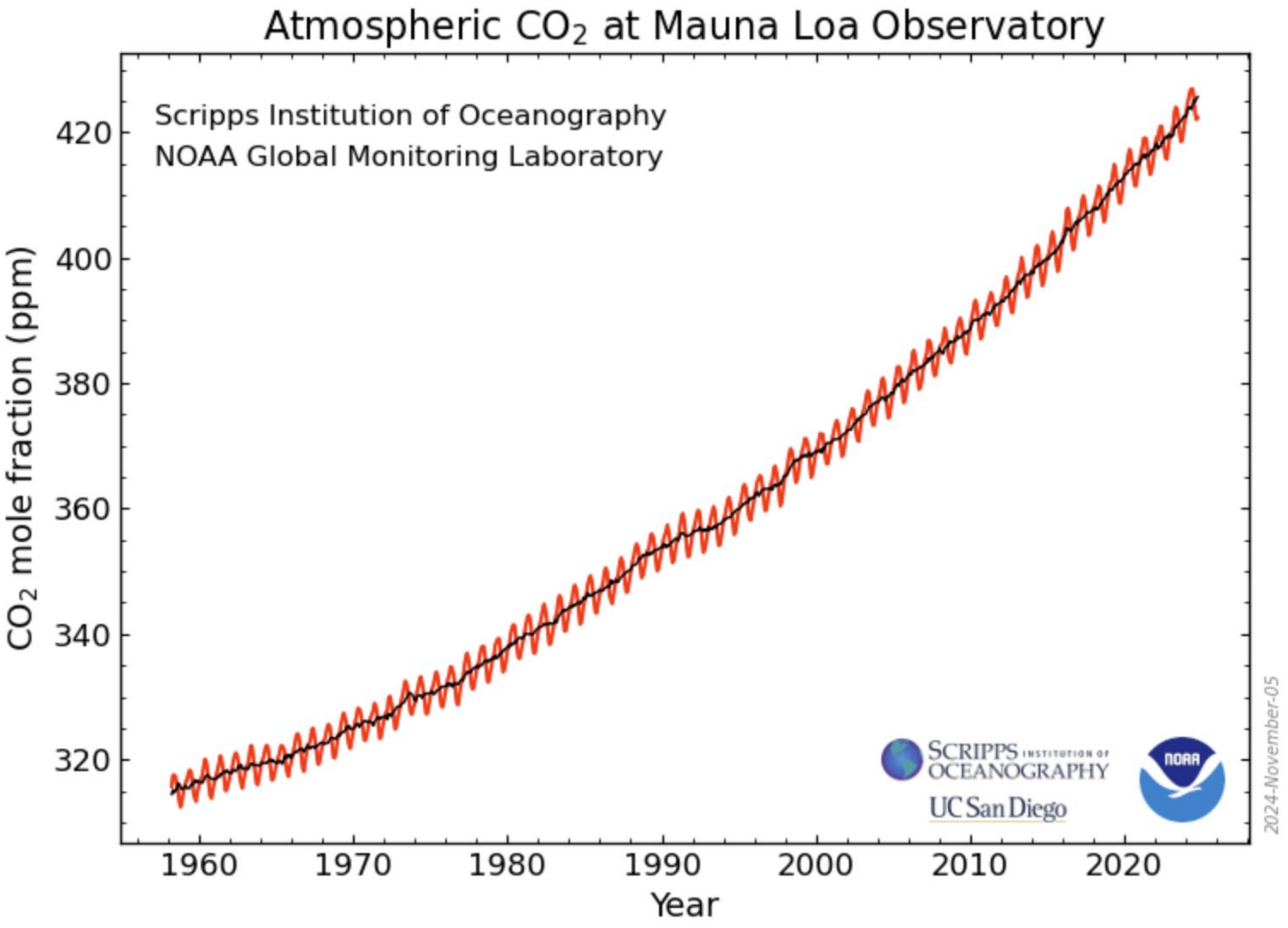
Temperature and climate sensitivity

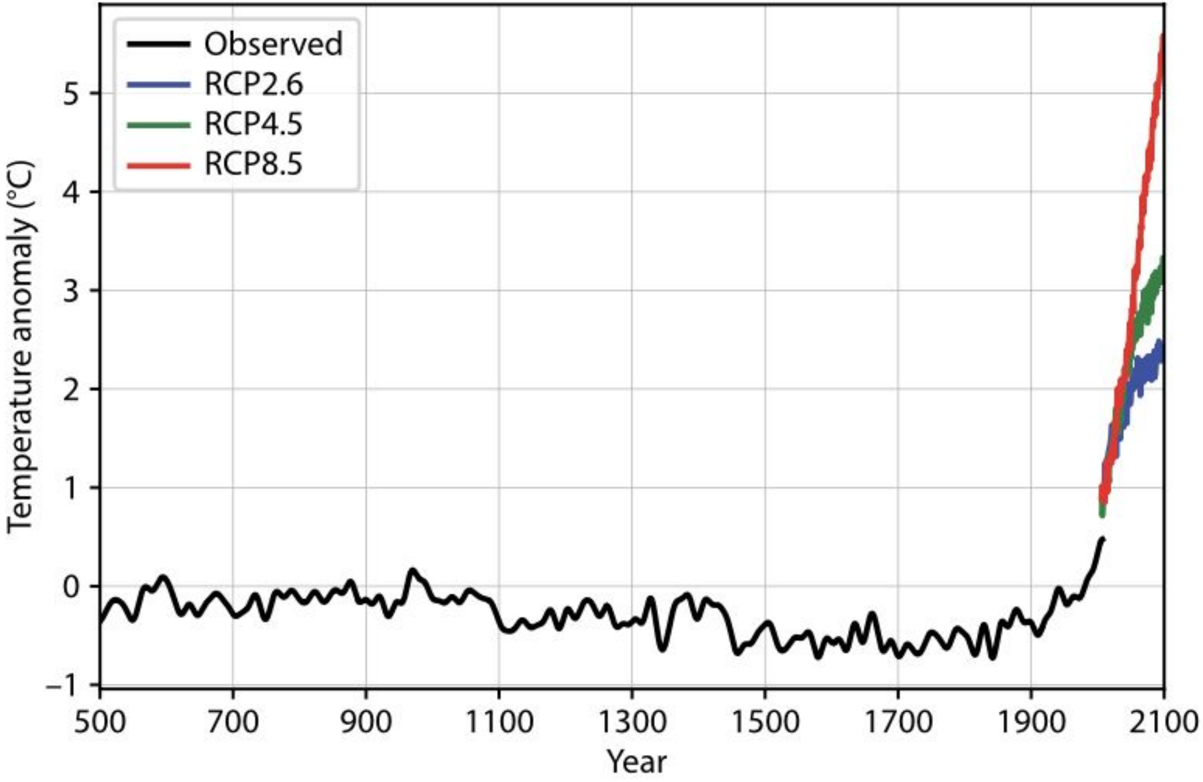
Resources:

- Global warming science: chapter 3



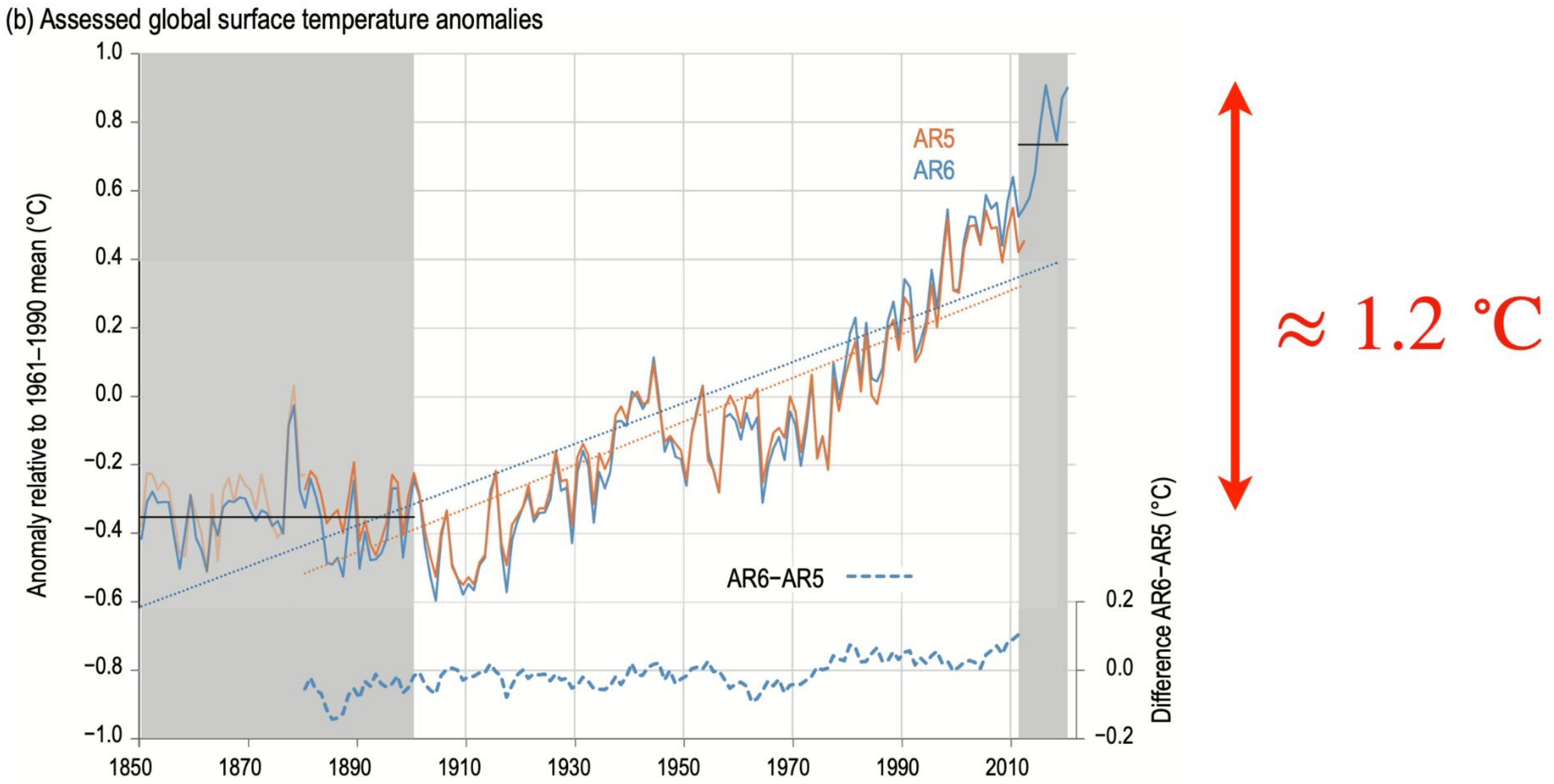
2020: CO_2 at 420 ppm but with other greenhouse gases it is ~500 ppm

Observed and projected warming



IPCC AR5, 2013

Global mean surface warming



(IPCC AR6, 2022)

Temperature increase is not steady and uniform in space

- **Hiatus periods:** warming is not constant in time (periods of no warming) due to internal climate variability
- **Transient response vs equilibrium climate sensitivity:** the key role of the ocean in delaying global warming
- **Polar amplification:** warming is larger at high latitudes (especially in the Northern Hemisphere)
- **Stratospheric cooling:** the stratosphere cools in response to increased greenhouse gases

