Climate sensitivity in an uncertain world

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Science on Tap
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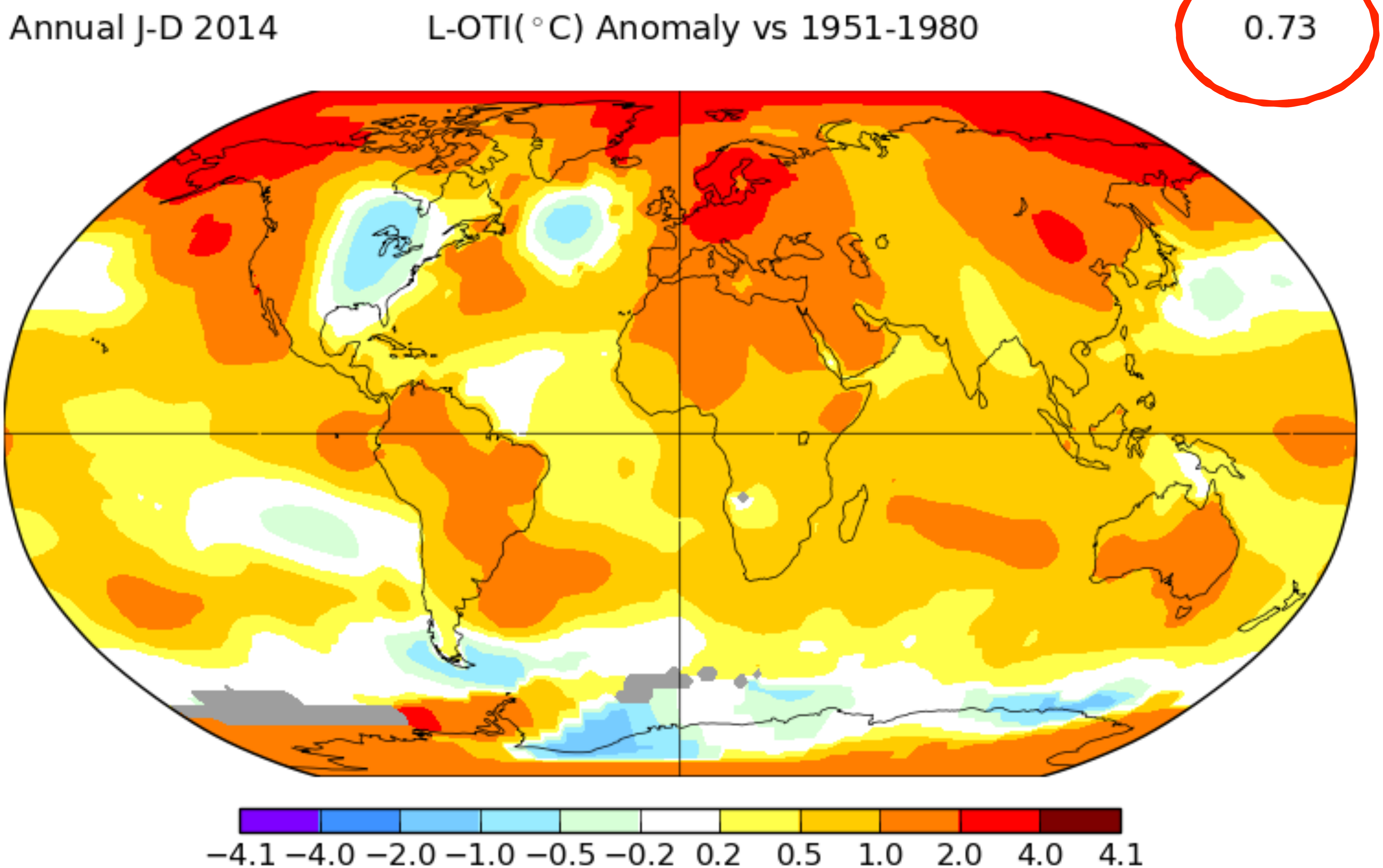
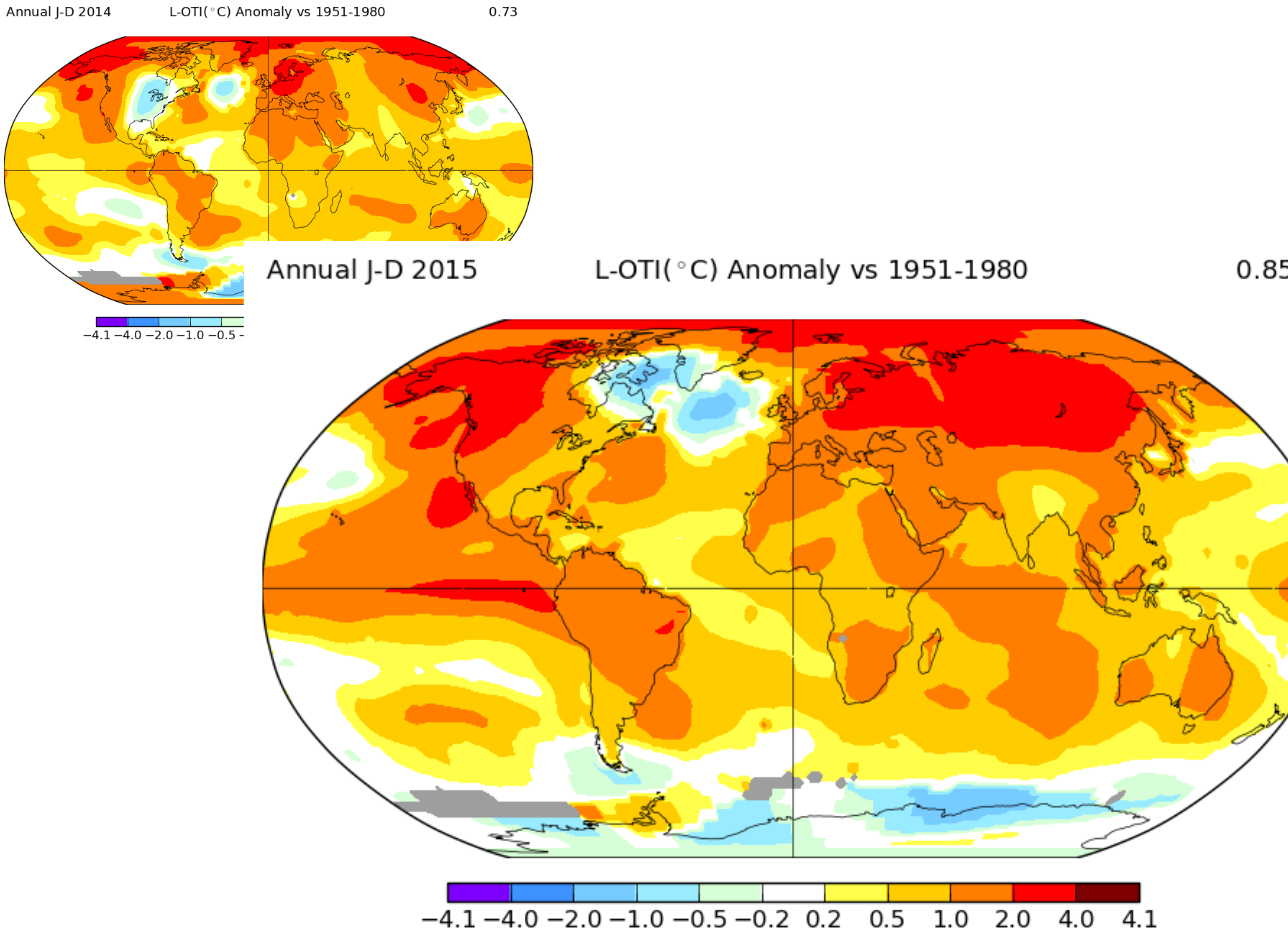
UNIVERSITY AT ALBANY
State University of New York

2014 **was** the warmest year on record



Though it did not feel that way here in the NE United States!

https://data.giss.nasa.gov/gistemp/maps/



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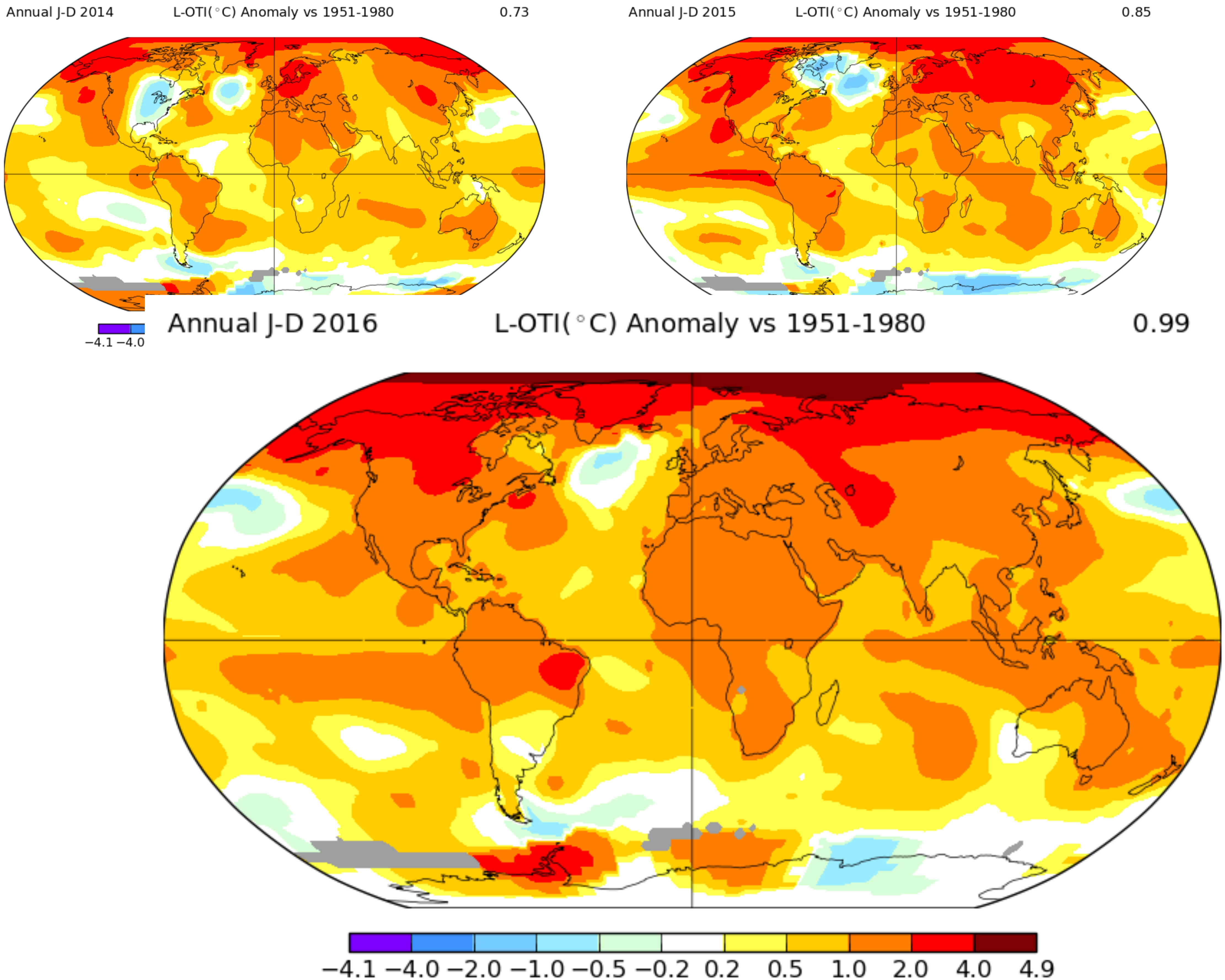

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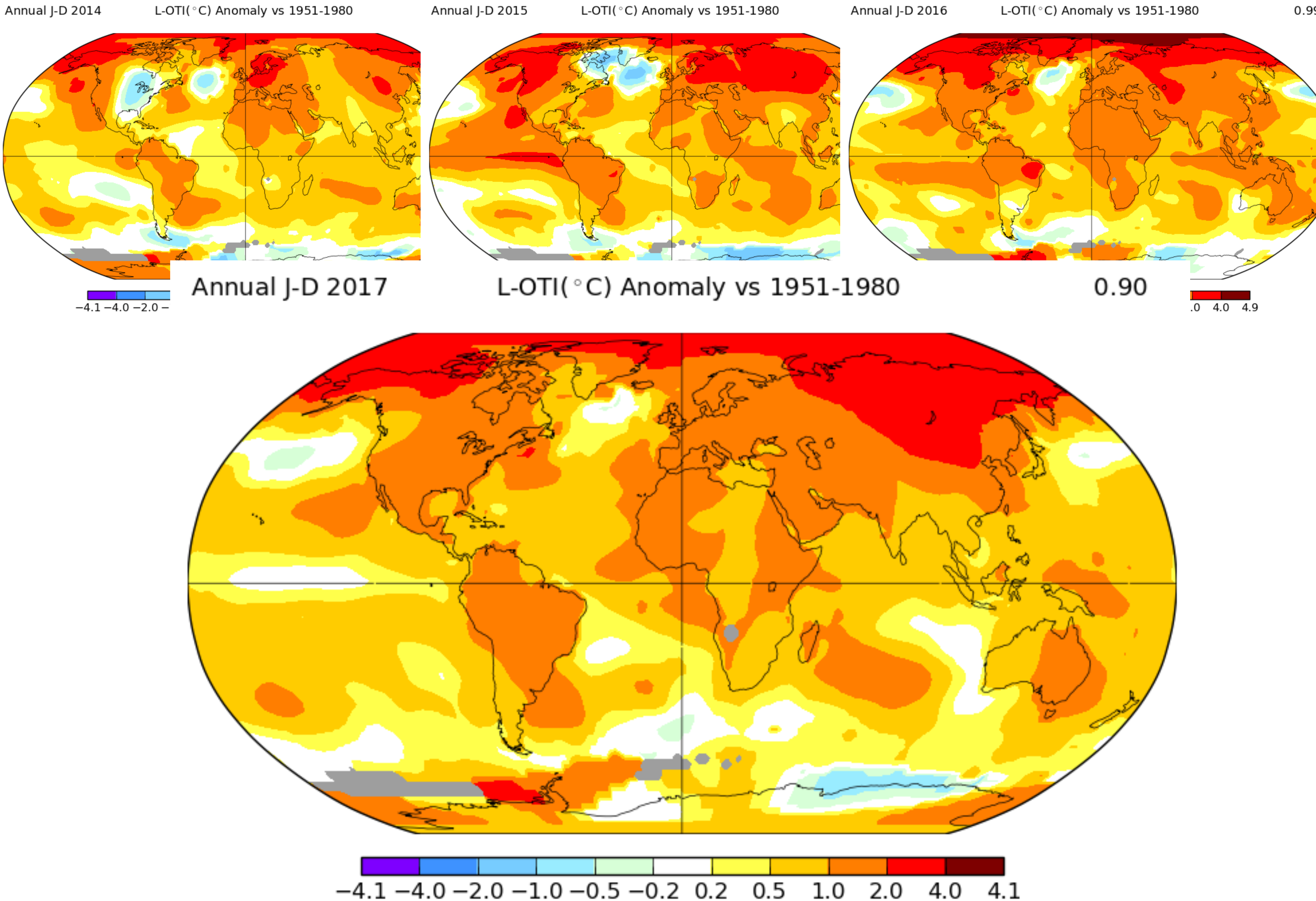

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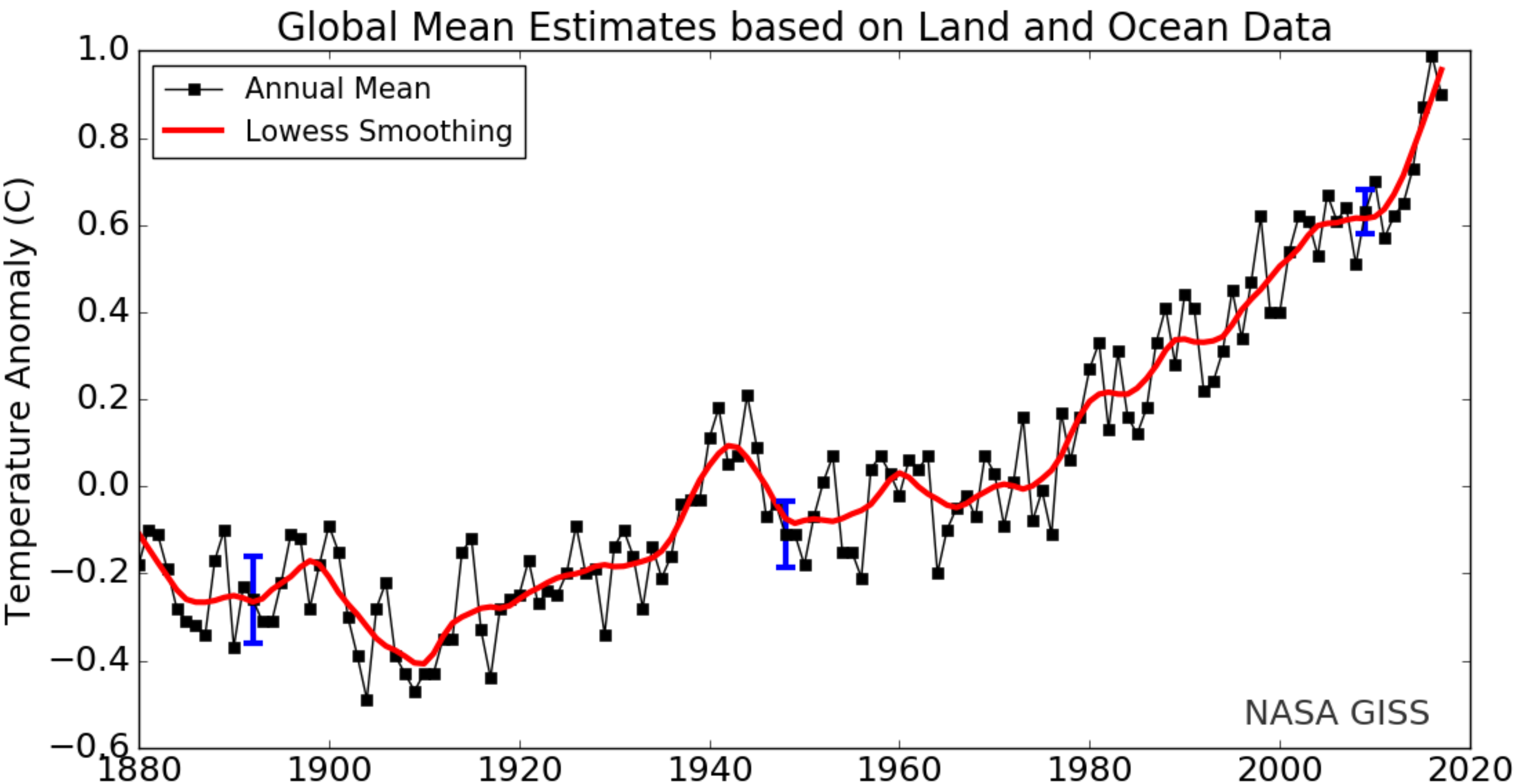


