Time dependence of cloud feedback & its implications for climate sensitivity

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Lawrence Livermore National Laboratory

CERES Science Team Meeting
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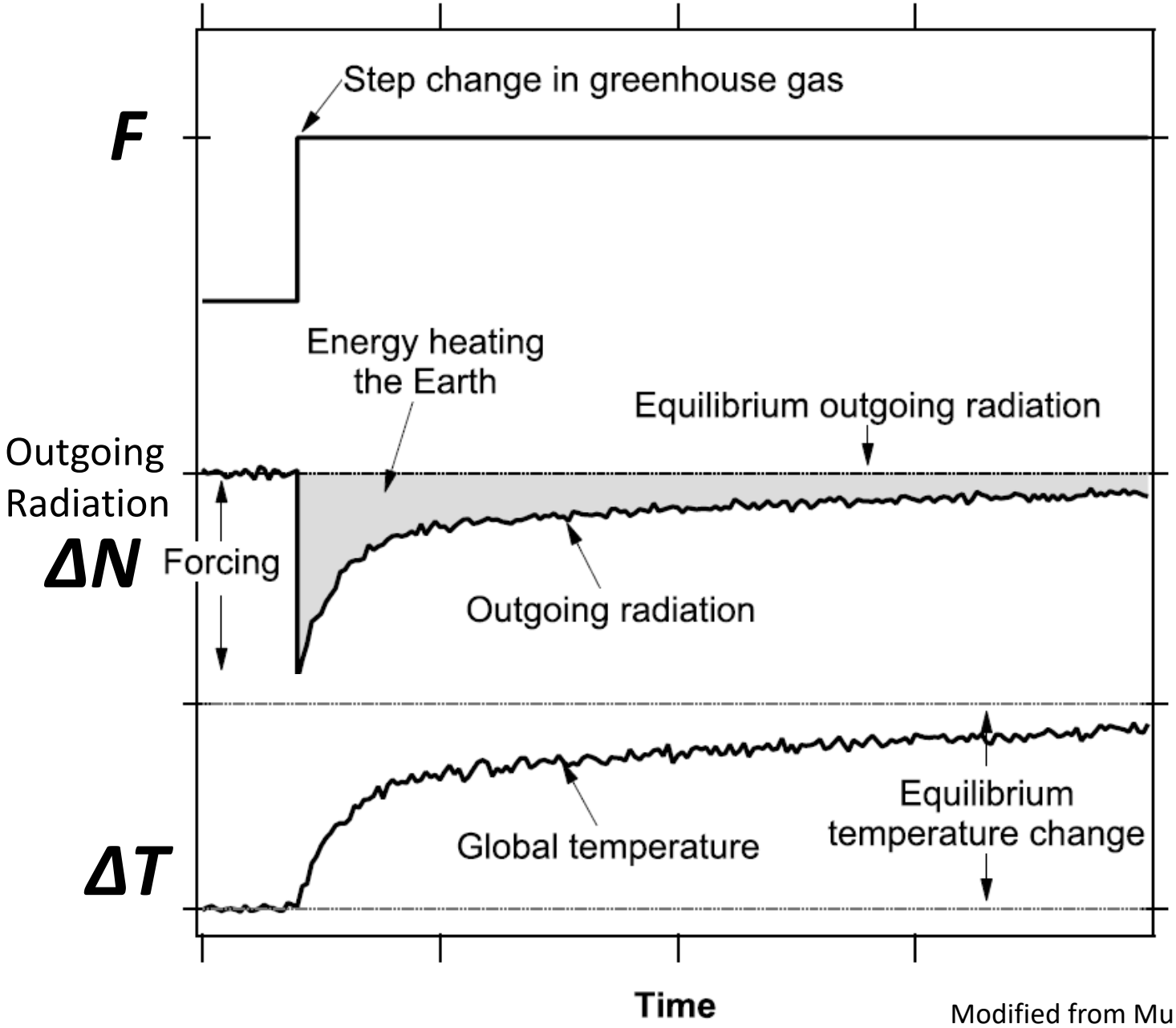
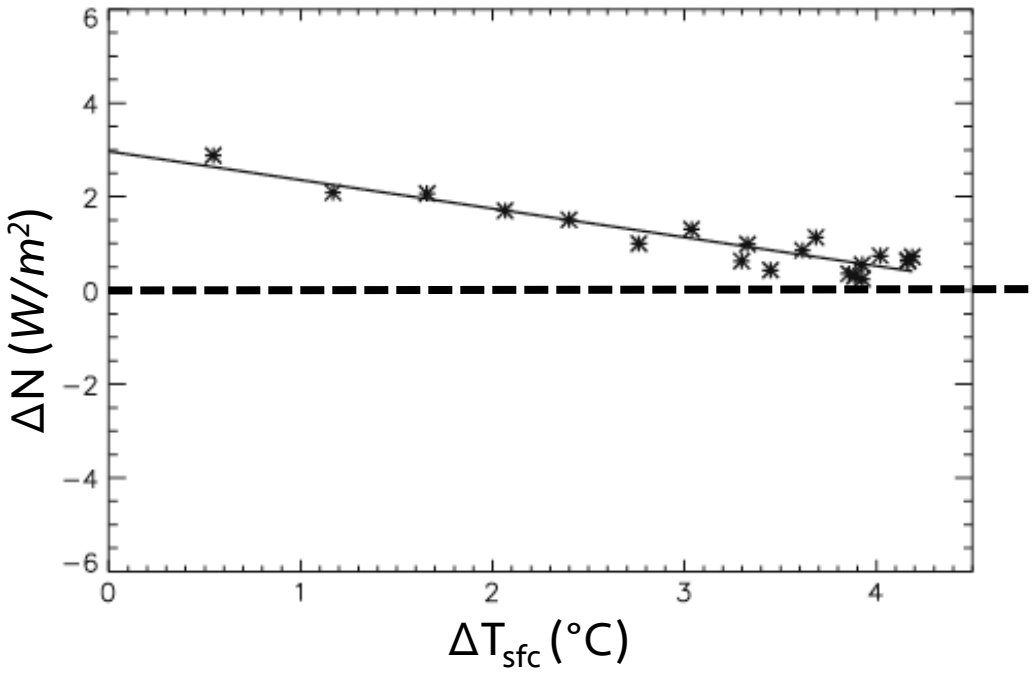


Modified from Murphy et al., *JGR* (2009)

Linear forcing-feedback framework

TOA net radiation anomaly (N) is expressed as

$$\Delta N = F + \lambda \Delta T$$



Gregory et al., *GRL* (2004)
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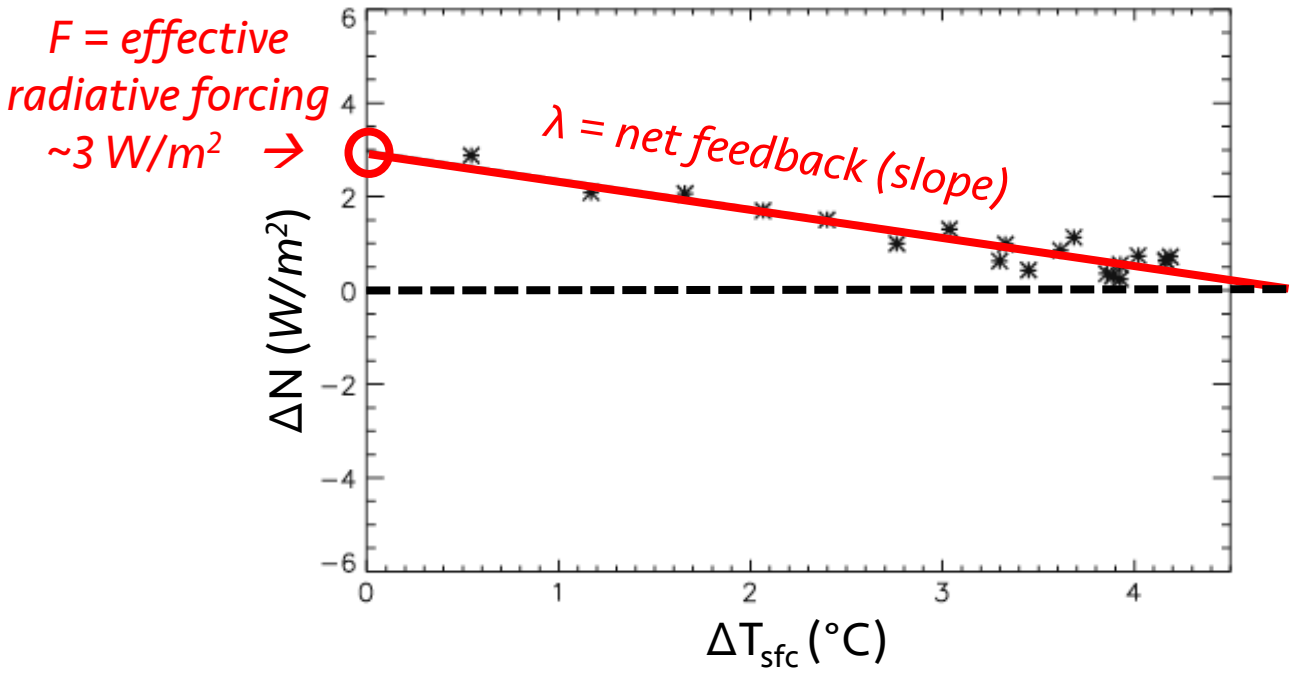

Gregory et al., *GRL* (2004)
Andrews, et al., *Surv. Geophys.* (2011)

Linear forcing-feedback framework

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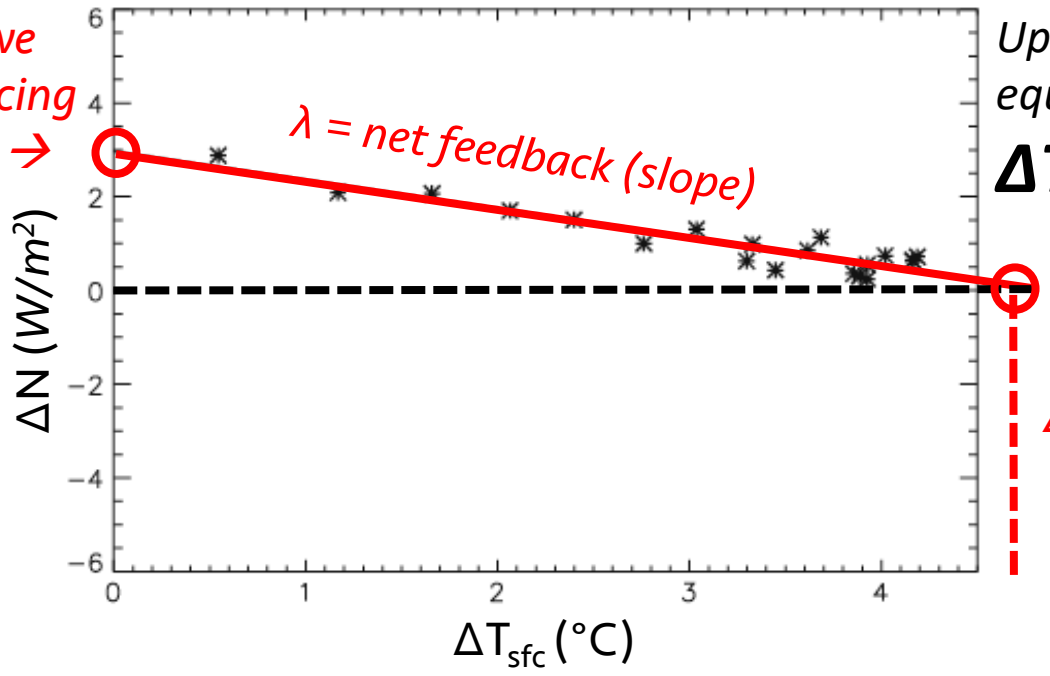
F = effective radiative forcing ~3 W/m² →



Upon reaching a new equilibrium, ΔN=0 and

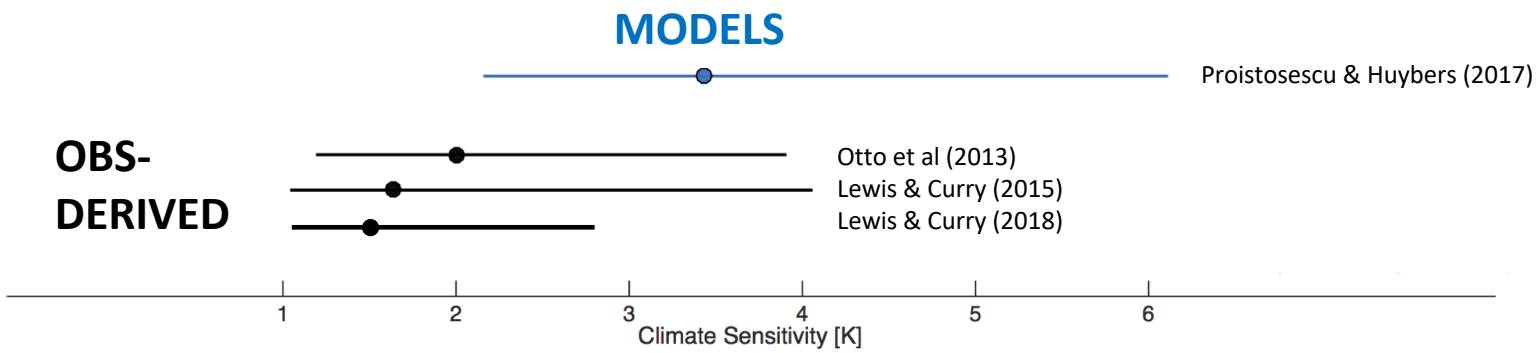
$$\Delta T_{2x} = -F_{2x}/\lambda \equiv ECS$$

ΔT_{2x} = equilibrium climate sensitivity ~4.7 K

Gregory et al., *GRL* (2004)
Andrews, et al., *Surv. Geophys.* (2011)

Model-obs ECS discrepancy

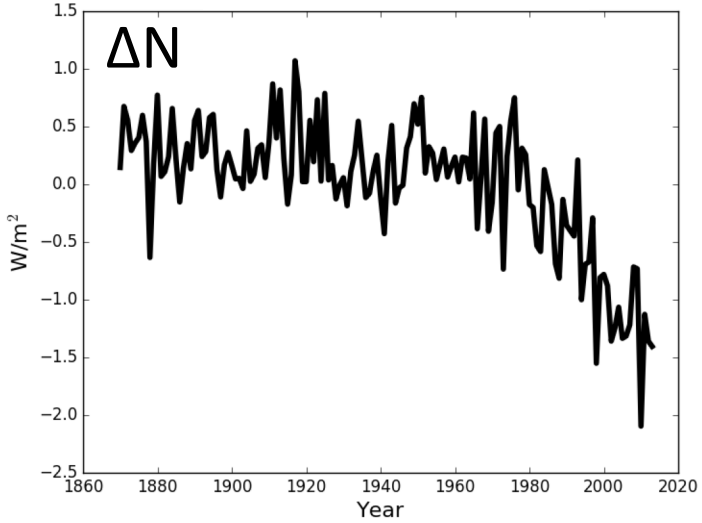
Observationally based analyses utilizing this linear forcing-feedback framework yield ECS estimates that are ***consistently smaller than those of climate models.***



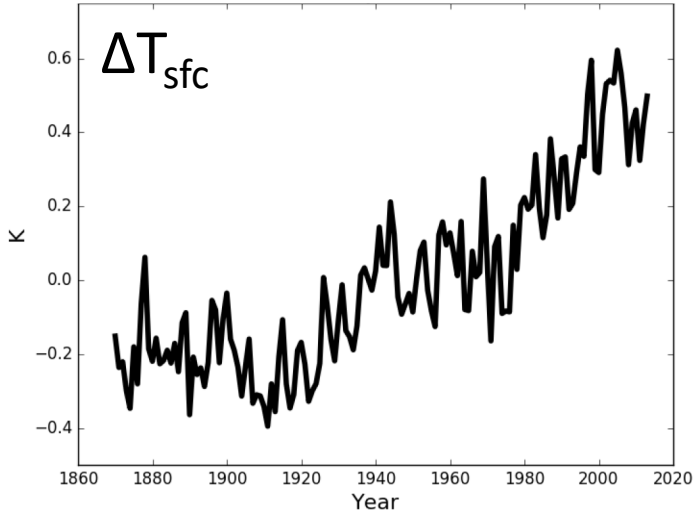
Updated from Proistosescu, et al. “Sensible Questions on Climate Sensitivity” (RealClimate post)

Assessing the constant λ assumption

HadCM3 AMIP experiments
(with constant forcing)

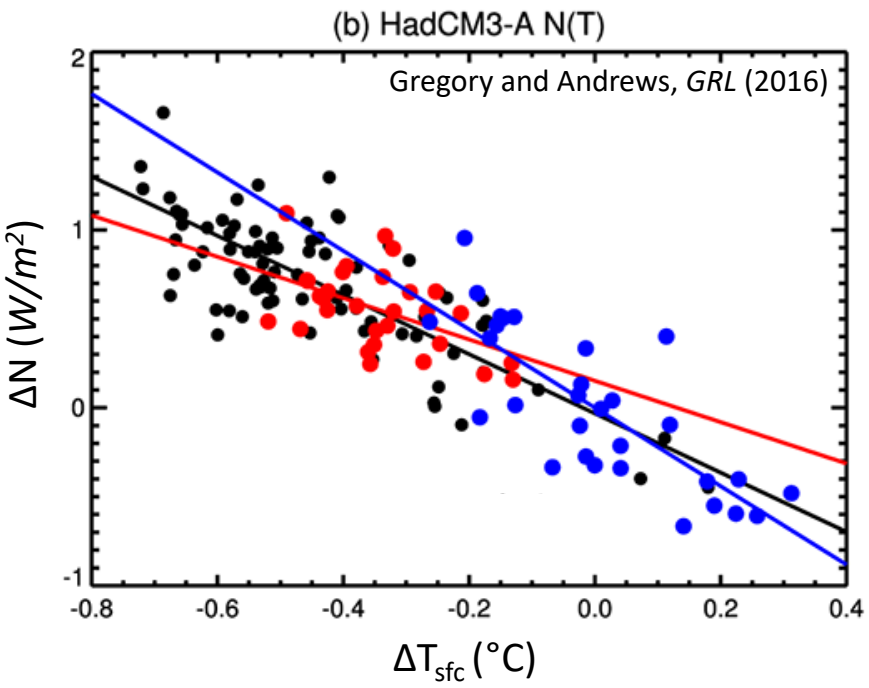


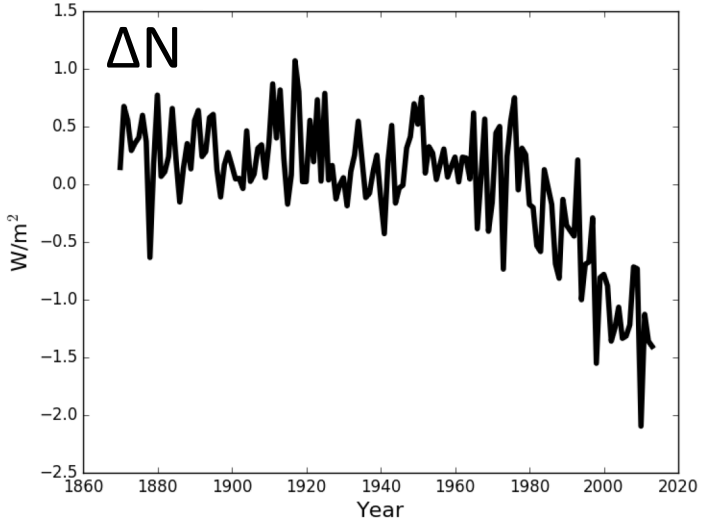
"Perfect model framework"

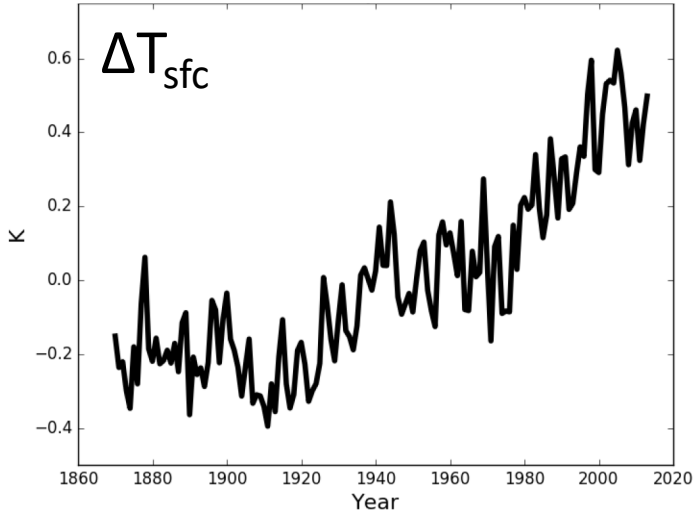


4xCO_2 exp: λ = -1.0 W/m²/K → ECS = 3.4°C

Assessing the constant λ assumption







All Years: λ = -1.7 W/m²/K → ECS = 2°C

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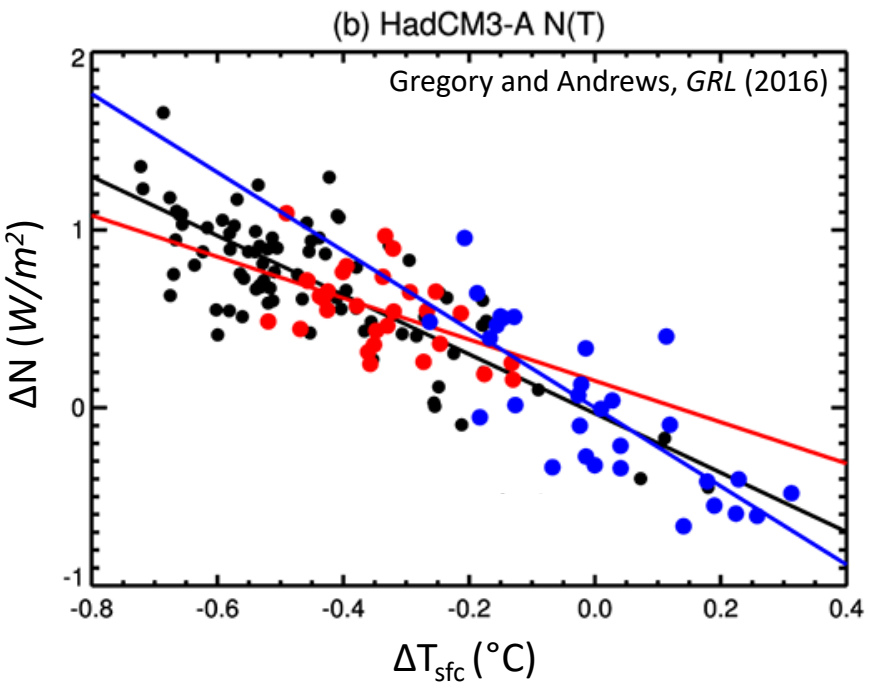