Warming over Land vs. Ocean, the recent acceleration

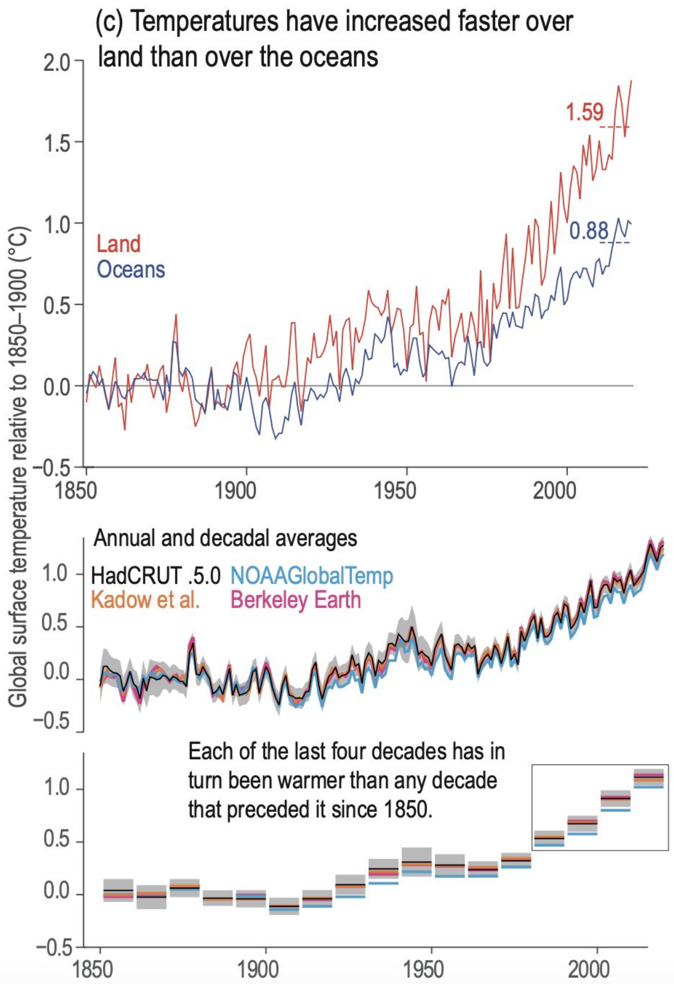


Figure 2.11 | Earth's surface temperature history with key findings annotated within each panel. (c) Temperature from instrumental data for 1850–2020, including (upper panel) multi-product mean annual time series for temperature over the oceans (blue line) and over land (red) and indicating the warming to the most recent 10 years;

Annually (middle panel) and decadally (bottom panel) resolved averages for the GMST datasets. The grey shading shows the uncertainty associated with the HadCRUT5 estimate (Morice et al., 2021). All temperatures relative to the 1850–1900 period.

acceleration in warming during past decades

(IPCC AR6, 2022)

Surface warming trends (°C/decade) 1900–1980 & 1980–2020

uncertainty…

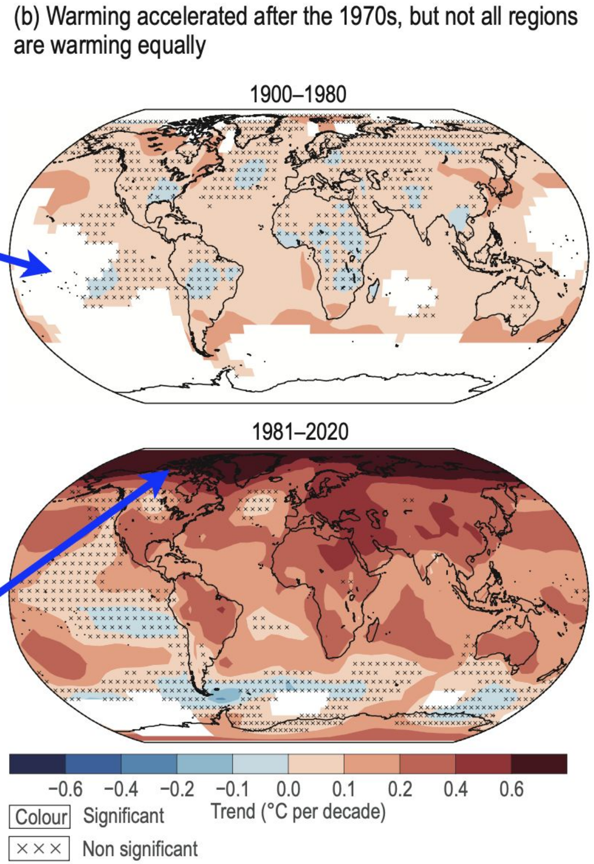
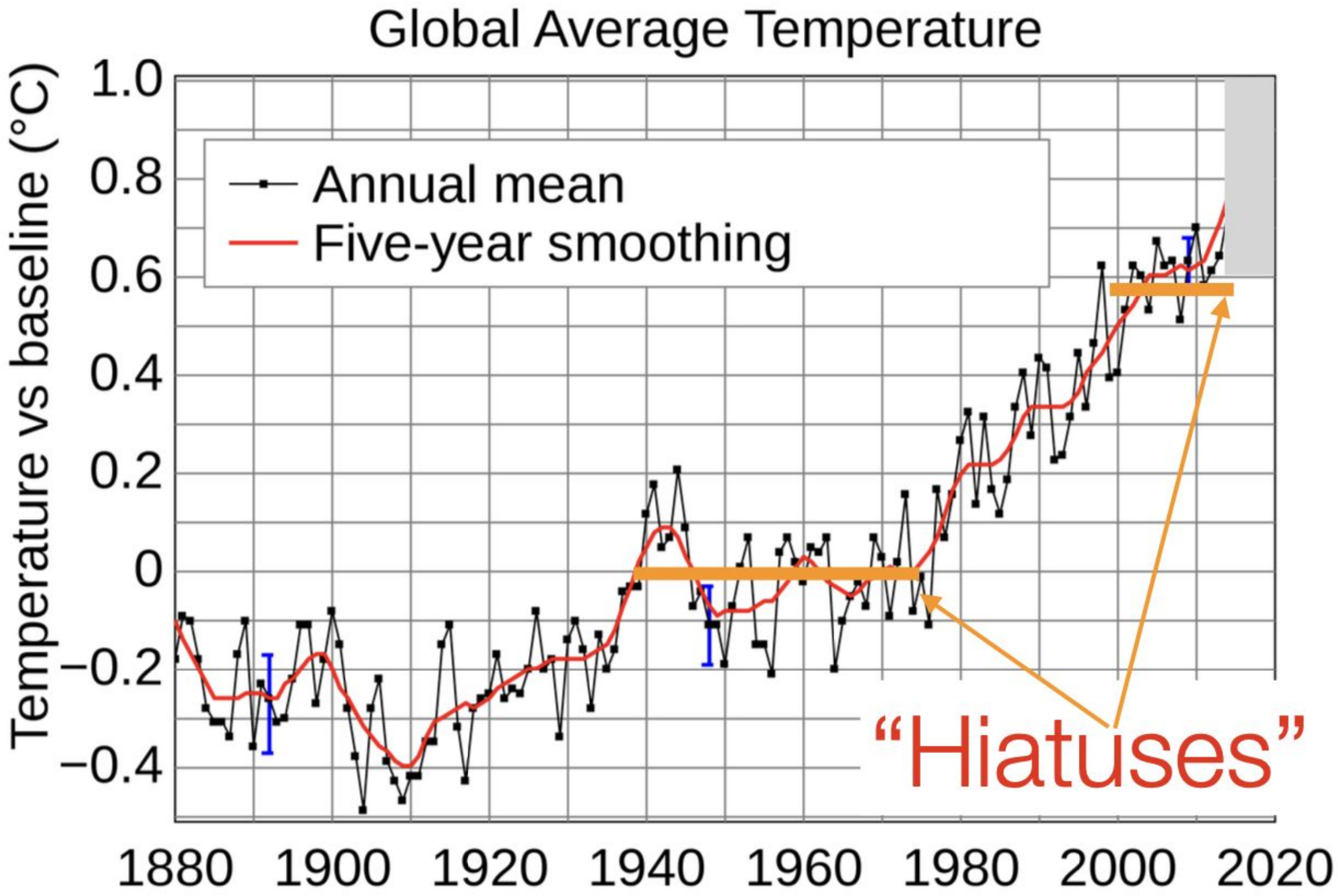


Figure 2.11 | Earth's surface temperature history with key findings annotated within each panel. (b) Spatially resolved **trends (°C per decade)** for HadCRUTv5 over (upper map) 1900–1980, and (lower map) 1981–2020. Significance is assessed following AR(1) adjustment after Santer et al. (2008), '×' marks denote non-significant trends.

polar amplification…

(IPCC AR6, 2022)



Global Average Temperature
Temperature vs baseline (°C)
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
Annual mean
Five-year smoothing
1880
1900
1920
1940
1960
1980
2000
2020
“Hiatuses”

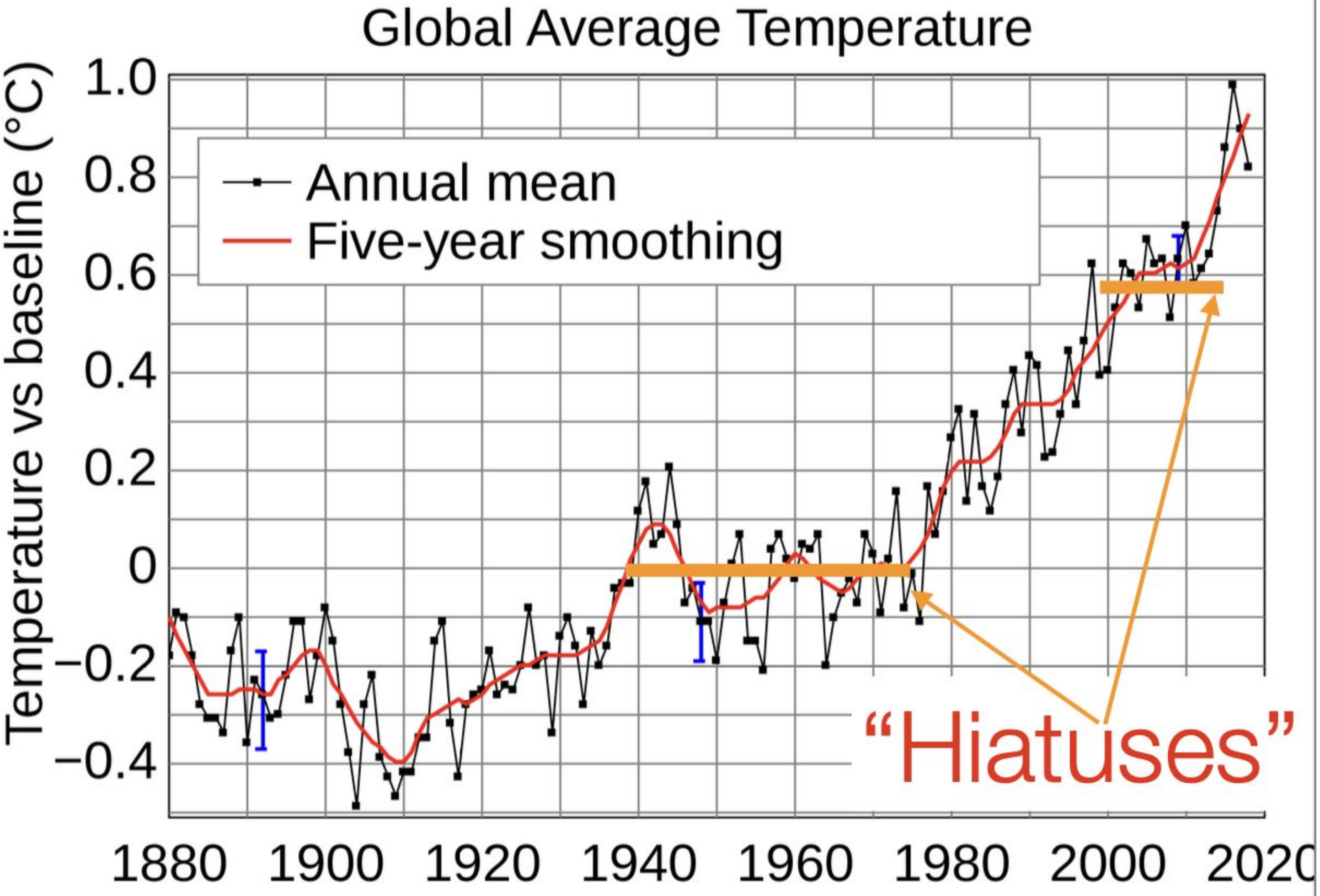
FOX NEWS

CLIMATE CHANGE * **Published** November 5, 2015 * **Last Update** January 12, 2017

Is the government tinkering with global warming data?

