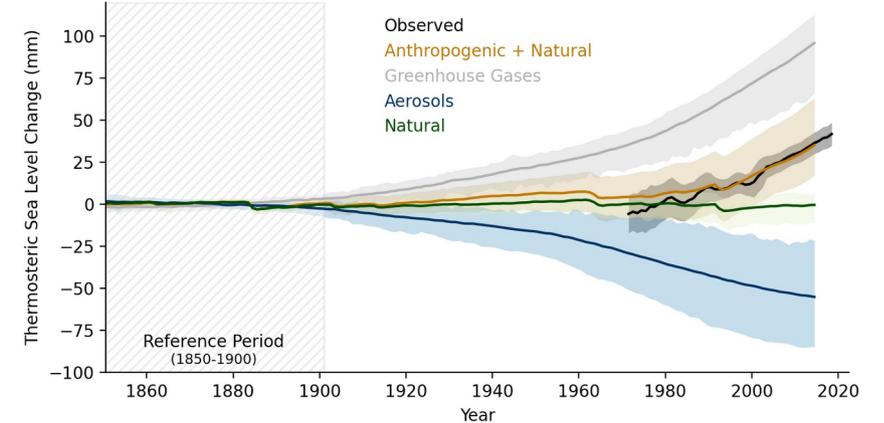


Sea ice

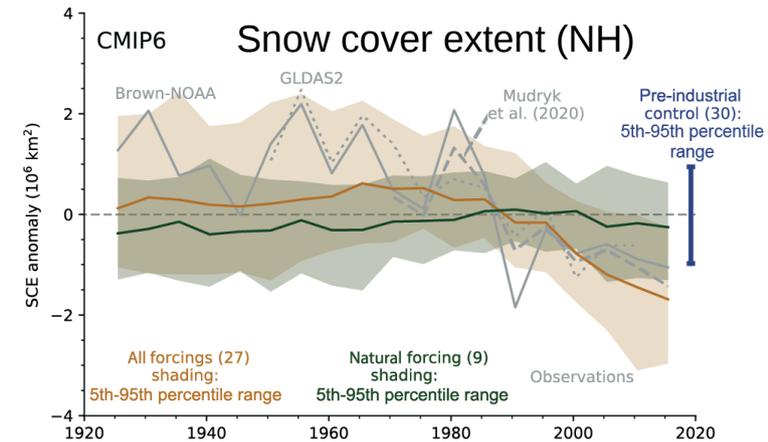
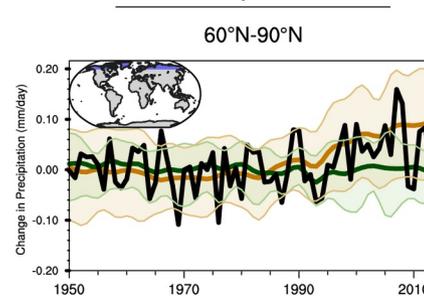


Attribution studies

Simulated and observed global mean sea level change due to thermal expansion



Precipitation

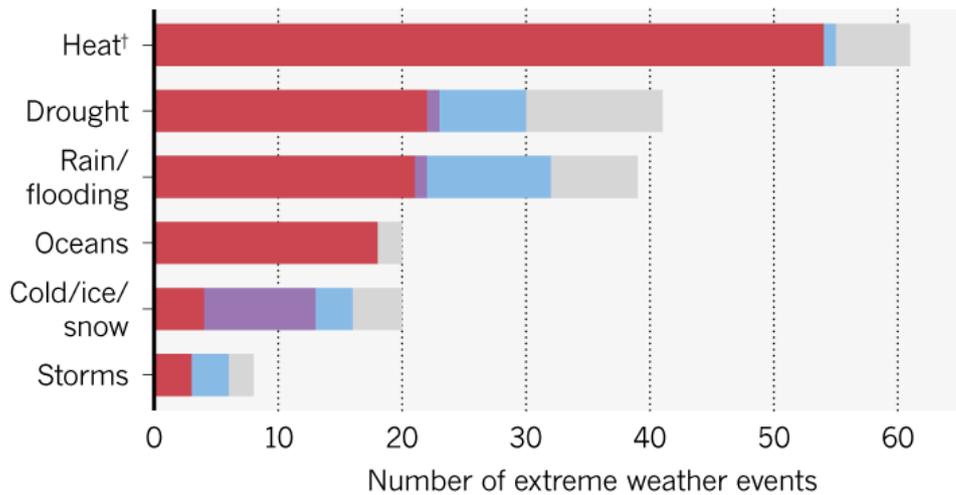


3. Climate models and human activities

Attribution science

Researchers have published more than 170 studies* examining the role of human-induced climate change in 190 extreme weather events.

- More severe or more likely to occur
- Less severe or likely to occur
- No discernible human influence
- Insufficient data/inconclusive

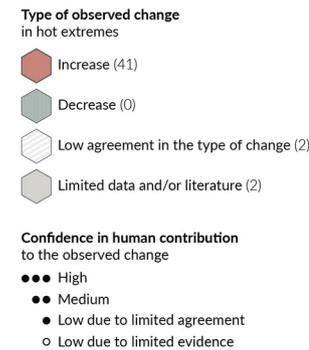


*Studies from 2004–18 collated by *Nature* and CarbonBrief. †Heat includes heatwaves and Oceans includes studies on marine heat, coral bleaching and marine-ecosystem d

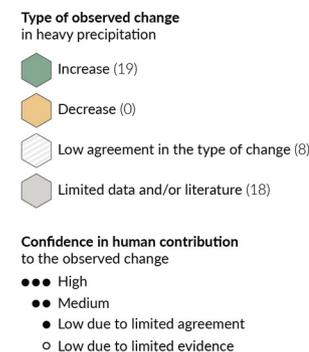
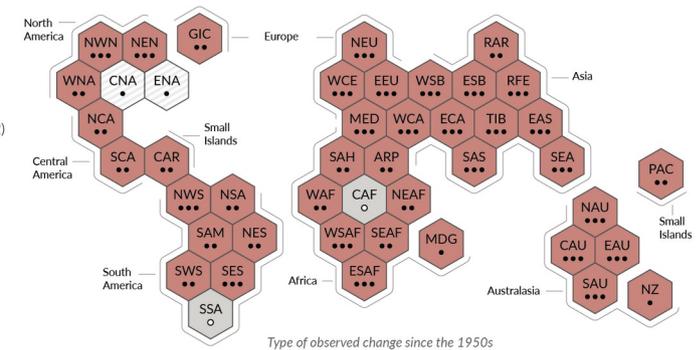
©nature

Attribution studies

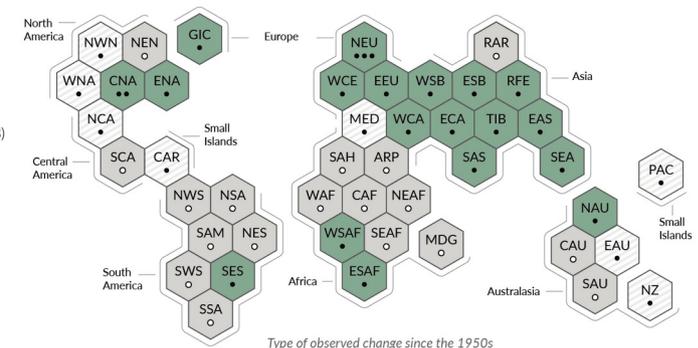
Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes



(a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions



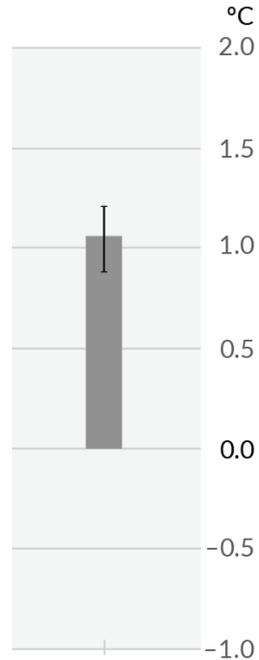
(b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions



3. Climate models and human activities

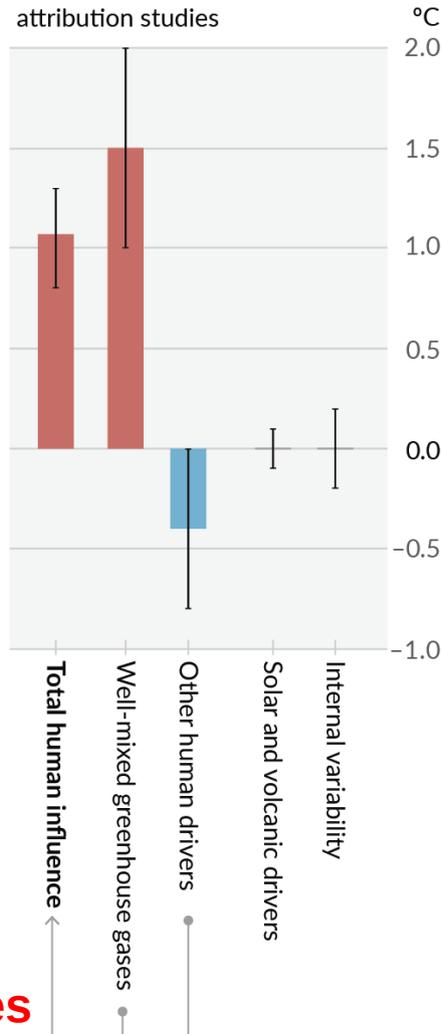
Observed warming

(a) Observed warming 2010–2019 relative to 1850–1900

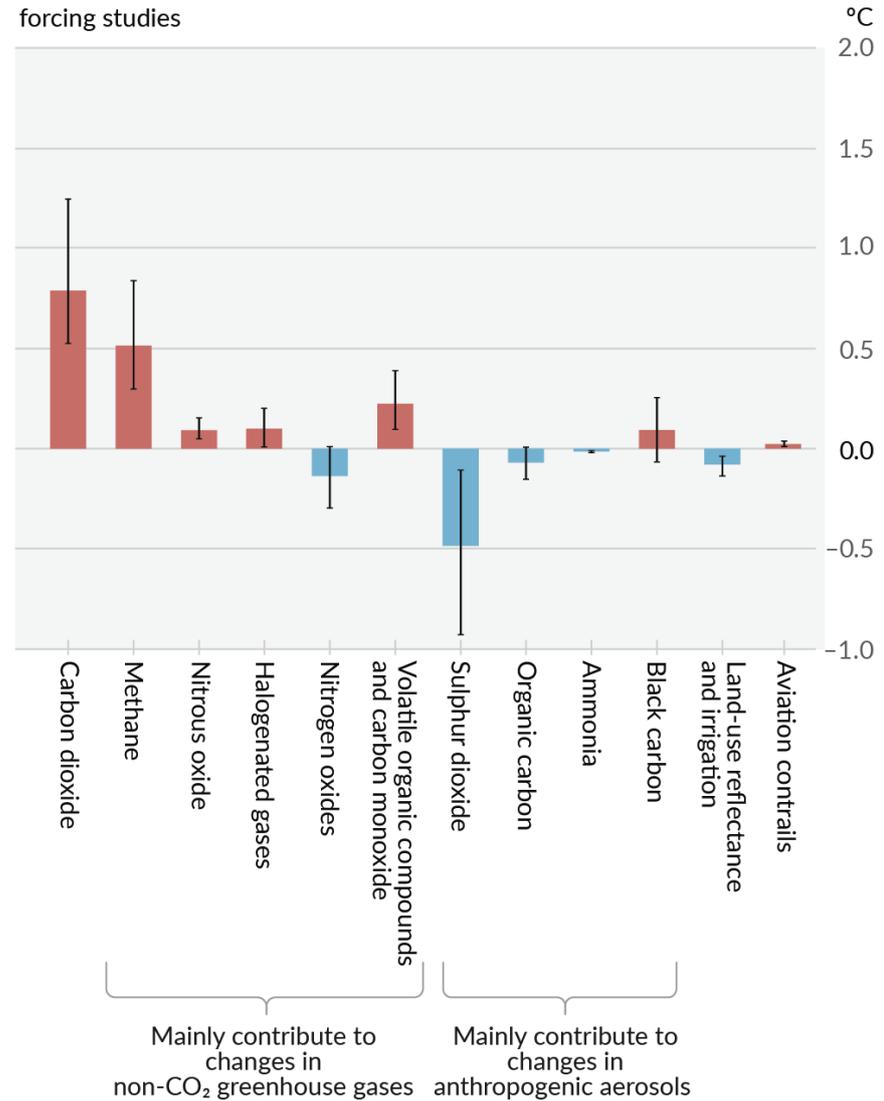


Contributions to warming based on two complementary approaches

(b) Aggregated contributions to 2010–2019 warming relative to 1850–1900, assessed from attribution studies



(c) Contributions to 2010–2019 warming relative to 1850–1900, assessed from radiative forcing studies



Some human activities induce a cooling!

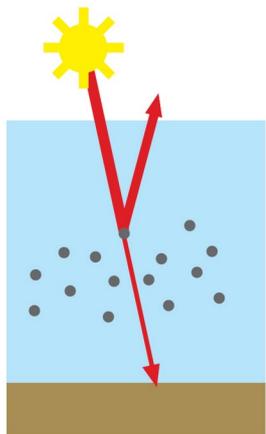
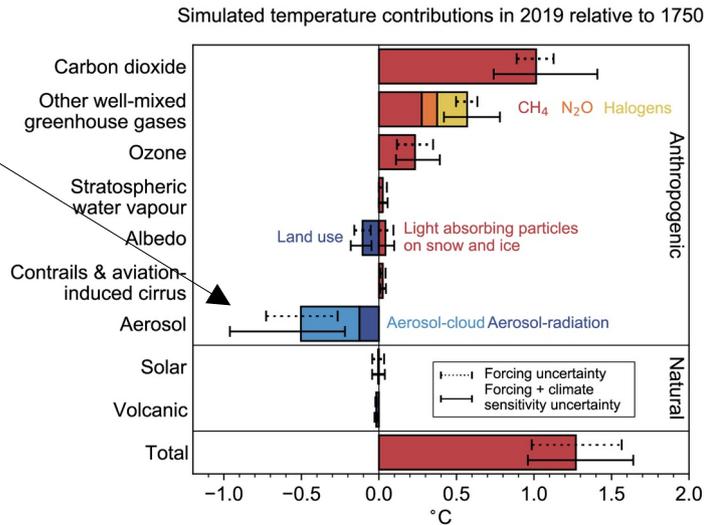
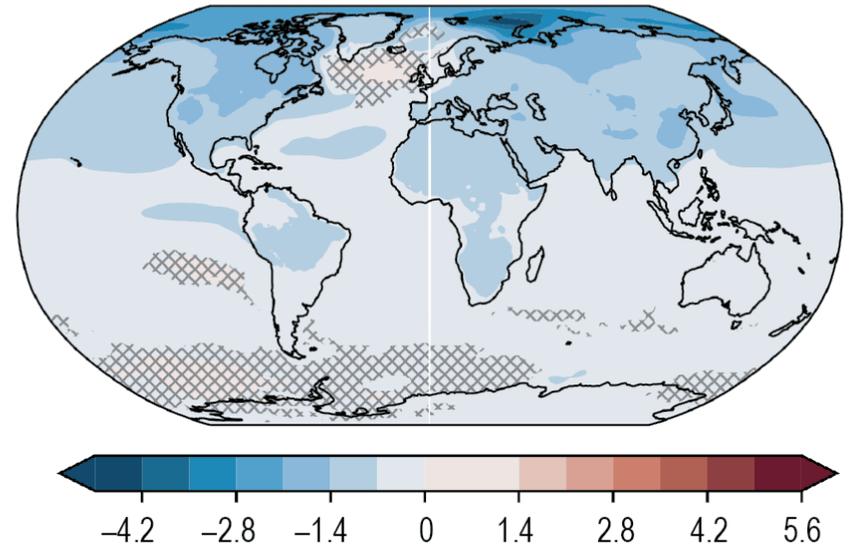
3. Climate models and human activities

Aerosols have a large cooling impact but they are decreasing a lot due to smog and direct impact on the human health.

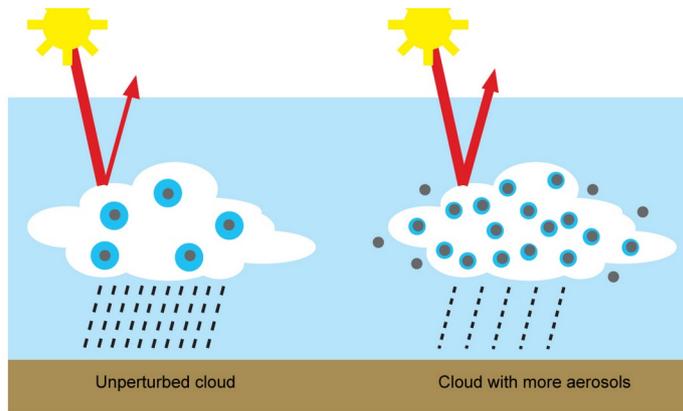
Aerosols residence time is very low.

Very uncertain.

