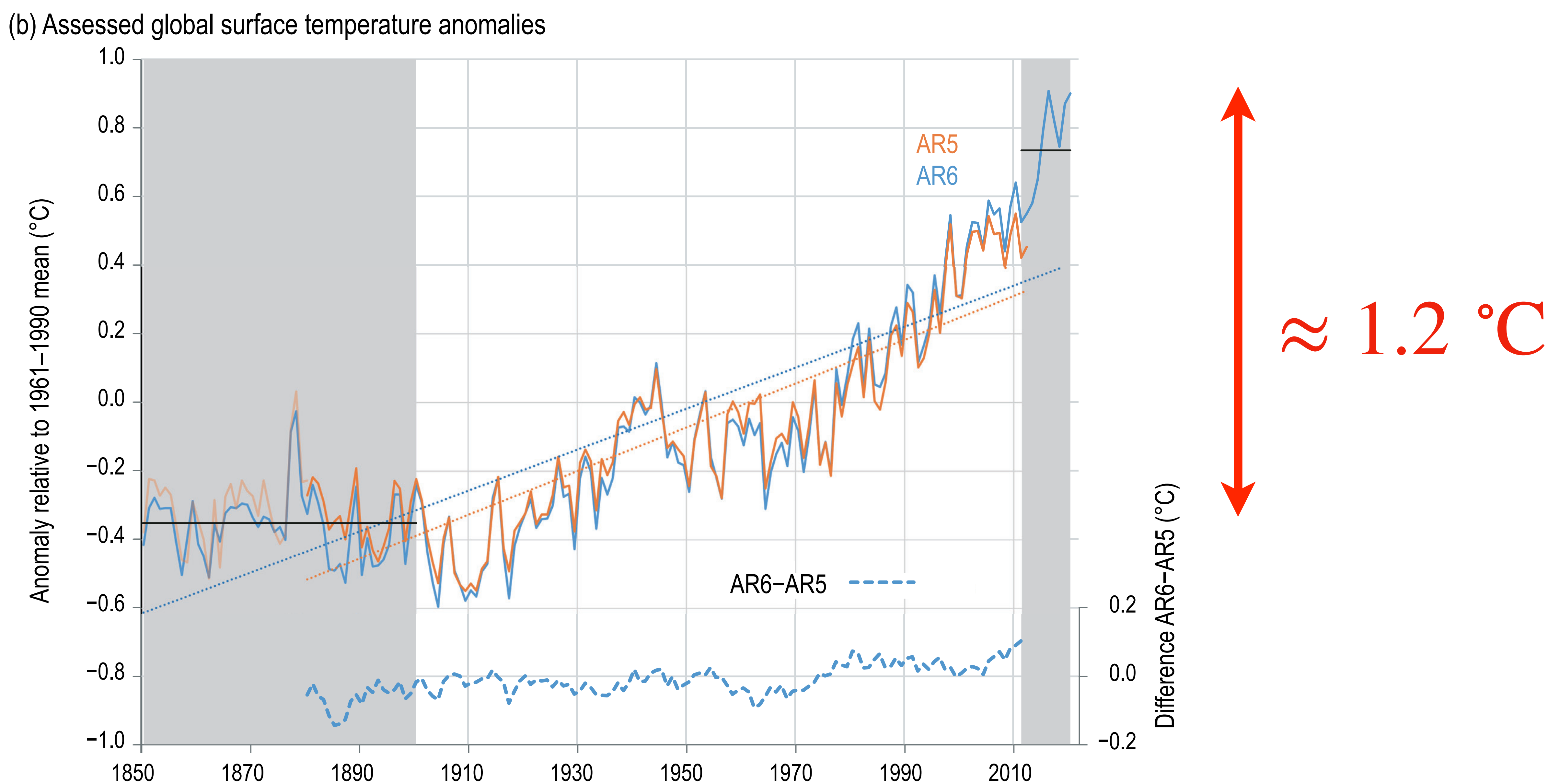
Temperature

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

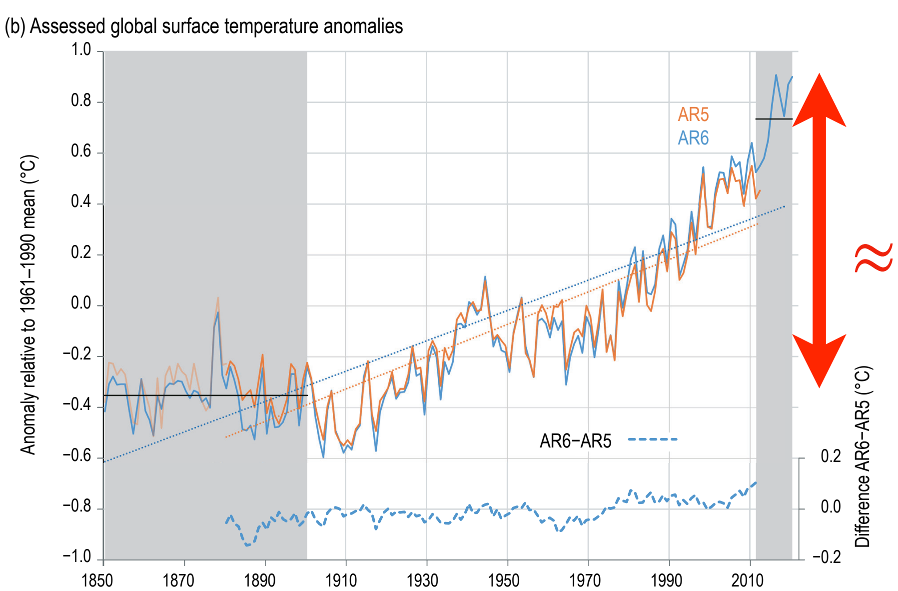
Global-mean surface warming



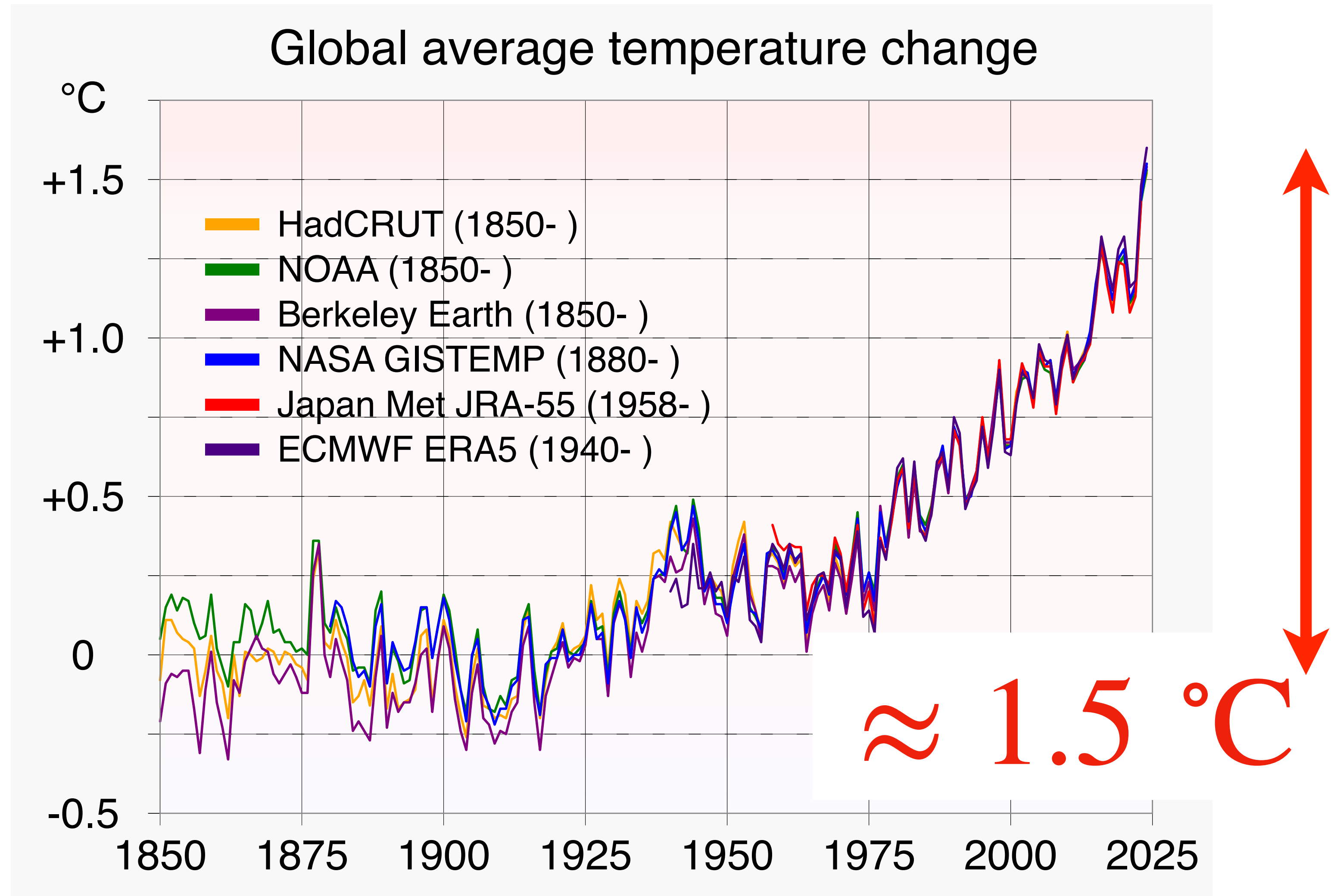
(IPCC AR6, 2022)

Cross-chapter Box 2.3, Figure 1 | Changes in assessed historical surface temperature changes since AR5. (b) Time series of the average of assessed AR5 series (orange, faint prior to 1880 when only HadCRUT4 was available) and AR6 assessed series (blue) and their differences (offset) including an illustration of the two trend fitting metrics used in AR5 and AR6. Further details on data sources and processing are available in the chapter data table (Table 2.SM.1).

Global-mean surface warming since last IPC report



≈ 1.2 °C



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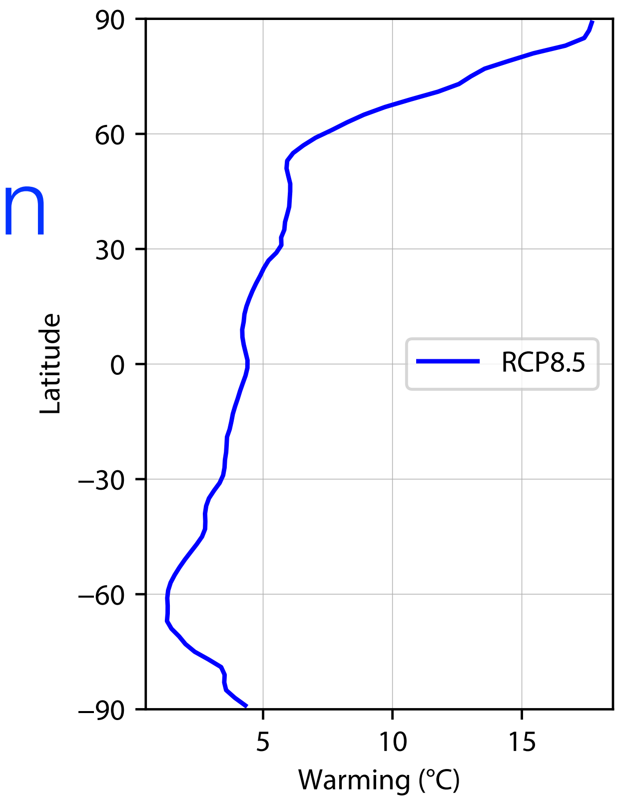
Main issues for today

- Polar amplification



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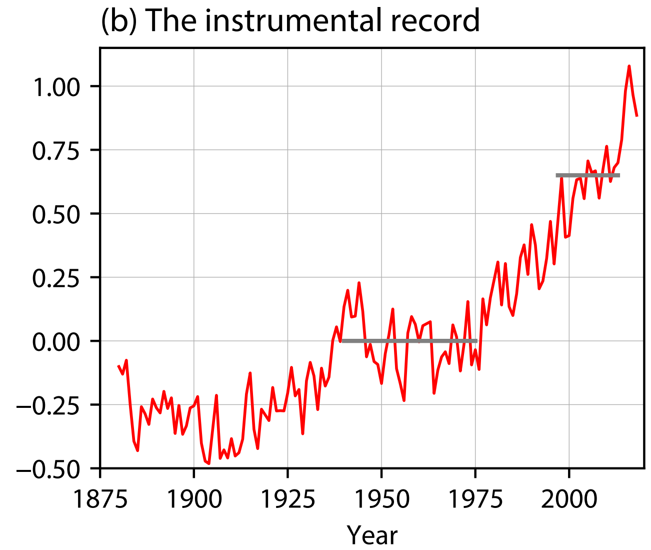
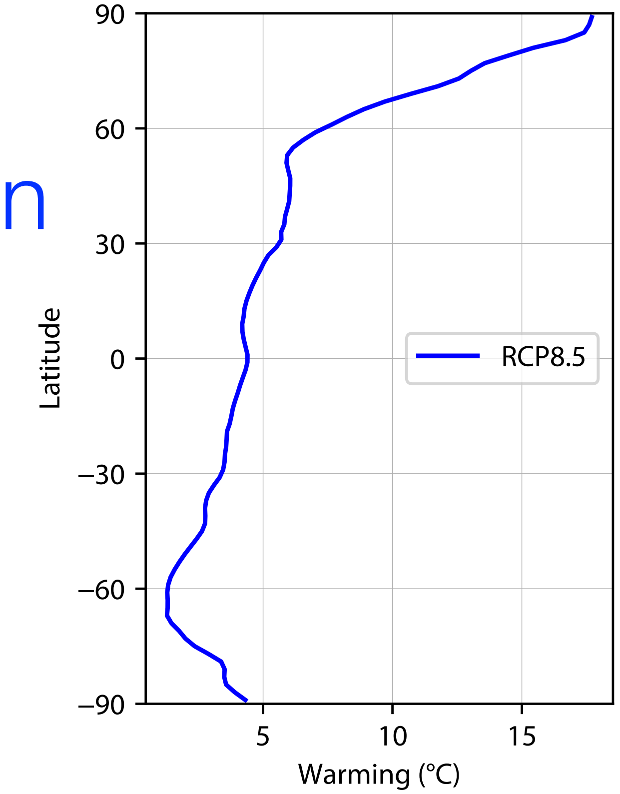
- Polar amplification
- “Hiatus” periods





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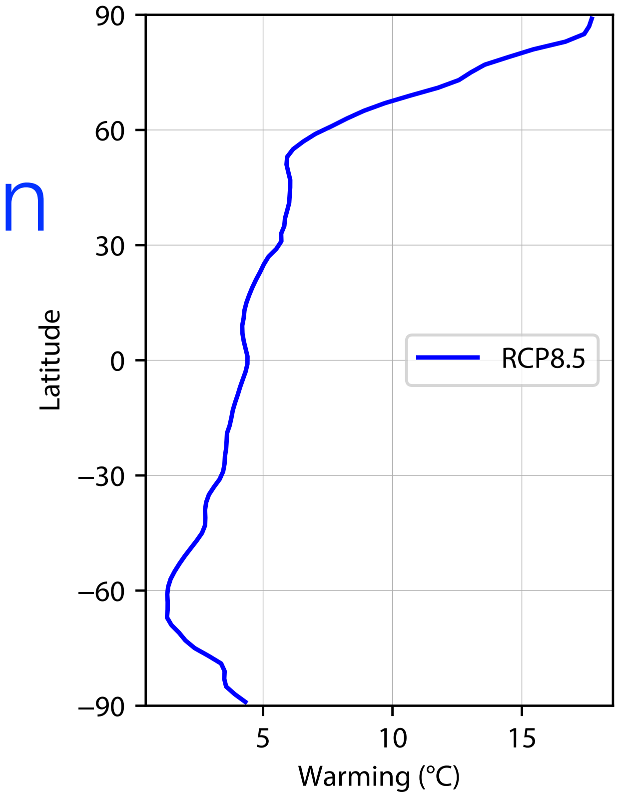
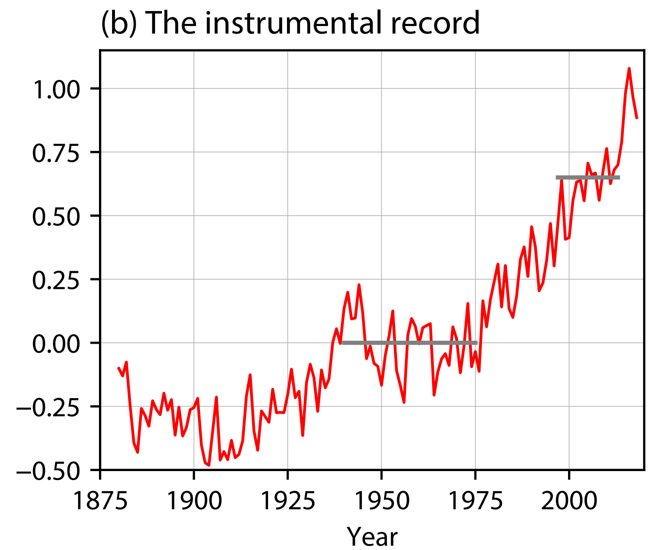
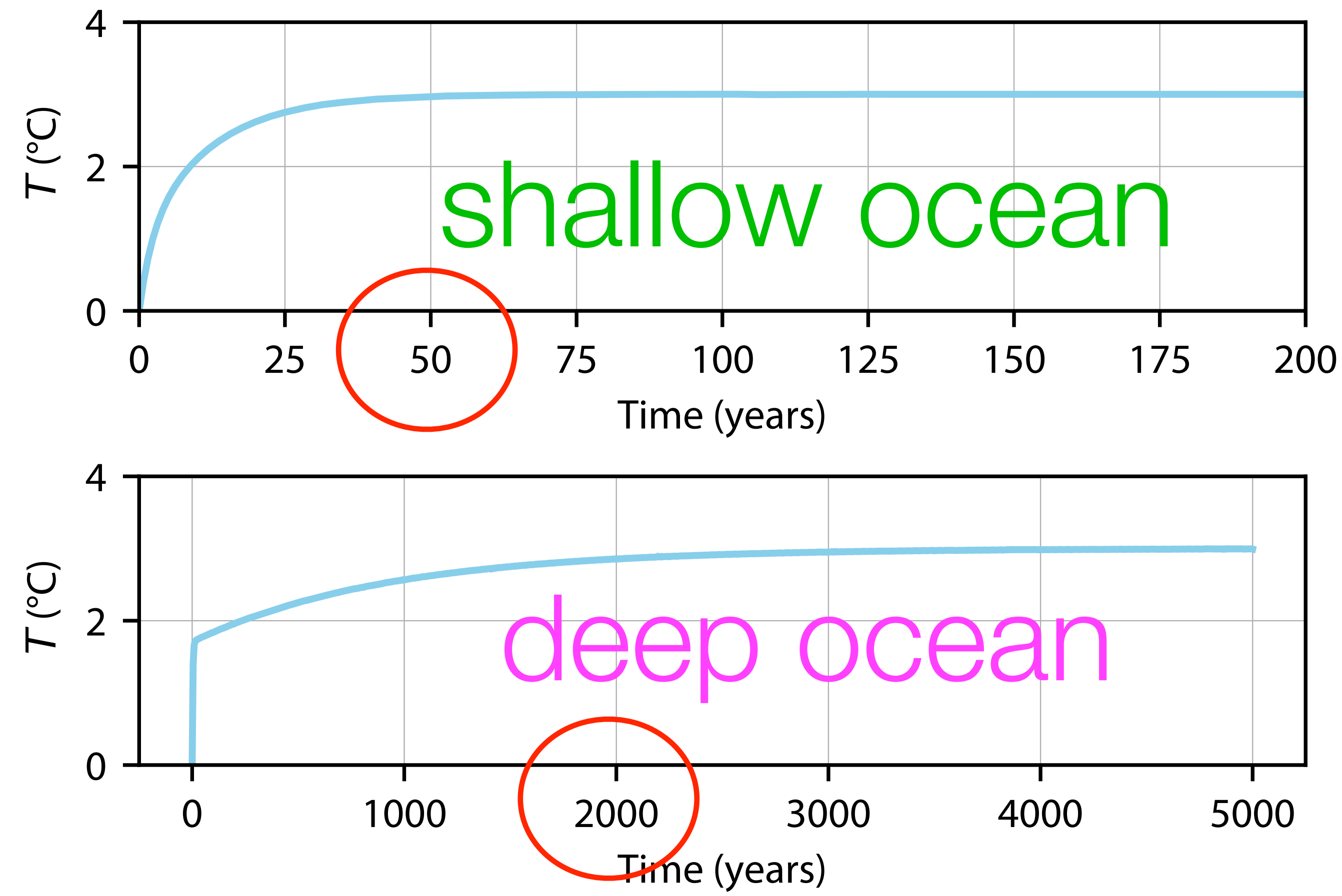


- "Hiatus" periods



- Equilibrium climate sensitivity: total warming for double CO_2 vs Delaying effect of ocean heat capacity (transient sensitivity)