The hottest topic in climate research is the observation that global average surface temperature, as well as satellite observations of temperatures in the atmosphere, has shown little or no warming during the 21st century.

https://www.foxnews.com/opinion/is-the-government-tinkering-with-global-warming-data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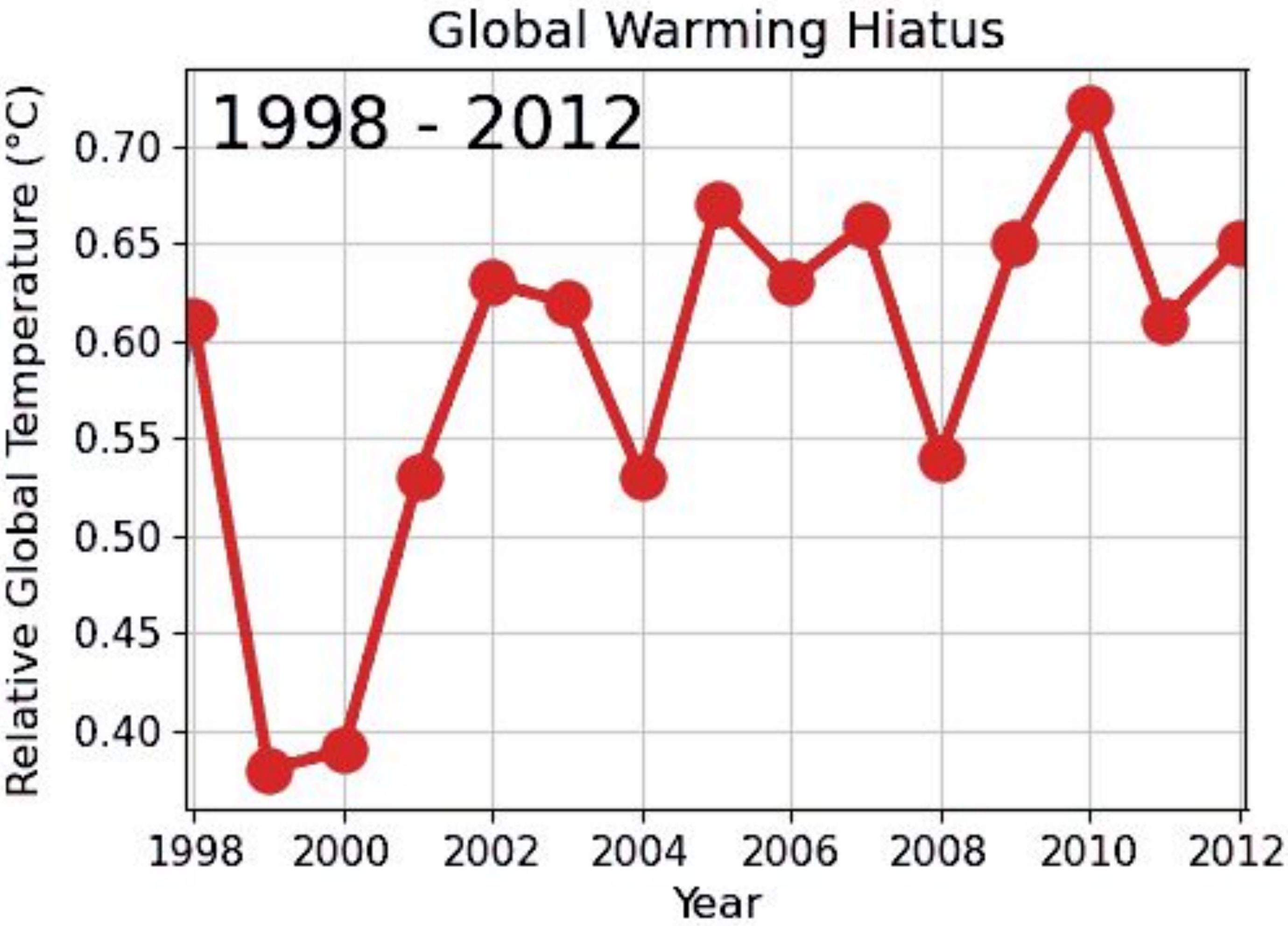
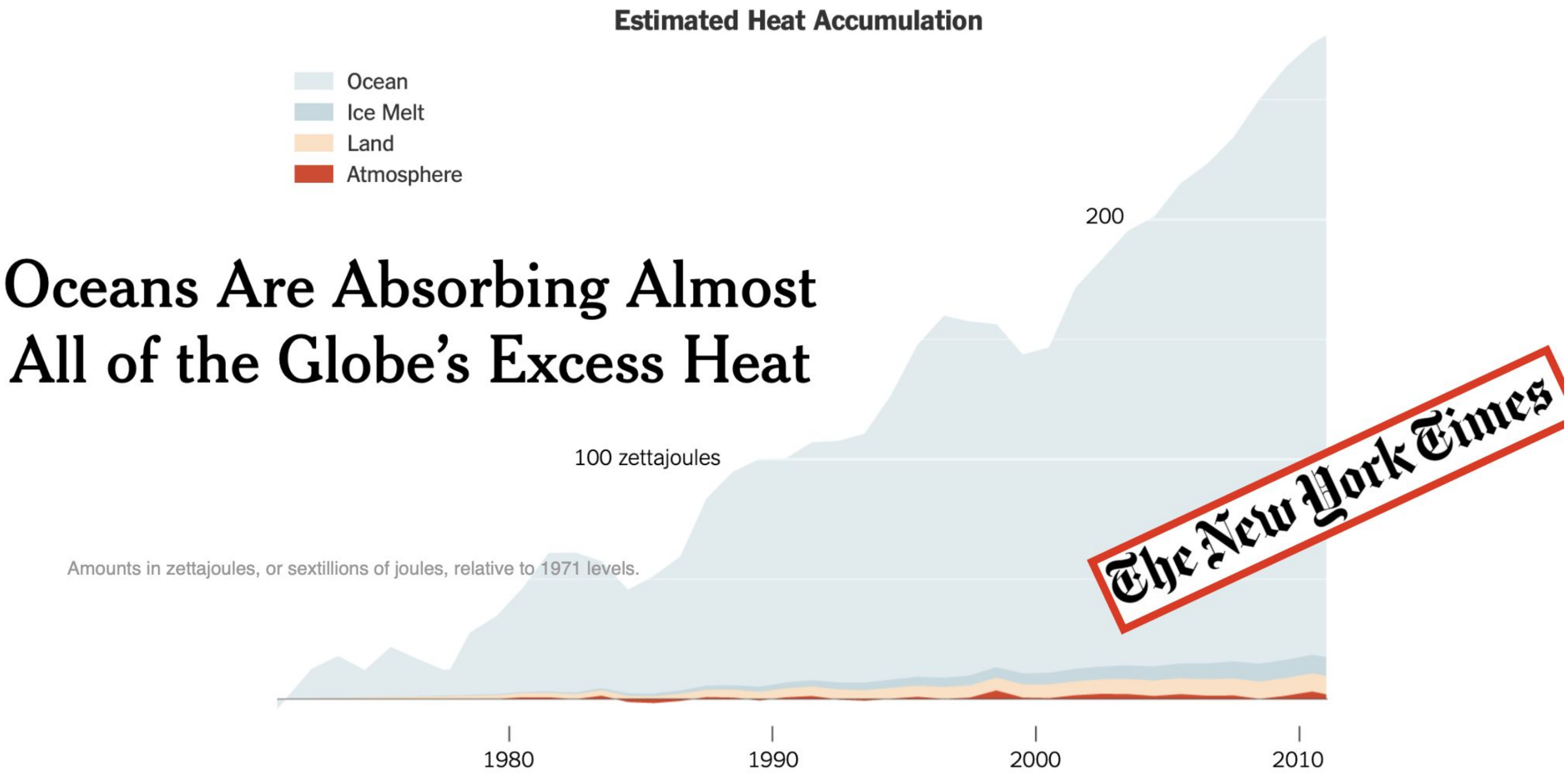

Global Warming Hiatus
1998 - 2012
Relative Global Temperature (°C)
0.70
0.65
0.60
0.55
0.50
0.45
0.40
1998
2000
2002
2004
2006
2008
2010
2012
Year

The key role of the ocean in delaying global warming



Heat Accumulates in the Oceans: "Since 1955, more than 90 percent of the excess heat retained by the Earth as a result of increased greenhouse gases has been absorbed by the oceans, leaving ocean scientists … at the National Oceanic and Atmospheric Administration feeling that **90 percent of the climate change story is being ignored**."

Climate sensitivity

"The change in the surface temperature in response to a doubling in the atmospheric carbon dioxide (CO_2) concentration from pre-industrial levels." *IPCC range: 2-4°C*

Transient climate response

Initial rise in global mean temperature when CO_2 levels double

Equilibrium climate sensitivity

The larger long-term temperature response after the planet adjusts to $2xCO_2$. Includes adjustments after **climate feedbacks**.

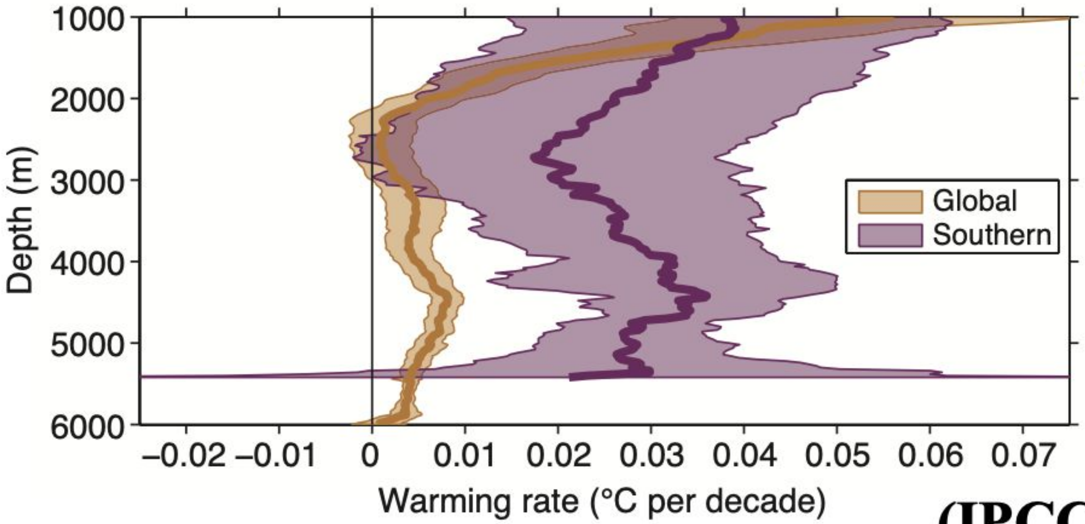
The warming you might have expected by now

The equivalent CO_2 mixing ratio, including other greenhouse gasses, is about 500 ppm.