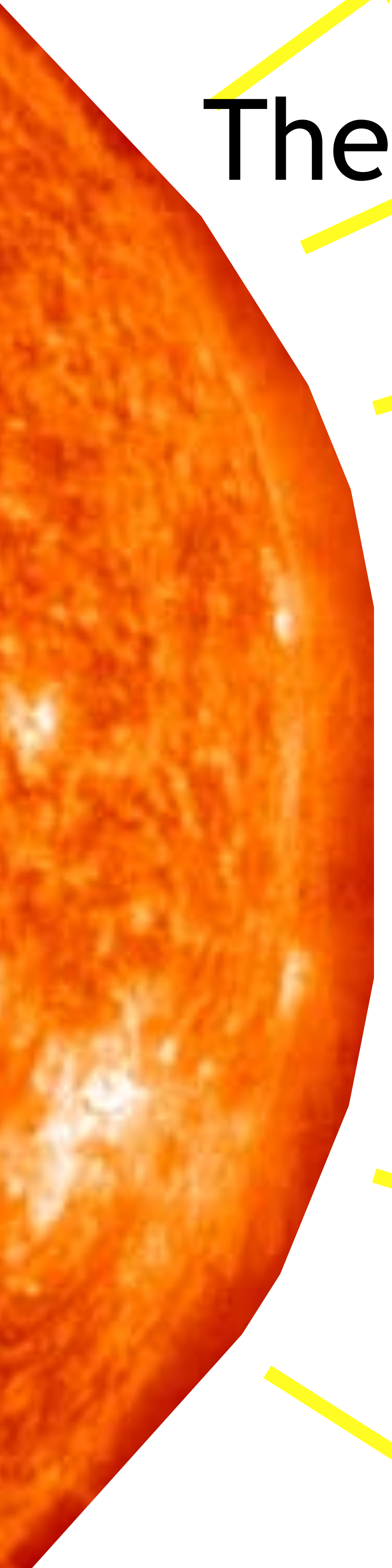
Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. [This is an update of Fig. 9a in Hansen et al. (2010).]

https://data.giss.nasa.gov/gistemp/graphs/

About this talk

- Look at some basic questions that are central in climate science
- **What is climate sensitivity, how (and how well) do we know what it is?**
- Weighted strongly toward some things that I'm interested in
- Not really a talk about…
    - ✴Evidence for human influence on climate
    - ✴Projected future climate change
    - ✴Local and regional climate
    - ✴Impacts of future climate change
- Pedagogical, not polemical

The Earth is a ball floating in space…



102 W m^{-2}

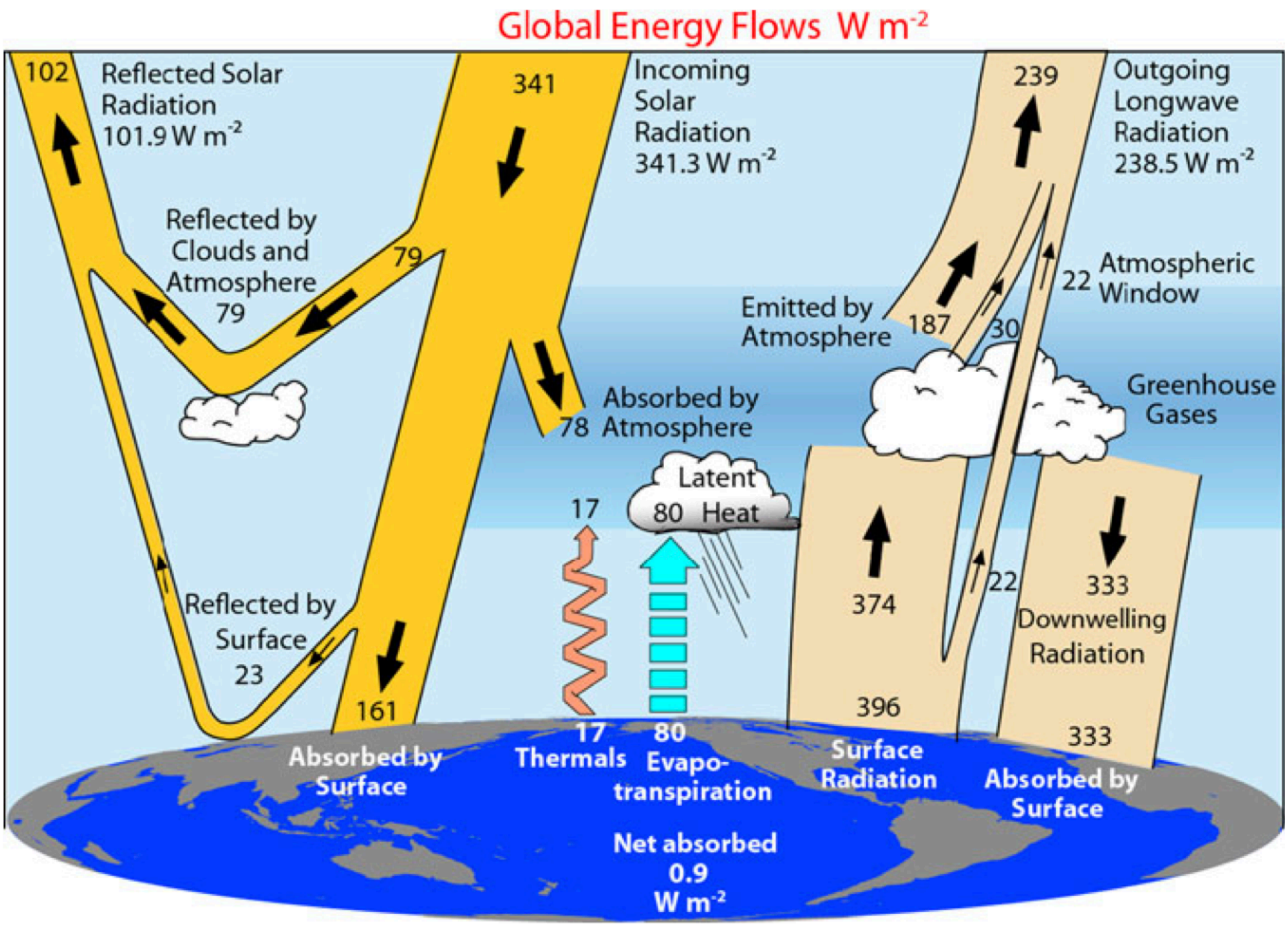
Energy REFLECTED

Energy IN (from Sun) **=** **Energy REFLECTED** **+** **Energy EMITTED**

341 W m^{-2}

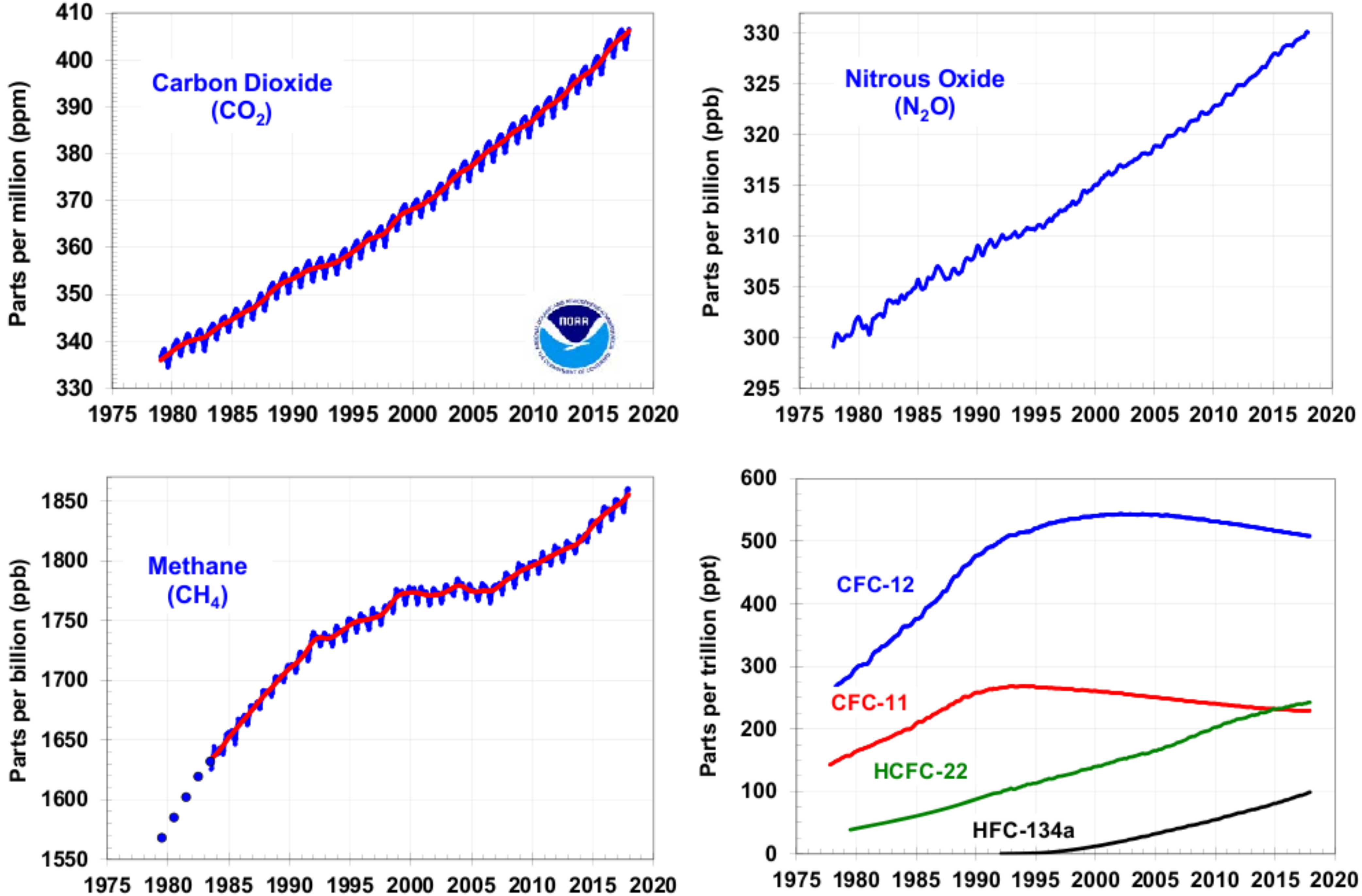
239 W m^{-2}

Its temperature is determined by a **balance** between heating from the sun and cooling through radiation to space

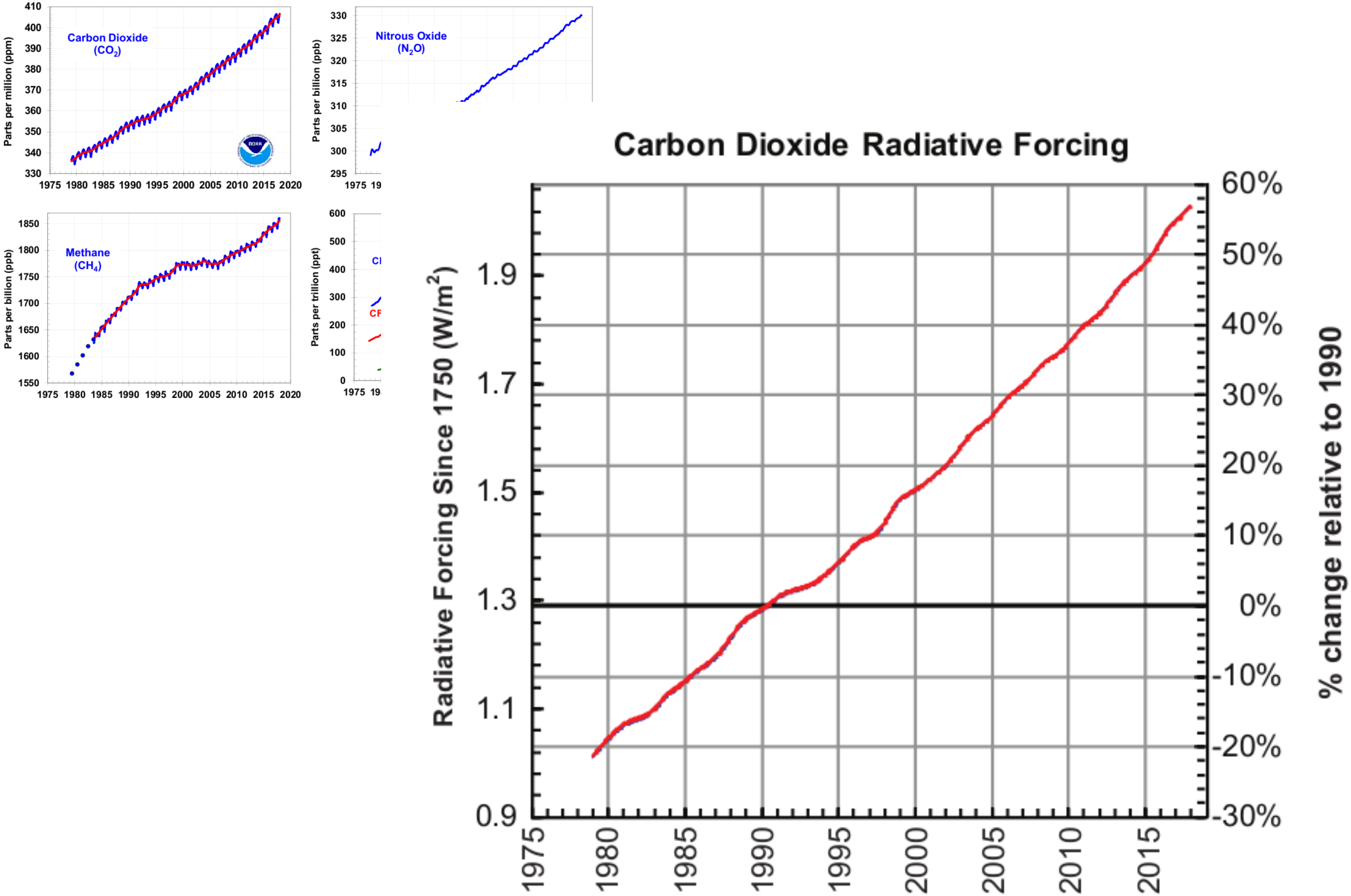


Trenberth and Fasullo (2012) Surv. Geophys.

The “forcing” — agents that cause energy to accumulate within the Earth system



NOAA's Annual Greenhouse Gas Index https://www.esrl.noaa.gov/gmd/aggi/



NOAA's Annual Greenhouse Gas Index https://www.esrl.noaa.gov/gmd/aggi/

Earth’s energy budget

All values are global, annual averages, expressed as deviations from a balanced pre-industrial state

“Radiative forcing” (new energy added to the system from greenhouse trapping) **-** **“Climate response” (change in emission to space due to warming)** **=** **“Heat uptake” (change in energy storage in Earth system — mostly the oceans)**

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$$\Delta F - \lambda \Delta T = \Delta Q$$

Earth's energy budget

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$$\Delta F - \lambda \Delta T = \Delta Q$$

A key assumption: warmer planet emits more to space ***(consistent with basic physics)***

λ **("lambda") is called the Climate Feedback parameter (W m^{-2} K^{-1})**

Hypothetical climate change scenario

$$\Delta F - \lambda \Delta T = \Delta Q$$

- Instantly double atmospheric CO2 — ΔF_{2x} = 3.7 W m-2
- Initially ΔT = 0, heat accumulates at a rate ΔQ = 3.7
- Oceans warm up, surface temperature increases
- Emission to space increases a bit, energy imbalance gets smaller
- Rate of warming ΔQ gets smaller
- Eventually… Earth returns to energy balance
- ΔQ = 0

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Ultimately, how much warming do we get???

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

We've just calculated something called the **Equilibrium Climate Sensitivity**

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

The eventual global average surface warming resulting from a doubling of atmospheric CO2

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$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

The eventual global average surface warming resulting from a doubling of atmospheric CO2

Quantifying ΔT_{2x} (or ECS) is one of the central questions in climate science!

Many **impacts** of climate change are expected to scale roughly with this number.

Low sensitivity (ΔT_{2x} <= 1.5°C) —> mild inconvenience

High sensitivity (ΔT2x > 4°C) —> a very different Earth for future generations

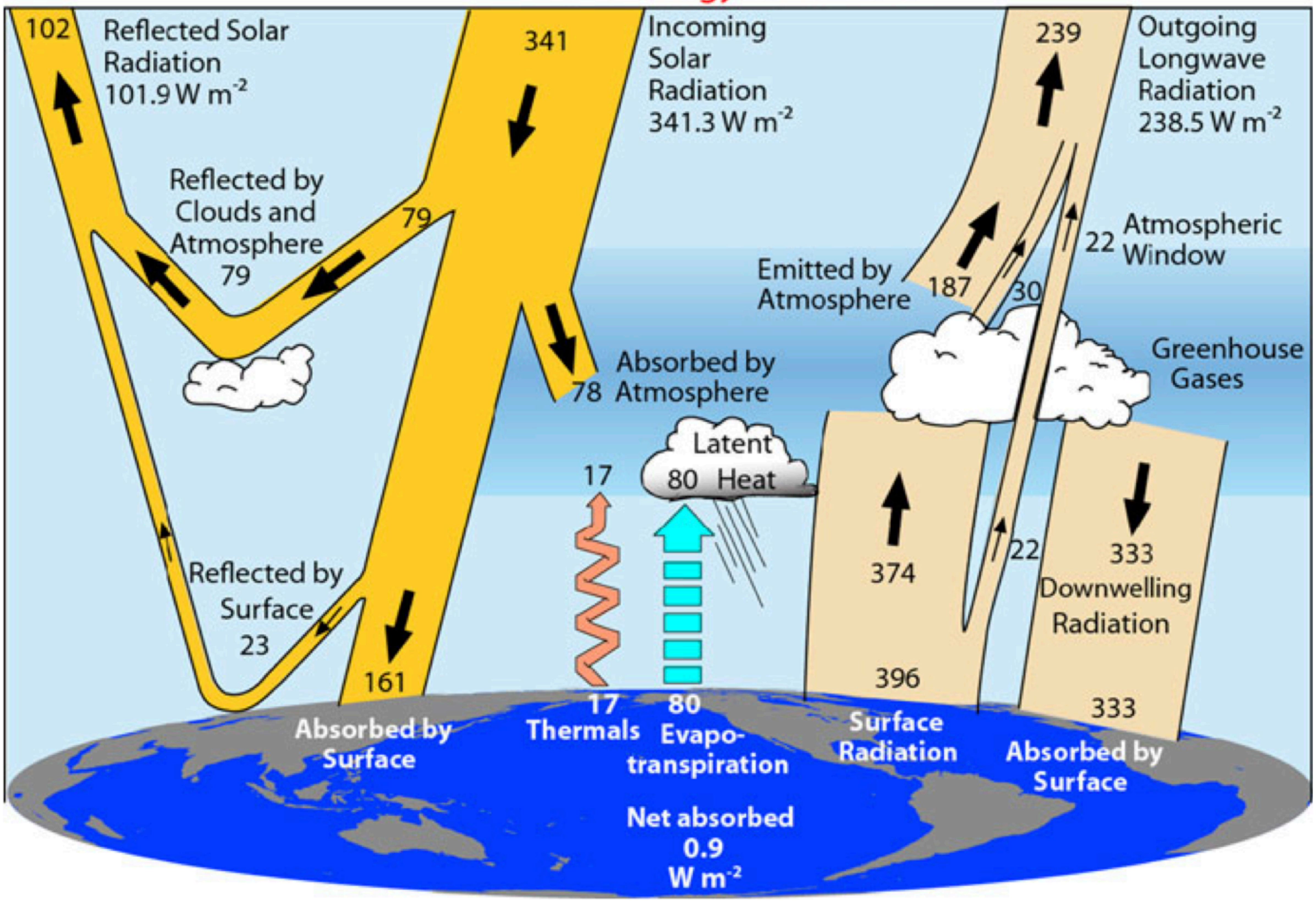
So what's the answer? How do we know it?