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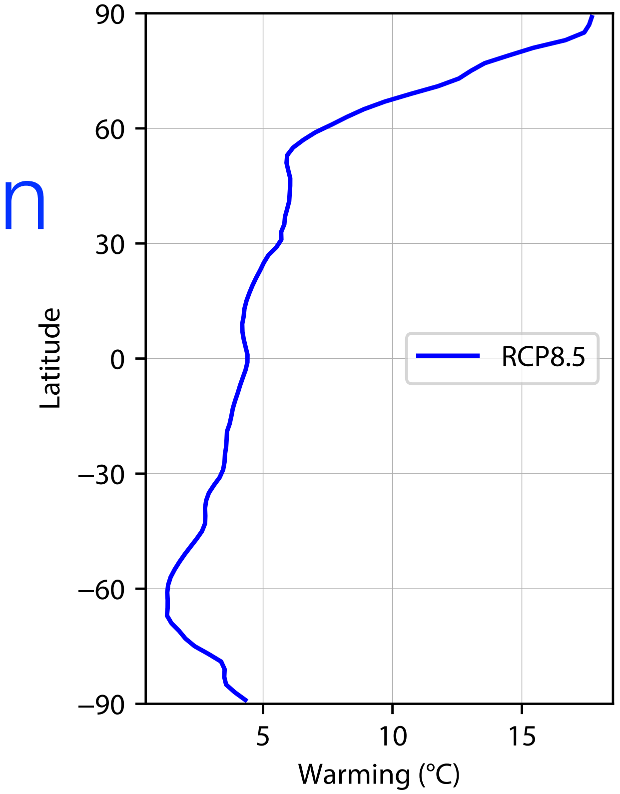

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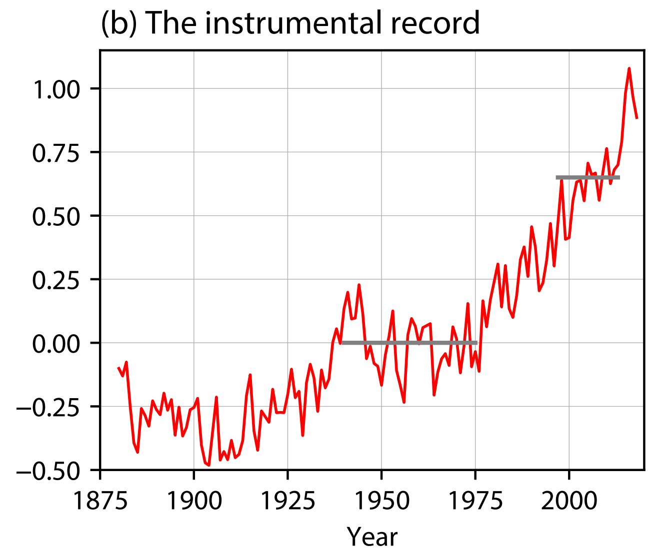

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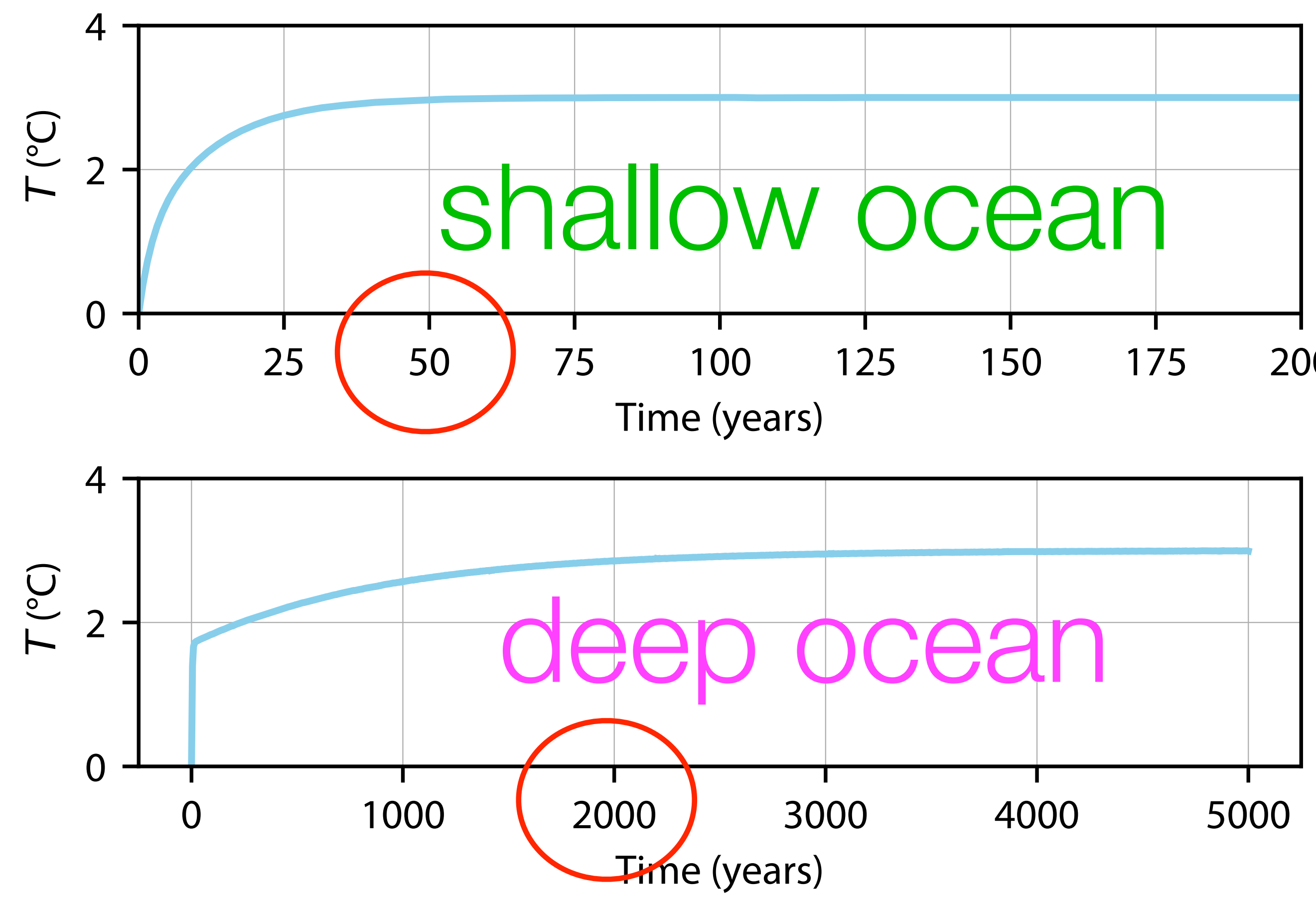
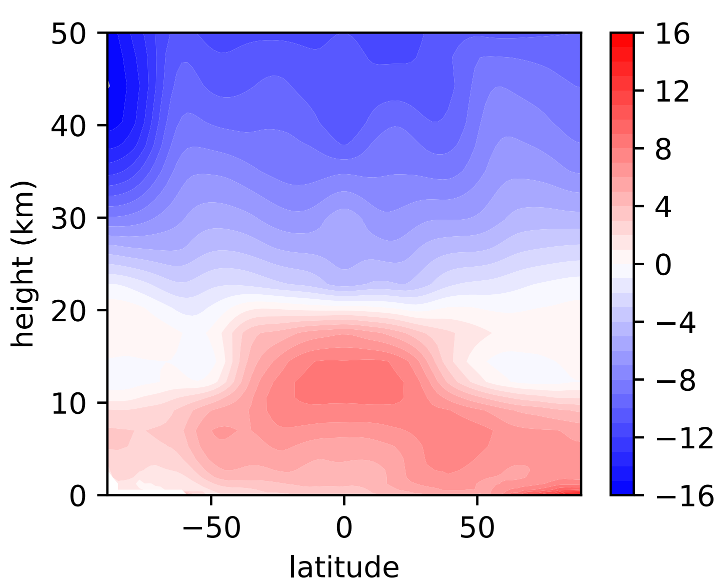


- Stratospheric cooling



Warming over Land vs. Ocean, the recent acceleration

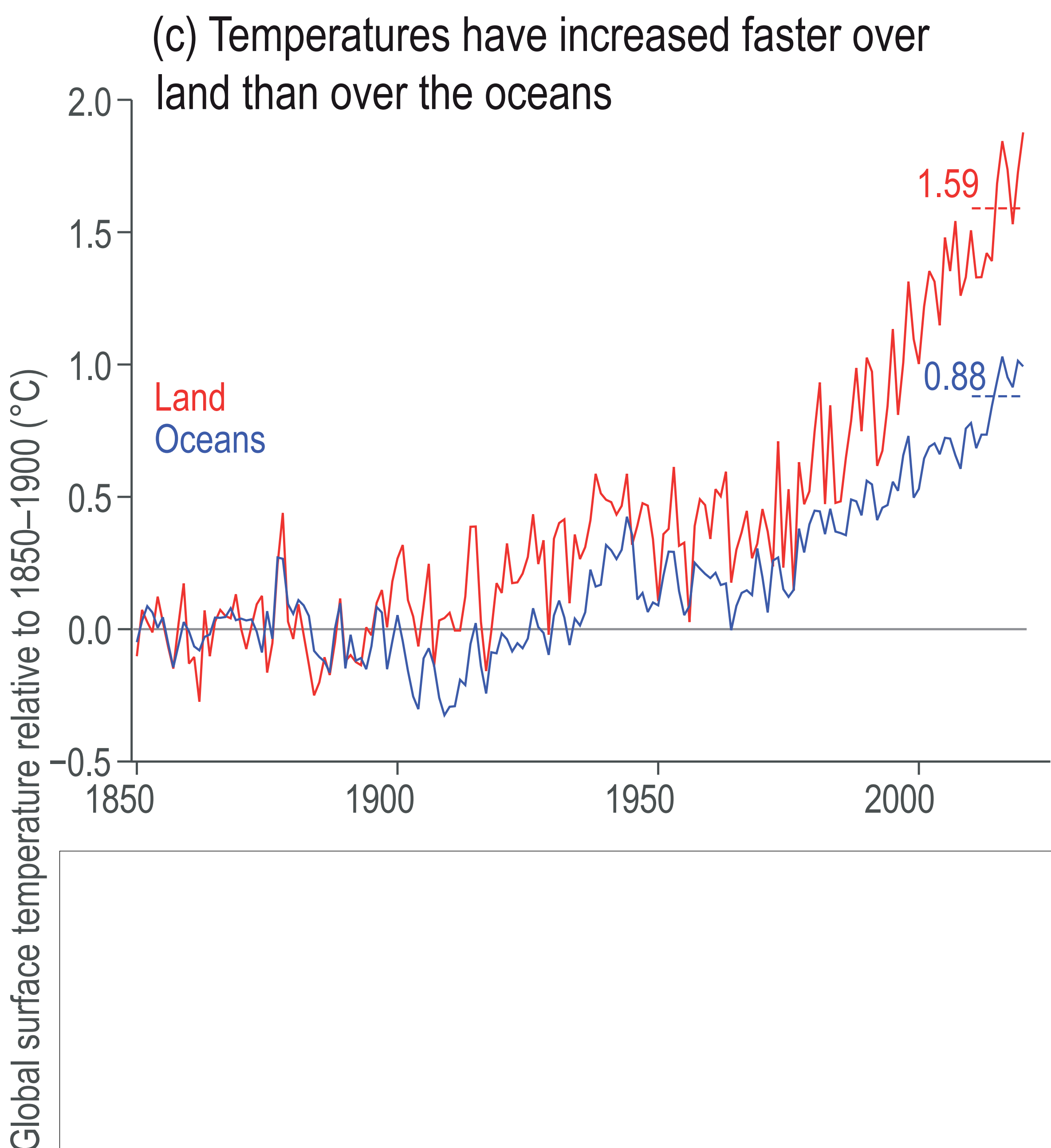


Figure 2.11 | Earth's surface temperature history with key findings annotated within each panel. (c) Temperature from instrumental data for 1850–2020, including (upper panel) multi-product mean annual time series for temperature over the oceans (blue line) and over land (red) and indicating the warming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

(IPCC AR6, 2022)

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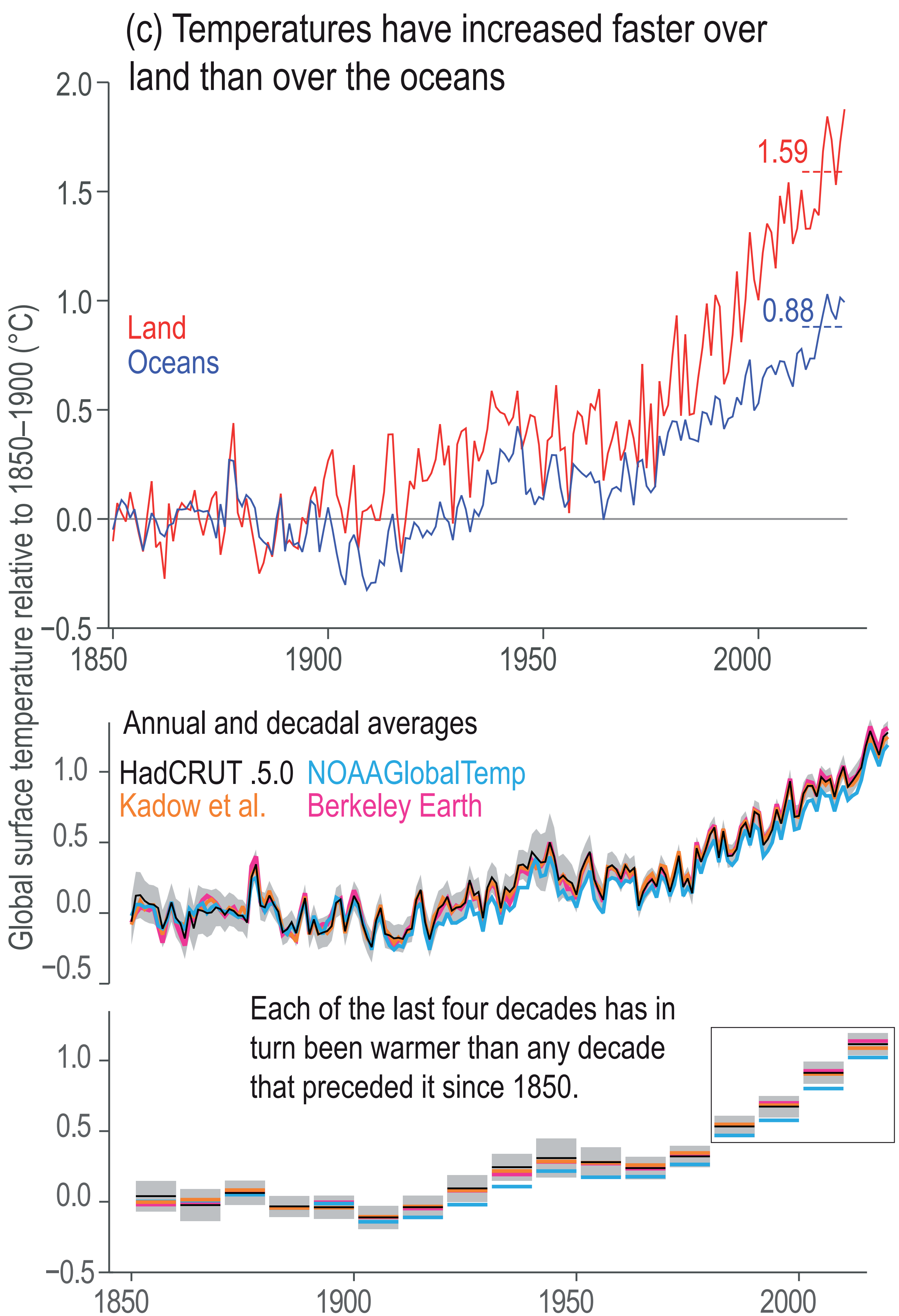

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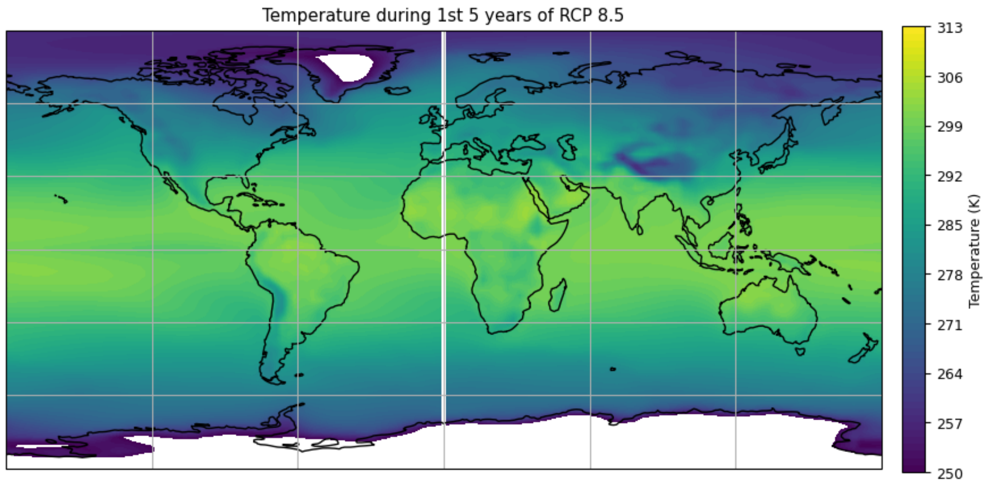
Annually (middle panel) and decadally (bottom panel) resolved averages for the GMST datasets. The grey shading shows the uncertainty associated with the HadCRUT5 estimate (Morice et al., 2021). All temperatures relative to the 1850–1900 period.

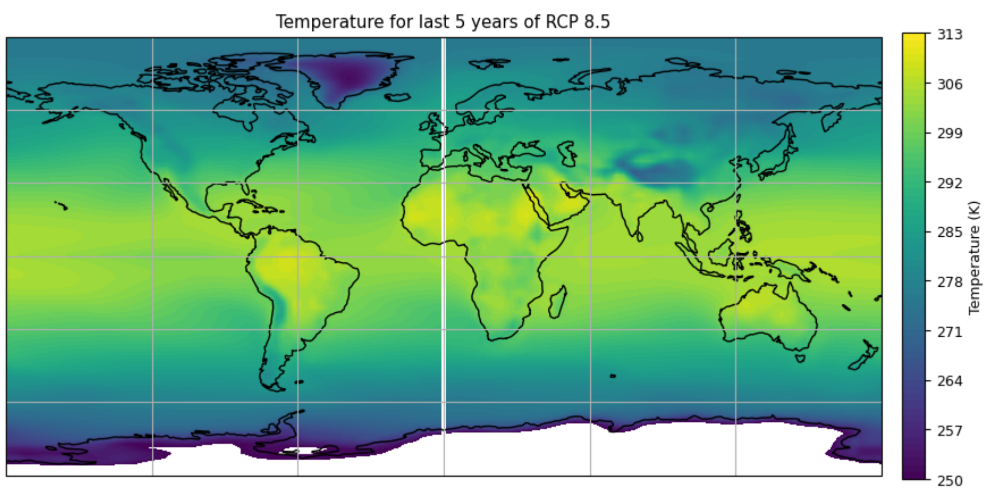
acceleration in warming during past decades

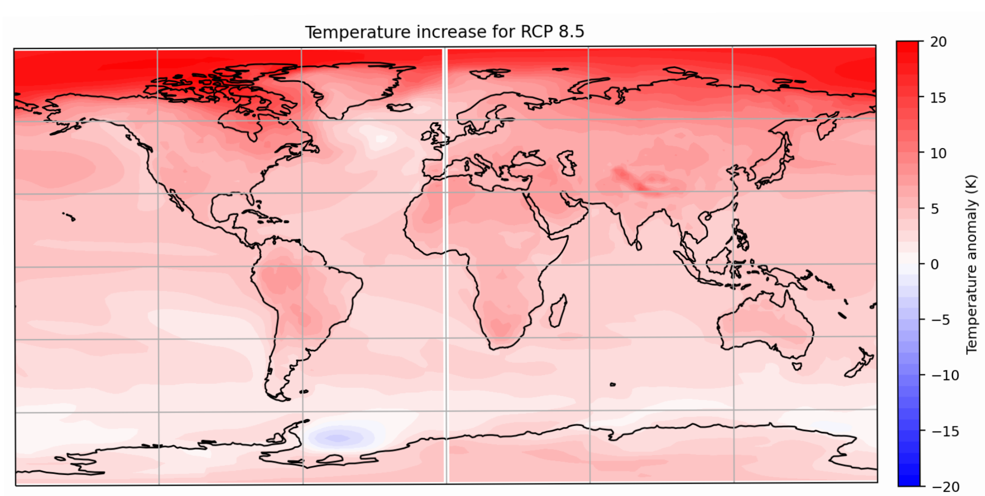
(IPCC AR6, 2022)

