Using historical climate change to estimate equilibrium warming

Mark Richardson[1,*], Kevin Cowtan[2], Martin B Stolpe[3], Ed Hawkins[4]

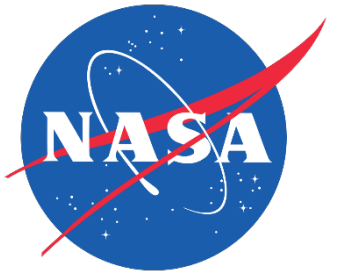
[1]NASA JPL, Caltech, UCLA JIFRESSE

[2]University of York, UK [3]ETH Zurich [4]University of Reading, UK

CIRA CSU seminar

*markr@jpl.Caltech.edu

Equilibrium Climate Sensitivity (ECS)

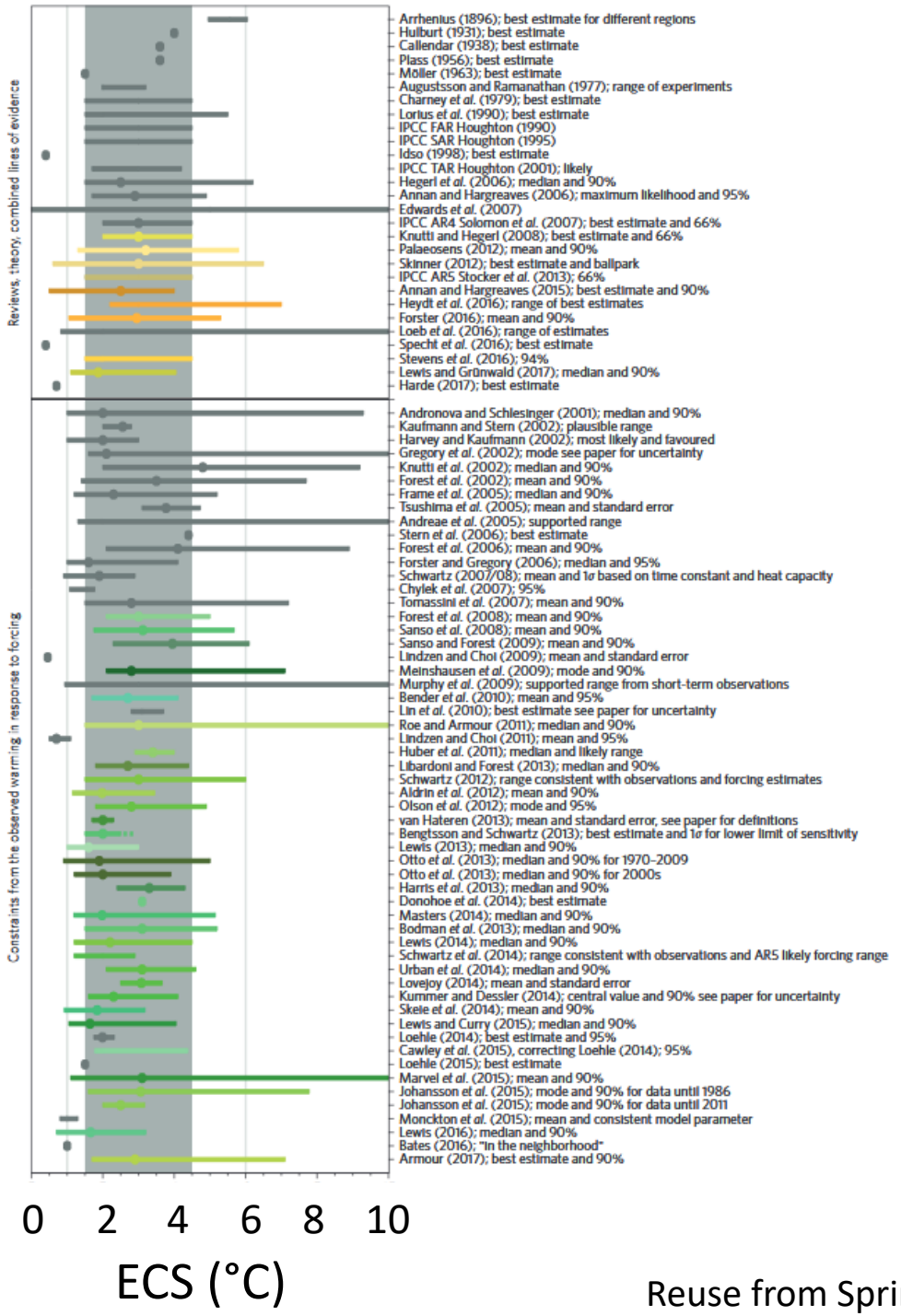


- ECS is eventual warming from doubled atmospheric CO_2
- Intergovernmental Panel on Climate Change (IPCC) 2013 report said range 1.5—4.5 °C with a best estimate of 3 °C
- Let's quickly summarise evidence then investigate the "historical energy budget" calculation approach.

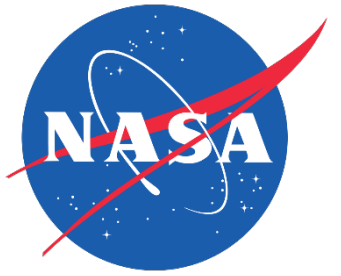
Don’t look at details!

Each bar is a study.

Most cover the shaded 1.5—4.5 °C.



Knutti & Rugenstein (2017)
doi: 10.1038/ngeo3017



Paleoclimate examples:

Look at what happened in the deep past.

This isn’t my business, but it’s cool.

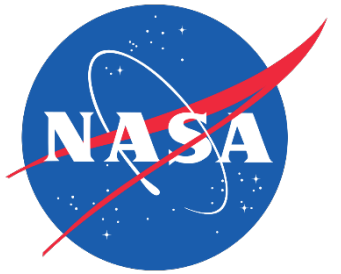
Climate Sensitivity Estimated from Temperature Reconstructions of the Last Glacial Maximum

Andreas Schmittner,[1]* Nathan M. Urban,[2] Jeremy D. Shakun,[3] Natalie M. Mahowald,[4] Peter U. Clark,[5] Patrick J. Bartlein,[6] Alan C. Mix,[1] Antoni Rosell-Melé[7]

Assessing the impact of future anthropogenic carbon emissions is currently impeded by uncertainties in our knowledge of equilibrium climate sensitivity to atmospheric carbon dioxide doubling. Previous studies suggest 3 kelvin (K) as the best estimate, 2 to 4.5 K as the 66% probability range, and nonzero probabilities for much higher values, the latter implying a small chance of high-impact climate changes that would be difficult to avoid. Here, combining extensive sea and land surface temperature reconstructions from the Last Glacial Maximum with climate model simulations, we estimate a lower median (2.3 K) and reduced uncertainty (1.7 to 2.6 K as the 66% probability range, which can be widened using alternate assumptions or data subsets). Assuming that paleoclimatic constraints apply to the future, as predicted by our model, these results imply a lower probability of imminent extreme climatic change than previously thought.

"Last Glacial Maximum" (cold period 19—23,000 years ago):

2.3 °C



PERSPECTIVE

doi:10.1038/nature11574

Making sense of palaeoclimate sensitivity

PALAEOSENS Project Members*

Many palaeoclimate studies have quantified pre-anthropogenic climate change to calculate climate sensitivity (equilibrium temperature change in response to radiative forcing change), but a lack of consistent methodologies produces a wide range of estimates and hinders comparability of results. Here we present a stricter approach, to improve intercomparison of palaeoclimate sensitivity estimates in a manner compatible with equilibrium projections for future climate change. Over the past 65 million years, this reveals a climate sensitivity (in K W^{-1} m^2) of 0.3–1.9 or 0.6–1.3 at 95% or 68% probability, respectively. The latter implies a warming of 2.2–4.8 K per doubling of atmospheric CO_2, which agrees with IPCC estimates.

"past 65 million years" :

2.2—4.8 °C

SCIENCE ADVANCES | RESEARCH ARTICLE

CLIMATE CHANGE

Nonlinear climate sensitivity and its implications for future greenhouse warming

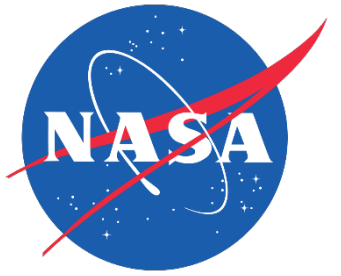
Tobias Friedrich,[1]* Axel Timmermann,[1] Michelle Tigchelaar,[2] Oliver Elison Timm,[3] Andrey Ganopolski[4]

Global mean surface temperatures are rising in response to anthropogenic greenhouse gas emissions. The magnitude of this warming at equilibrium for a given radiative forcing—referred to as specific equilibrium climate sensitivity (*S*)—is still subject to uncertainties. We estimate global mean temperature variations and *S* using a 784,000-year-long field reconstruction of sea surface temperatures and a transient paleoclimate model simulation. Our results reveal that *S* is strongly dependent on the climate background state, with significantly larger values attained during warm phases. Using the Representative Concentration Pathway 8.5 for future greenhouse radiative forcing, we find that the range of paleo-based estimates of Earth's future warming by 2100 CE overlaps with the upper range of climate simulations conducted as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). Furthermore, we find that within the 21st century, global mean temperatures will very likely exceed maximum levels reconstructed for the last 784,000 years. On the basis of temperature data from eight glacial cycles, our results provide an independent validation of the magnitude of current CMIP5 warming projections.