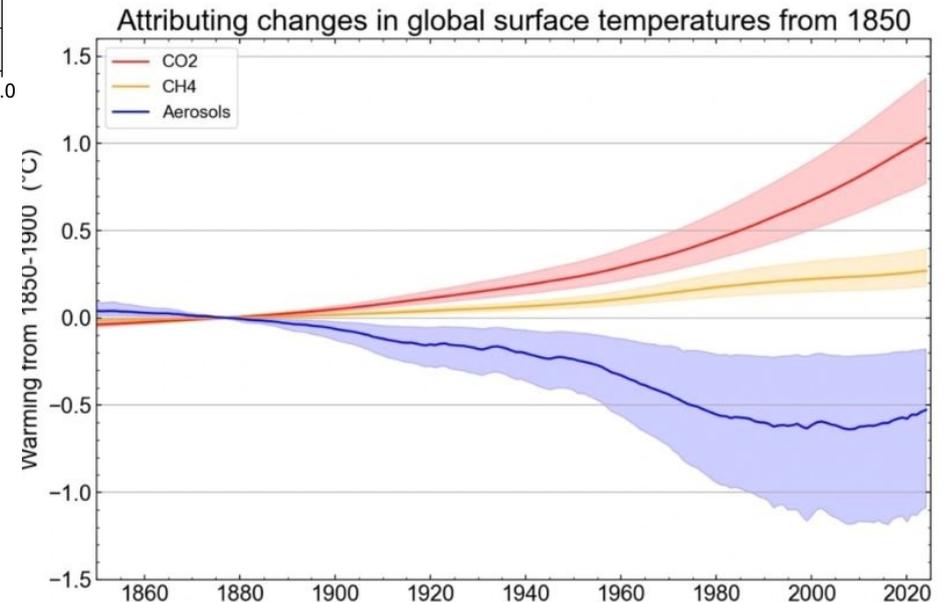
(a) Surface air temperature response due to aerosols



Aerosol direct effect
Scattering and absorption of solar radiation

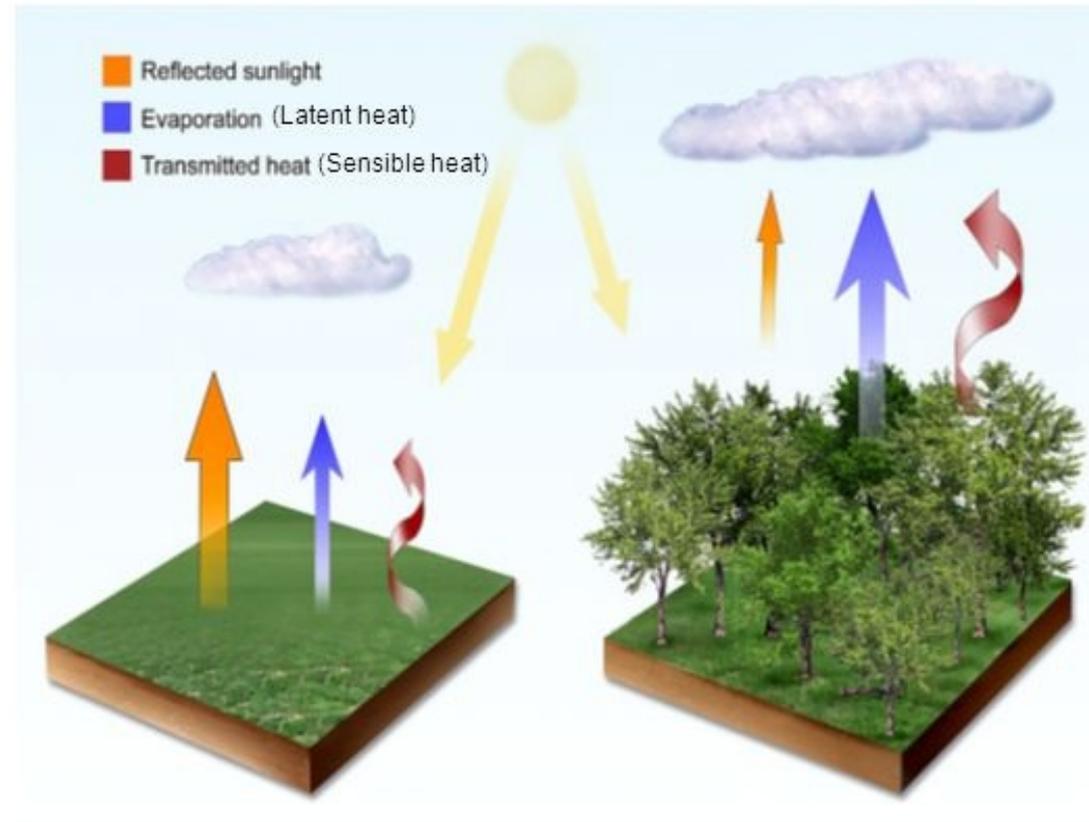


Aerosol indirect effect
Decrease of cloud droplet size, increase of droplet number, increased scattering of solar radiation, decrease of precipitation



3. Climate models and human activities

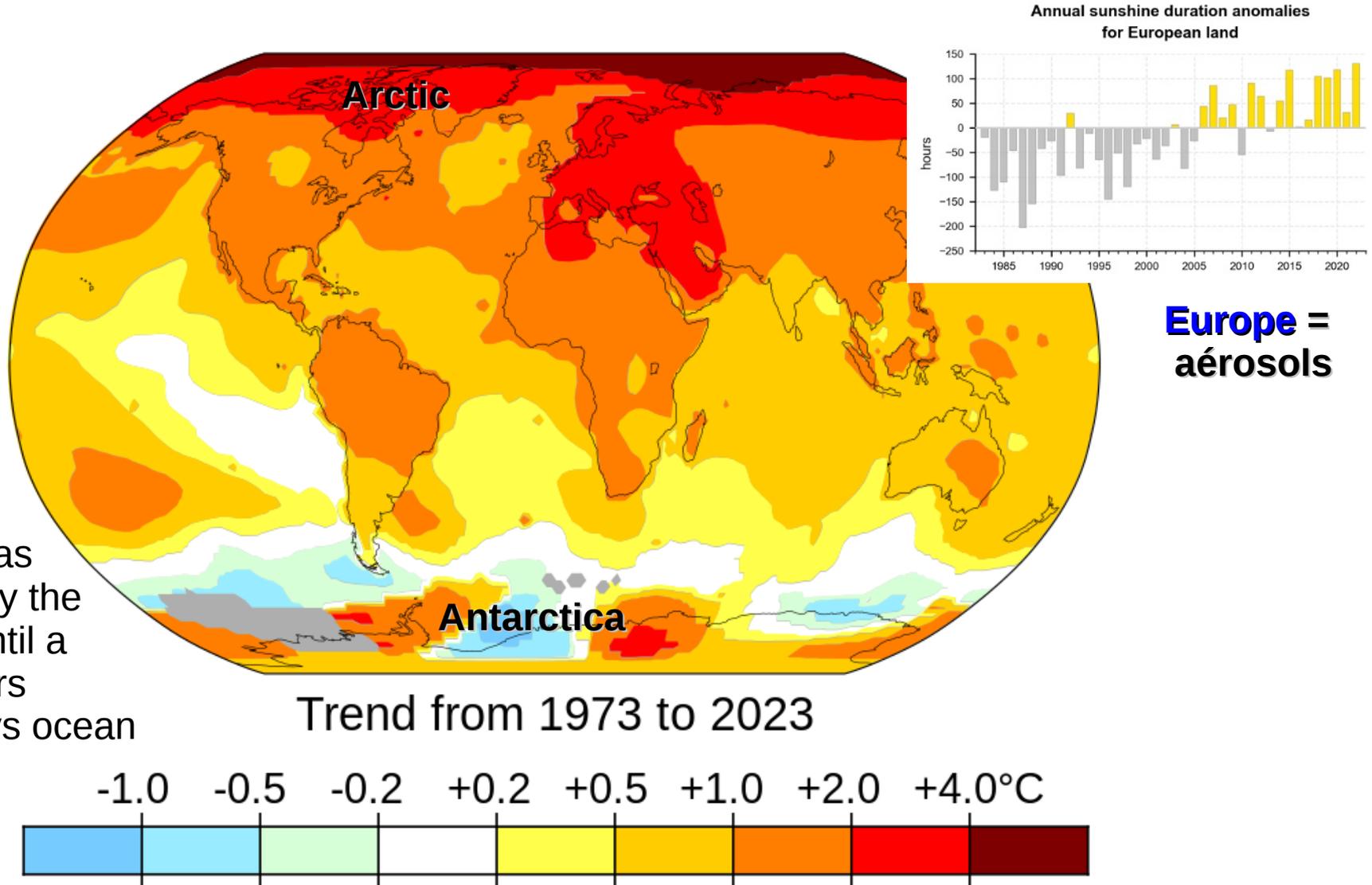
Land cover change impacts on climate: very uncertain and complex



Less forests => albedo ++ (cooling effect)
=> latent heat flux -- + clouds -- (warming effect)
=> less absorbed CO2 (warming effect)

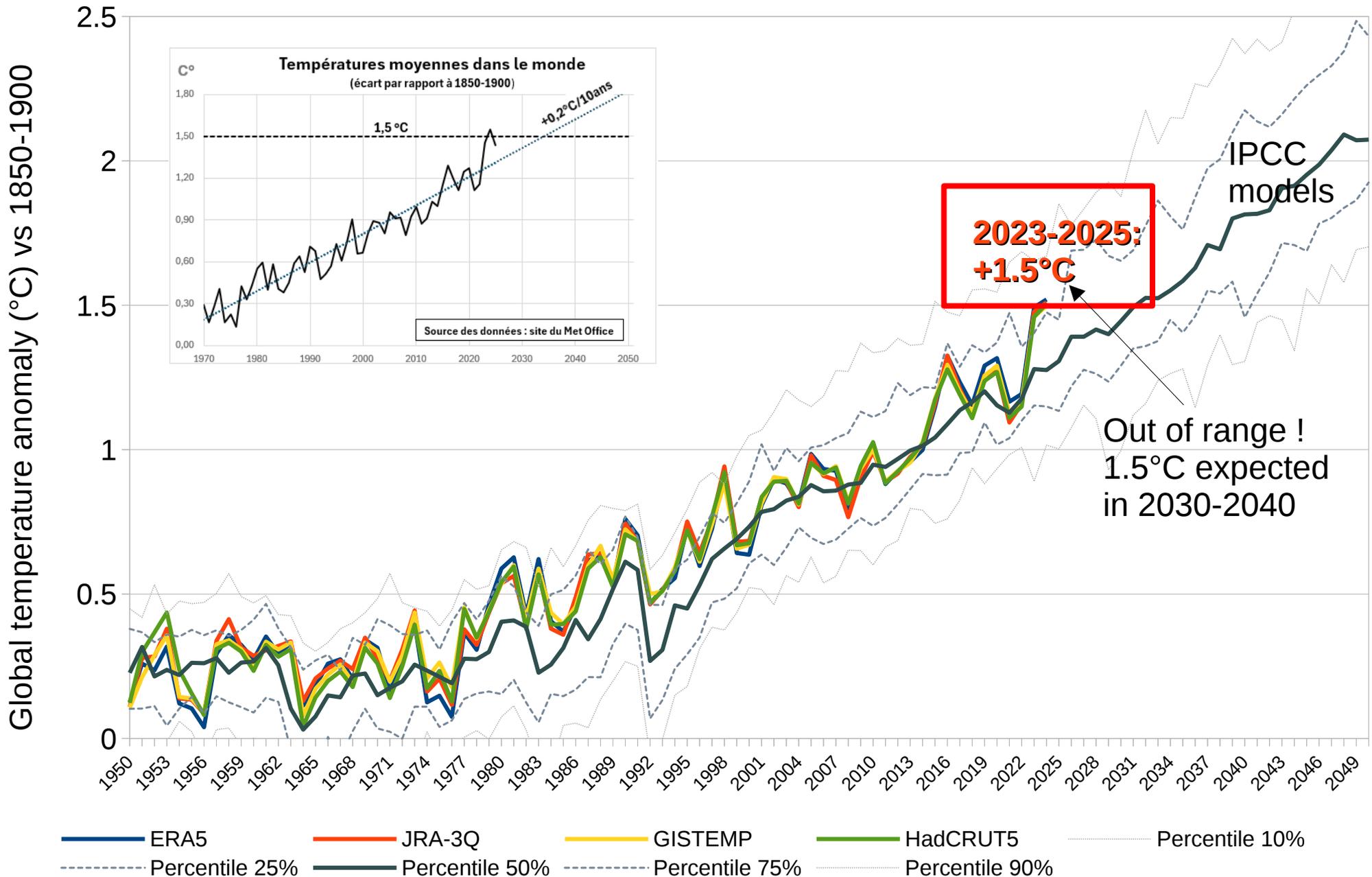
3. Climate models and human activities

Arctic is warming 4 x faster than Equator due to the albedo feedback, water vapour feedback and lapse rate feedback

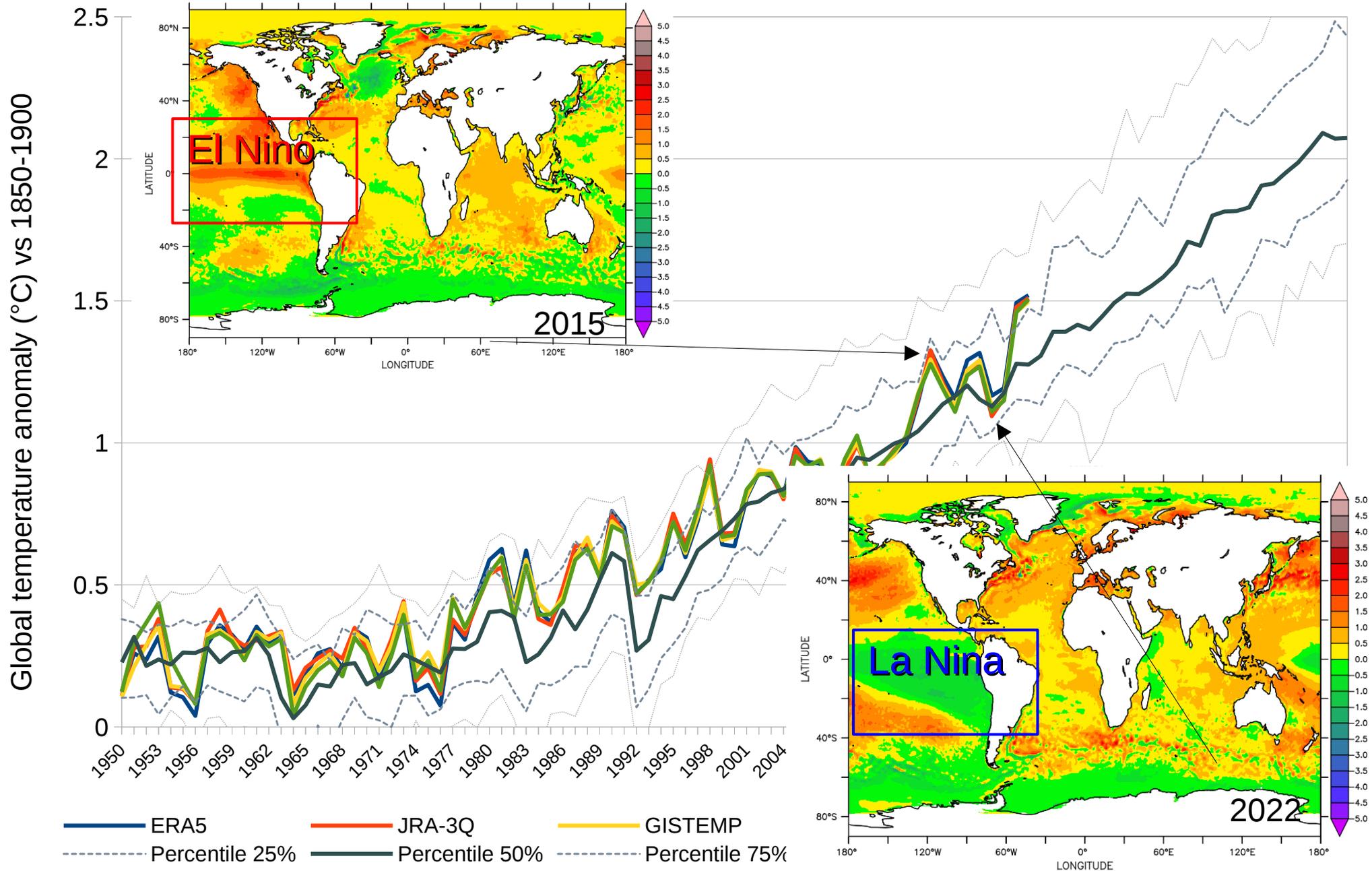


Antarctica was “protected” by the ozone hole until a couple of years + it is a land vs ocean in Arctic