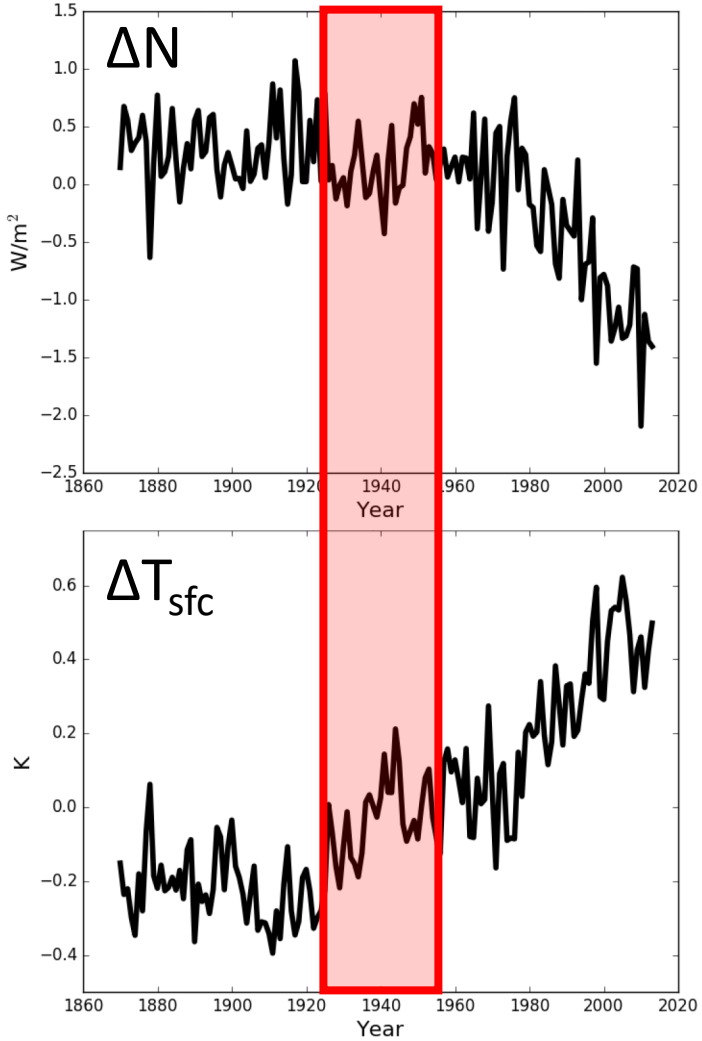

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1926-1955: λ = -1.2 W/m²/K → ECS = 2.8°C

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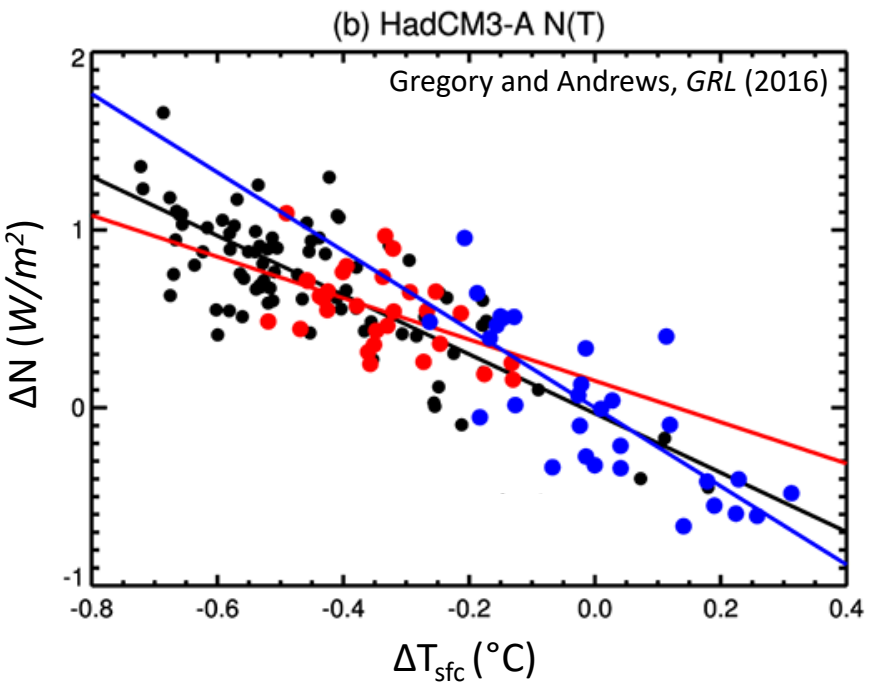

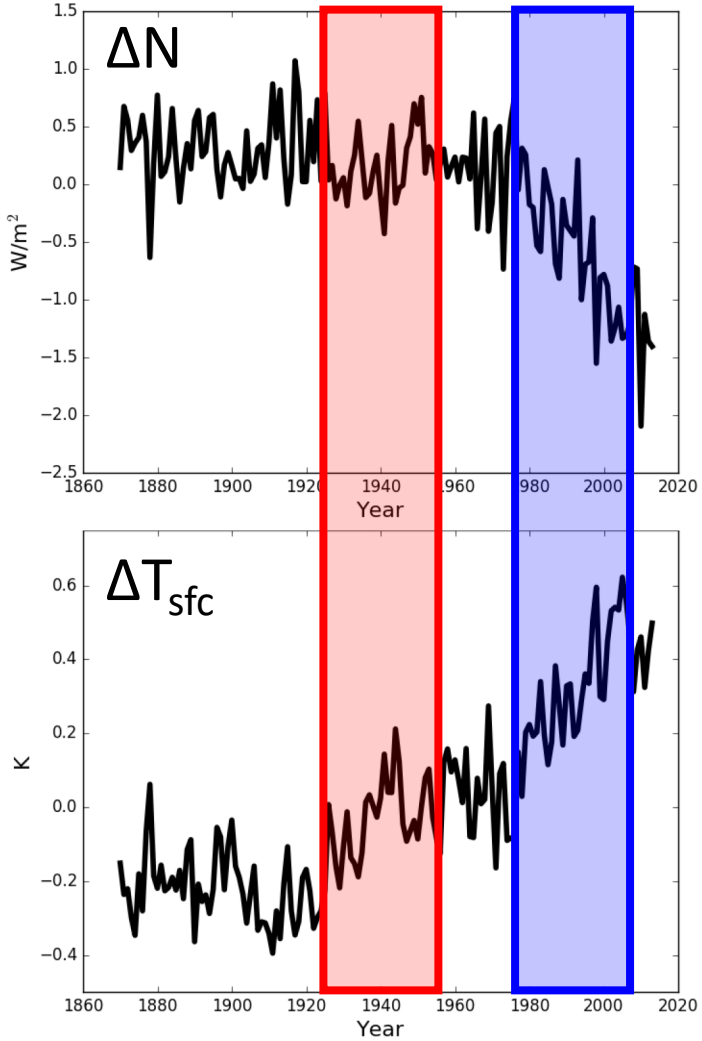

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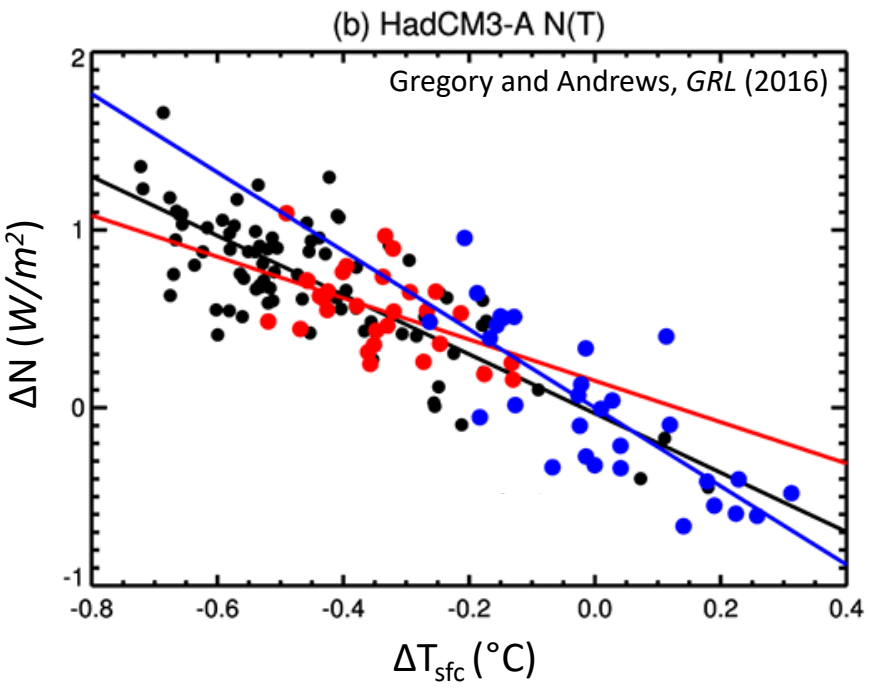

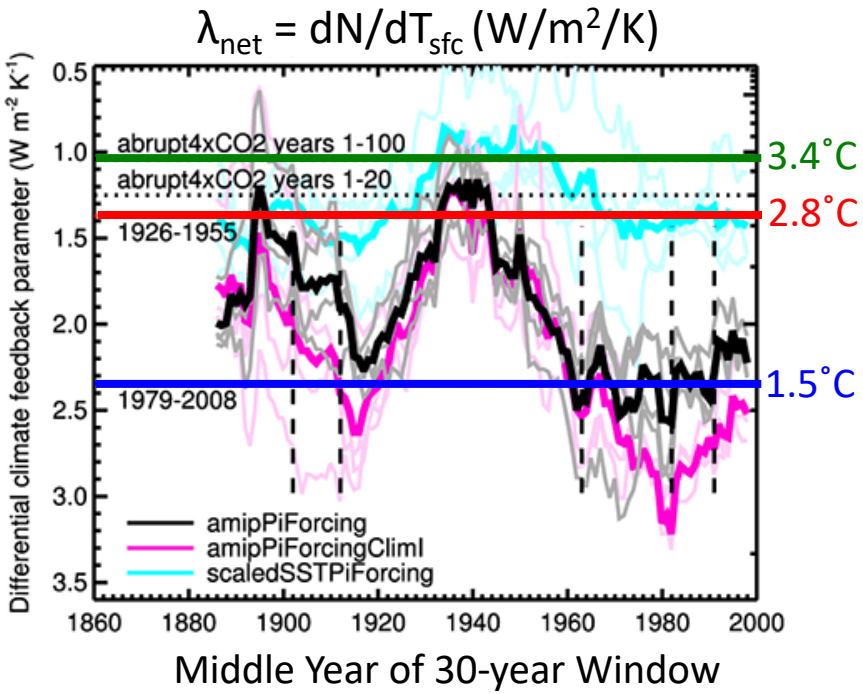

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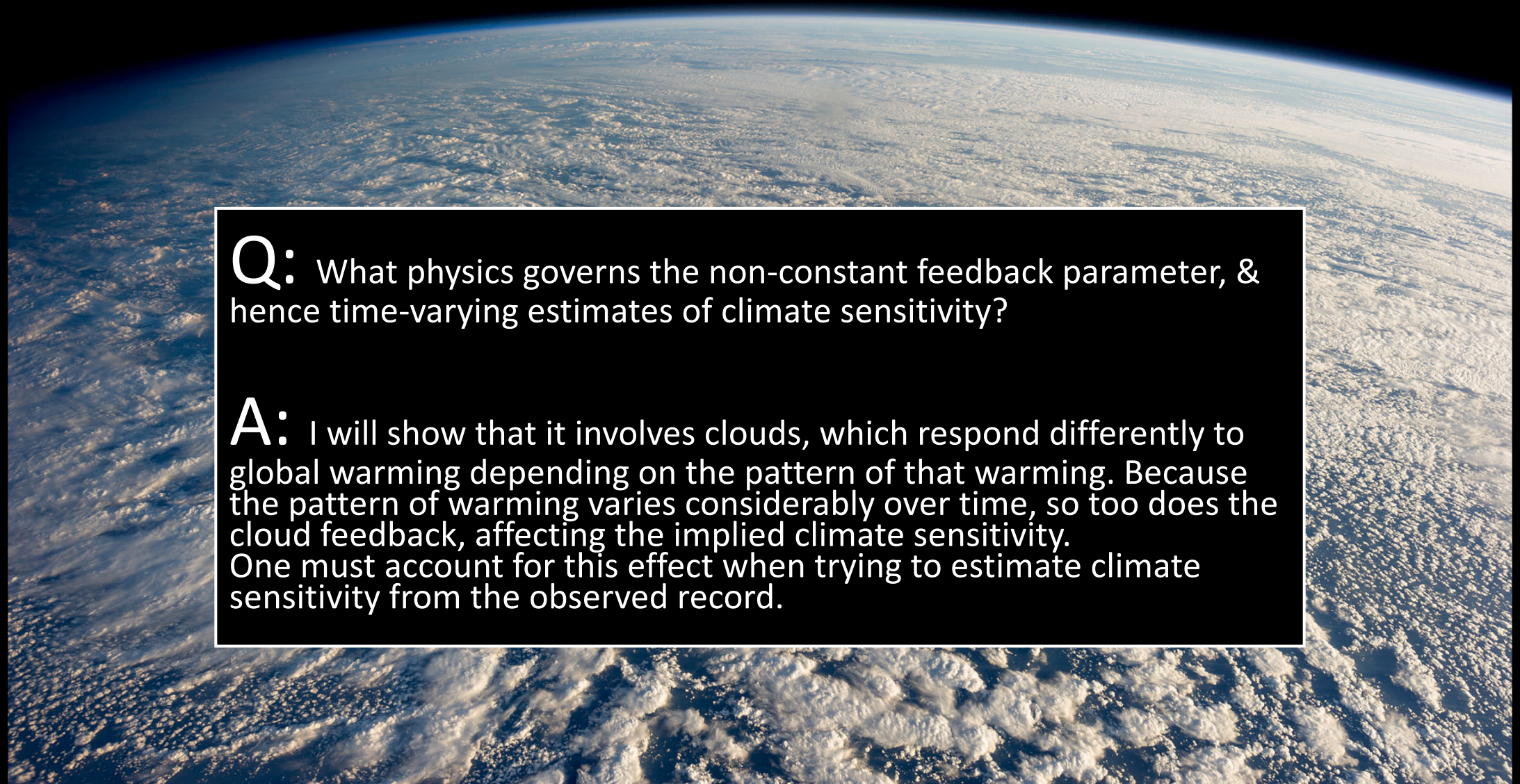
Nope.

Preview

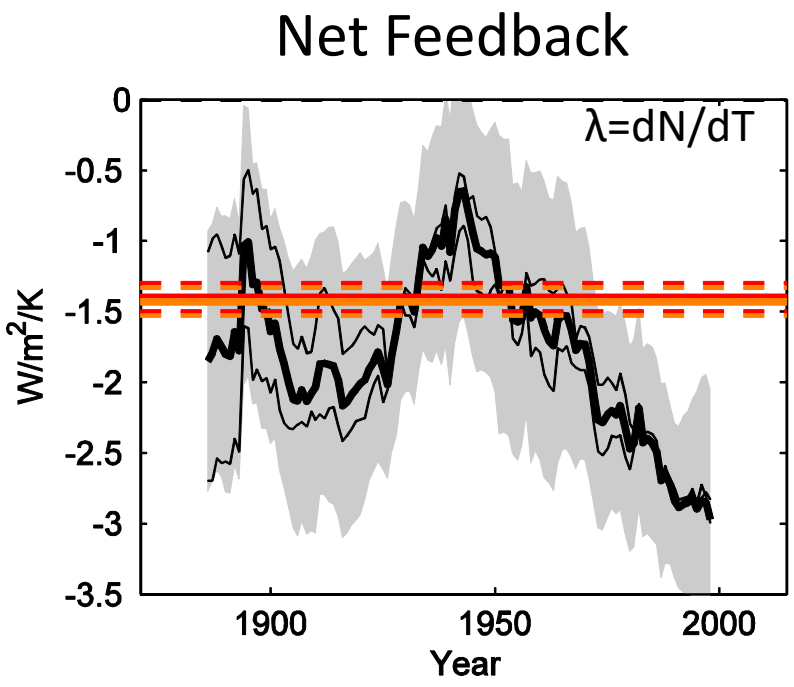


Q: What physics governs the non-constant feedback parameter, & hence time-varying estimates of climate sensitivity?

A: I will show that it involves clouds, which respond differently to global warming depending on the pattern of that warming. Because the pattern of warming varies considerably over time, so too does the cloud feedback, affecting the implied climate sensitivity.
One must account for this effect when trying to estimate climate sensitivity from the observed record.

Zhou et al., *Nature Geoscience*, 2016

Decadal feedbacks in CAM5



AMIPFF = Historical (observed) SSTs / sea ice, but fixed radiative forcing

AMIPFF
Uniform warming
Patterned future warming

- Decadal feedbacks: Gregory regression slopes over sliding 30-year windows.
- Net feedback varies dramatically and is roughly twice as large as the long-term net feedback in the most recent 30-year period.

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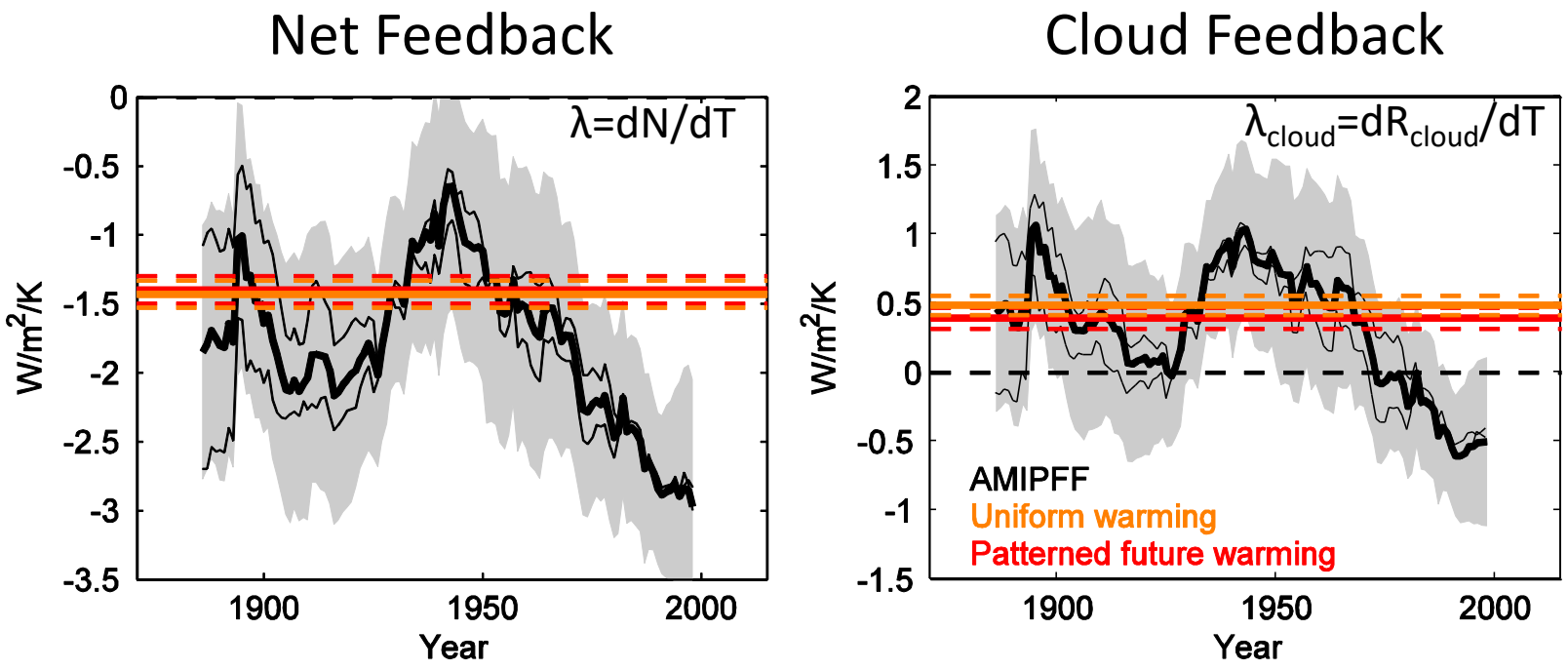

- Decadal feedbacks: Gregory regression slopes over sliding 30-year windows.
- Net feedback varies dramatically and is roughly twice as large as the long-term net feedback in the most recent 30-year period.
- This is mostly due to the cloud feedback.

What drives R_{cloud} fluctuations?

$$\Delta R_{cloud} = \lambda_c \Delta T_s + \Delta R_{PSST} + \varepsilon$$

Cloud-induced TOA radiation anomalies in AMIPFF exp

=

Global mean ΔT_s-induced component
(λ_c = cloud feedback from uniform 4K warming)

+

SST pattern-induced component
from patterned SST experiment (PSST):
- Historical SSTs, w/global mean removed
- Forcings constant at 1850/2000 levels

- All time series shown afterwards are annual anomalies smoothed w/9-year moving average. ***Orange lines*** will represent components that depend primarily on ***uniform warming***.
- ***Red lines*** will represent components that depend primarily on the ***pattern of warming***.