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

- **ΔF_{2x} = 3.7 W m^{-2} is reasonable well known**
- **Almost all the uncertainty is in the value of the feedback parameter lambda**
- **This measures the net effect of many processes that act to *amplify* (positive feedback) or *dampen* (negative feedback) the warming response.**

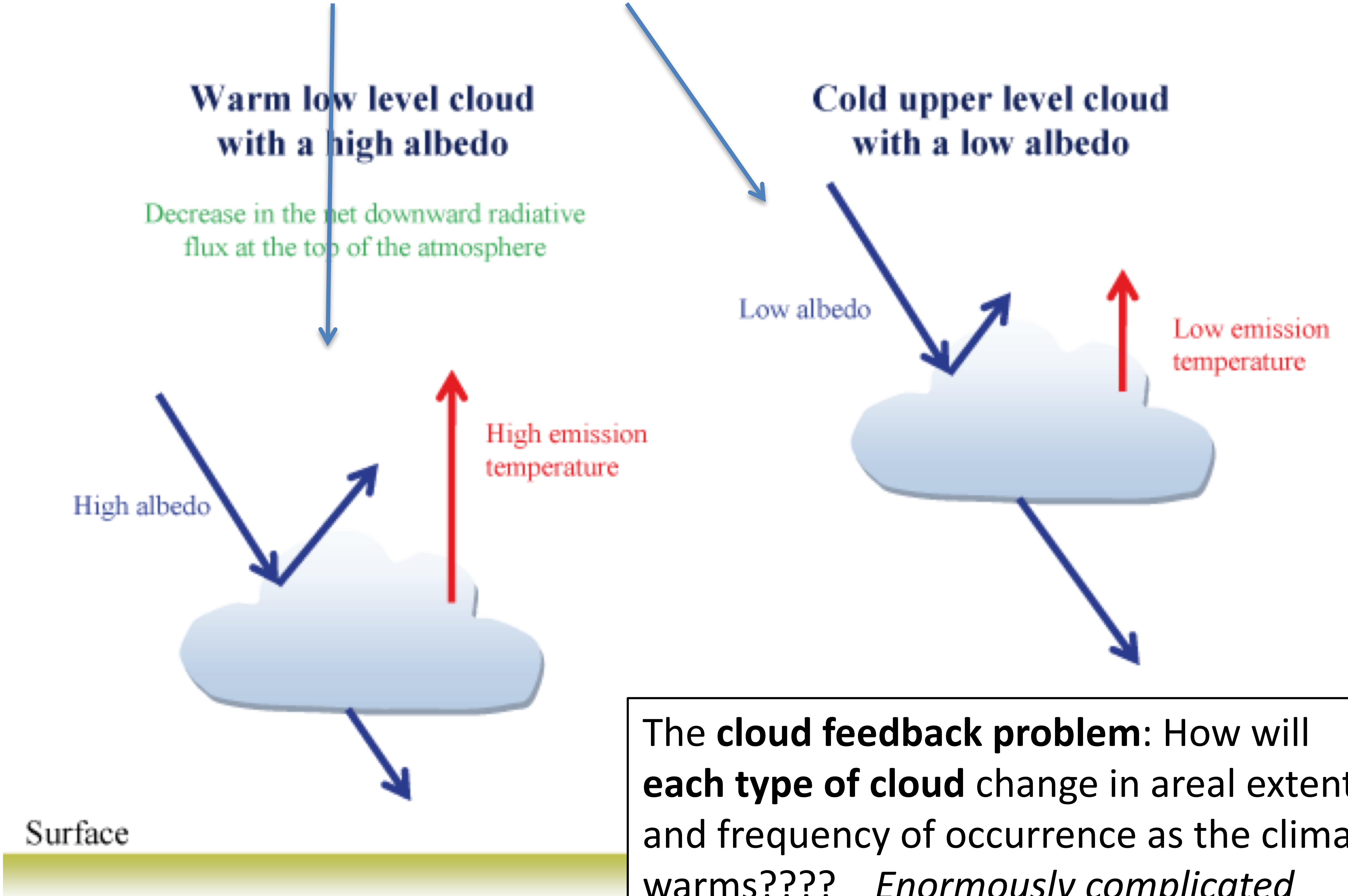
Ice Albedo Feedback

Global Energy Flows W m^{-2}



Trenberth and Fasullo (2012) Surv. Geophys.

Clouds **cool** and **warm** the planet's surface

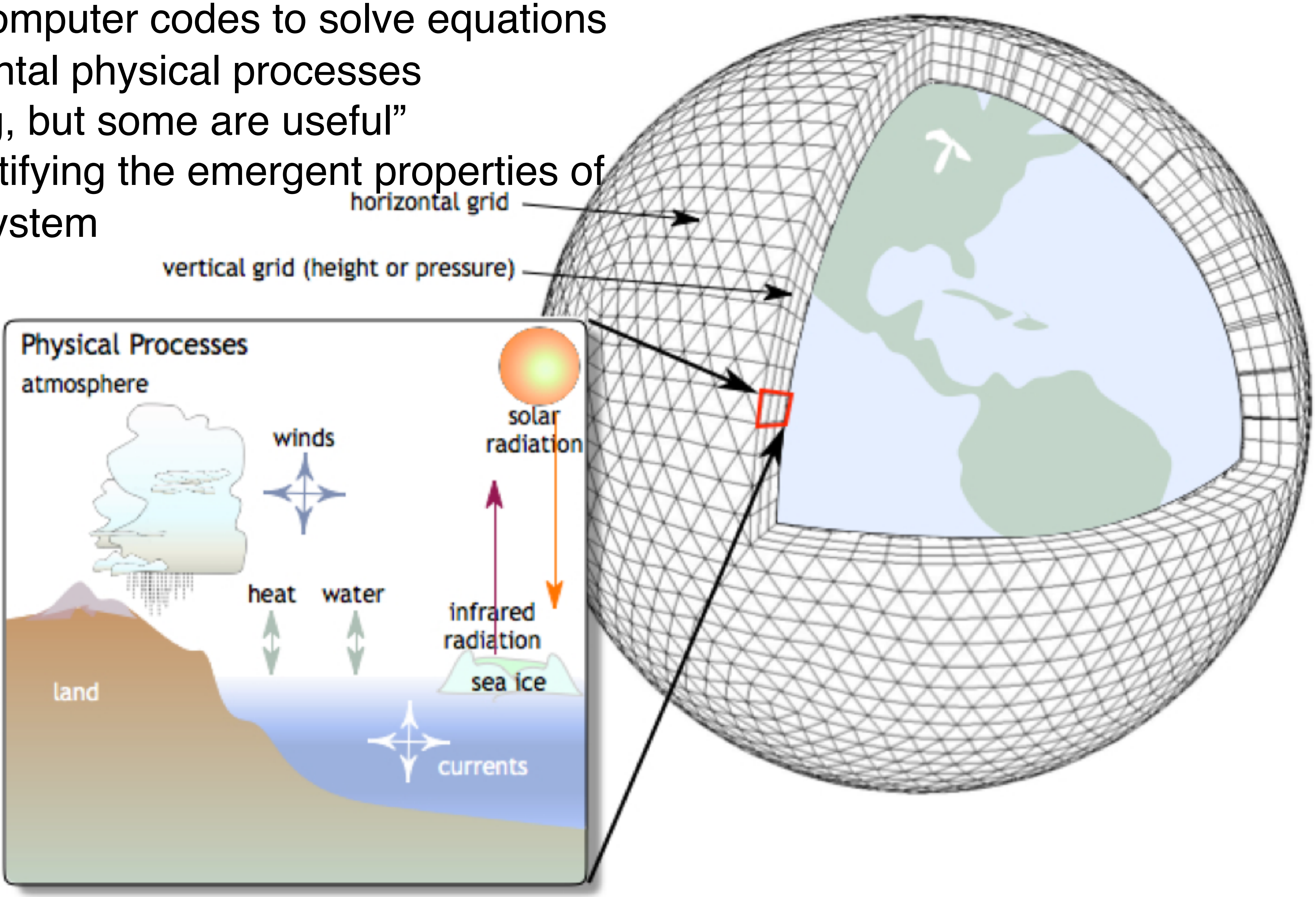


The **cloud feedback problem**: How will **each type of cloud** change in areal extent and frequency of occurrence as the climate warms???? *Enormously complicated*

Goosse H., P.Y. Barriat, W. Lefebvre, M.F. Loutre and V. Zunz. Introduction to climate dynamics and climate modeling. http://www.climate.be/textbook

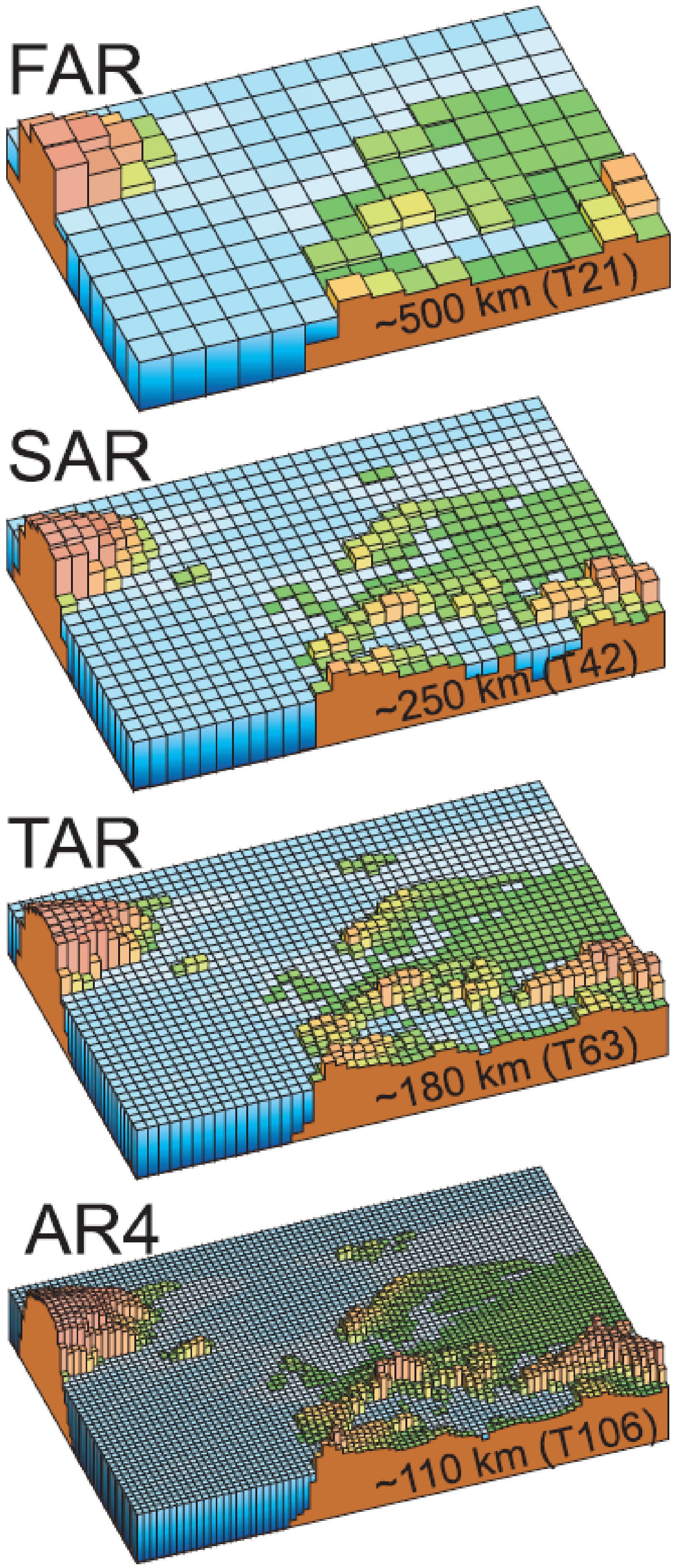
Global climate models…

•Extremely complex computer codes to solve equations representing fundamental physical processes
•“All models are wrong, but some are useful”
•Our best way of quantifying the emergent properties of the complex climate system



Lots of **different models** with slight differences in the way processes are represented. That’s a good thing! Lets us sample some of the **uncertainty** in our **climate projections**.

Progress in climate modeling (1)



1990

1995

2001

2007

Increasing model resolution typically means **more simulation** and **less parameterization**

IPCC, AR4, WG1, 2007

Climate models require enormous computer power!

Somewhere in Japan

Somewhere in Albany

Higher resolution + more processes resolved + longer simulations + bigger ensembles = more computing resources needed

History of climate sensitivity estimates

Knowledge and confidence increasing

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

- 1979 (NAS “Charney report”): 3ºC ± 1.5ºC
- 1990 (IPCC first assessment): 1.5ºC to 4.5ºC, best guess = 2.5ºC
- 2001 (IPCC third assessment): “likely in the range of 1.5 to 4.5 °C”
- 2007 (IPCC fourth assessment): “very likely is greater than 1.5 °C and **likely to lie in the range 2 to 4.5 °C**, with a most likely value of about 3°C”
- 2013 (IPCC fifth assessment): “**likely in the range 1.5 °C to 4.5 °C** (high confidence), extremely unlikely less than 1 °C (high confidence), and very unlikely greater than 6 °C (medium confidence)”

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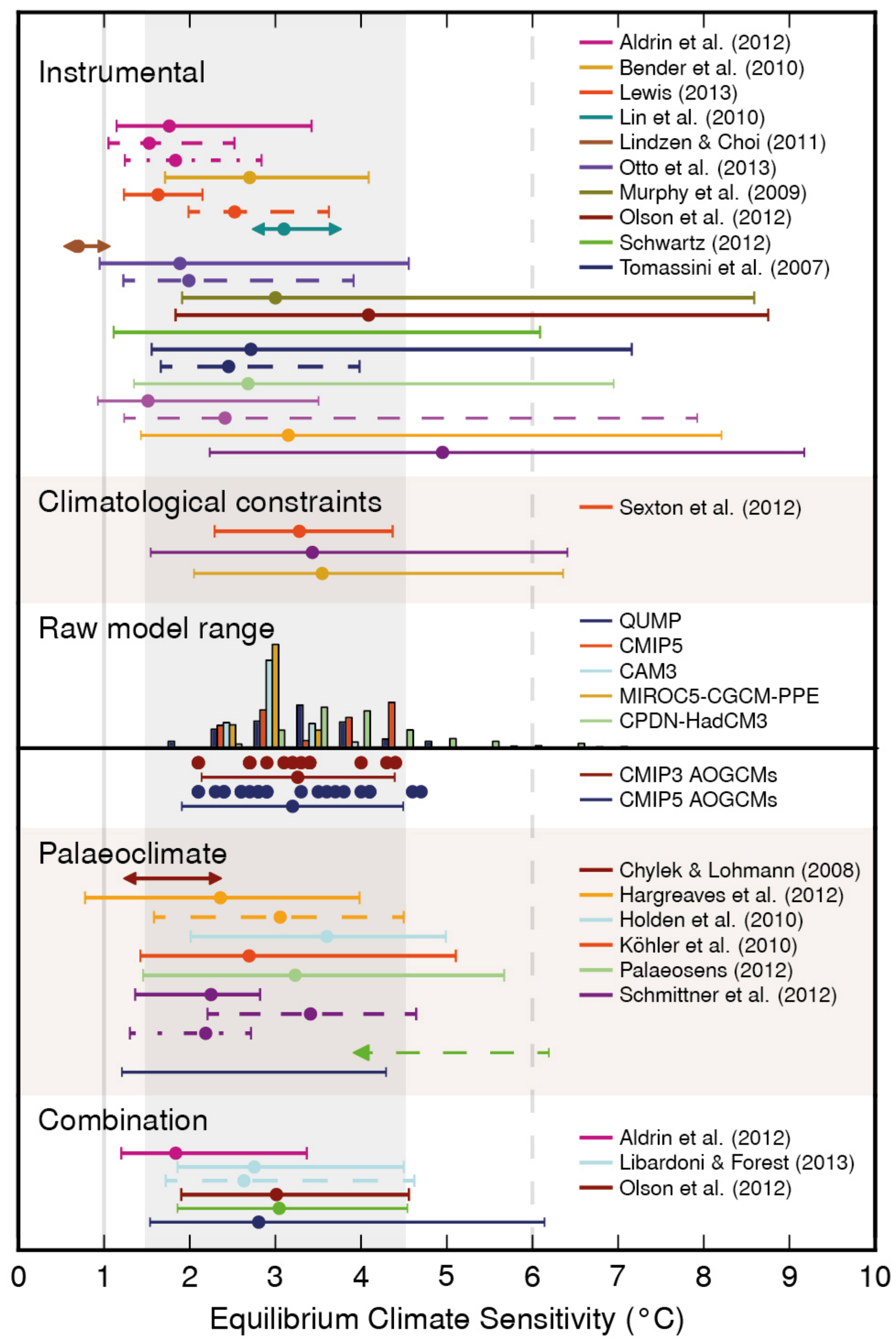
Why did low sensitivity become more likely between 2007 and 2013?
Is this correct?