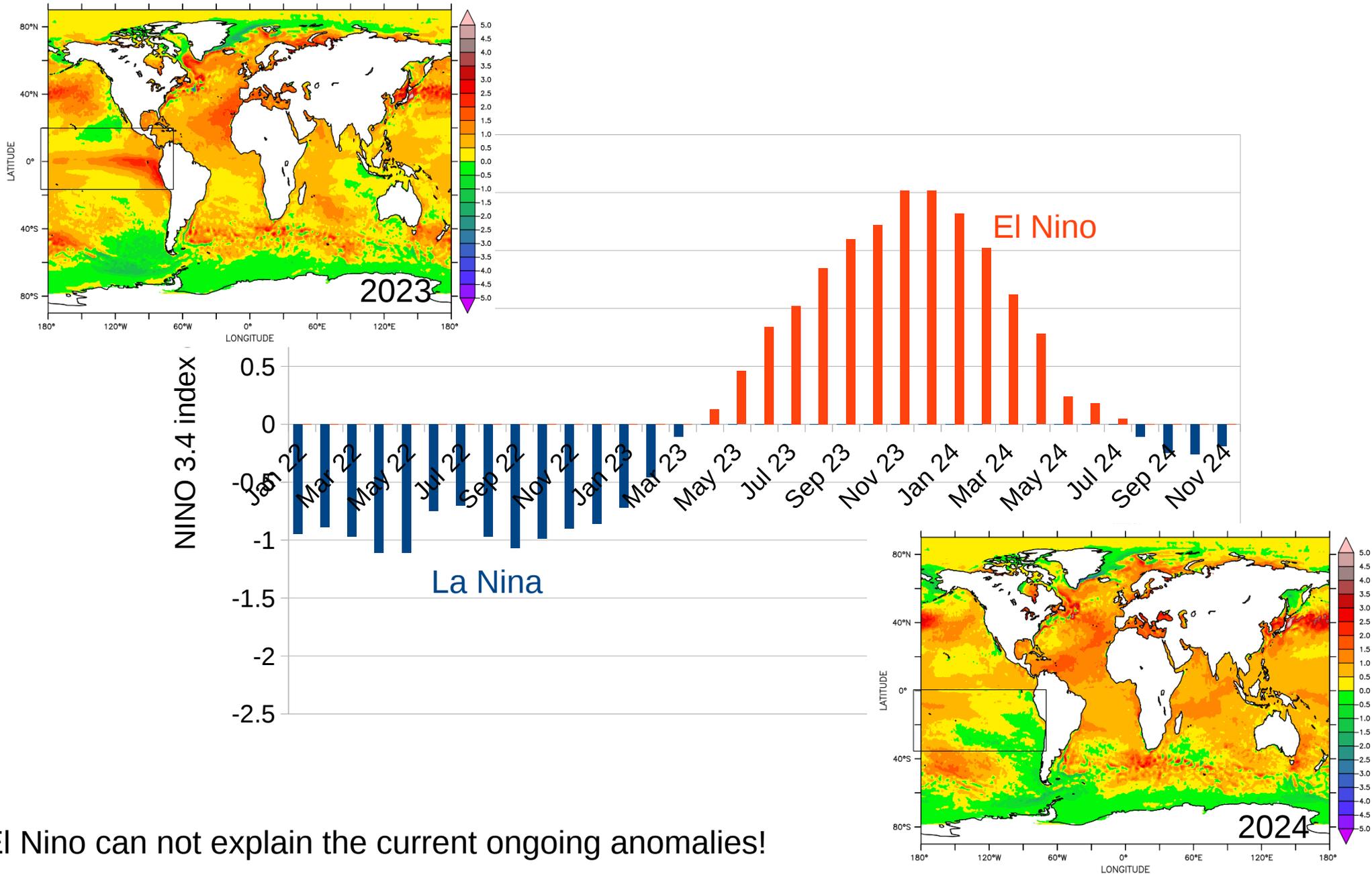
4. Anomalies of 2023-2025



4. Anomalies of 2023-2025



4. Anomalies of 2023-2025

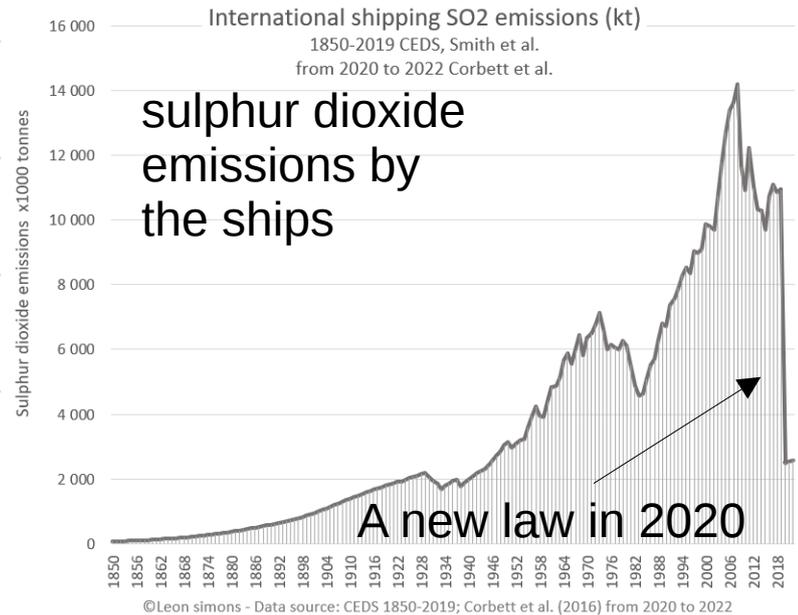
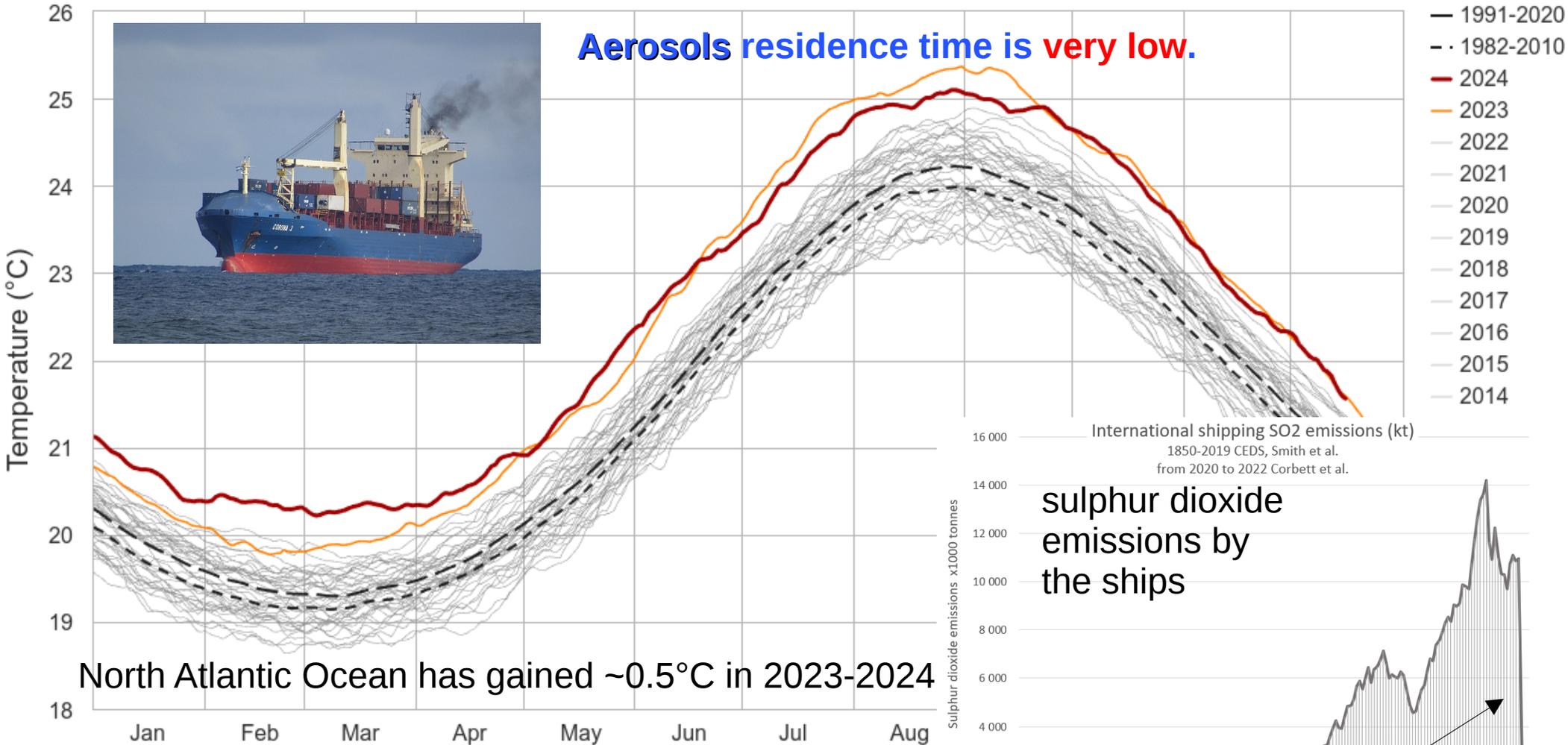


El Nino can not explain the current ongoing anomalies!

4. Anomalies of 2023-2025

Daily SST, North Atlantic (0–60°N, 0–80°W)

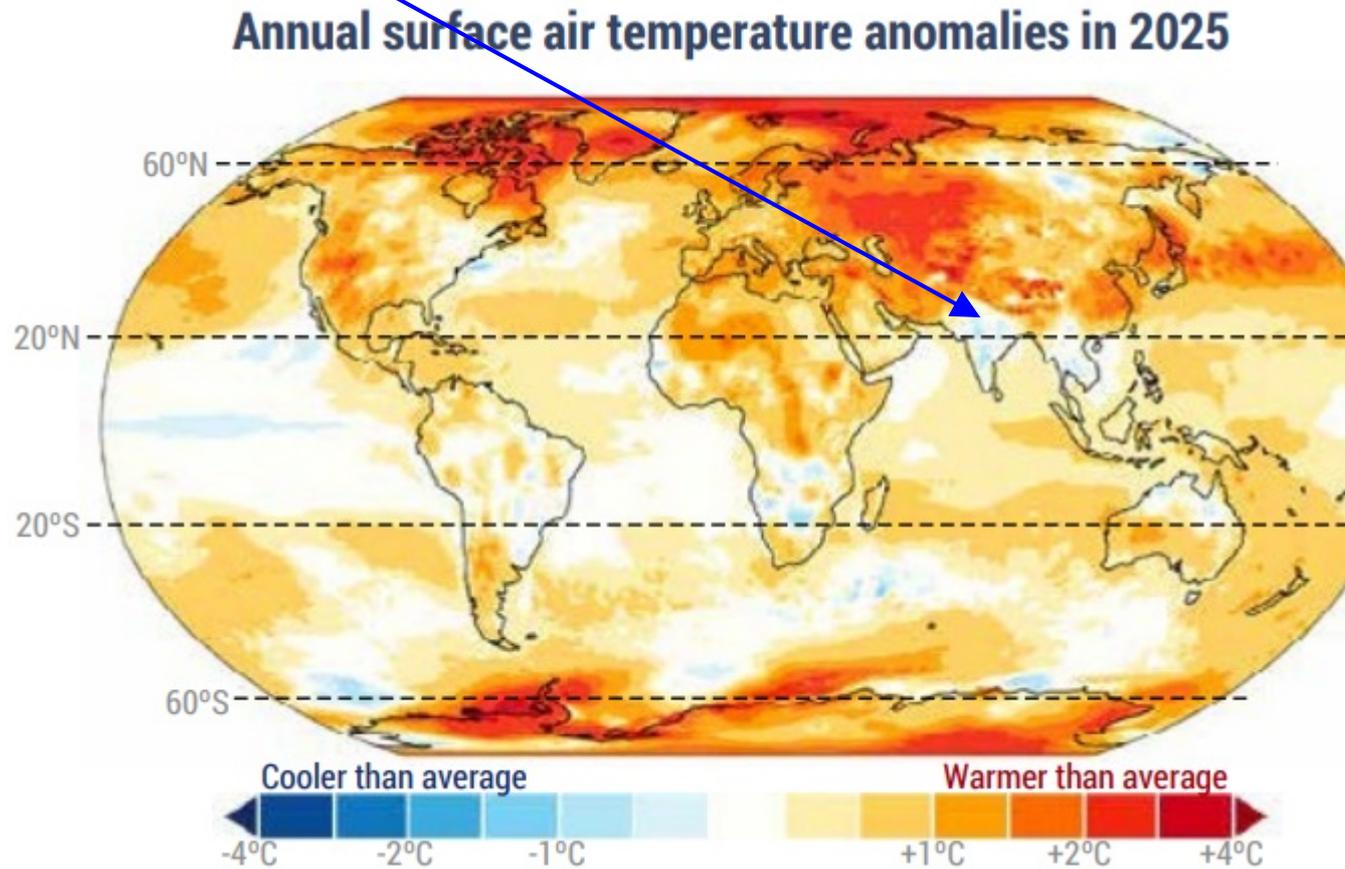
Dataset: NOAA OISST V2.1 | Image Credit: ClimateReanalyzer.org, Climate Change Institute, University of Maine



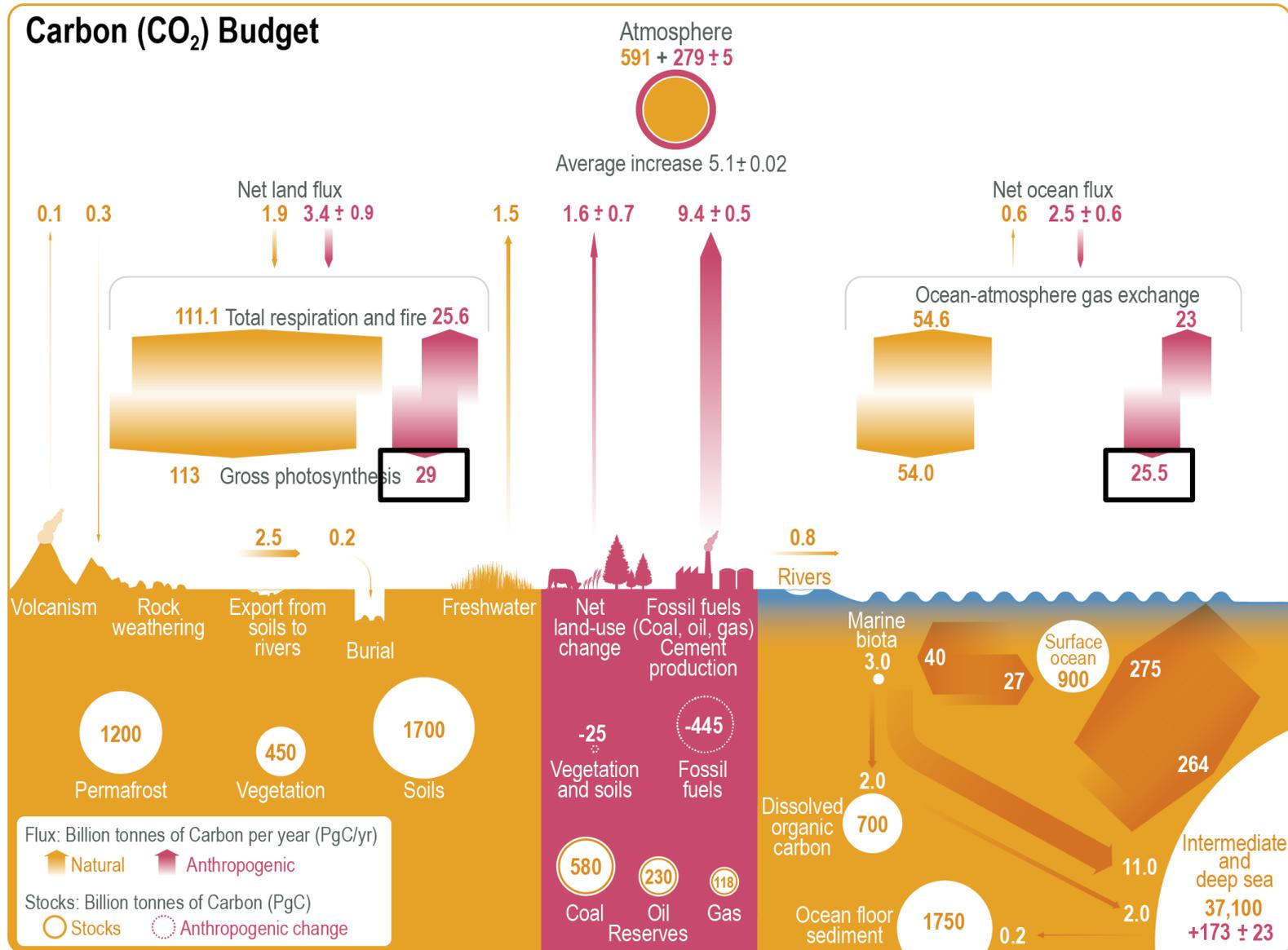
Ship pollution decrease can not explain the current ongoing anomalies!

4. Anomalies of 2023-2025

Signal from aerosols ?



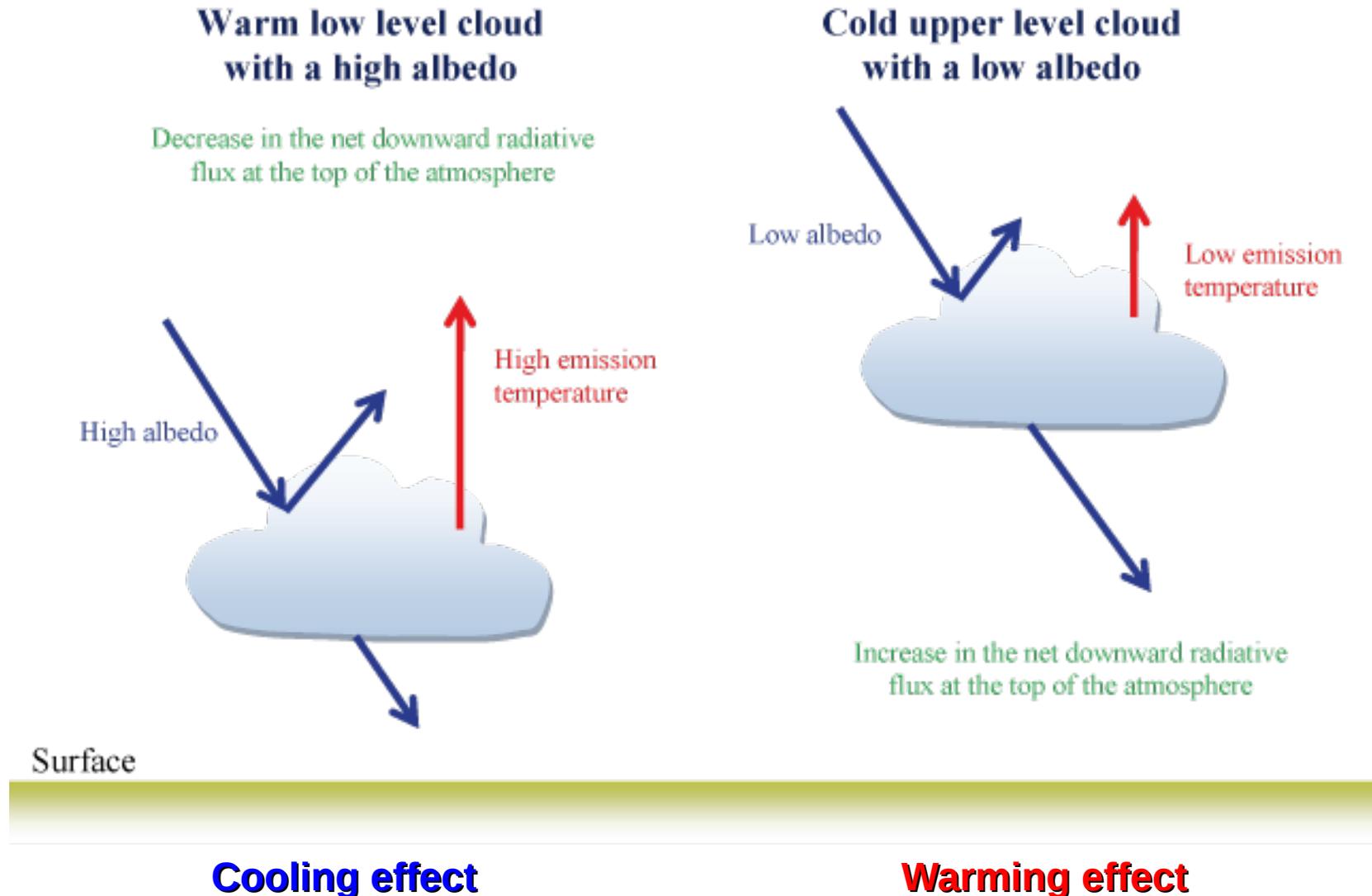
4. Anomalies of 2023-2025



Until recently, the oceans and vegetation absorbed ~50% of our emissions.

