Making Sense of Equilibrium Climate Sensitivity and Other Climate Responses

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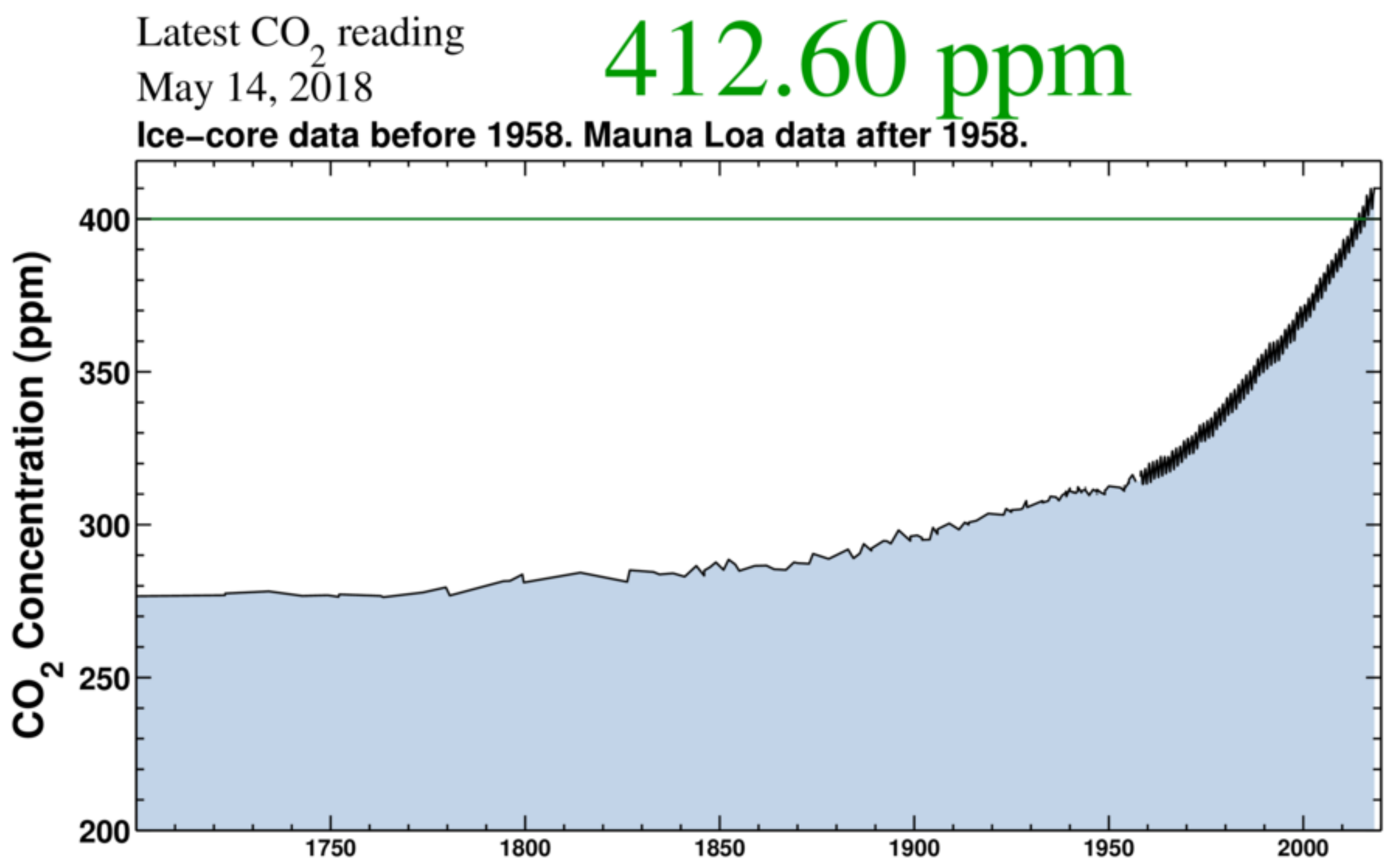
Some "Known Knowns" about Anthropogenic Climate Change

- Atmospheric CO_2 concentration has increased since pre-industrial era from 275 to over 410 ppm



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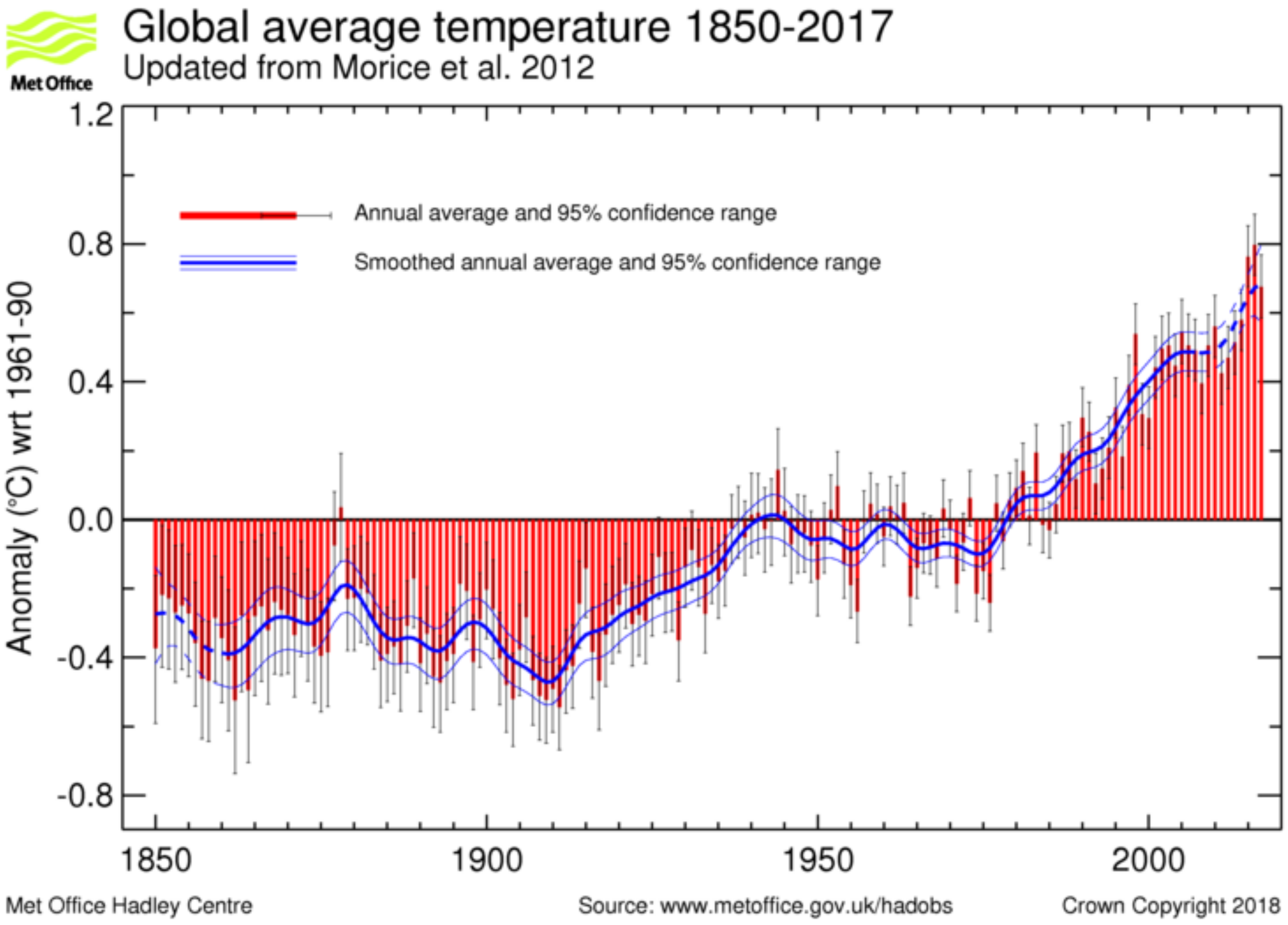
Some “Known Knowns” about Anthropogenic Climate Change