IPCC report (2013): multiple lines of evidence for climate sensitivity

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$



Box 12.2, Figure 1 | Probability density functions, distributions and ranges for equilibrium climate sensitivity, based on Figure 10.20b plus climatological constraints shown in IPCC AR4 (Meehl et al., 2007b; Box 10.2, Figure 1), and results from CMIP5 (Table 9.5). The grey shaded range marks the *likely* 1.5°C to 4.5°C range, and the grey solid line the *extremely unlikely* less than 1°C, the grey dashed line the *very unlikely* greater than 6°C. See Figure 10.20b and Chapter 10 Supplementary Material for full caption and details. Labels refer to studies since AR4. Full references are given in Section 10.8.

Climate Change 2013: The Physical Science Basis (IPCC)

IPCC report (2013): multiple lines of evidence for climate sensitivity

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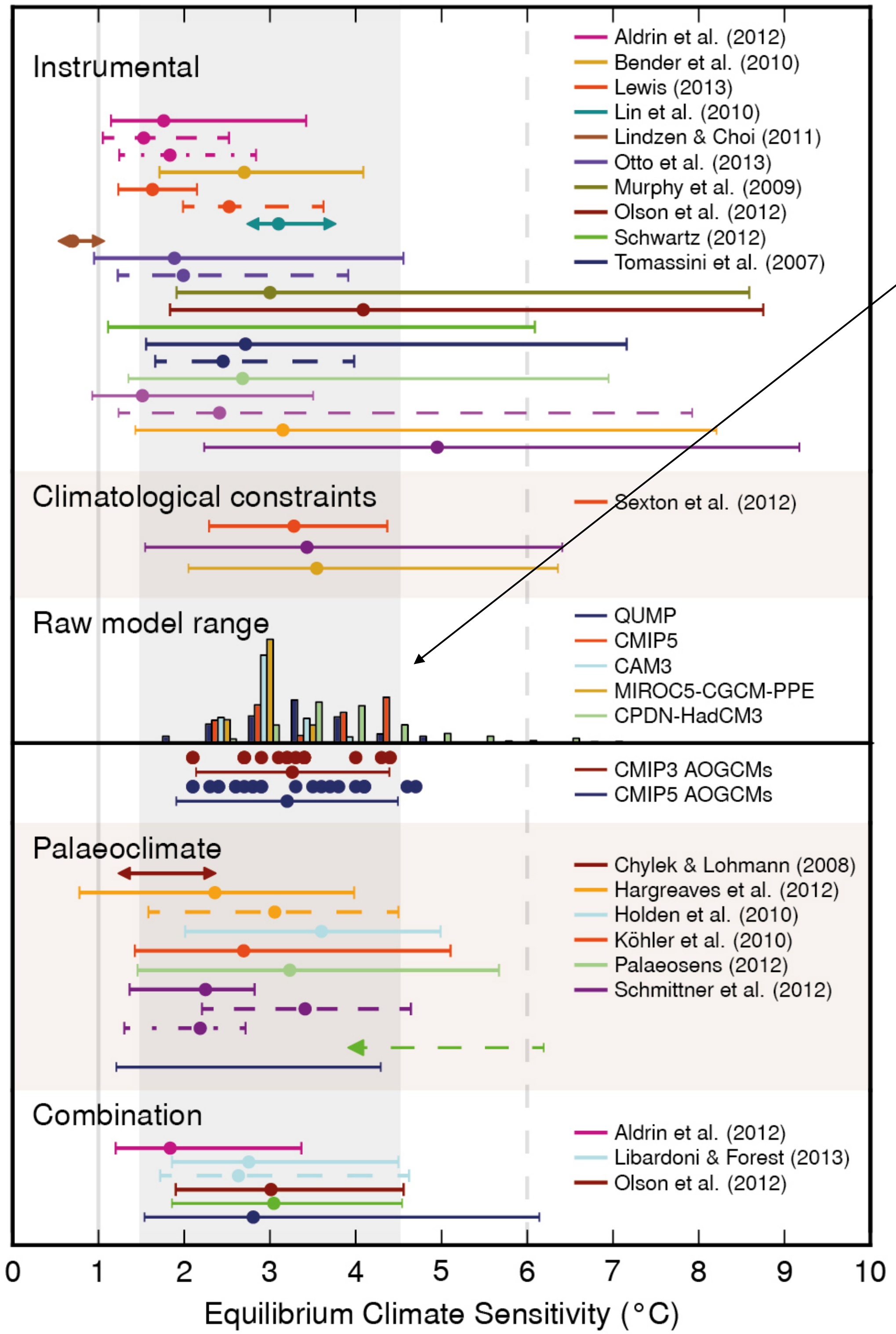

Predictions from climate models consistently medium to high sensitivity

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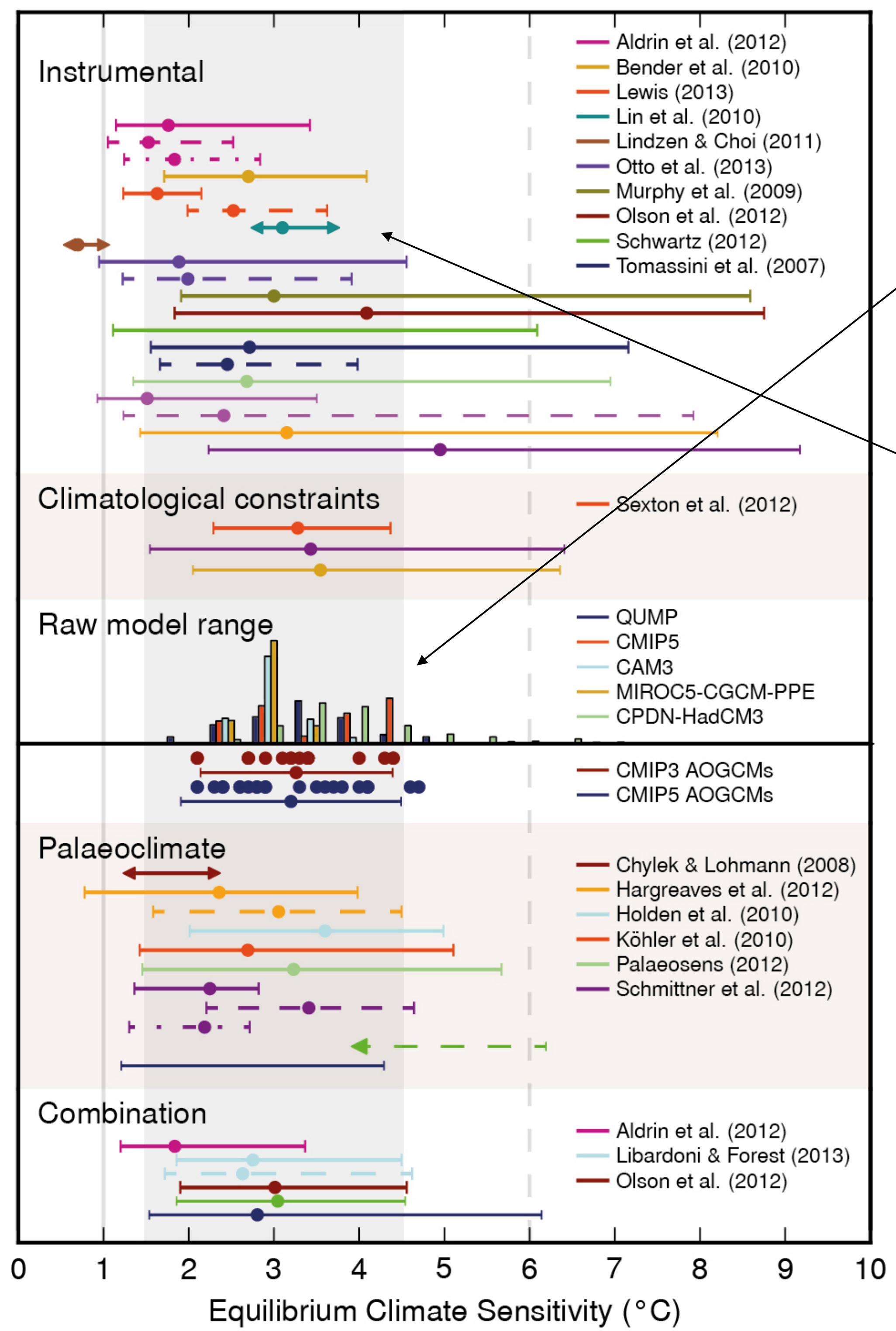

Predictions from climate models consistently medium to high sensitivity

But some studies using the instrumental (observed) climate record argued for lower sensitivity

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Climate Change 2013: The Physical Science Basis (IPCC)

One influential study: observations of global energy budget cannot rule out low sensitivity, e.g. ΔT_{2x} ~ 1.5ºC

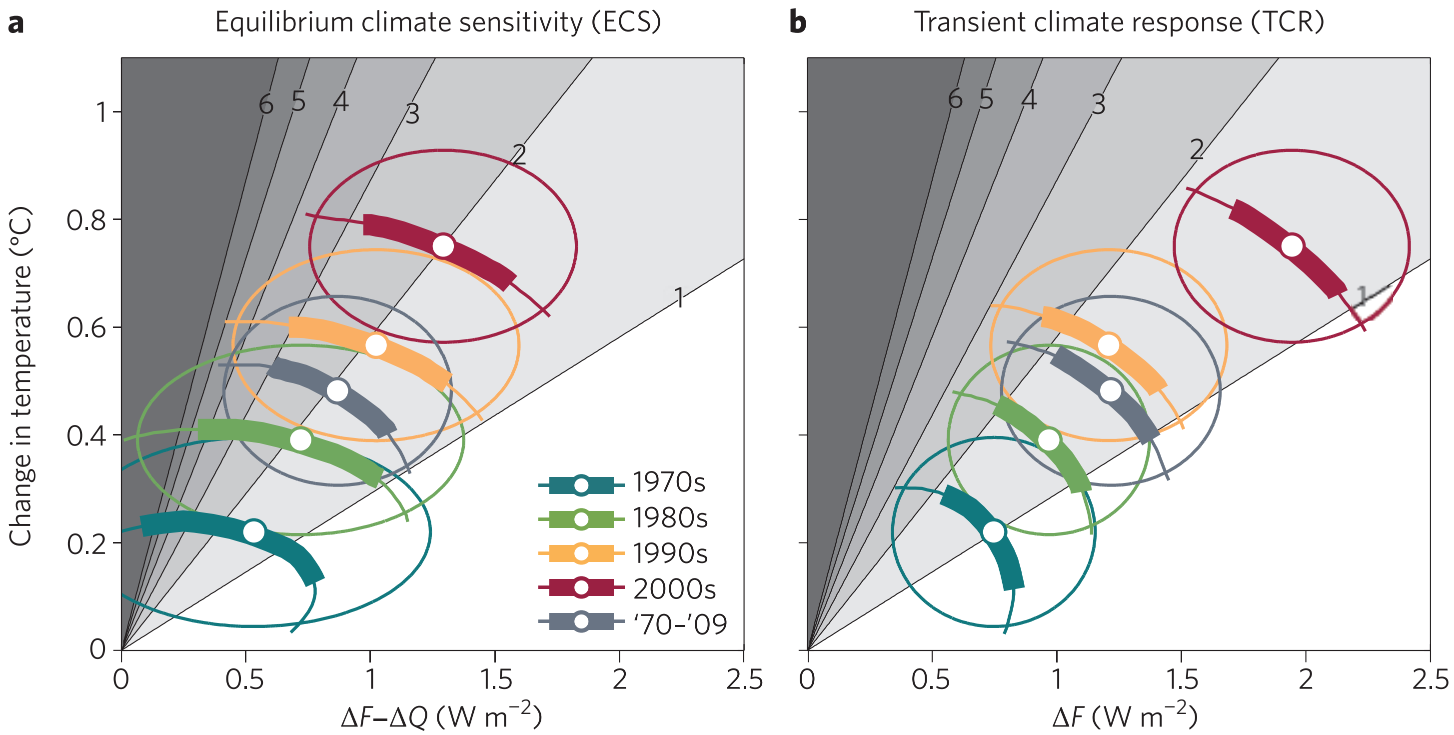


Figure 1 | Observations of the global energy budget and their implications. Observations of the global mean temperature change plotted against change in forcing minus heat uptake (ΔF–ΔQ) for the equilibrium climate sensitivity (ECS) (**a**) and against ΔF for the transient climate response (TCR) (**b**), for each of the four decades 1970s, 1980s, 1990s and 2000s and for the 40-year period 1970–2009. Ellipses represent likelihood contours enclosing 66% two-dimensional confidence regions; best-fit points of maximum likelihood are indicated by the circles; and the curved thick and thin lines represent the 17–83% and 5–95% confidence intervals of the resulting one-dimensional likelihood profile in ECS (or TCR), respectively. All time periods are referenced to 1860–1879, including a small correction in ΔQ to account for disequilibrium in this reference period[14]. Straight contours show iso-lines of ECS (**a**) and TCR (**b**), calculated using a best-fit value of F_{2x} of 3.44 W m^{-2} (also adjusted for fast feedbacks)[10]. Uncertainty in F_{2x} is assumed to be correlated with forcing uncertainty in long-lived greenhouse gases[10]. To avoid dependence on previous assumptions[16], we report results as likelihood-based confidence intervals.

Otto et al. (2013), *Nature Geosci.*
doi:10.1038/ngeo1836

The “Energy Budget” method

using observations of global planetary energy budget to calculate climate sensitivity

Assume the observed period obeys our basic climate model

$$\Delta F - \lambda \Delta T = \Delta Q$$

We can quantify these (global averages) from observations

Historical radiative forcing is reasonably well known (greenhouse gases, anthropogenic aerosols, volcanoes, etc)

The “Energy Budget” method

using observations of global planetary energy budget to calculate climate sensitivity

Then from historical observations we can calculate (with some uncertainty) the historical feedback parameter

$$\lambda_{obs} = \frac{\Delta F_{obs} - \Delta Q}{\Delta T_{obs}}$$

The “Energy Budget” method

using observations of global planetary energy budget to calculate climate sensitivity

$$\lambda_{obs} = \frac{\Delta F_{obs} - \Delta Q}{\Delta T_{obs}}$$

Since Climate Sensitivity is given by $$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda}$$

it then follows that, using historical observations, we can infer

$$\Delta T_{2x} = \frac{\Delta T_{obs} \Delta F_{2x}}{(\Delta F_{obs} - \Delta Q)}$$

Empirical measure of climate sensitivity, independent of climate models! (??)

The "Energy Budget" method

using observations of global planetary energy budget to calculate climate sensitivity

$$\Delta T_{2x} = \frac{\Delta T_{obs} \Delta F_{2x}}{(\Delta F_{obs} - \Delta Q)}$$

The method is simple and satisfying…
so simple that we often forget that it DOES depend on a climate model

Specifically, the assumption is that $$\lambda_{2x} = \lambda_{obs}$$

.. the feedbacks for short-term climate variability ARE THE SAME as the feedbacks governing long-term greenhouse warming

But this is not true!

Big thrust of recent research: understanding how and why lambda (i.e. the feedback) varies in time

An uncertain world: many possible simulated climatic histories. Reality chose one particular path