Zhou et al., *Nature Geoscience*, 2016

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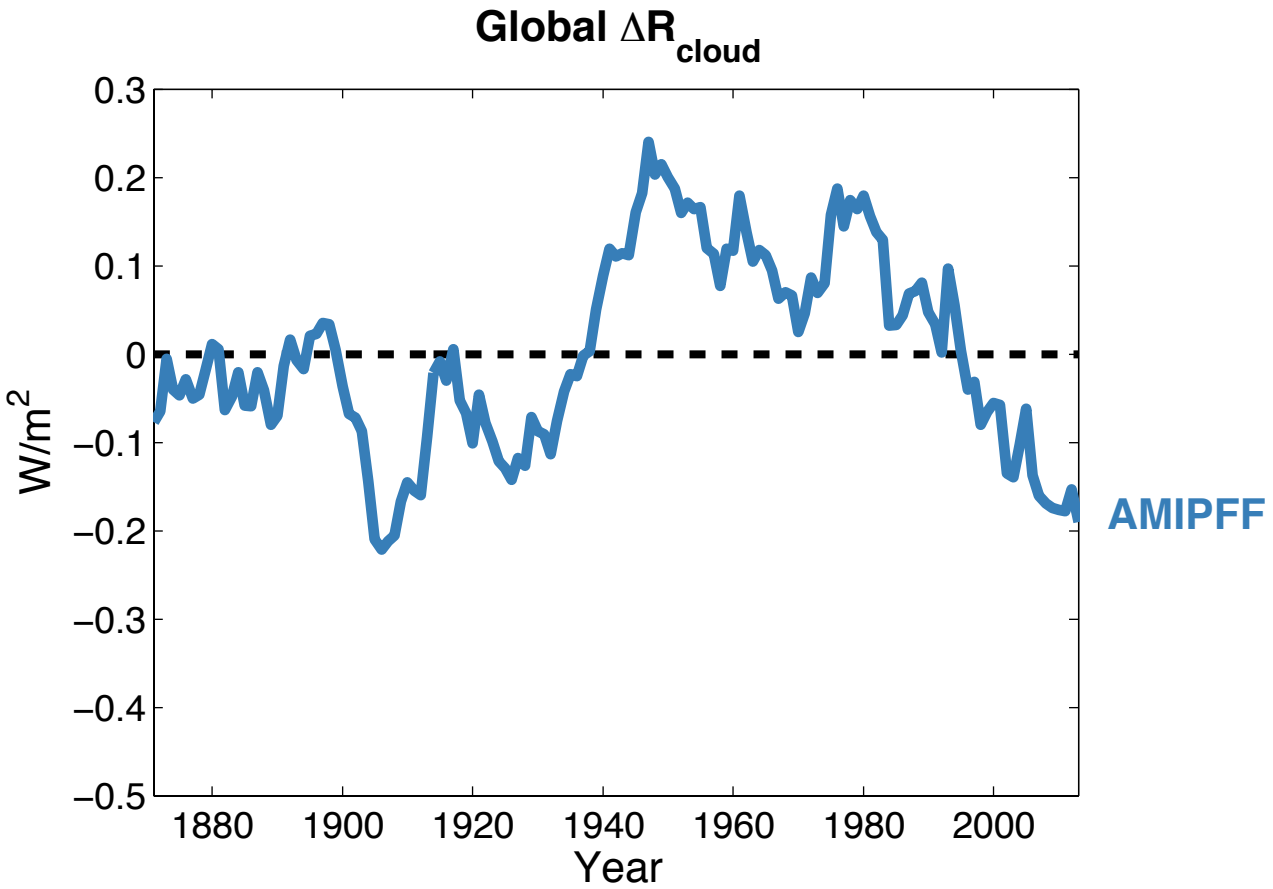

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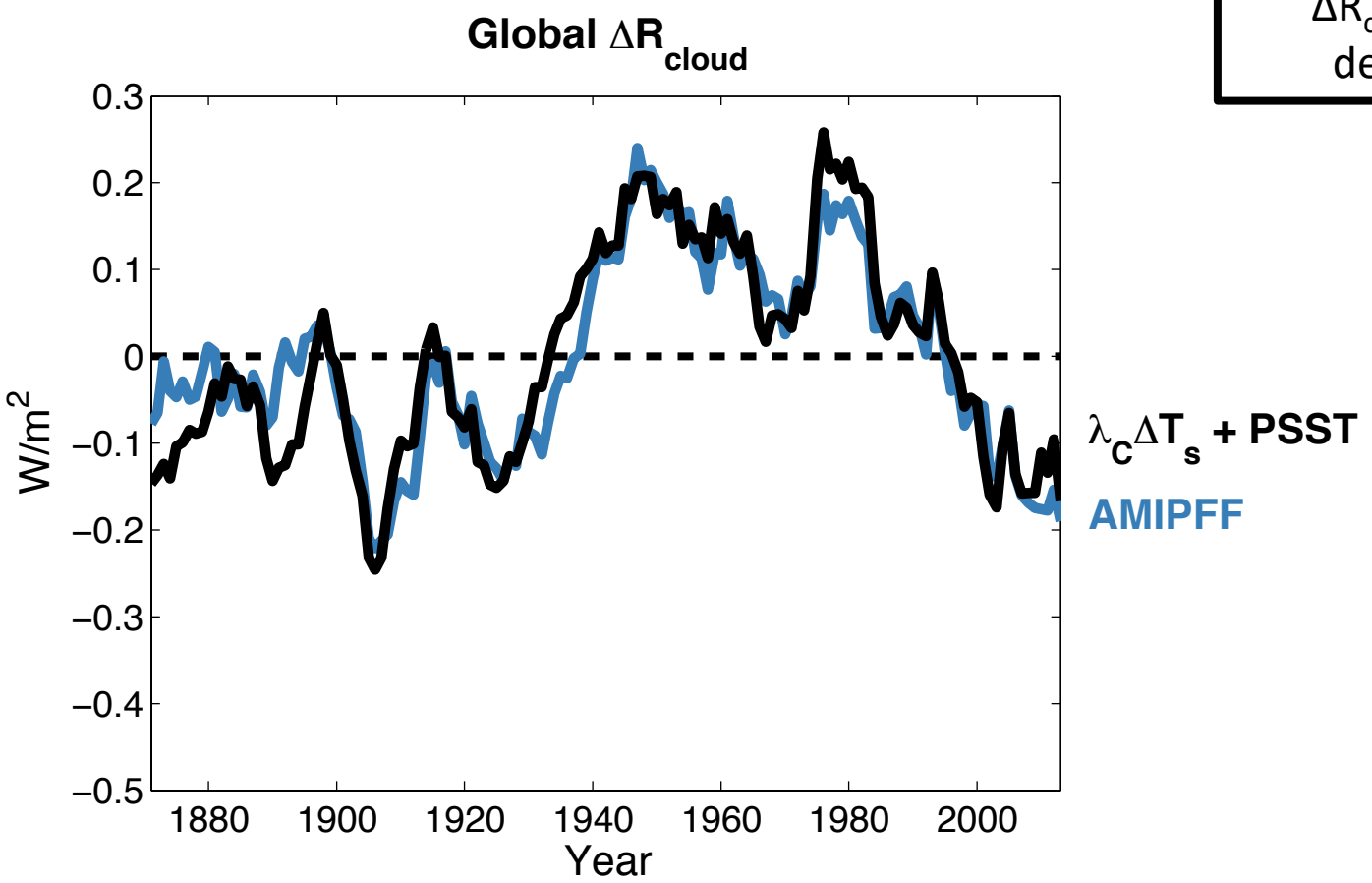
$$\boxed{\Delta R_{cloud}} = \lambda_c \Delta T_s + \Delta R_{PSST}$$

ΔR_{cloud} can be accurately decomposed this way.



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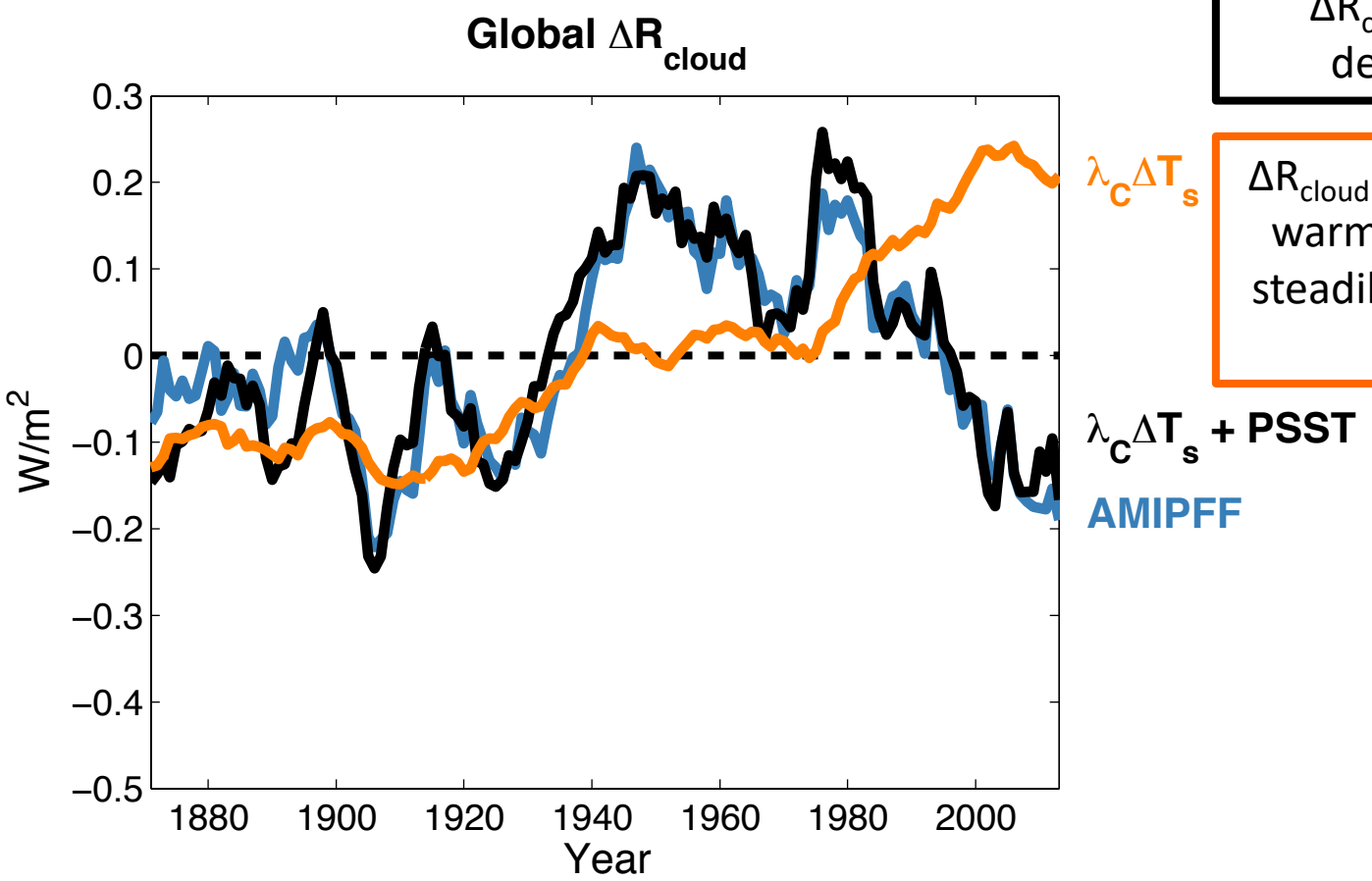

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ΔR_{cloud} due to spatially uniform warming increases relatively steadily over the course of the simulation.

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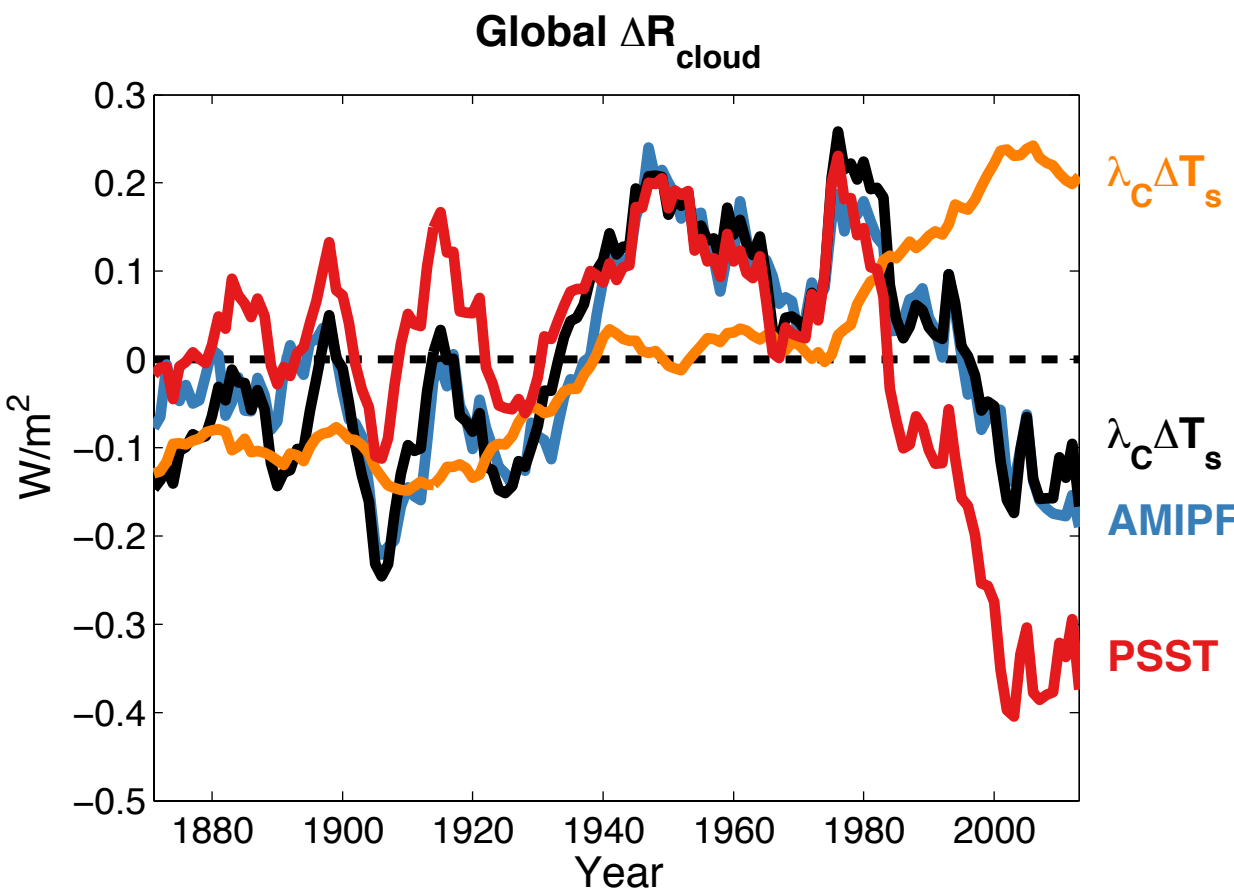

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Large fluctuations in ΔR_{cloud} are mainly driven by the SST pattern-induced component.

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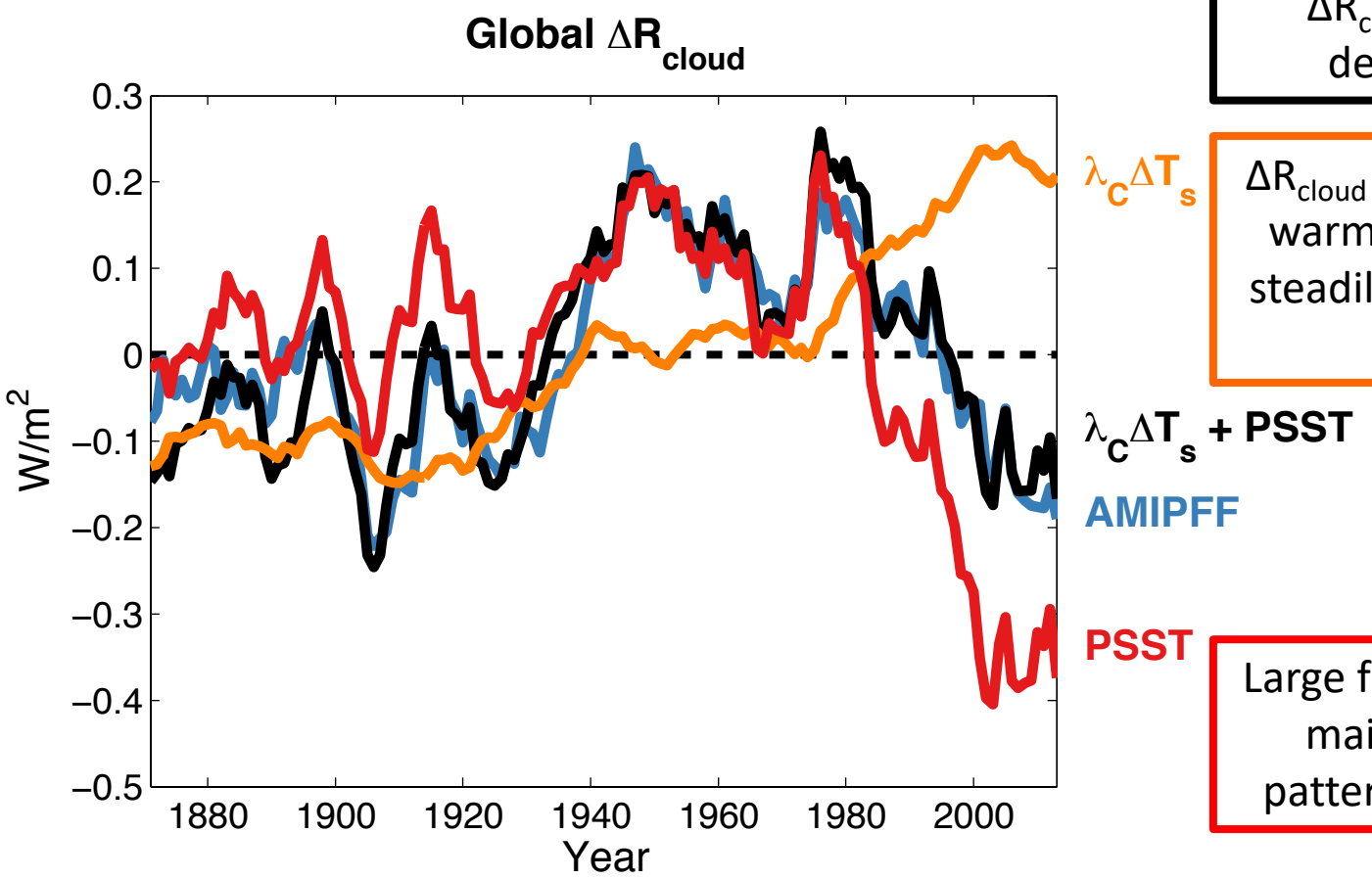
What drives R_{cloud} fluctuations?

Answer: Changing SST patterns. What's the physical mechanism?



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What drives low cloud cover fluctuations?

- Decadal R_{cloud} anomalies are primarily caused by changes in low cloud cover (LCC) over the tropical oceans (r = -0.77).
- These are the same cloud types that are most important for driving the inter-model spread in cloud feedback and climate sensitivity.
- So what drives LCC fluctuations? Consider low cloud-controlling factors…

$$\Delta LCC = \frac{\partial LCC}{\partial EIS}\Delta EIS + \frac{\partial LCC}{\partial SST}\Delta SST + R$$

Qu et al (2014, 2015), Myers and Norris (2016), Brient and Schneider (2016), McCoy et al (2017)

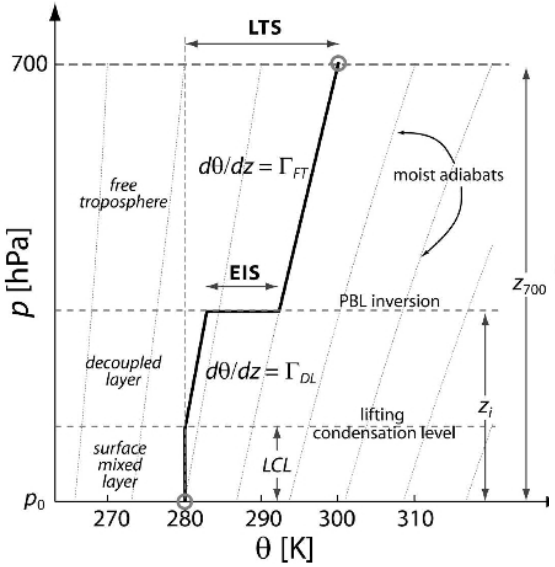
Low Cloud Controlling Factors

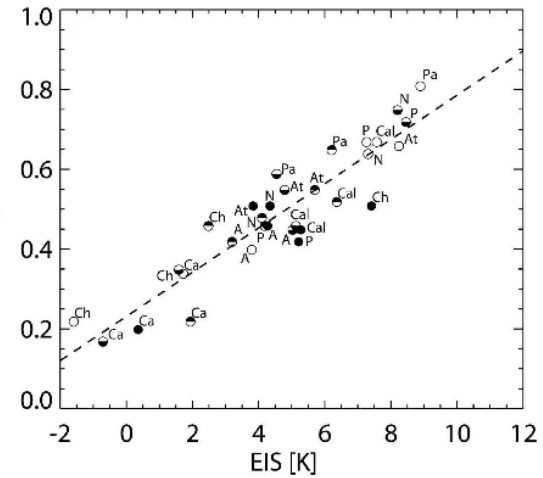
$$\Delta LCC = \boxed{\frac{\partial LCC}{\partial EIS}\Delta EIS} + \boxed{\frac{\partial LCC}{\partial SST}\Delta SST} + R$$

The Estimated Inversion Strength (EIS) contribution captures the fact that a stronger inversion…

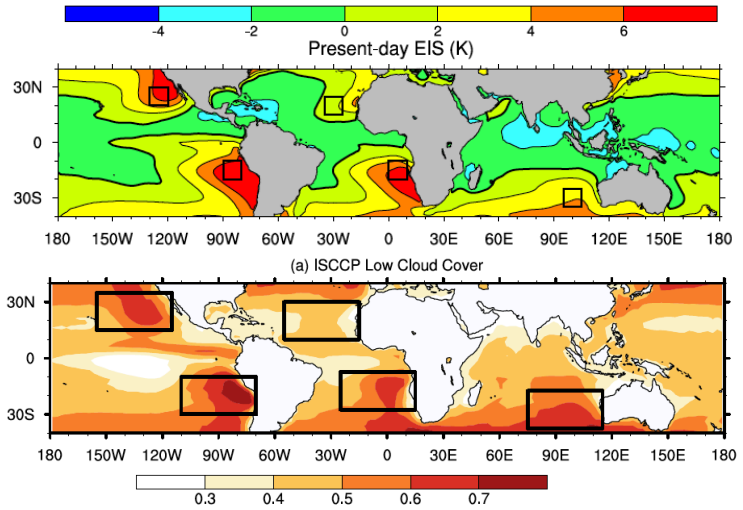
…suppresses mixing of BL with drier free tropospheric air

…leads to a shallower, moister, and cloudier BL





Wood & Bretherton (2006)



Qu et al., *GRL* (2015)

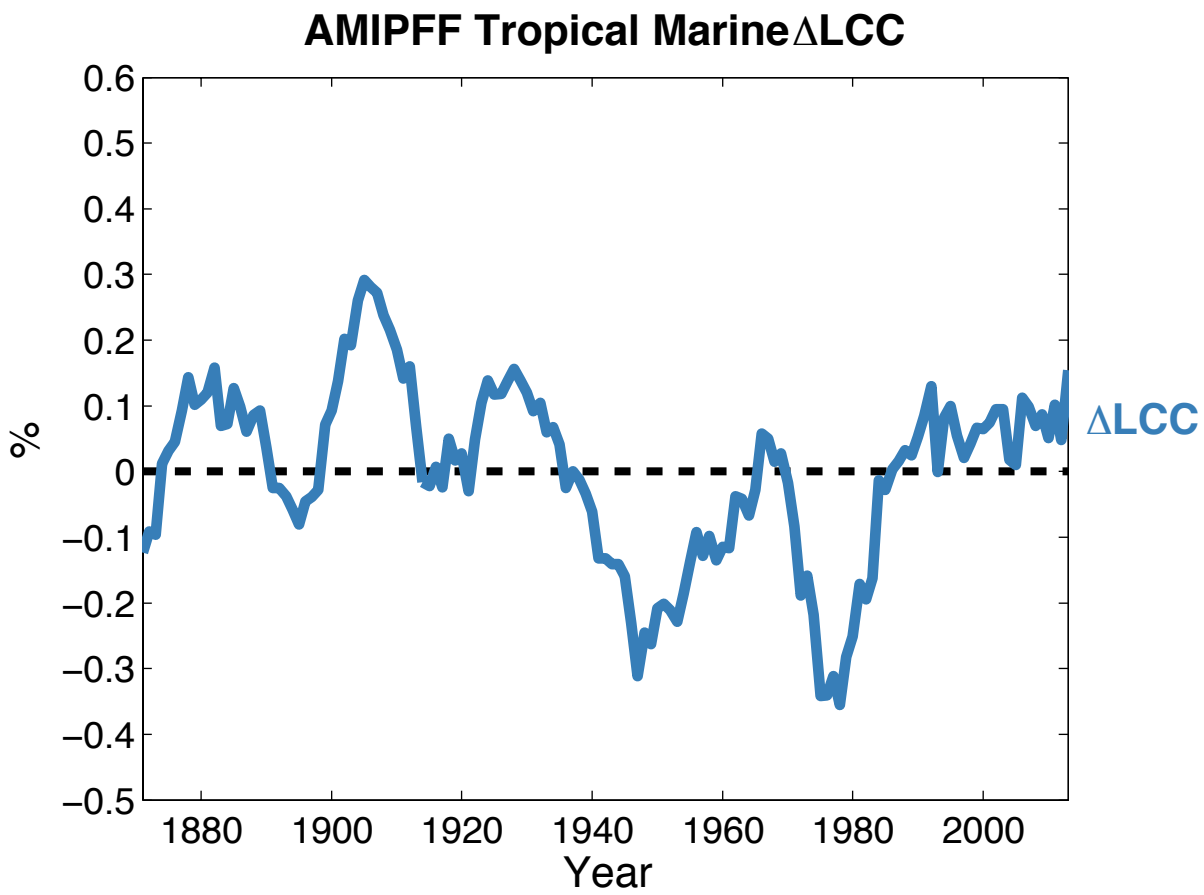
Qu et al., *Clim. Dyn.* (2015)

The SST contribution can be interpreted as the sum of contributions from increases in

- surface latent heat flux (which enhances buoyancy-driven mixing of dry free trop air into BL)
- vertical moisture gradient in the lower-troposphere (drier entrainment for a given mixing)

Zhou et al., *Nature Geoscience*, 2016

What drives low cloud cover fluctuations?