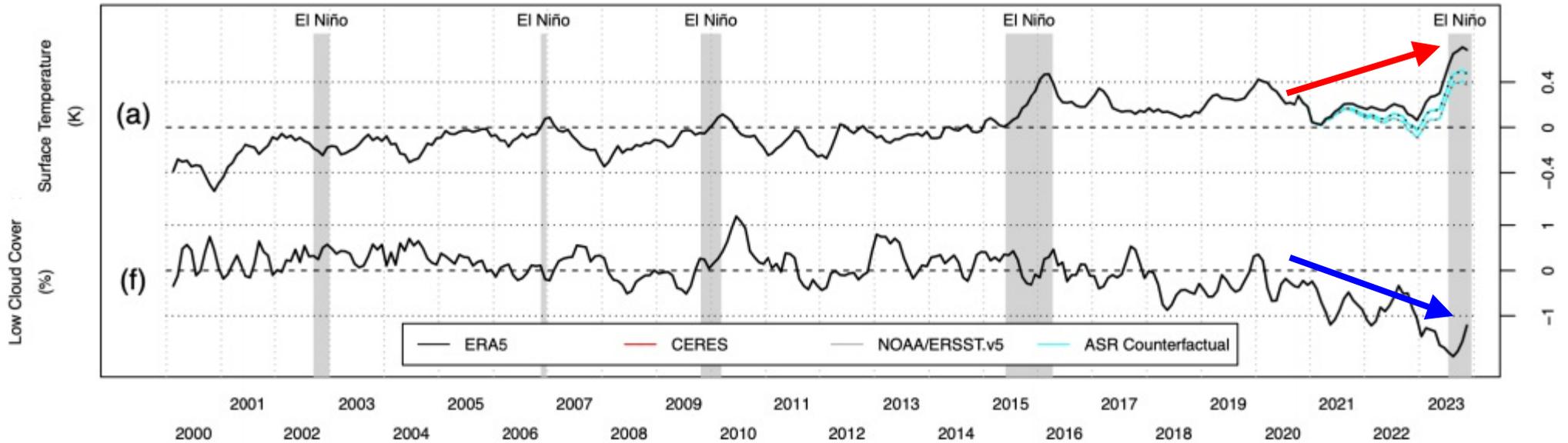
4. Anomalies of 2023-2025

Parasol effect vs Greenhouse effect

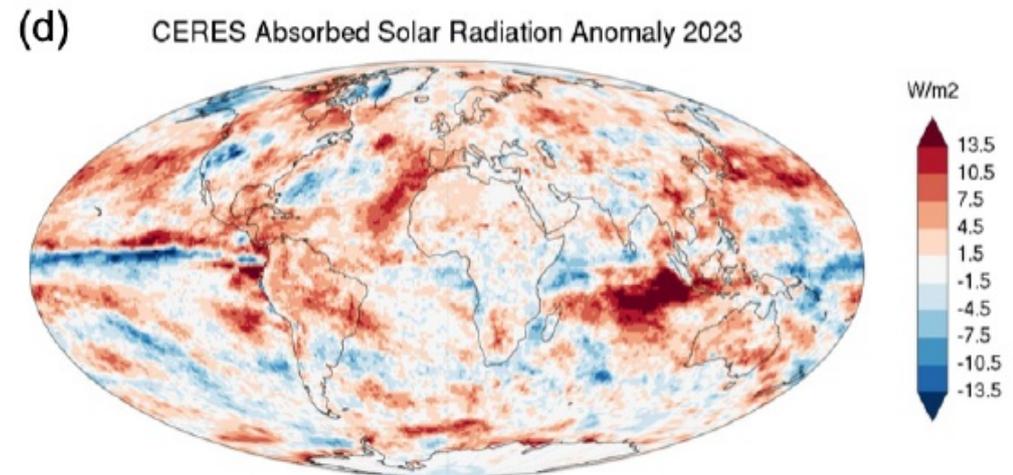
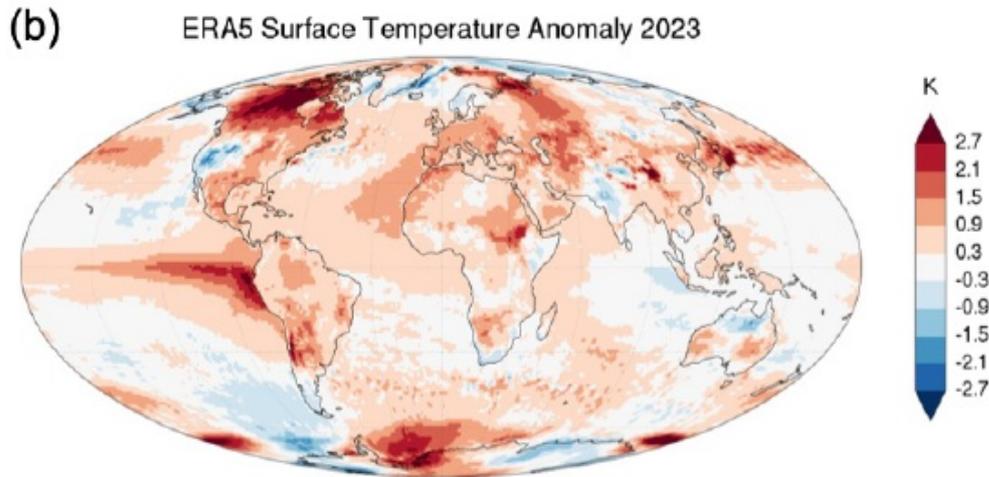


Change in **Low Clouds** could explain the current ongoing anomalies!

4. Anomalies of 2023-2025



Source: Goessling et al. (2024)



Change in **Low Clouds** could explain the current ongoing anomalies!

4. Anomalies of 2023-2025

FAQ 7.2: What is the role of clouds in a warming climate?

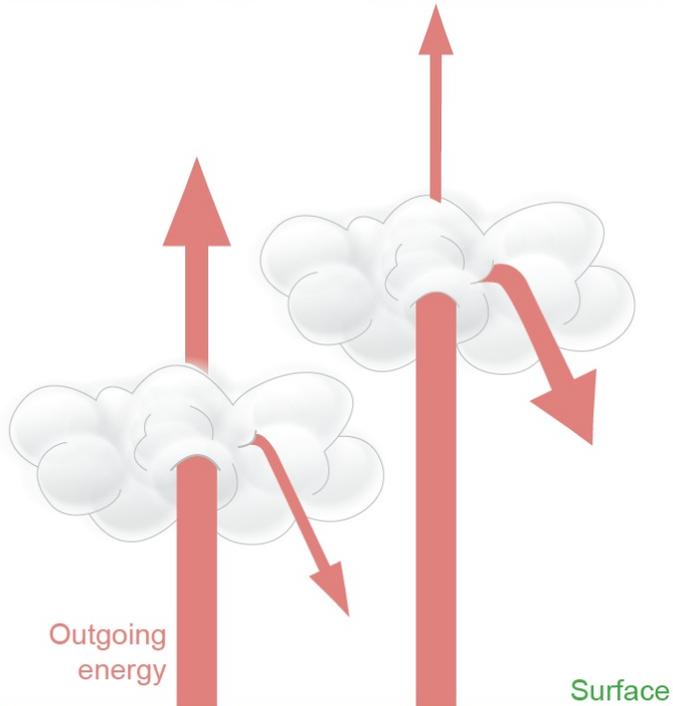
Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.

Altitude (Warming)

Higher clouds

More outgoing energy trapped by clouds

Present climate → Future climate

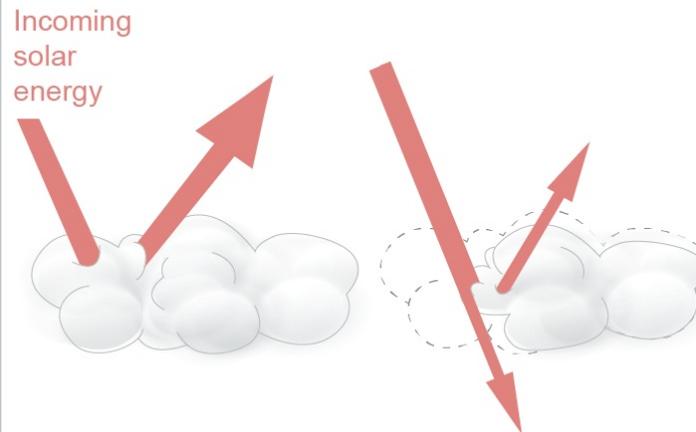


Amount (Warming)

Fewer (low level) clouds

Less incoming energy reflected back to space

Present climate → Future climate

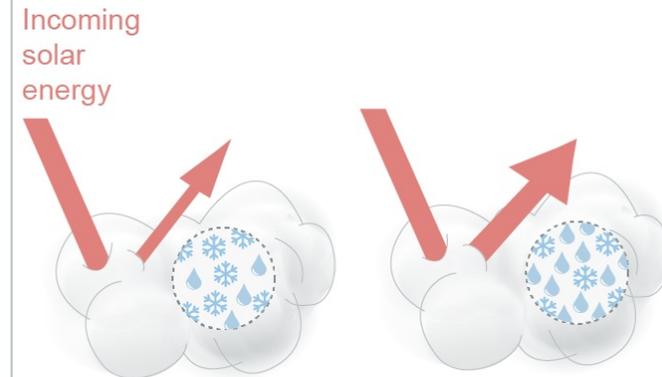


Composition (Cooling)

More water droplets

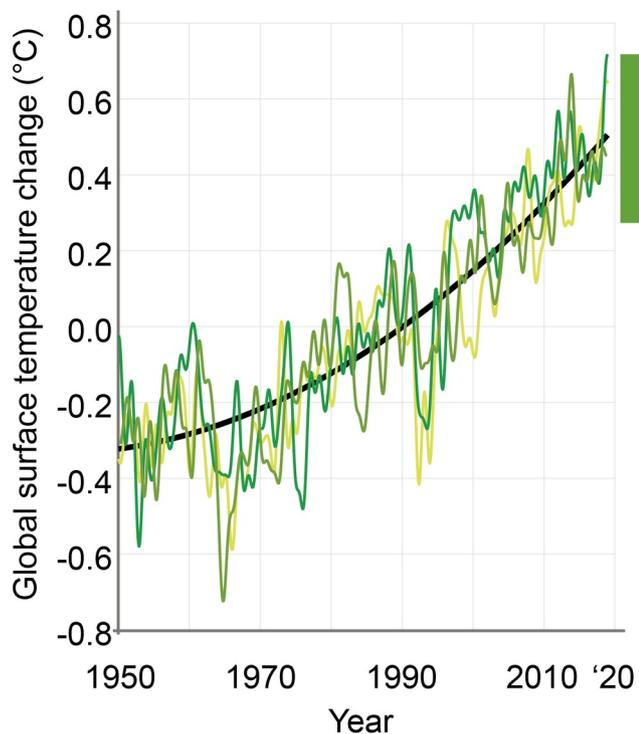
More incoming energy reflected back to space

Present climate → Future climate

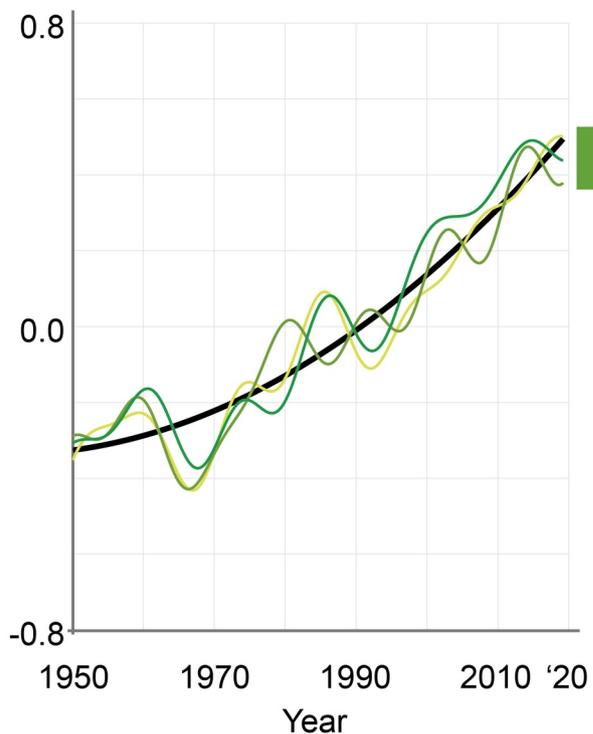


5. Natural variability vs climate change

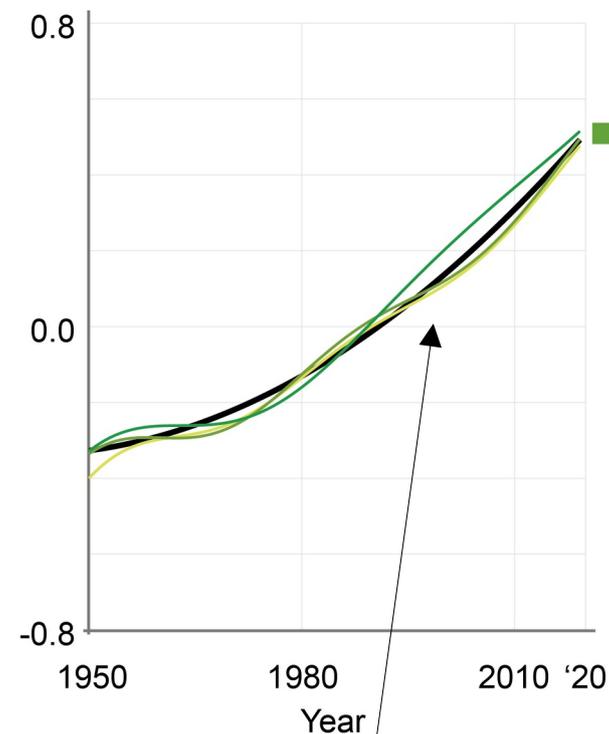
Annual (1 year) variations
Dominated by natural variability



Decadal (10 year) variations
Less influenced by natural variability,
but natural cooling or more intense
warming can still occur

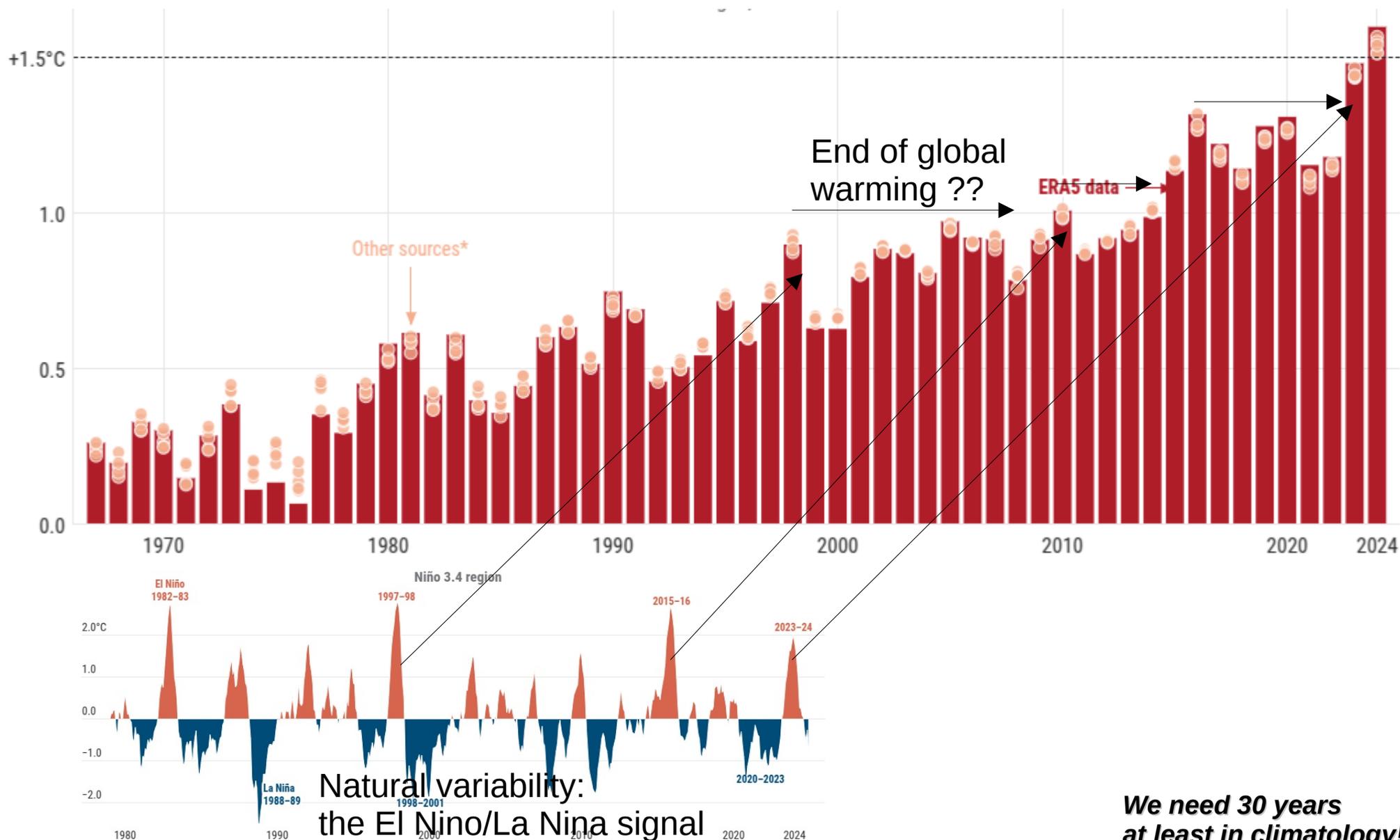


Multi-decadal (30 year) variations
Dominated by the human influence



**We need 30 years
at least in climatology**

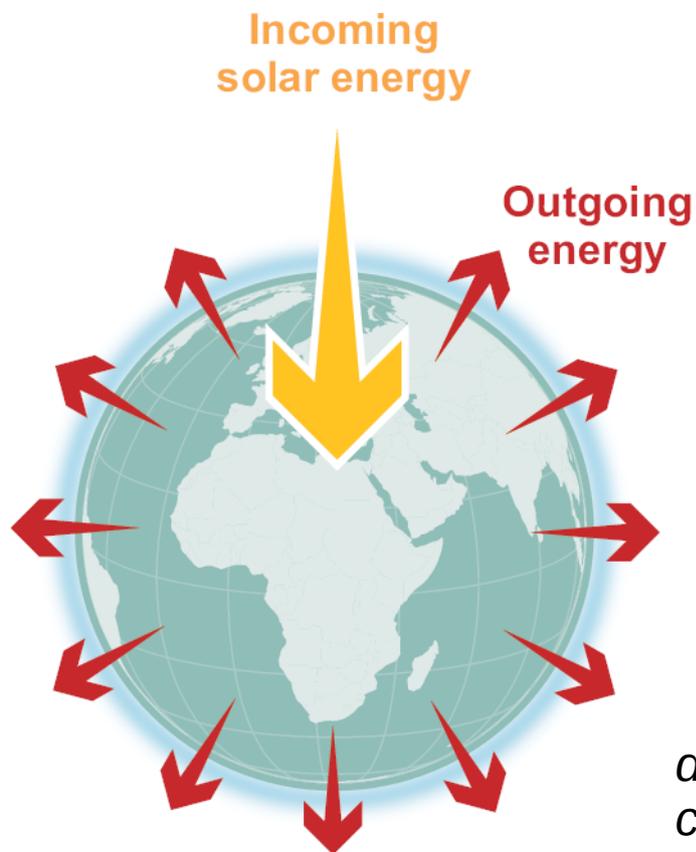
5. Natural variability vs climate change