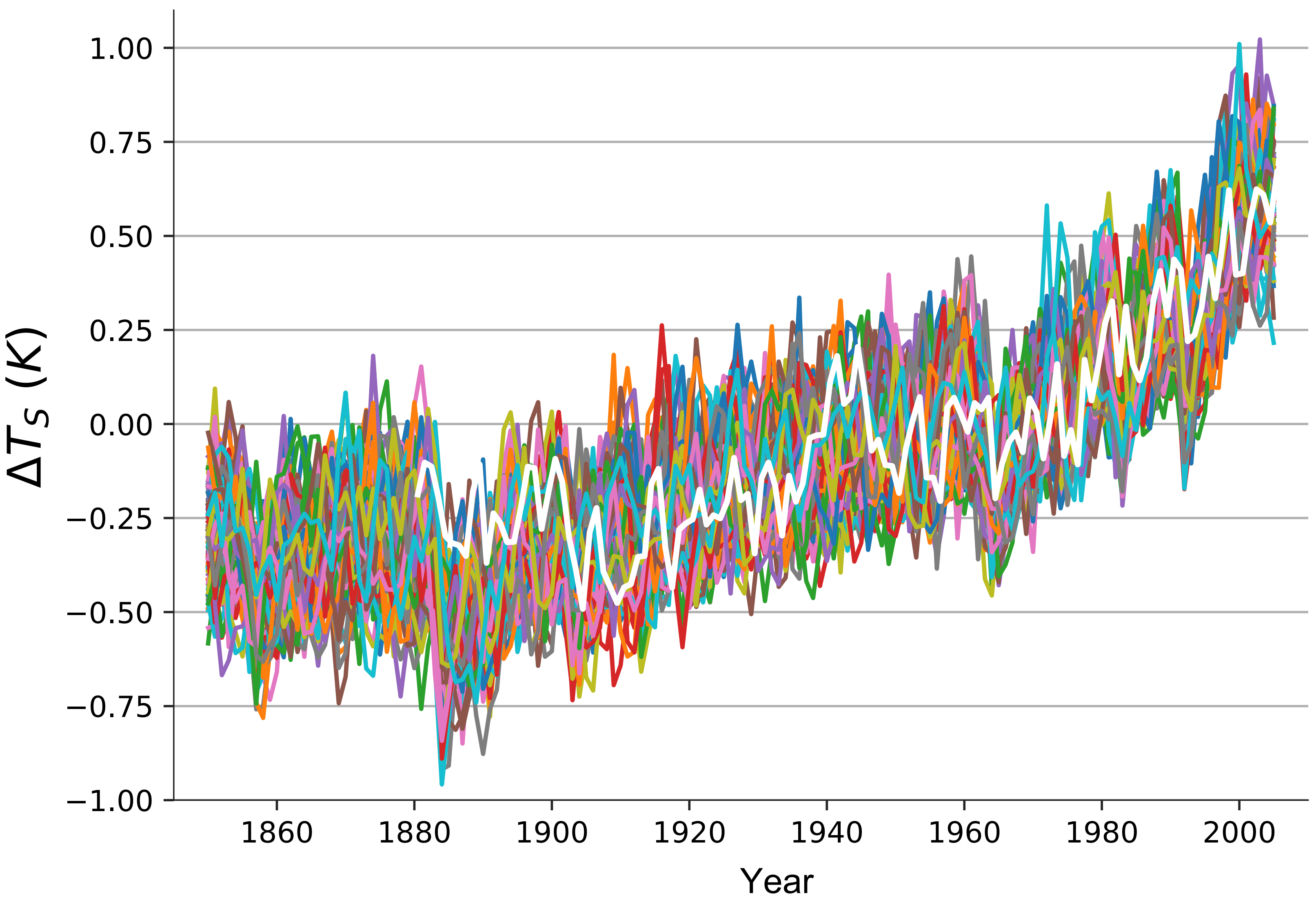
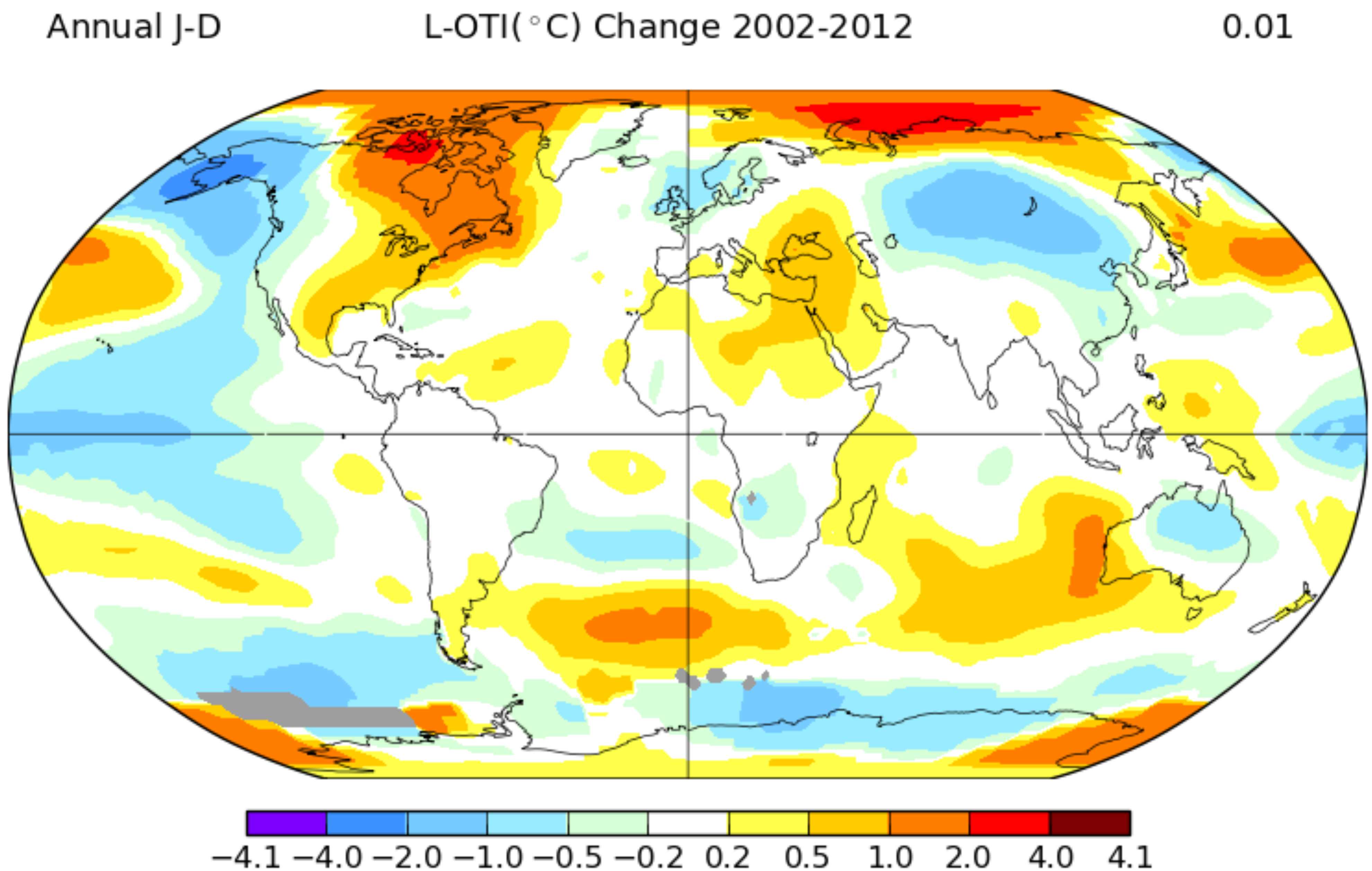


Figure 1. Plot of annual and global average surface temperature from the 100 members of the MPI-ESM1.1 ensemble (colored lines), along with the GISTEMP measurements (Hansen et al., 2010) (white line). Temperatures are referenced to the 1951–1980 average.

Dessler et al. (2018), *ACP*
doi:10.5194/acp-2017-1236

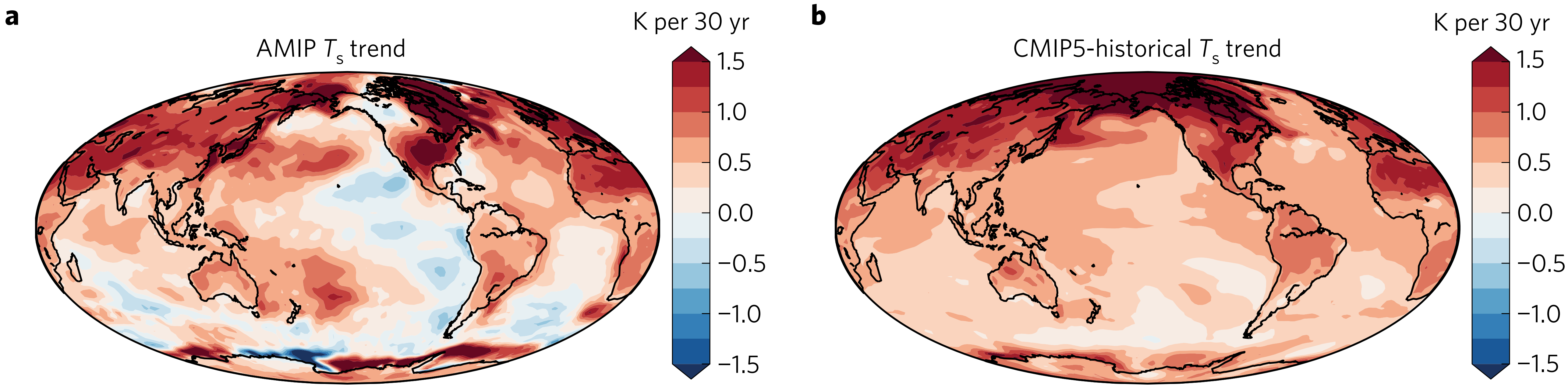
Temperature trends, 2002 - 2012 (the "hiatus" period)



Anomalous cooling in central and east tropical Pacific

https://data.giss.nasa.gov/gistemp/maps/

Climate models did not “predict” the hiatus.



Observations

Models

Averaging over many simulations gives the “forced” response — the variability is not as predictable

Zhou et al. (2016), *Nature Geosci.*
doi:10.1038/NGEO2828

A clever use of complex climate model as laboratory:

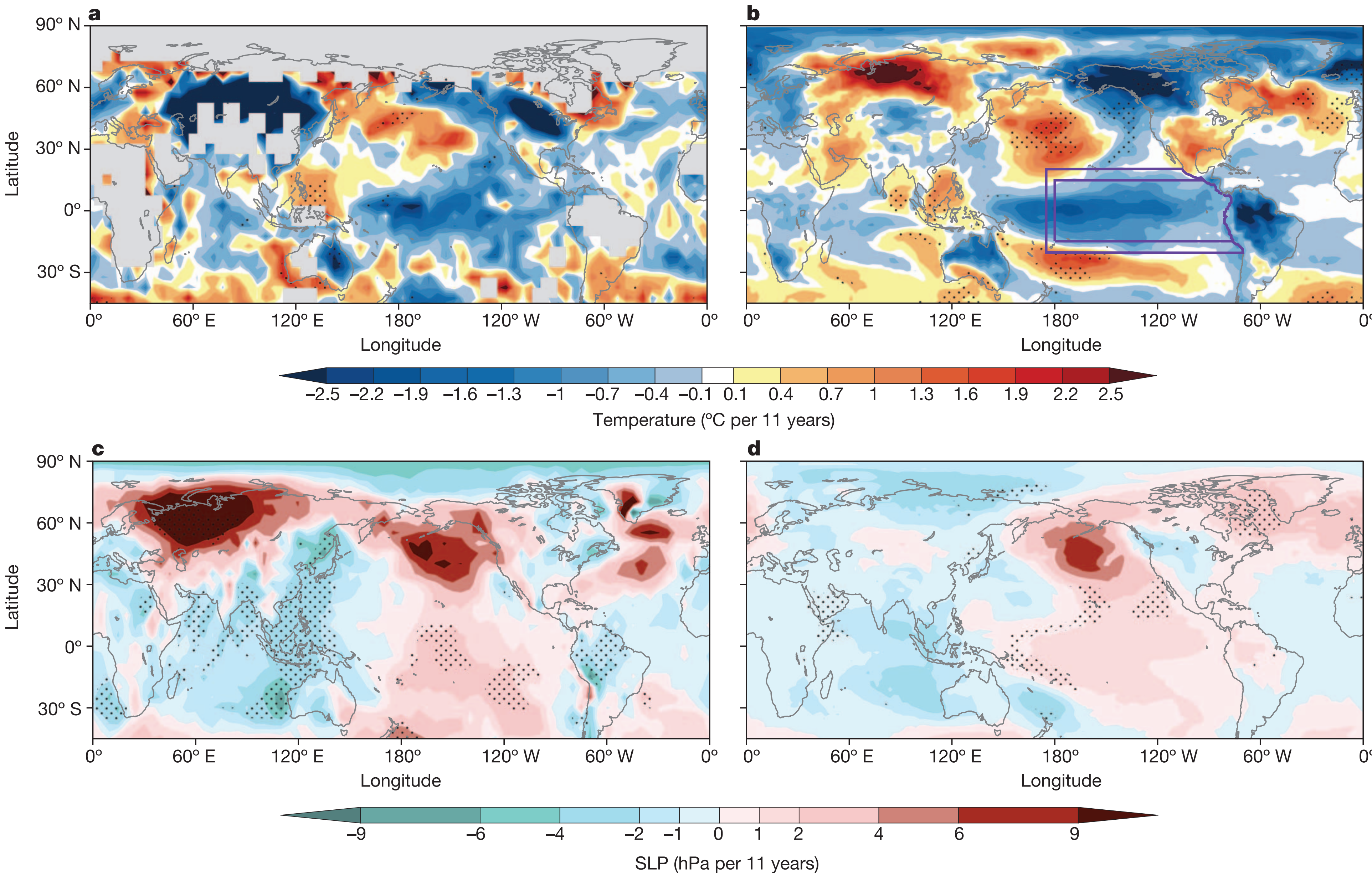
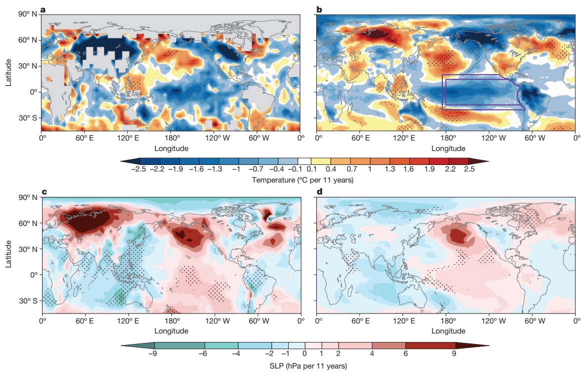


Figure 2 | Observed and simulated trend patterns in boreal winter for 2002–2012. **a** and **b** show near-surface temperature and **c** and **d** show SLP from observations (**a** and **c**) and POGA-H (**b** and **d**) in DJF. Grey shading represents missing values. Stippling indicates regions exceeding 95% statistical confidence. Purple boxes in **b** show the restoring region of POGA experiments.

Simulations where the surface temperature is pinned to observations only with the tropical Pacific box

Kosaka and Xie (2013), *Nature*
doi:10.1038/nature12534



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As goes the tropical Pacific, so goes the world…

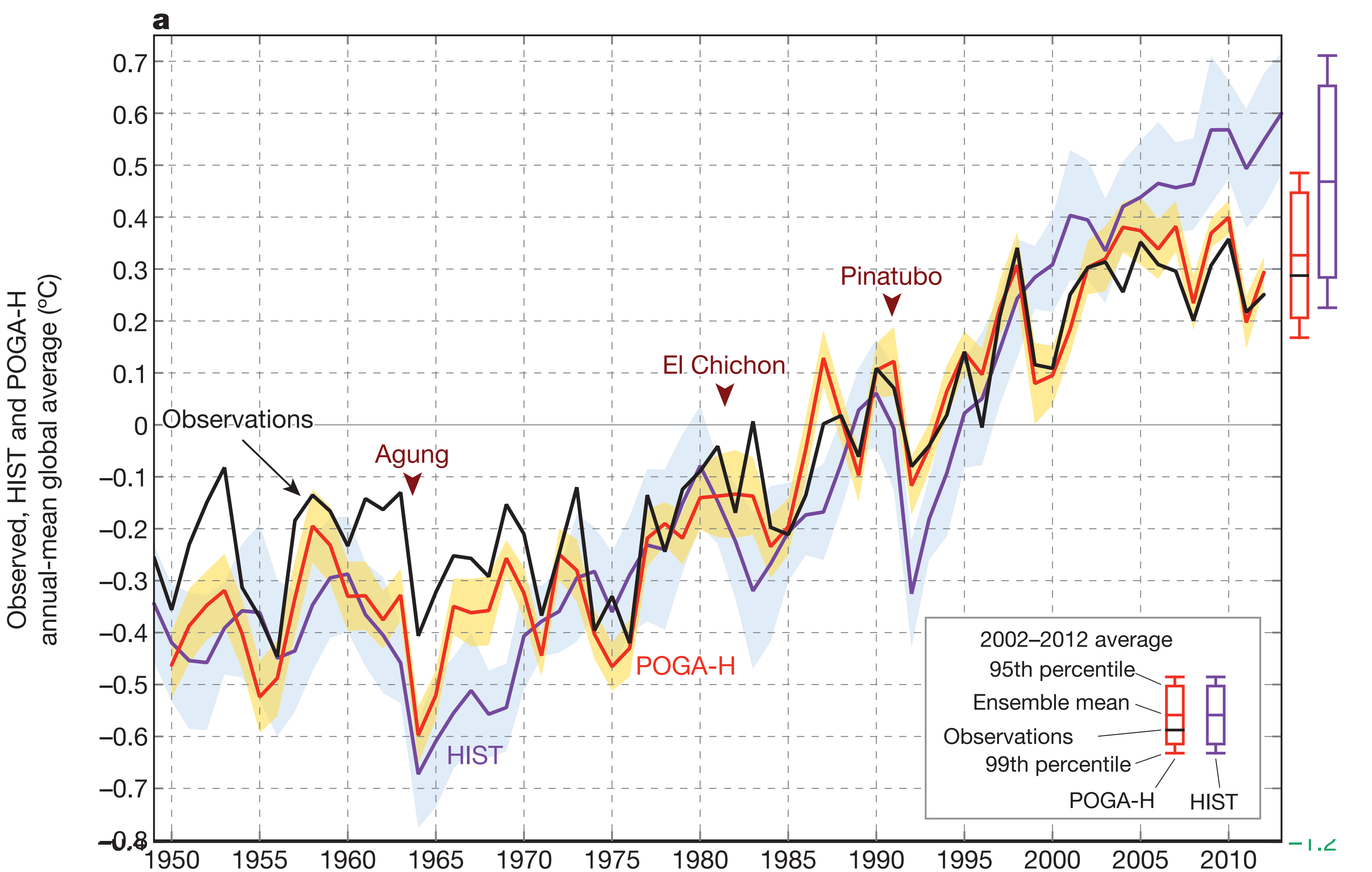


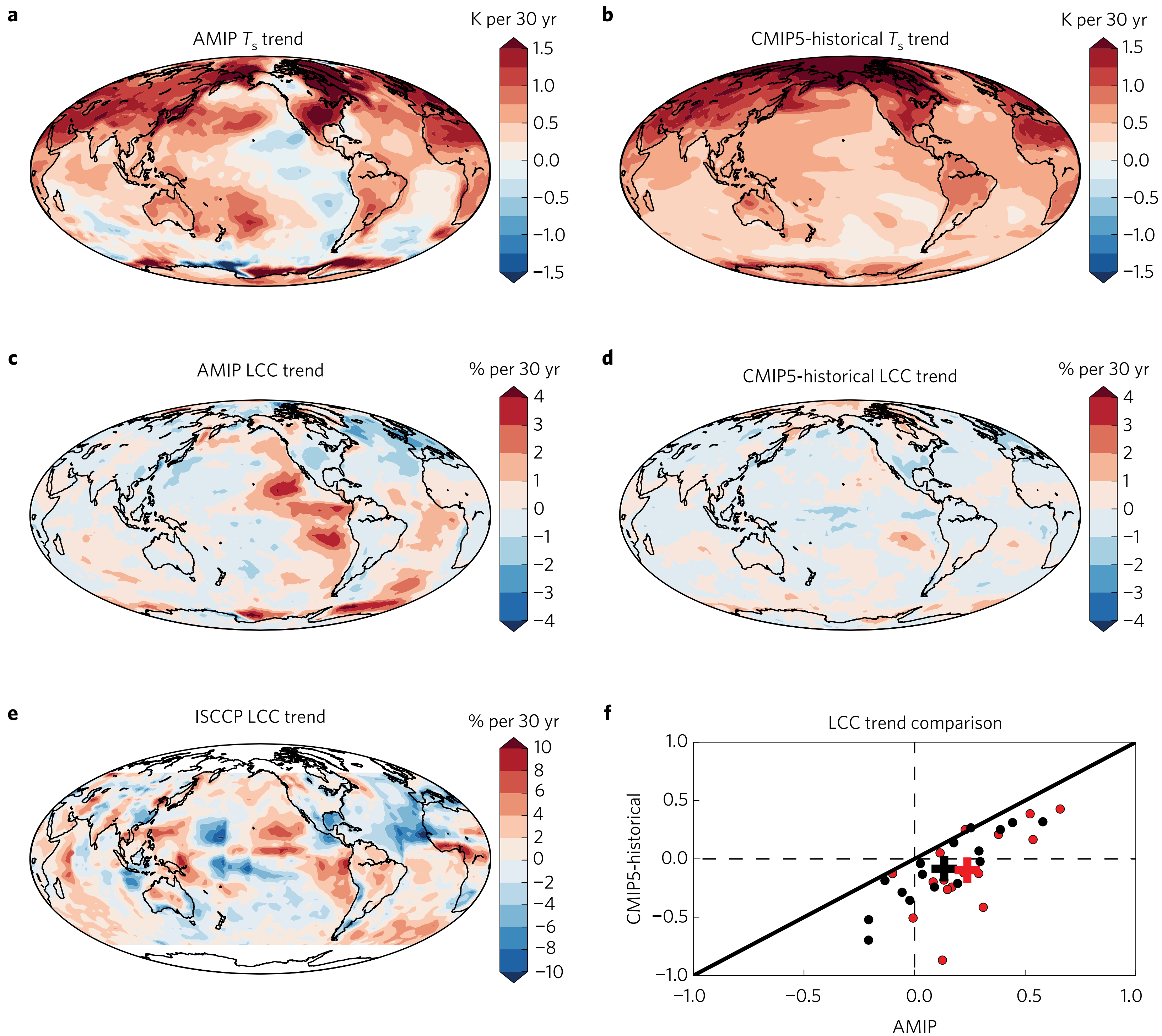
Figure 1 | Observed and simulated global temperature trends. Annual-mean time series based on observations, HIST and POGA-H (**a**) and on POGA-C (**b**). Anomalies are deviations from the 1980–1999 averages, except for HIST, for which the reference is the 1980–1999 average of POGA-H. SAT anomalies over the restoring region are plotted in **b**, with the axis on the right. Major volcanic eruptions are indicated in **a**. **c**, Trends of seasonal global temperature for 2002–2012 in observations and POGA-H. Shading represents 95% confidence interval of ensemble means. Bars on the right of **a** show the ranges of ensemble spreads of the 2002–2012 averages.