"784,000-year-long field reconstruction":

3.2 °C (full period),

4.8 °C (warm periods, like now)

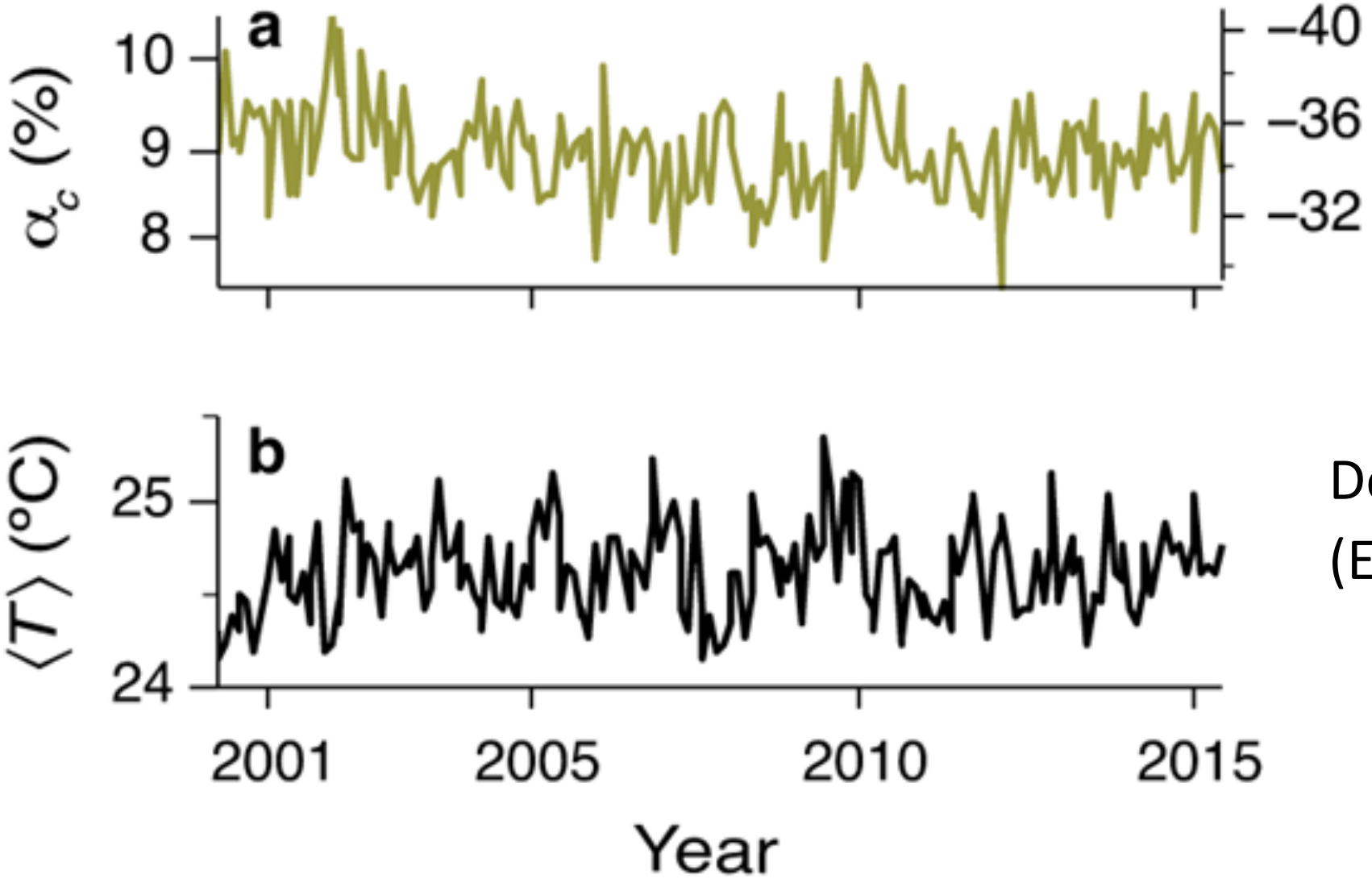


Methods using more modern data include "emergent constraints"

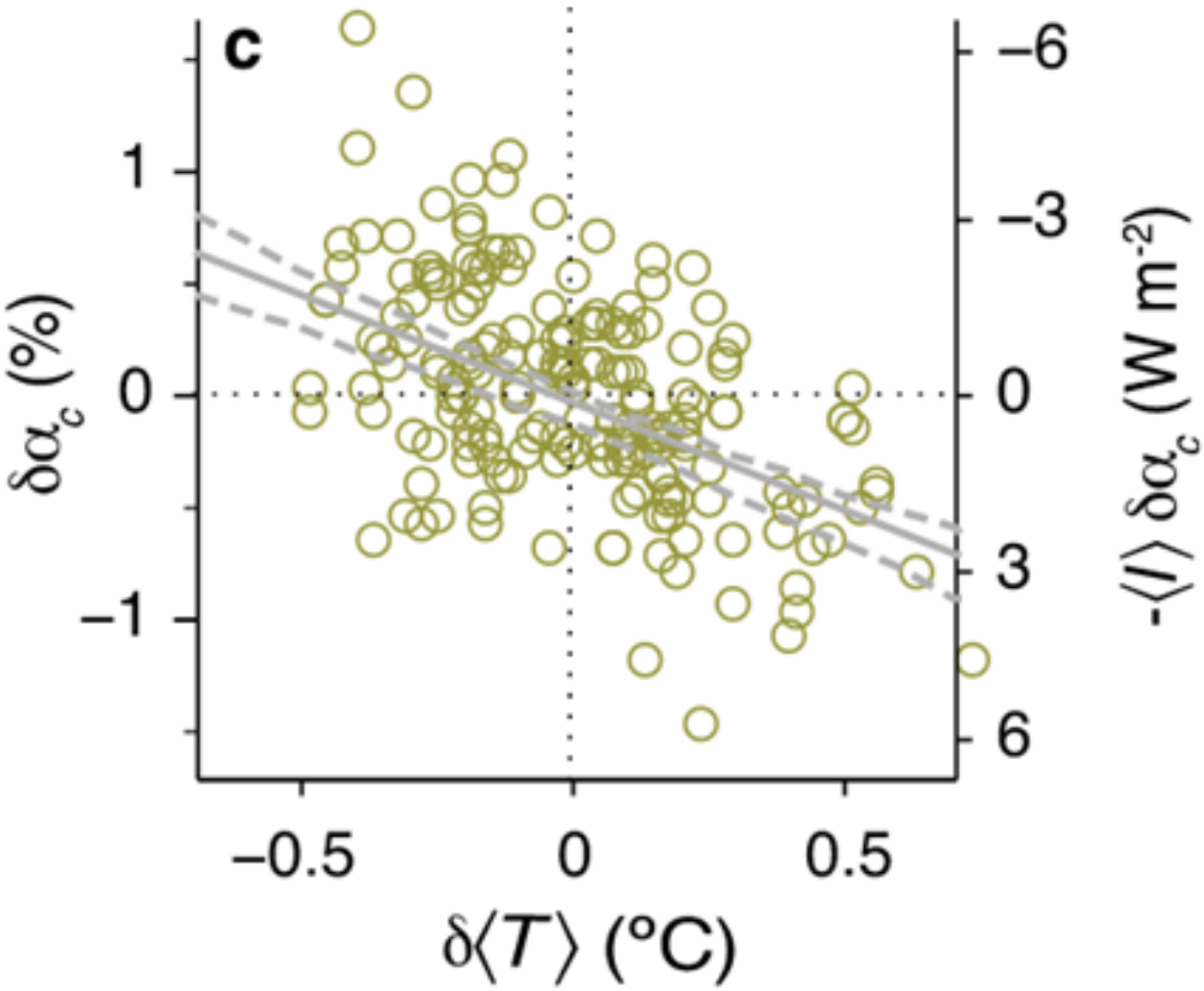
Find a process that relates to climate sensitivity and constrain it with observations.

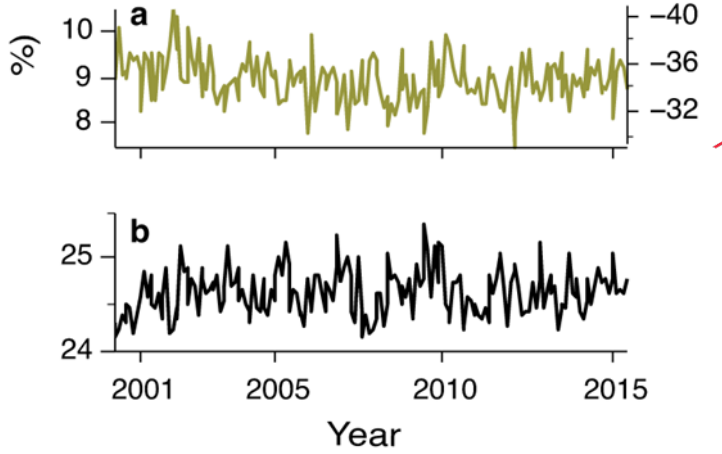
Using Brient & Schneider (2016, doi: 10.1175/JCLI-D-15-0897.1)

Tropical low cloud cover (CERES)



Deseasonalised SST (ERSST)