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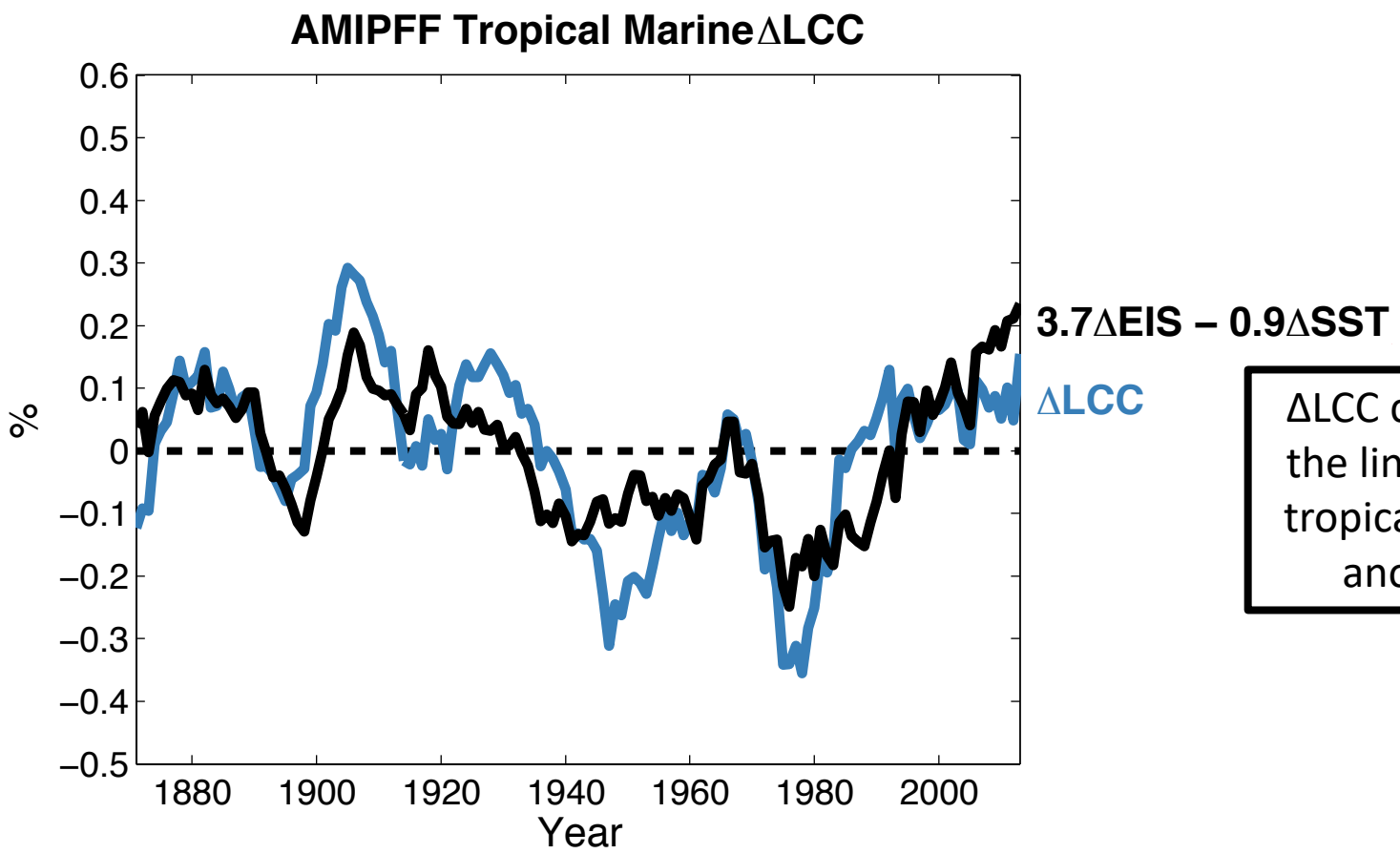

ΔLCC can be explained by the linear combination of tropical mean SST and EIS anomalies (r=0.76).

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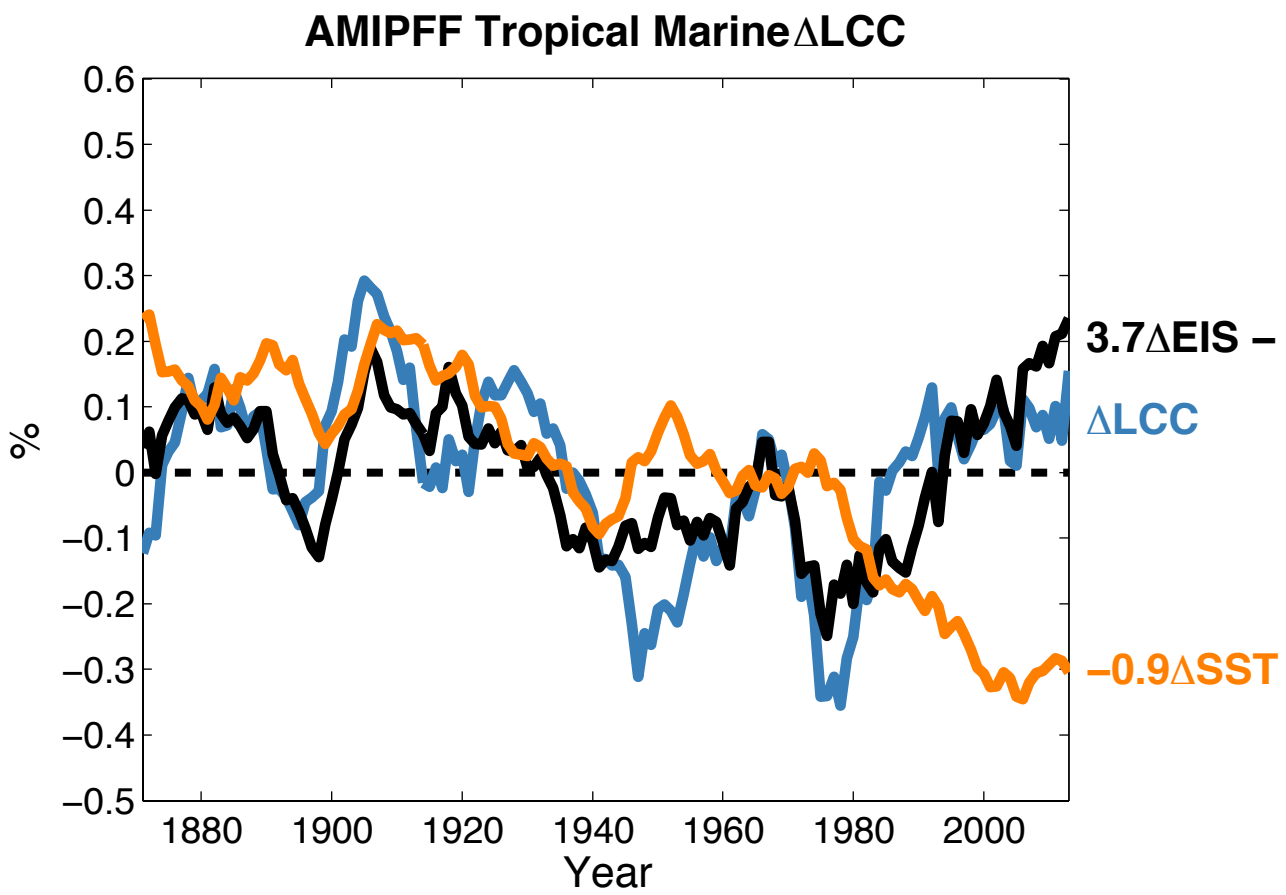

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Global warming over this period induces a fairly steady decrease in LCC

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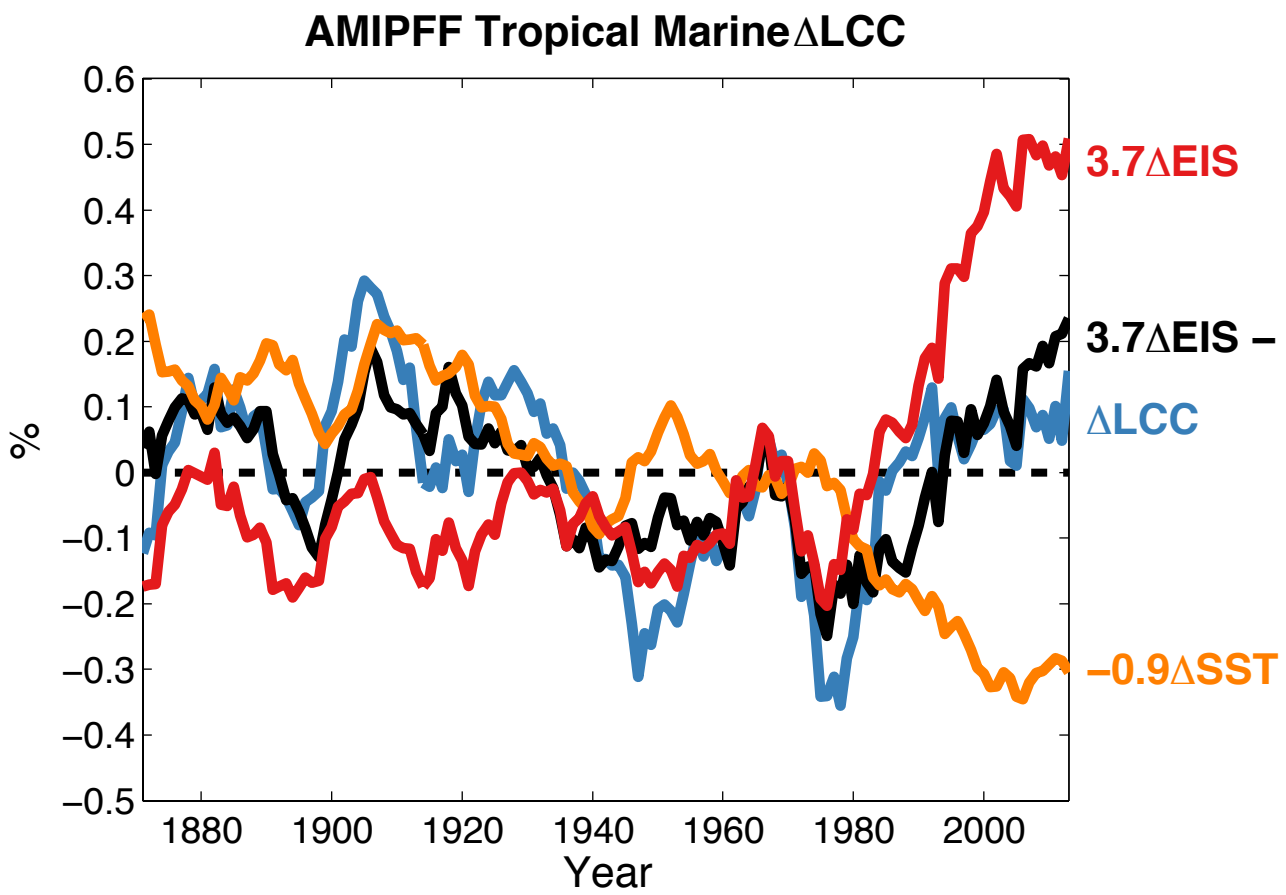

ΔEIS explains more decadal variance in LCC than ΔSST, and the EIS-driven component exhibits a hockey stick shape.

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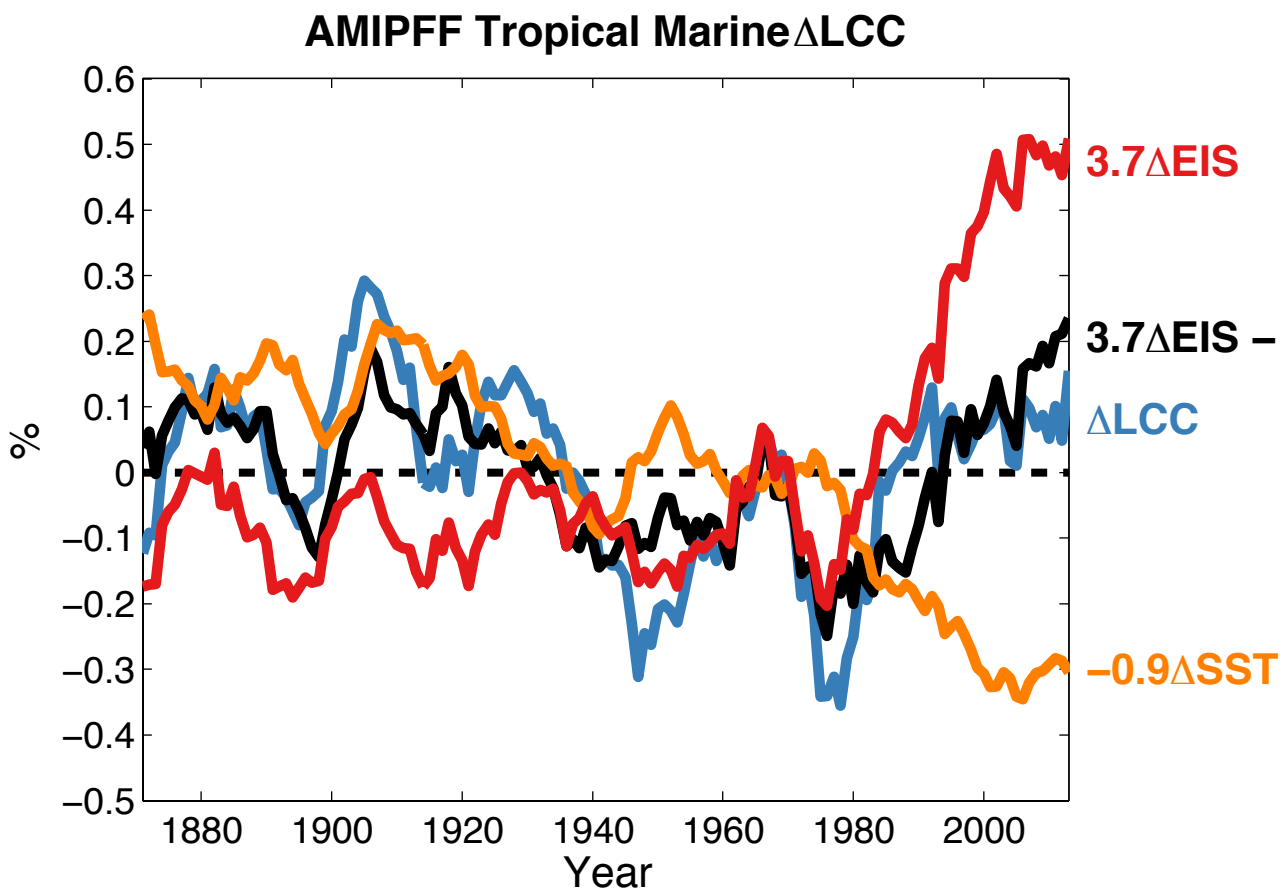
Answer: EIS fluctuations. So what drives them?



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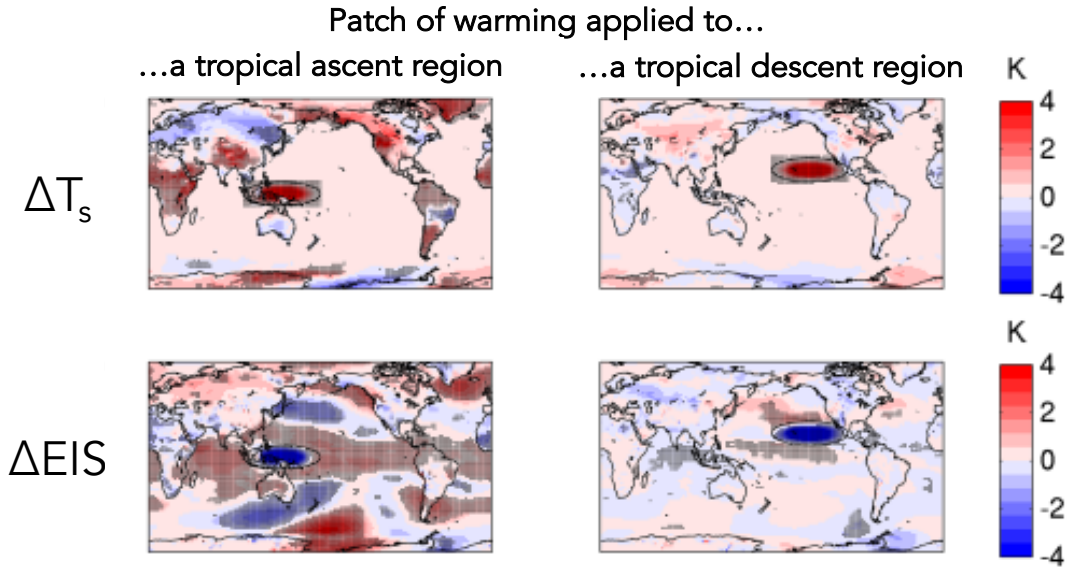
Local vs. nonlocal warming impacts



CAM5 Green's Function Experiments
Zhou et al., *JAMES (*2017)
See also Andrews & Webb, *J. Climate* (2018)

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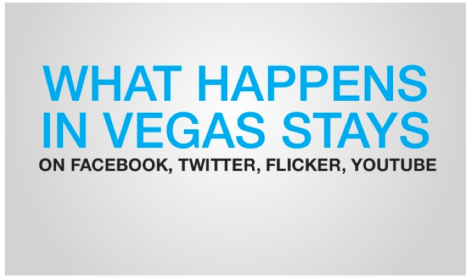

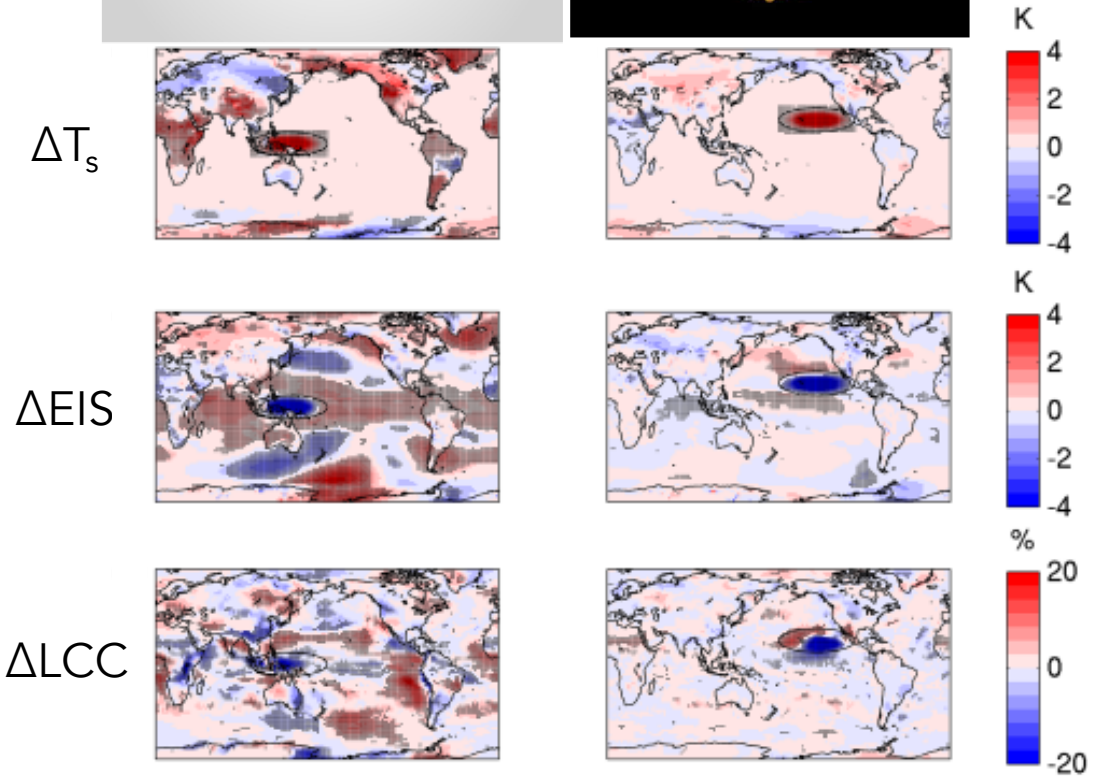

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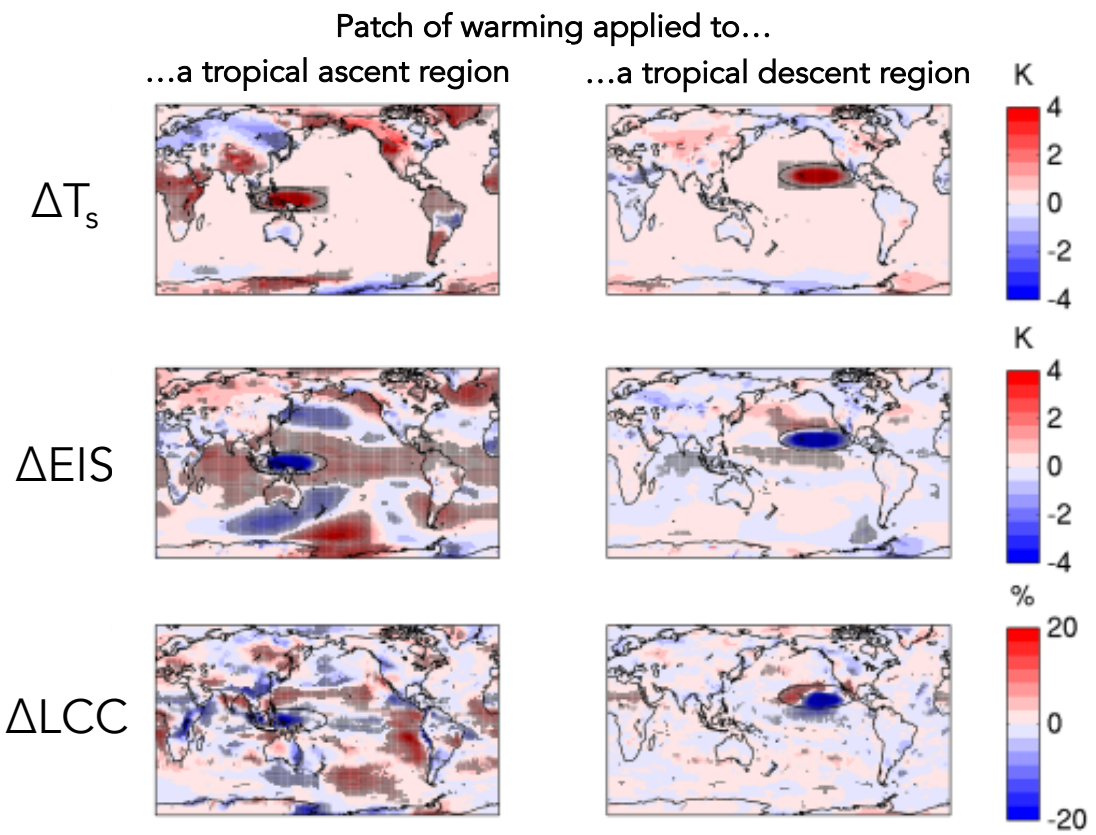