- Atmospheric CO_2 concentration has increased since pre-industrial era from 275 to over 410 ppm
- Global-mean Temperature has increased since pre-industrial by over 1ºC (1.8 ºF)



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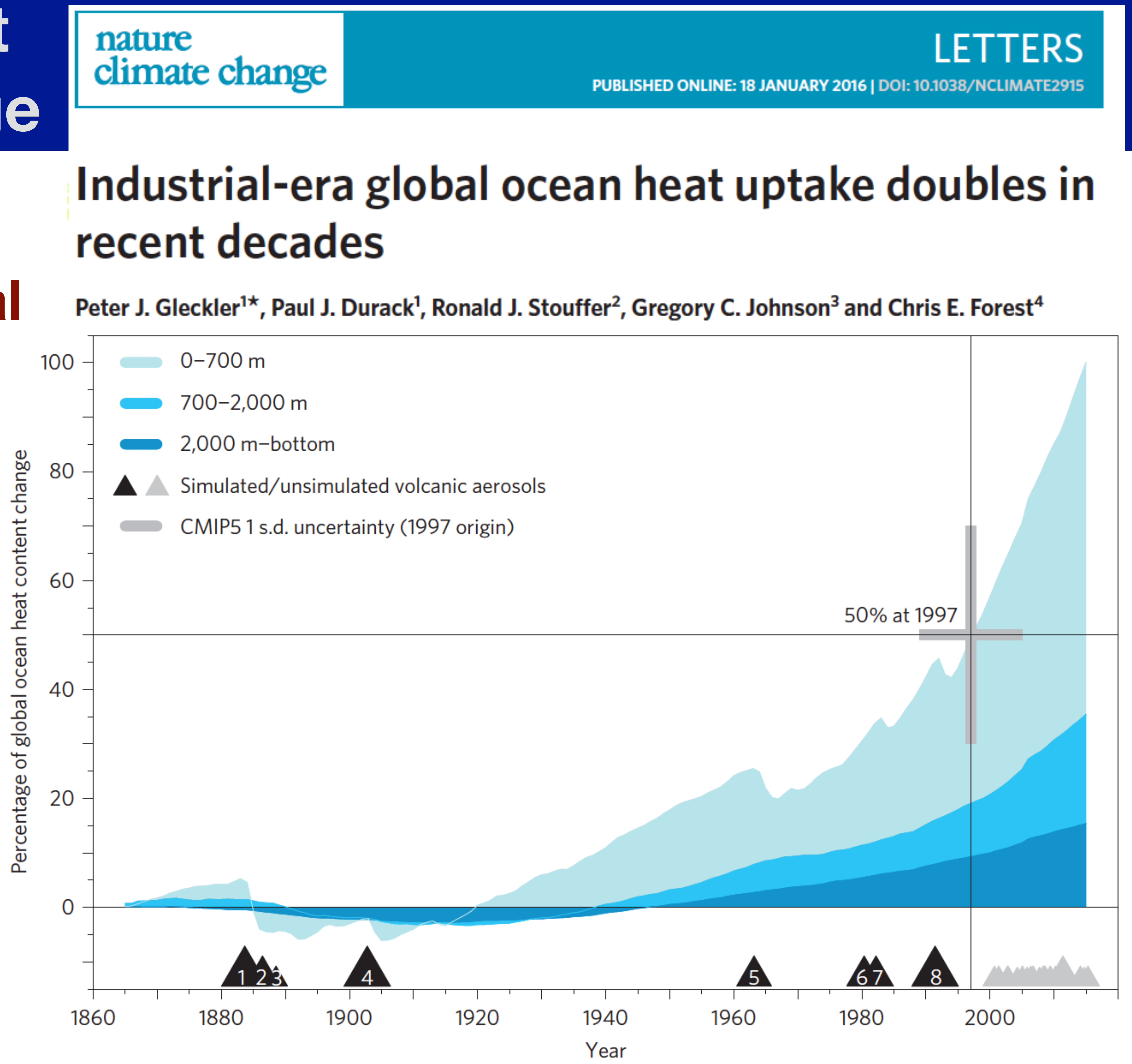
Some "Known Knowns" about Anthropogenic Climate Change

- Atmospheric CO_2 concentration has increased since pre-industrial era from 275 to over 410 ppm
- Global-mean Temperature has increased since pre-industrial by over 1ºC (1.8 ºF)
- Over 90% of the extra heat is stored in the oceans and its accumulating fast.



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What matters for long-term climate prediction of global mean temperature?

- **Controls on:**
  - Long-term warming
  - Delay by ocean
  - Net forcing

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How do we define Equilibrium Climate Sensitivity?
Start with a “simple” equation for the Earth’s Energy Balance.

Consider the energy balance equation for the change in global-mean surface temperature (ΔT) from equilibrium:

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Change in global mean heat content	Future Forcings	Net Feedbacks $\lambda = 1/S$	Flux of heat into deep-ocean

Conceptually: This is a good framework for organizing how climate sensitivity is defined.

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Let's start with the energy balance equation for the change in global-mean surface temperature (ΔT) from equilibrium:

$$c_p \cancel{\frac{d\Delta T(t)}{dt}} = F(t) - \lambda \Delta T(t) - \cancel{\Phi(K_v)}$$

Change in global mean heat content	Future Forcings	Net Feedbacks λ = 1/S	Flux of heat into deep-ocean

POINT 1:

At equilibrium, d/dt = 0 and the heat flux into the deep ocean is zero

so we define Equilibrium Climate Sensitivity (ECS) as:

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

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Change in global mean heat content	Future Forcings	Net Feedbacks λ = 1/S	Flux of heat into deep-ocean

POINT 2: The Feedback term and the Ocean Heat Flux are always trying to counteract the Forcing term …

POINT 3: … but, Earth has multiple feedbacks and they are not always active. So the net feedbacks are changing with time and are estimated as Effective Climate Sensitivity.

$$\lambda_{eff} = \frac{F(t) - \Phi_o(K_v)(t)}{T(t)}$$

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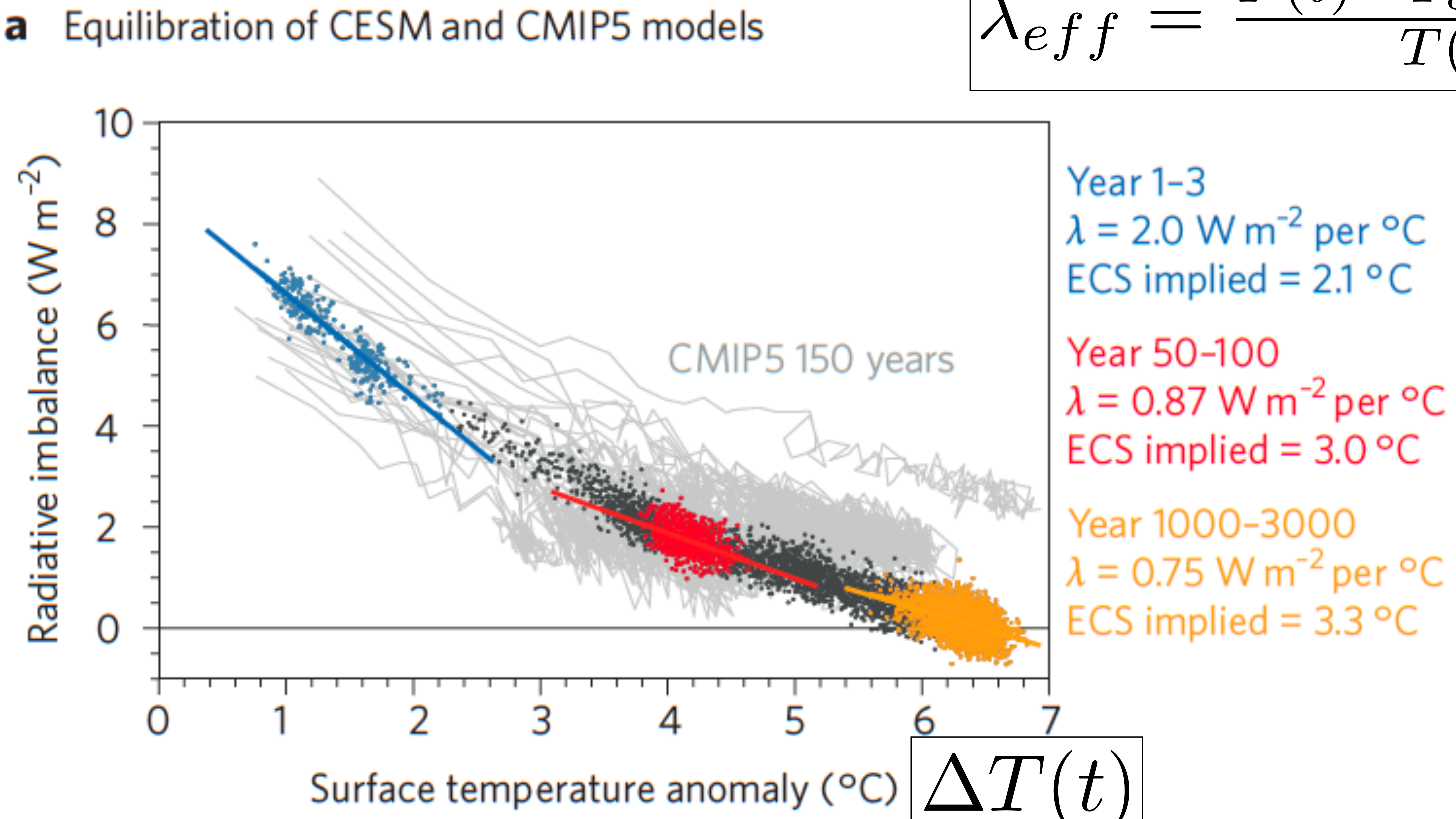
Why does it matter if feedbacks change with time? Let’s visualize the transition to equilibrium.