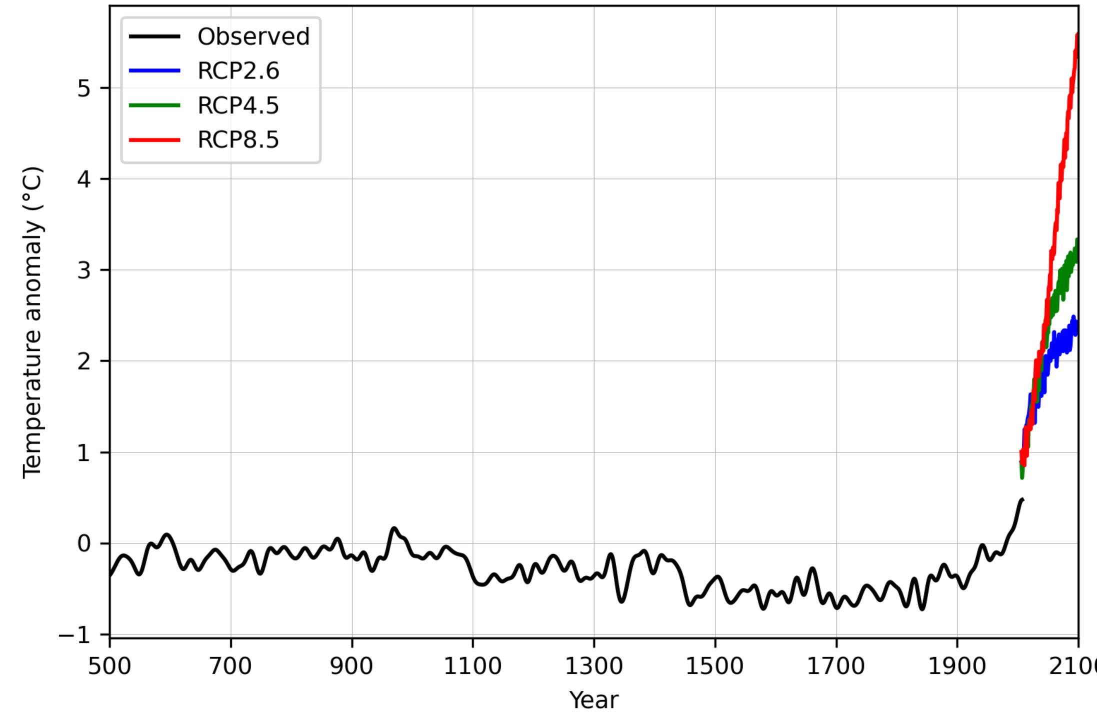
Workshop 1 a, b (leave c for HW) characterizing the warming in space and time, historical and future projections

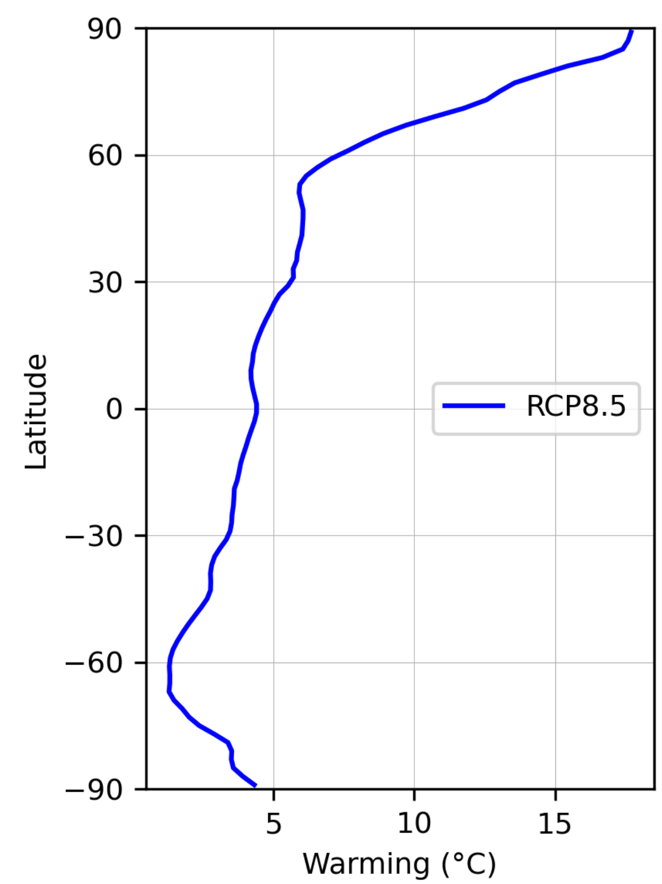
Workshop 1 results







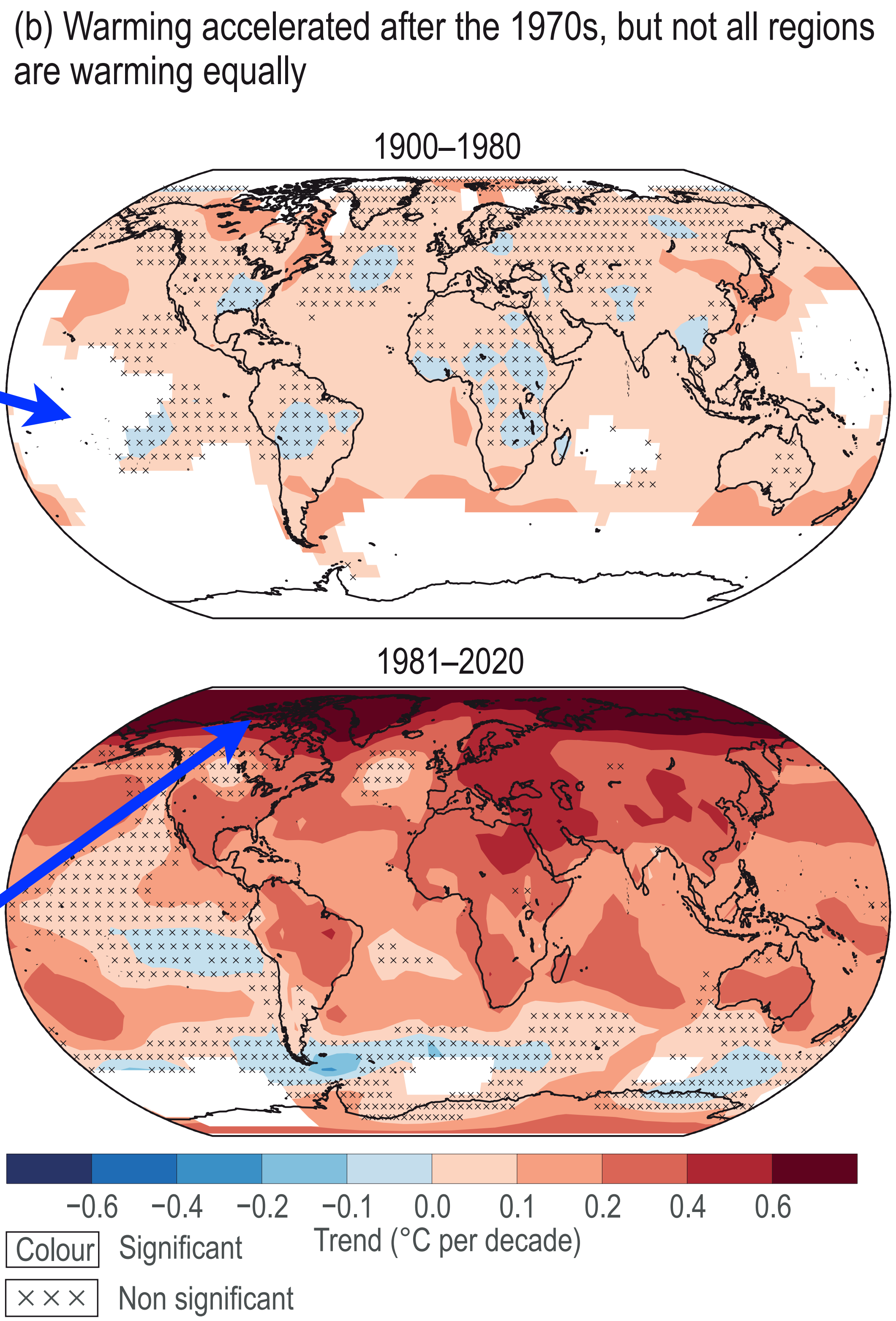




Surface warming trends (°C/decade) 1900–1980 & 1980–2020

uncertainty…

polar amplification…



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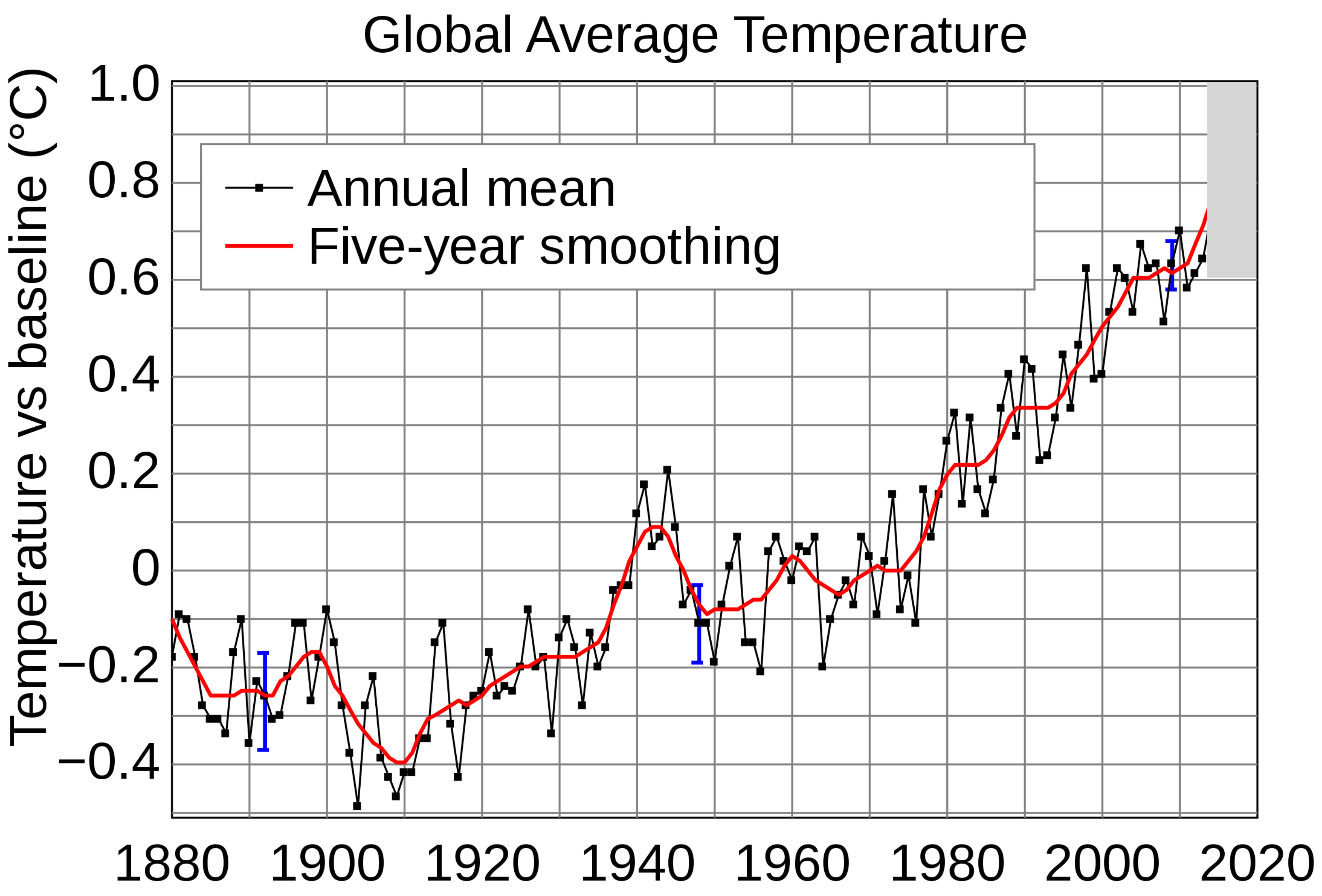
(IPCC AR6, 2022)

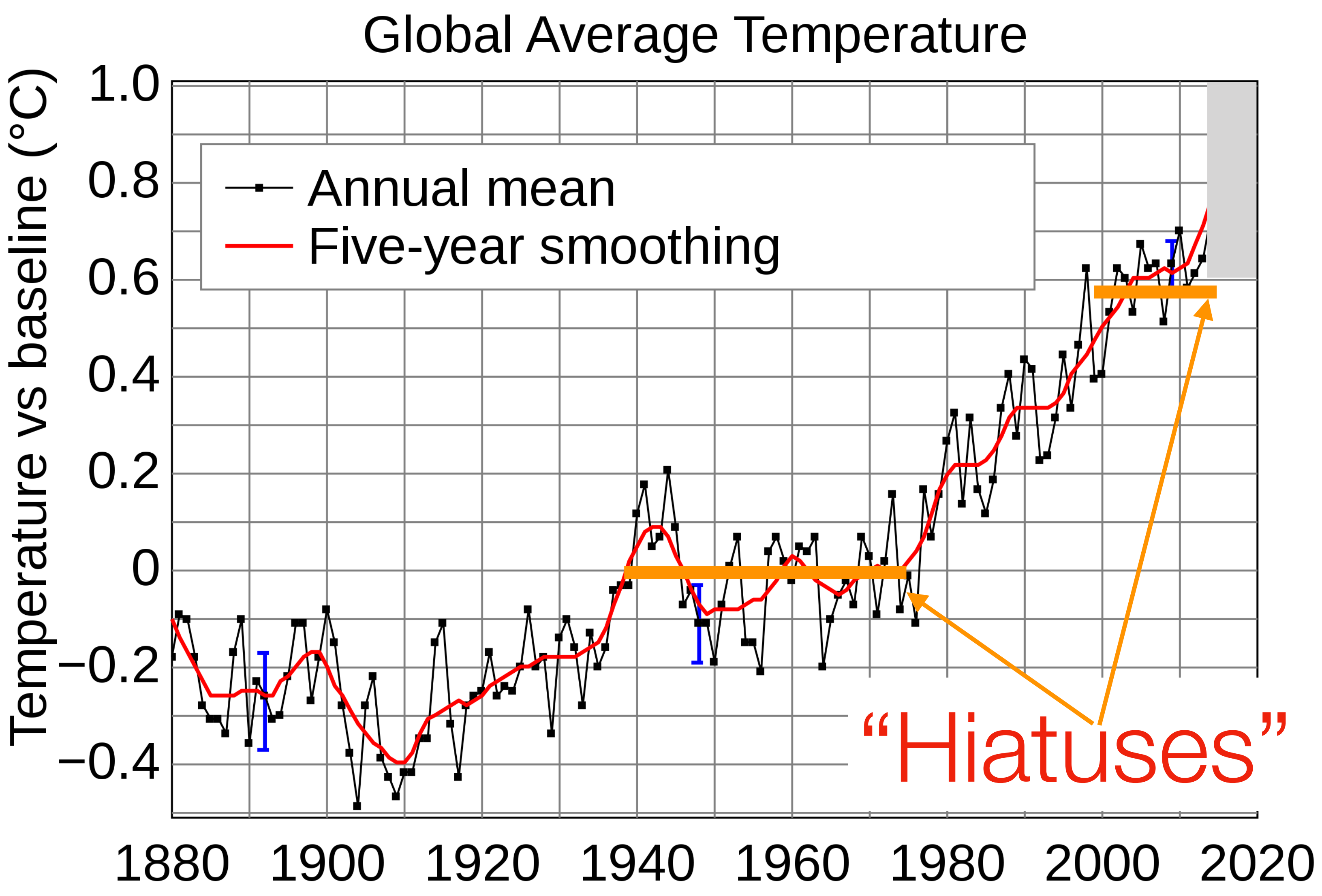
Global warming hiatus?

Global warming hiatus



https://en.wikipedia.org/wiki/Global_temperature_record

Global warming hiatus



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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.

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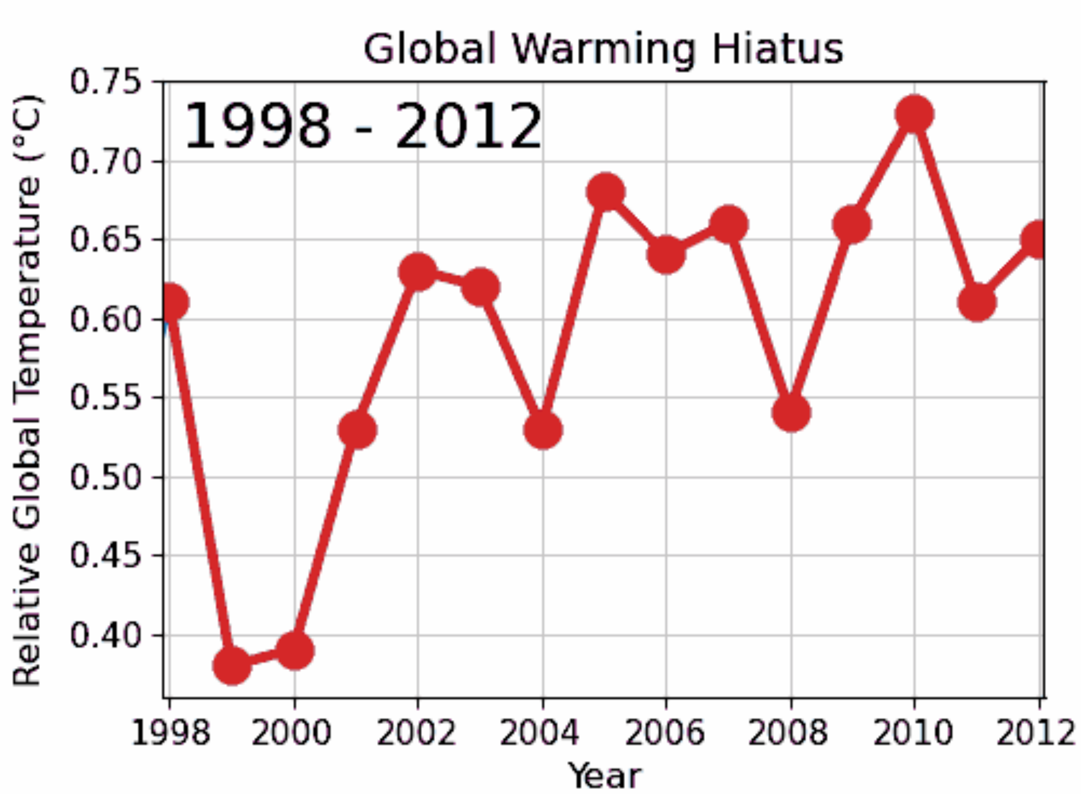

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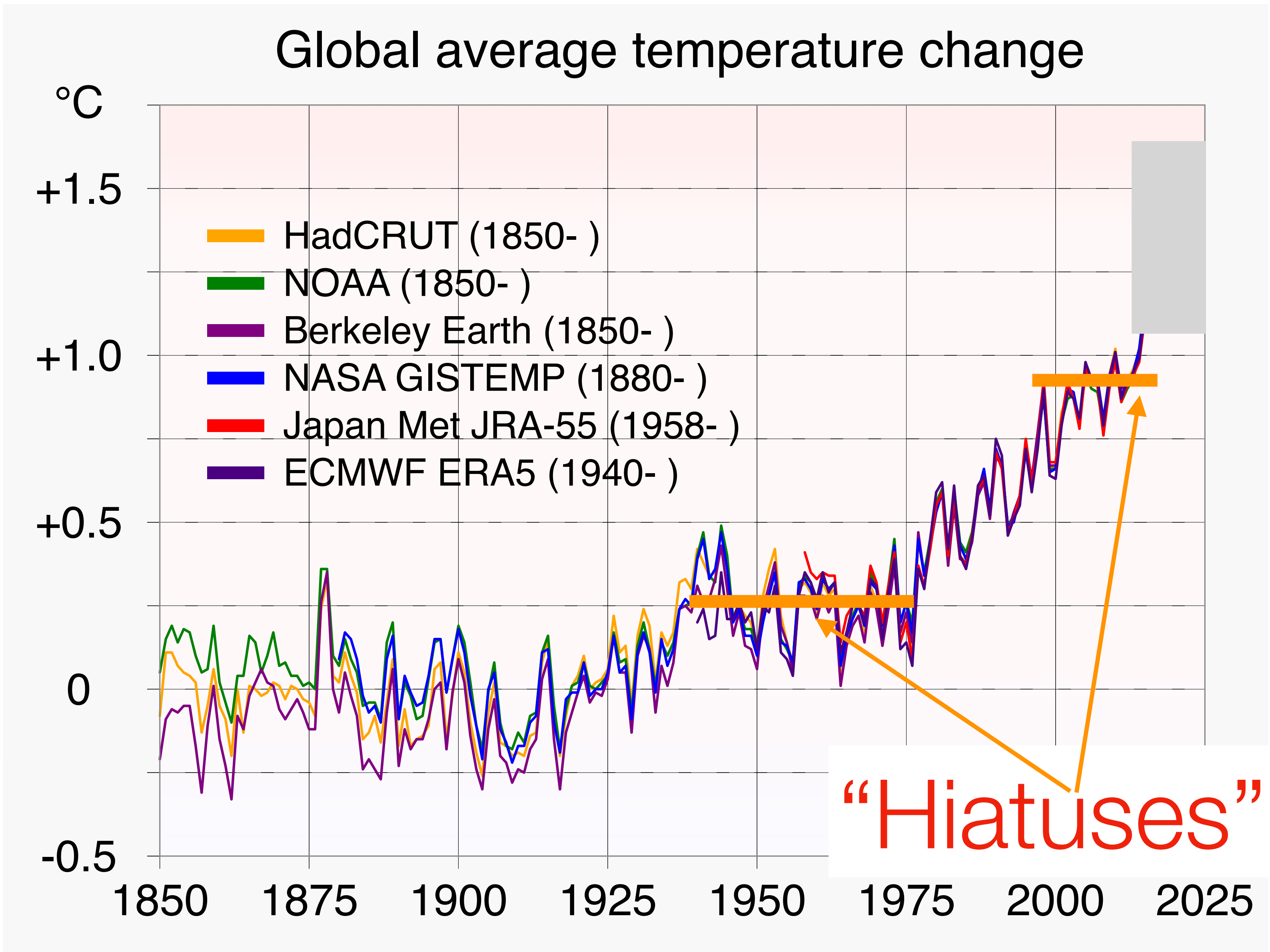