Kosaka and Xie (2013), *Nature*
doi:10.1038/nature12534

Low clouds (reflectors!!) respond strongly to East Pacific temperatures

Observed temperature

Observed low clouds

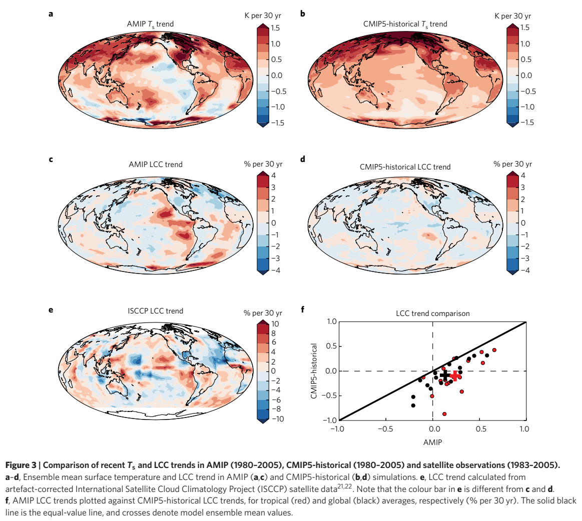


Climate models get the cloud trends right if they have the right ocean temperatures!

Figure 3 | Comparison of recent T_s and LCC trends in AMIP (1980–2005), CMIP5-historical (1980–2005) and satellite observations (1983–2005). **a**–**d**, Ensemble mean surface temperature and LCC trend in AMIP (**a**,**c**) and CMIP5-historical (**b**,**d**) simulations. **e**, LCC trend calculated from artefact-corrected International Satellite Cloud Climatology Project (ISCCP) satellite data[21,22]. Note that the colour bar in **e** is different from **c** and **d**. **f**, AMIP LCC trends plotted against CMIP5-historical LCC trends, for tropical (red) and global (black) averages, respectively (% per 30 yr). The solid black line is the equal-value line, and crosses denote model ensemble mean values.

Zhou et al. (2016), *Nature Geosci.* doi:10.1038/NGEO2828

Historical warming/cooling patterns are not good analogs for future warming…



Recent history, especially the "hiatus" in the 2000s:

- **suppressed warming of East Pacific**
    - ***not entirely understood, but due to slowly evolving ocean circulation***
- **Increased marine low cloud cover**
    - ***Suppressed surface warming stabilizes the atmosphere, makes low clouds***
- **More reflection of sunlight**
- **slower global warming**
- **smaller inferred climate sensitivity**

https://data.giss.nasa.gov/gistemp/maps/

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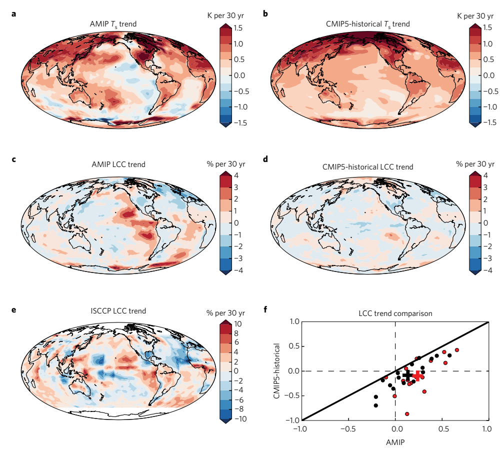

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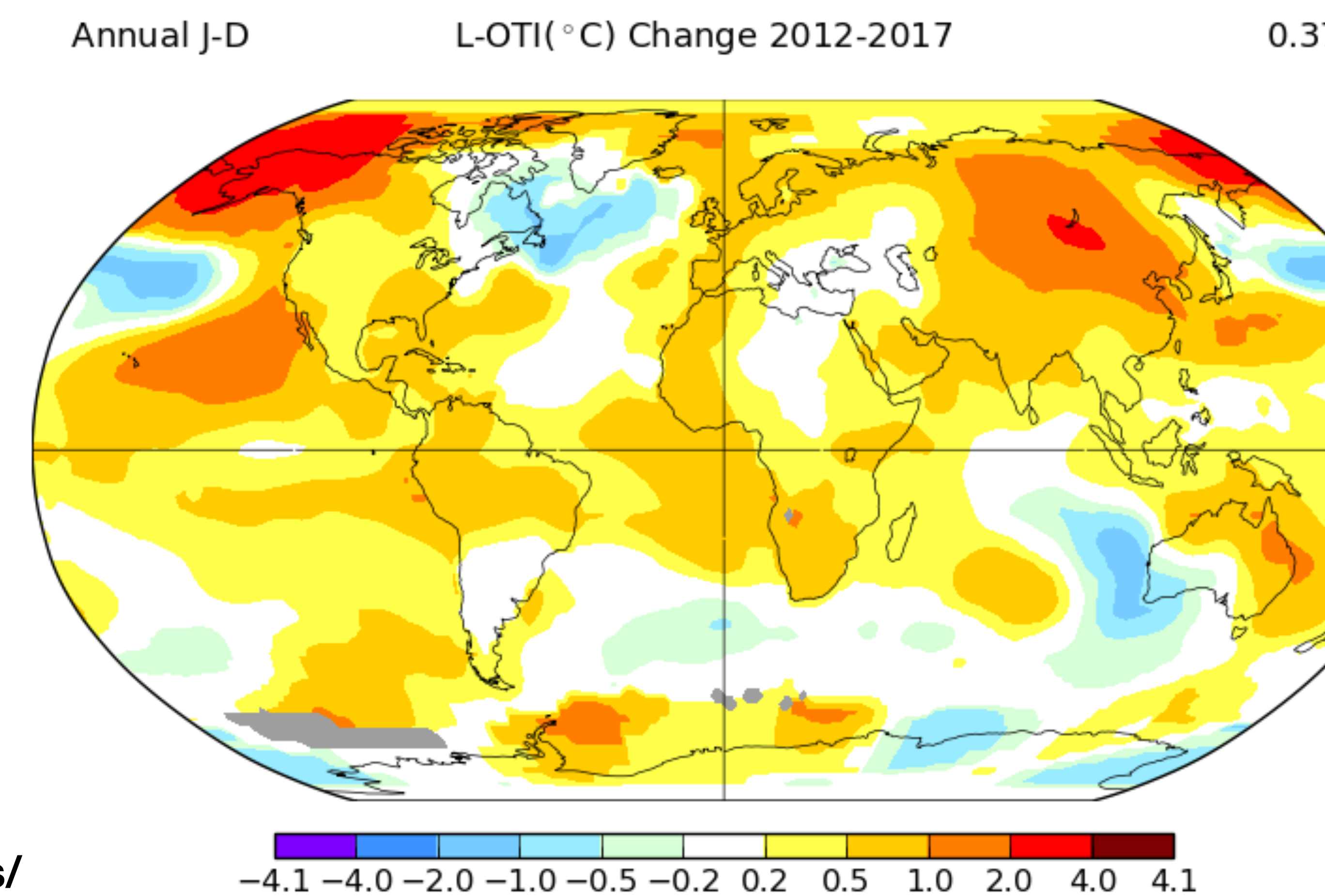
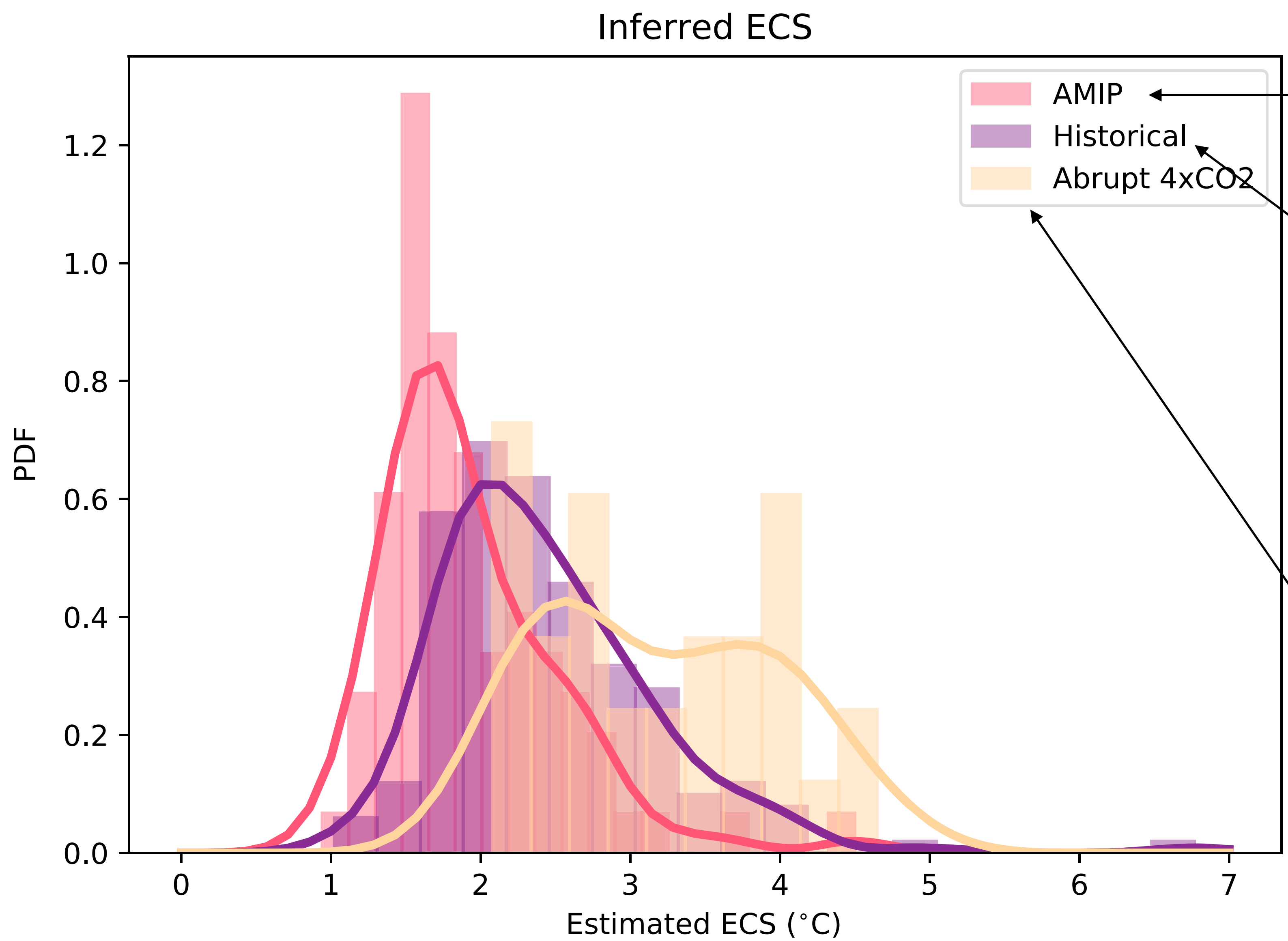
There is no reason to expect this pattern to continue… and it is not continuing



https://data.giss.nasa.gov/gistemp/maps/

Using the climate models to differentiate between past and future sensitivity…



The models **get the correct** historical surface temperature

The models **predict** historical surface temperatures from historical forcing

The models calculate **future forced warming** from increased CO_2

Figure 1. Equilibrium climate sensitivities inferred from amip (pink), historical (purple), and long-term (yellow) simulations, with kernel density estimates overplotted for visual clarity.

Marvel et al. (2018), *GRL*
doi:10.1002/2017GL076468

Reinterpreting observations of Earth's energy budget

$$\Delta T_{2x} = \frac{\Delta T_{obs} \Delta F_{2x}}{S(\Delta F_{obs} - \Delta Q)}$$

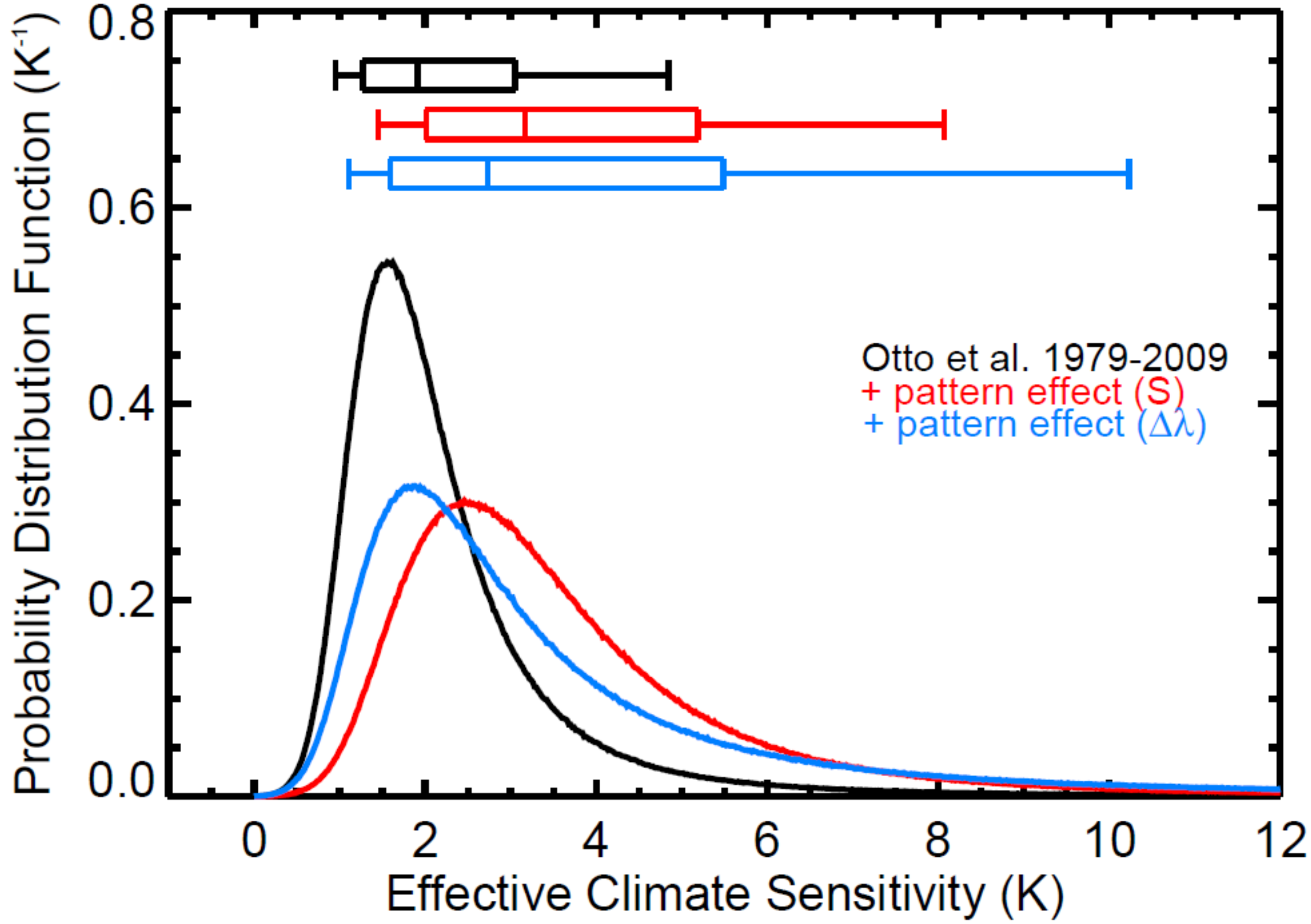


Figure 3: Comparison of the EffCS probability distribution function from a historical energy budget constraint (Otto et al, 2013), before (black) and after (colours) accounting for the pattern effect between historical climate change and abrupt-4xCO2. 'Red' accounts for the pattern effect by scaling the historical feedback parameter λ_{hist} by the ratio ($S=\lambda_{4xCO2}/\lambda_{amip}$) of the feedbacks found in the *amip-piForcing* and *abrupt-4xCO$_2$* simulations. 'Blue' accounts for the pattern effect by adding the difference in feedbacks ($\Delta\lambda=\lambda_{4xCO2}-\lambda_{amip}$) to λ_{hist} (see Section 4 and Table 1). Box plots show the 5-95% confidence interval (end bars), the 17-83% confidence interval (box ends) and the median (line in box).