$$\lambda_{eff} = \frac{F(t) - \Phi_o(K_v)(t)}{T(t)}$$

$$\lambda T(t) + \Phi_o(t)$$



$$\Delta T(t)$$

Knutti, Rugenstein, and Hegerl, 2017, Nature Geoscience, DOI: 10.1038/NGEO3017

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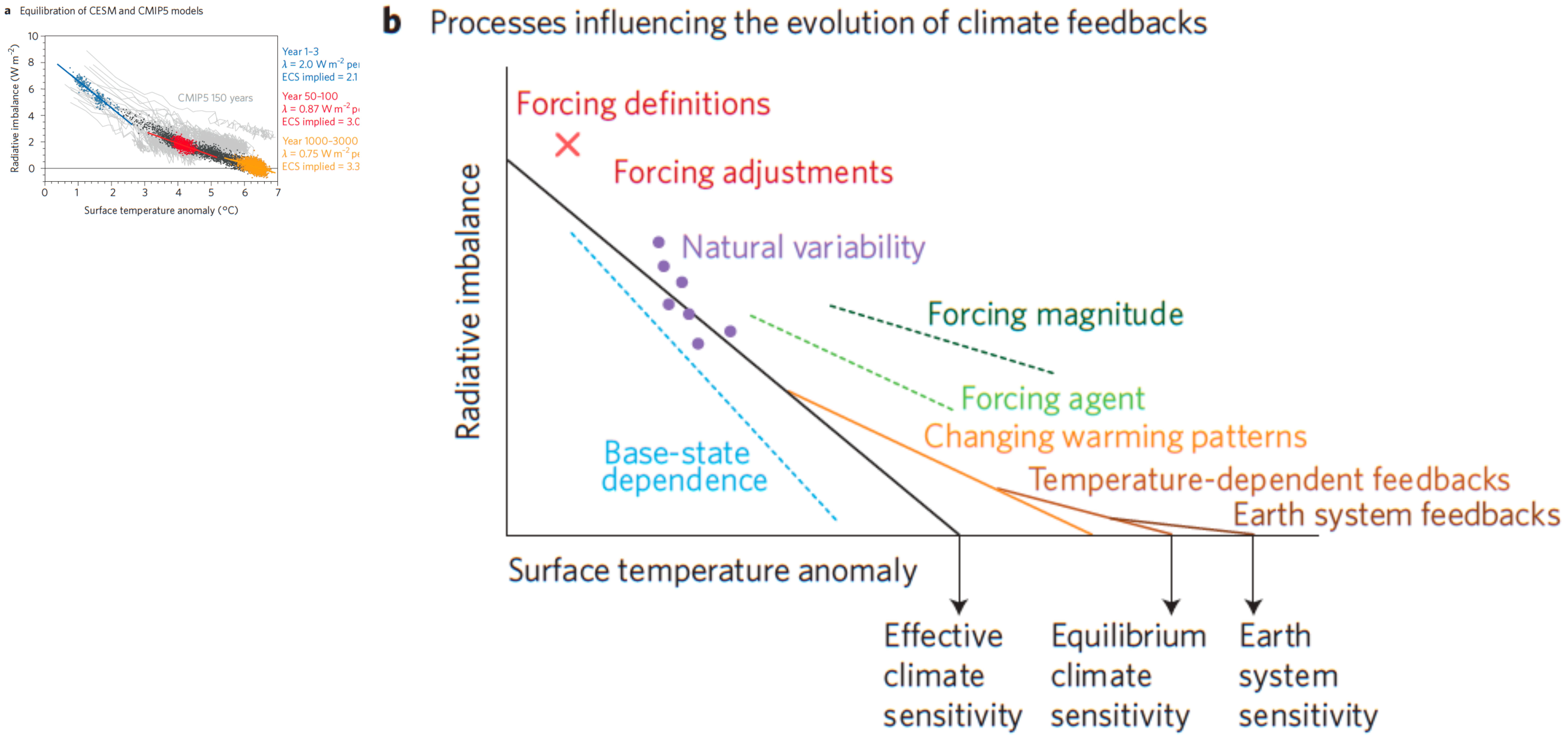
Why does it matter if feedbacks change with time?



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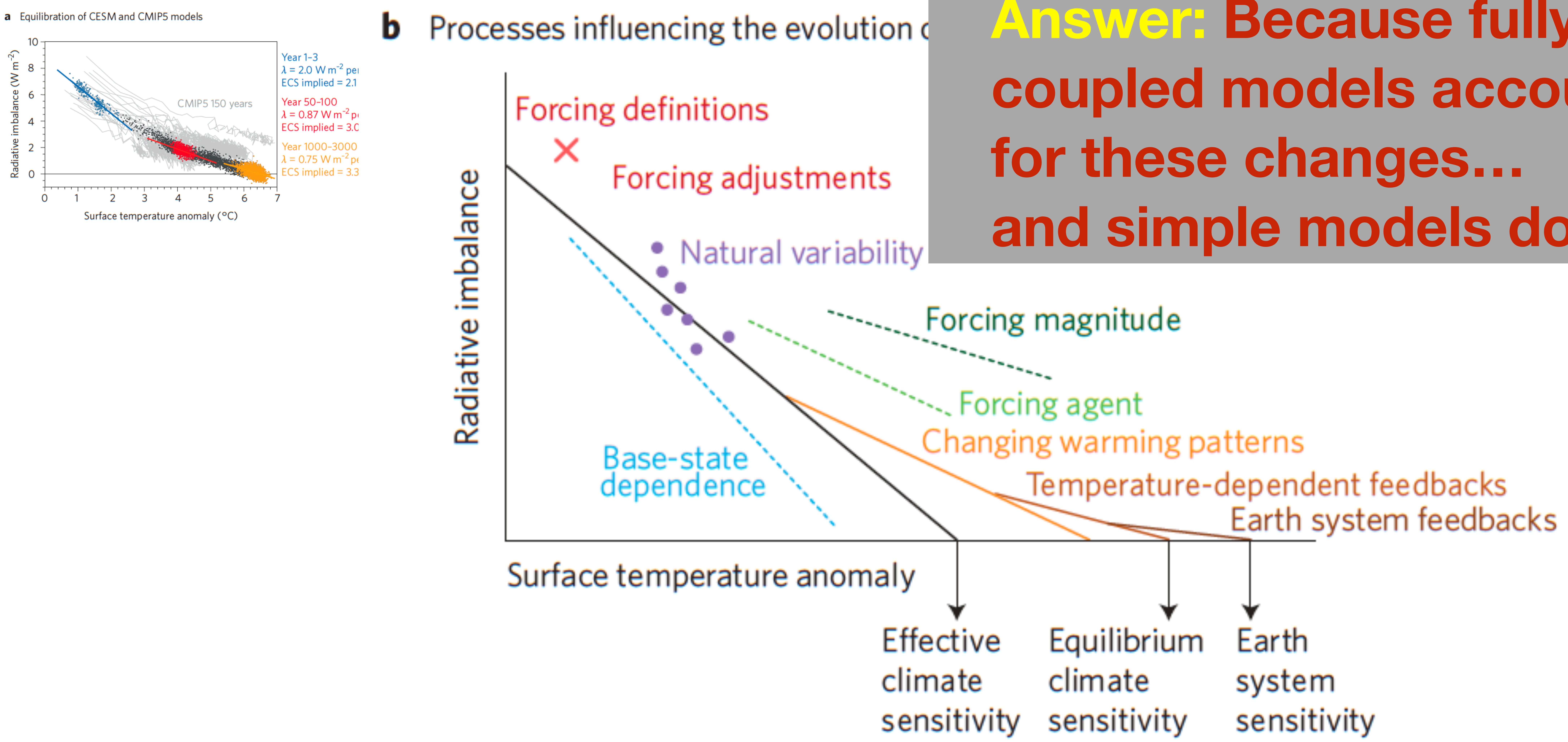