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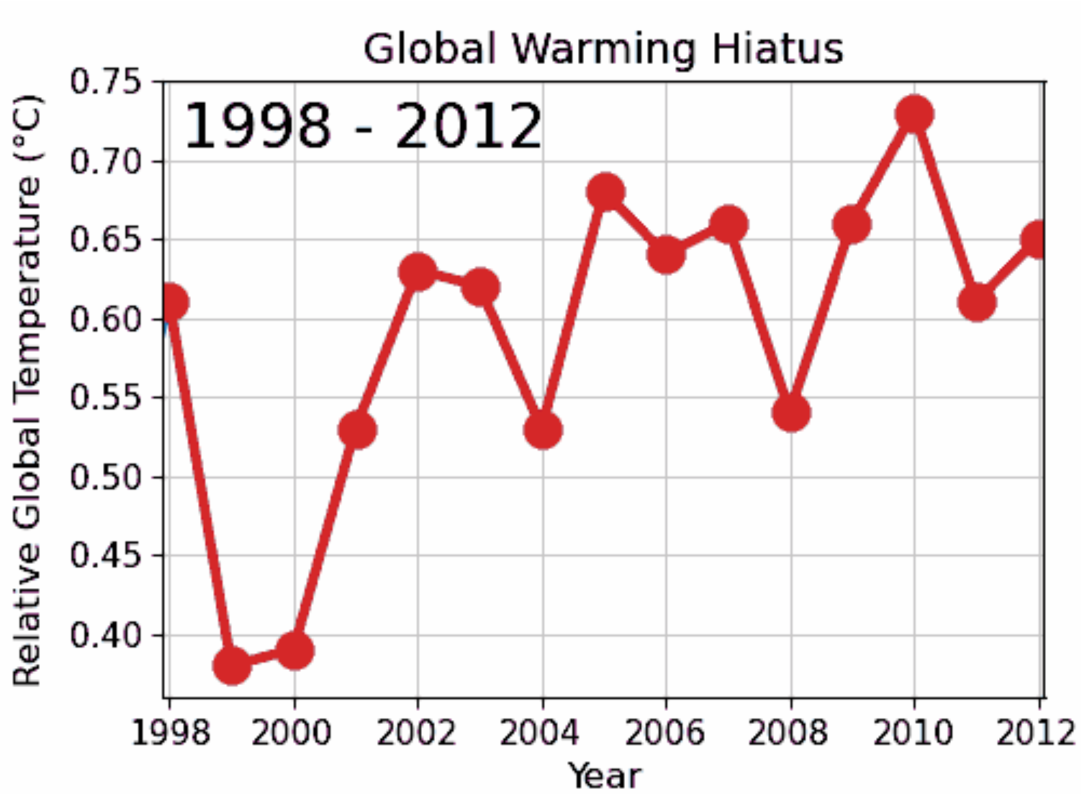

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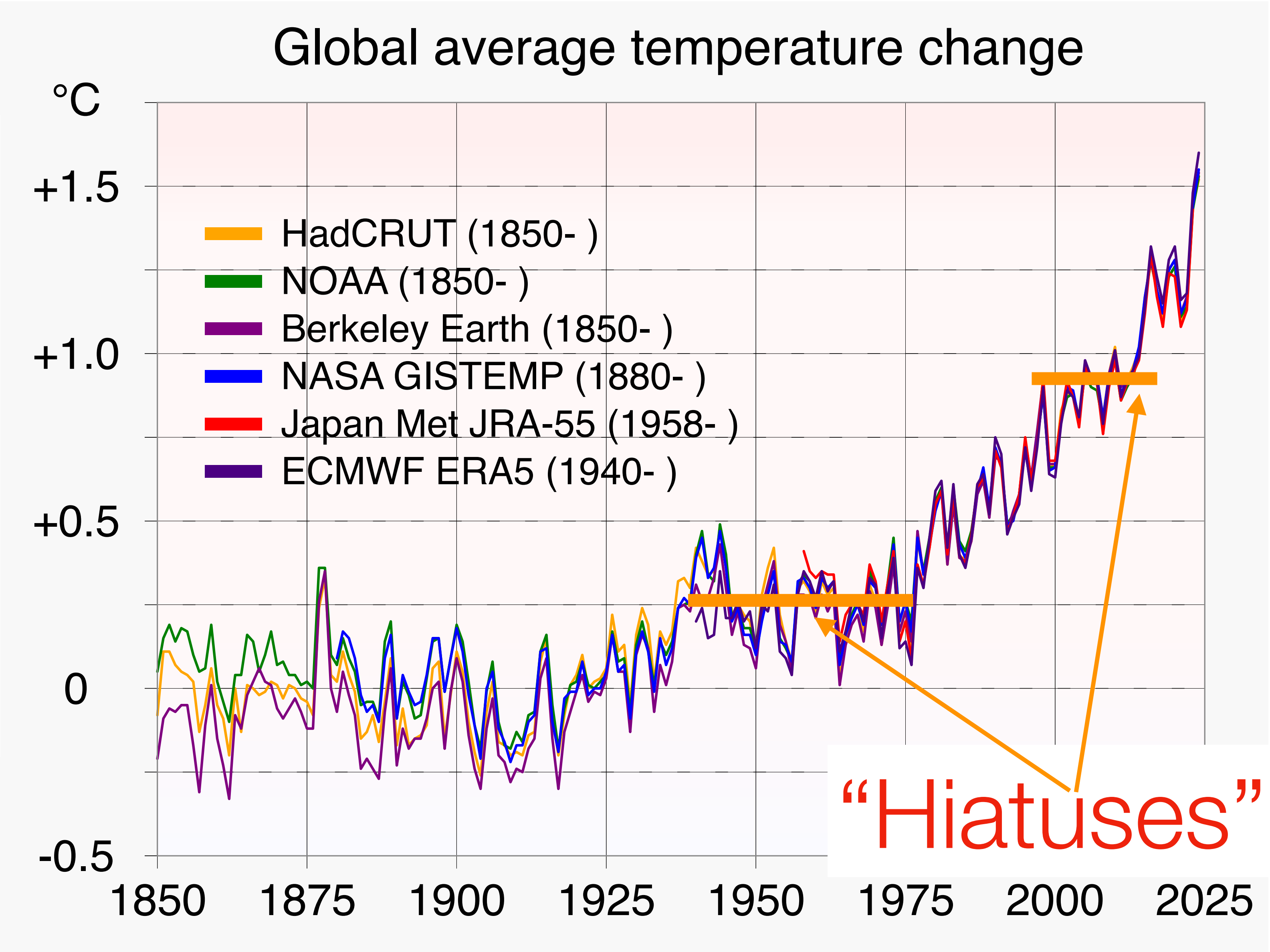

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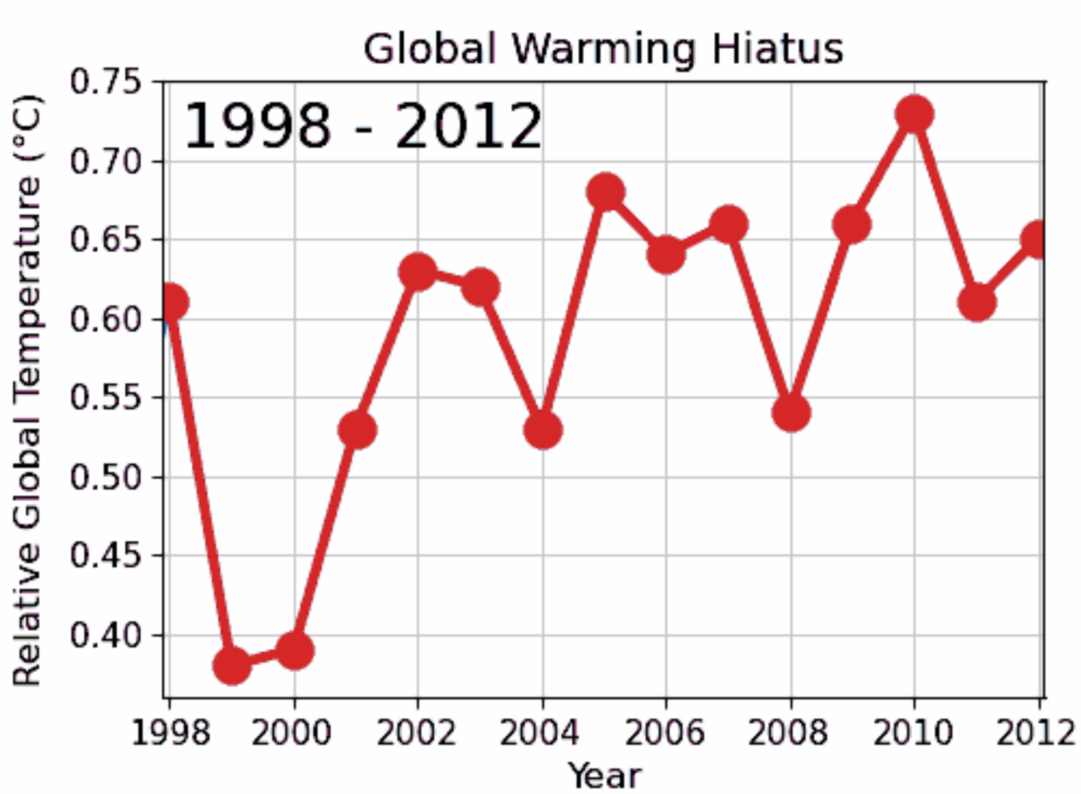

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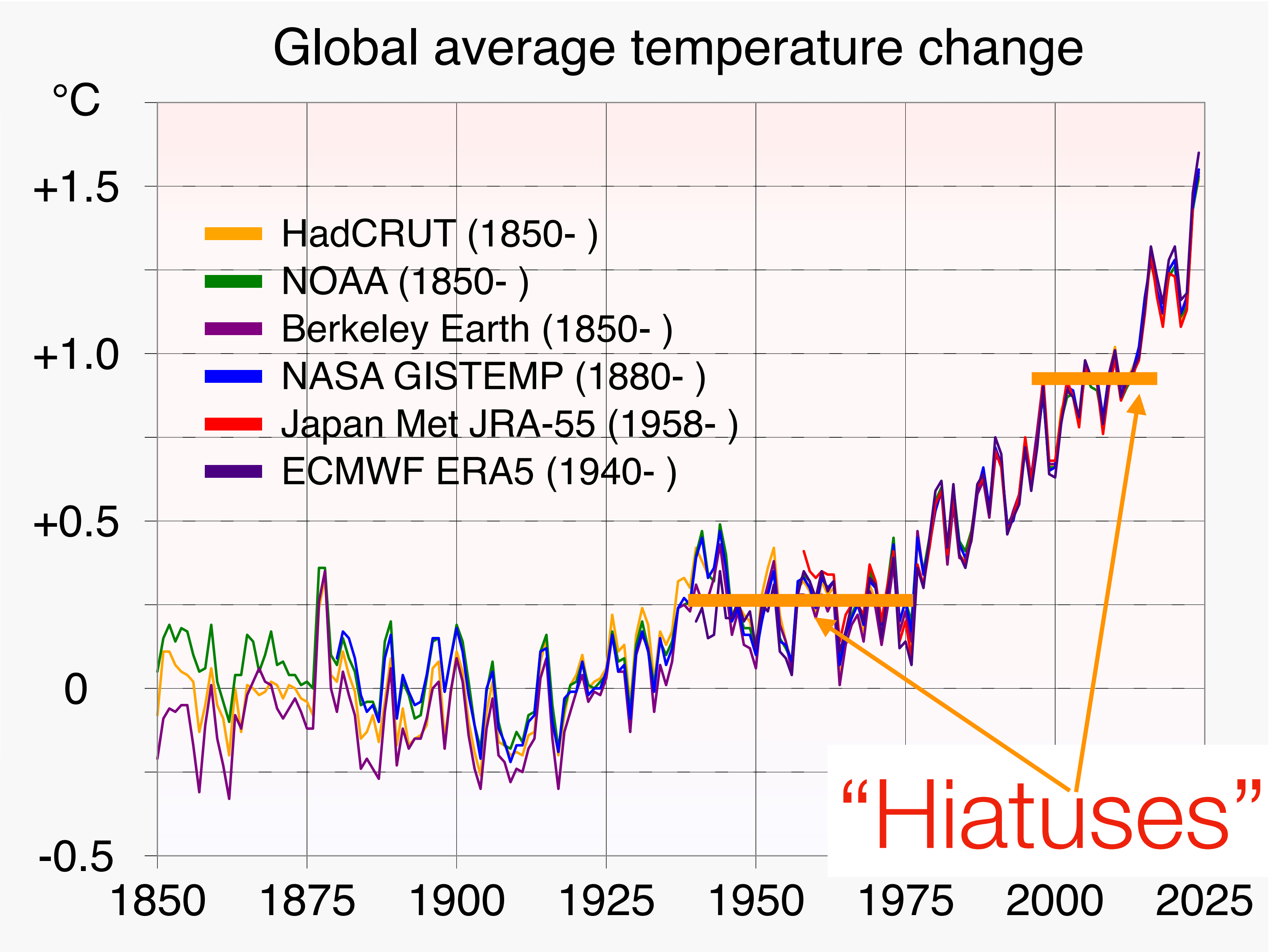

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workshop 2a (leave b for HW)
global warming “hiatus” periods

workshop 2 results

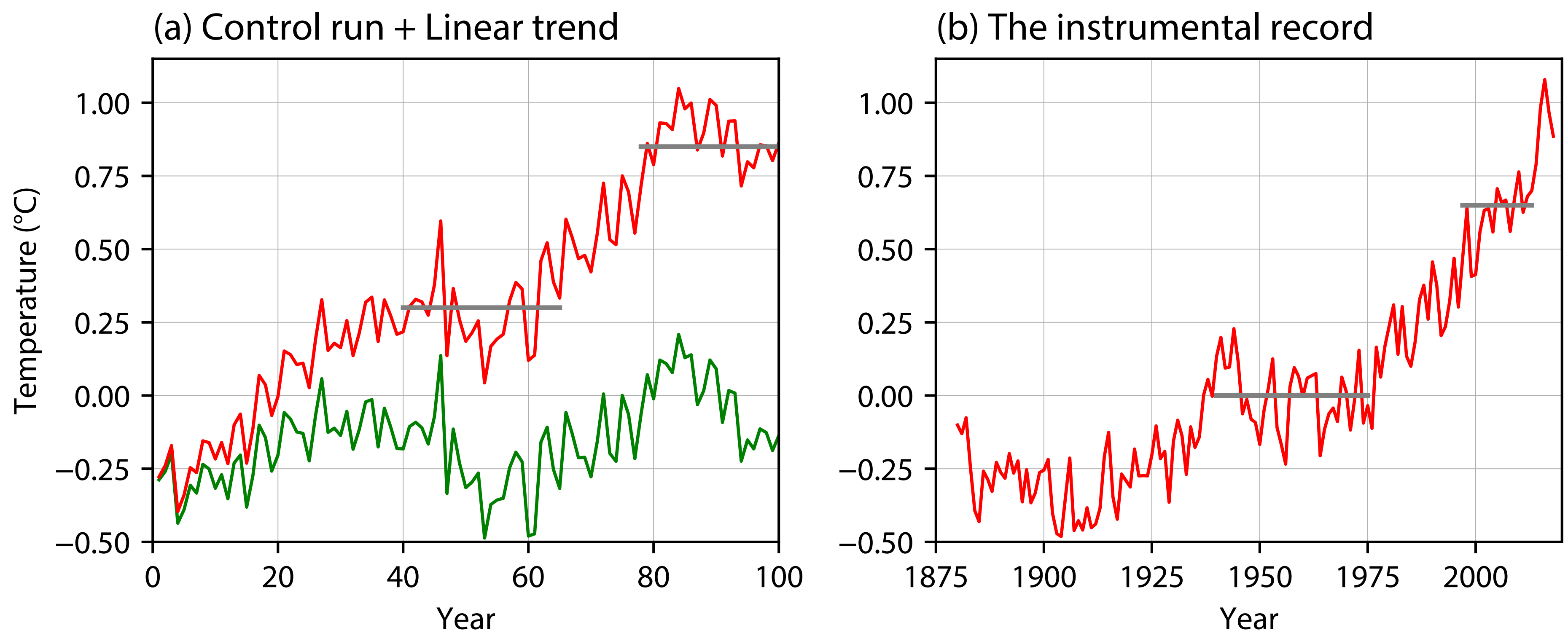
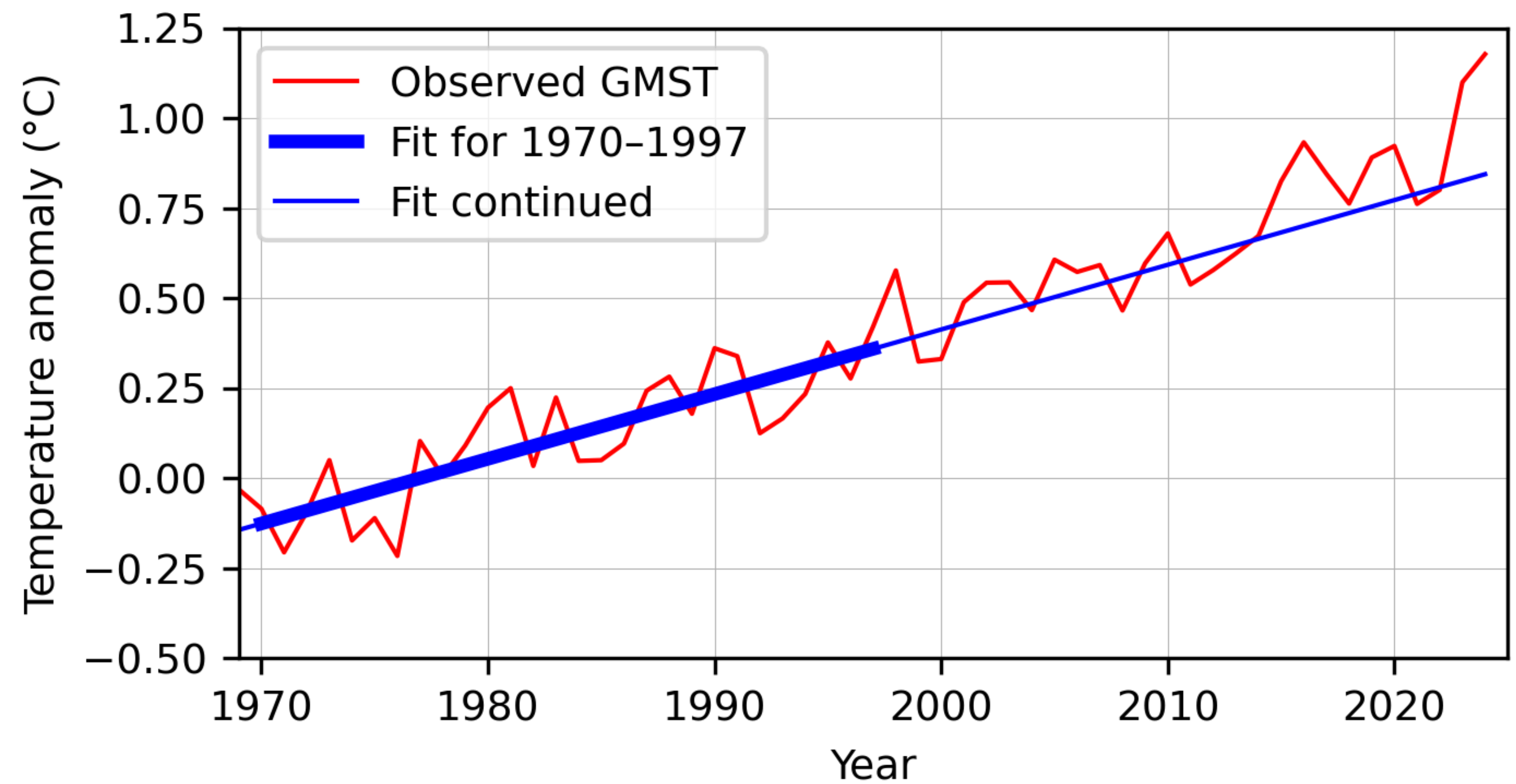
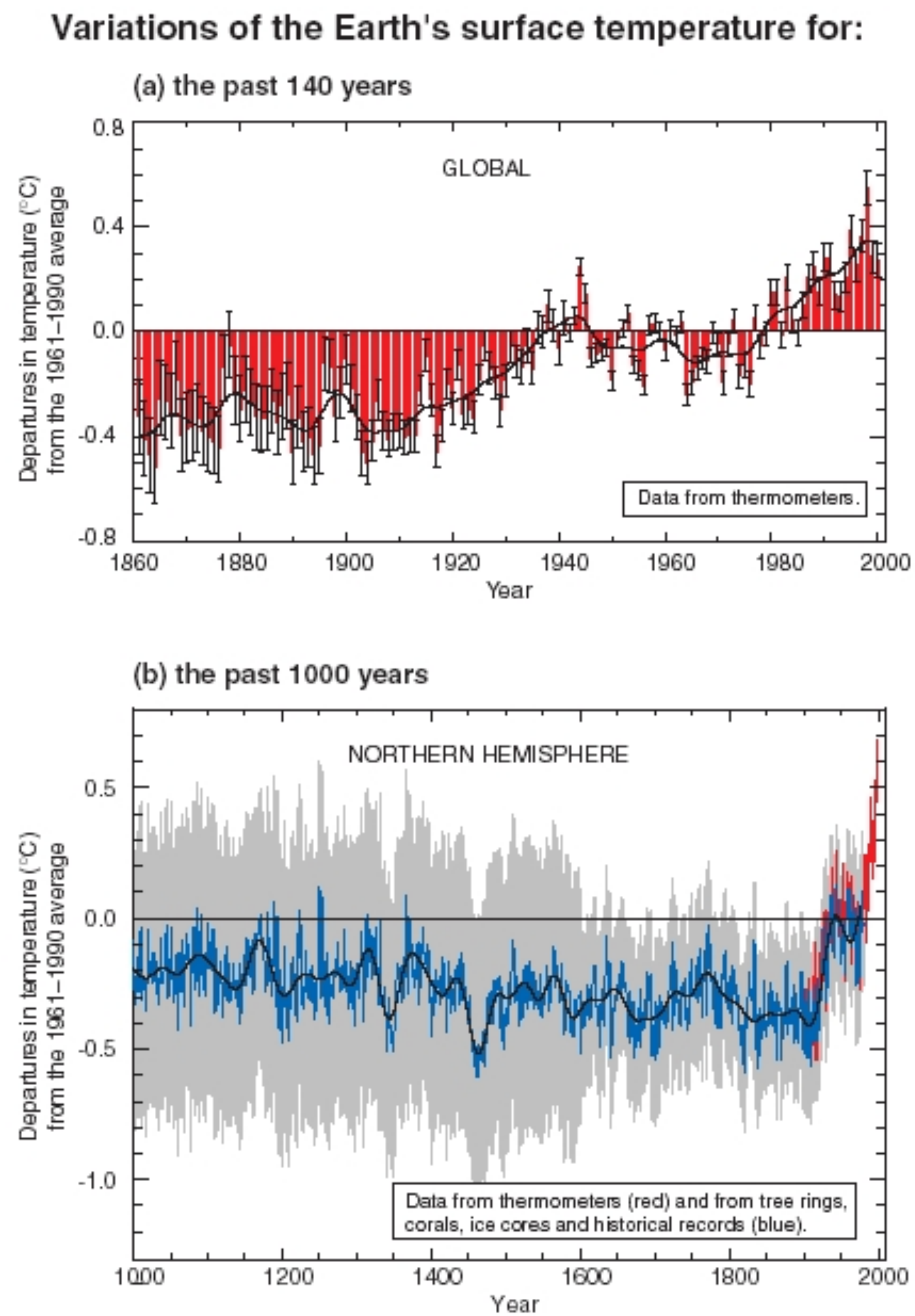