Using state-of-the-art climate models to account for differences in the feedbacks affecting historical and future climate change

Andrews et al. (2018), *GRL*
doi:10.1029/2018GL078887

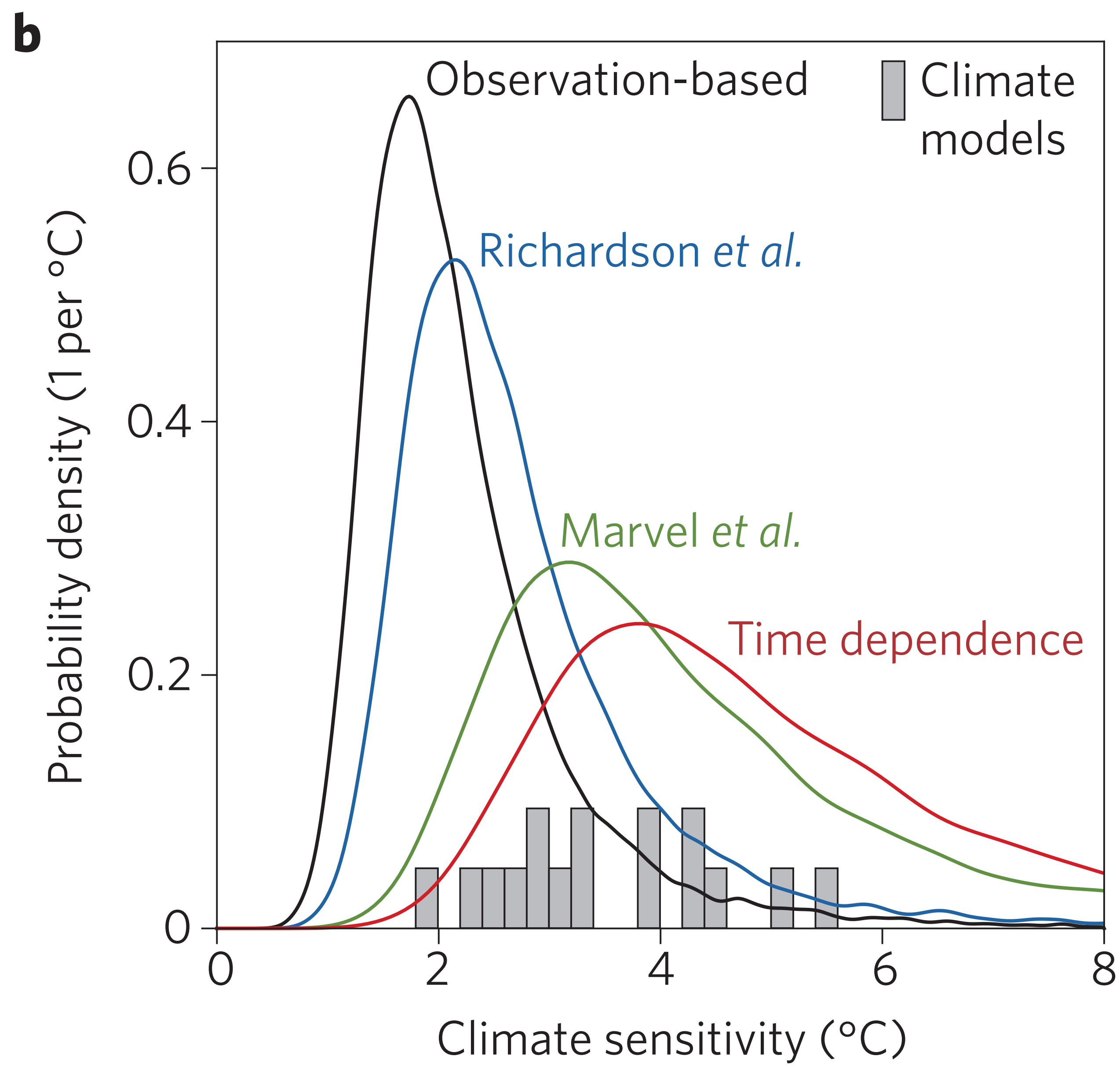
Making best use of Earth observations to infer climate sensitivity… is a work in progress!

The simplest budget-based estimates are almost surely biased low — for a variety of reasons!

Almost every serious attempt to correct these estimates using detailed knowledge of the workings of the climate system yield higher sensitivities.

There is no compelling evidence that current climate models are too sensitive.

(also… we cannot rule out very high sensitivity through these arguments)



Armour (2016), *Nature Clim. Change*
doi:10.1038/nclimate3079

Conclusion: *learning the right lessons about the future from the past*

- Climate change was/will be a combination of **forced warming** (more predictable) and complex regional variability (less predictable)
- Recent observations tell us about one (only) out of many possible histories
- There is (unfortunately) **no such thing as a measurement of climate sensitivity** — only fitting observations to climate models!
- **Naively fitting** to the **simplest model** of the global energy balance leads us astray in several ways:
    - **Pattern effects**: parts of the world that warm the slowest (East Pacific, Southern Ocean) are (coincidentally?) also regions associated with strongly amplifying feedbacks (clouds and ice)
    - Sensitivity **inferred from any short-term period of warming** is likely to be **biased low**. Future loss of marine cloud will give additional warming.
    - The **“hiatus” period of the 2000s** is especially problematic! Anomalous cooling of East Pacific really exacerbated this low bias. This period was simply **not a good proxy for future global warming**.
    - Other ongoing work: teasing apart effects of **greenhouse gases** from **aerosols** on past warming, biases in global temperature datasets, etc etc etc.
- Detailed studies, informed by nuanced physical understanding of climatic processes, show that **a lukewarm future** (e.g. sensitivity < 2°C) **is very unlikely**.

Extra slides

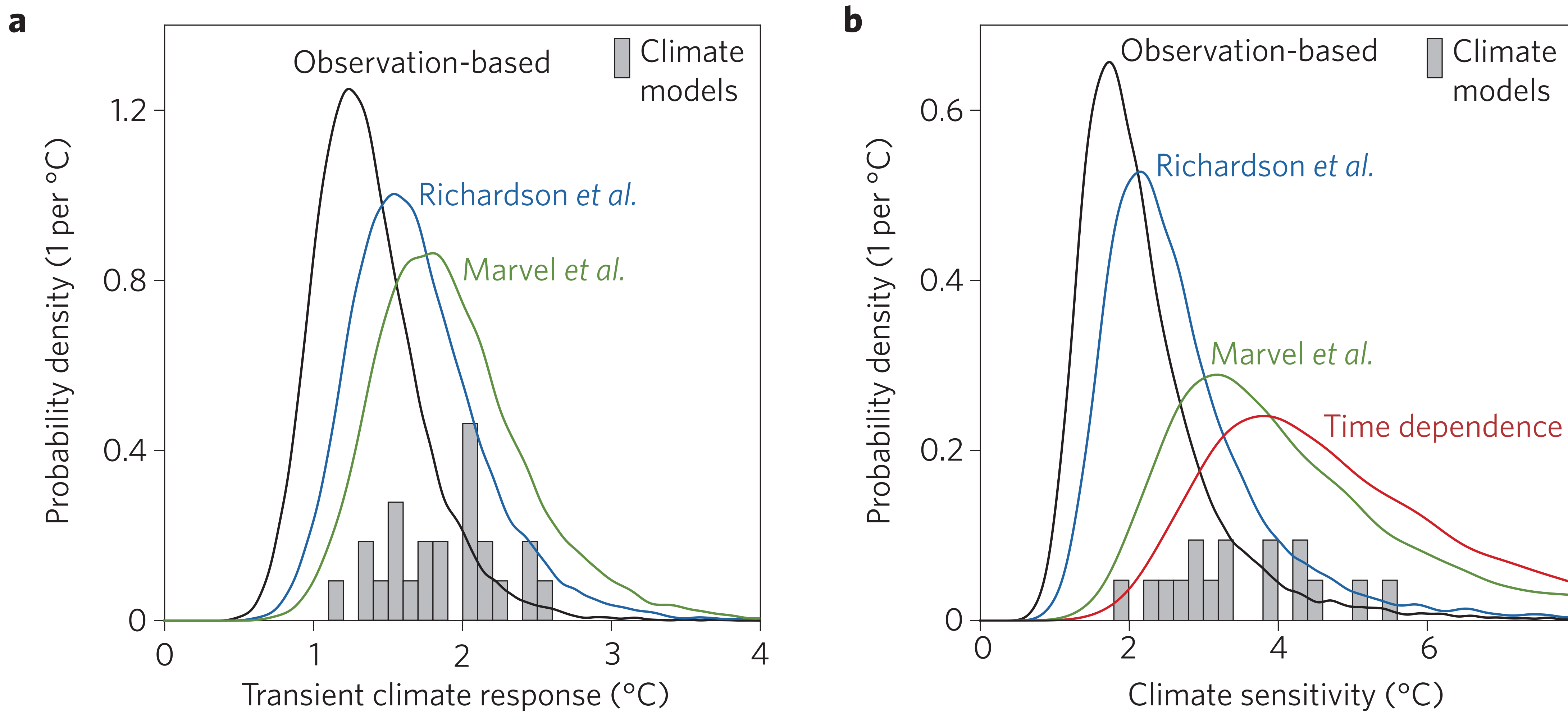
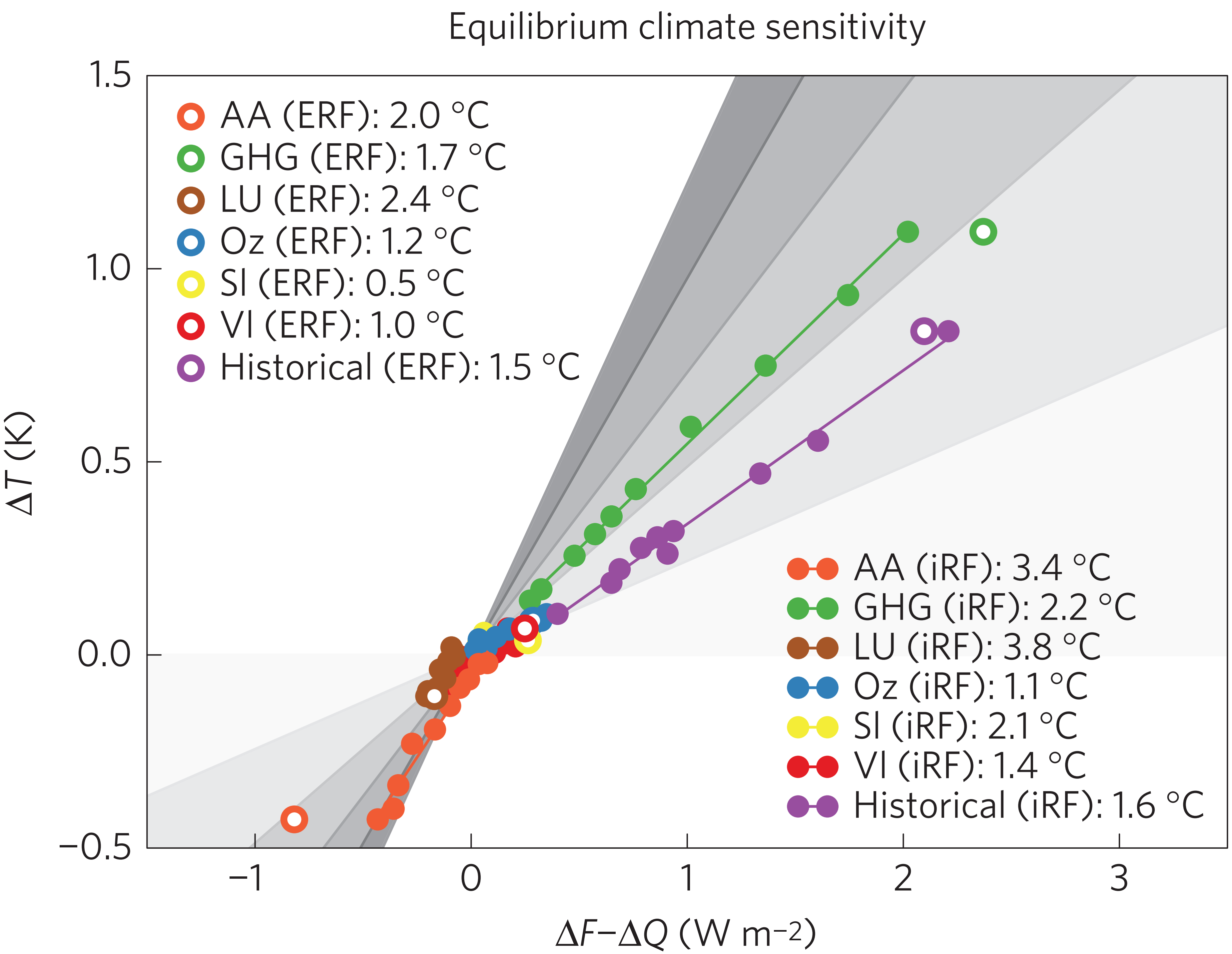
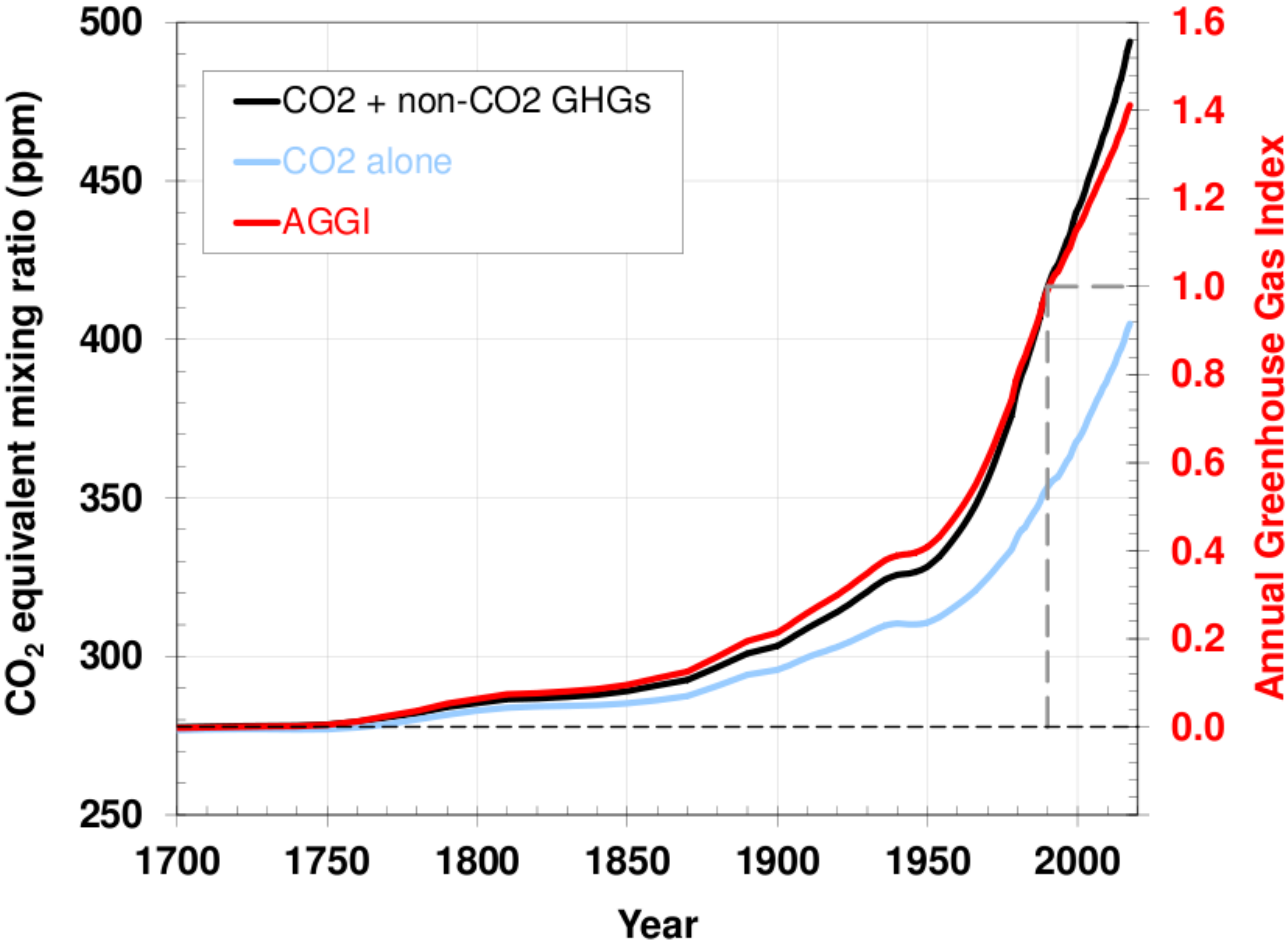


Figure 1 | Probability distribution of climate response to forcings. **a**, Transient climate response estimated from observations[1] (black), and its revision following Richardson *et al.*[3] (blue) then following Marvel *et al.*[6] (green). **b**, As with **a** but for climate sensitivity, with an additional revision for climate sensitivity appearing smaller than its true value[7–11] (red). Histogram of climate model values shown in grey.