Assuming logarithmic dependence, and a climate sensitivity of 3 °C, we might naively expect a warming of

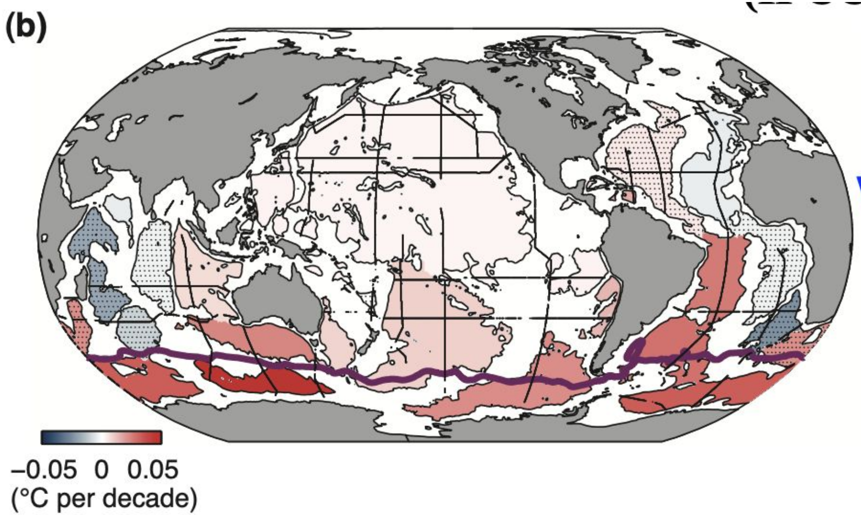
$$\Delta T = 3 \log_2(500/280) = 2.5 \text{ °C}$$

more than twice as much as has been observed! what's going on?



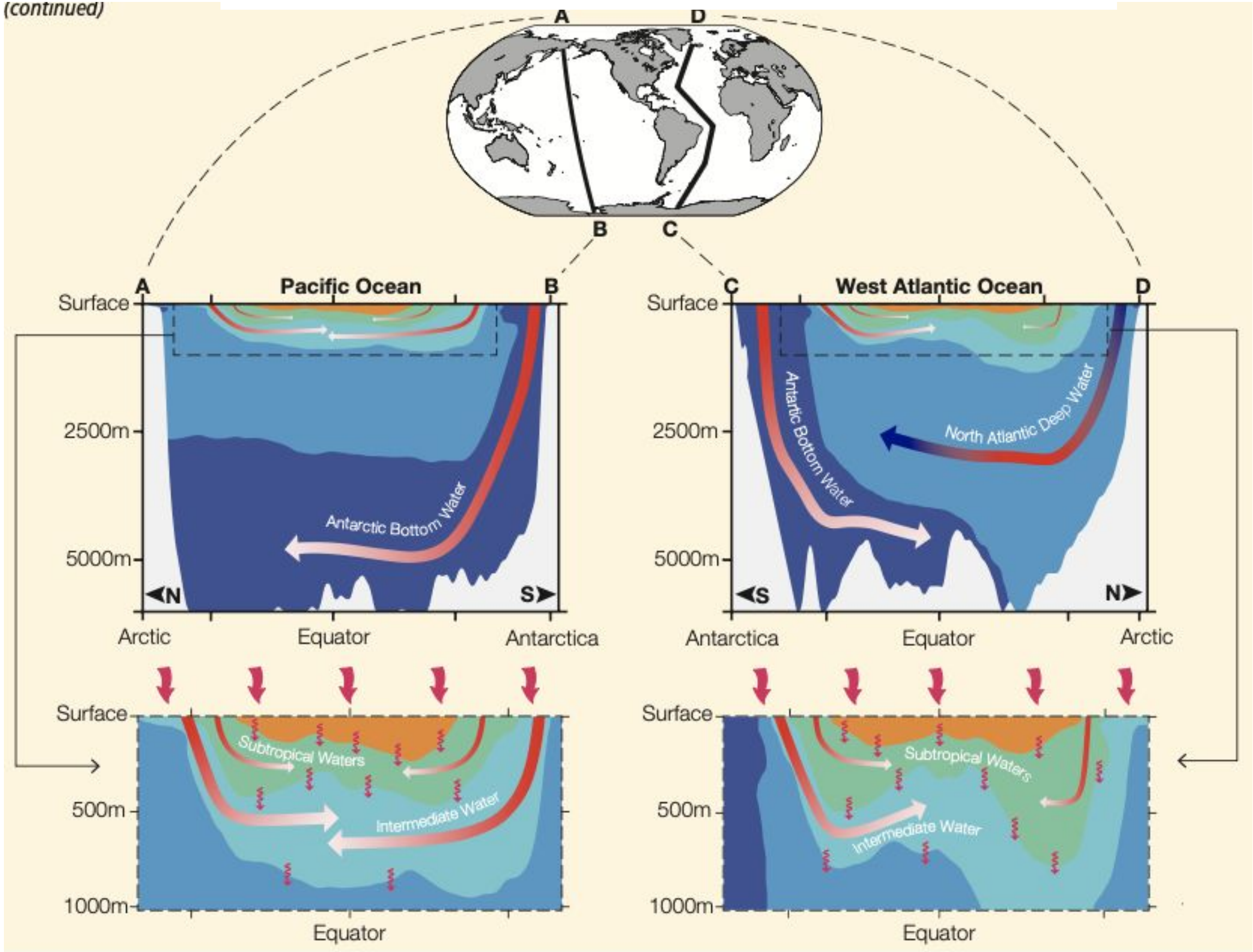
warming per decade globally and Southern Ocean

(IPCC AR5, 2013)



warming per decade below 4000 m

Ocean heat uptake pathways

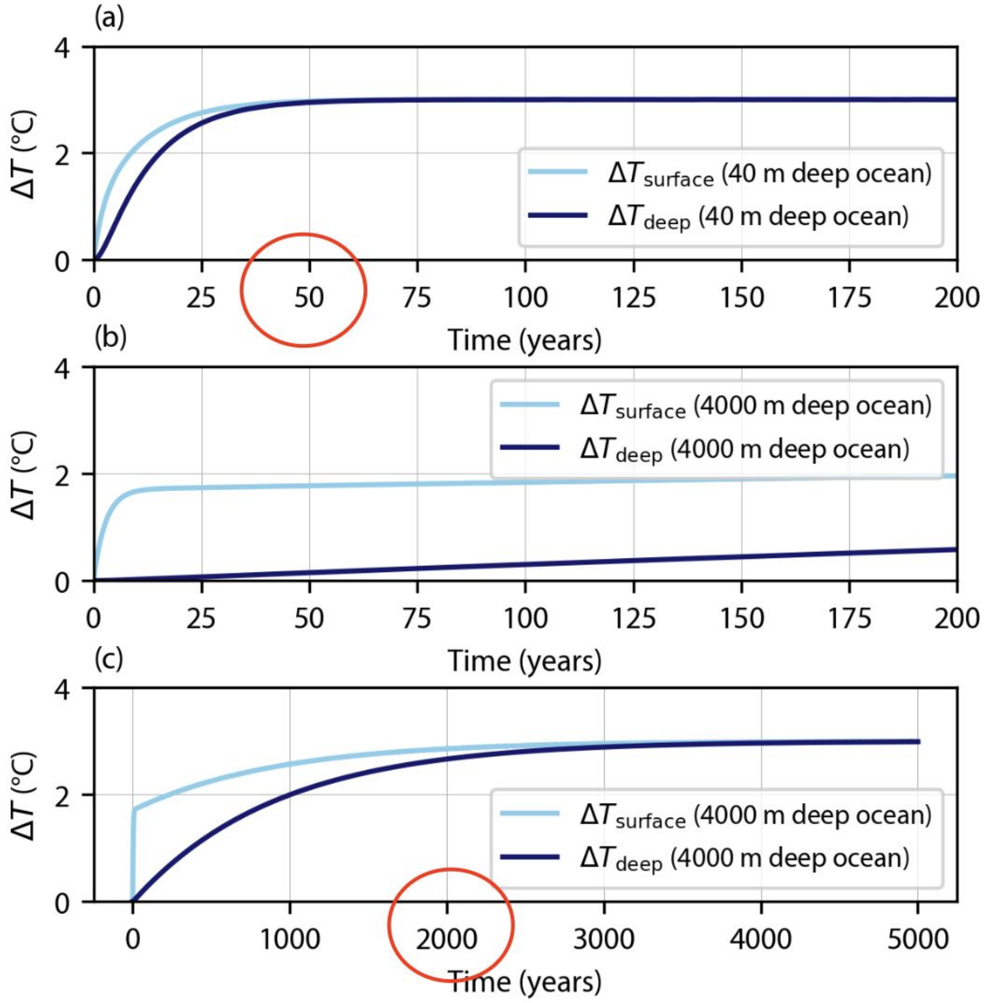


(IPCC AR5, 2013)

To explain smaller temperature increase observed today we need to take into account the **ocean**

Transient climate response:

the role of ocean depth in an idealized mathematical model



Transient climate sensitivity

The heat budgets of the upper ocean and the deep ocean:

$$C_{\text{surface}} \frac{d\Delta T_{\text{surface}}}{dt} = \Delta F_{2\times} - \lambda_{LW} \Delta T_{\text{surface}} - \gamma \left(\Delta T_{\text{surface}} - \Delta T_{\text{deep}} \right)$$

Radiative forcing   Outgoing LW Radiation   transport into the deep ocean

$$C_{\text{deep}} \frac{d\Delta T_{\text{deep}}}{dt} = \gamma \left(\Delta T_{\text{surface}} - \Delta T_{\text{deep}} \right). \quad (3.3)$$

where

$C_{\text{surface}} \approx \rho_w c_p \, 50\,\text{m}$ $C_{\text{deep}} = \rho_w c_p H,$ and H is the ocean depth

Steady solution is consistent with equilibrium climate sensitivity from before

$$\Delta T_{2\times} = \frac{\Delta F_{2\times}}{\lambda_{LW}}$$

but it takes a long time to get there, due to the large heat capacity of the ocean.