**We need 30 years
at least in climatology!**

5. Natural variability vs climate change

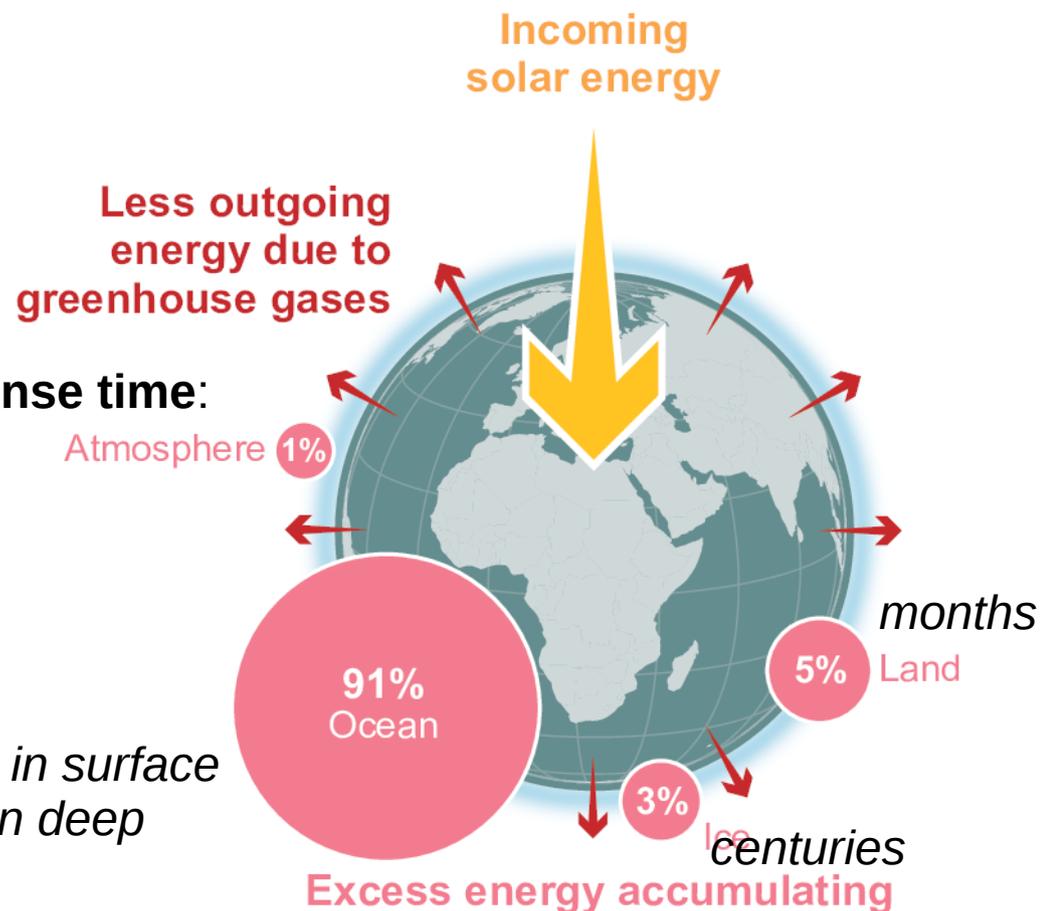
Stable climate: in balance



Response time:
week

*decades in surface
century in deep*

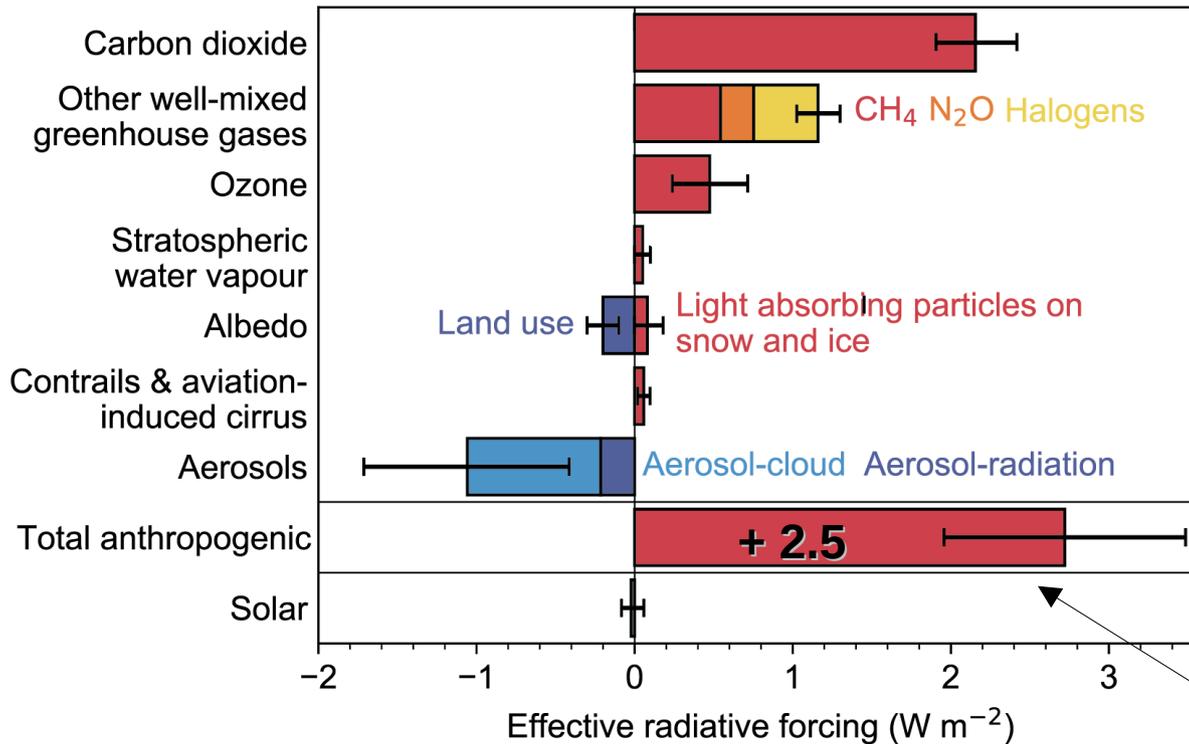
Today: imbalanced



The radiative forcing are difficult to evaluate as the climate is not in stable state!

6. Future scenarios

Change in effective radiative forcing from 1750 to 2019



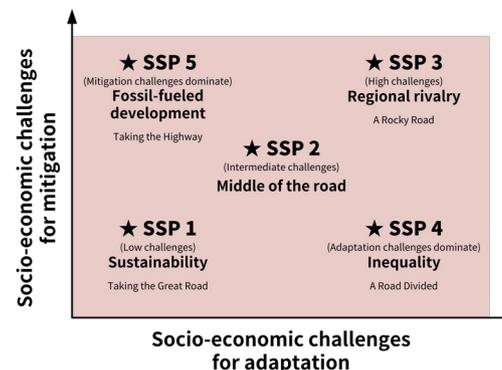
Shared Socio-economic Pathways

SSPx-Y.Z

Lower than now

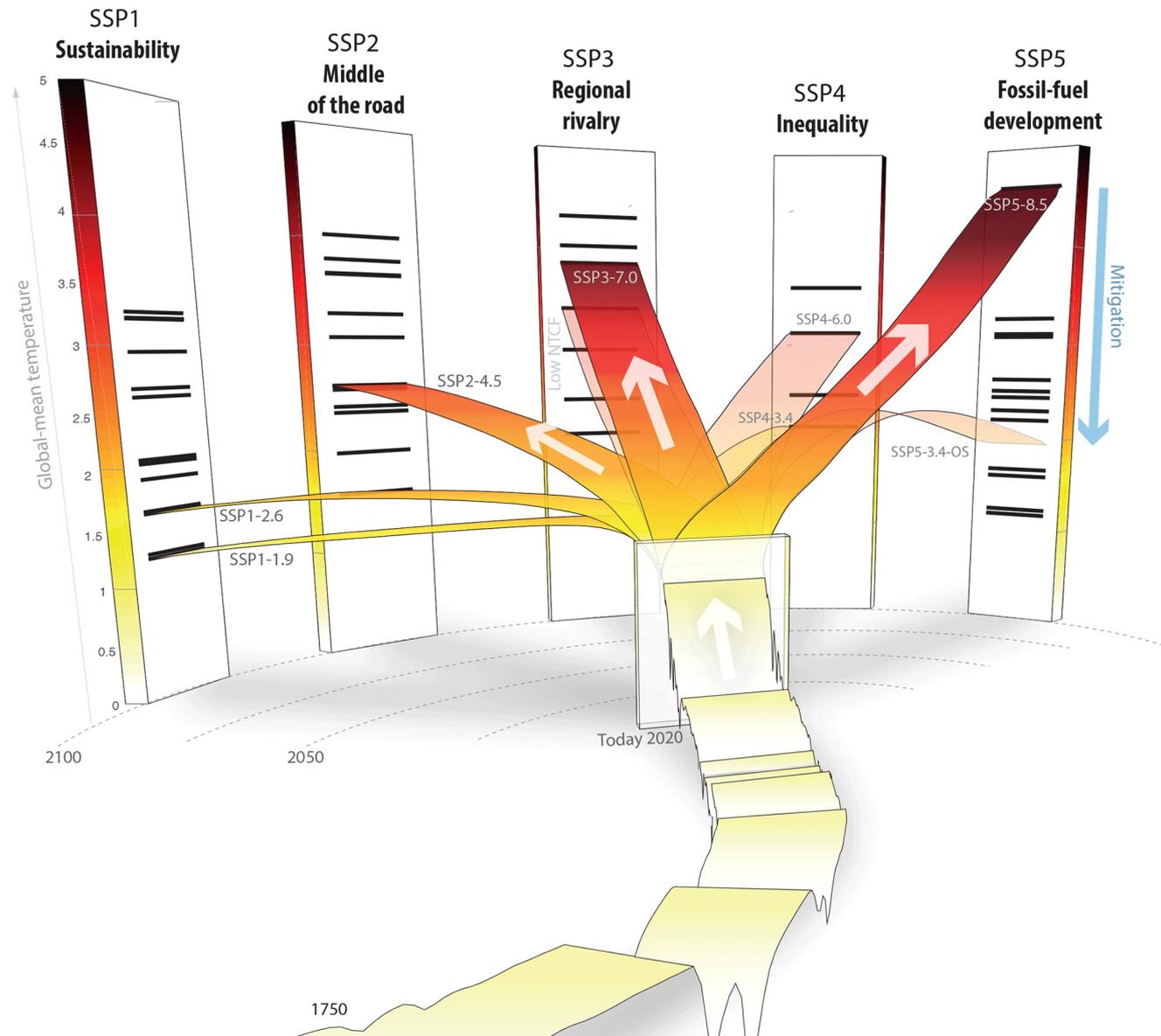
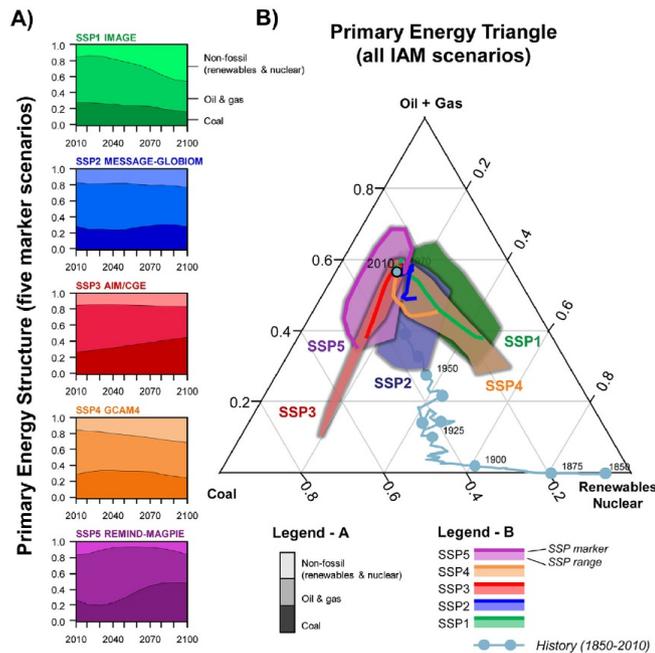
Future scenarios are also defined in radiative forcing in 2100.

SSPx-1.6 => +1.6W/m²
 SSPy-4.5 => +4.5W/m²
 SSPz-8.5 => +8.5W/m²
 en 2100

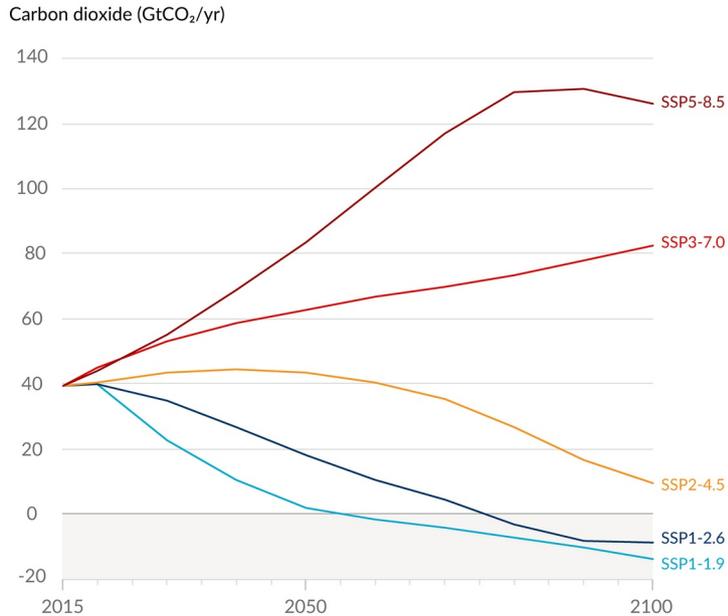


X, Y, Z refer to different kinds of economy, politic, ... evolution

6. Future scenarios



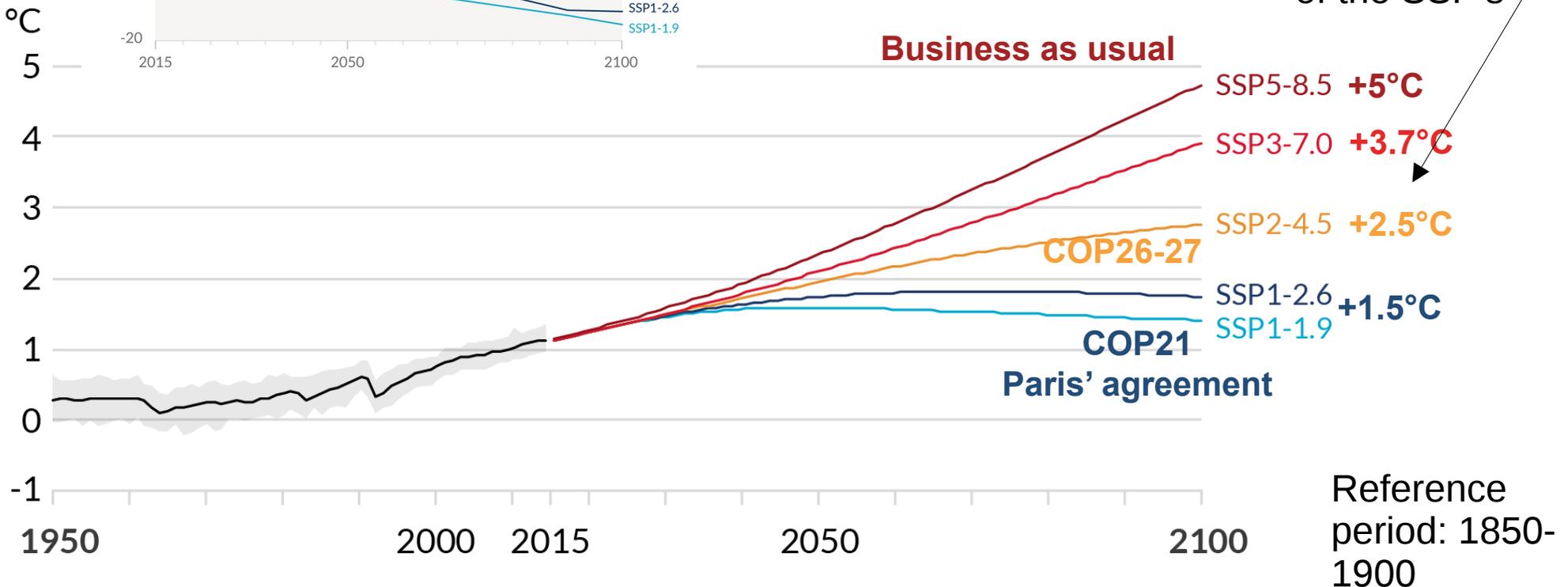
6. Future scenarios



+2° World starting in the 2030s ...

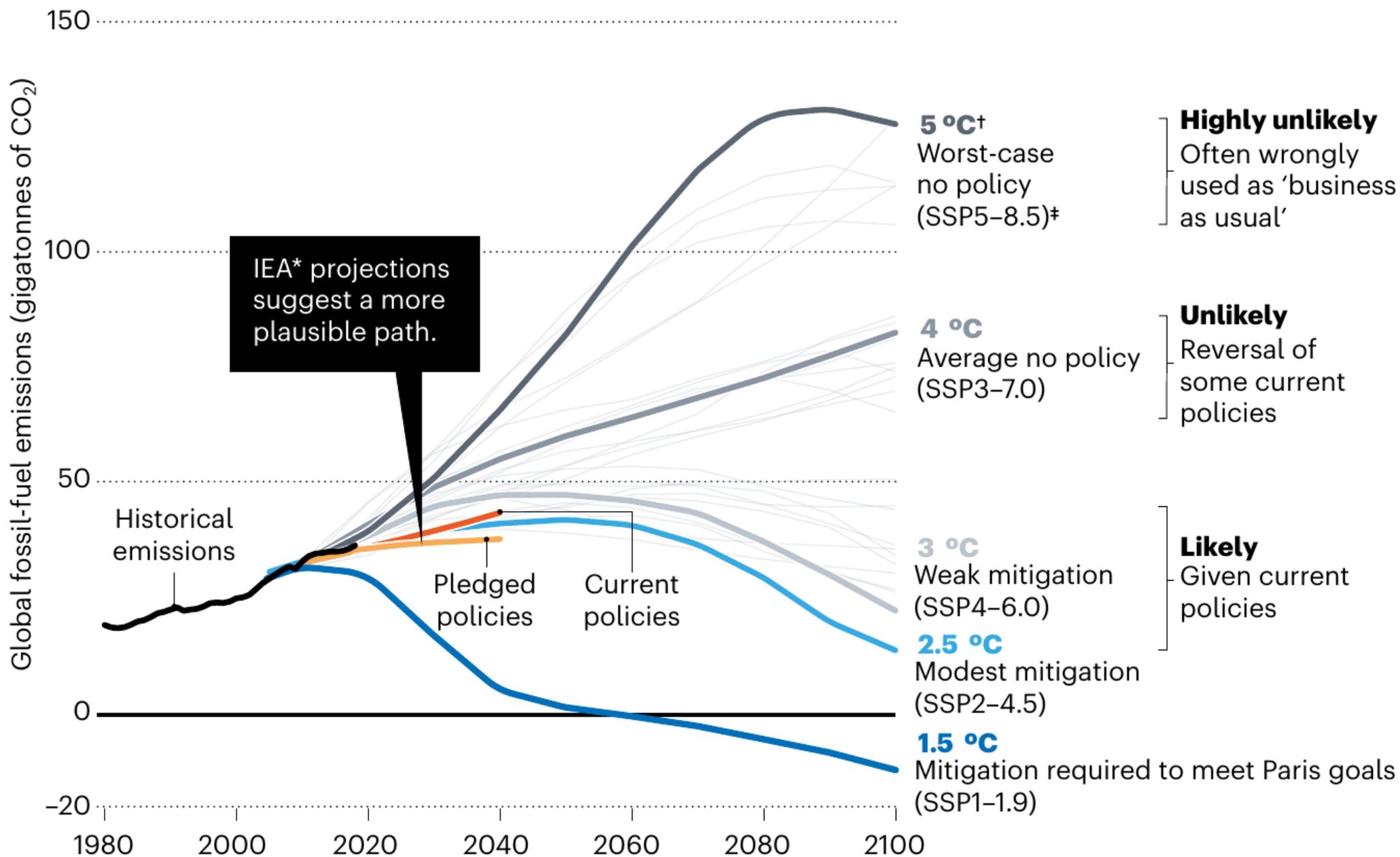
Target towards a **+3°C World** with the current politics commitments.