Figure 3.7: ``Hiatus'' periods. (a) Globally averaged surface temperature anomaly from a control (CO_2 fixed at preindustrial concentration) run of a climate model (green), and the same temperature record with a linear trend added (red). (b) The instrumental record of globally averaged surface temperature anomaly. Both panels show "hiatus" periods marked by gray horizontal bars.



global warming hiatus: a presidential perspective



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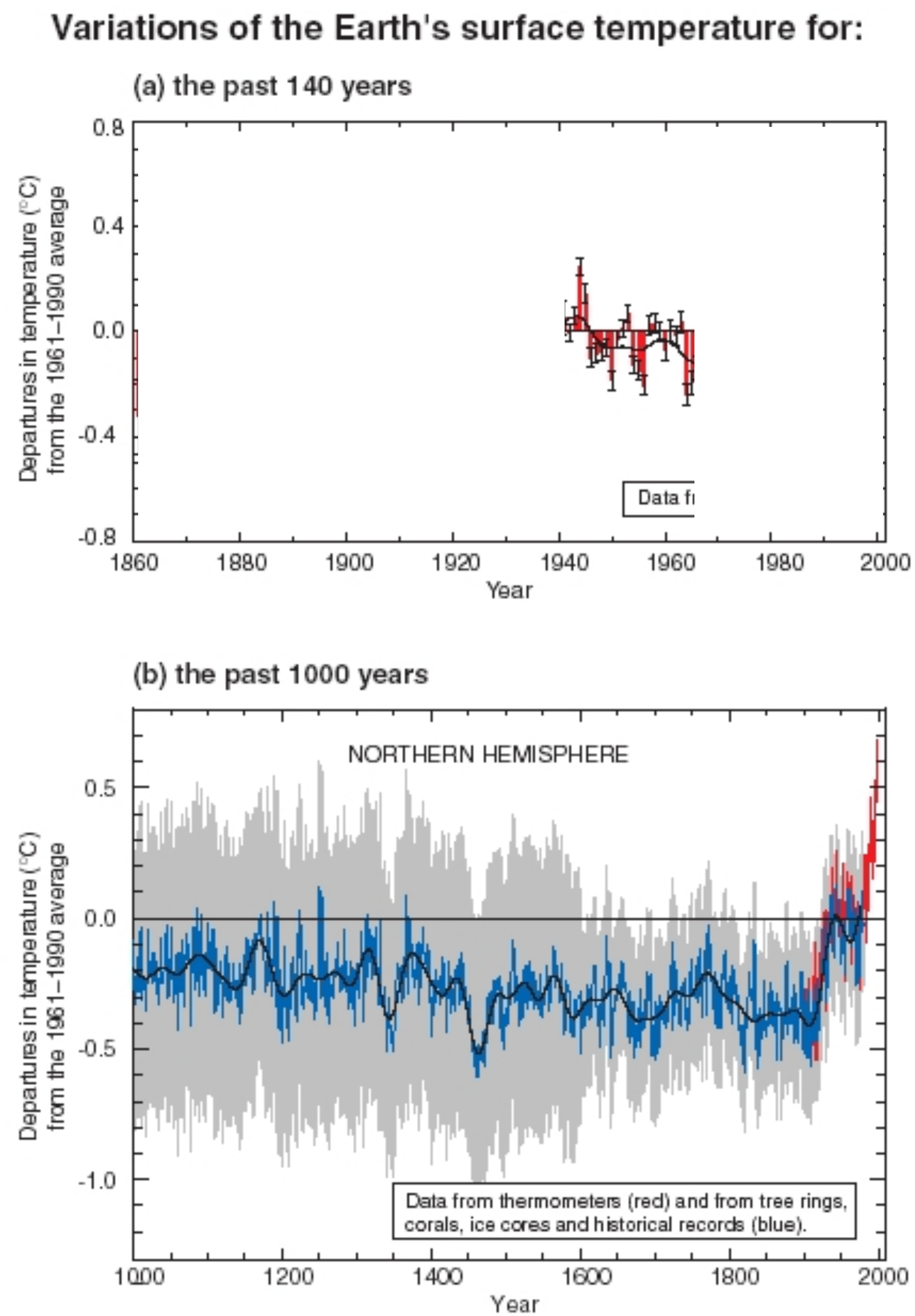

DEPARTMENT OF GEOLOGICAL SCIENCES
(401) 863-2240

B. M. NIXON

December 3, 1972

global warming hiatus

The President
The White House
Washington, D. C.

Dear Mr. President:

Aware of your deep concern with the future of the world, we feel obliged to inform you on the results of the scientific conference held here recently. The conference dealt with the past and future changes of climate and was attended by 42 top American and European investigators. We enclose the summary report published in Science and further publications are forthcoming in Quaternary Research.

The main conclusion of the meeting was that a global deterioration of climate, by order of magnitude larger than any hitherto experienced by civilized mankind, is a very real possibility and indeed may be due very soon. The cooling has natural cause and falls within the rank of processes which produced the last ice age. This is a surprising result based largely on recent studies of deep sea sediments.

global warming hiatus

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Existing data still do not allow forecast of the precise timing of the predicted development, nor the assessment of the man's interference with the natural trends. It could not be excluded however that the cooling now under way in the Northern Hemisphere is the start of the expected shift. The present rate of the cooling seems fast enough to bring glacial temperatures in about a century, if continuing at the present pace.

global warming hiatus

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The practical consequences which might be brought by such developments to existing social institutions are among others:

1) Substantially lowered food production due to the shorter growing seasons and changed rain distribution in the main grain producing belts of the world, with Eastern Europe and Central Asia to be first affected.

2) Increased frequency and amplitude of extreme weather anomalies such as those bringing floods, snowstorms, killing frosts etc.

global warming hiatus

Mr. President — 2 — December 3, 1972

With the efficient help of the world leaders, the research could be effectively organized and could possibly find the answers to the menace. We hope that your Administration will take decisive steps in this direction as it did with other serious international problems in the past. Meantime however it seems reasonable to prepare the agriculture and industry for possible alternatives and to form reserves.

global warming hiatus

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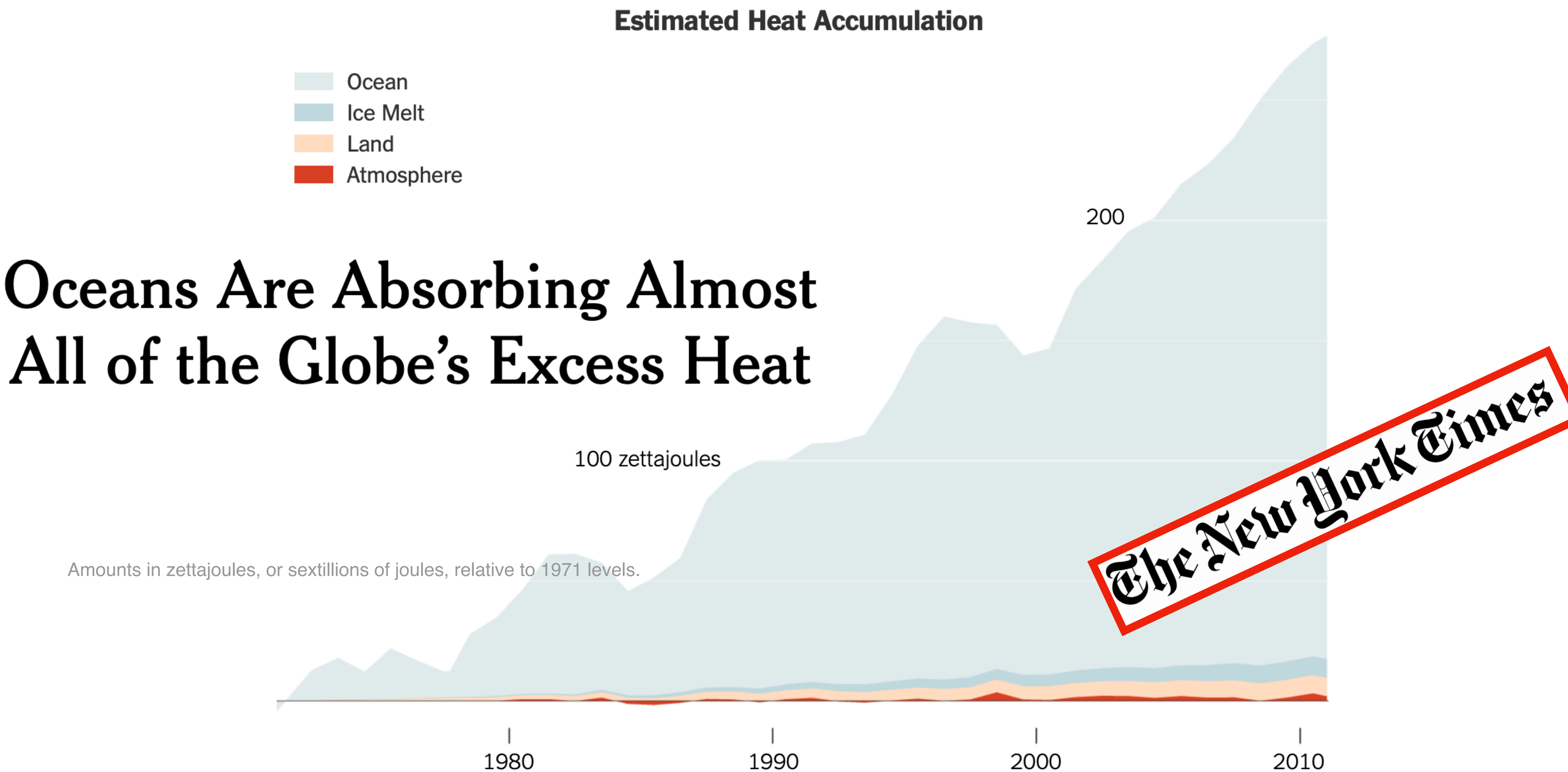
It might also be useful for Administration to take into account that the Soviet Union, with large scientific teams monitoring the climate change in Arctic and Siberia, may already be considering these aspects in its international moves.

With best regards,

The ocean is absorbing all that heat, what would have happened otherwise?
(Equilibrium vs transient climate sensitivity)

The ocean is absorbing all that heat, what would have happened otherwise?



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**."

The ocean is absorbing all that heat, what would have happened otherwise?

The New York Times

Oceans Are Absorbing Almost All of the Globe's Excess Heat

Agence France-Presse — Getty Images

Bruno C. Vellutini

Marine Species Are at Risk
Warmer temperatures are threatening some marine animal and plant species, like these bleached coral on the Great Barrier Reef. Scientists also predict that some birds, like the black-legged kittiwakes in Norway, may soon die off in warmer waters.

Habitats Are Changing
The warmer conditions have allowed some jellyfish, like the comb jellyfish, pictured above, in Narragansett Bay, to have longer seasons. Others have expanded their territory. In some cases, United States fisheries have shifted north to cooler waters.

The ocean is absorbing all that heat, what would have happened otherwise?

The New York Times

Ocean Warming Is Accelerating Faster Than Thought, New Research Finds

As the planet has warmed, the oceans have provided a critical buffer. They have slowed the effects of climate change by absorbing 93 percent of the heat trapped by the greenhouse gases humans pump into the atmosphere.

"If the ocean wasn't absorbing as much heat, the surface of the land would heat up much faster than it is right now … In fact, the ocean is saving us from massive warming right now."

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"If the ocean wasn't absorbing as much heat, the surface of the land would heat up much faster than it is right now … In fact, the ocean is saving us from massive warming right now."

But the surging water temperatures are already killing off marine ecosystems, raising sea levels and making hurricanes more destructive.

"The actual ability of the warm oceans to produce food is much lower, so that means they're going to be more quickly approaching food insecurity,"

Too strong language…?

notes section 3.1.1
Equilibrium climate sensitivity

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

$$\Delta T = 3\log_2(500/280) = 2.5\ ^\circ\mathrm{C}$$

➡ Significantly more than as has been observed (1.5 °C)!

What's going on?

Equilibrium climate sensitivity

The excess heat budget of the upper ocean at present:

$$\Delta Q_{\text{now}} = \Delta F_{\text{now}} - \lambda_{LW} \Delta T_{\text{now}}.$$

In words: excess heat flux into ocean=radiative forcing–TOA OLR

And at equilibrium after doubling of CO_2: $0 = \Delta F_{2\times} - \lambda_{LW} \Delta T_{2\times}$

From which we deduce:

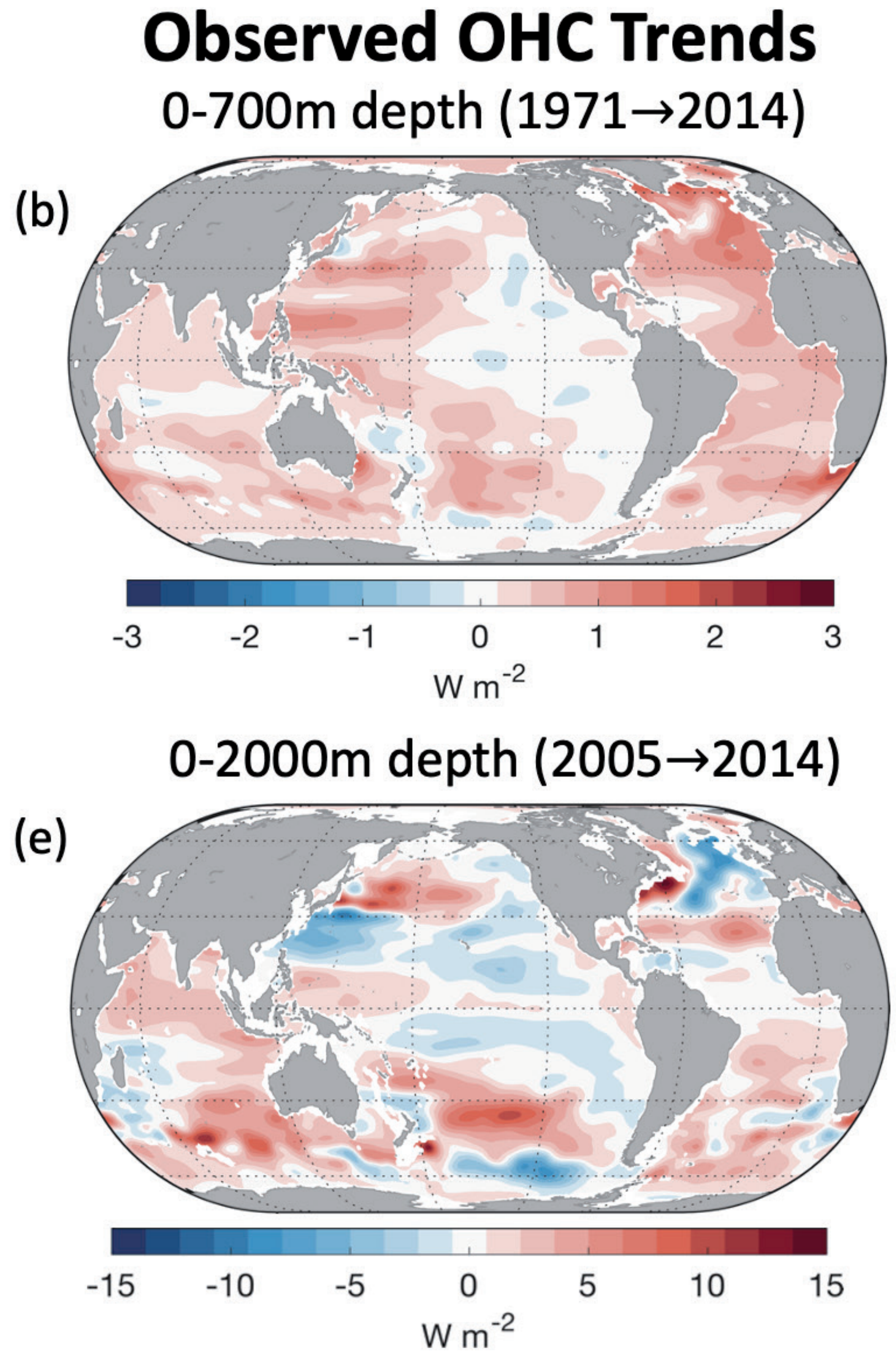
$$\Delta T_{2\times} = \frac{\Delta F_{2\times}}{\lambda_{LW}} \qquad \lambda_{LW} = \frac{\Delta F_{\text{now}} - \Delta Q_{\text{now}}}{\Delta T_{\text{now}}},$$

Leading to our final result for the equilibrium doubling in terms of observed quantities

$$\Delta T_{2\times} = \frac{\Delta F_{2\times} \Delta T_{\text{now}}}{\Delta F_{\text{now}} - \Delta Q_{\text{now}}}.$$

Bottom line: roughly 3 °C, consistent with everything else

Ocean warming



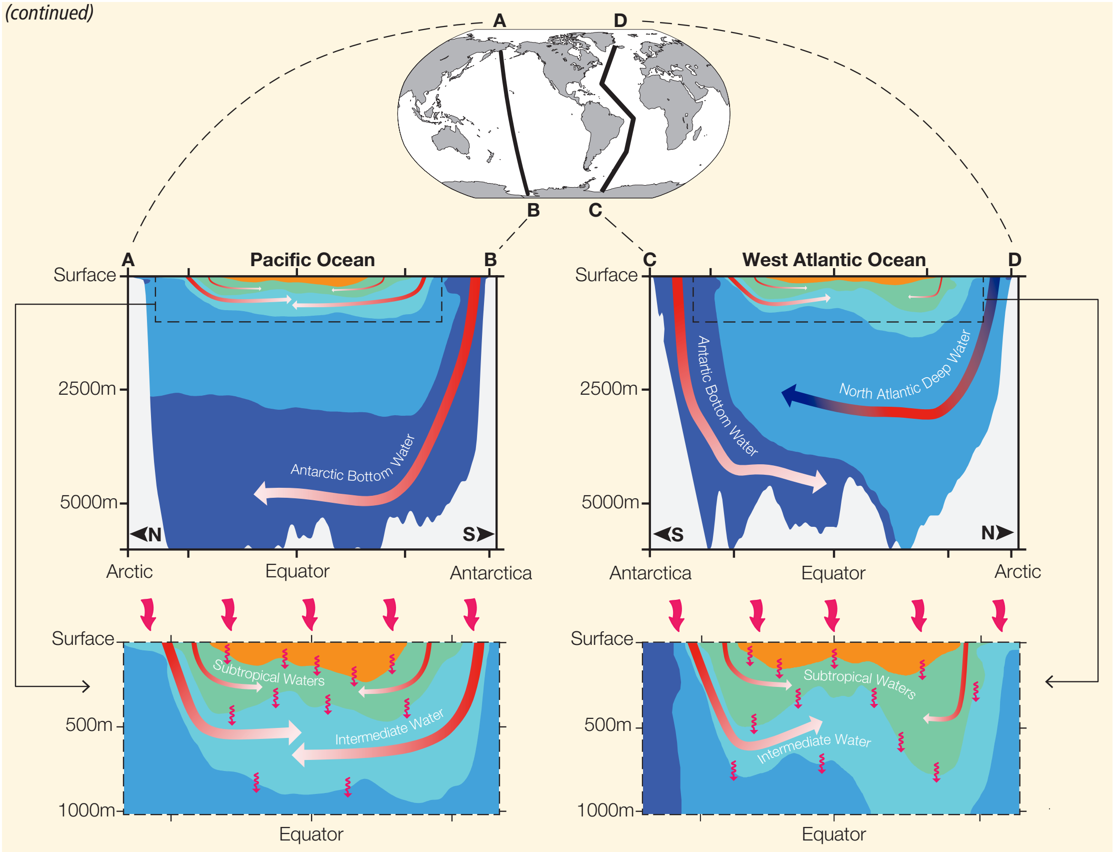
upper ocean warming rate (W/m²) 0–700 m

(IPCC AR6, 2022)

warming rate (W/m²) further into deeper ocean, 0–2000 m

Figure 9.6 | Ocean heat content (OHC) and its changes with time. (b–g) Maps of OHC across different time periods, in different layers. Maps show the observed (Ishii et al., 2017) trends of OHC for (b) 0–700 m for the period 1971–2014, and (e) 0–2000 m for the period 2005–2017.