Answer: Because fully coupled models account for these changes… and simple models do not.

Knutti, Rugenstein, and Hegerl, 2017, Nature Geoscience, DOI: 10.1038/NGEO3017

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Here is an example using the MIT MESM, an Earth System Model of Intermediate Complexity, with ECS = 3.01 K

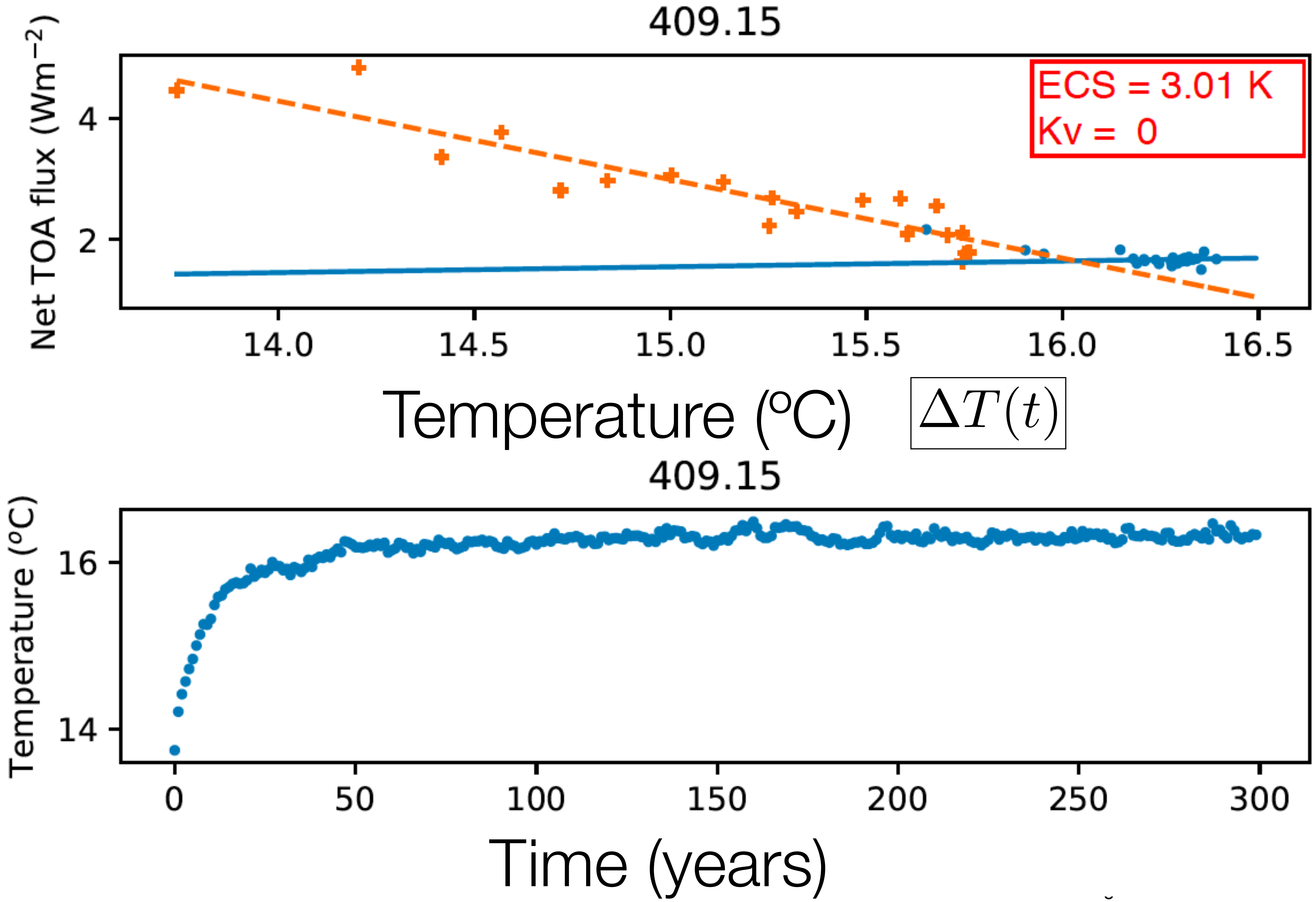
Radiative Imbalance (Wm^{-2})

$$\boxed{\lambda T(t) + \Phi_o(t)}$$

Orange: Years 1-20

Blue: Years 20-300

$$\boxed{\Delta T(t)}$$



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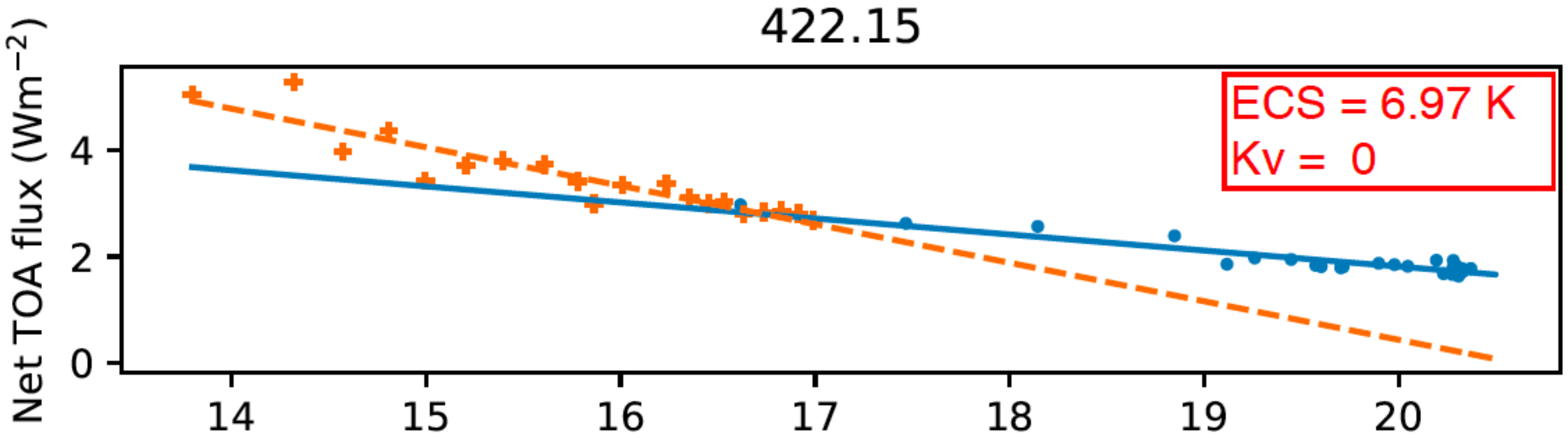
Here is an example using the MIT MESM with ECS = 6.97 K