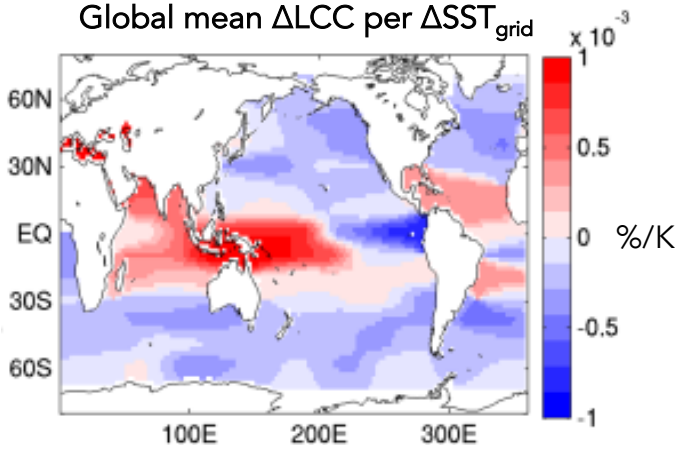

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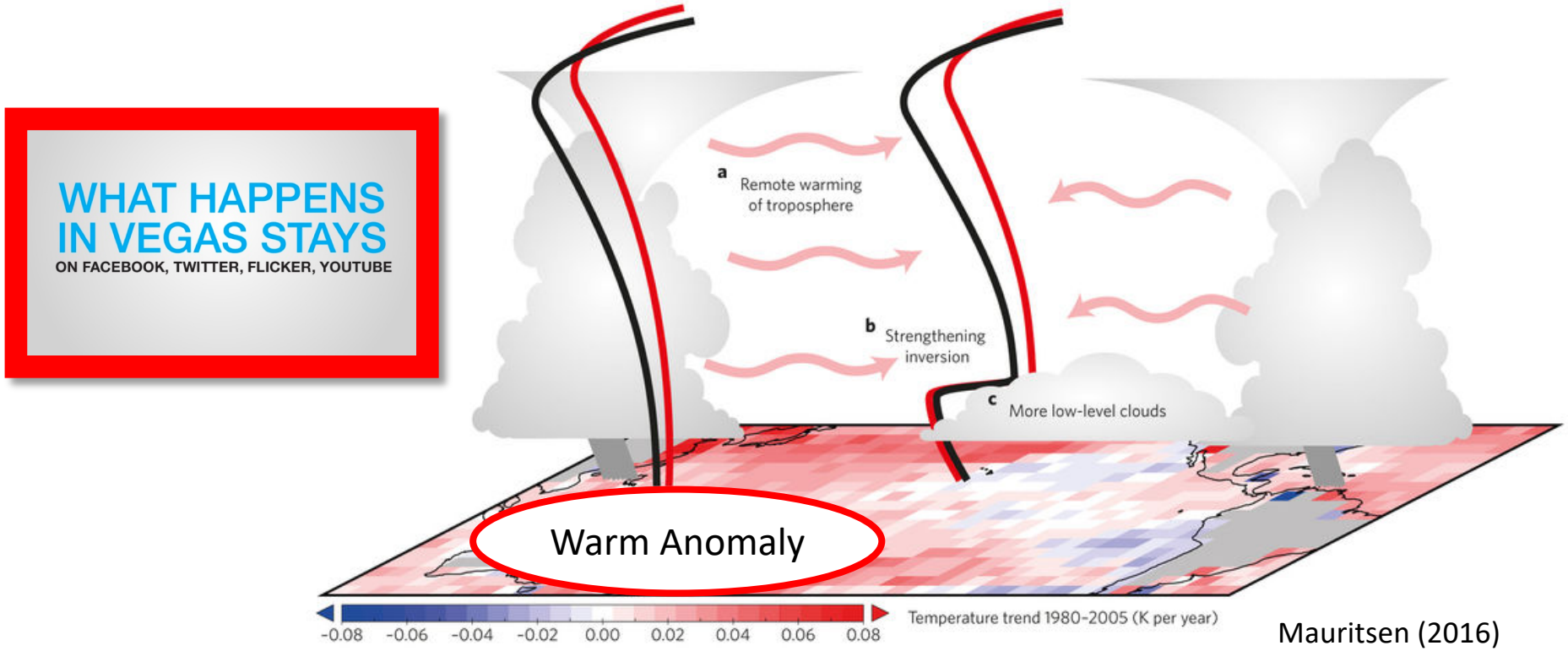
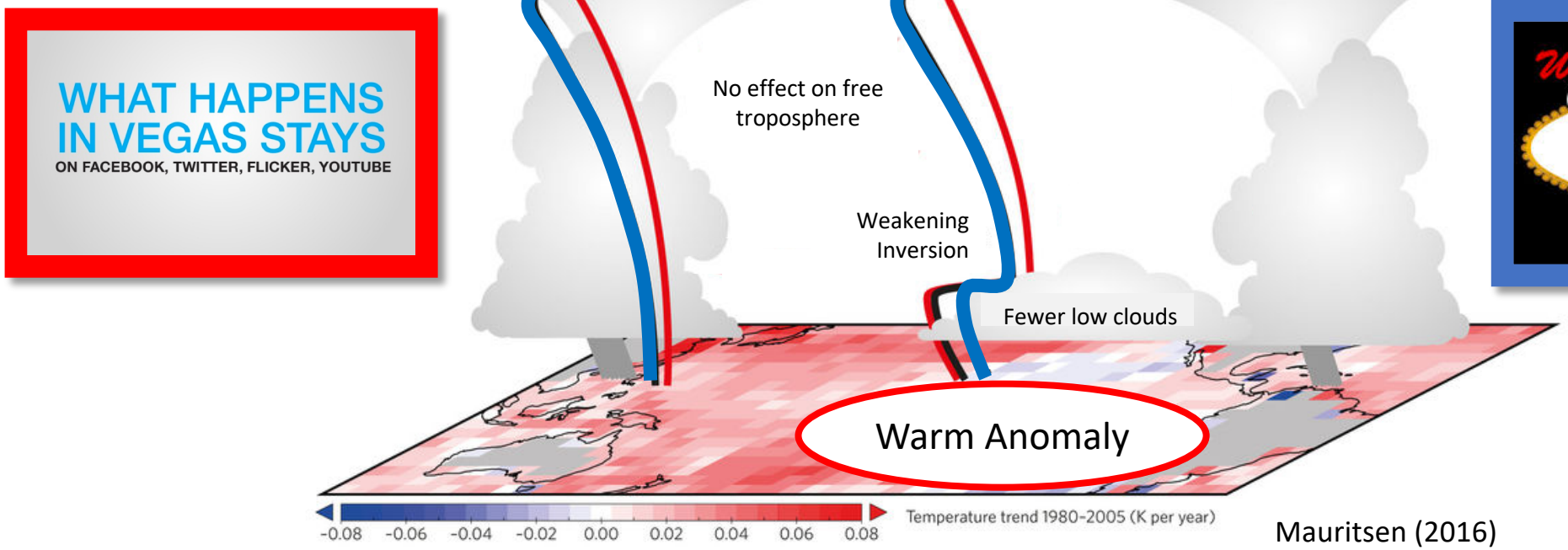
The Mechanism



Mauritsen (2016)

Free-tropospheric temperatures are controlled by the moist adiabat set by the SST in tropical ascent regions, whereas SSTs in tropical descent regions affect only the local boundary layer temperature. Warming concentrated in warm ascent regions favors increases in EIS and LCC, and vice versa.

The Mechanism



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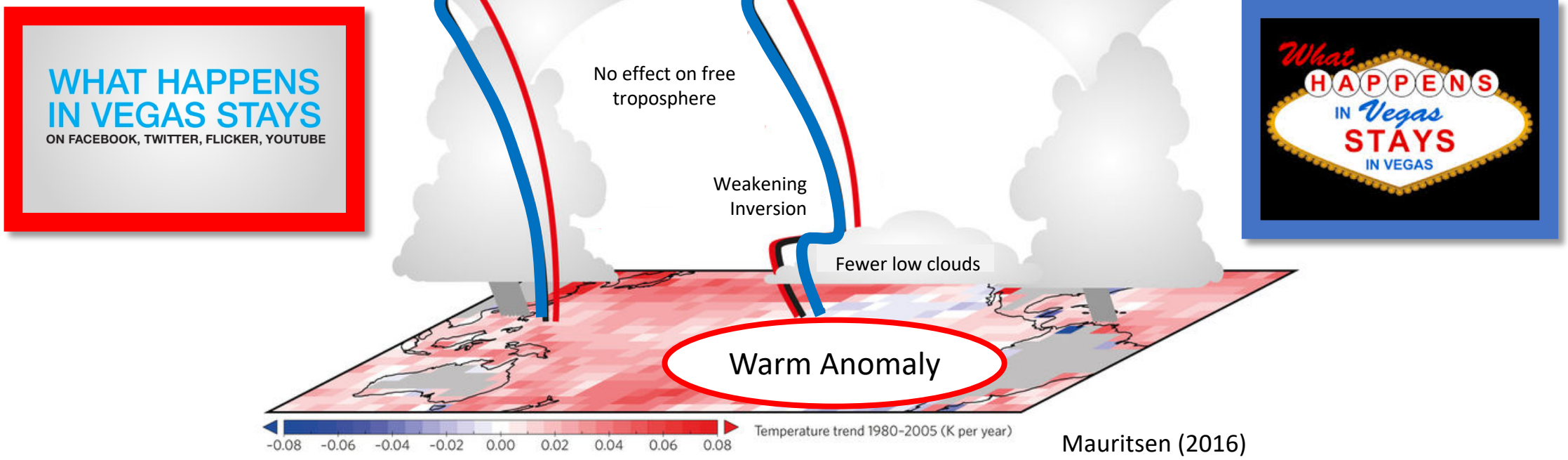

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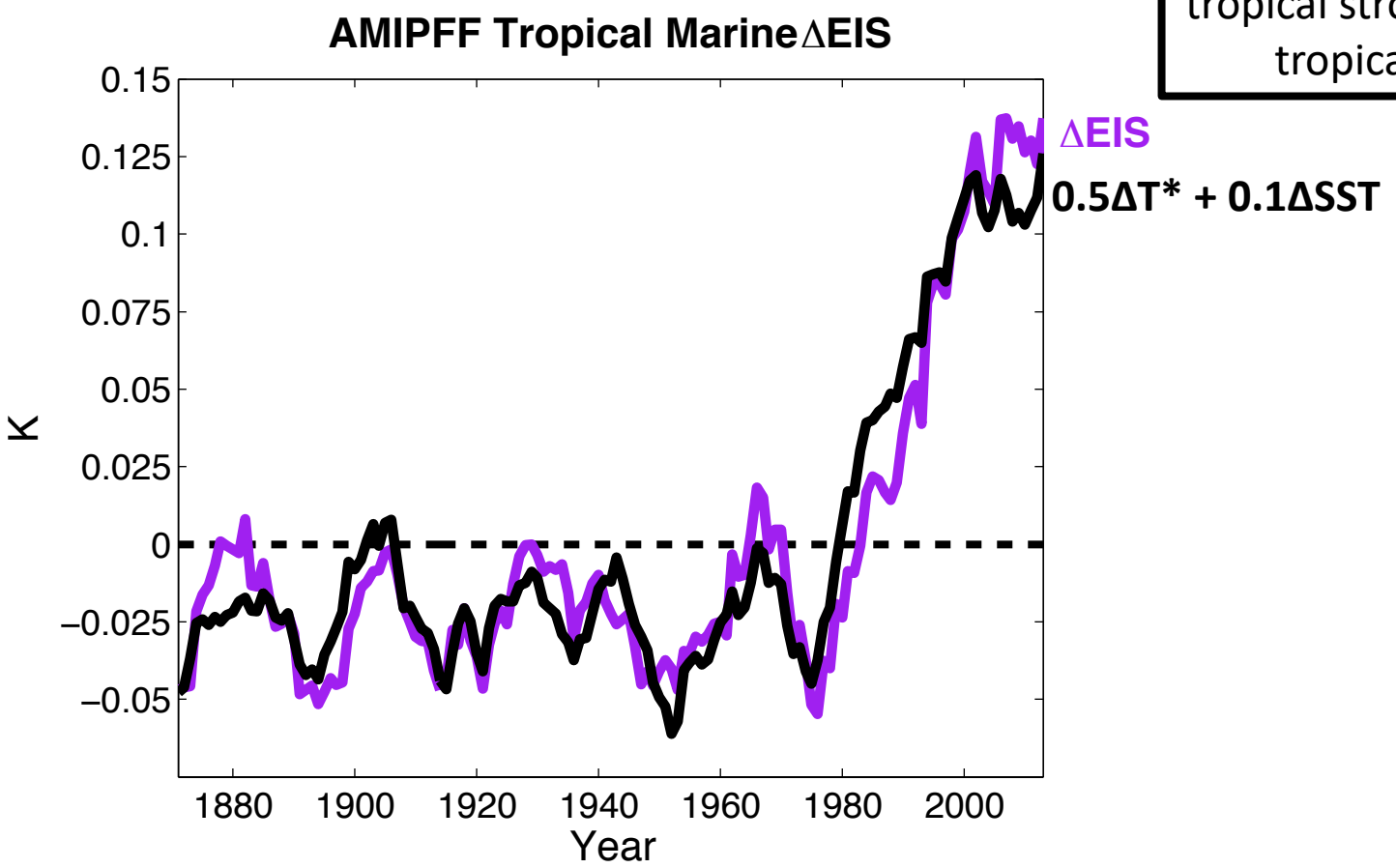
*This motivates us to define **T***, the difference between SST in tropical strong ascent regions and tropical mean SST.*

Zhou et al., *Nature Geoscience*, 2016

What drives EIS fluctuations?

ΔEIS well explained (r=0.94) by a linear combo of tropical mean SST and the difference between SST in tropical strong ascent regions and tropical mean SST [ΔT*].



Zhou et al., *Nature Geoscience*, 2016

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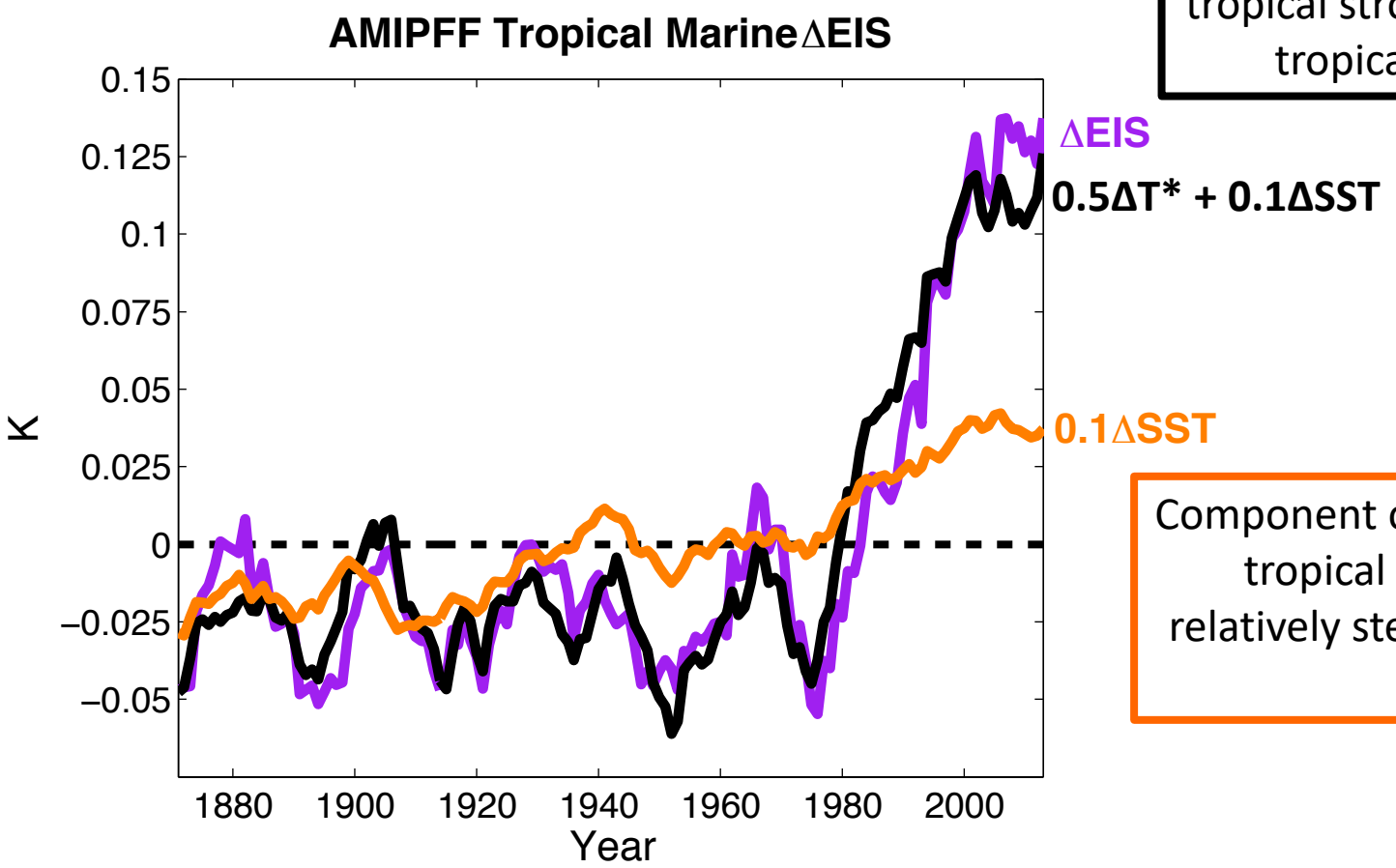

Component of EIS change driven by tropical mean SST exhibits relatively steady increase over the record.

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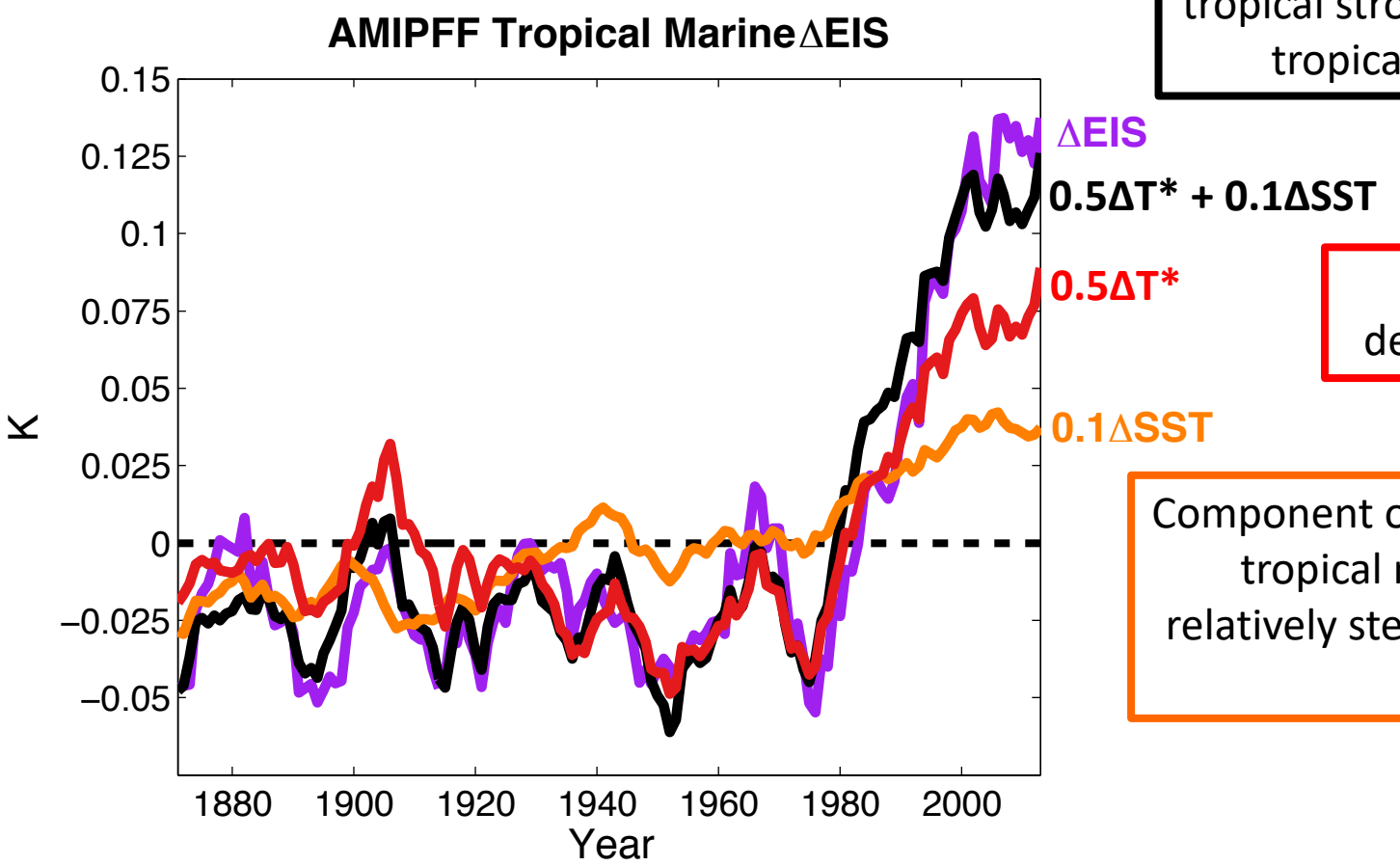

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ΔT* explains more decadal variance in EIS.