SSP370 is today the more likely



To retain the name of the SSP's

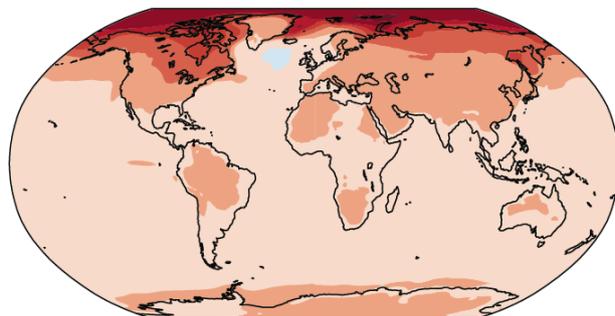
6. Future scenarios



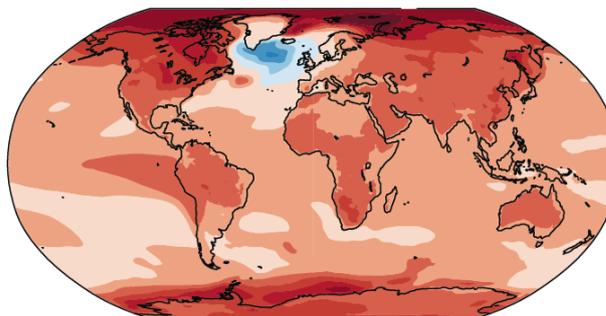
7. Uncertainties and climate sensitivity

SSP1-2.6 (2081–2100)

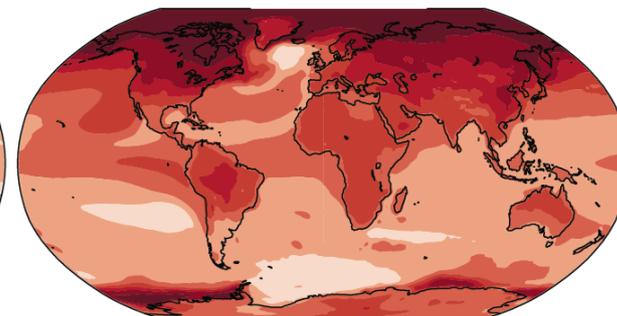
(a) Best estimate (scaled)



(b) High-warming models



(c) Very-high-warming models



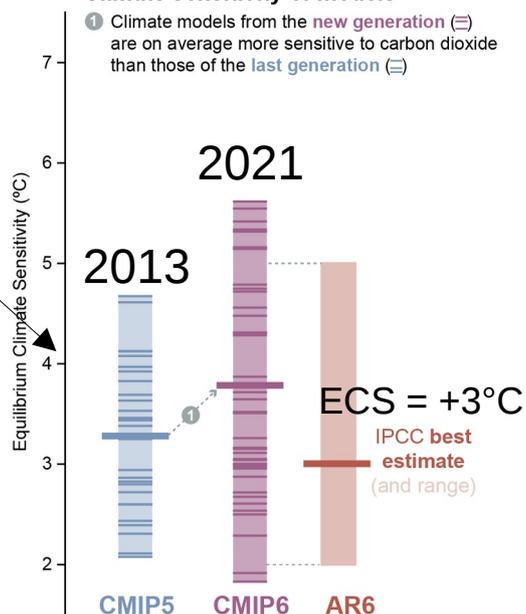
FAQ 7.3: Equilibrium climate sensitivity and future warming

Equilibrium climate sensitivity measures how climate models respond to a doubling of carbon dioxide in the atmosphere.

Recent ice core measurements suggest a ECS of +4°C

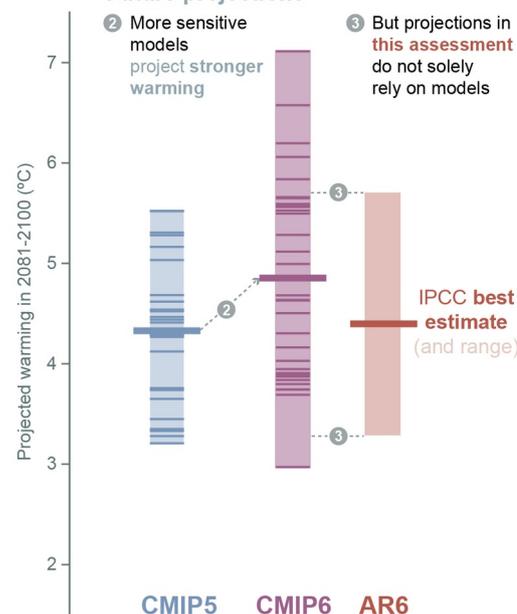
Climate sensitivity of models

1 Climate models from the **new generation** (≡) are on average more sensitive to carbon dioxide than those of the **last generation** (≡)



Future projections

2 More sensitive models project stronger warming
3 But projections in this assessment do not solely rely on models

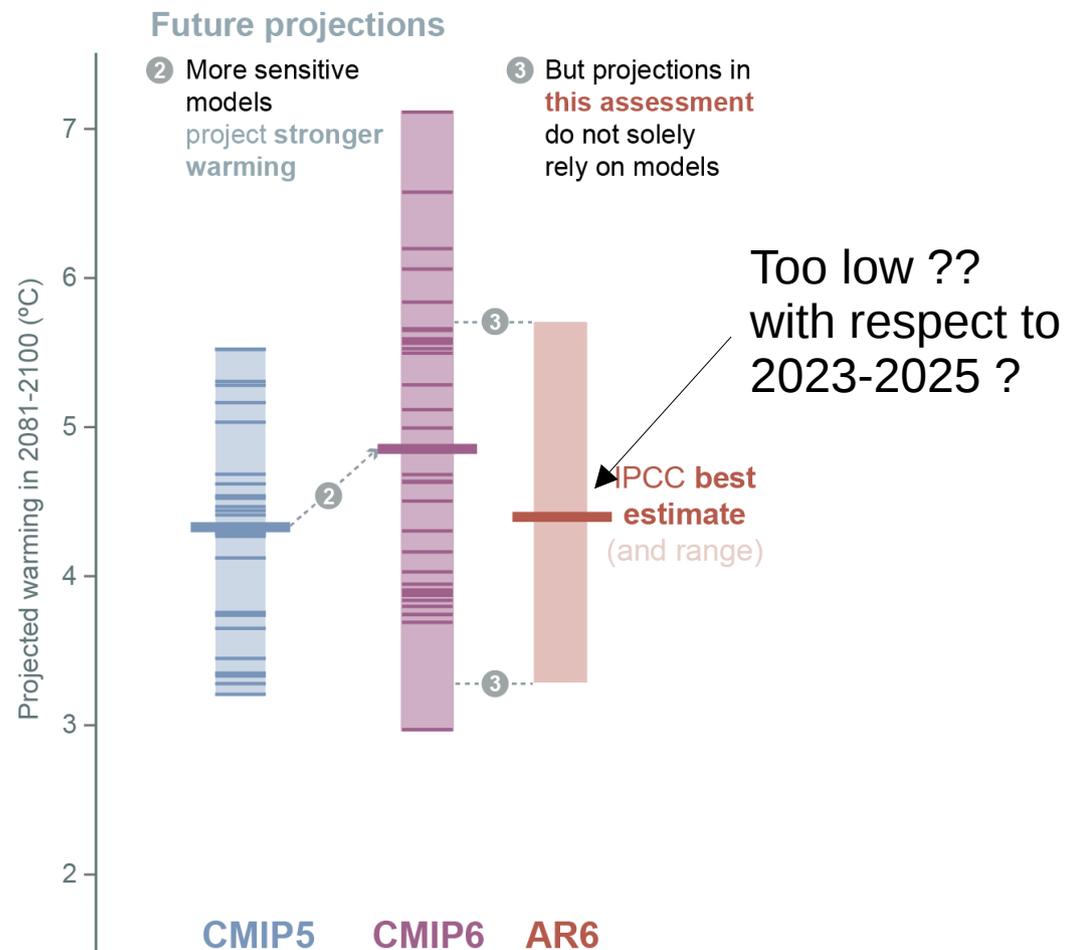
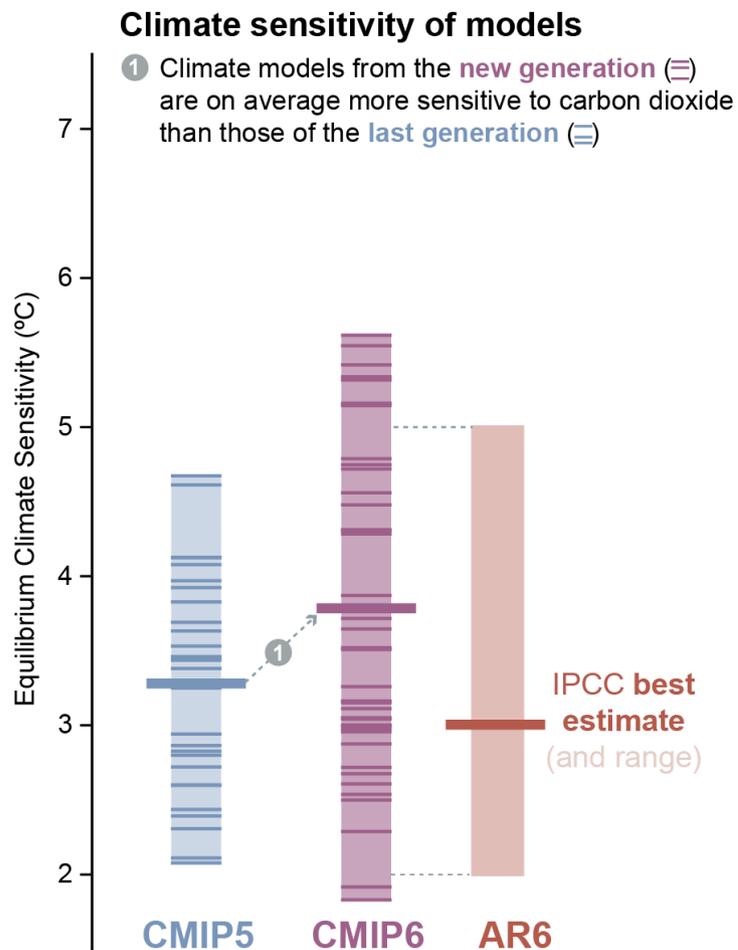


IPCC projections too conservative ?

7. Uncertainties and climate sensitivity

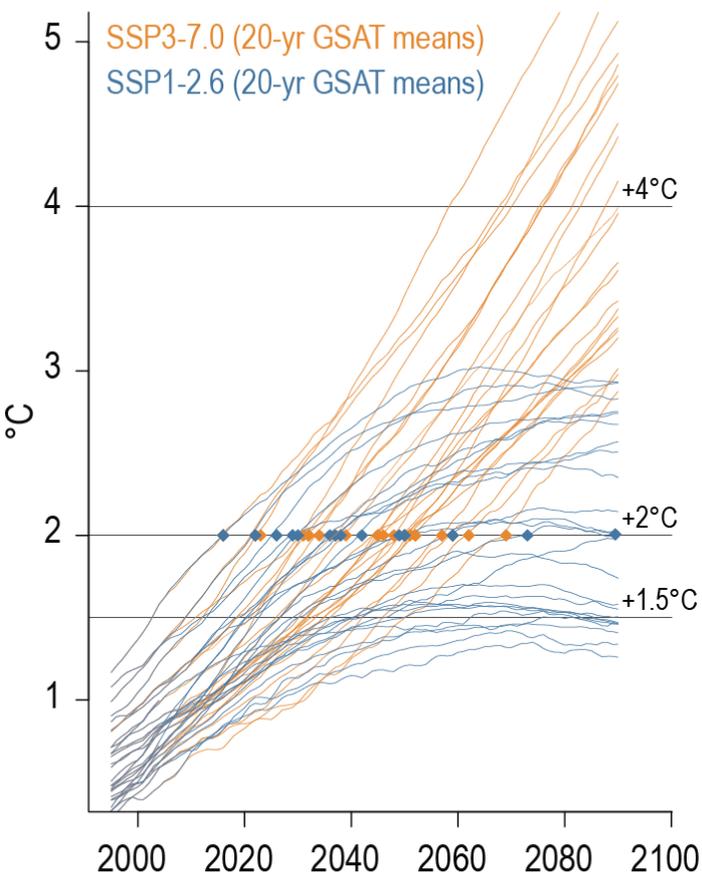
FAQ 7.3: Equilibrium climate sensitivity and future warming

Equilibrium climate sensitivity measures how climate models respond to a doubling of carbon dioxide in the atmosphere.

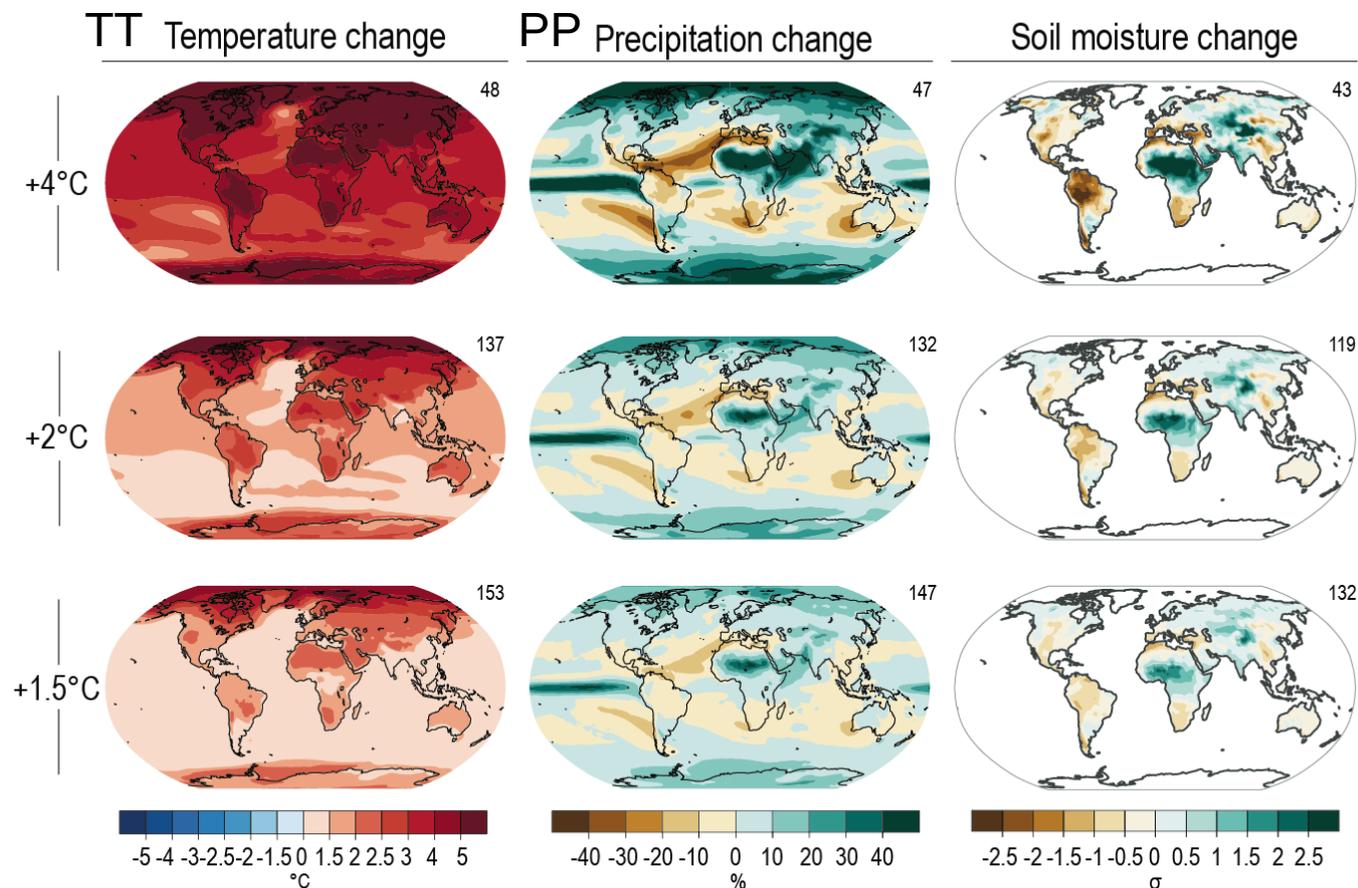


7. Uncertainties and climate sensitivity

(a) Global mean temperature in CMIP6



(b) Patterns of change in near-surface air temperature, precipitation and soil moisture

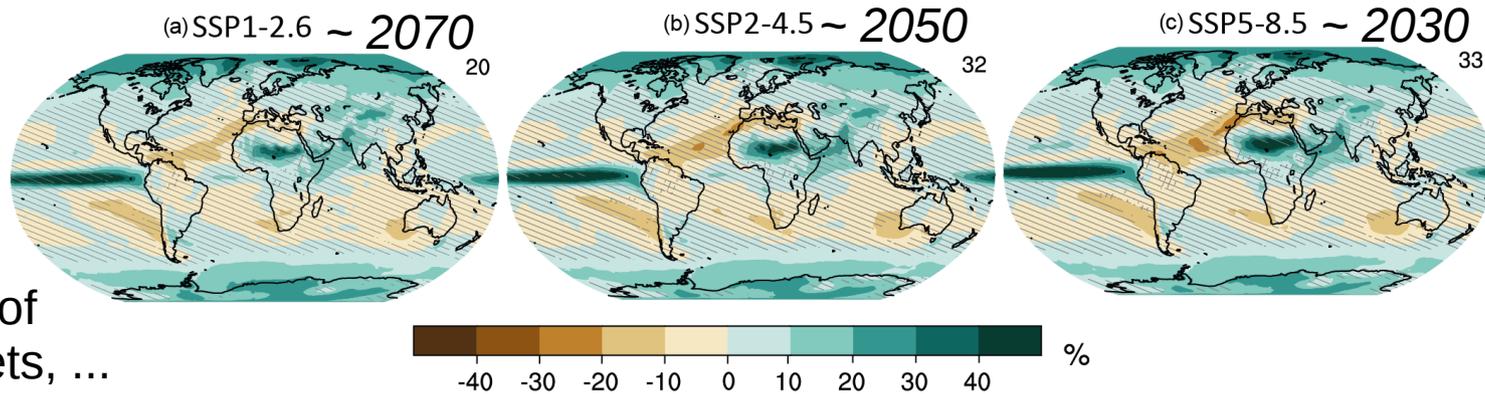


Reference period: 1850-1900

Instead of talking about scenarios, IPCC introduced in its last AR a world at +X°C but ...