Radiative Imbalance
(Wm^{-2})

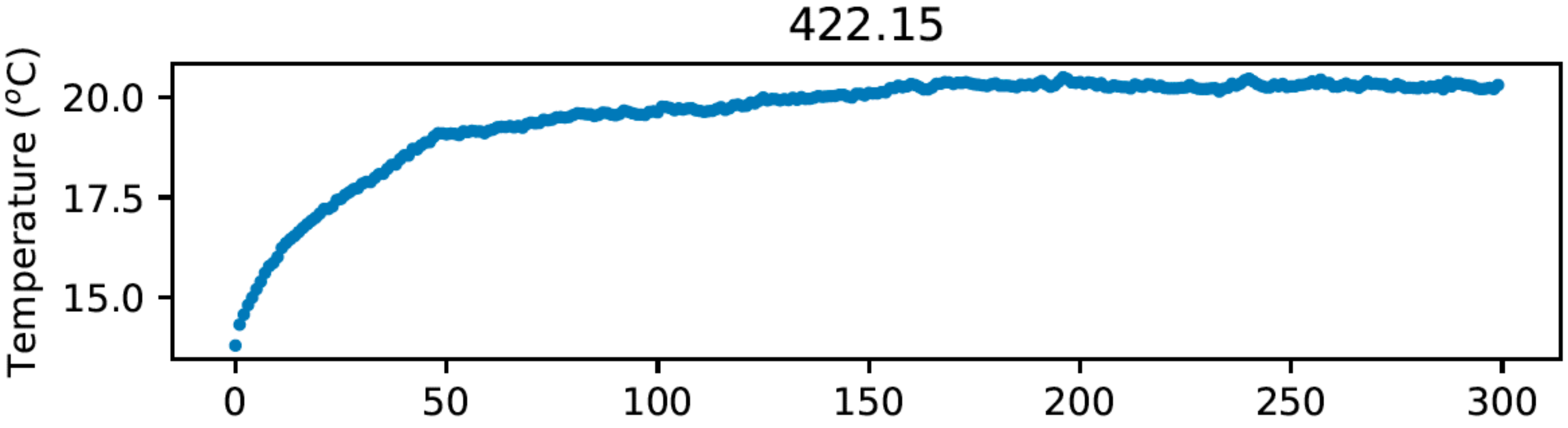
$$\boxed{\lambda T(t) + \Phi_o(t)}$$

Orange: Years 1-20
Blue: Years 20-300

$$\boxed{\Delta T(t)}$$



$\boxed{\Delta T(t)}$



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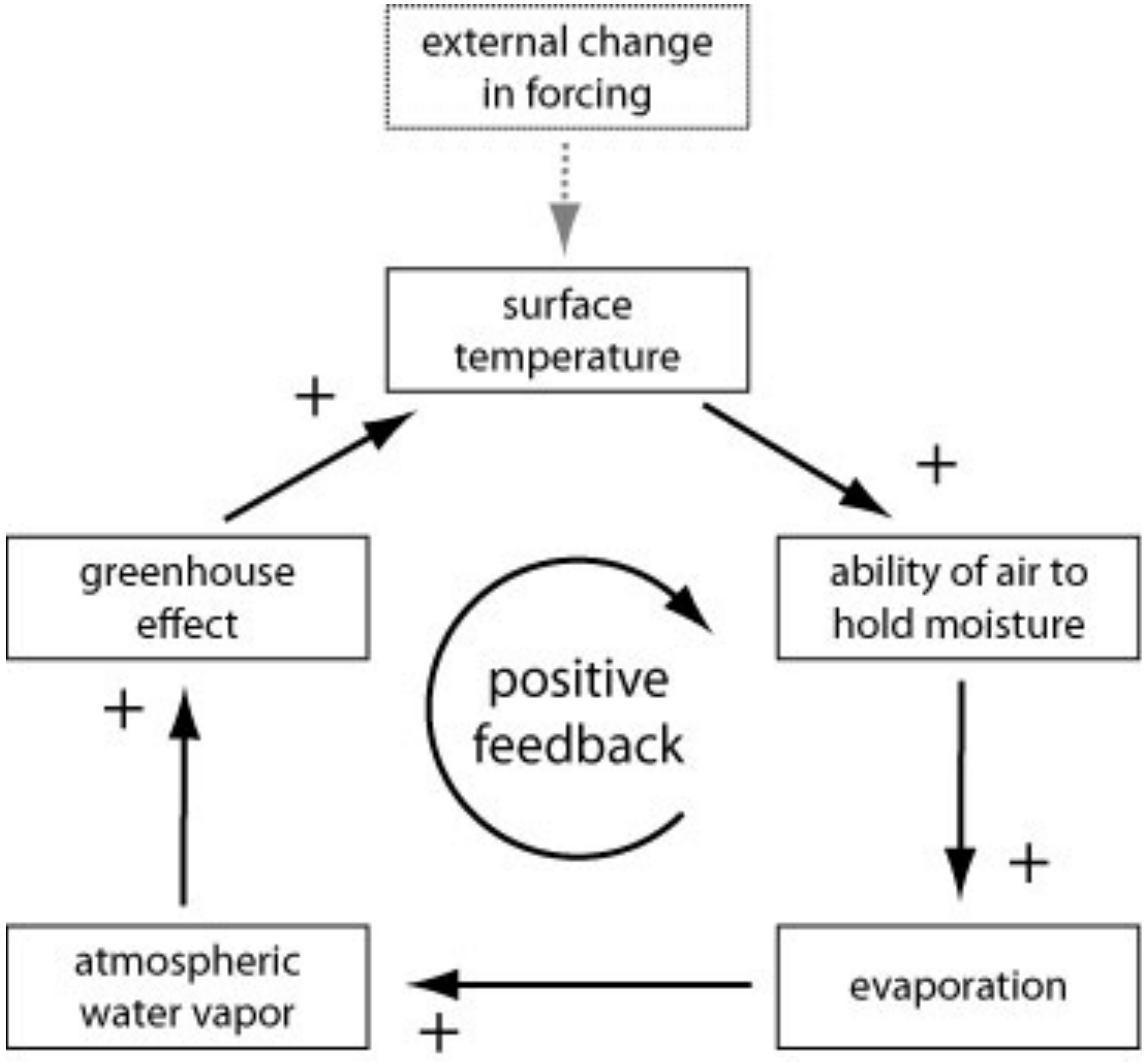
Climate System Feedbacks

(IPCC WG1 AR5 Figure 9.43)