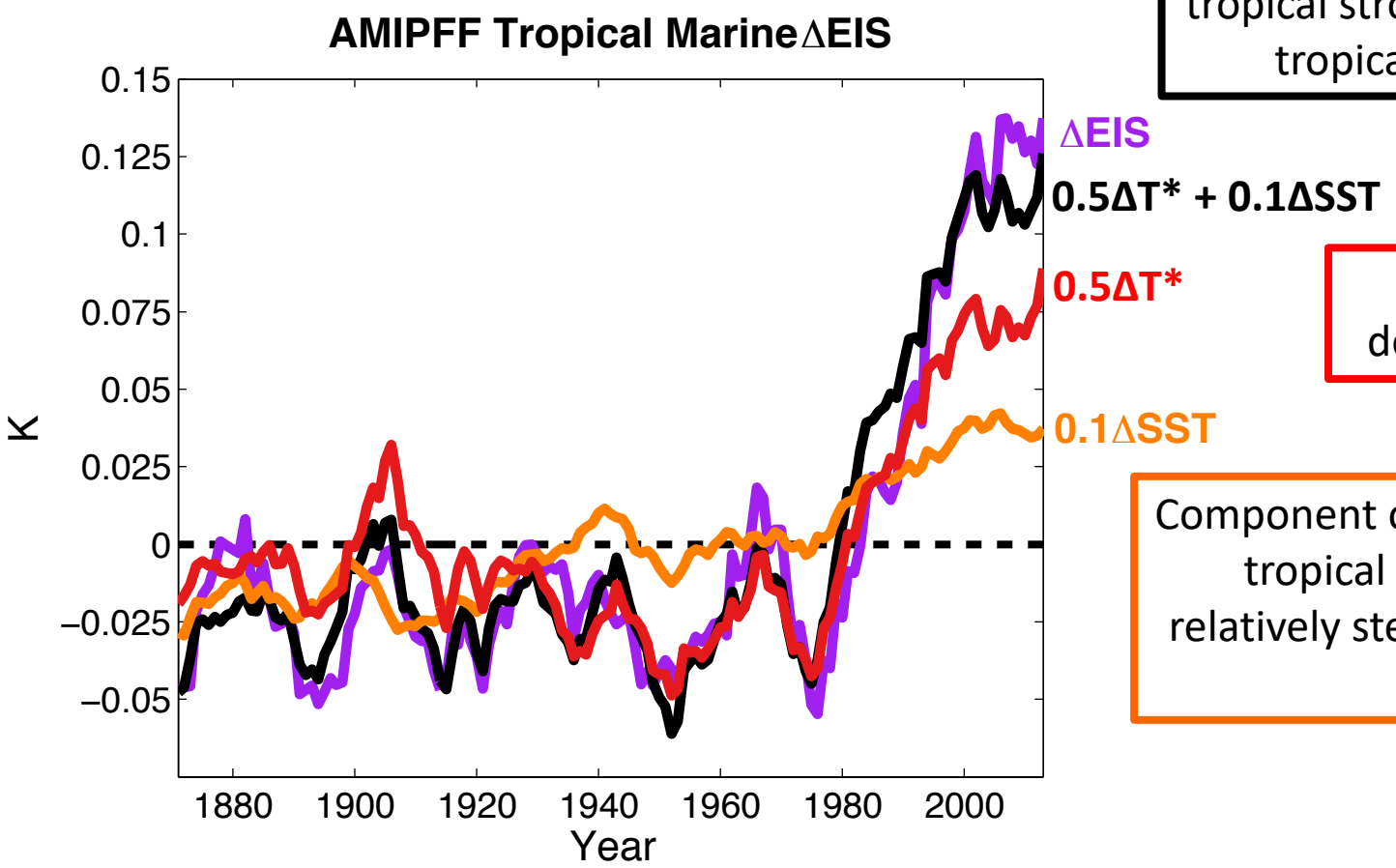
Component of EIS change driven by tropical mean SST exhibits relatively steady increase over the record.

Zhou et al., *Nature Geoscience*, 2016

What drives EIS fluctuations?

Answer: The degree to which warming is concentrated in regions of strong ascent.

ΔEIS well explained (r=0.94) by a linear combo of tropical mean SST and the difference between SST in tropical strong ascent regions and tropical mean SST [ΔT*].



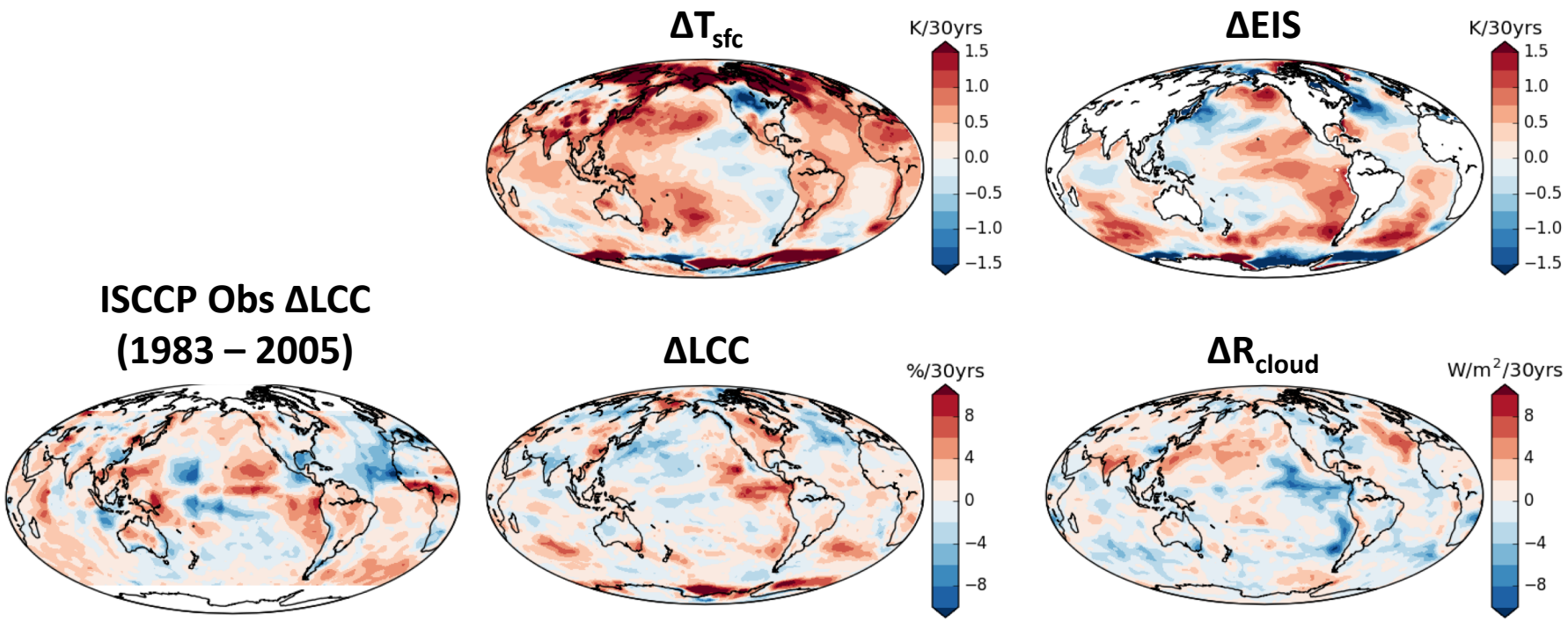
ΔT* explains more decadal variance in EIS.

Component of EIS change driven by tropical mean SST exhibits relatively steady increase over the record.

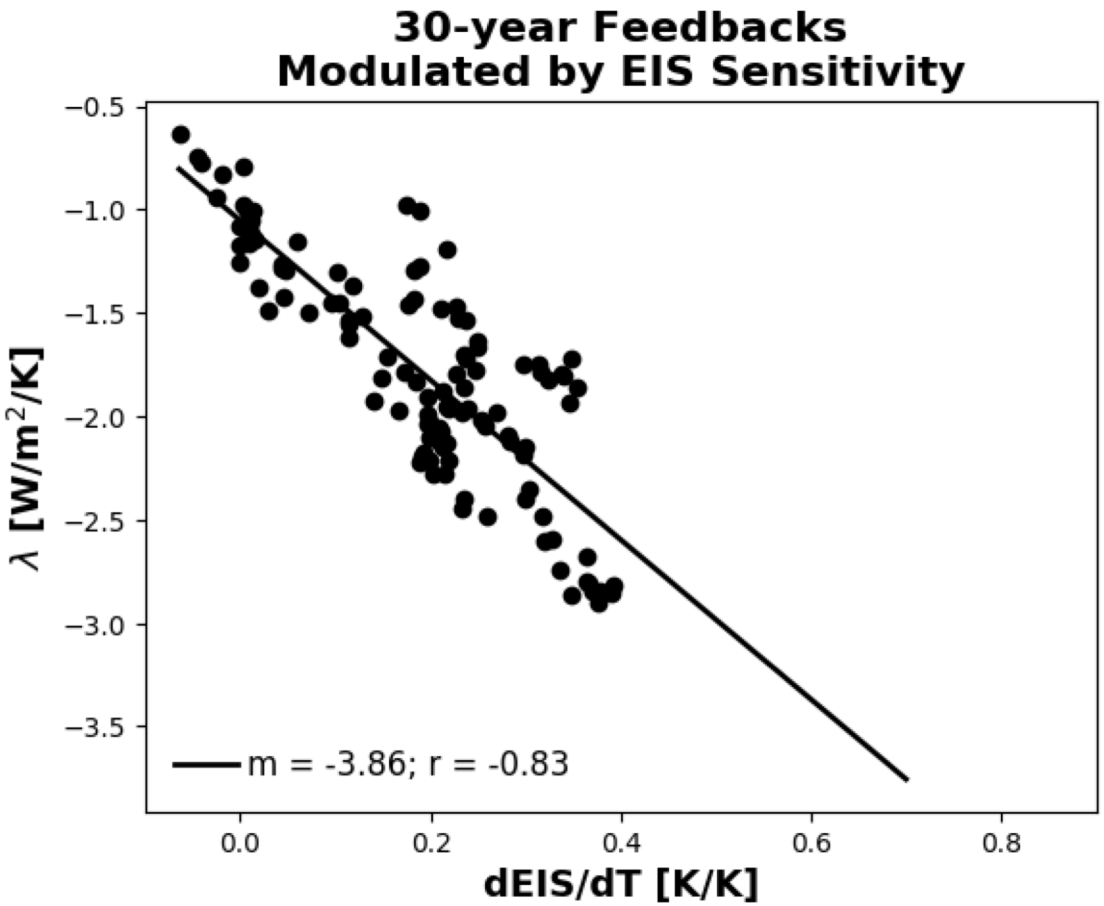
Zhou et al., *Nature Geoscience*, 2016

What's driving the EIS hockey stick?

AMIPFF experiment between 1980 and 2005



Decadal feedbacks are strongly modulated by warming pattern thru its impact on inversion strength



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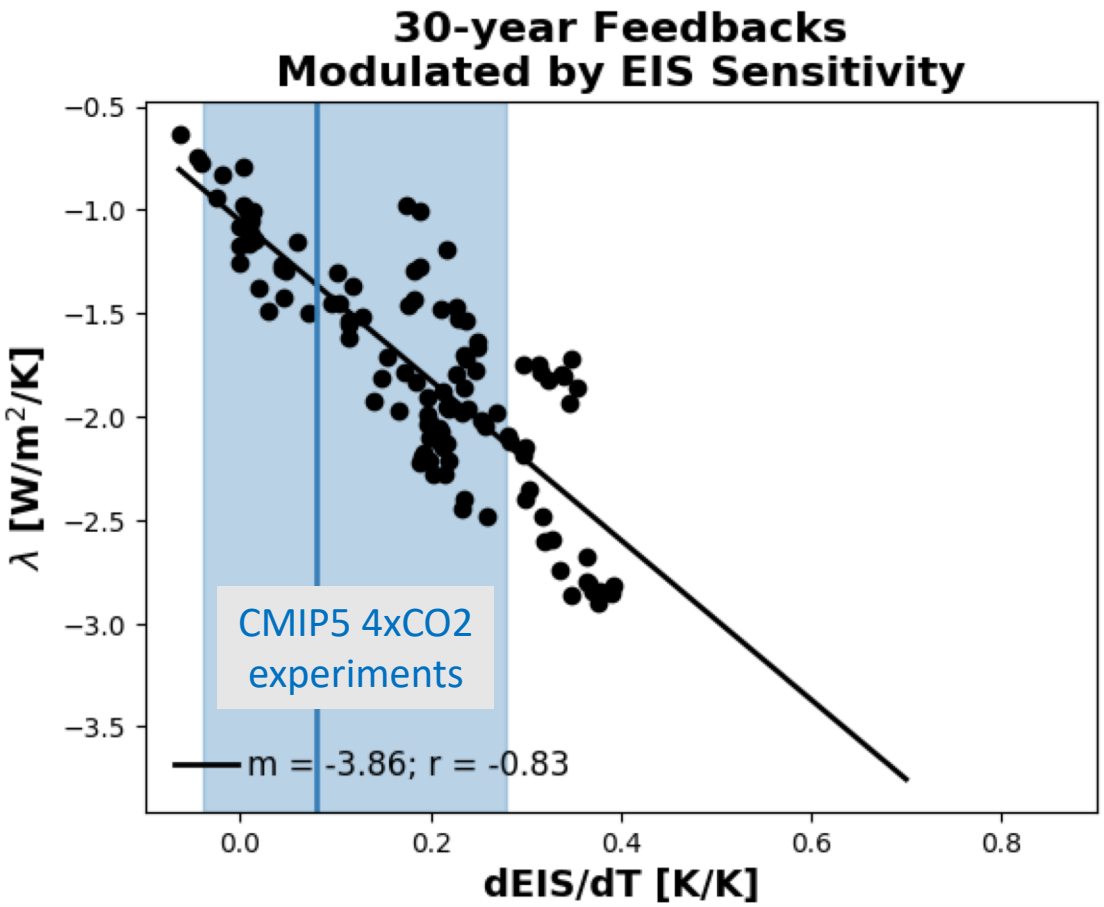

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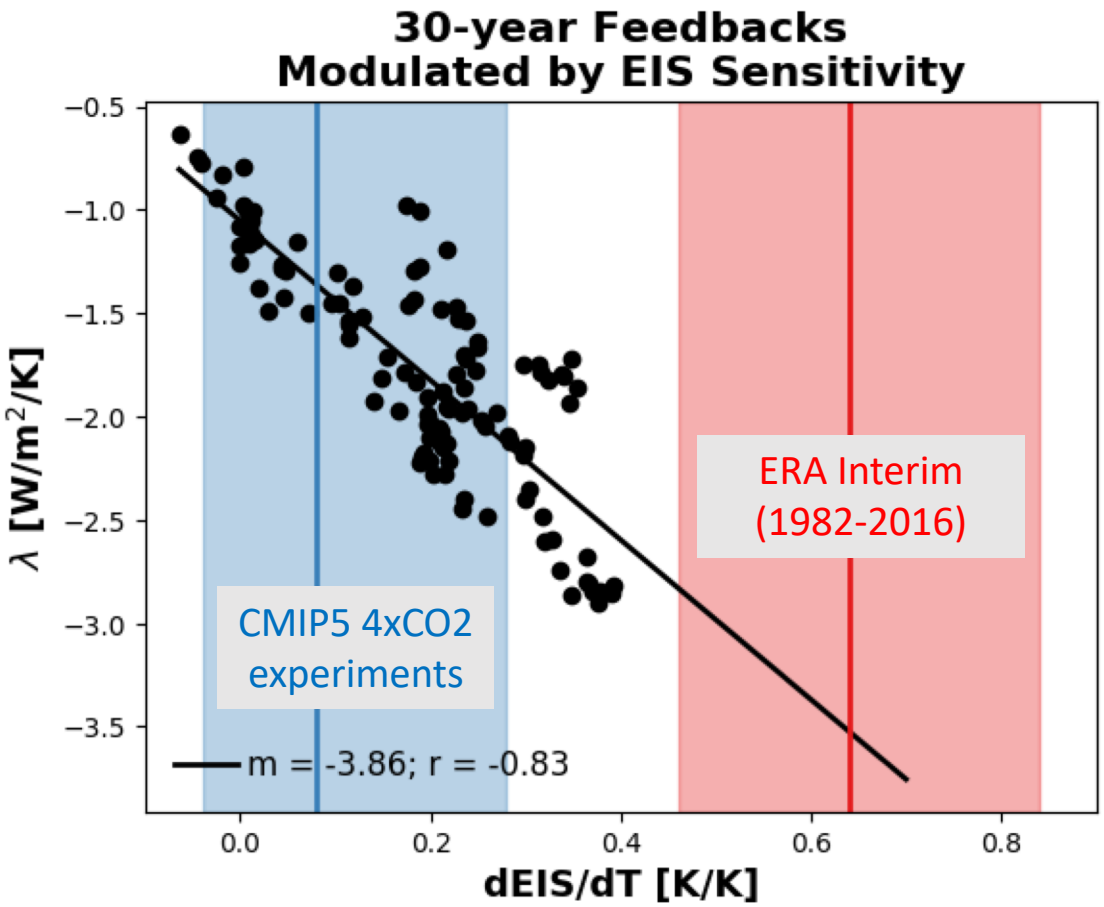

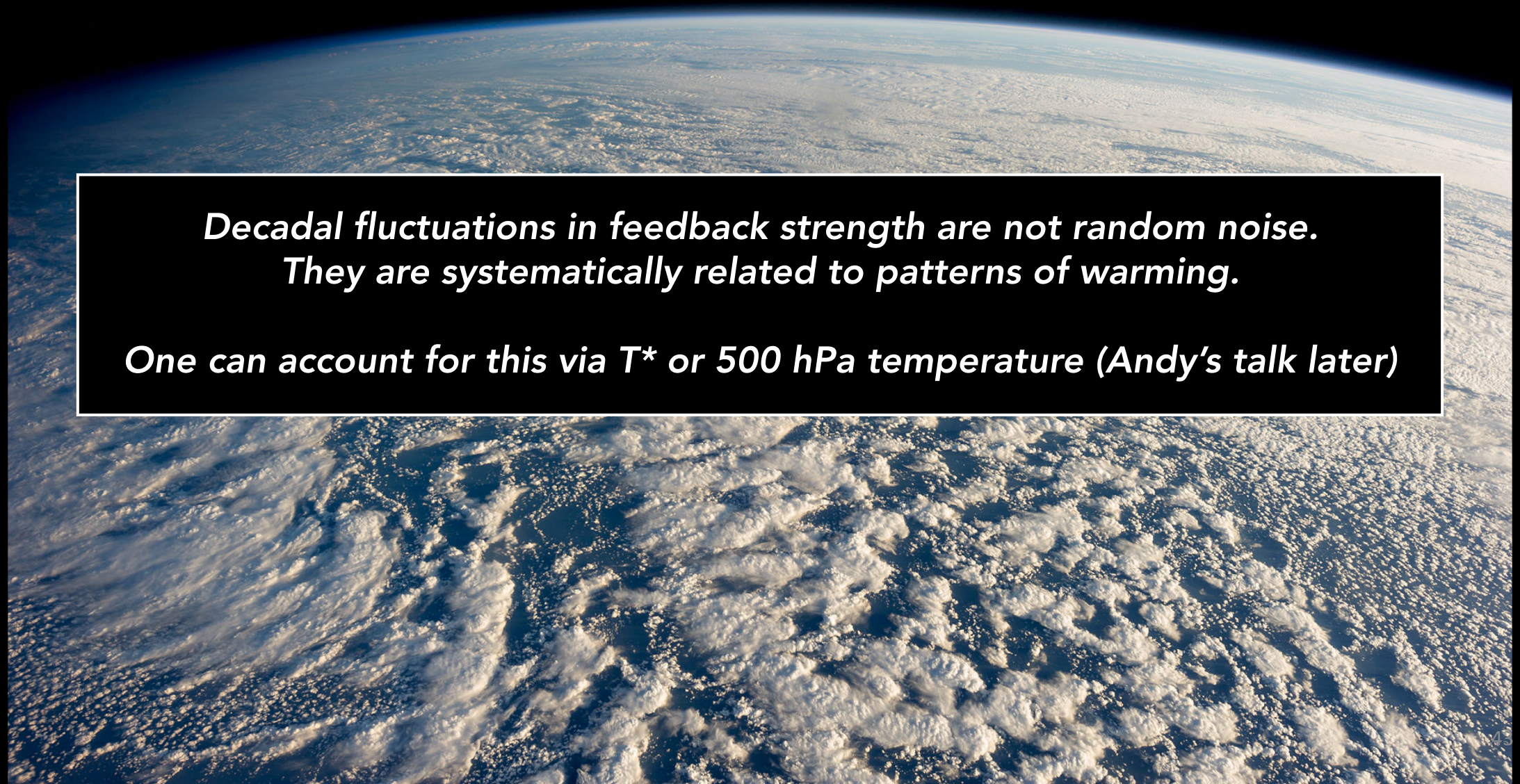

Decadal fluctuations in feedback strength are not random noise.
They are systematically related to patterns of warming.

One can account for this via T or 500 hPa temperature (Andy's talk later)*

Take Home Messages

- There is not "one feedback to rule them all"
  - Inferences about climate sensitivity from the observed record must account for a time-varying climate feedback.
- Sign and magnitude of cloud feedbacks depend sensitively on the pattern of warming
  - Warming concentrated in tropical ascending regions strengthens low-level stability across the Tropics, increases low cloud cover, and makes the cloud feedback more negative than in response to uniform warming.
  - The recent 30 years are a particularly bad analogy for the more spatially-uniform greenhouse warming and lead to underestimates of climate sensitivity.

Zhou, C., M. D. Zelinka, and S. A. Klein, 2016: Impact of decadal cloud variations on the Earth's energy budget, *Nature Geoscience*, 9, 871–874, doi:10.1038/ngeo2828.