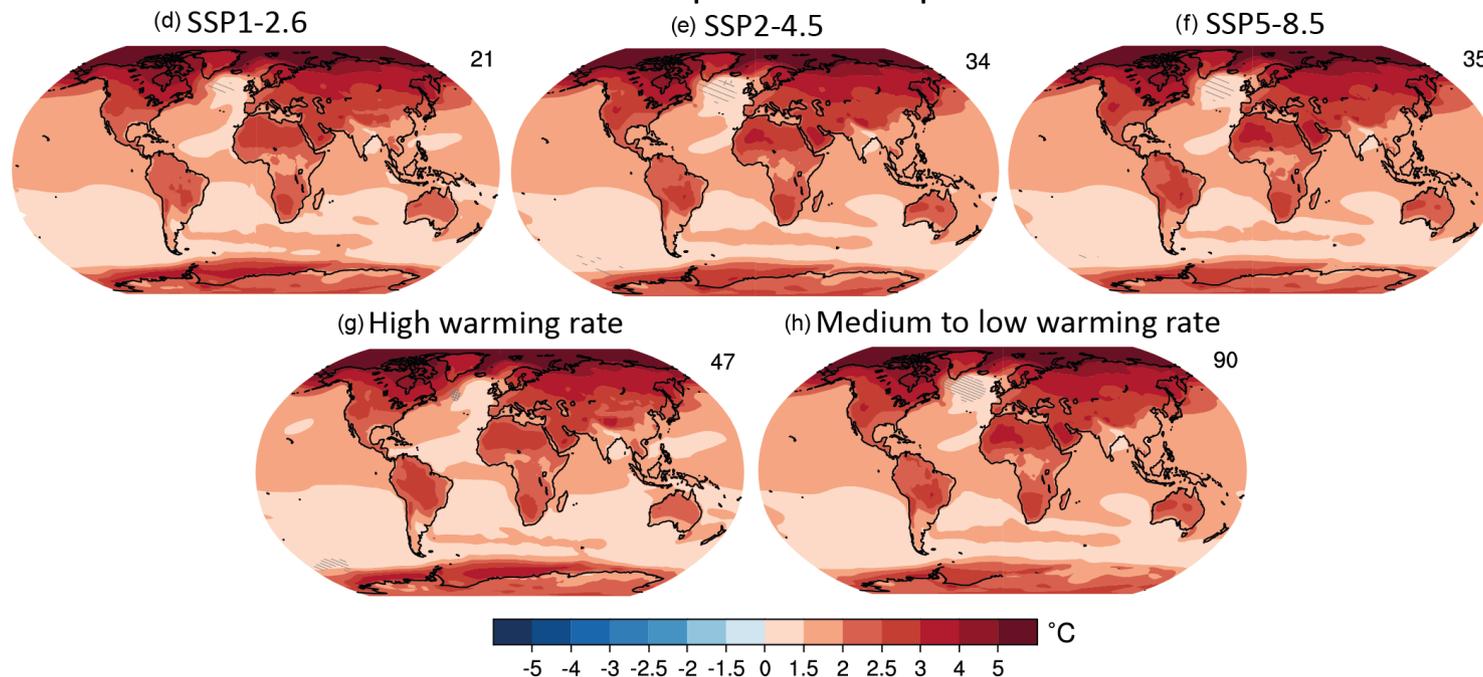
7. Uncertainties and climate sensitivity

Annual mean precipitation response at 2°C



Responses of
PP, ice sheets, ...
are different for a same
warming!

Annual mean temperature response at 2°C

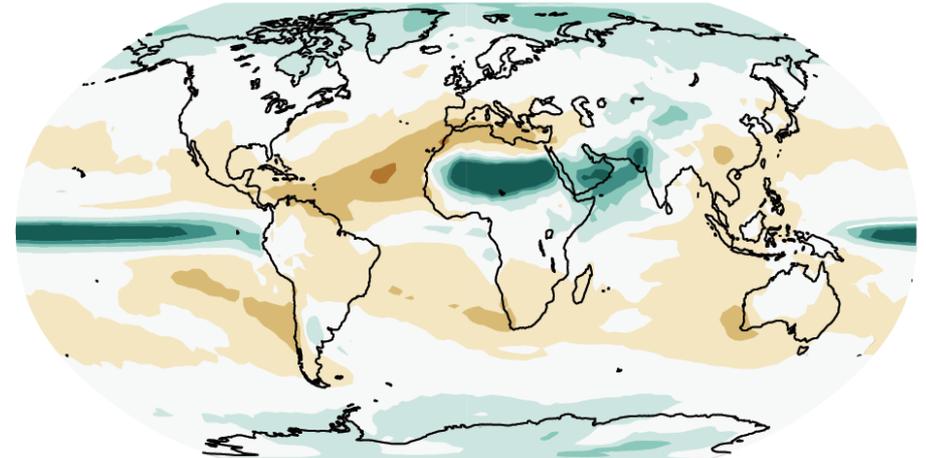
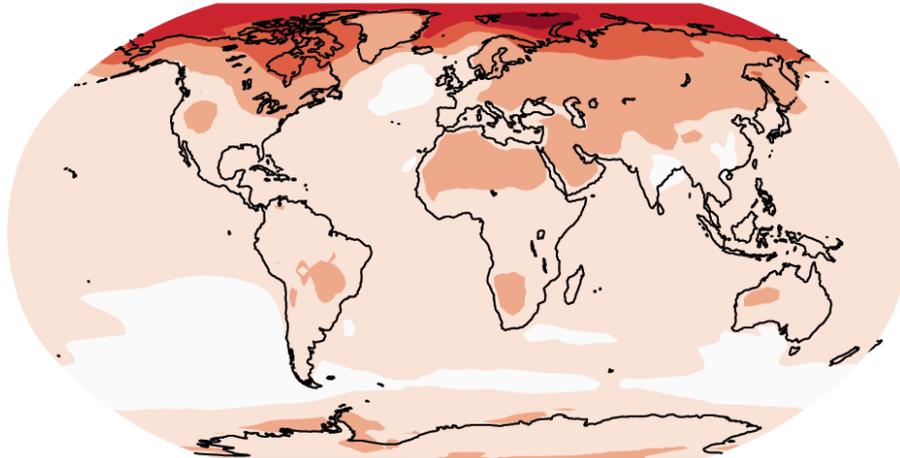


8. Global future projections

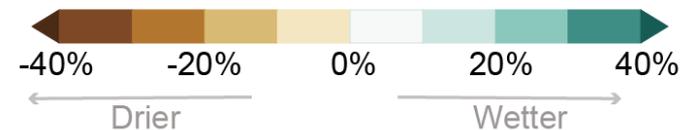
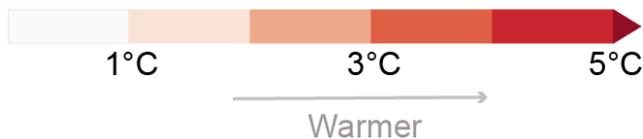
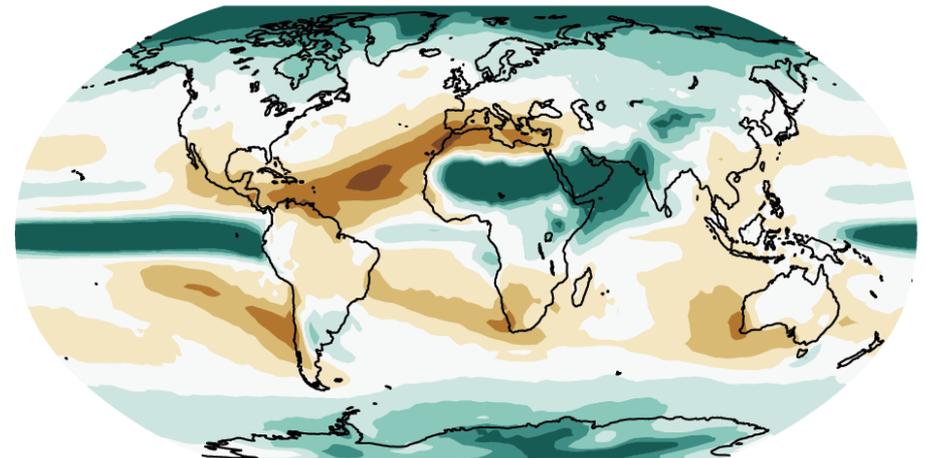
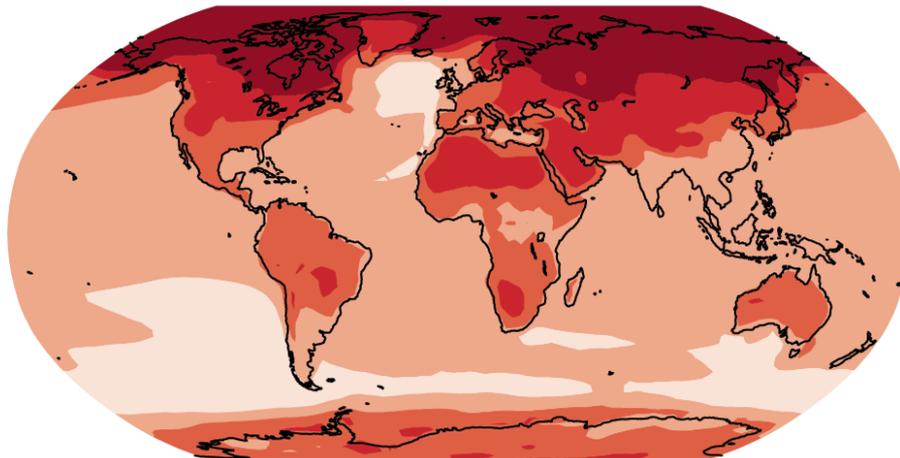
Warming will be **stronger** in the Arctic, on land and in the Northern Hemisphere

Precipitation will **increase** in high latitudes, the tropics and monsoon regions and **decrease** in the subtropics

+1.5°C



+3.0°C

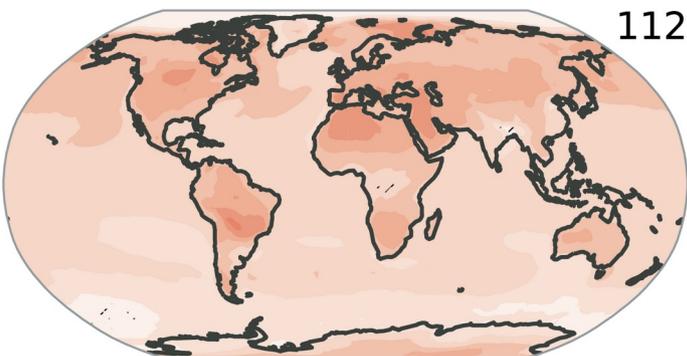


8. Global future projections

Annual maximum temperature (TXx) - median

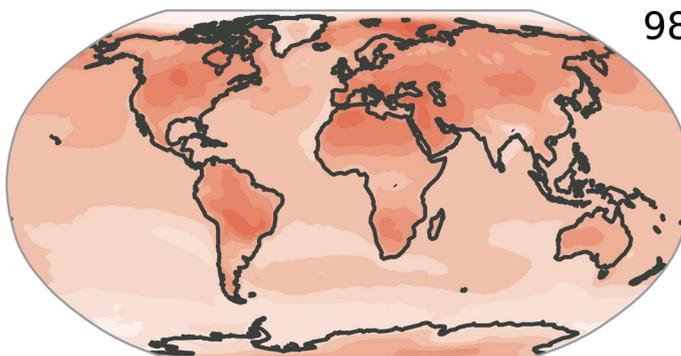
(a) At 1.5°C global warming

112



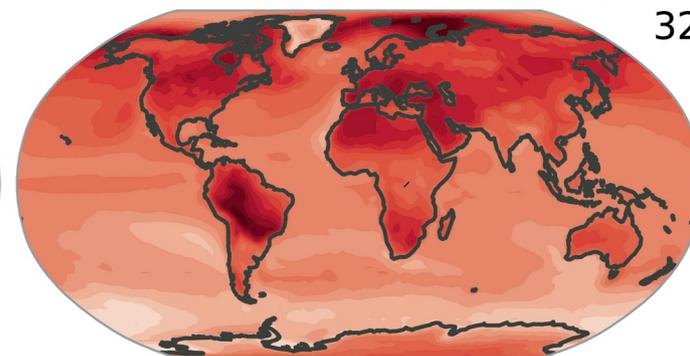
(b) At 2.0°C global warming

98



(c) At 4.0°C global warming

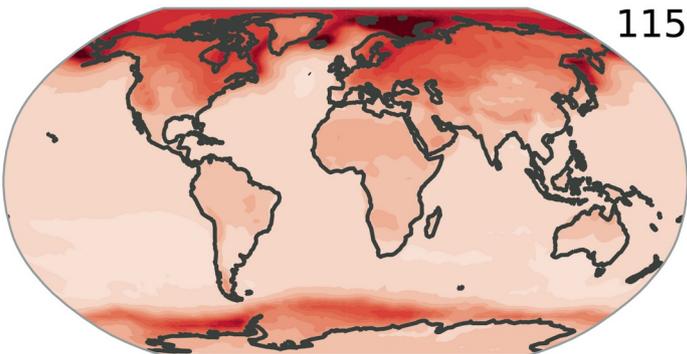
32



Annual minimum temperature (TNn) - median

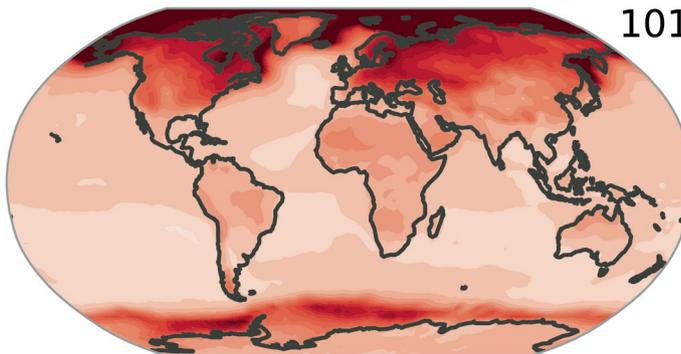
(d) At 1.5°C global warming

115



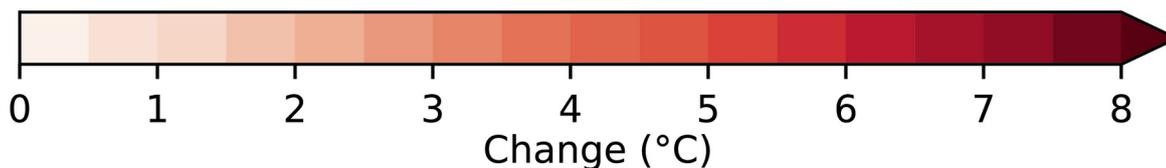
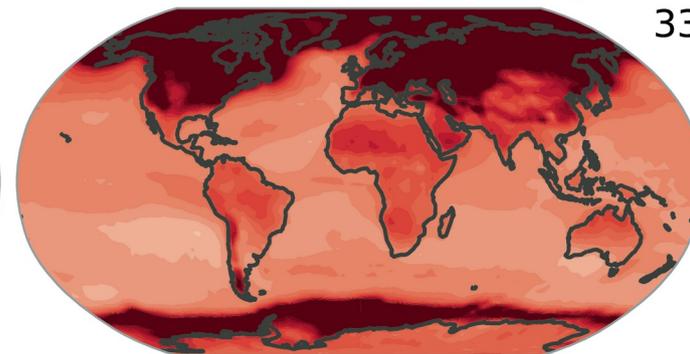
(e) At 2.0°C global warming