Example for Water Vapor Feedback



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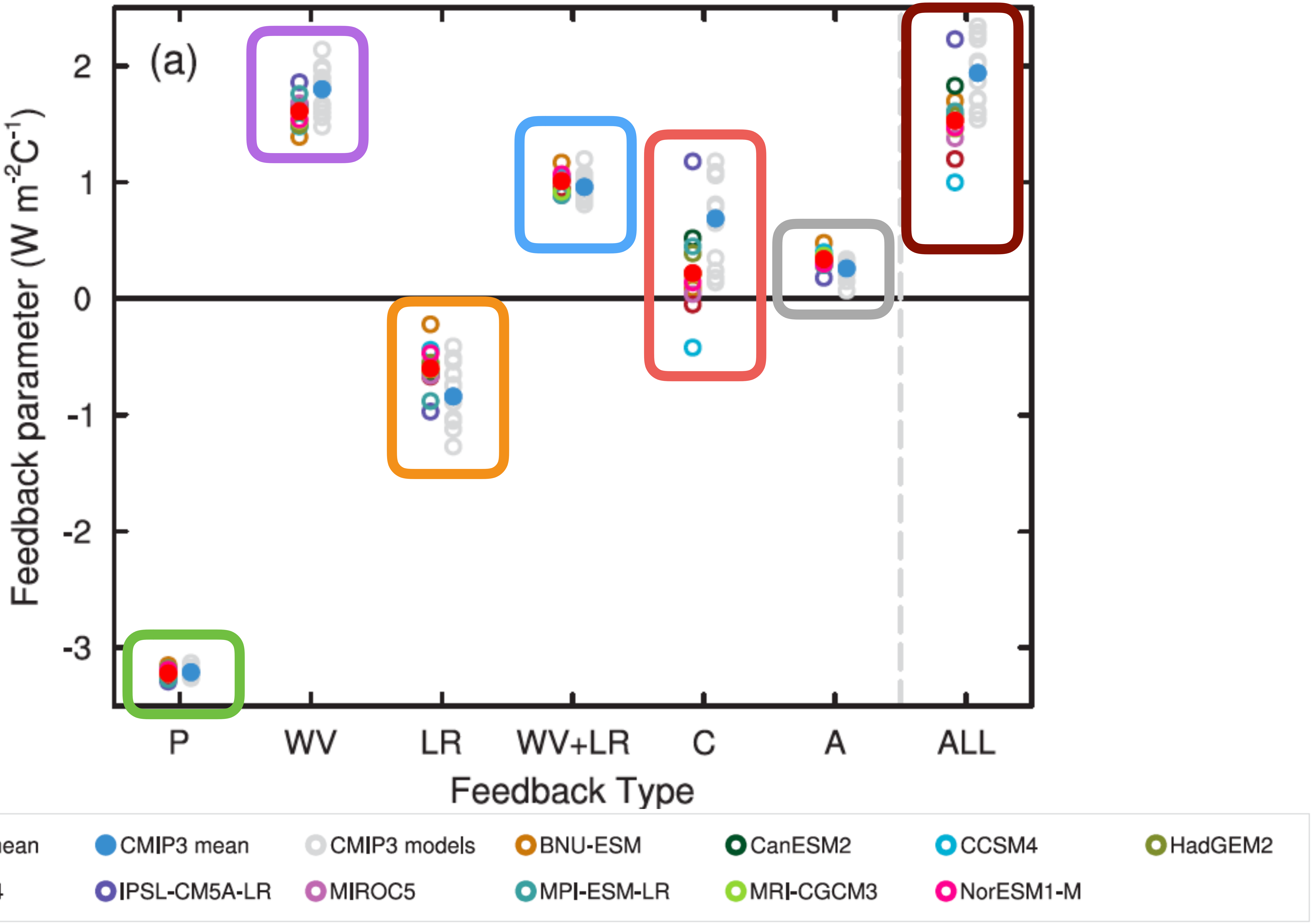
Understanding Climate System Feedbacks

(IPCC WG1 AR5 Figure 9.43)

- **Climate System Feedbacks**
  - Planck function,
  - Water Vapor (WV),
  - Lapse Rate (LR),
  - WV + LR
  - Cloud,
  - Albedo, and
  - ALL Combined



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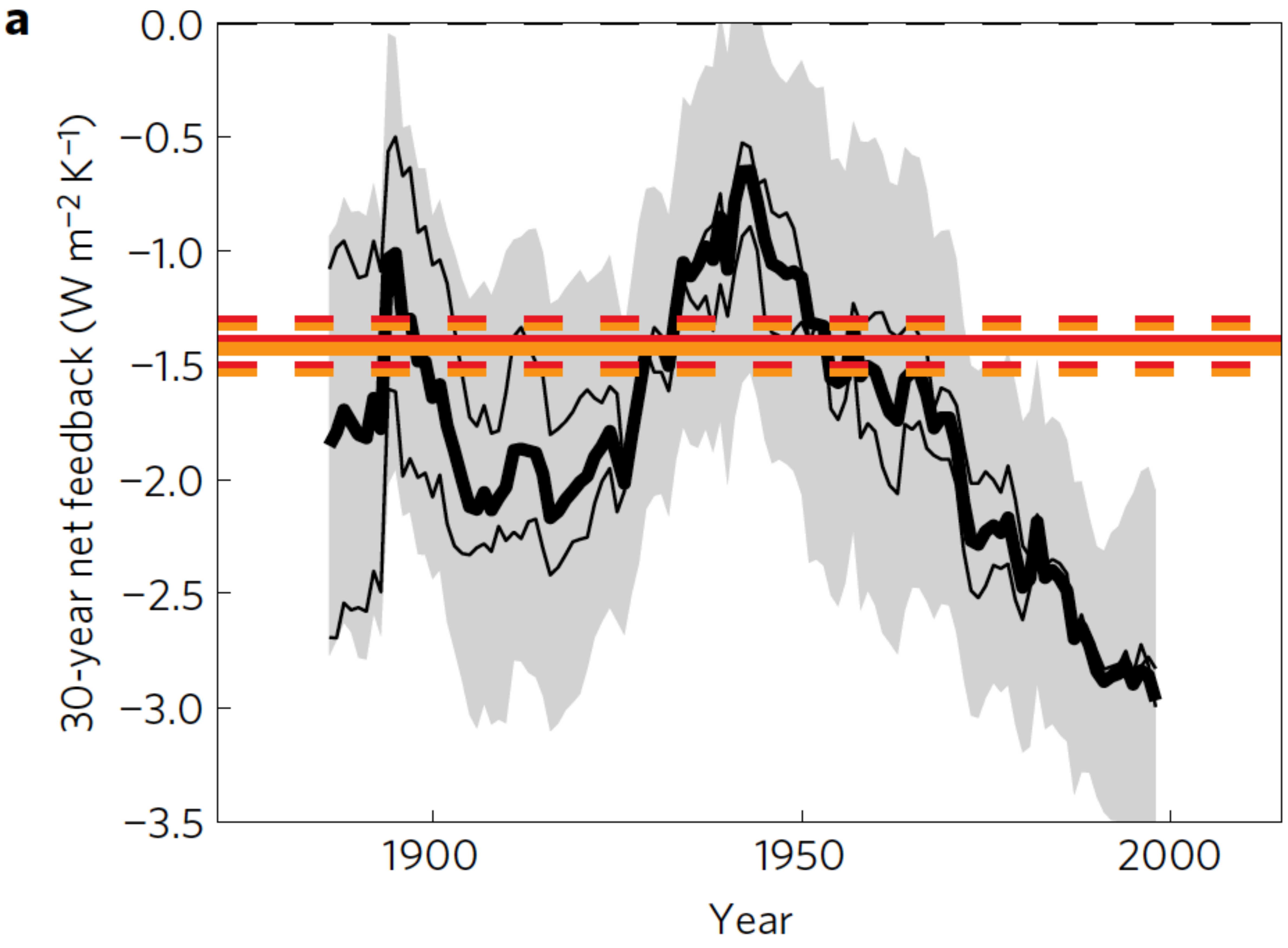
Do Climate Feedbacks stay constant with time? NO!

nature geoscience LETTERS
PUBLISHED ONLINE: 31 OCTOBER 2016 | DOI: 10.1038/NGEO2828