Ocean heat uptake pathways



(IPCC AR5, 2013)

FAQ 3.1, Figure 1 | Ocean heat uptake pathways. The ocean is stratified, with the coldest, densest water in the deep ocean (upper panels: use map at top for orientation). Cold Antarctic Bottom Water (dark blue) sinks around Antarctica then spreads northward along the ocean floor into the central Pacific (upper left panel: red arrows fading to white indicate stronger warming of the bottom water most recently in contact with the ocean surface) and western Atlantic oceans (upper right panel), as well as the Indian Ocean (not shown). Less cold, hence lighter, North Atlantic Deep Water (lighter blue) sinks in the northern North Atlantic Ocean (upper right panel: red and blue arrow in the deep water indicates decadal warming and cooling), then spreads south above the Antarctic Bottom Water. Similarly, in the upper ocean (lower left panel shows Pacific Ocean detail, lower right panel the Atlantic), cool Intermediate Waters (cyan) sink in sub-polar regions (red arrows fading to white indicating warming with time), before spreading toward the equator under warmer Subtropical Waters (green), which in turn sink (red arrows fading to white indicate stronger warming of the intermediate and subtropical waters most recently in contact with the surface) and spread toward the equator under tropical waters, the warmest and lightest (orange) in all three oceans. Excess heat or cold entering at the ocean surface (top curvy red arrows) also mixes slowly downward (sub-surface wavy red arrows).

workshop problem 3
Estimating equilibrium climate sensitivity

notes section 3.1.2
Transient climate sensitivity

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

Transient climate sensitivity

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Radiative forcing   Outgoing LW Radiation   transport into the deep ocean

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

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

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

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

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

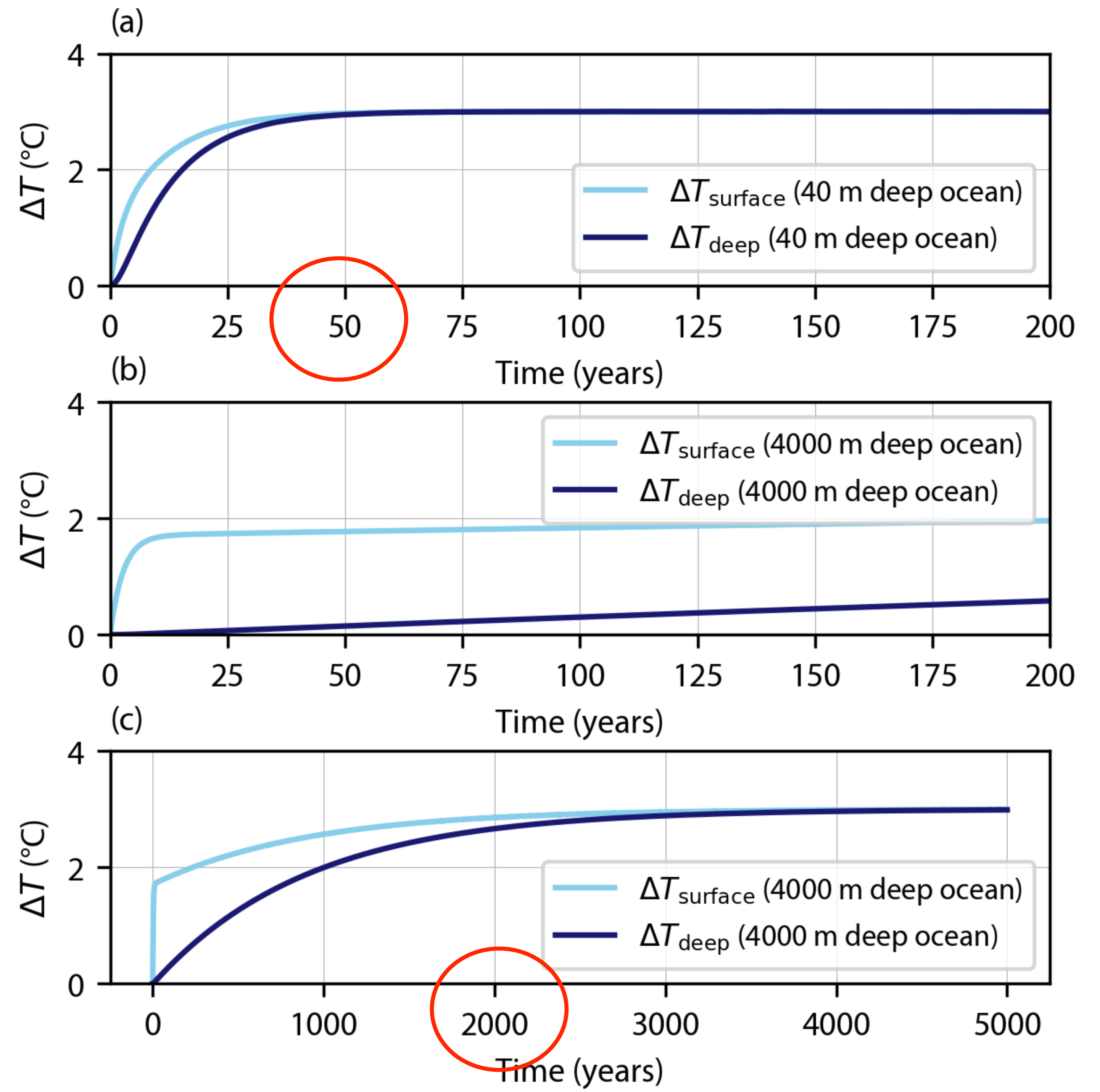


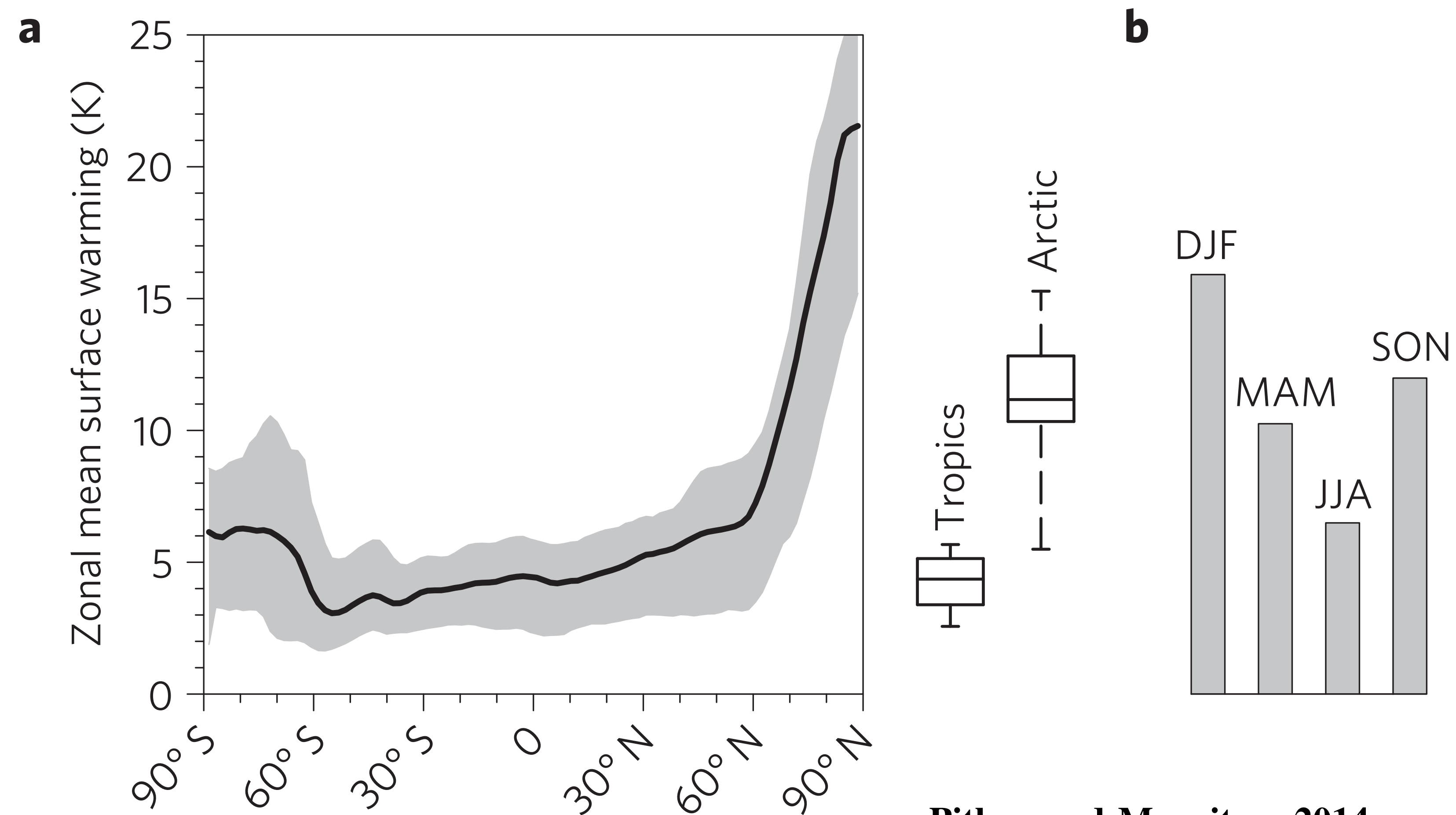
Figure 3.3: Transient climate sensitivity.
The temperature anomalies of the upper ocean and of the deep ocean, as a function of time in a scenario of instantaneous CO_2 doubling. (a) An artificial case assuming the subsurface ocean is only 40 m deep. (b) A more realistic scenario, assuming an ocean depth 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.

workshop problem 4
Transient climate sensitivity: role of ocean depth

leave for HW

Polar amplification

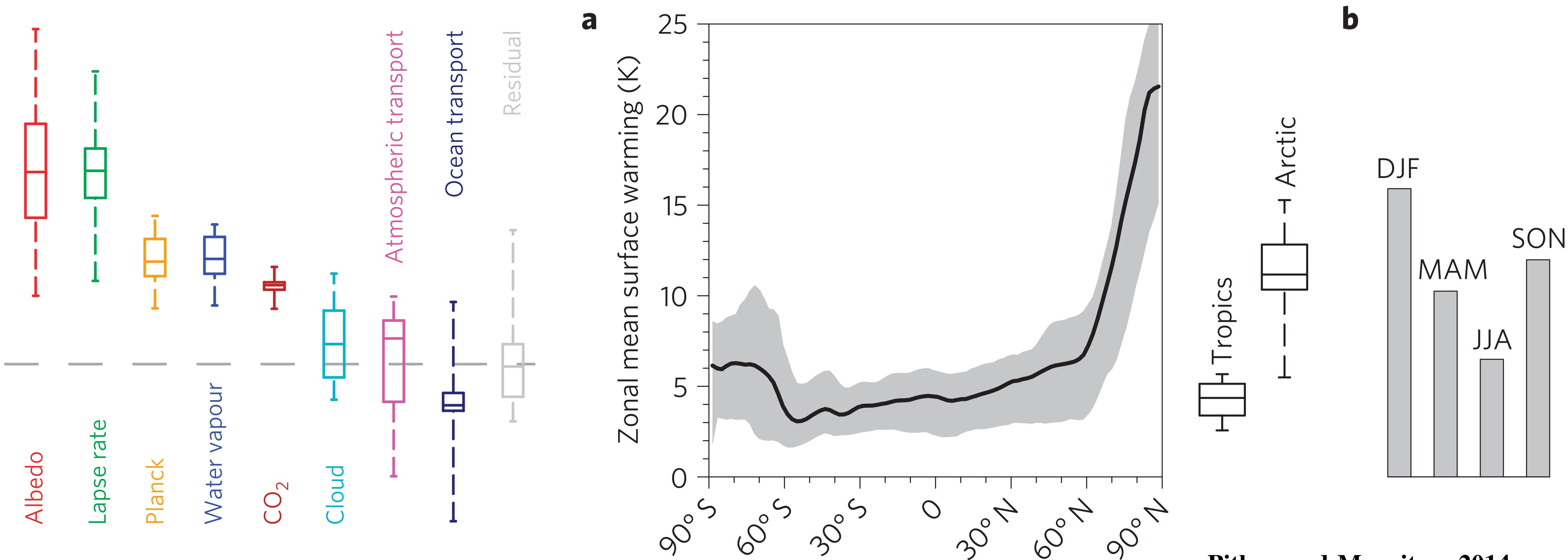
Polar amplification



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.

Polar amplification



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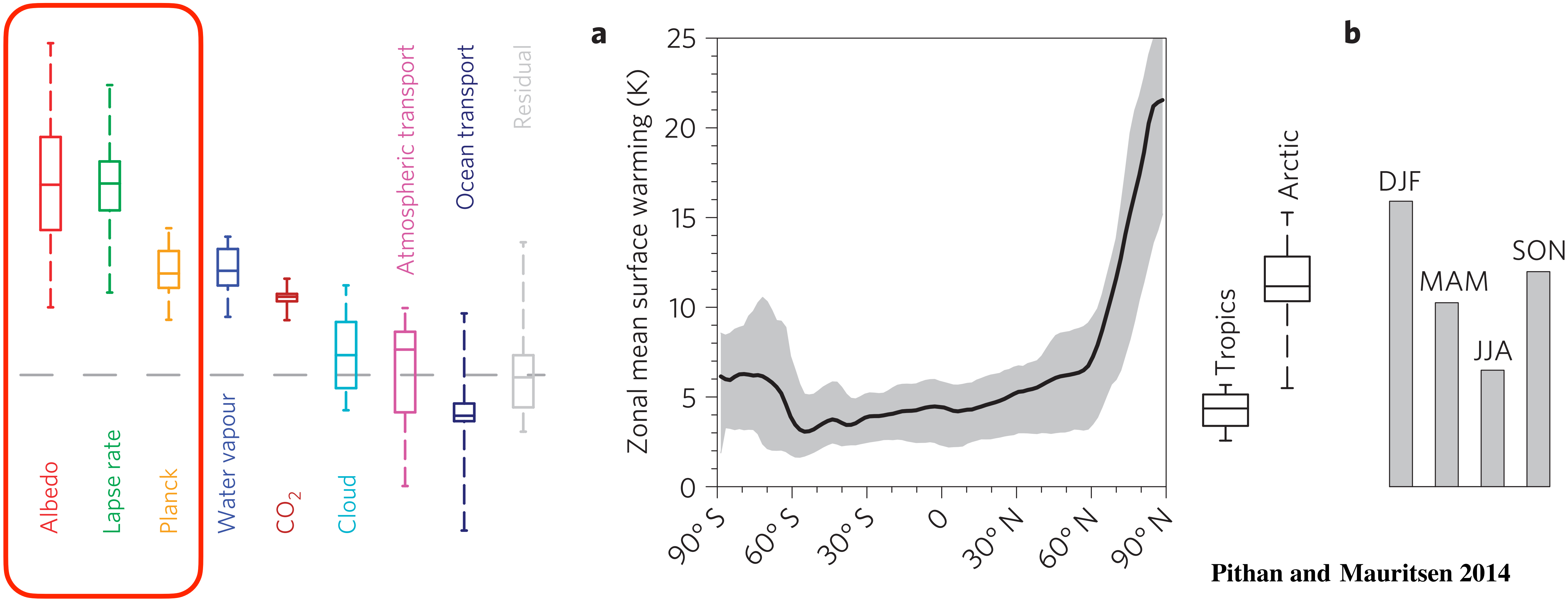

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notes section 3.2

Polar amplification

(use next slides)

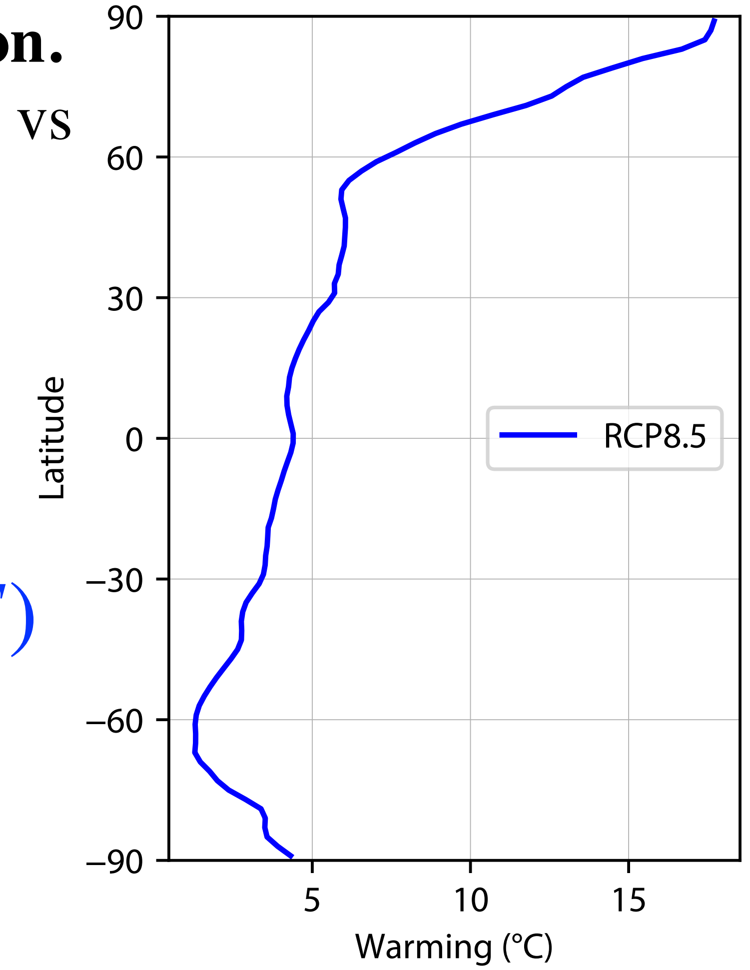
notes section 3.2
Polar amplification
(use next slides)

Three main mechanisms are responsible for polar amplification:

1. Albedo feedback (simple: snow and ice melting in polar areas lead to more warming there)
2. Plank feedback
3. Lapse-rate “feedback”