Transient climate sensitivity: role of ocean depth

The heat budgets of the upper ocean and the deep ocean:

$$C_{\text{surface}} \frac{d\Delta T_{\text{surface}}}{dt} = \Delta F_{2\times} - \lambda_{LW} \Delta T_{\text{surface}} - \gamma \left(\Delta T_{\text{surface}} - \Delta T_{\text{deep}}\right)$$

Radiative forcing — Outgoing LW Radiation — transport into the deep ocean

$$C_{\text{deep}} \frac{d\Delta T_{\text{deep}}}{dt} = \gamma \left(\Delta T_{\text{surface}} - \Delta T_{\text{deep}}\right). \qquad (3.3)$$

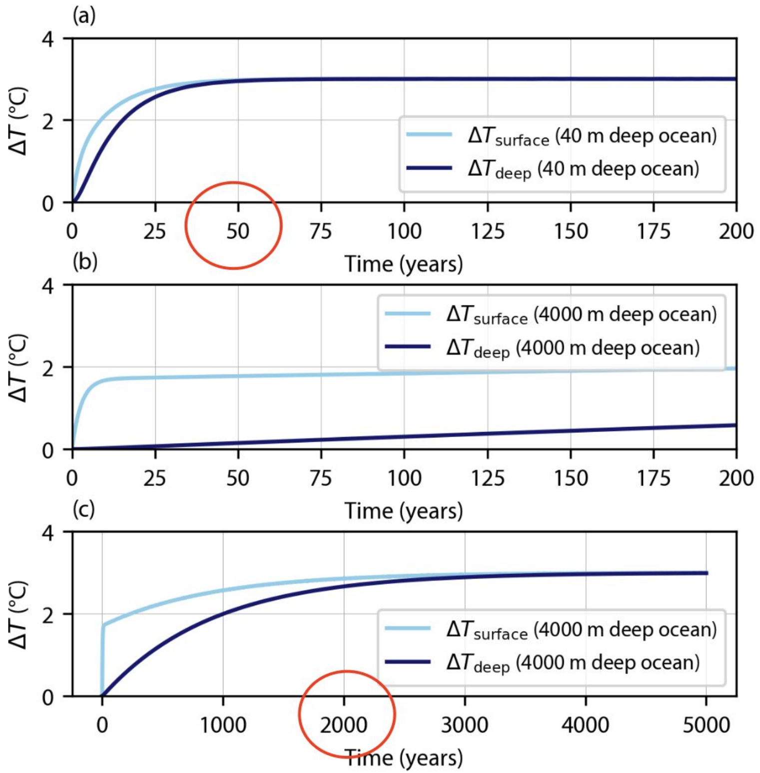
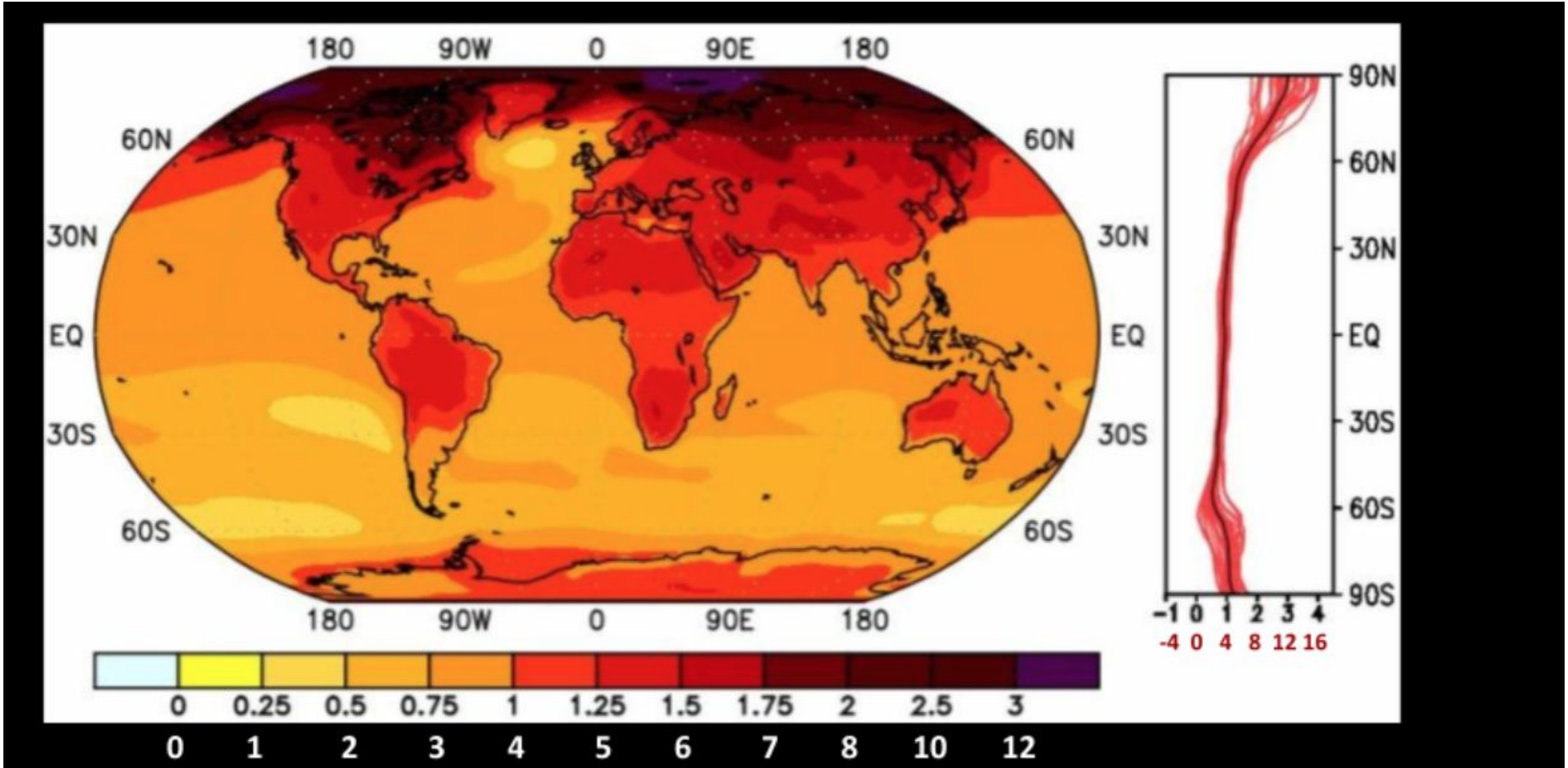


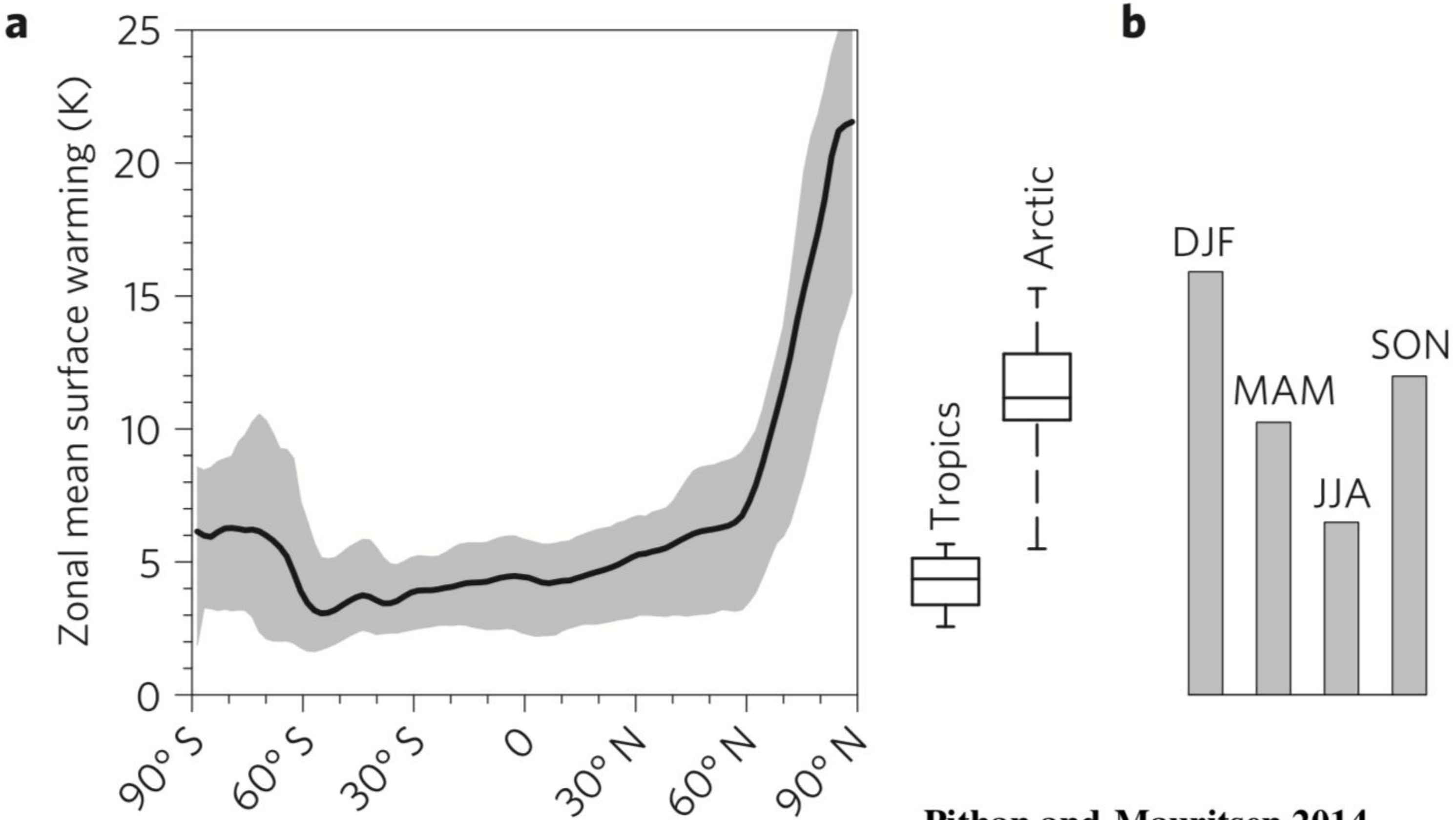
Figure 3.3: Transient climate sensitivity.
The temperature anomalies of the upper ocean and of the deep ocean, as a function of time in a scenario of instantaneous CO_2 doubling. (a) An artificial case assuming the subsurface ocean is only 40 m deep. (b) A more realistic scenario, assuming an ocean depth of 4000 m and showing only the first 200 yr of adjustment to an abrupt doubling of CO_2. (c) Same scenario as in (b), and showing the full period of adjustment.

Polar amplification

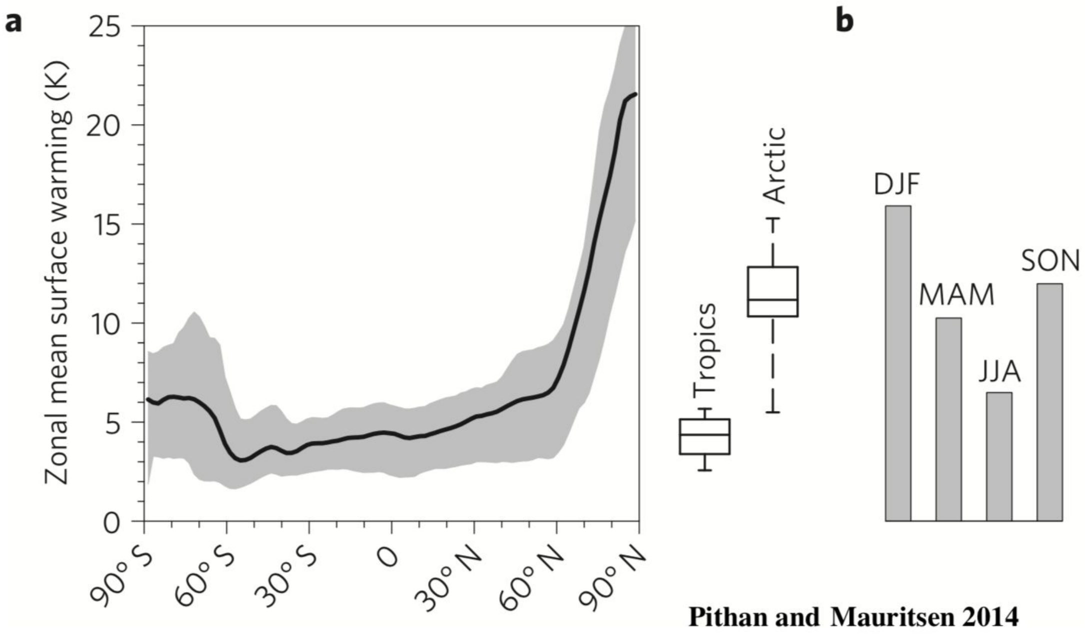


CMIP5 model mean pattern (RCP8.5, 2100-2000)