Impact of decadal cloud variations on the Earth's energy budget

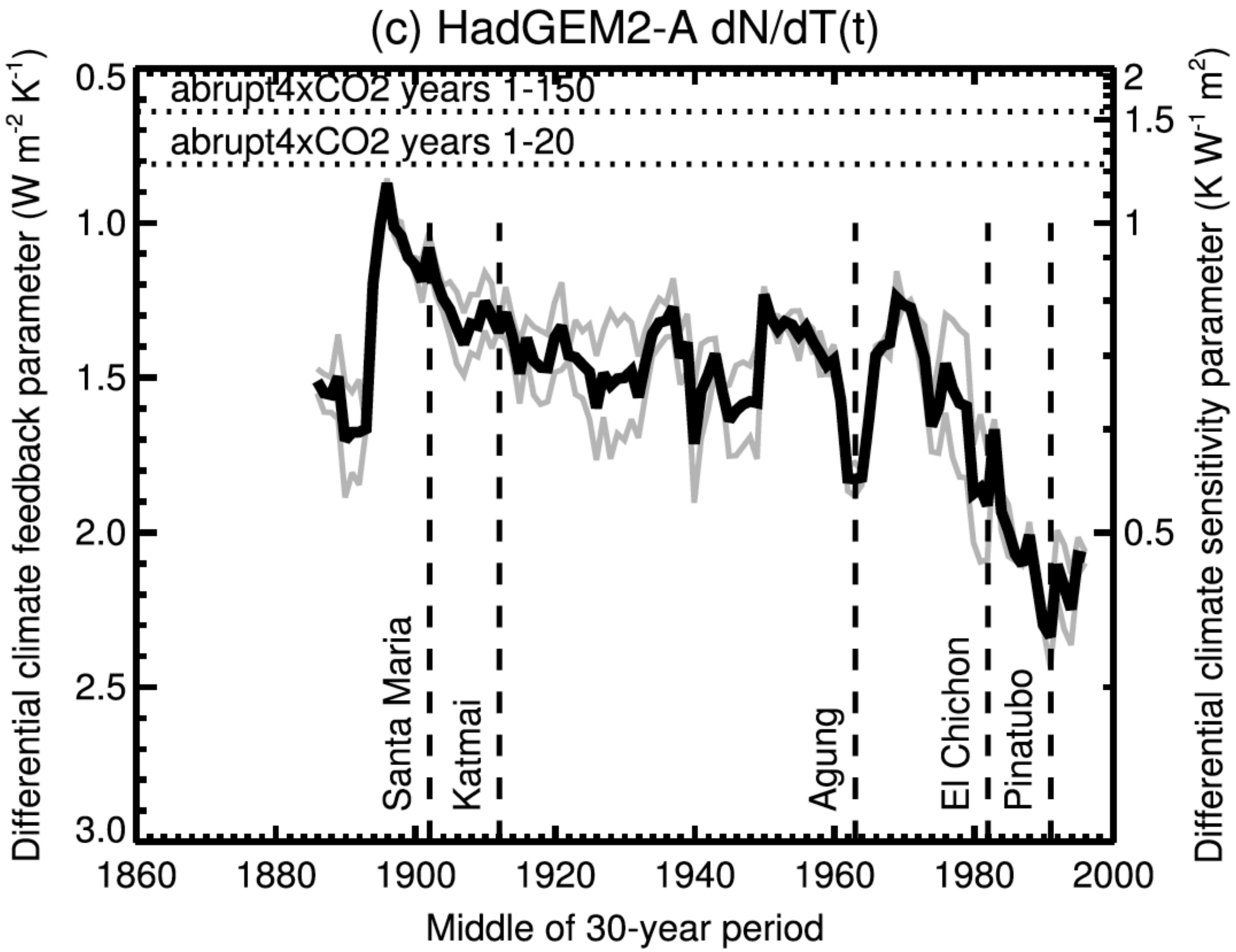
Chen Zhou*, Mark D. Zelinka and Stephen A. Klein



Geophysical Research Letters

Variation in climate sensitivity and feedback parameters during the historical period

J. M. Gregory[1,2] and T. Andrews[2]



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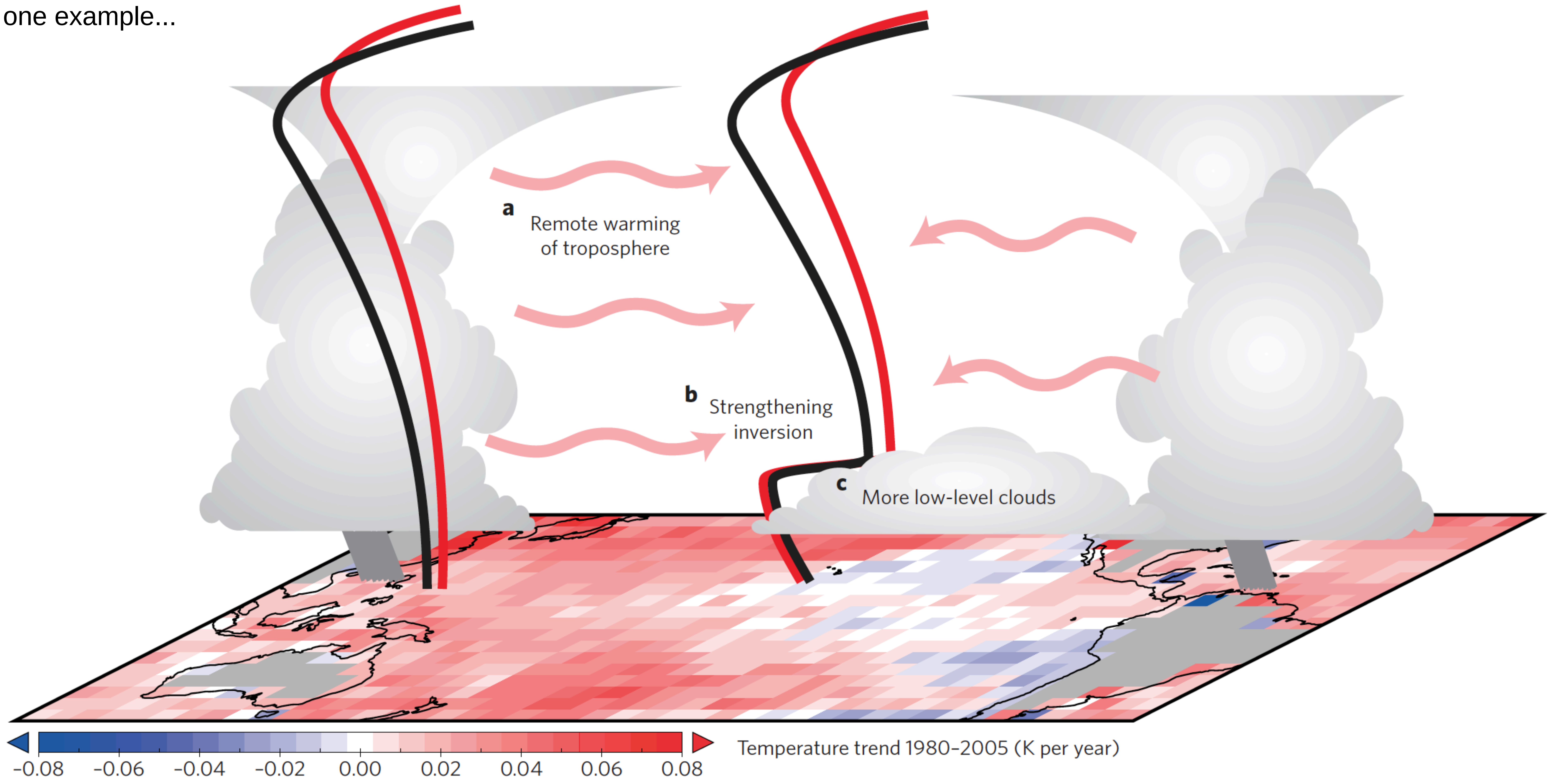
Zhou et al., 2016, Nature Geo

Gregory and Andrews, 2016, GRL

Do Climate Feedbacks stay constant with time?
NO!
But why not?
Because cloud patterns shift when Sea Surface Temperatures change

As one example...



Mauritsen, 2016, Nature Geo

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How uncertain are estimates of ECS now?