101



(f) At 4.0°C global warming

33

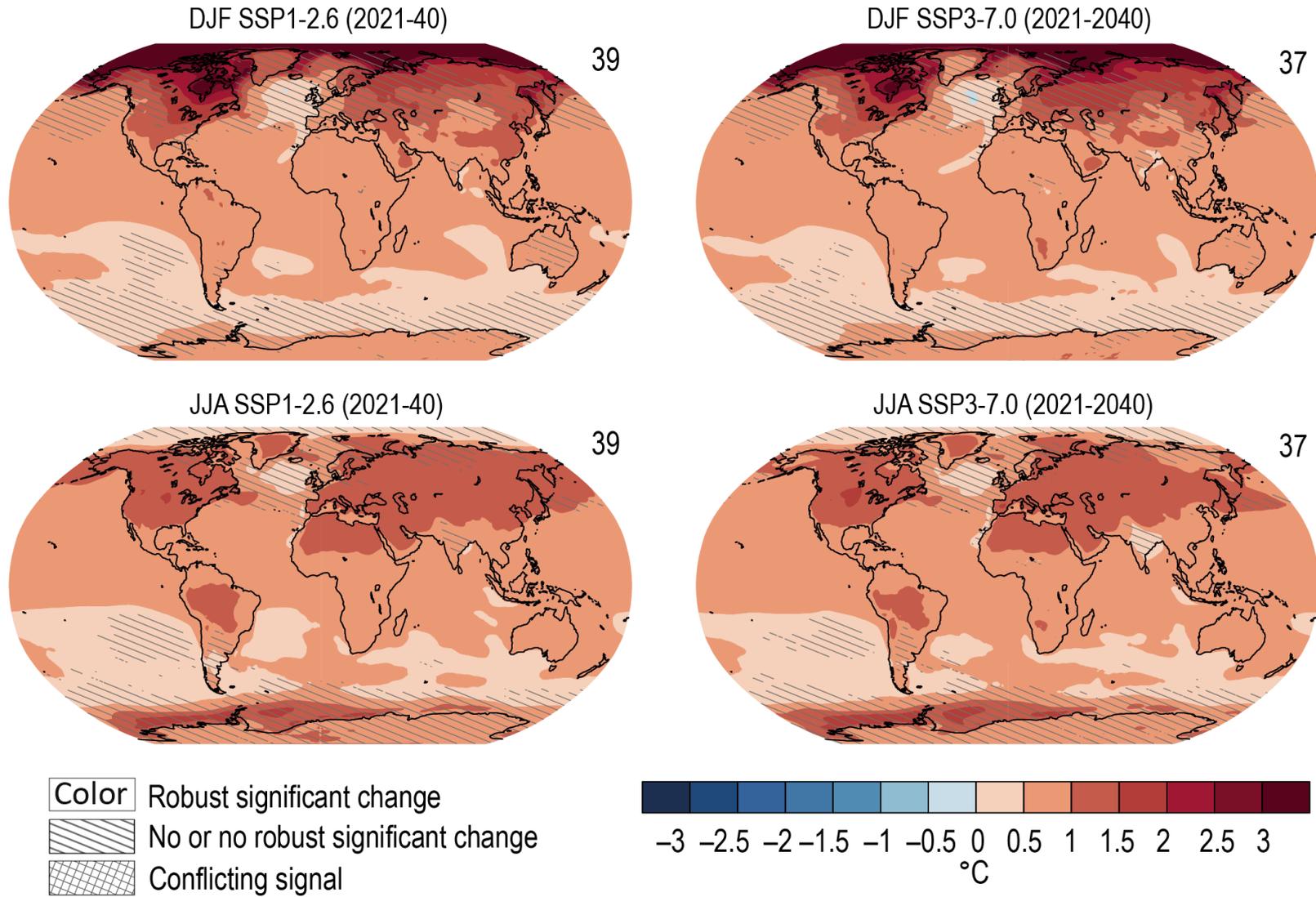


Colour High model agreement
Low model agreement

Increase of TTmin >> TTmax

8. Global future projections

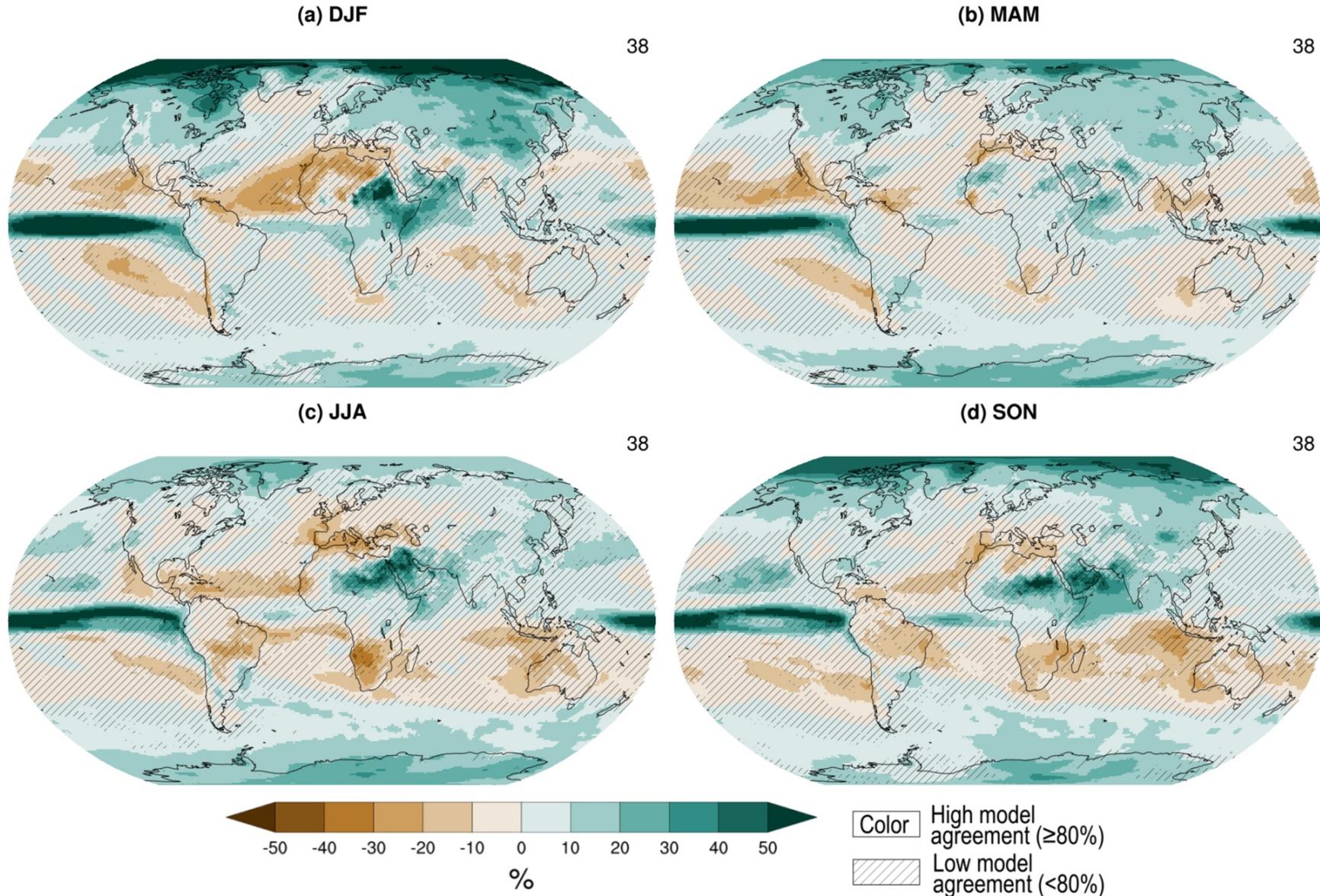
Seasonal mean temperature change



In Europe: increase in TT JJA >> TT DJF

8. Global future projections

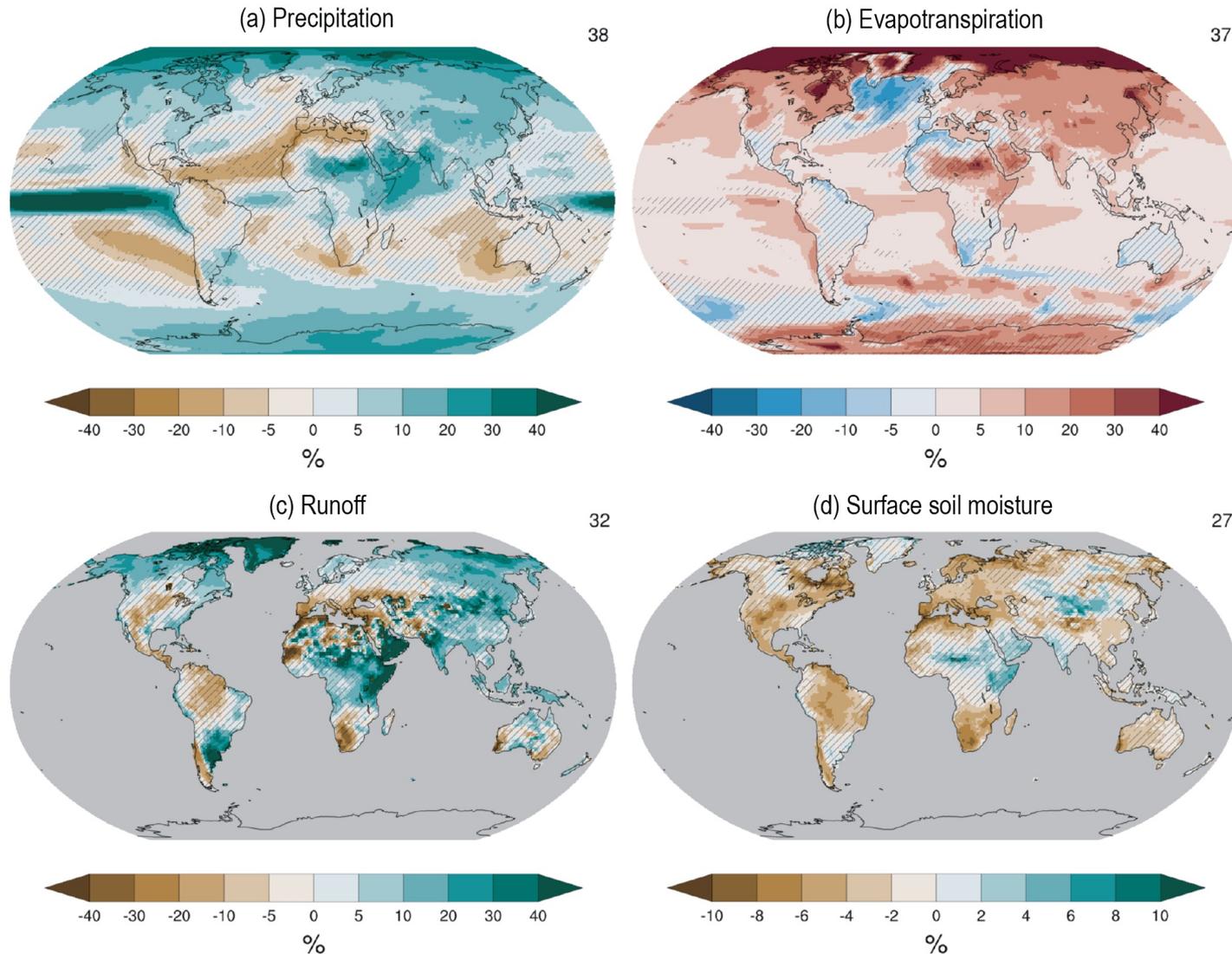
Multi-model seasonal mean precipitation percentage change for SSP2-4.5 (2081-2100 vs 1995-2014)



In Europe: increase in PP DJF vs decrease in PP JJA

8. Global future projections

Long-term water cycle variables changes for SSP2-4.5 (2081–2100 vs 1995–2014)



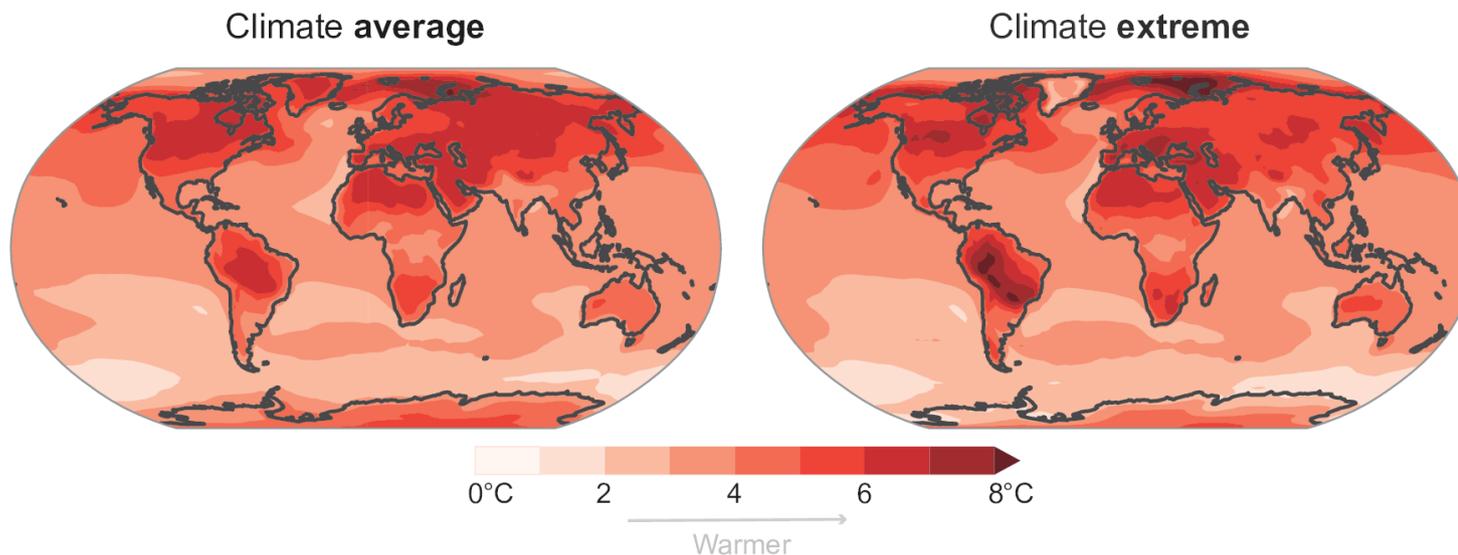
Surface soil moisture --, even if PP ++

8. Global future projections

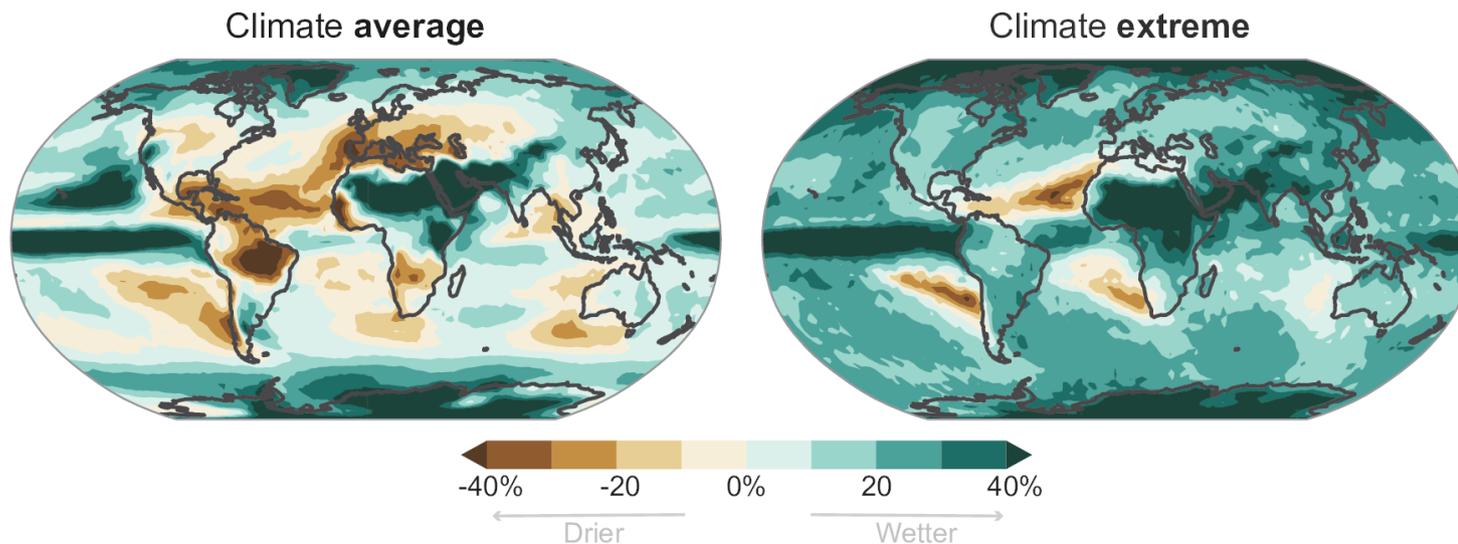
FAQ 11.1: How will changes in climate extremes compare with changes in climate averages?

The direction and magnitude of future changes in climate extremes and averages depend on the variable considered.

Future **changes in temperature** averages and extremes will be **similar**



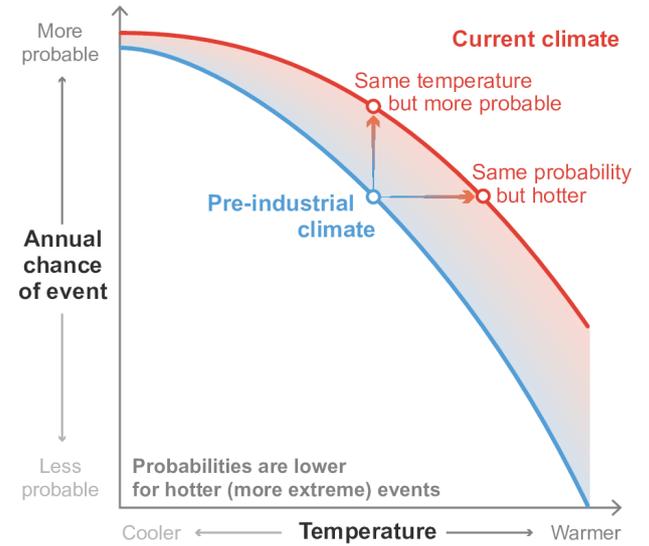
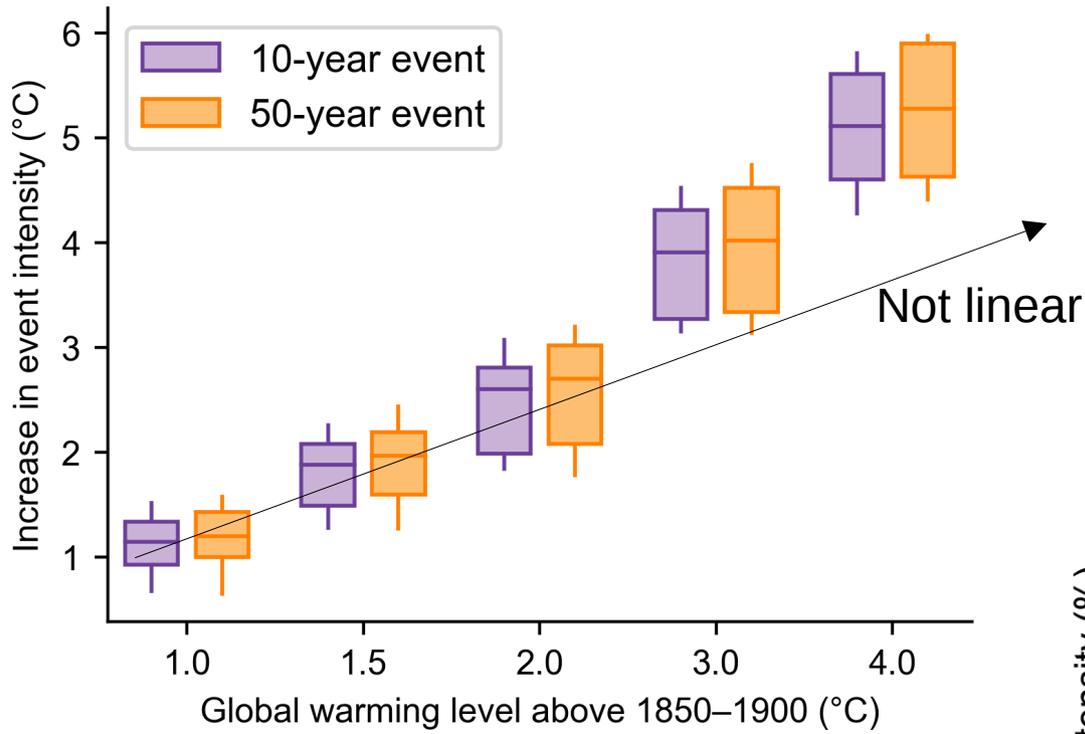
Future **changes in precipitation** averages and extremes can be **very different**



Extremes of TT follow mean change but not for PP

8. Global future projections

Extremely high temperature event



Extremely high precipitation event