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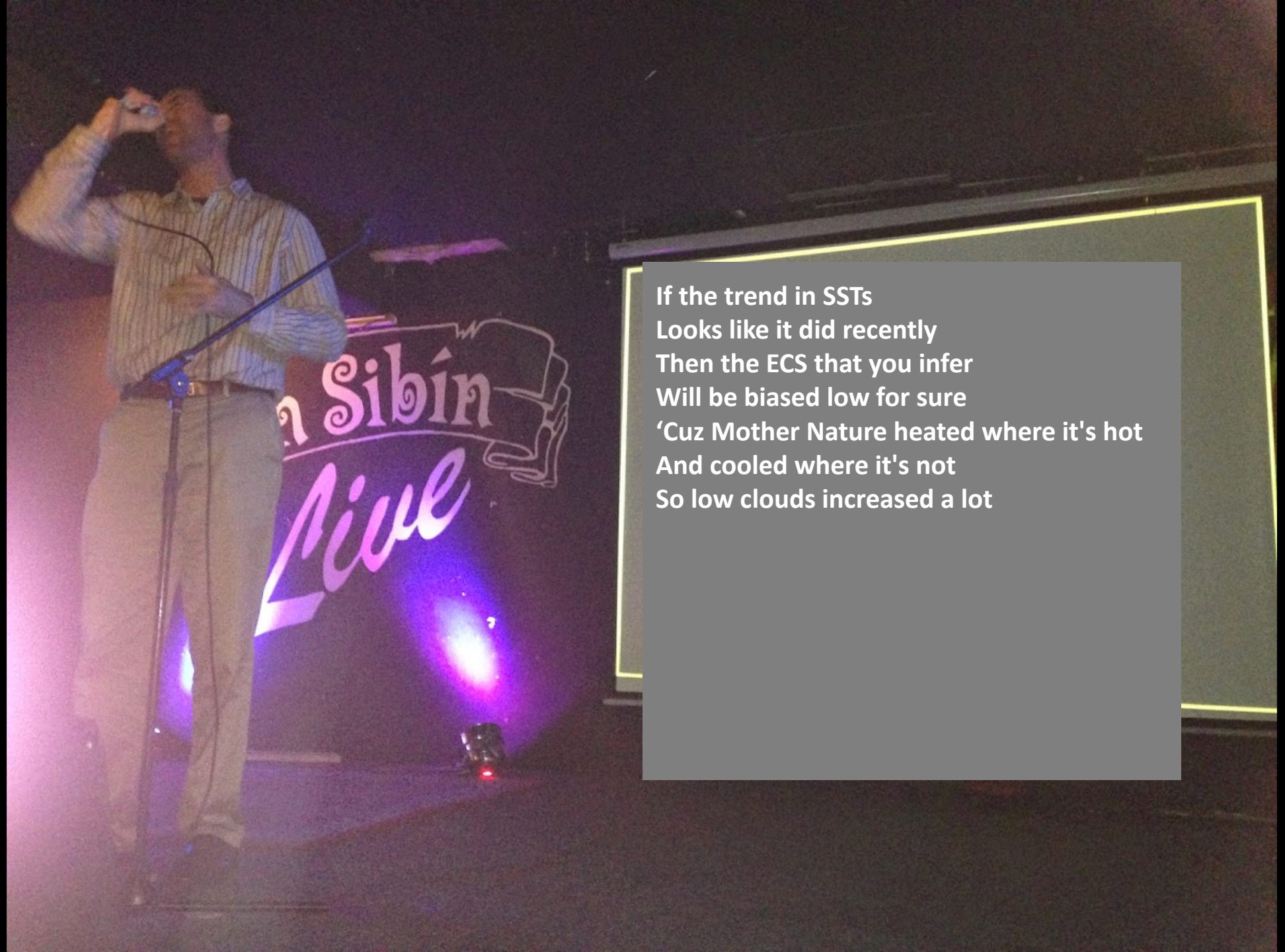
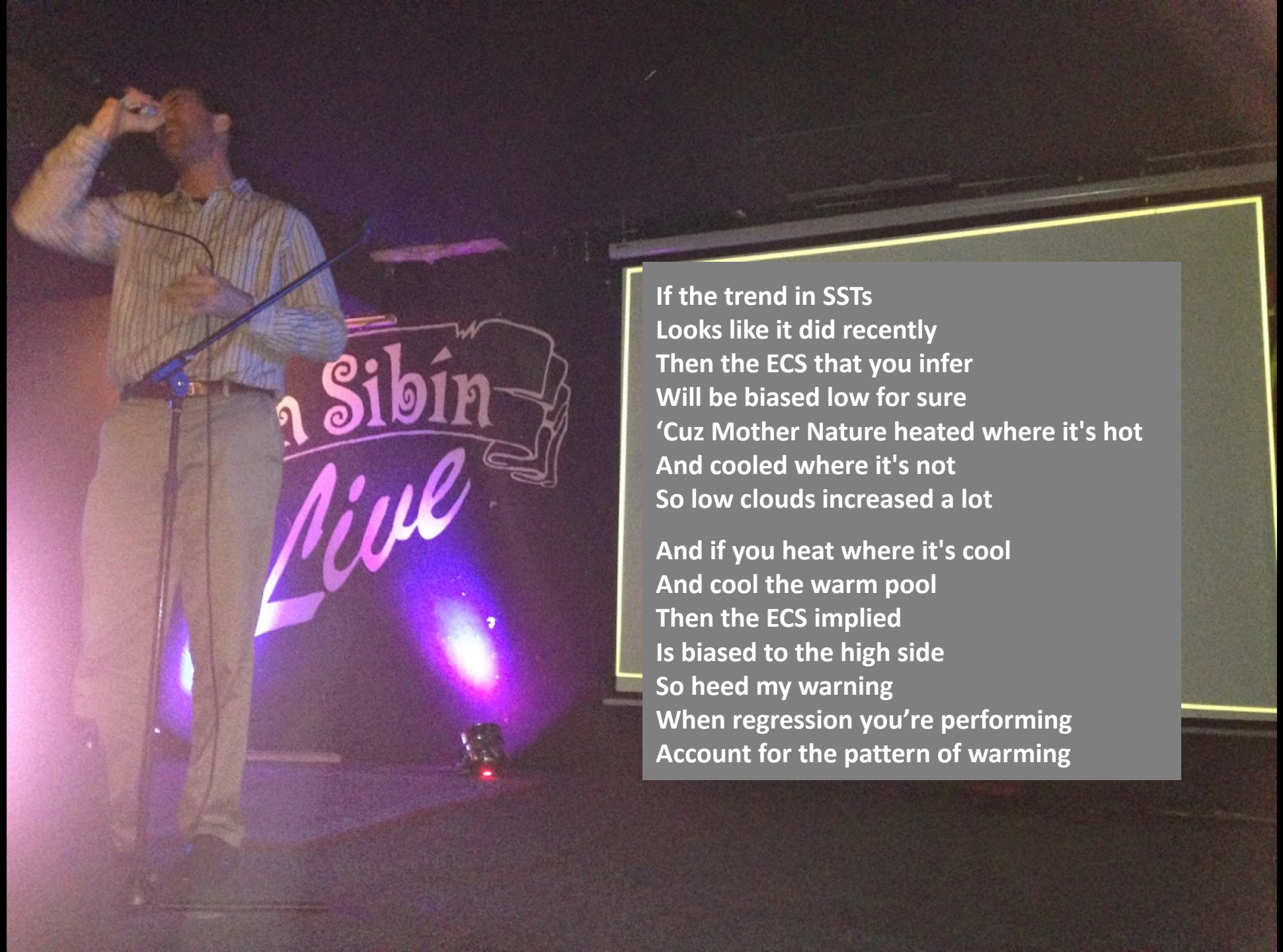
Sibín
Live
Oh you're a loaded gun,



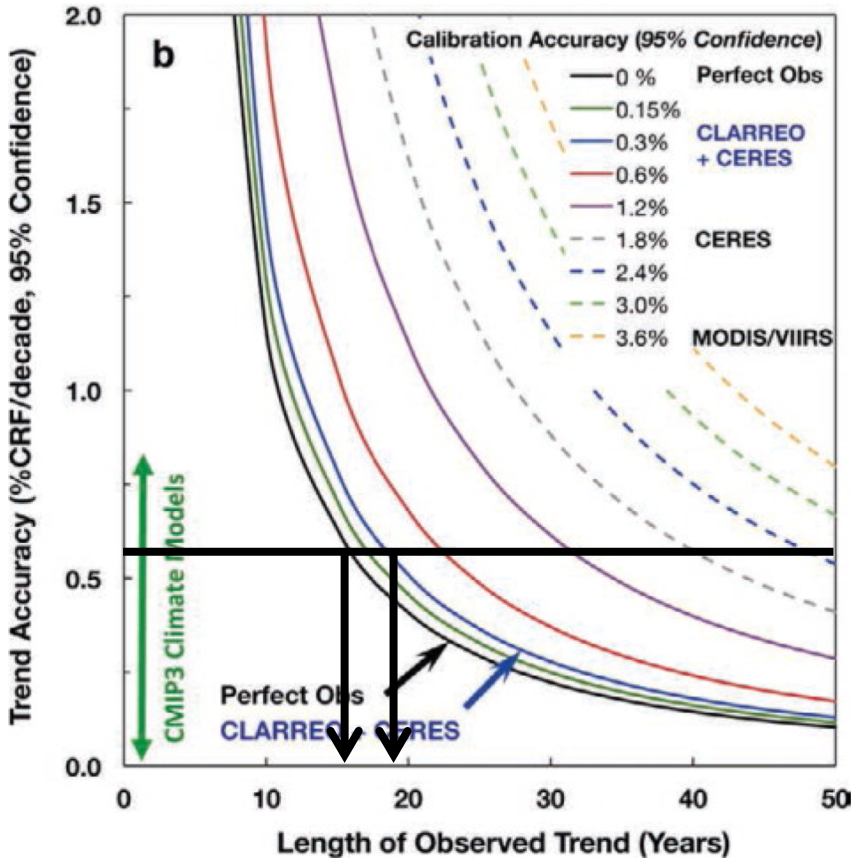
If the trend in SSTs
Looks like it did recently
Then the ECS that you infer
Will be biased low for sure
‘Cuz Mother Nature heated where it's hot
And cooled where it's not
So low clouds increased a lot



If the trend in SSTs
Looks like it did recently
Then the ECS that you infer
Will be biased low for sure
‘Cuz Mother Nature heated where it's hot
And cooled where it's not
So low clouds increased a lot

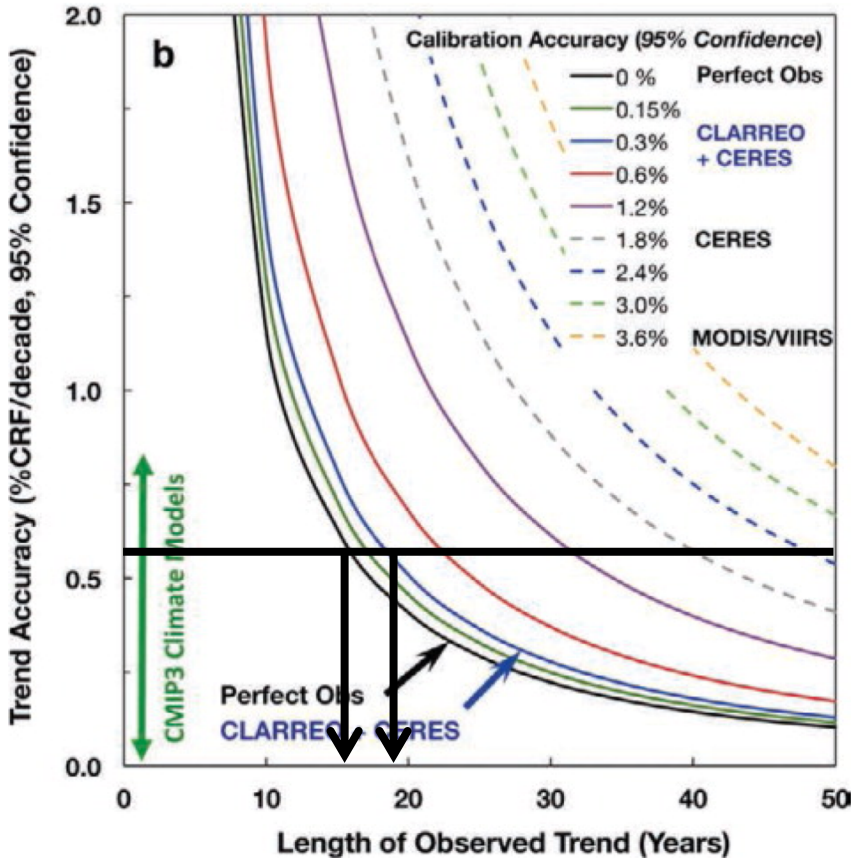
And if you heat where it's cool
And cool the warm pool
Then the ECS implied
Is biased to the high side
So heed my warning
When regression you’re performing
Account for the pattern of warming

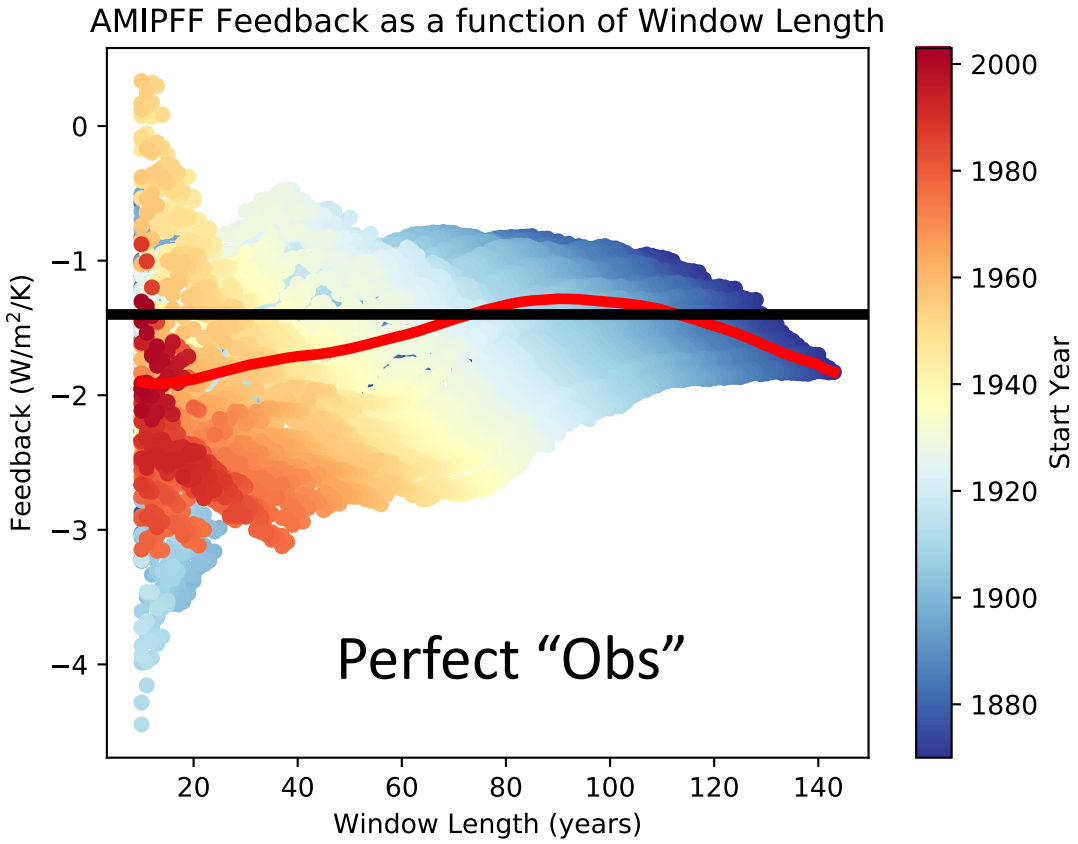
Detecting Trends vs Detecting Meaningful Trends



Wielicki et al., *BAMS*, 2013

Detecting Trends vs Detecting Meaningful Trends





Even for long trends, convergence to "truth" not guaranteed if pattern of warming does not resemble that in response to greenhouse warming

Wielicki et al., *BAMS*, 2013

Take Home Messages

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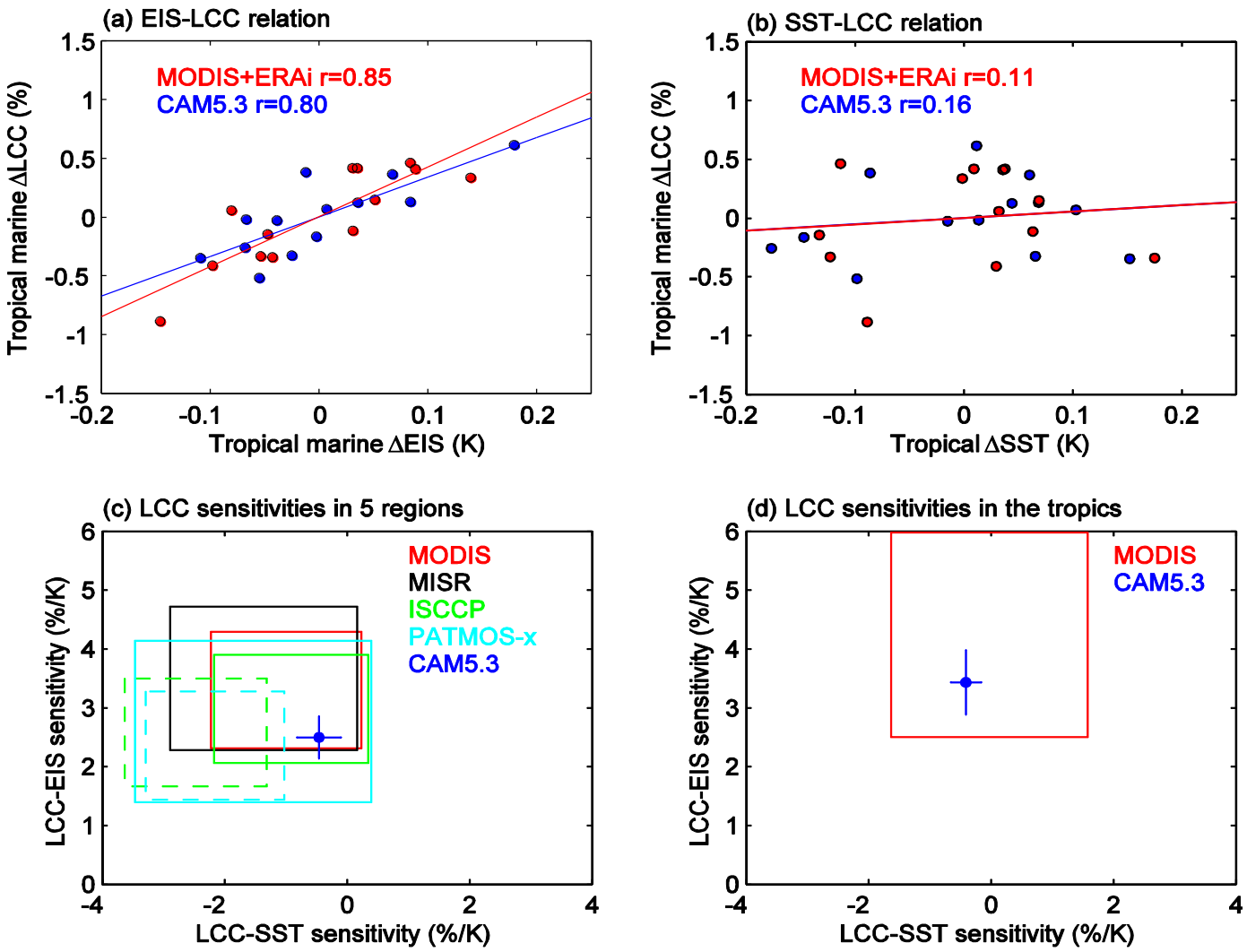
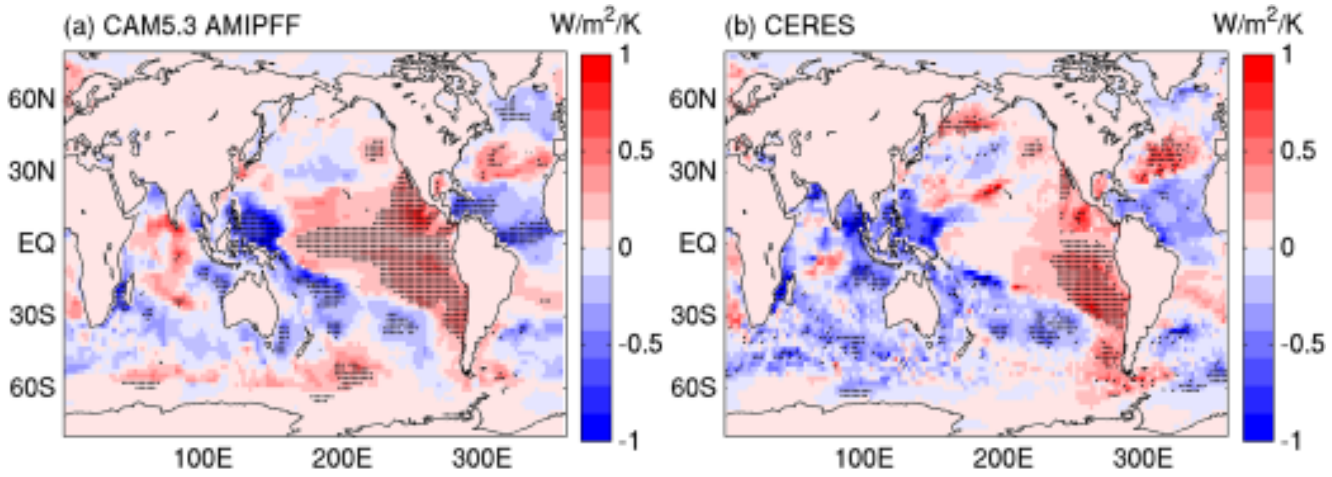
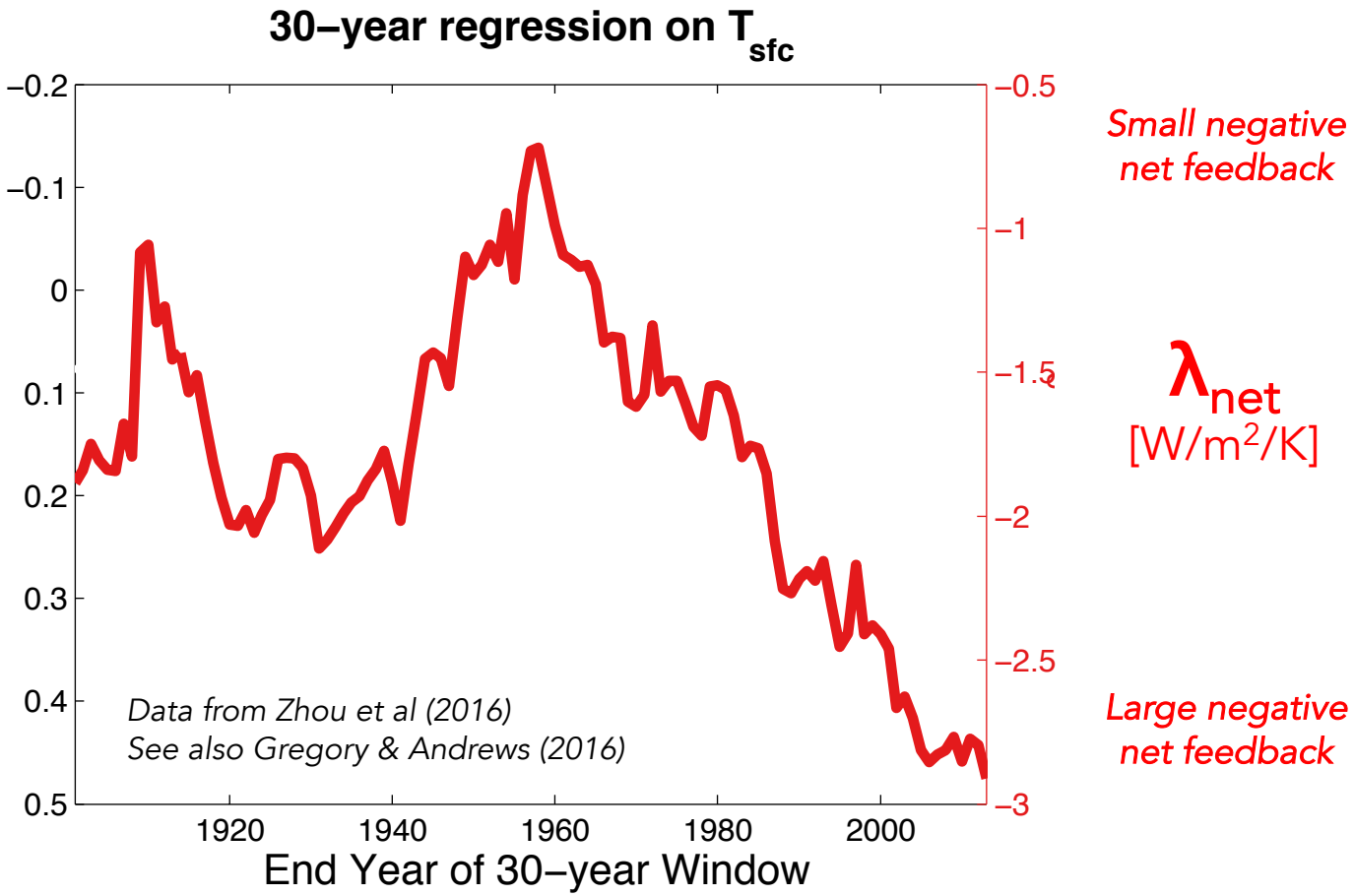
Model evaluation: Dependence of LCC on SST & EIS