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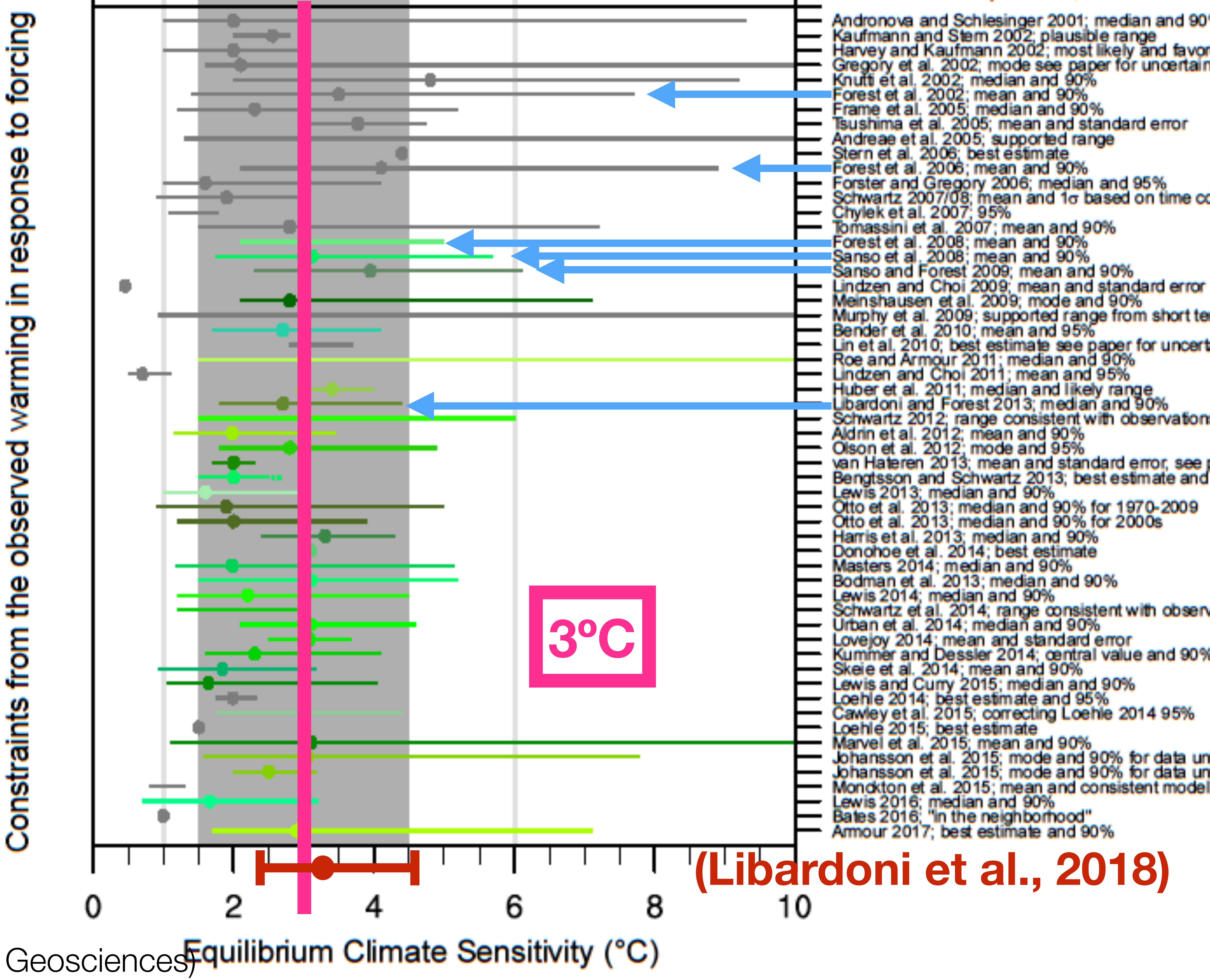
Knutti et al. (2017, Nature Geosciences)

- **Forest et al. Results**

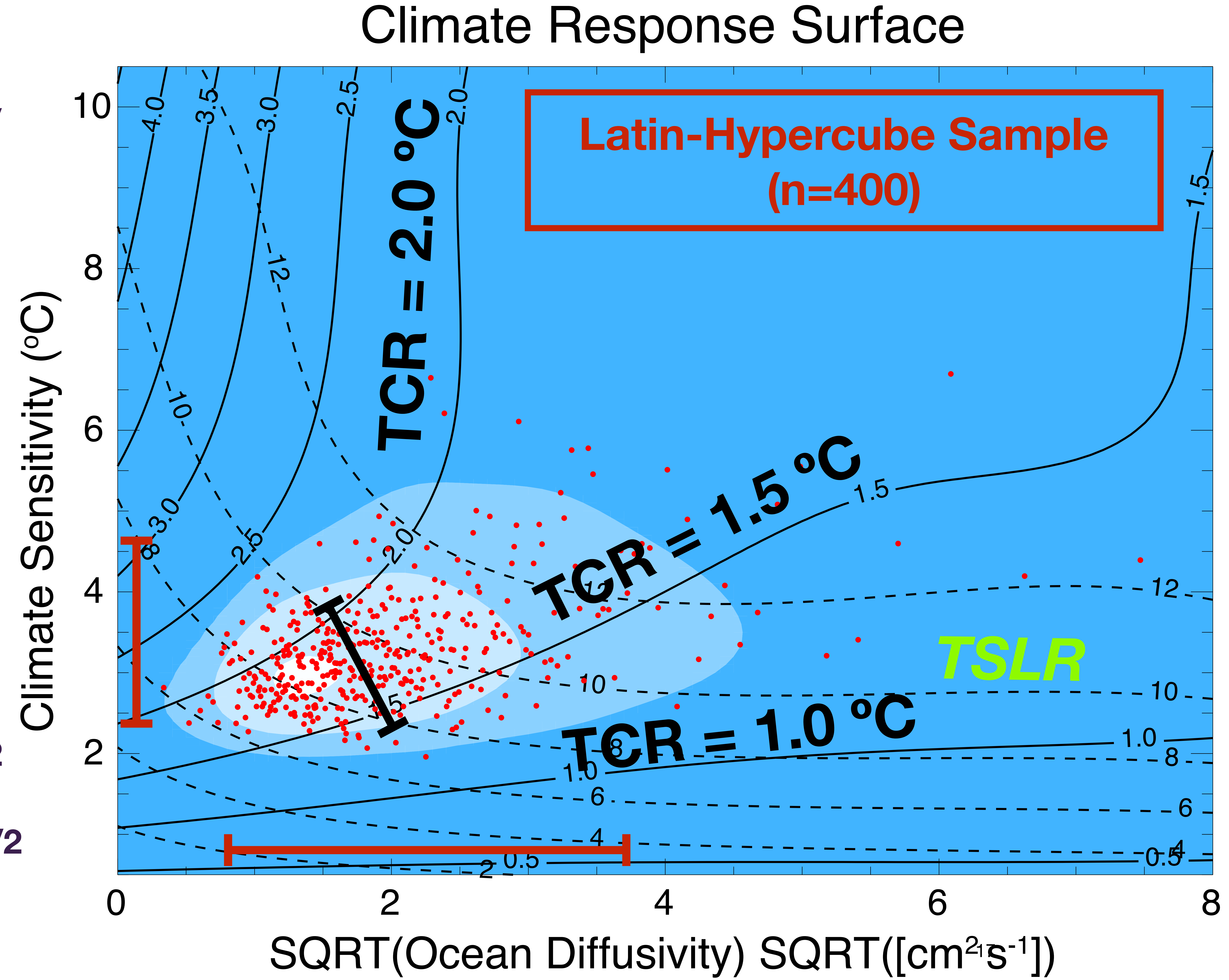
- **Latest Results from (Libardoni et al., 2018)**



Knutti et al. (2017, Nature Geosciences)

Latest Results from Libardoni et al. (2018, in prep)

Revised PDFs using only 1991-2010 Ocean Heat Content data



<u>**Percentiles: 5, 50, 95%**</u>

- **ECS: 2.4, 3.2, 4.6 °C**
- **TCR: 1.4, 1.7, 2.0 °C**
- **F_{aer}: -0.47,-0.24,-0.05 Wm^{-2}**
- **sqrt(K_v): 0.9, 1.8, 3.7 $cms^{-1/2}$**

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What's missing from this discussion?

- Earth System Sensitivity (Very long time-scale feedbacks):
    - Carbon cycle feedbacks
    - Ice sheet feedbacks
    - Ocean circulation feedbacks on heat and carbon budgets
- Observations of Paleoclimate
- Other regional or transient climate sensitivity issues

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Conclusions:

- Equilibrium Climate Sensitivity is defined by the set of feedbacks.
- Feedbacks change with time and are “model” dependent.
- Not accounting for changing feedbacks leads to wrong estimates of ECS.
- The additional climate data from the past 20 years has a significant impact on our understanding of the ECS and TCR.

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Extra slides

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How uncertain are estimates of TCR now?

Knutti et al. (2017, Nature Geosciences)

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