Arctic amplification & the Planck feedback

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

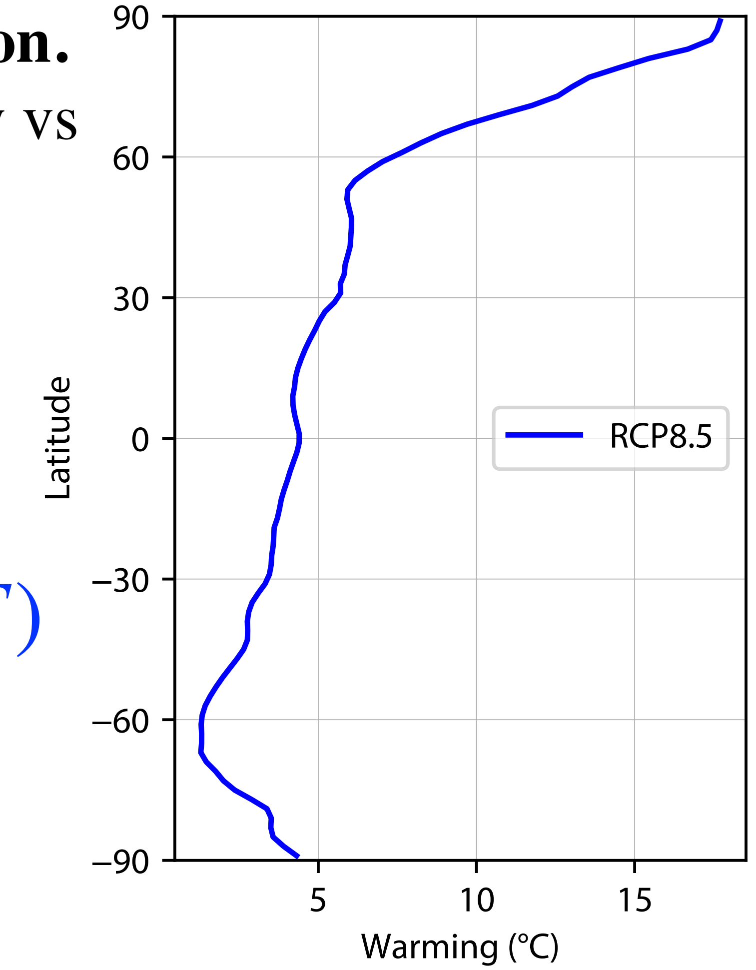


Consider a ΔF radiative forcing. Calculate the resulting warming ΔT assuming a Planck balance, $F_0 = \epsilon\sigma T_0^4$:

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

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

Arctic amplification & the Planck feedback



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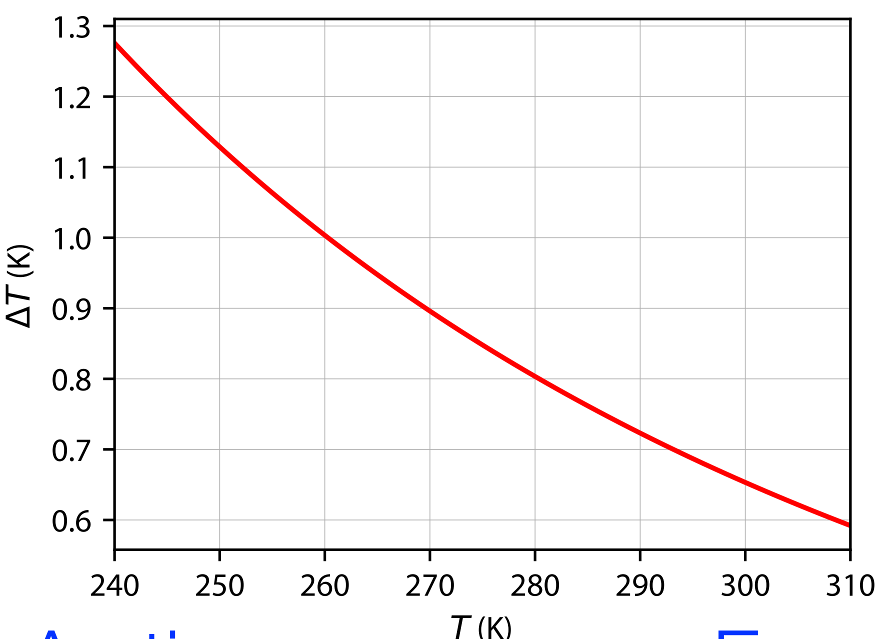
$$\Rightarrow\ \Delta F \approx \epsilon 4\sigma T_0^3 \Delta T \qquad \Rightarrow\ \Delta T \approx \Delta F/(\epsilon 4 \sigma T_0^3) \quad (3.5)$$



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 $\epsilon = 1$.

Arctic amplification & the Planck feedback

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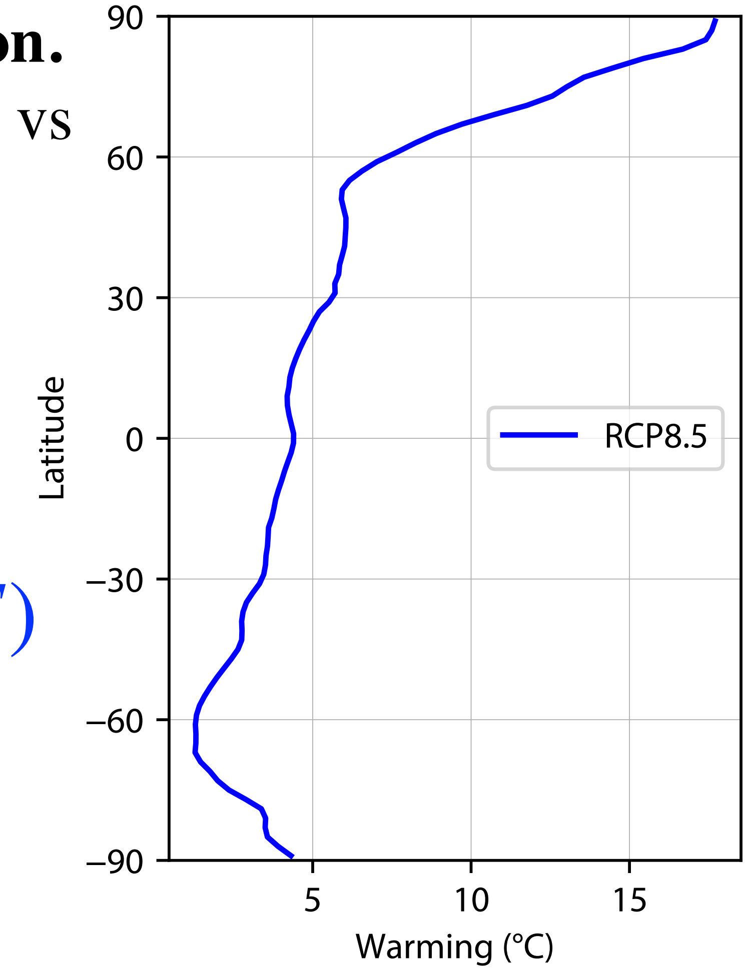

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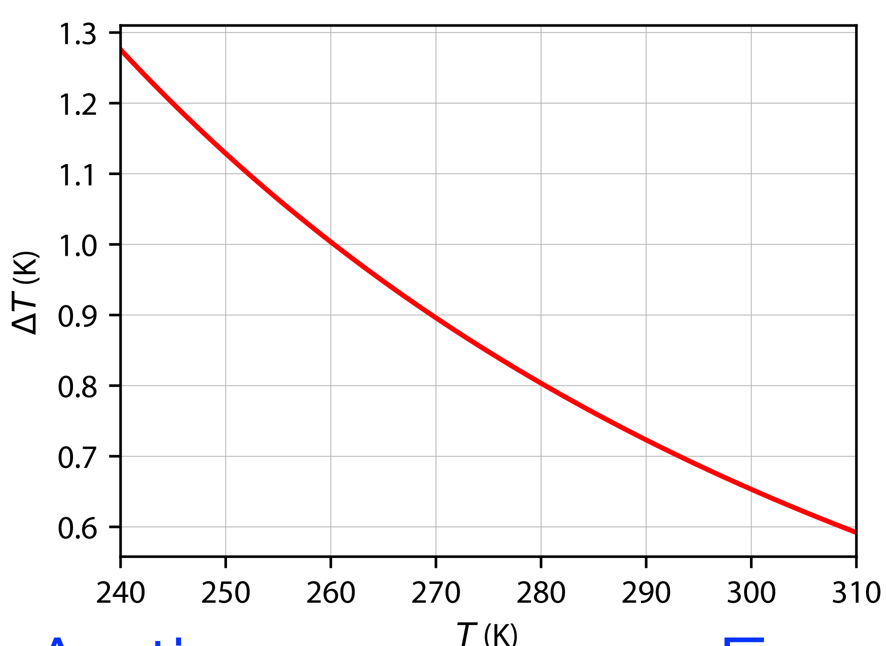


Arctic Equator

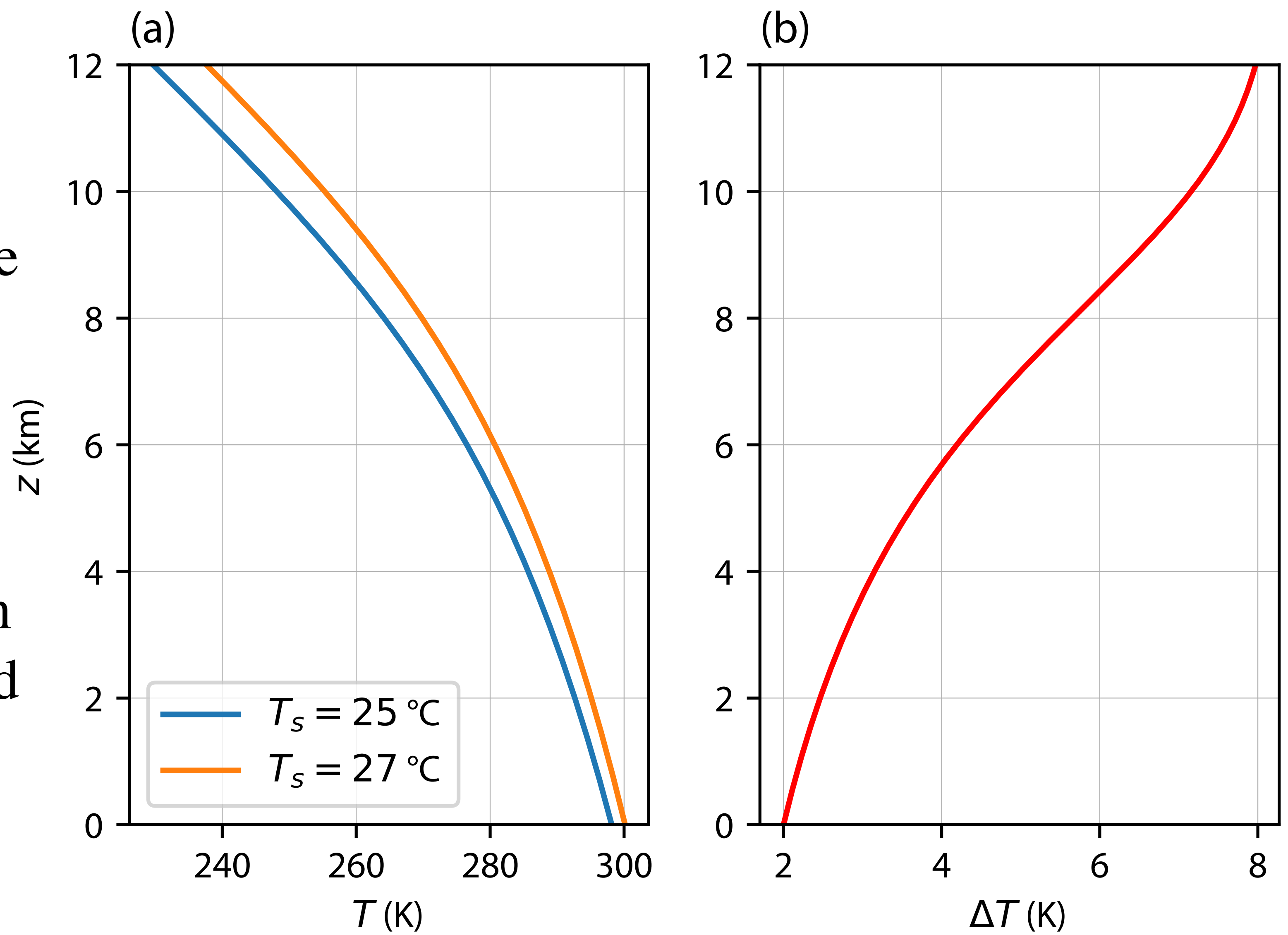
Figure 3.4: The Planck feedback. The warming expected due to an increase in radiative forcing of 4 W/m^2 based on equation (3.5) with an emissivity of $\epsilon = 1$.

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

Arctic amplification & tropical 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.



Arctic amplification & lapse-rate "feedback"

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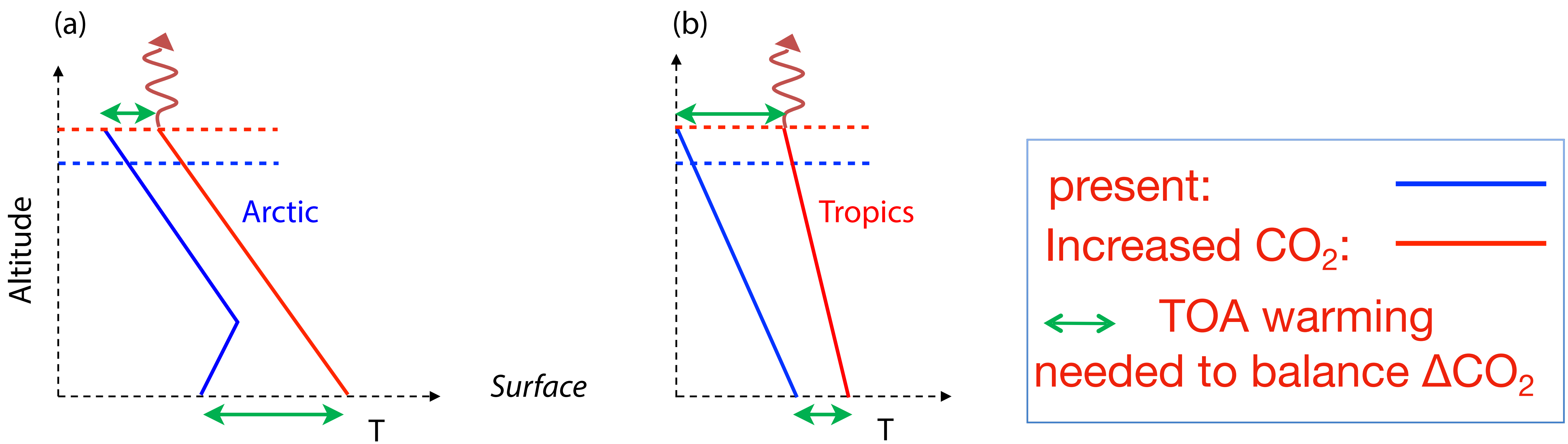

Figure 3.5: Schematics of the Arctic (a) and tropical (b) lapse rate feedbacks. Solid blue (red) lines show the temperature profiles before (after) warming. Dashed blue (red) lines show the emission level before (after) the warming (see section 2.1.3). The green double arrows show the warmings at the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

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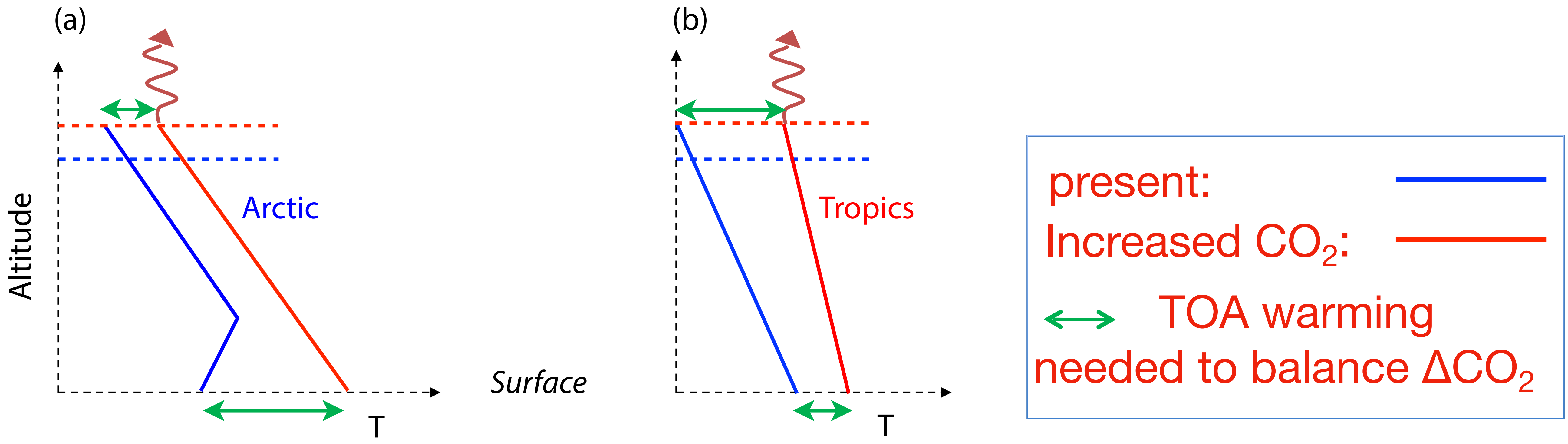

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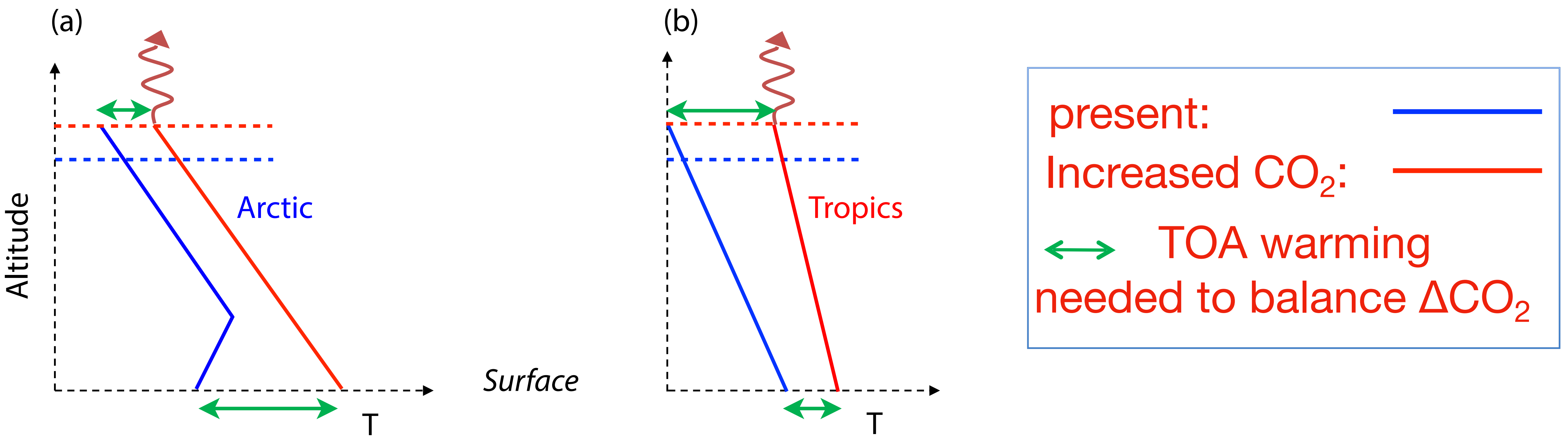
➡ Lapse-rate "feedback" is negative in tropics & positive in Arctic: same TOA warming leads to larger surface warming in Arctic

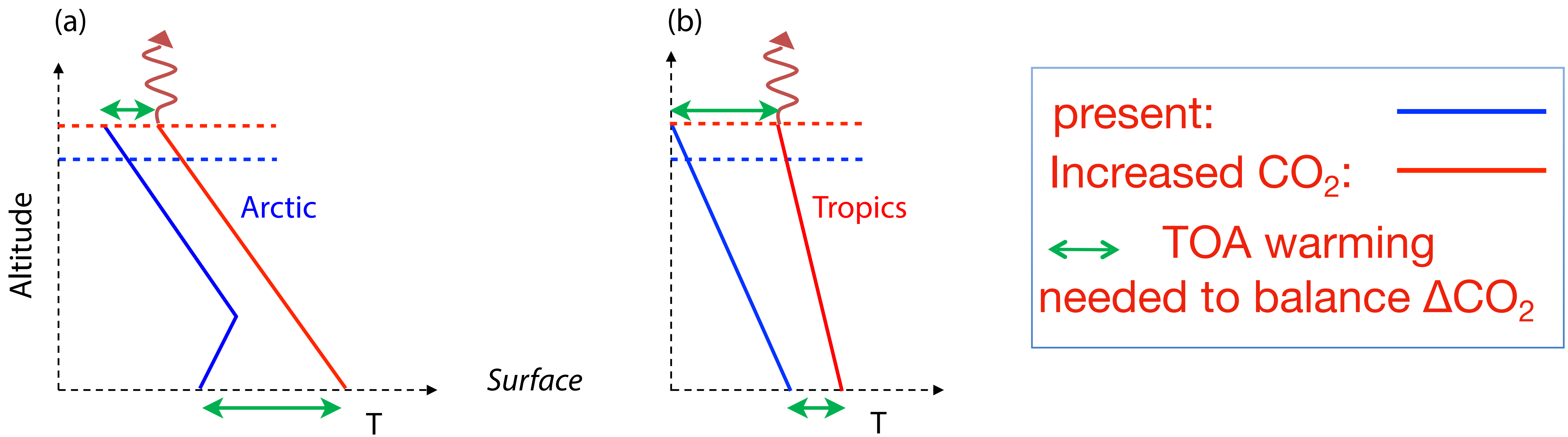
Arctic amplification & lapse-rate "feedback"



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.