Polar amplification



Pithan and Mauritsen 2014

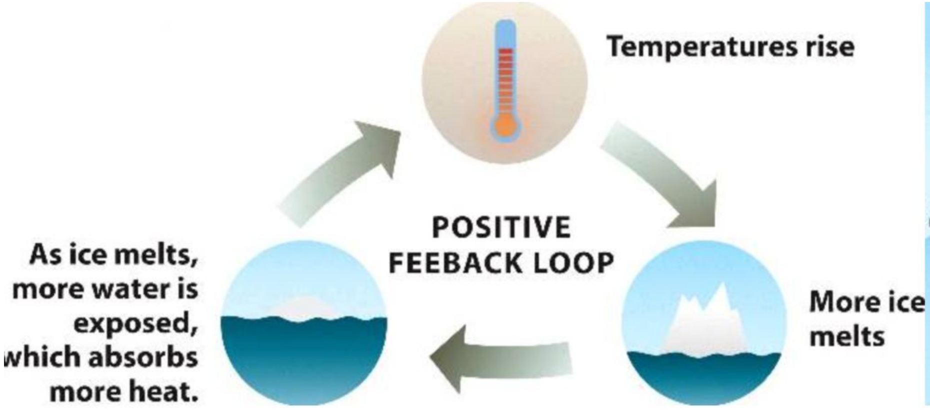


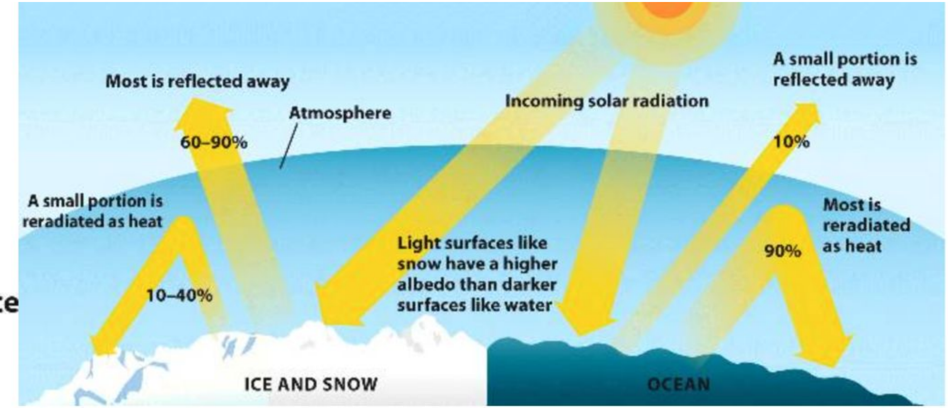
Pithan and Mauritsen 2014

Figure 1 | Arctic amplification in CMIP5 models. a, Zonal mean surface temperature change for the last 30 years of the CMIP5 4 × CO_2 experiment compared with the last 30 years of the control run. Box and whisker plots show the median (lines), 25th to 75th percentiles (boxes) and full spread (whiskers) of temperature change averaged over the tropics (30°S–30°N) and the Arctic (60°N–90°N). **b**, Bars show the intermodel mean warming for different seasons. Intermodel mean warming is 11.2 K in the Arctic and 4.3 K in the tropics. Arctic warming is strongest in winter (15.9 K) and weakest in summer (6.5 K). March–May, MAM; September–November, SON.

Mechanisms leading to Arctic warming amplification compared to mid-latitudes

1) Albedo feedback





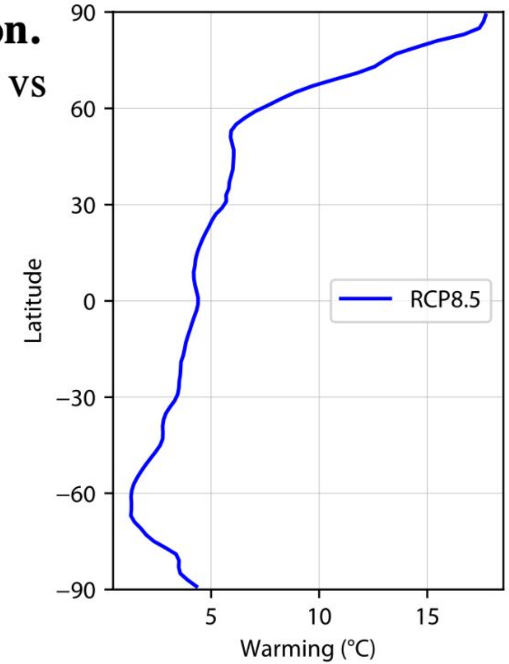
Leads to very dramatic warming of the ocean in the Arctic

Temperature of air over sea-ice: -20/30°C

Min. temperature of seawater: -1.8°C

2) Planck feedback

Figure 3.2: Polar amplification. Warming over the 21st century vs latitude, RCP8.5 scenario.

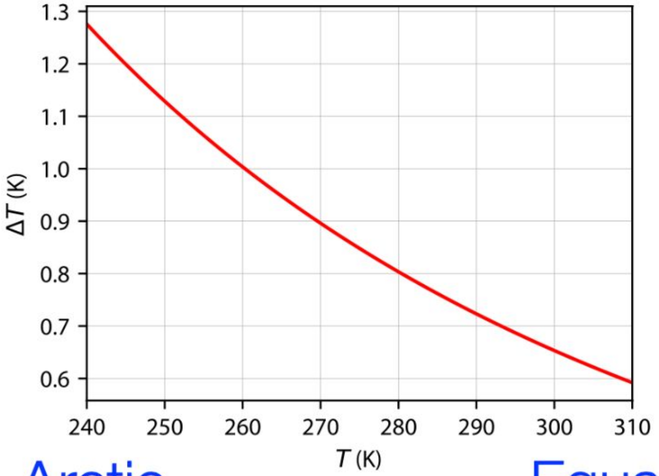


Consider a ΔF radiative forcing. Calculate the resulting warming ΔT assuming a Planck balance, $F_0 = \epsilon\sigma T_0^4$:

➡ $F_0 + \Delta F = \epsilon\sigma \times (T_0 + \Delta T)^4 \approx \epsilon\sigma \times (T_0^4 + \frac{dT^4}{dT}\Delta T)$

➡ $\Delta F \approx \epsilon 4\sigma T_0^3 \Delta T$ ➡ $\Delta T \approx \Delta F / (\epsilon 4 \sigma T_0^3)$ (3.5)

2) Planck feedback



Arctic Equator

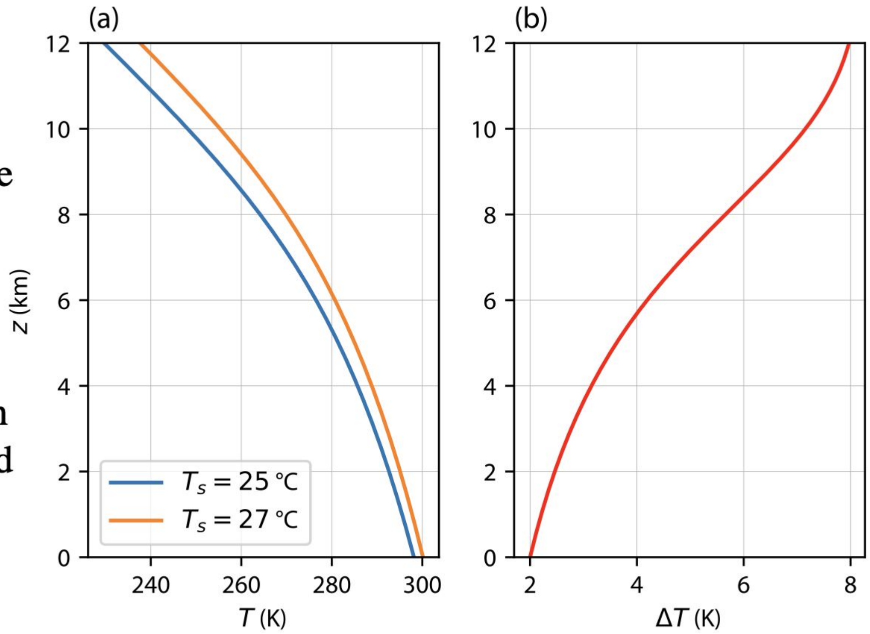
Figure 3.4: The Planck feedback.
The warming expected due to an increase in radiative forcing of 4 W/m^2 based on equation (3.5) with an emissivity of $\epsilon = 1$.

➡ The warming due to the same radiative forcing is significantly larger for a cold initial temperature than for a warm temperature

3) Lapse rate feedback

[Pithan & Mauritsen 2014]: In tropics, greater warming in the upper troposphere than at surface ➔ Smaller increase in $T_{surface}$ required to balance CO_2 radiative forcing at Top Of Atmosphere (TOA) ➔ weaker surface warming response to CO_2.

Figure 3.6: Tropical lapse rate feedback.
(a) Temperature profiles of two surface air parcels starting with a relative humidity of 100% and two different surface temperatures and rising adiabatically in the atmosphere. (b) The difference in temperature between the two profiles, showing the enhanced upper atmosphere warming of the parcel that starts with a slightly warmer surface temperature.



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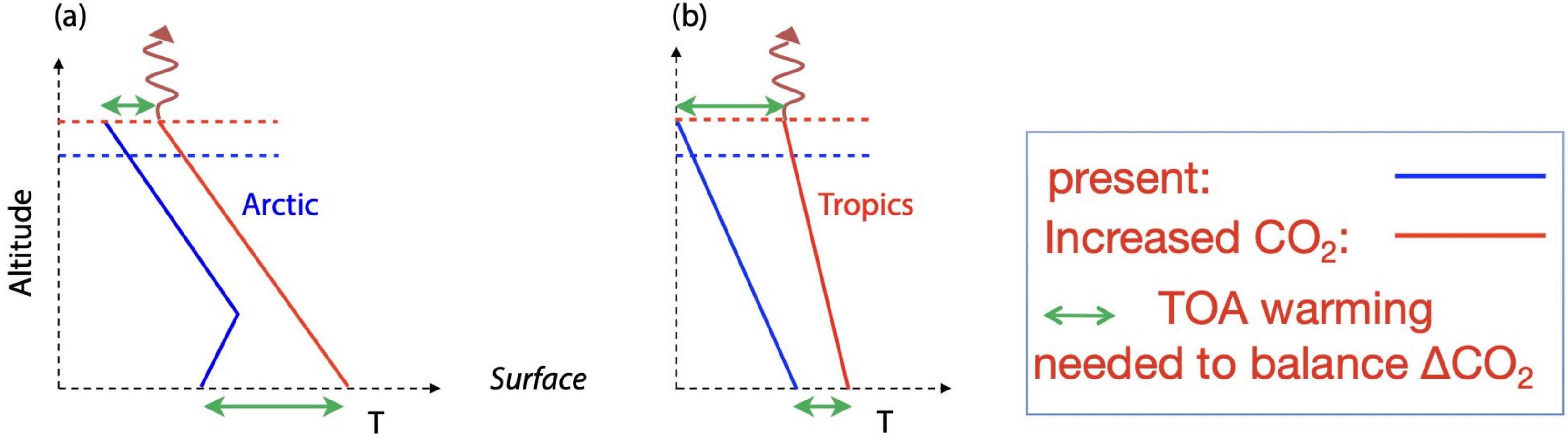
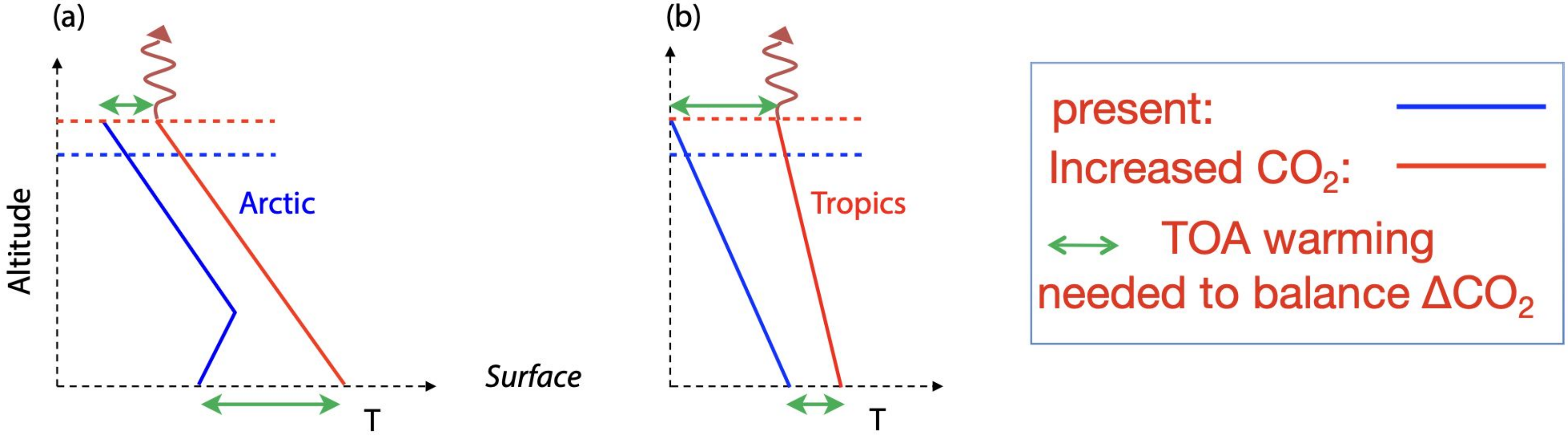