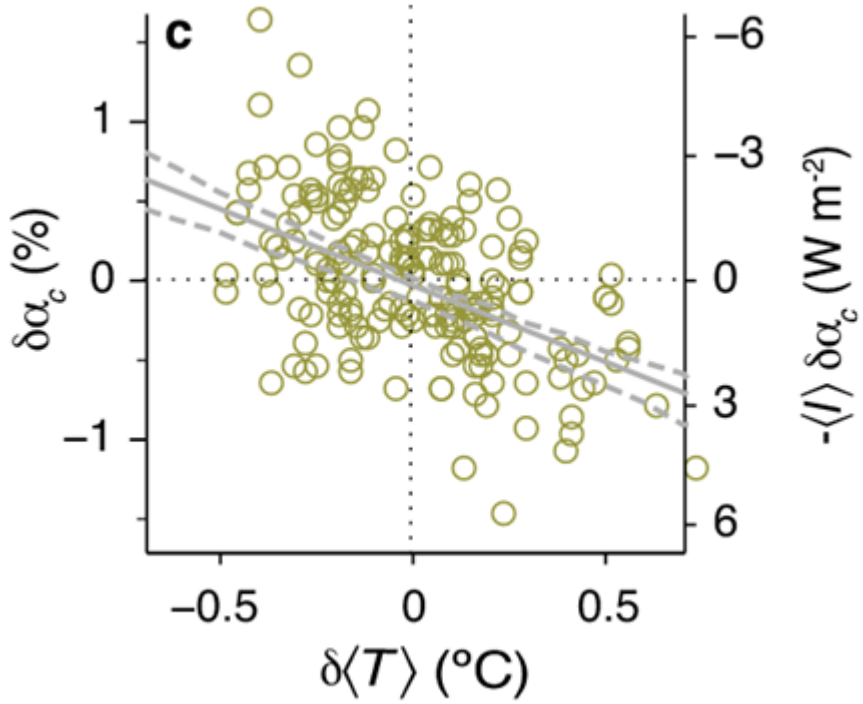


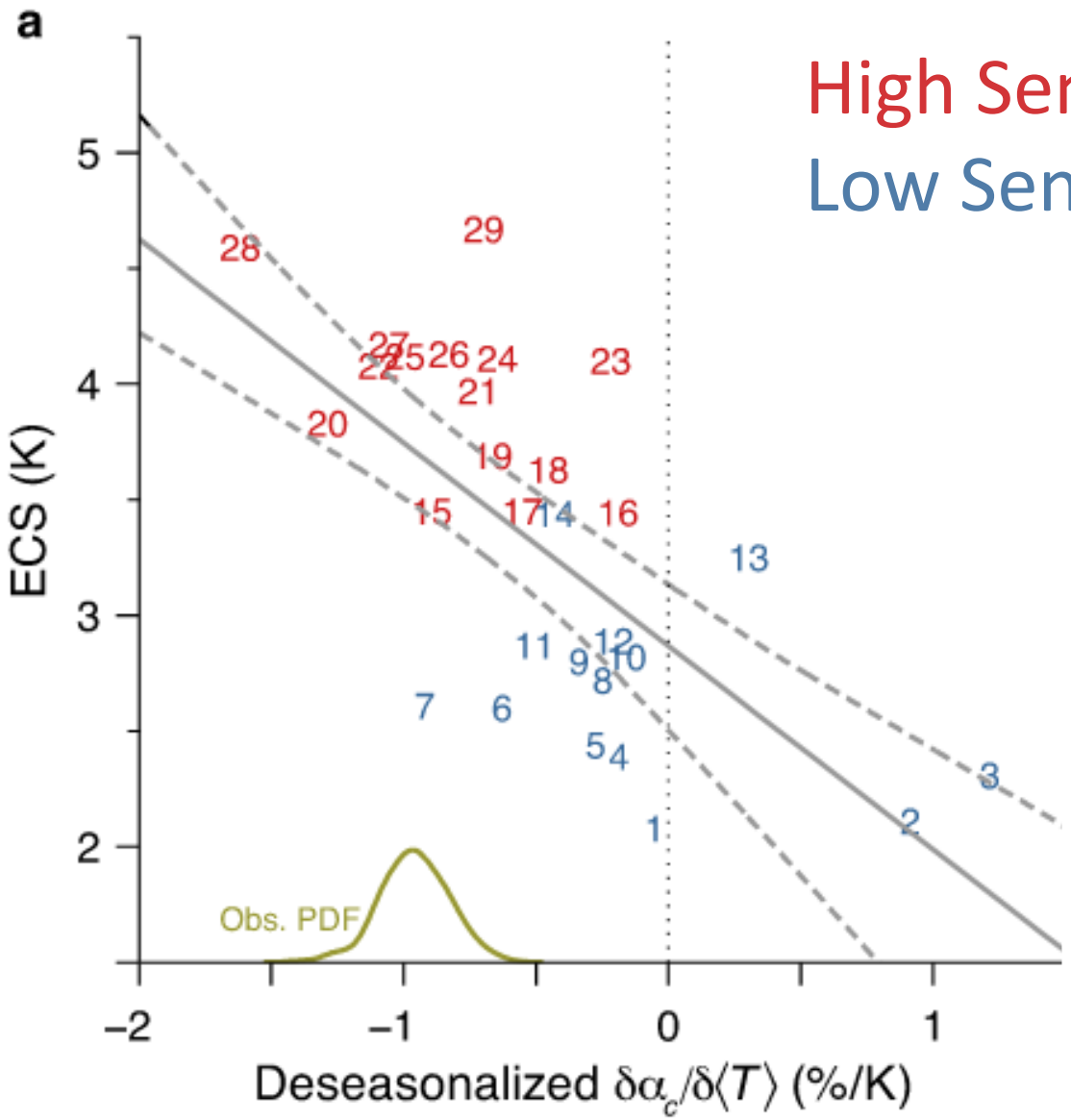


Warmer T corresponds to less low cloud reflection.

- From observations we have a probability distribution of: $\frac{\delta \alpha_c}{\delta <T>}$

- See if this relates to ECS in CMIP5 climate models

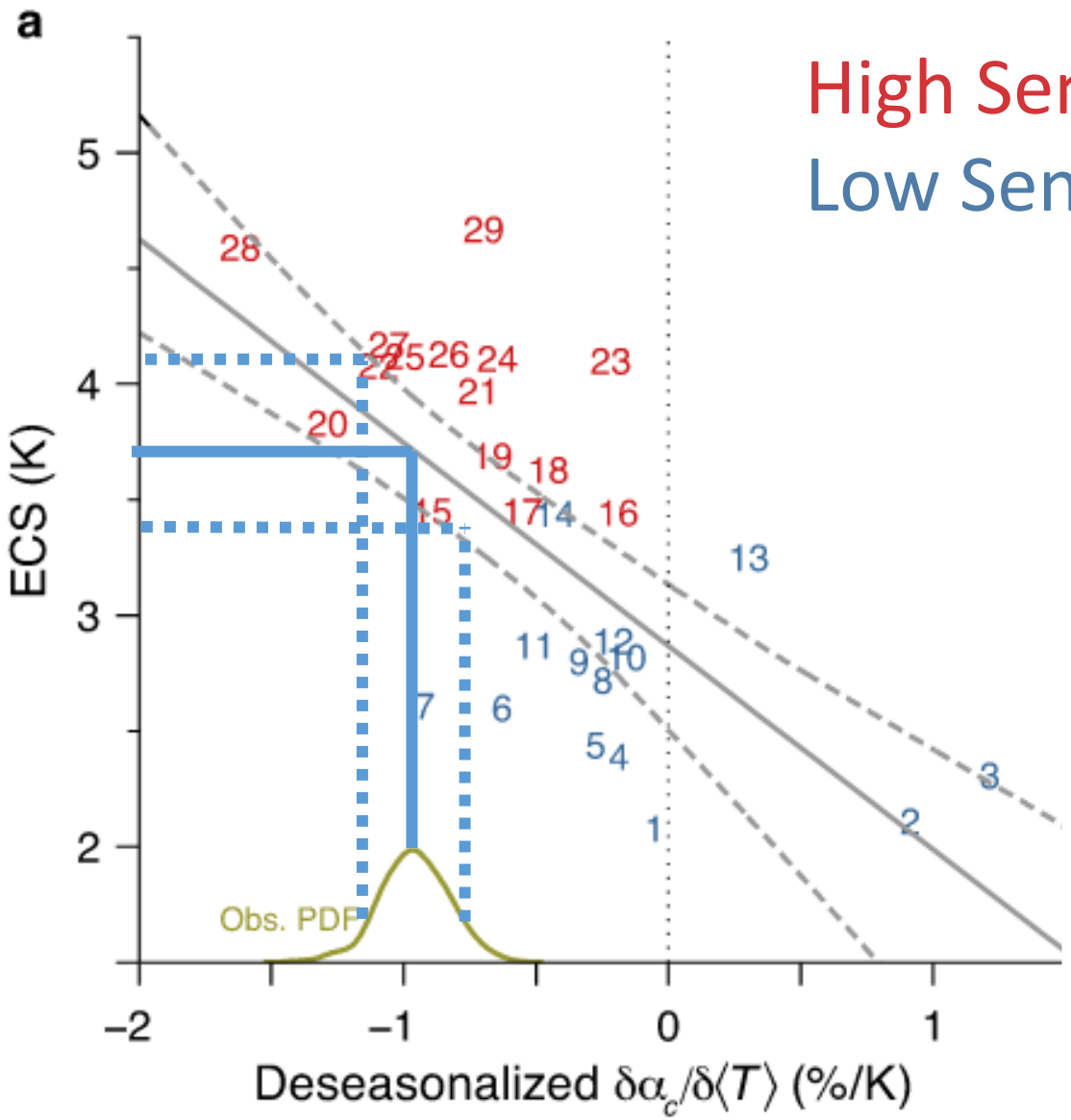




High Sensitivity Models

Low Sensitivity Models

ECS is bigger when low clouds retreat a lot under warming.