Armour (2016), *Nature Clim. Change*
doi:10.1038/nclimate3079



Marvel et al. (2015), ***Nature Clim. Change***
doi:10.1038/NCLIMATE2888



https://www.esrl.noaa.gov/gmd/aggi/

“Radiative forcing”: sources of energy to the climate system

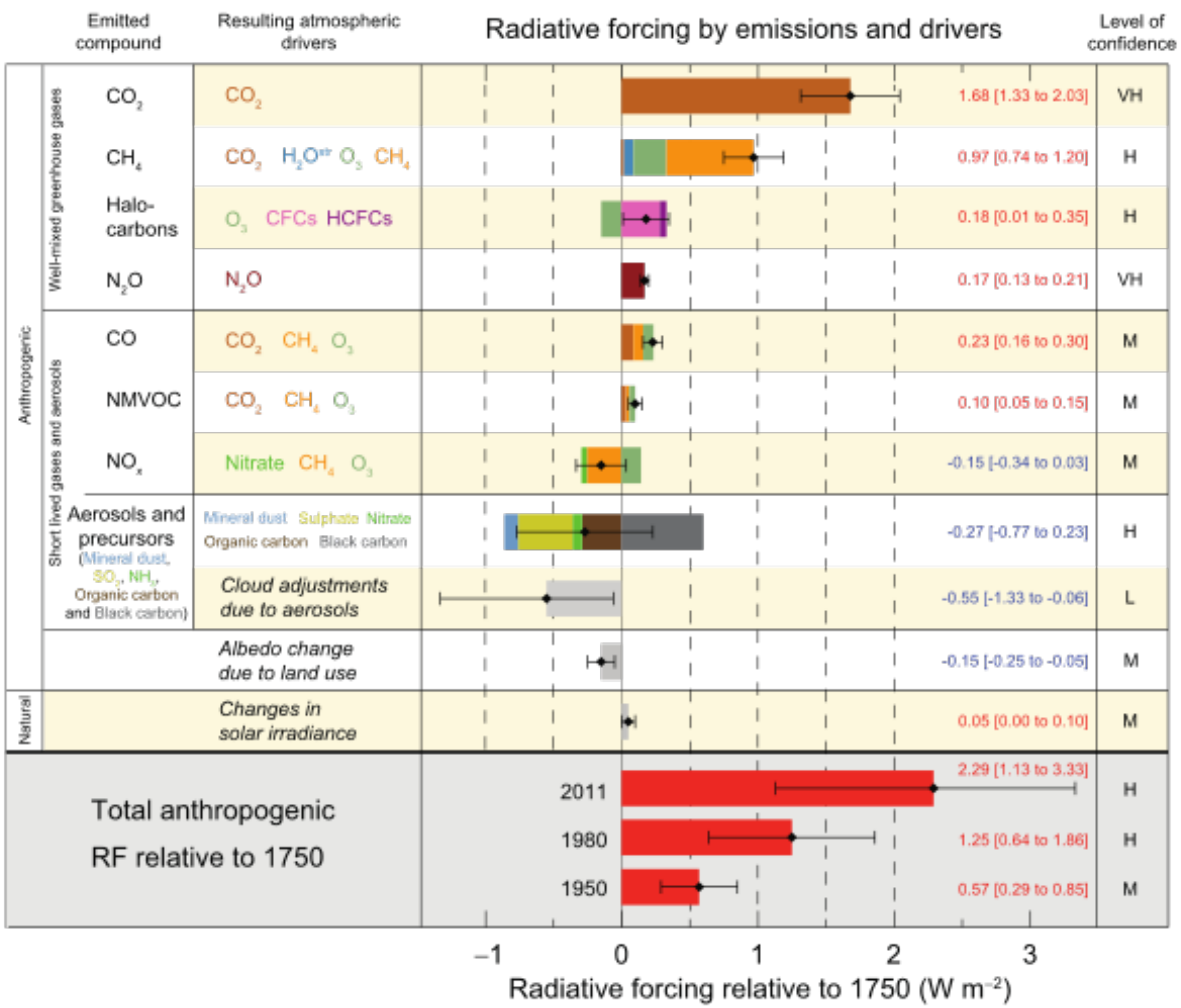
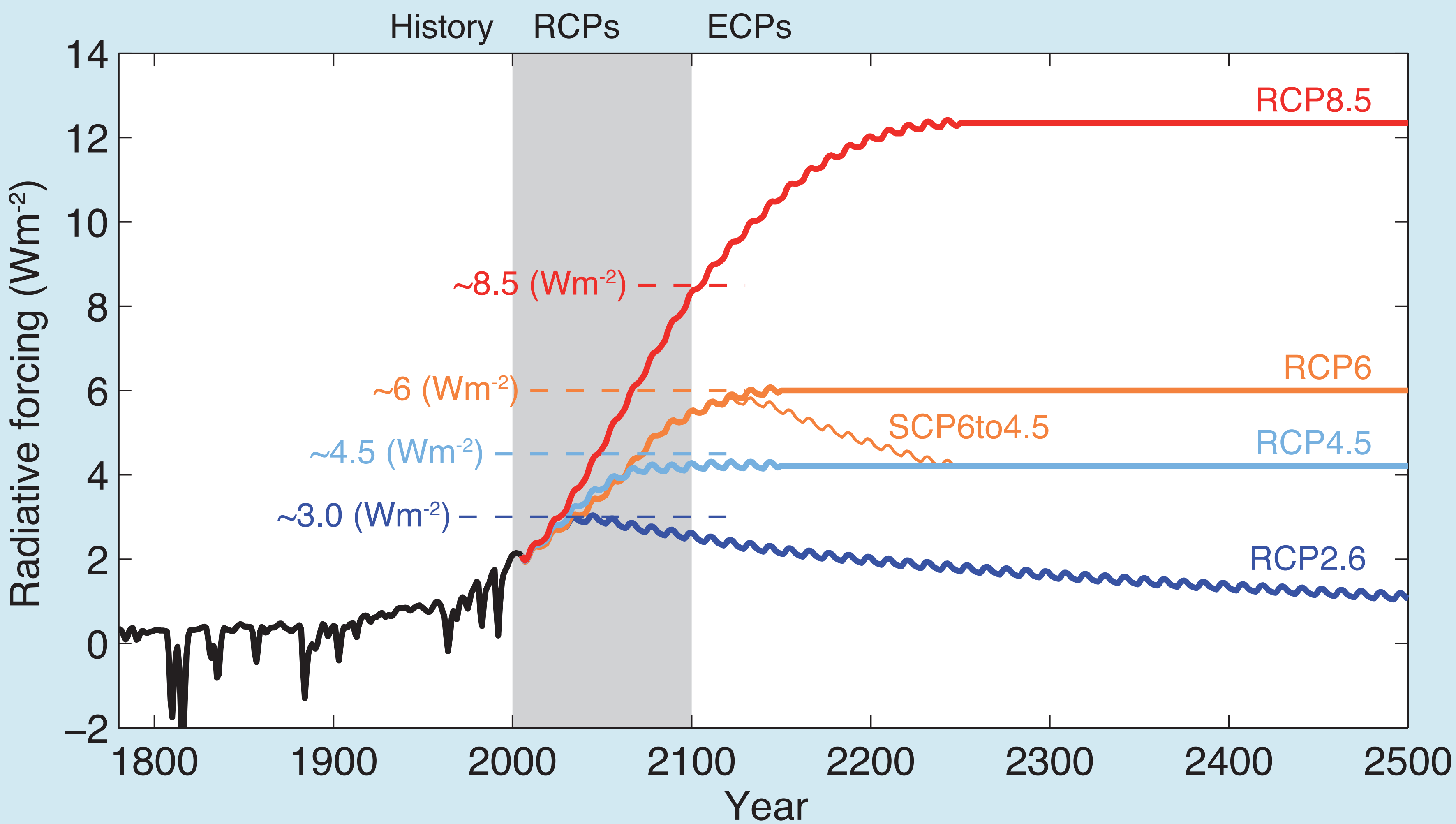


Figure SPM.5 | Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF[14]), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – *very high*, H – *high*, M – *medium*, L – *low*, VL – *very low*). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W m^{-2}, including contrail induced cirrus), and HFCs, PFCs and SF_6 (total 0.03 W m^{-2}) are not shown. Concentration-based RFs for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes is difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three different years relative to 1750. For further technical details, including uncertainty ranges associated with individual components and processes, see the Technical Summary Supplementary Material. {8.5; Figures 8.14–8.18; Figures TS.6 and TS.7}

The total energy input into the climate system by human activities over the industrial era is about 2.3 W m^{-2}.

CO_2 from fossil fuel combustion is the single largest culprit.

Climate Change 2013: The Physical Science Basis (IPCC)



Box 1.1, Figure 1 | Total RF (anthropogenic plus natural) for RCPs and extended concentration pathways (ECP)—for RCP2.6, RCP4.5, and RCP6, RCP8.5, as well as a supplementary extension RCP6 to 4.5 with an adjustment of emissions after 2100 to reach RCP4.5 concentration levels in 2250 and thereafter. Note that the stated RF levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future RF levels for any given scenario. Short-term variations in RF are due to both volcanic forcings in the past (1800–2000) and cyclical solar forcing assuming a constant 11-year solar cycle (following the CMIP5 recommendation), except at times of stabilization. (Reproduced from Figure 4 in Meinshausen et al., 2011.)

Climate Change 2013: The Physical Science Basis (IPCC)

Global mean temperature changes

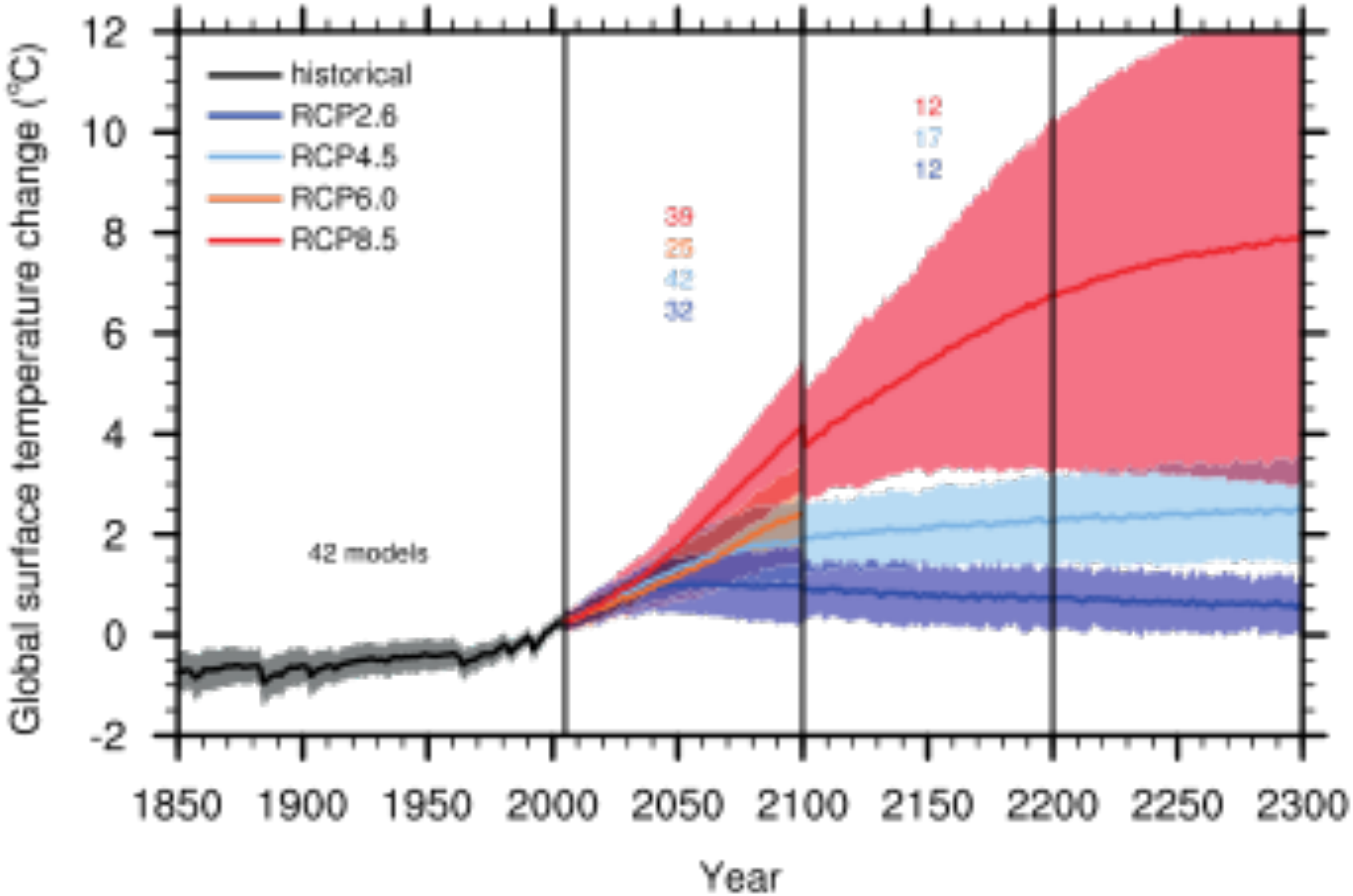


Figure 12.5 | Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are

Climate Change 2013: The Physical Science Basis (IPCC)

Figure 12.9 | Surface air temperature change in 2081–2100 displayed as anomalies with respect to 1986–2005 for RCP4.5 from one ensemble member of each of the concentration-driven models available in the CMIP5 archive.

42 different possible futures under one particular radiative forcing scenario

Climate Change 2013: The Physical Science Basis (IPCC)

50-year warming trends simulated in a single climate model…

each one of these scenarios is equally likely!

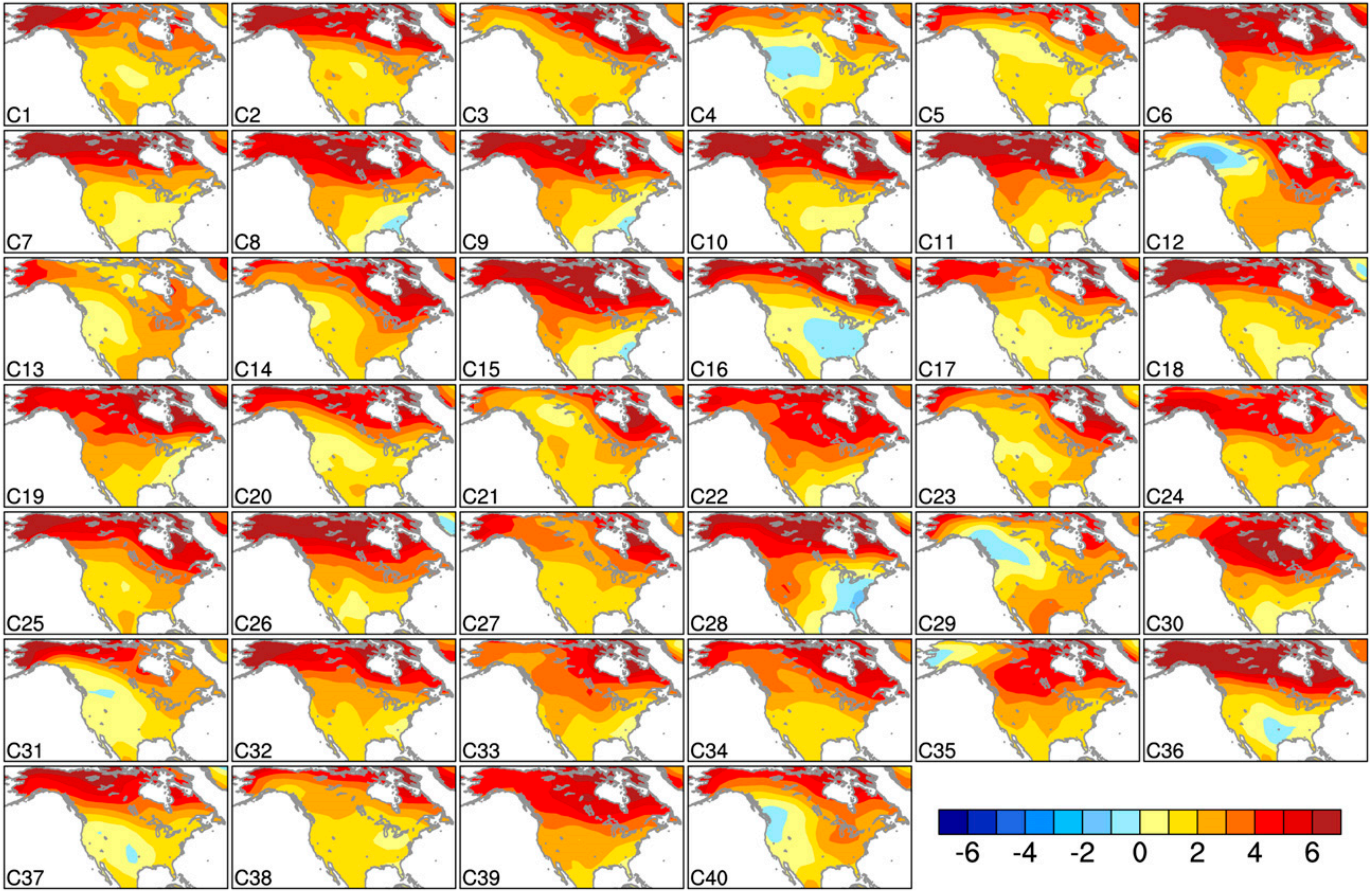
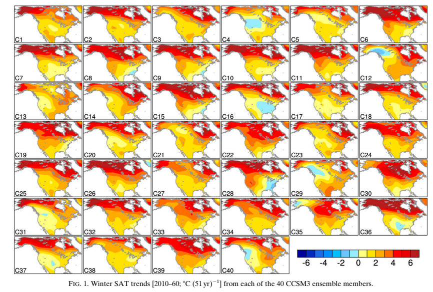


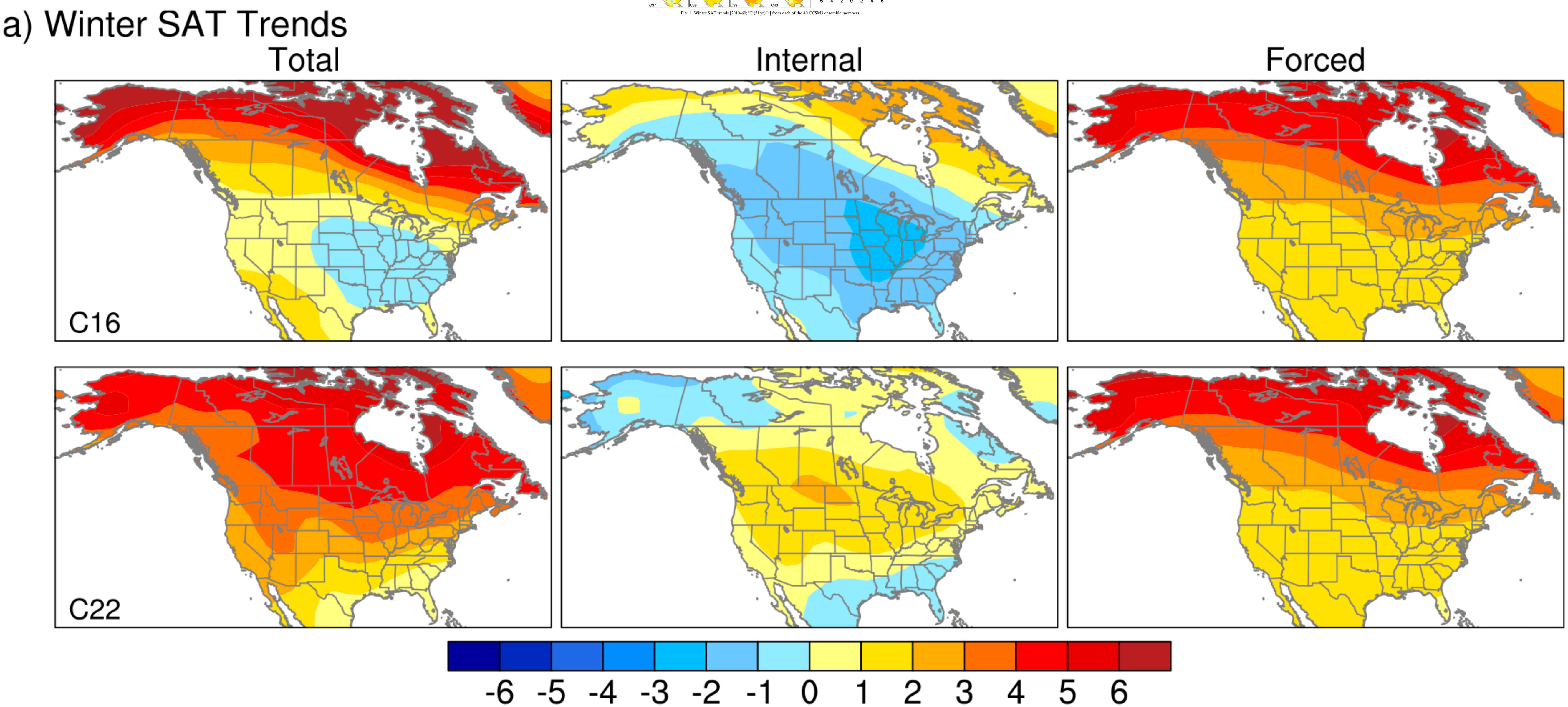
FIG. 1. Winter SAT trends [2010–60; °C (51 yr)$^{-1}$] from each of the 40 CCSM3 ensemble members.

Deser et al. (2014), *J. Climate*

doi:10.1175/JCLI-D-13-00451.s1

Averaging over all these 40 simulations gives the "forced warming" — the part of the future change attributable to increased greenhouse gases





Deser et al. (2014), *J. Climate*
doi:10.1175/JCLI-D-13-00451.s1