Figure 3.5: Schematics of the Arctic (a) and tropical (b) lapse rate feedbacks.
Solid blue (red) lines show the temperature profiles before (after) warming. Dashed blue (red) lines show the emission level before (after) the warming (see section 2.1.3). The green double arrows show the warmings at the surface and at the emission level.

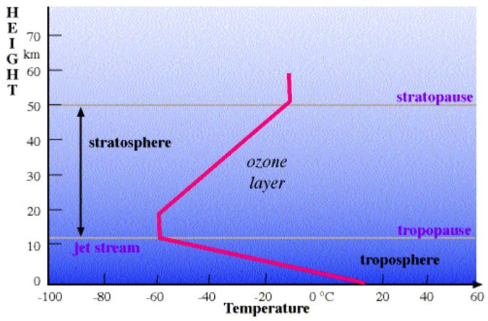
3) Lapse rate feedback



Suppose the warming at the TOA (say at the emission height) is the same in the tropics and the Arctic, determined by an average greenhouse-gas-induced radiative forcing and change in emission height.

➡ The warming at the surface will be larger in Arctic ➡ Arctic amplification.

The troposphere is warming, the stratosphere is cooling



(IPCC AR6, 2022)

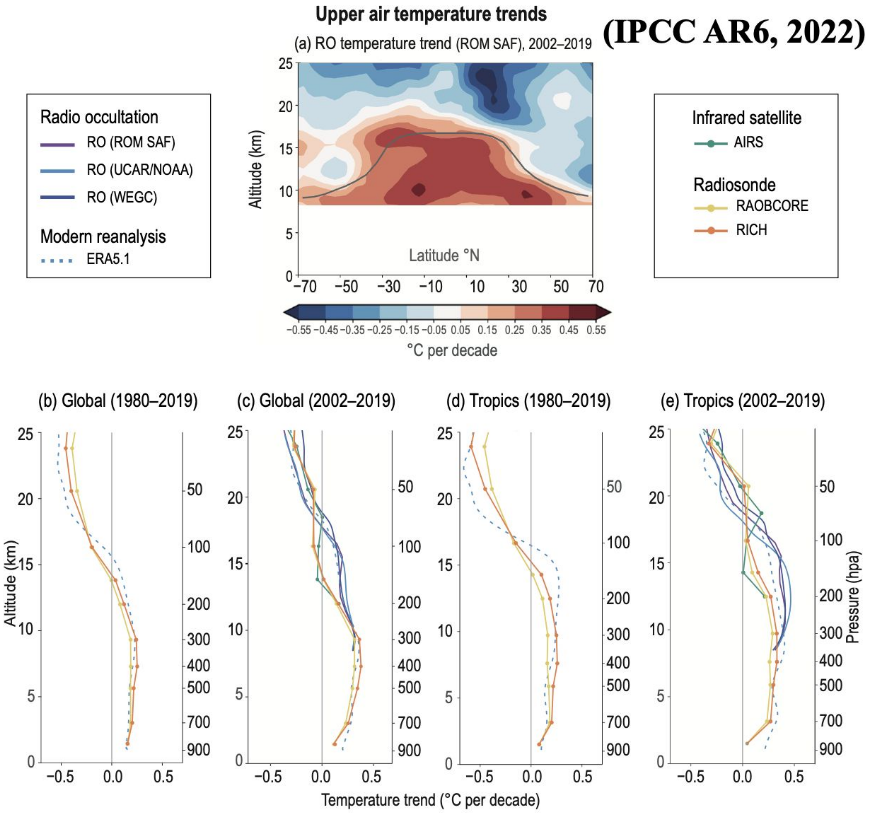


Figure 2.12 | Temperature trends in the upper air. (a) Zonal cross-section of temperature anomaly trends (2007–2016 baseline) for 2002–2019 in the upper troposphere and lower stratosphere region. Tropopause marked by grey line.

(b, c) Trends in temperature at various atmospheric heights for 1980–2019 and 2002–2019 for 70°N–70°S. **(d, e)** as for (b, c) but for the tropical (20°N–20°S) region.

Stratospheric cooling

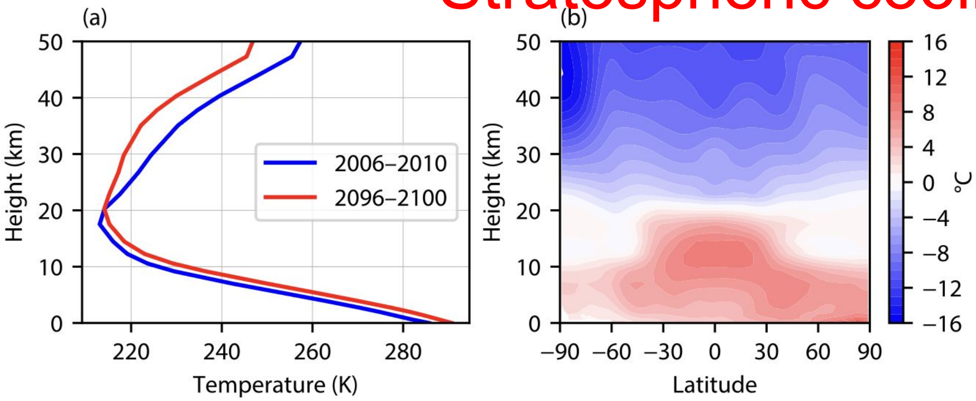
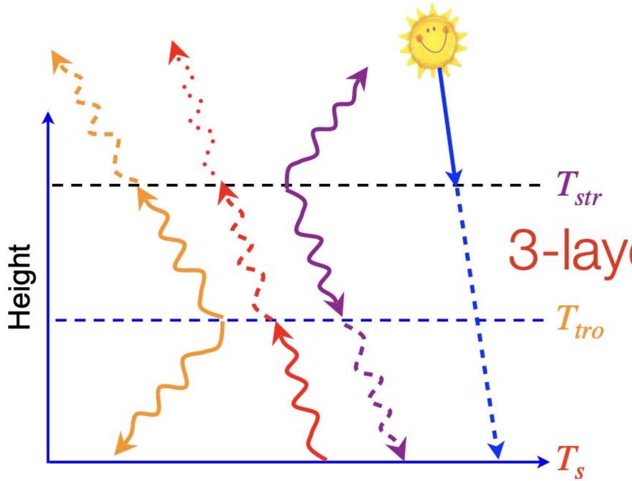


Figure 3.8: Stratospheric cooling.
(a) Mid-latitude (30°N–50°N) zonally averaged temperature profiles for an RCP8.5 projection at the beginning and end of the 21st century. (b) The zonally averaged atmospheric temperature response during the 21st century to the RCP8.5 scenario, showing a tropospheric warming and a stratospheric cooling.

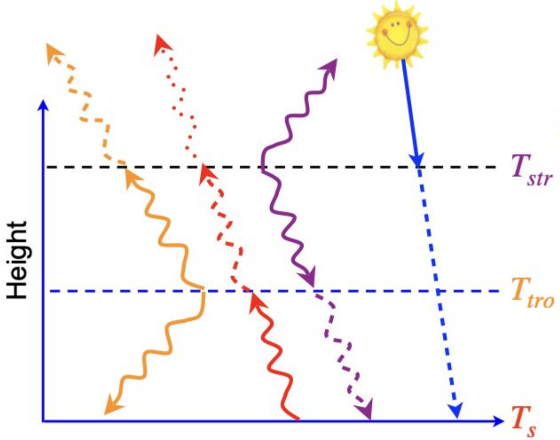
Tropospheric warming, stratospheric cooling, RCP8.5



3-layer energy balance model

Stratospheric cooling

3-layer energy balance model



← Sources →←Sinks→

Surface $$(1-\beta_{str})\frac{1}{4}S_0+\varepsilon_{tro}\sigma T_{tro}^4+(1-\varepsilon_{tro})\varepsilon_{str}\sigma T_{str}^4=\sigma T_s^4$$

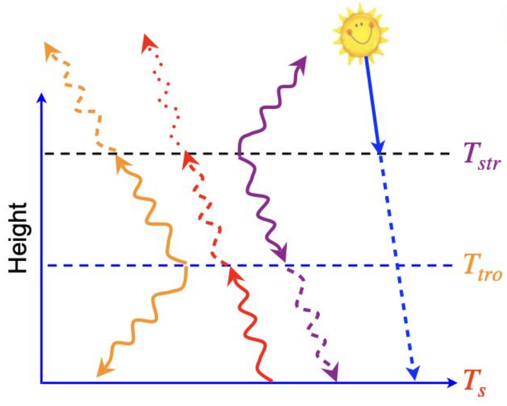
Troposphere $$\varepsilon_{tro}\sigma T_s^4+\varepsilon_{tro}\varepsilon_{str}\sigma T_{str}^4=2\varepsilon_{tro}\sigma T_{tro}^4$$

Stratosphere $$\beta_{str}\frac{1}{4}S_0+\varepsilon_{str}(1-\varepsilon_{tro})\sigma T_s^4+\varepsilon_{str}\varepsilon_{tro}\sigma T_{tro}^4=2\varepsilon_{str}\sigma T_{str}^4.$$

Solve by writing as a matrix equation for T^4

$$\begin{pmatrix}\sigma & -\varepsilon_{tro}\sigma & -(1-\varepsilon_{tro})\varepsilon_{str}\sigma\\ -\varepsilon_{tro}\sigma & 2\varepsilon_{tro}\sigma & -\varepsilon_{tro}\varepsilon_{str}\sigma\\ -(1-\varepsilon_{tro})\varepsilon_{str}\sigma & -\varepsilon_{str}\varepsilon_{tro}\sigma & 2\varepsilon_{str}\sigma\end{pmatrix}\begin{pmatrix}T_s^4\\ T_{tro}^4\\ T_{str}^4\end{pmatrix}=\begin{pmatrix}(1-\beta_{str})\frac{1}{4}S_0\\ 0\\ \beta_{str}\frac{1}{4}S_0\end{pmatrix}$$

3-layer energy balance model



$$(1-\beta_{str})\frac{1}{4}S_0 + \varepsilon_{tro}\sigma T_{tro}^4 + (1-\varepsilon_{tro})\varepsilon_{str}\sigma T_{str}^4 = \sigma T_s^4$$

$$\varepsilon_{tro}\sigma T_s^4 + \varepsilon_{tro}\varepsilon_{str}\sigma T_{str}^4 = 2\varepsilon_{tro}\sigma T_{tro}^4$$

$$\beta_{str}\frac{1}{4}S_0 + \varepsilon_{str}(1-\varepsilon_{tro})\sigma T_s^4 + \varepsilon_{str}\varepsilon_{tro}\sigma T_{tro}^4 = 2\varepsilon_{str}\sigma T_{str}^4.$$

←Source→ ←Sink→

CO_2 increase

➨ Sink on RHS increases due to stratospheric emissivity ϵ_{str} change.