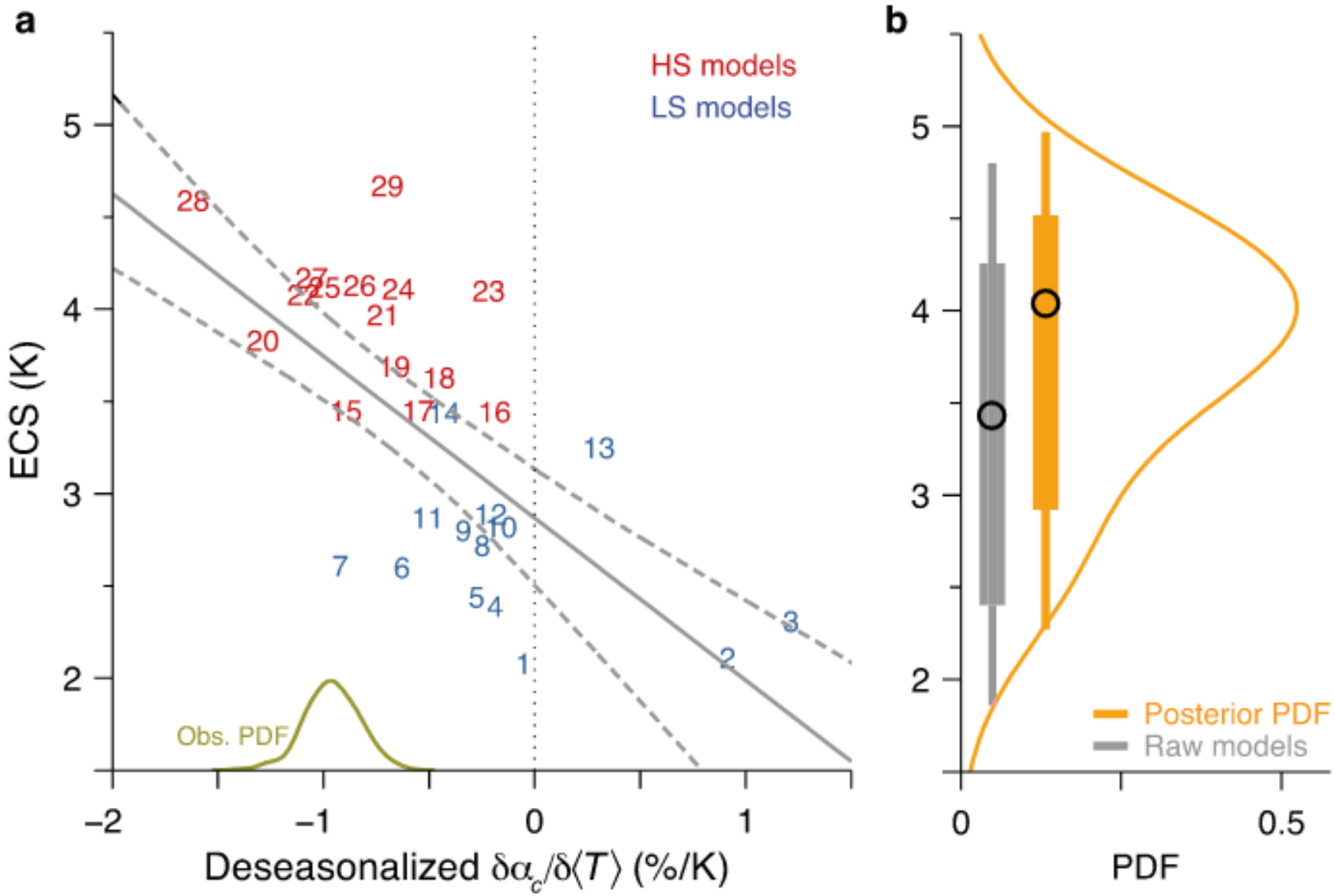


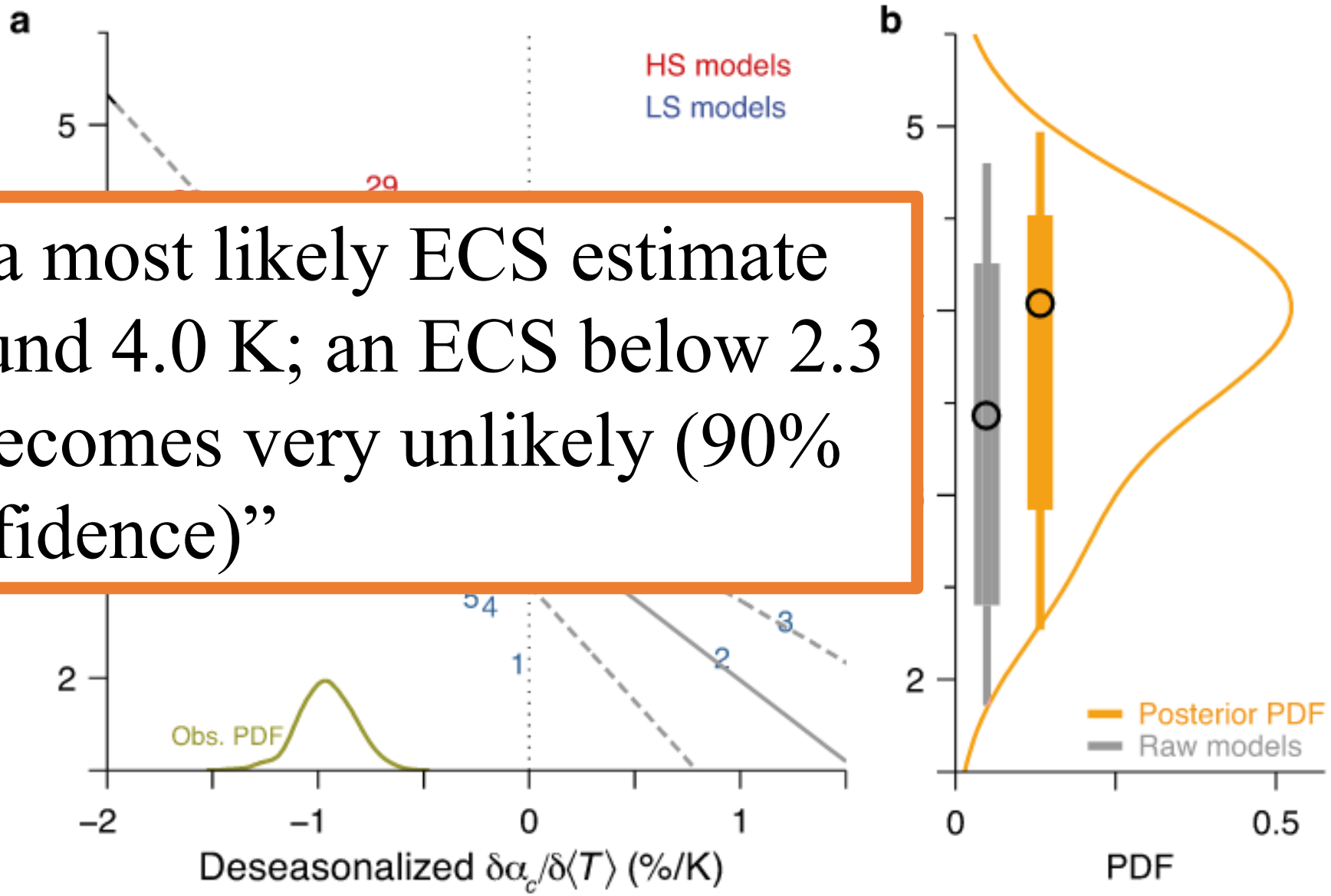
High Sensitivity Models

Low Sensitivity Models

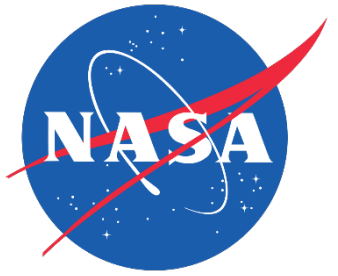
ECS is bigger when low clouds retreat a lot under warming.

Link observed retreat to ECS using model fit with Bayes' theorem





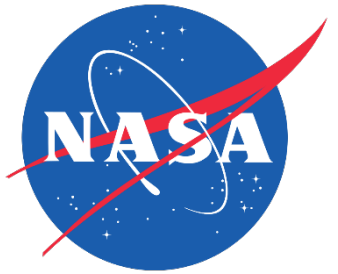
"…a most likely ECS estimate around 4.0 K; an ECS below 2.3 K becomes very unlikely (90% confidence)"



Summaries of emergent constraints:
Caldwell et al. (2018), doi: 10.1175/JCLI-D-17-0631.1
Qu et al. (2018), doi: 10.1175/JCLI-D-17-0482.1

Lots, they have some issues, but usually $ECS_{emergent} > 3$ °C.

Cox et al. (2018, doi: 10.1038/nature25450) on low end from variability of historical temperatures: 2.8 °C.



- Lots of ECS studies with different techniques
- Paleo spans the range
- Physics plus observation “emergent constraints” favour ECS > 3 °C
- What about the low end?

Linear model of Earth response

$$\Delta N(t) = \Delta F(t) - \lambda(t)\Delta T(t)$$

ΔN = Change in Earth's net heat imbalance (W m^{-2})

ΔF = Radiative forcing (W m^{-2})

λ = Feedback parameter (W m^{-2} K^{-1})

ΔT = Change in temperature (°C)

Linear model of Earth response

$$\Delta N(t) = \Delta F(t) - \lambda(t)\Delta T(t)$$

Assume:

$$\lambda(t) = \lambda$$

$$\Delta N_{eq} = \Delta N(t \to \infty) = 0$$

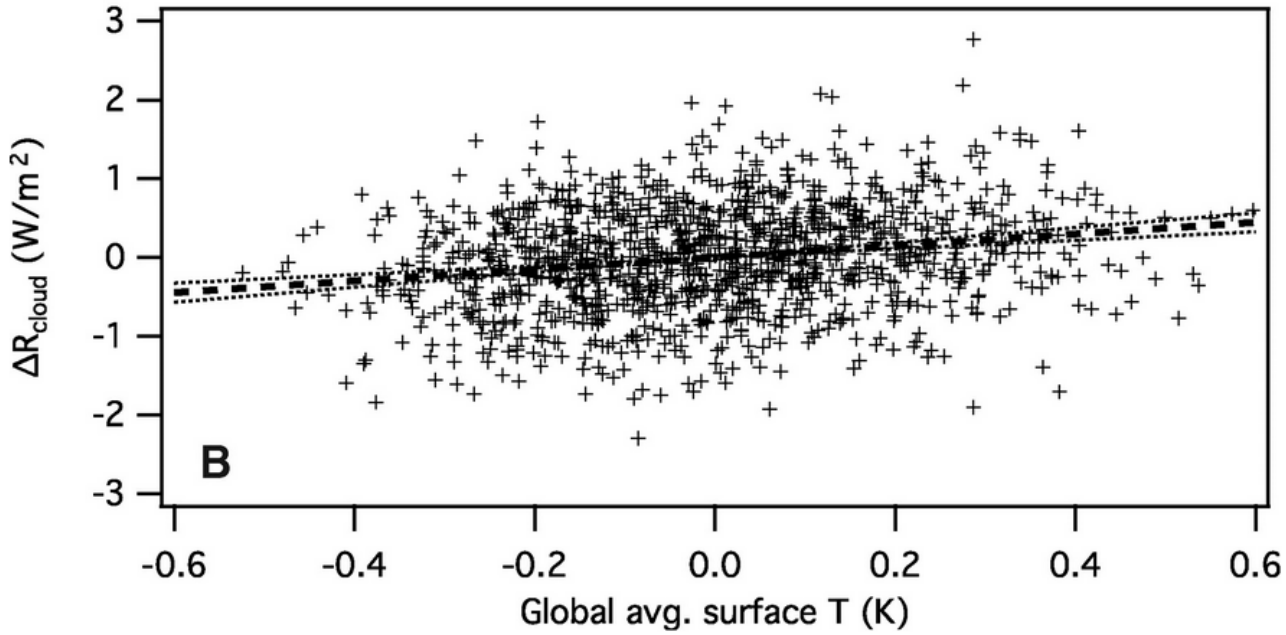
Linear model of Earth response

$$\lambda = \frac{\Delta F(t) - \Delta N(t)}{\Delta T(t)}$$

$$ECS = \Delta T_{eq,2\times CO2} = \frac{\Delta F_{2\times CO2}}{\lambda}$$

$$\lambda = \frac{\Delta F(t) - \Delta N(t)}{\Delta T(t)}$$

Dessler (2010): cloud feedback “likely positive”
ECS > 2 °C



Dessler (2010) *Science* doi: 10.1126/science.1192546

$$\lambda = \frac{\Delta F(t) - \Delta N(t)}{\Delta T(t)}$$

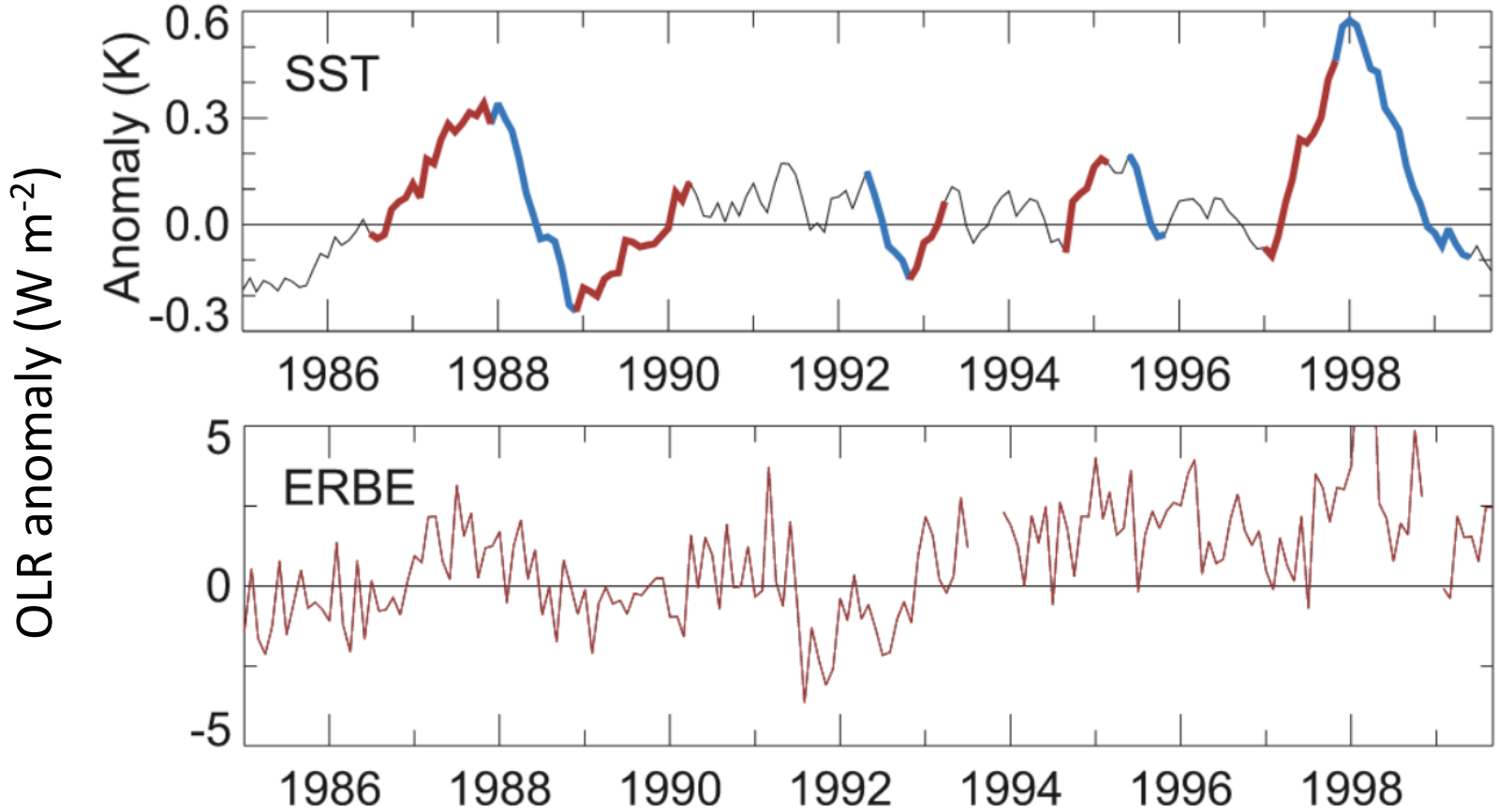
BUT THIS EQUATION IS THE SOURCE OF SEVERAL LOW ECS ESTIMATES…

We must understand *why* some methods give higher/lower values to better estimate ECS.

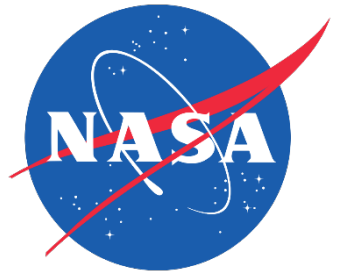
Lindzen & Choi (2009):

ECS is much lower than in models

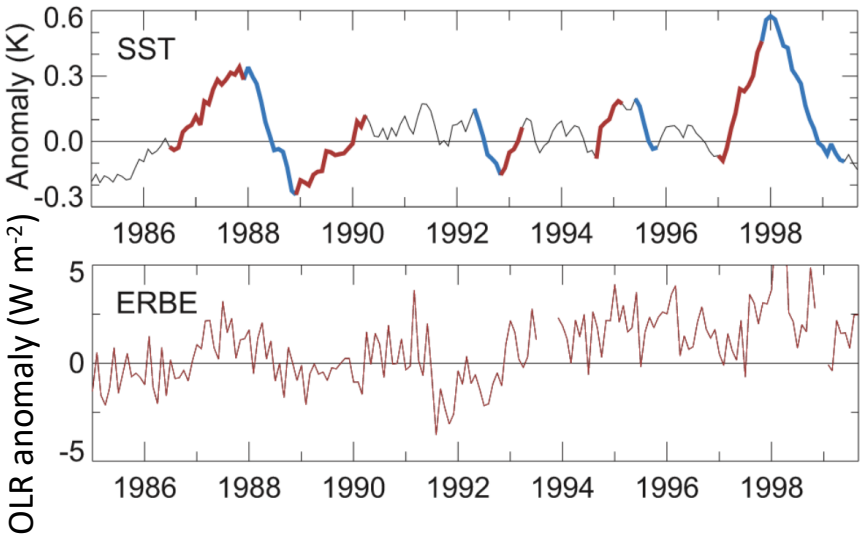
Lindzen and Choi (2009) picked ΔT and ΔN for the below coloured periods:



doi: 10.1029/2009GL039628



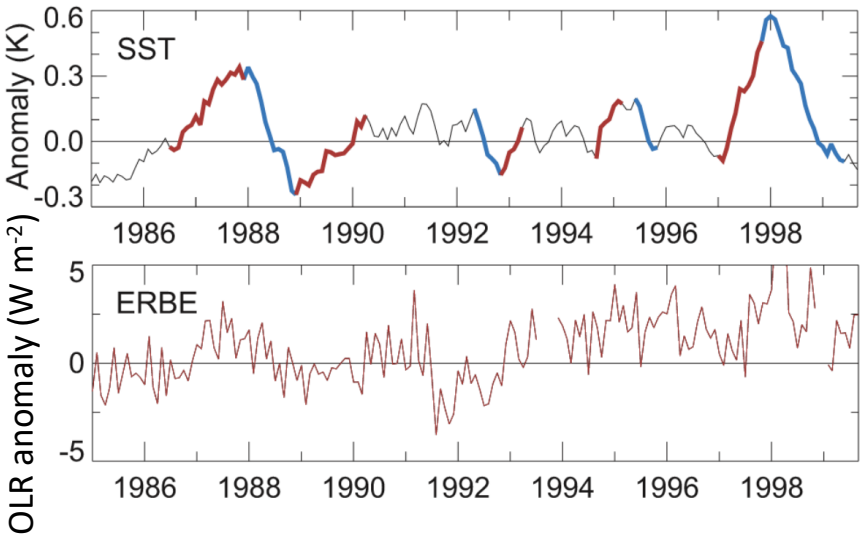
Lindzen and Choi (2009) picked ΔT and ΔN for the below coloured periods:



"ERBE data appear to demonstrate a climate sensitivity of about 0.5 °C"

doi: 10.1029/2009GL039628

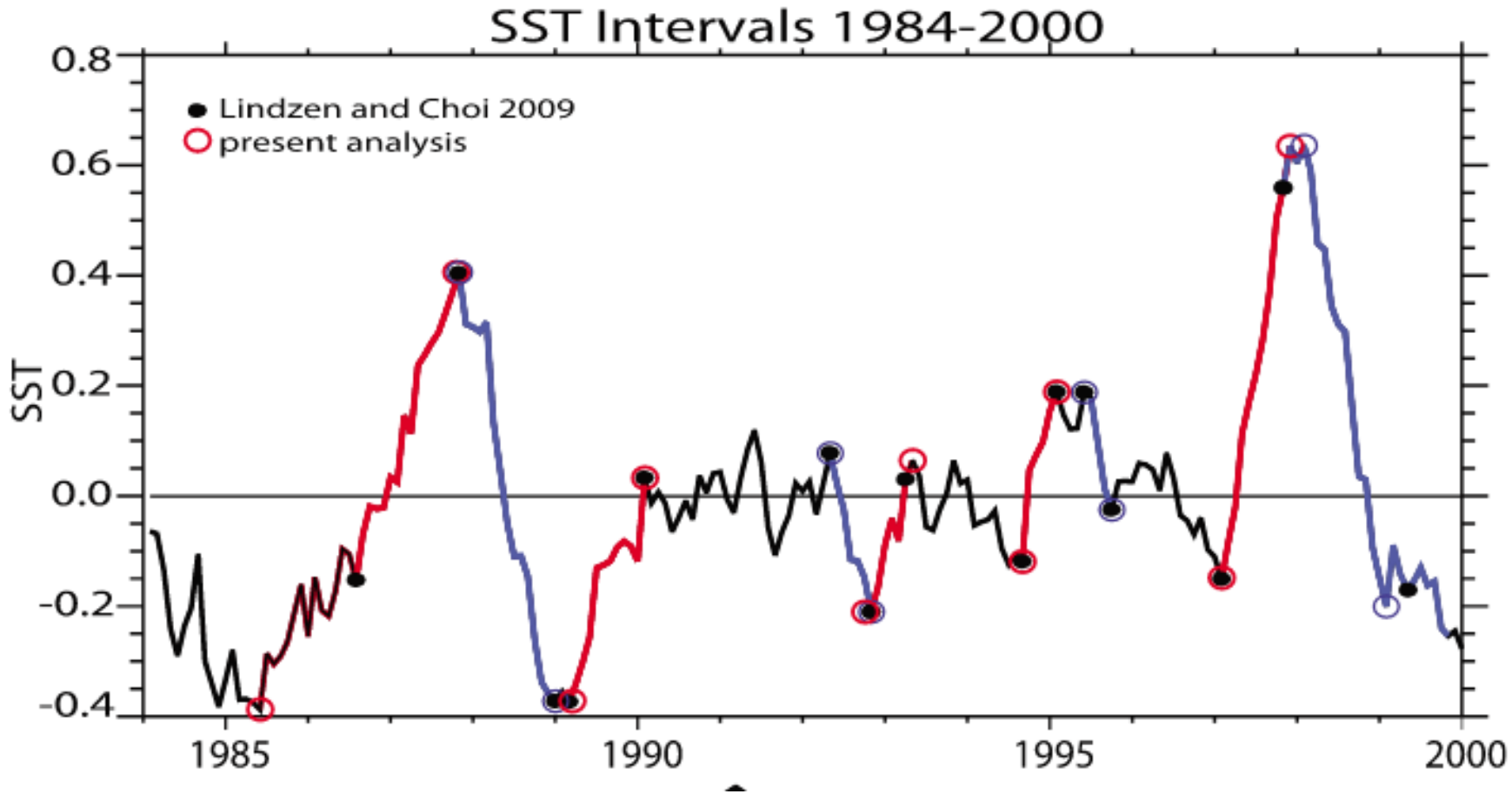
Lindzen and Choi (2009) picked ΔT and ΔN for the below coloured periods:



But how and why did they pick those coloured periods?

doi: 10.1029/2009GL039628

BUT:

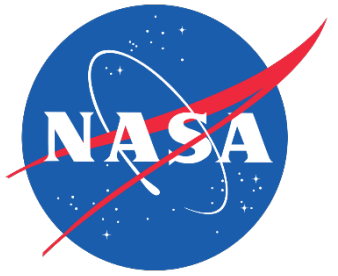


Trenberth, Wong & O'Dell (2010) : "[Lindzen & Choi's 2009] results are neither robust nor meaningful, as small sensible changes in the dates bounding their warming and cooling intervals entirely change the conclusions."