Model evaluation:
Local dependence of R_{cloud} on SST



Decadal feedback strongly modulated by warming pattern



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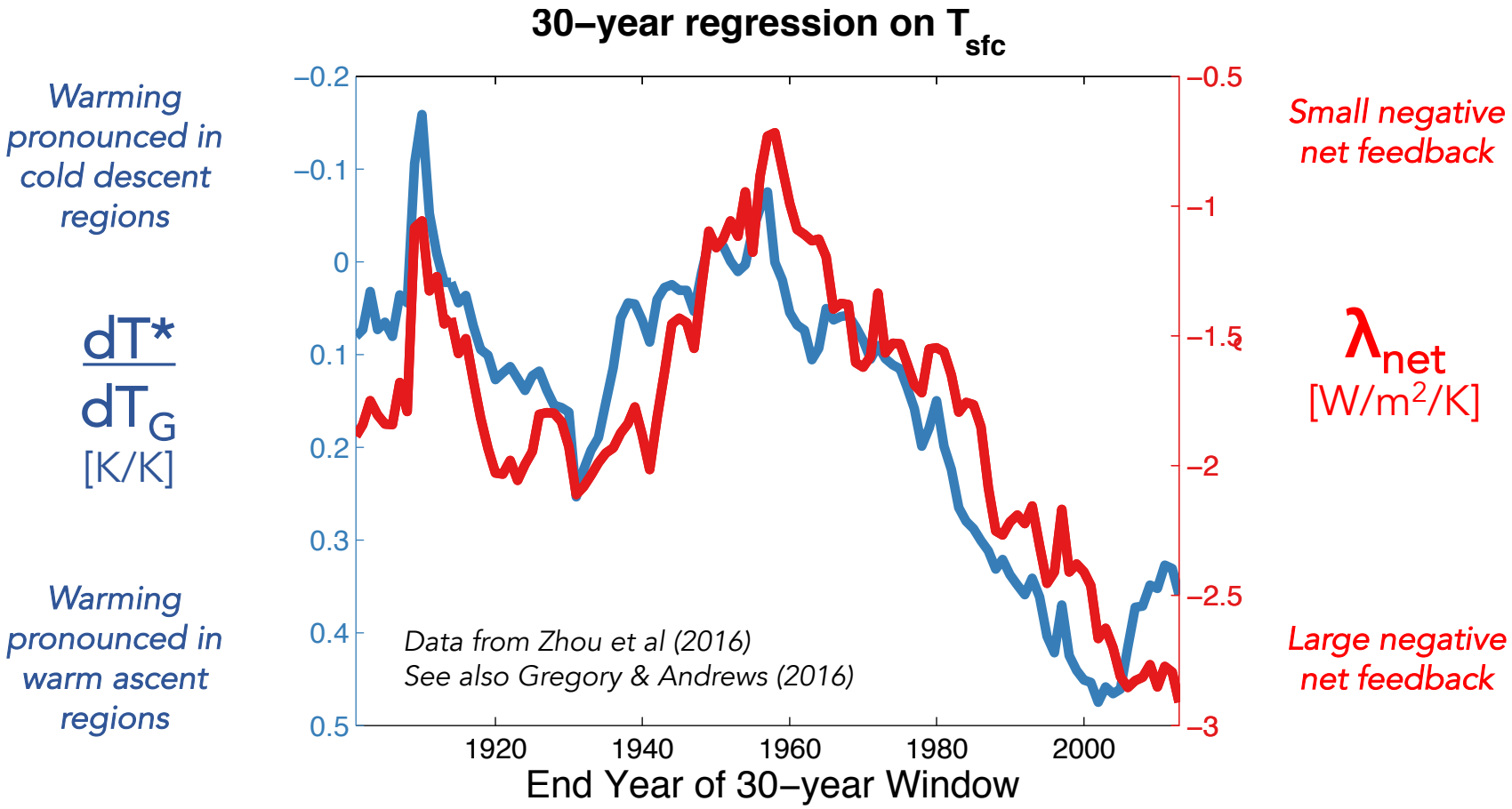


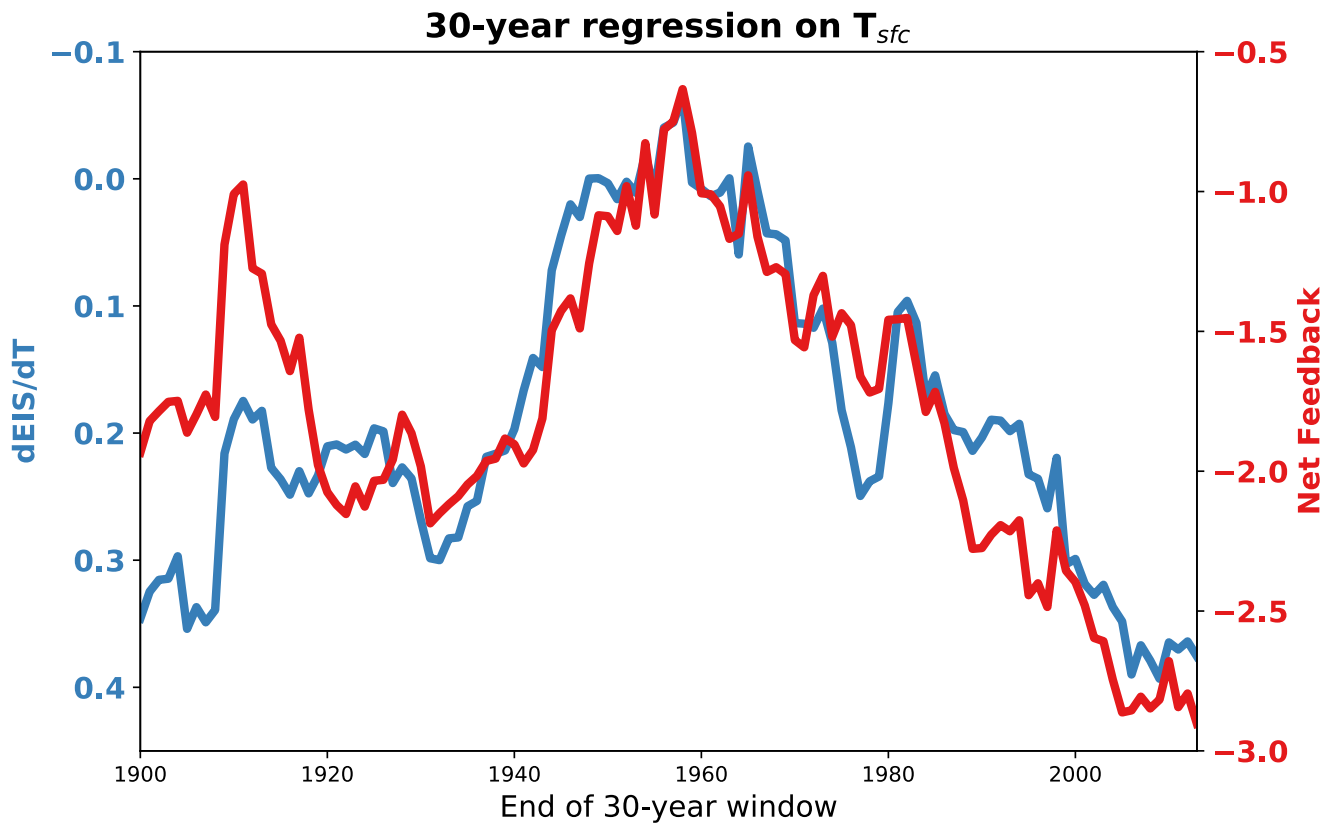
T* = SST(strong ascent regs) – SST(entire tropics)

…through its impact on inversion strength

Inversion weakens with warming

$$\frac{dEIS}{dT_G}$$
[K/K]

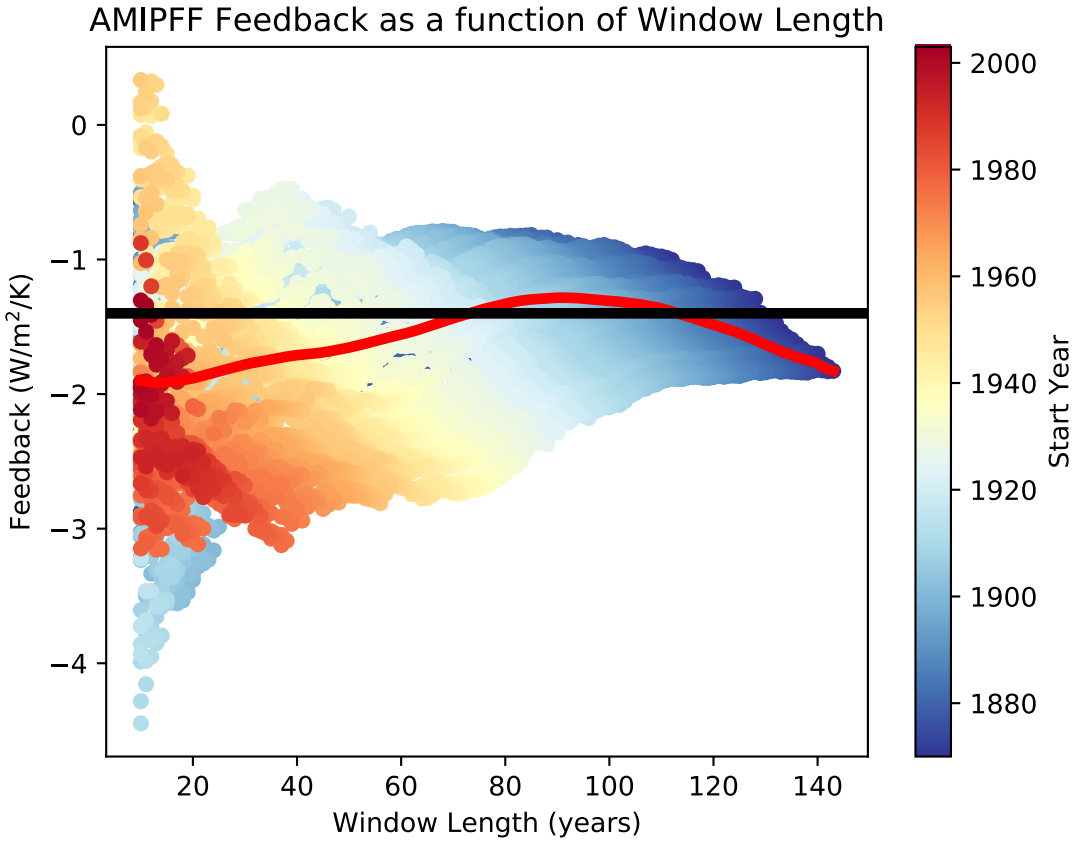
Inversion strengthens with warming

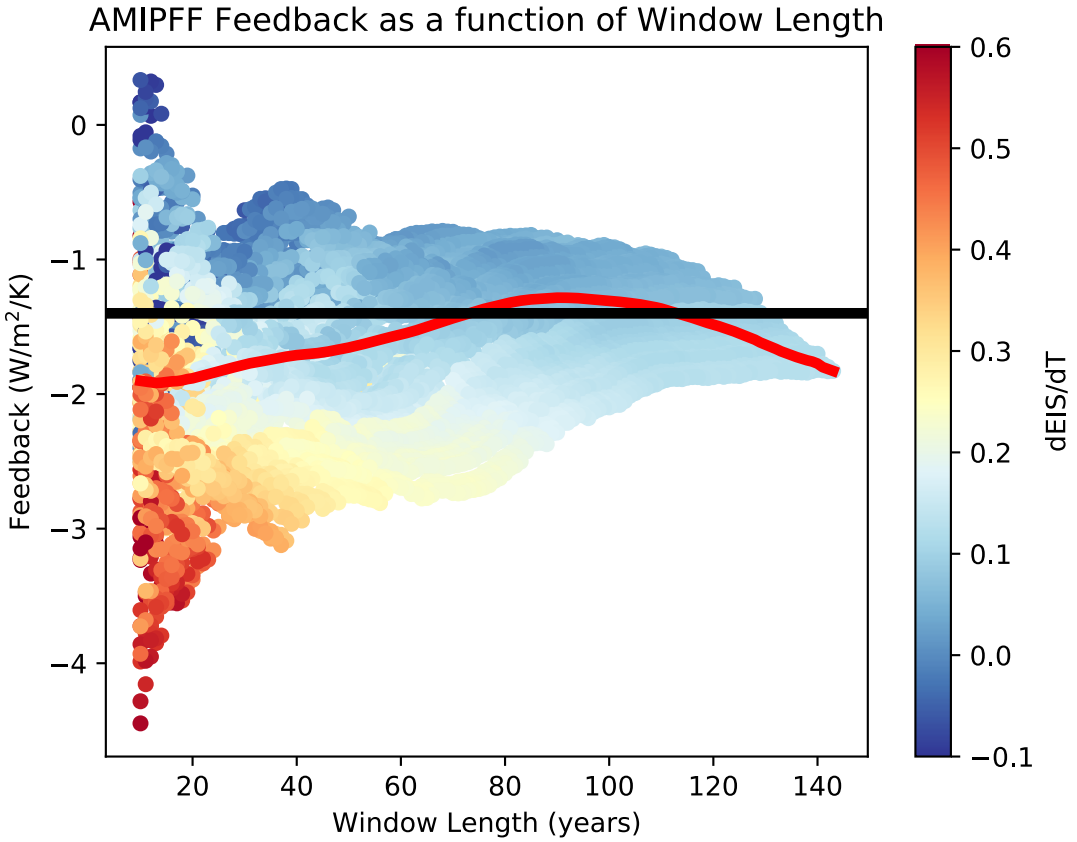


Small negative net feedback

λ_{net}
[W/m^2/K]

Large negative net feedback


AMIPFF Feedback as a function of Window Length
Feedback (W/m²/K)
Window Length (years)
Start Year
0
−1
−2
−3
−4
20
40
60
80
100
120
140
2000
1980
1960
1940
1920
1900
1880


AMIPFF Feedback as a function of Window Length
Feedback (W/m²/K)
Window Length (years)
dEIS/dT
0
−1
−2
−3
−4
20
40
60
80
100
120
140
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1

VOL. 35, NO. 12 JOURNAL OF THE ATMOSPHERIC SCIENCES DECEMBER 1978

This notion has been around for at least 40 years

Cloudiness as a Climatic Feedback Mechanism: Effects on Cloud Amounts of Prescribed Global and Regional Surface Temperature Changes in the NCAR GCM

STEPHEN H. SCHNEIDER, WARREN M. WASHINGTON AND ROBERT M. CHERVIN

National Center for Atmospheric Research,[1] Boulder, CO 80307

(Manuscript received 6 June 1978, in final form 29 August 1978)

cloud heights. In essence, if one is to think of the cloud feedback problem in global terms, then we can write the equation

$$\Delta C_l = f(\Delta T_g) + g[\langle \Delta T_g(\phi,\lambda) w(\phi,\lambda) \rangle]. \quad (3)$$

That is, a change in globally averaged cloudiness ΔC_l is equal to a term functionally related to the change in globally averaged surface temperature ΔT_g, plus an "eddy" function g which spatially integrates the correlation between the local prescribed change in surface temperature $\Delta T_g(\phi,\lambda)$ and the local vertical velocity distribution $w(\phi,\lambda)$. [In addition, other terms could be important as well, for example, see Roads (1978b).] As we have seen from our general circulation model zonal strip experiments, this eddy term could well be as large as the globally averaged term, and not necessarily even of the same sign (as for example, the 3 km clouds' response in the ZA$^+$−C case shown in Table 3).

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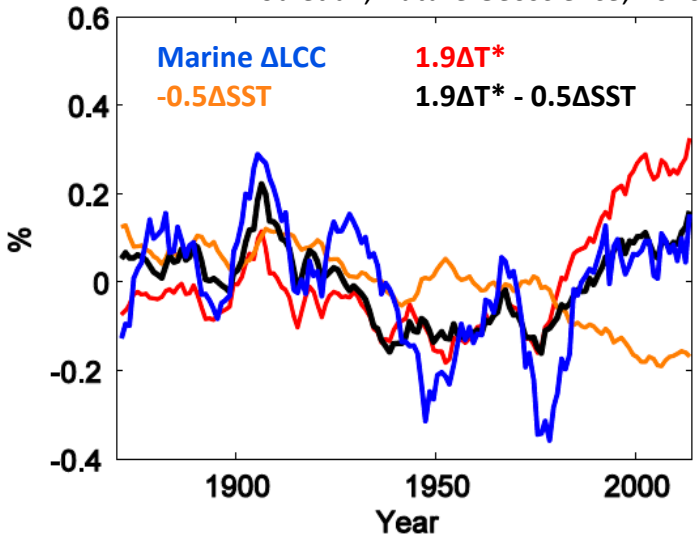
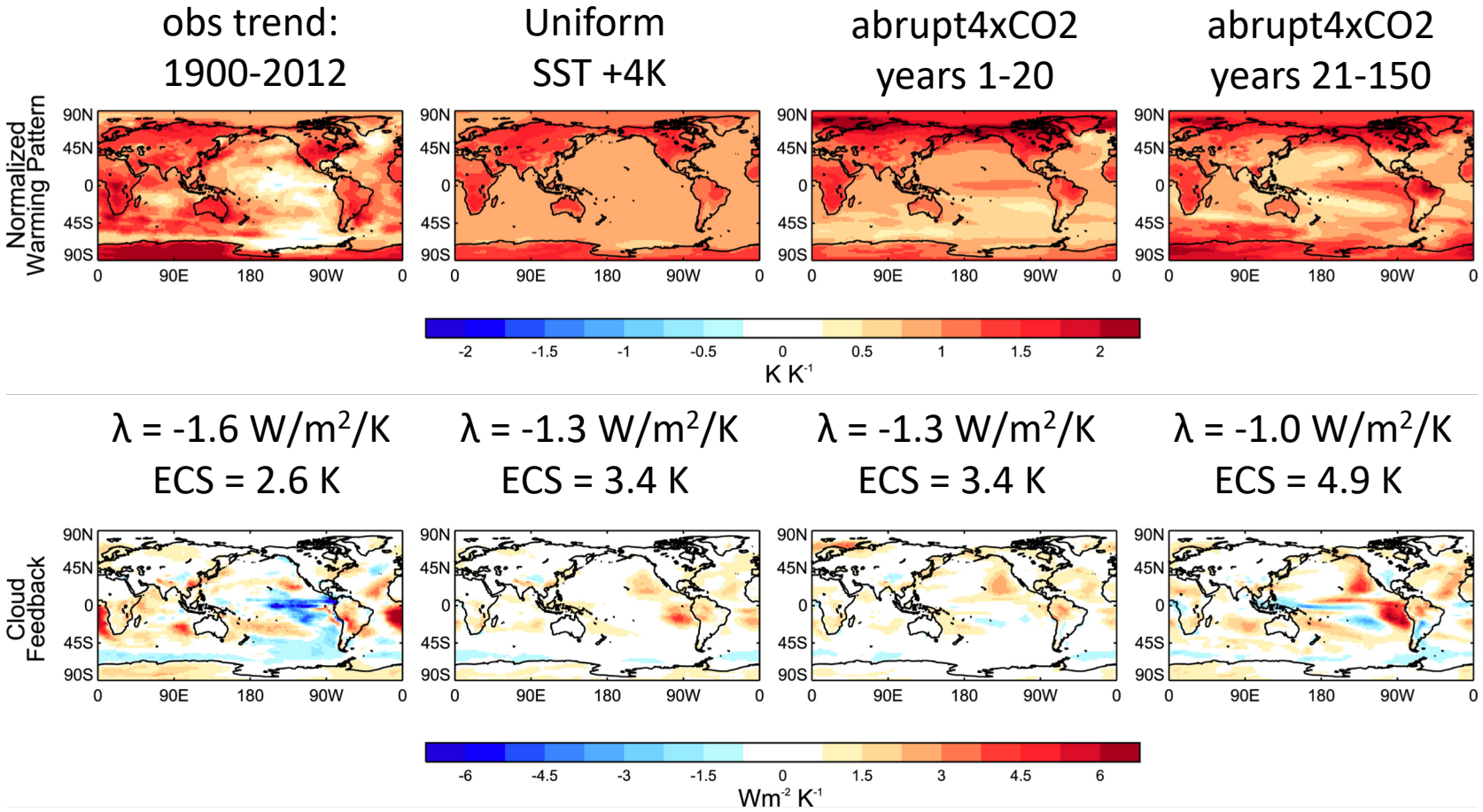


Indeed, we find that ΔT plays a **more important role** than ΔSST driving decadal changes in ΔLCC, and is of the **opposite sign** in recent years.*



Andrews and Webb (2018)