Arctic amplification & lapse-rate “feedback”



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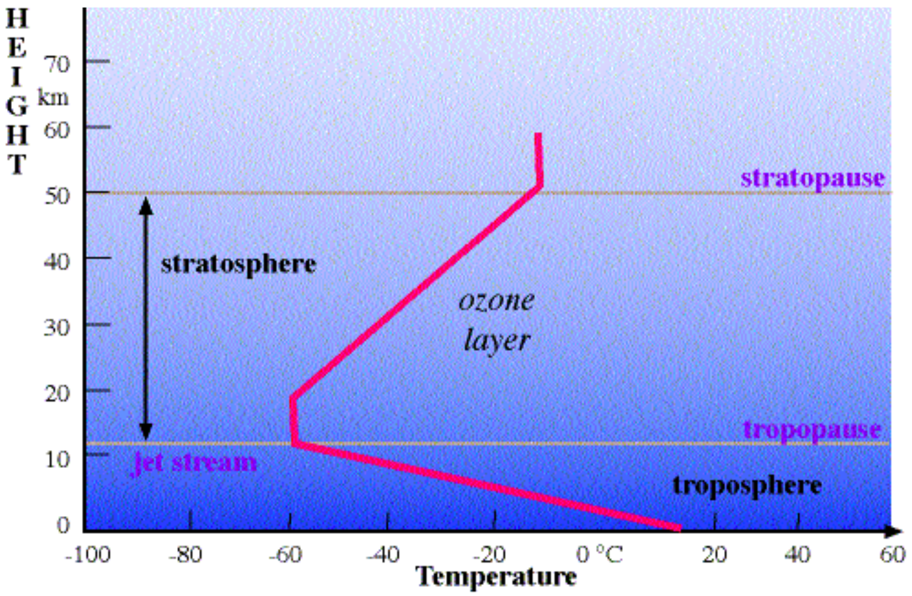
➨ The warming at the surface will be larger in Arctic ➨ Arctic amplification.

The polar amplification induced by this “lapse-rate feedback” is of a similar magnitude to that of the albedo feedback!

workshop 5 a (leave b, c for HW)
Polar amplification

notes section 3.4
Stratospheric cooling
(use next slides)

The troposphere is warming, the stratosphere is cooling



(IPCC AR6, 2022)

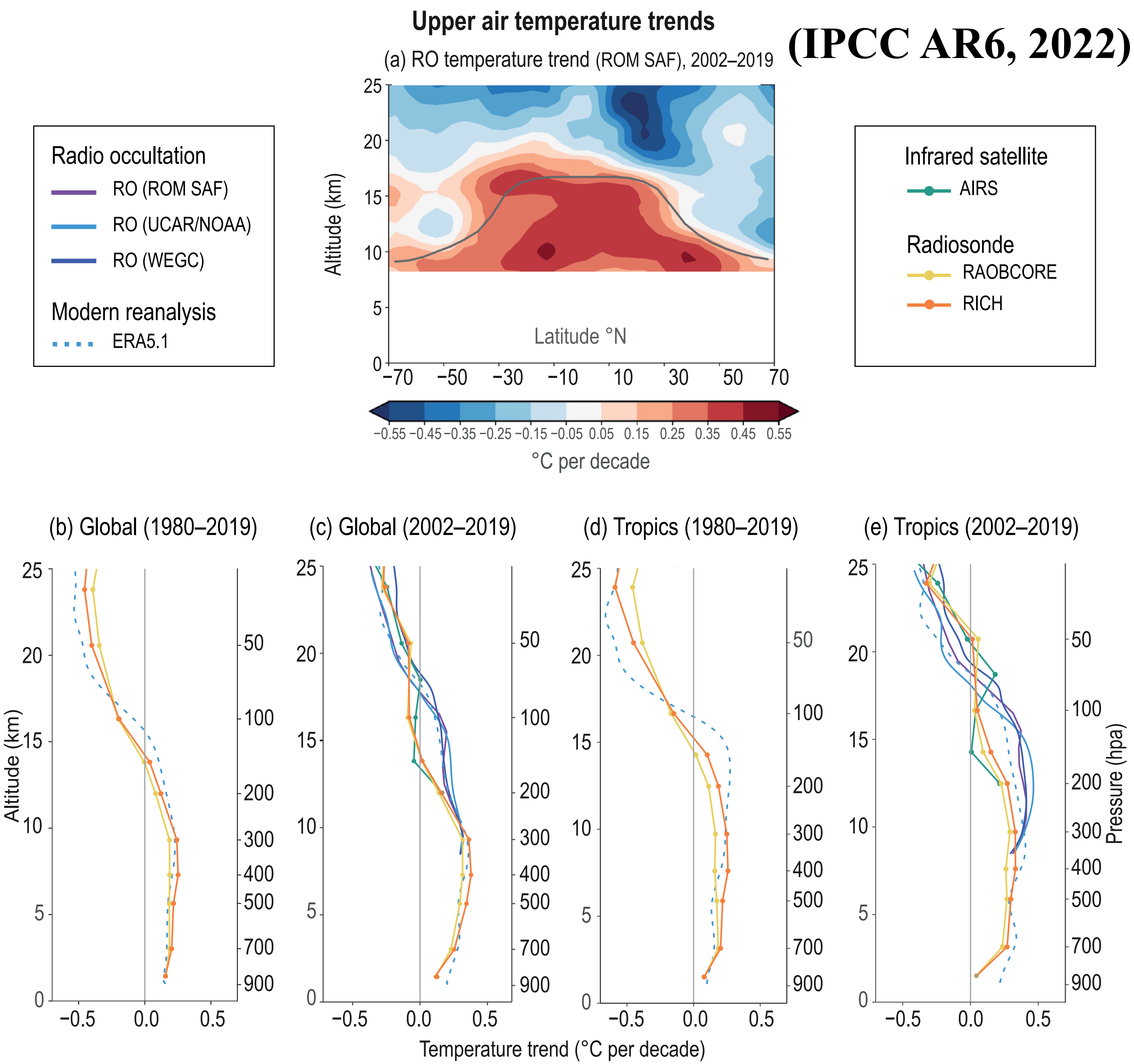
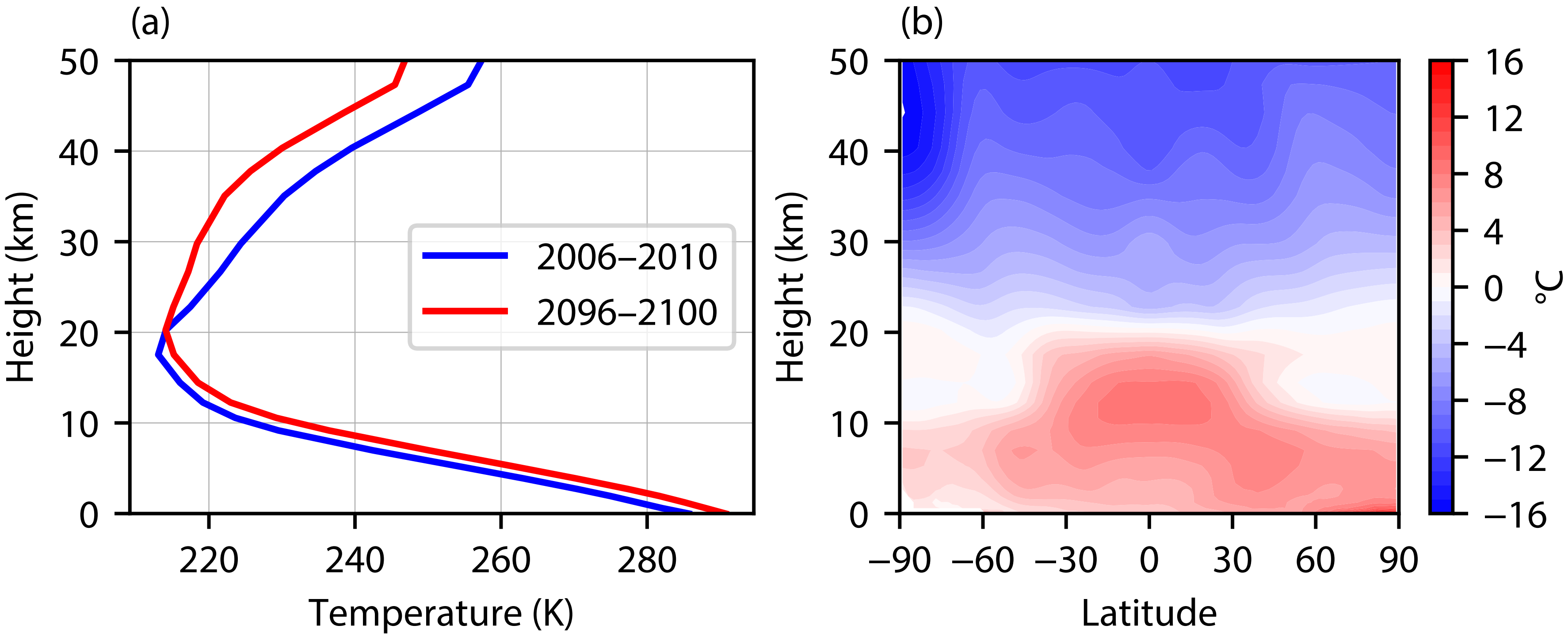


Figure 2.12 | Temperature trends in the upper air. (a) Zonal cross-section of temperature anomaly trends (2007–2016 baseline) for 2002–2019 in the upper troposphere and lower stratosphere region. Tropopause marked by grey line.

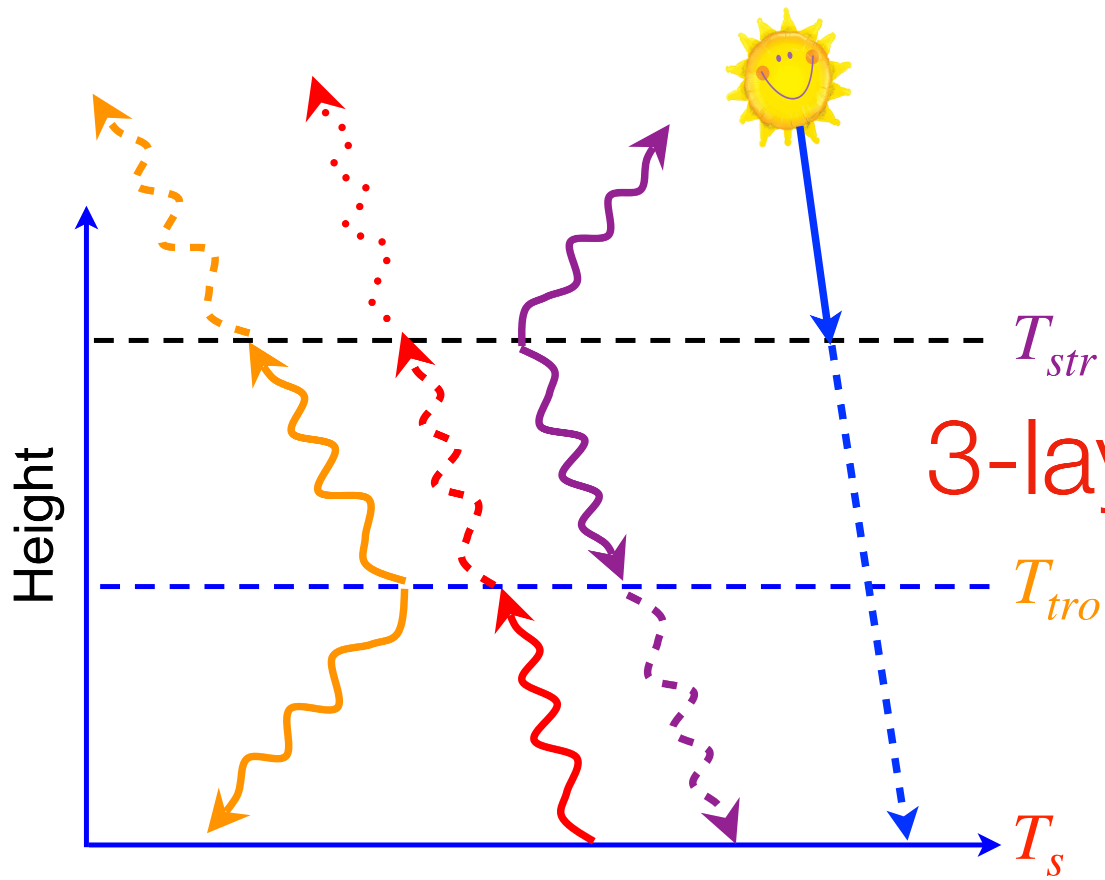
(b, c) Trends in temperature at various atmospheric heights for 1980–2019 and 2002–2019 for 70°N–70°S. **(d, e)** as for (b, c) but for the tropical (20°N–20°S) region.

Stratospheric cooling



Tropospheric warming, stratospheric cooling, projected for RCP8.5

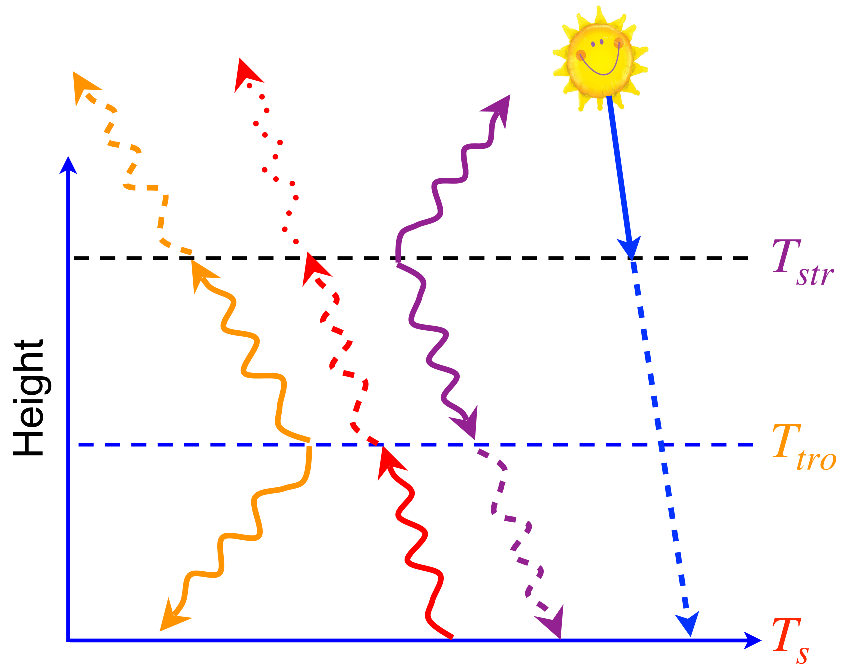
Figure 3.8: Stratospheric cooling.
(a) Mid-latitude (30°N–50°N) zonally averaged temperature profiles for an RCP8.5 projection at the beginning and end of the 21st century. (b) The zonally averaged atmospheric temperature response during the 21st century to the RCP8.5 scenario, showing a tropospheric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



3-layer energy balance model

Stratospheric cooling

3-layer energy balance model



← Sources → ←Sinks→

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

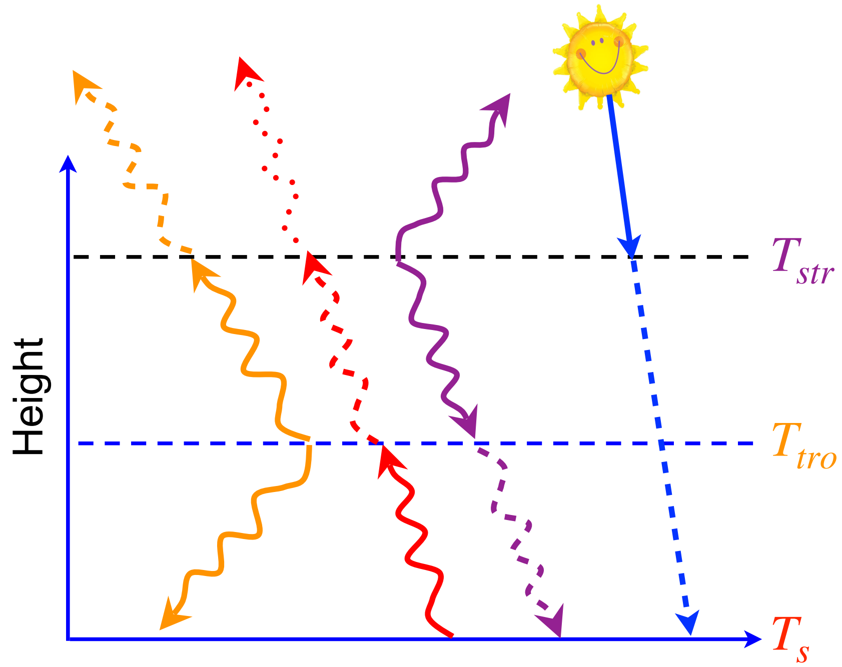
Troposphere $$\varepsilon_{tro}\sigma T_s^4+\varepsilon_{tro}\varepsilon_{str}\sigma T_{str}^4=2\varepsilon_{tro}\sigma T_{tro}^4$$

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 (Thanks Xiaoting!):

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

Stratospheric cooling



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

Summary

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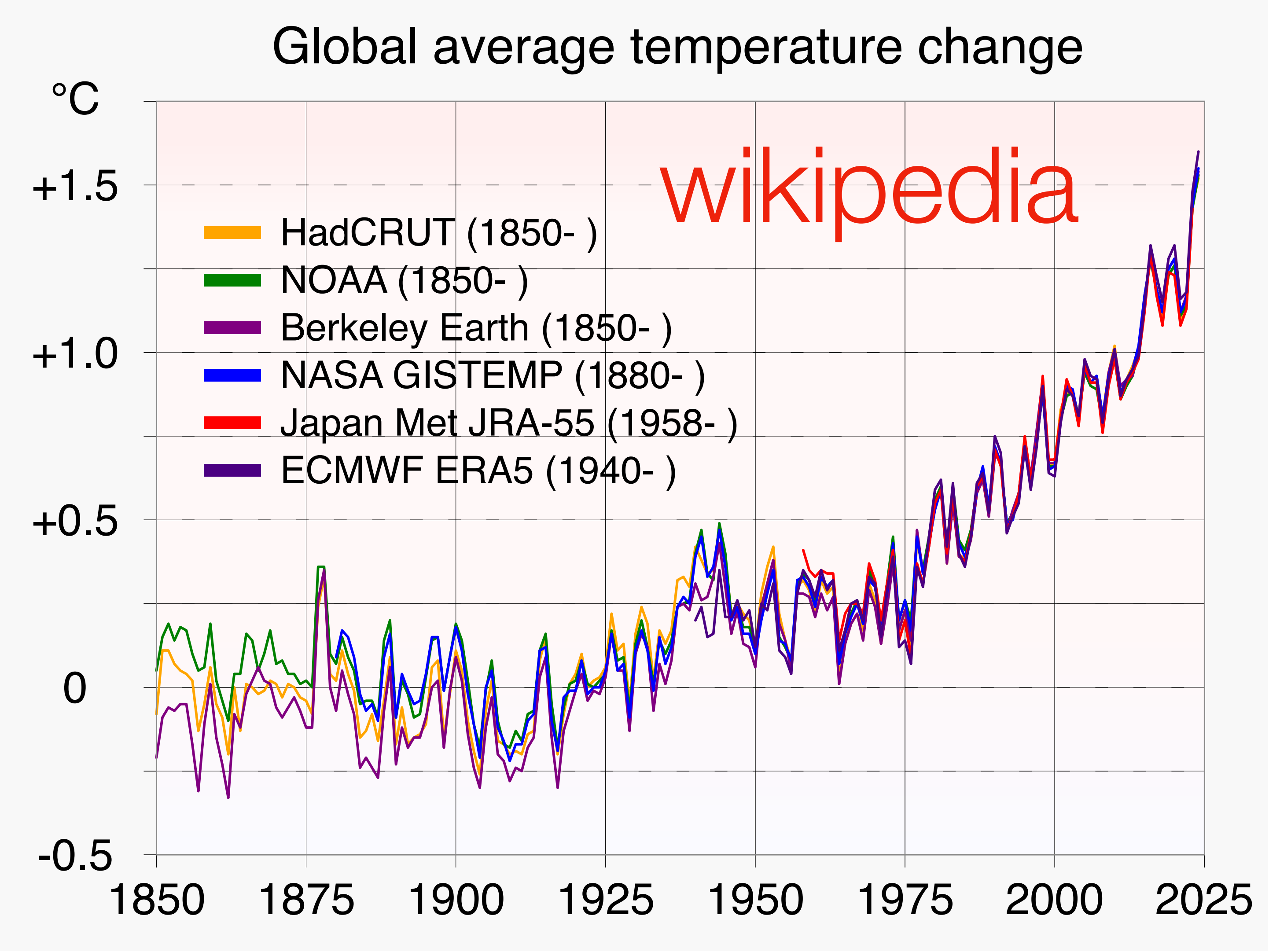

The End