Lindzen & Choi (2009):

If you select time periods in just the right way, then

ECS is much lower than in models



Lindzen & Choi (2009):

If you select time periods in just the right way, then

ECS is much lower than in models

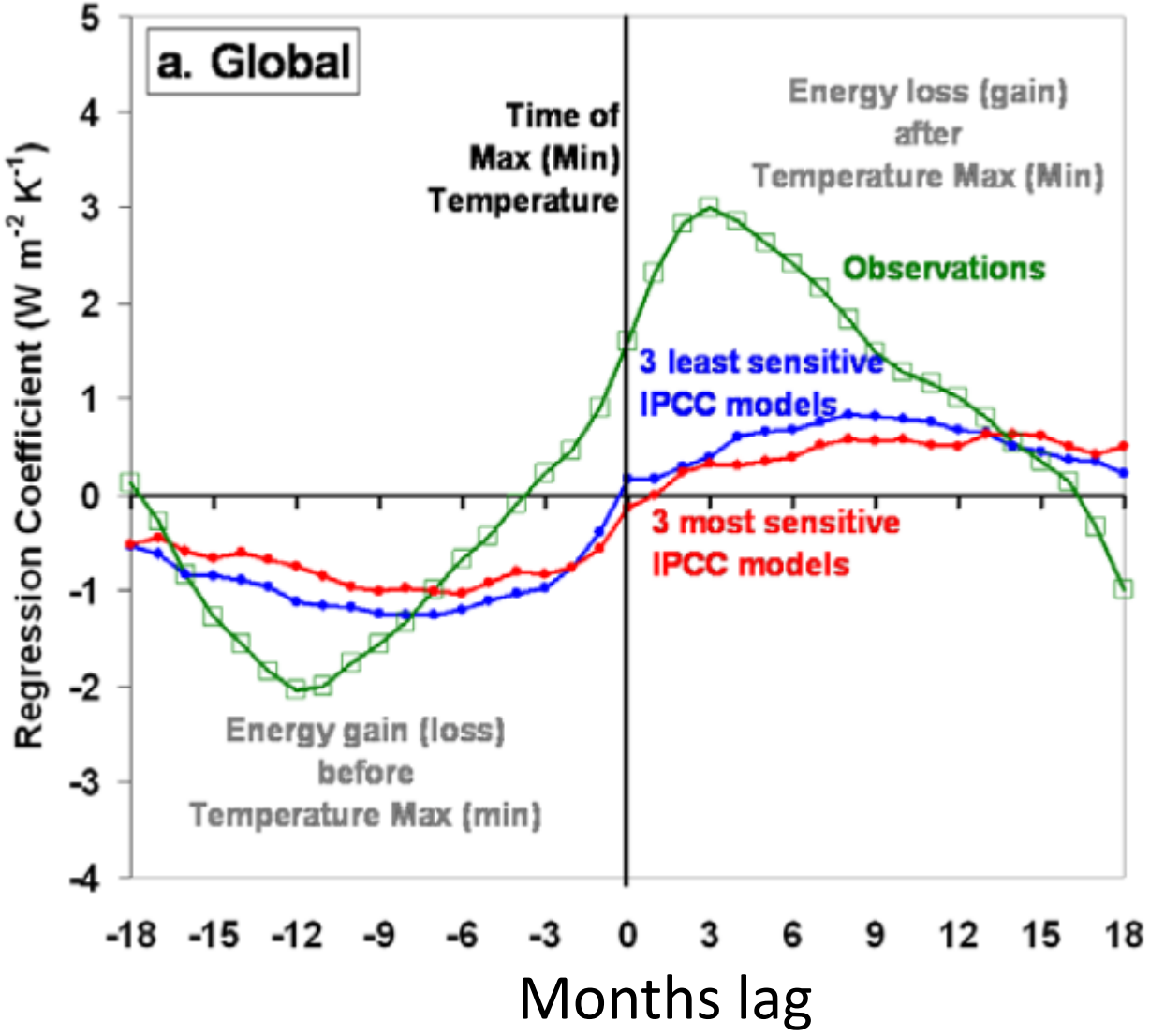
Spencer & Braswell (2011):

ECS is much lower than in models

ScienceDaily.com – “Earth’s atmosphere may be more efficient at releasing energy to space than climate models indicate, satellite data suggest”

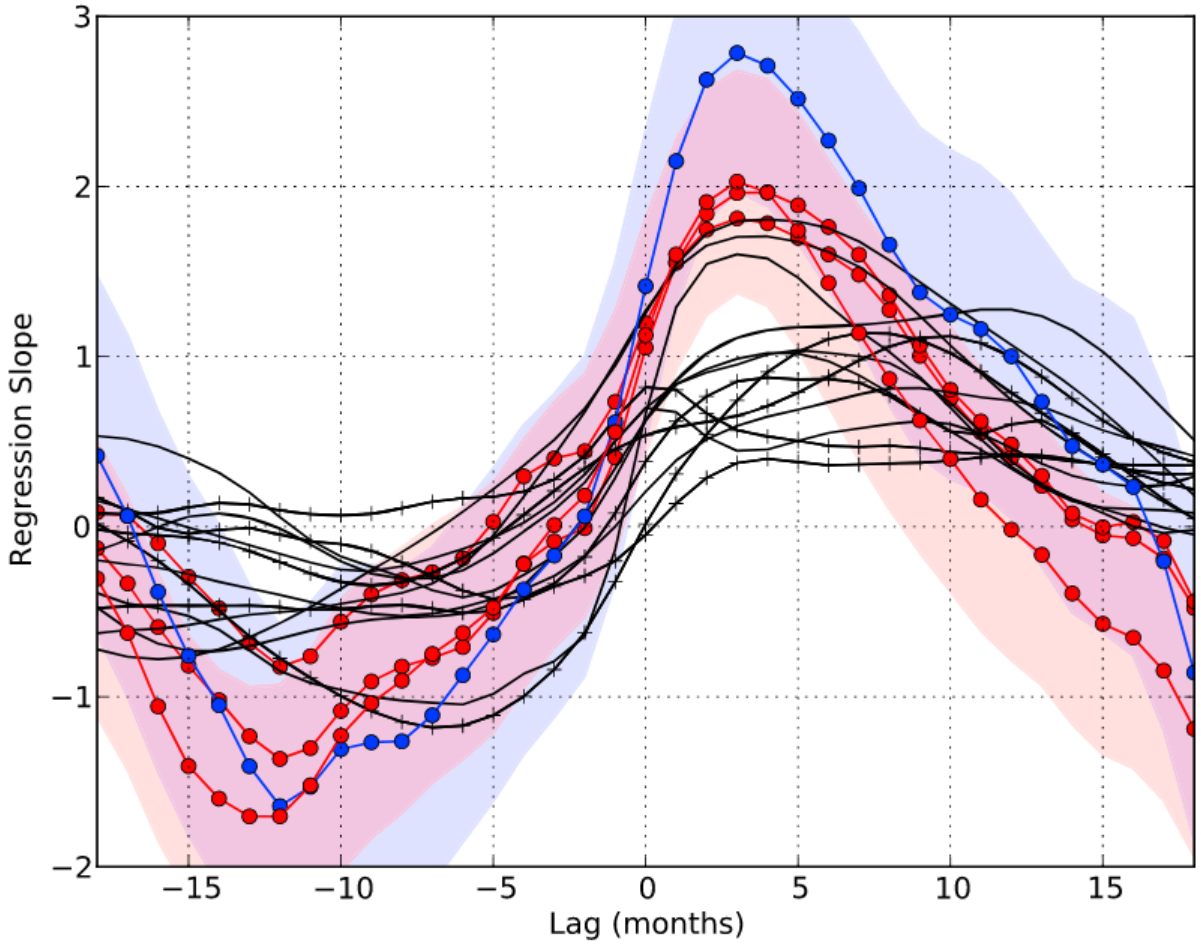
Forbes – “New NASA Data Blow Gaping Hole in Global Warming Alarmism”

Spencer and Braswell (2011)



"…satellite-based metric …depart substantially in the direction of lower climate sensitivity …we find that, with traditional methods, it is not possible to accurately quantify this discrepancy"

Dessler (2011):



Colours = obs ± uncertainty
Black lines = models

Original paper looked at 14 models, plotted just 6. Only plotted ¼ of obs datasets.

“[Plotting all] of the data provide a much different conclusion.”

Lindzen & Choi (2009):

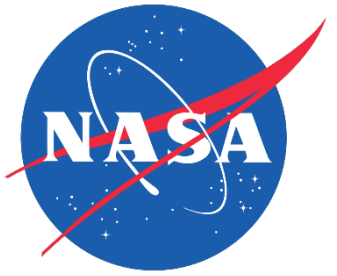
If you select time periods in just the right way, then

ECS is much lower than in models

Spencer & Braswell (2011):

If you remove most of the model and obs, then

ECS is much lower than in models



Lindzen & Choi (2009):

If you select time periods in just the right way, then

ECS is much lower than in models

Spencer & Braswell (2011):

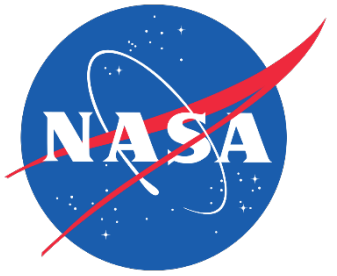
If you remove most of the model and obs, then

ECS is much lower than in models

Monckton et al. (2015)

ECS is much lower than in models

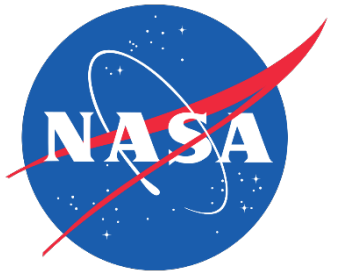
Monckton et al. (2015)



"Peer-reviewed pocket-calculator climate model exposes serious errors in complex computer models" – Phys.org

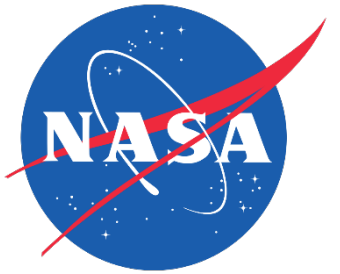
"Is climate change really that dangerous? Predictions are 'very greatly exaggerated', claims study" – The Daily Mail

Monckton et al. (2015)



"The model indicates…that, since feedbacks are likely to be net-negative, a better estimate is 1.0 K;"

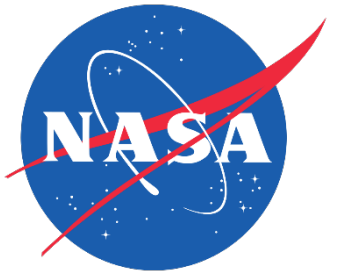
Monckton et al. (2015)



"The model indicates…that, since feedbacks are likely to be net-negative, a better estimate is 1.0 K;"

"The simple model has only five tunable parameters:"

Monckton et al. (2015)

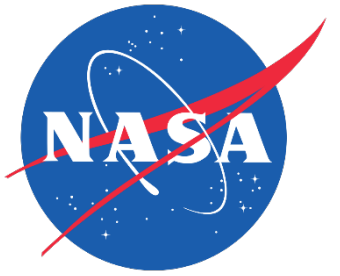


"The model indicates…that, since feedbacks are likely to be net-negative, a better estimate is 1.0 K;"

"The simple model has only five tunable parameters:"