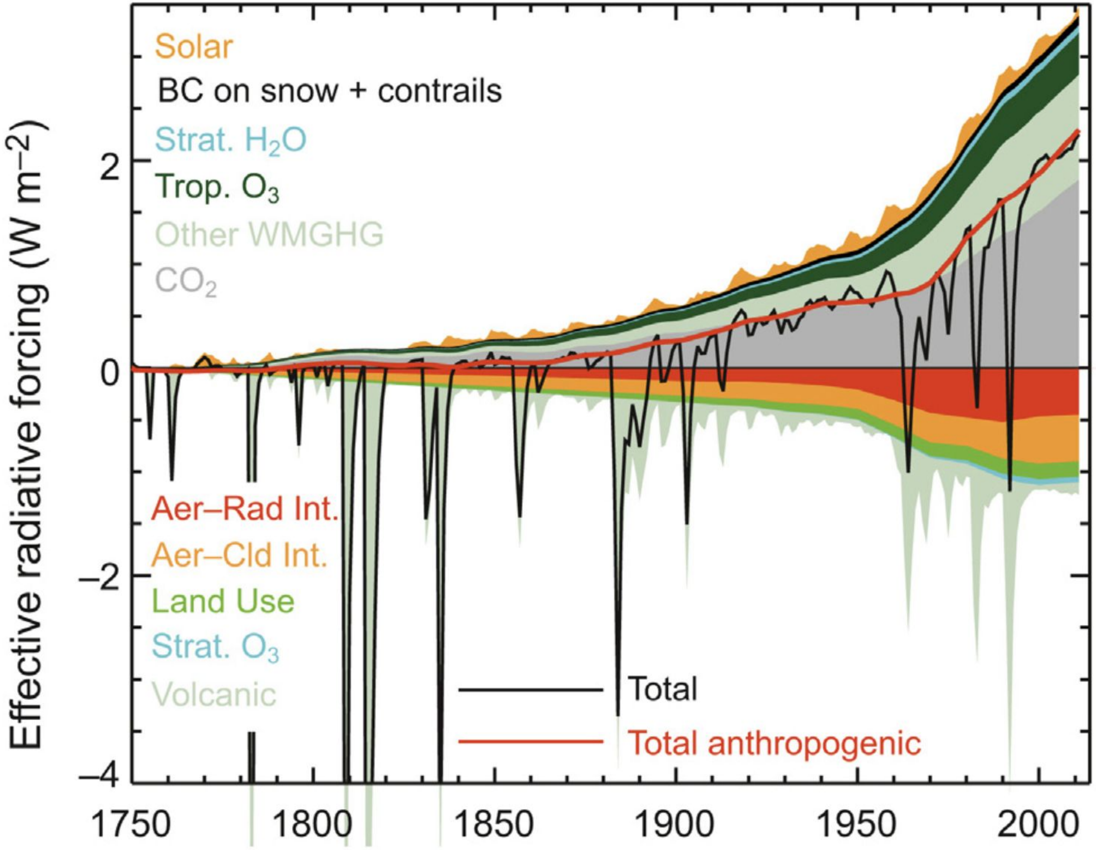
But the source terms on LHS only partially increase, due to the presence of SW source term

➨ Stratospheric cooling

- Global-mean surface warming: not much uncertainty about the magnitude, nor about it being unusual relative to past centuries…
- Warming as a function of time over land vs. ocean.
- Hiatus periods.
- Climate sensitivity from present-day data w/o models.
- Delaying effect of ocean heat capacity (transient climate sensitivity).
- Polar amplification: Albedo, lapse rate (tropical/Arctic), Planck feedbacks.
- Stratospheric cooling as a powerful attribution indicator.

Climate sensitivity
&
climate feedbacks

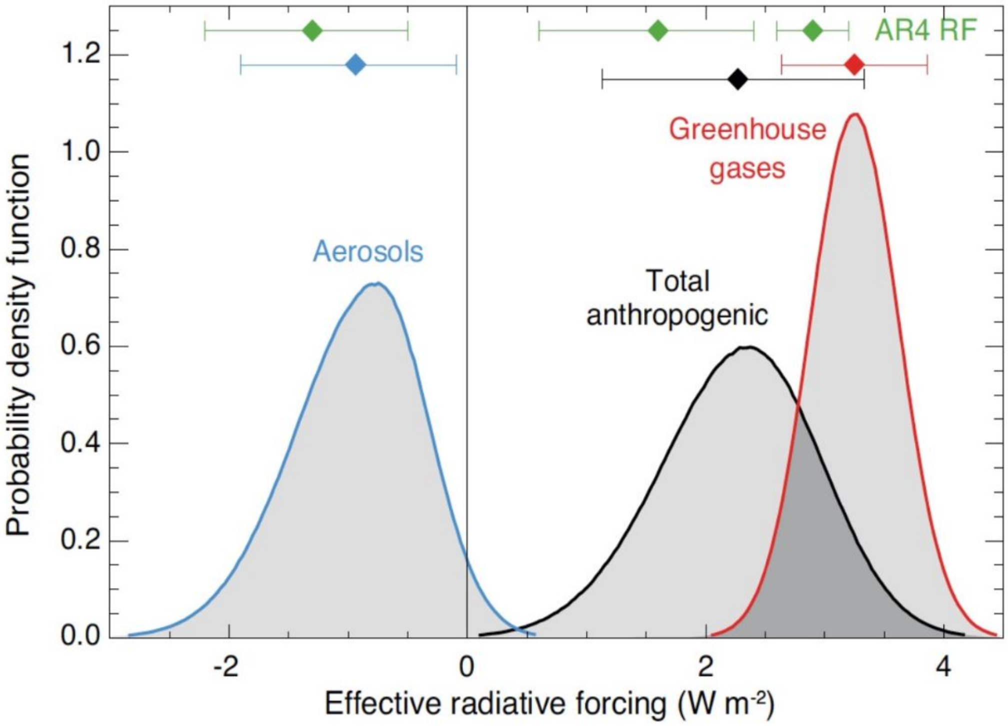
Climate sensitivity ← $\Delta T = -\lambda \Delta F$ → Forcing



Feedback parameter

$\lambda = \lambda_1 + \lambda_2 + \ldots$

$[\lambda] = [K/(Wm^{-2})]$



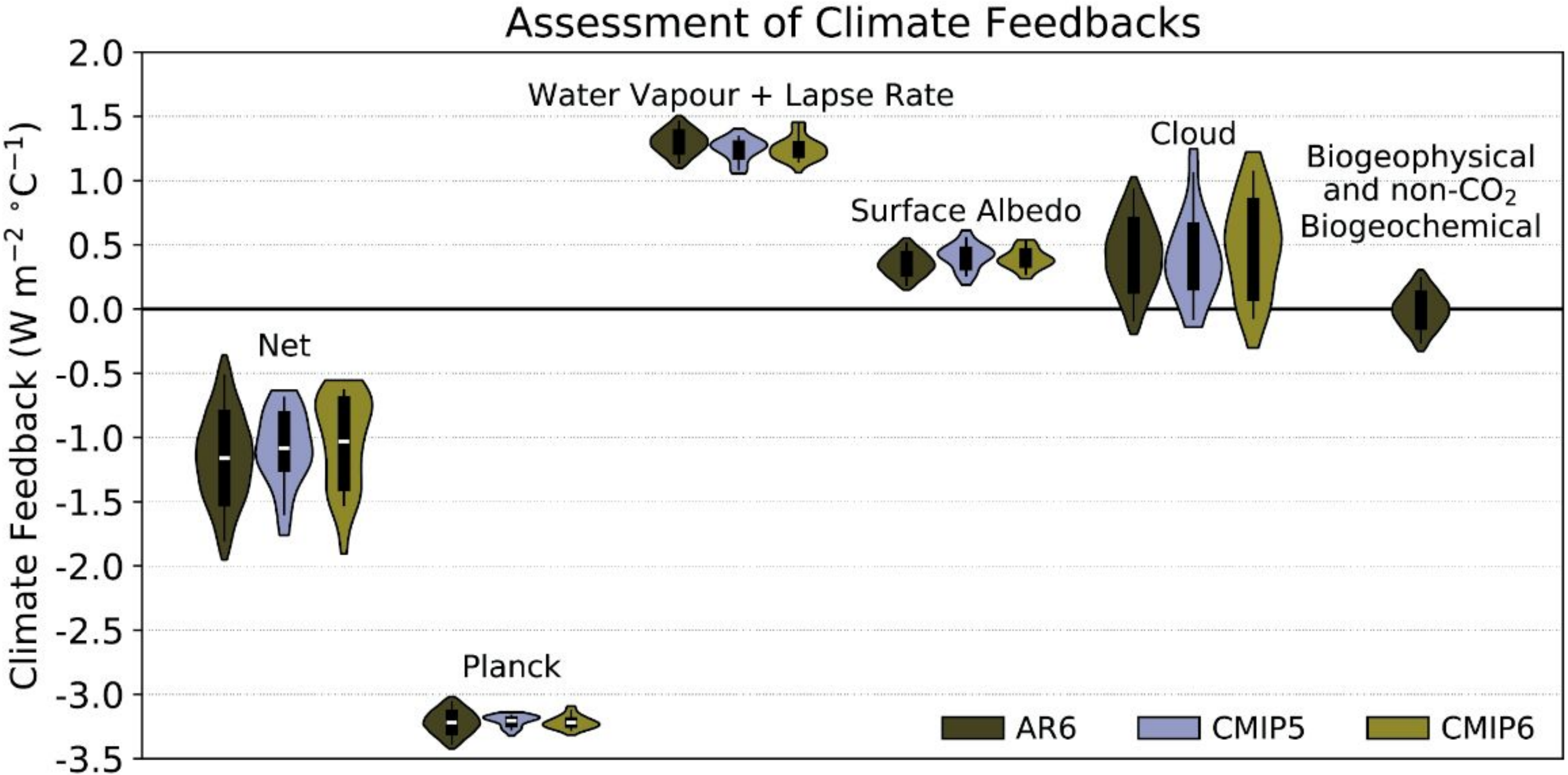
Forcing by Humans up to now

- Its about +2.2 Wm^{-2} Total
- Greenhouse gases +2.8 Wm^{-2} well known
- Aerosols ~ –0.8 Wm^{-2} very uncertain
- Plus a bunch of other minor players

List of major climate feedbacks:

- **Planck**: always negative (globally at TOA)
- **Water vapor**: positive
- **Albedo**: positive
- **Lapse rate**: negative (tropics), positive (poles), net is positive
- **Cloud feedback**: <u>negative</u> if low-level clouds increase due to more water vapor, <u>positive</u> if high-levels clouds increase due to more water vapor (highly uncertain)

IPCC AR6


Assessment of Climate Feedbacks
Climate Feedback (W m−2 °C−1)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
Water Vapour + Lapse Rate
Surface Albedo
Cloud
Biogeophysical and non-CO2 Biogeochemical
Net
Planck
AR6
CMIP5
CMIP6