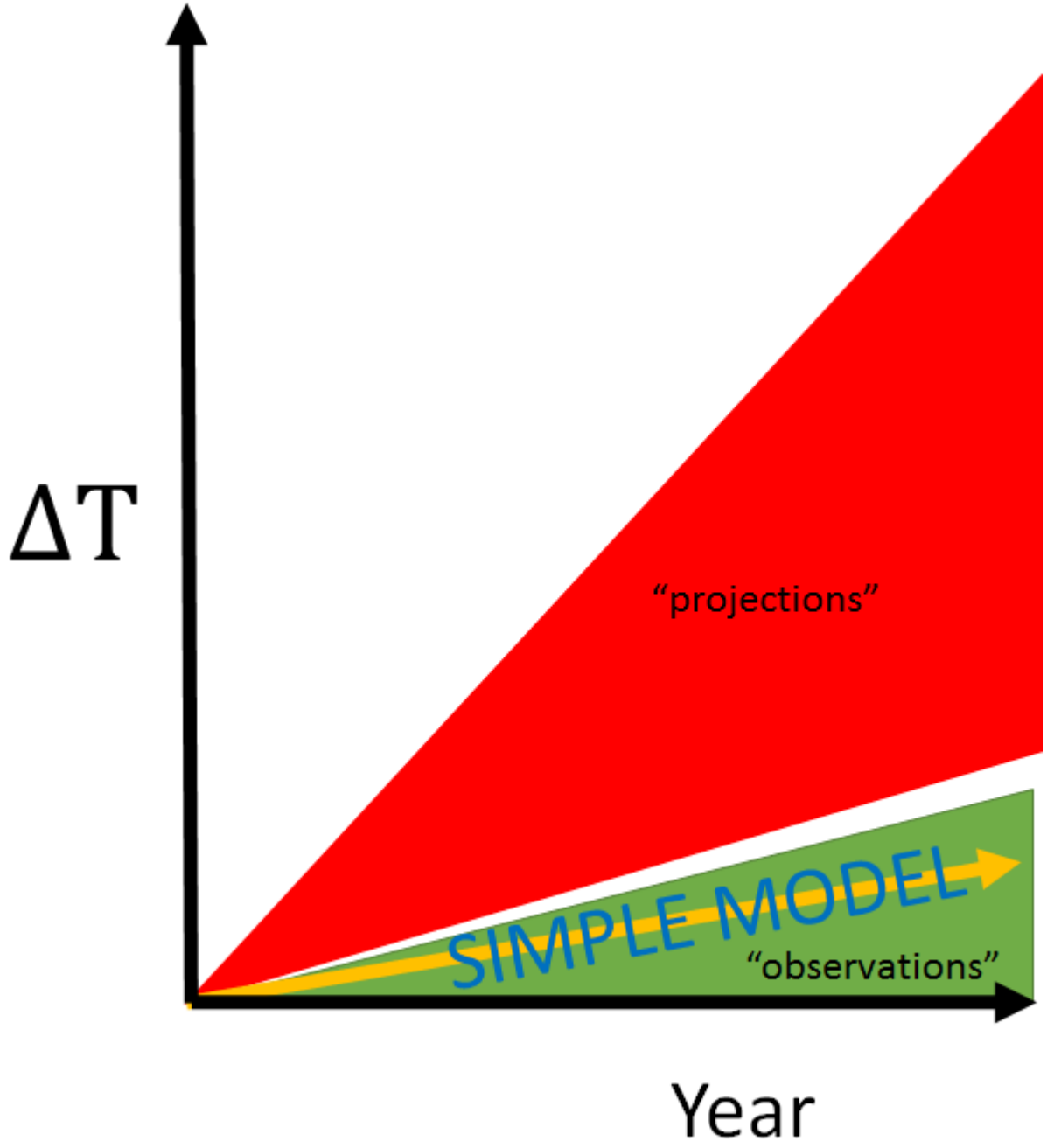
"In Fig. 5, a regime of temperature stability is represented by $g_\infty \leq +0.1$, the maximum value allowed by process engineers designing electronic circuits intended not to oscillate under any operating conditions."

Monckton et al. (2015)

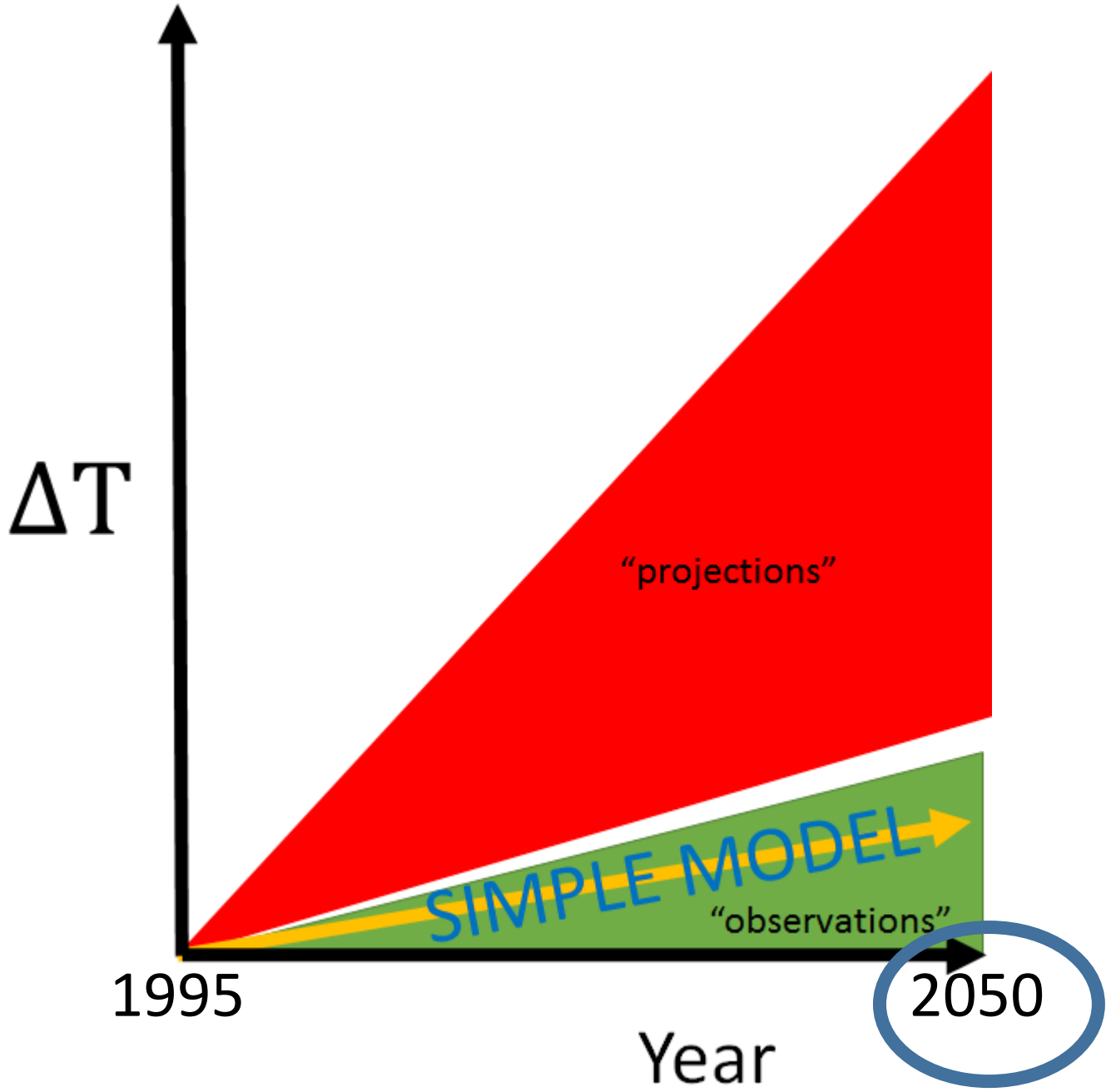


"[The model's] output proves to be broadly consistent with observation, while the now-realized projections of the general-circulation models have proven to be relentlessly exaggerated."

Adapted from doi: 10.1007/s11434-014-0699-2



Adapted from doi: 10.1007/s11434-014-0699-2



Lindzen & Choi (2009):

If you select time periods in just the right way, then

ECS is much lower than in models

Spencer & Braswell (2011):

If you remove most of the model and obs, then

ECS is much lower than in models

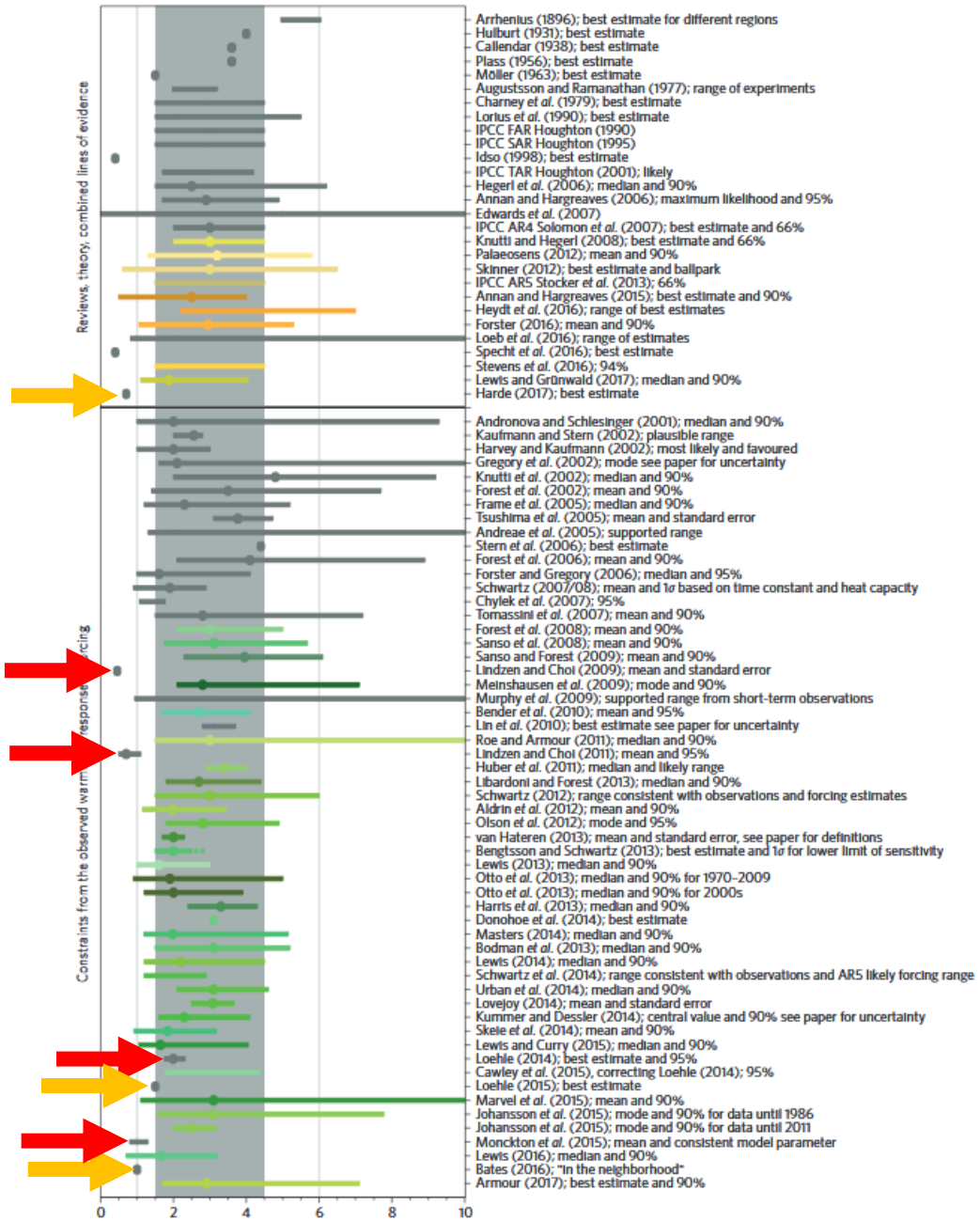
Monckton et al. (2015)

If you make up parameters and data

ECS is much lower than in models

Red published comments show errors

Orange use same or similar techniques to those known to be flawed.



Lindzen & Choi (2009):

If you select time periods in just the right way, then

ECS is much lower than in models

Spencer & Braswell (2011):

If you remove most of the model and obs, then

ECS is much lower than in models

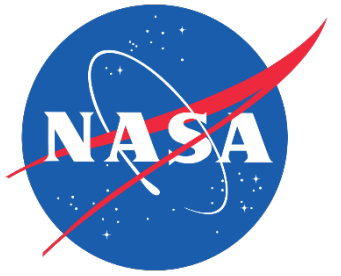
Monckton et al. (2015)

If you make up parameters and data

ECS is much lower than in models

Lewis & Curry (2018)

ECS is quite a bit lower than in models



“IPCC Overestimates Climate Sensitivity: Study” – Competitive Enterprise Institute

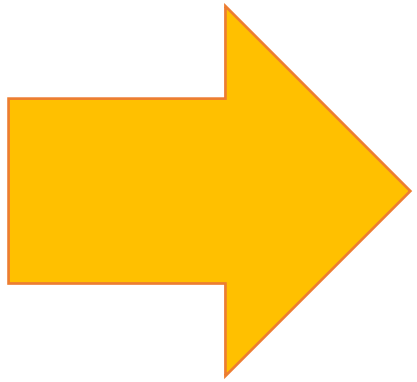
“Some More Insensitivity about Global Warming” – Cato Institute

“Is Climate Alarmist Consensus about to Shatter?” – Heartland Institute

How does this paper compare?

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

$\Delta F_{2\times CO2}$	3.81 W m^{-2}
ΔT	0.80 °C
ΔF	2.52 W m^{-2}
ΔN	0.50 W m^{-2}



ECS 1.50 °C

5—95 %: 1.05—2.45 °C

How does this paper compare?

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

Come from models

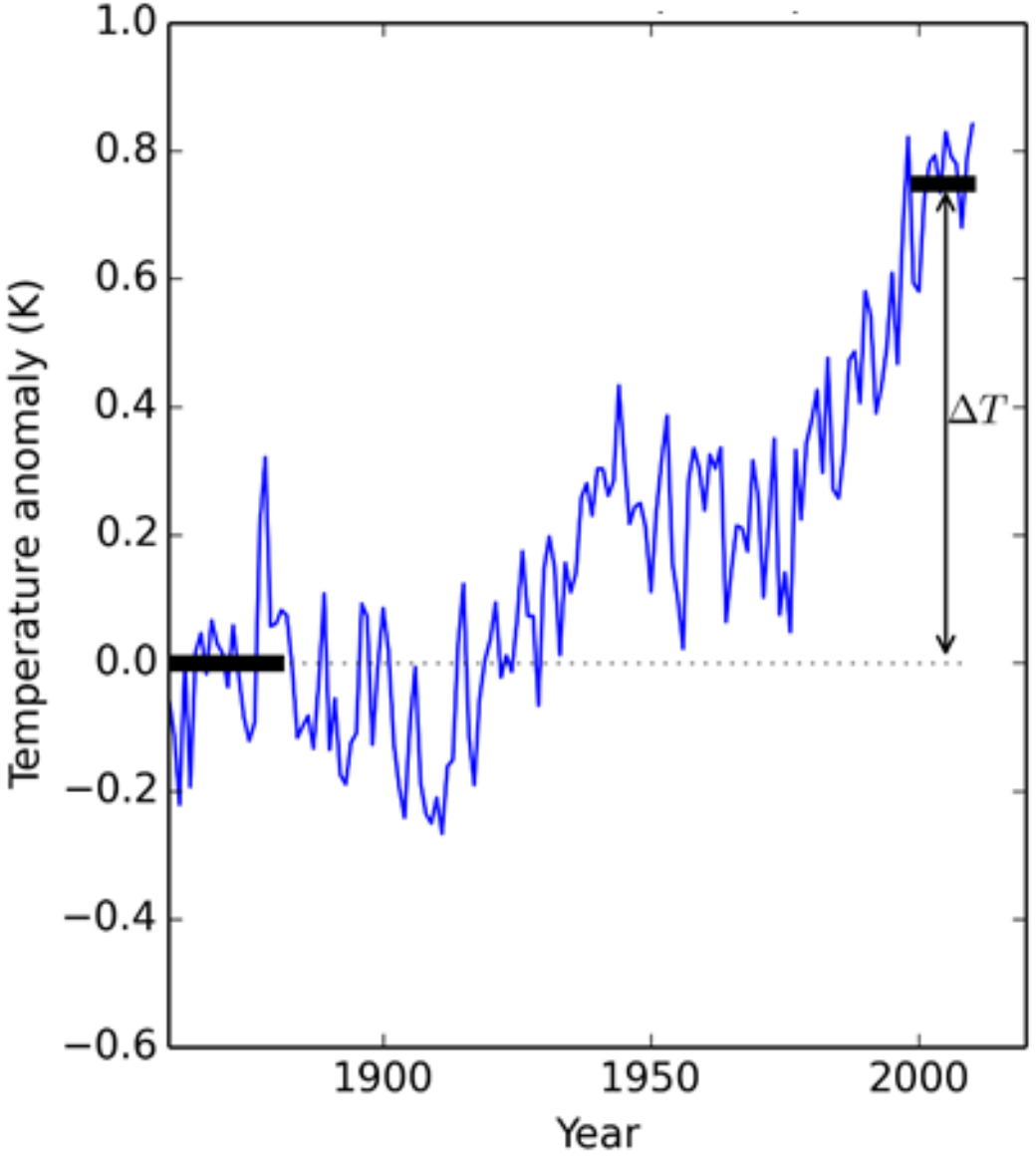
How does this paper compare?

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

Come from models

Let's look at the ΔT and ΔN to see if they explain the difference between Lewis & Curry and IPCC

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

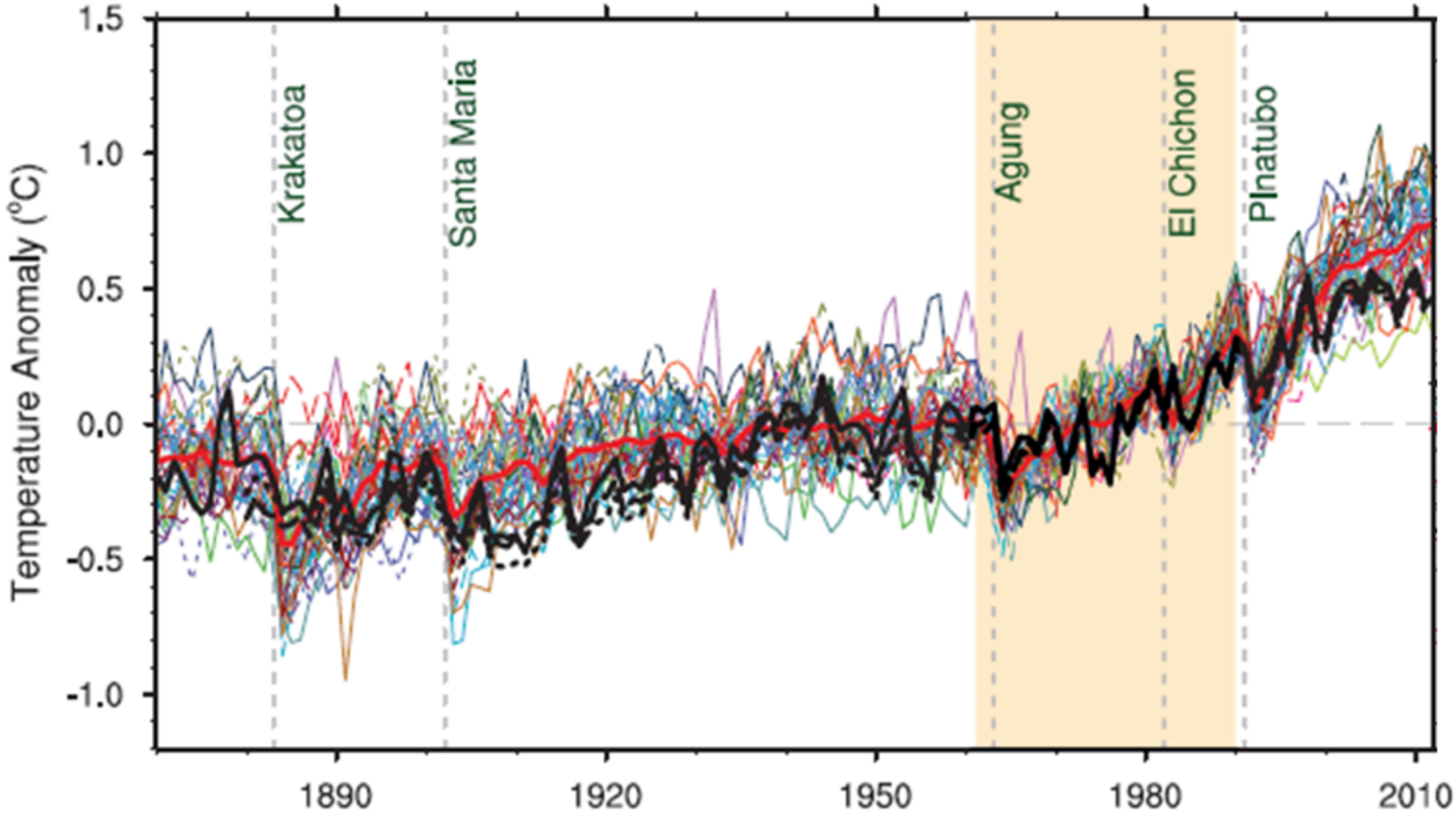


Lewis & Curry use:

$$\Delta T = \overline{T_{2007-2016}} - \overline{T_{1869-1882}}$$

IPCC AR5 Figure 9-08,
CMIP5 vs HadCRUT4 (obs)

$$ECS = \Delta F_{2\times co2} \frac{\Delta T}{\Delta F - \Delta N}$$

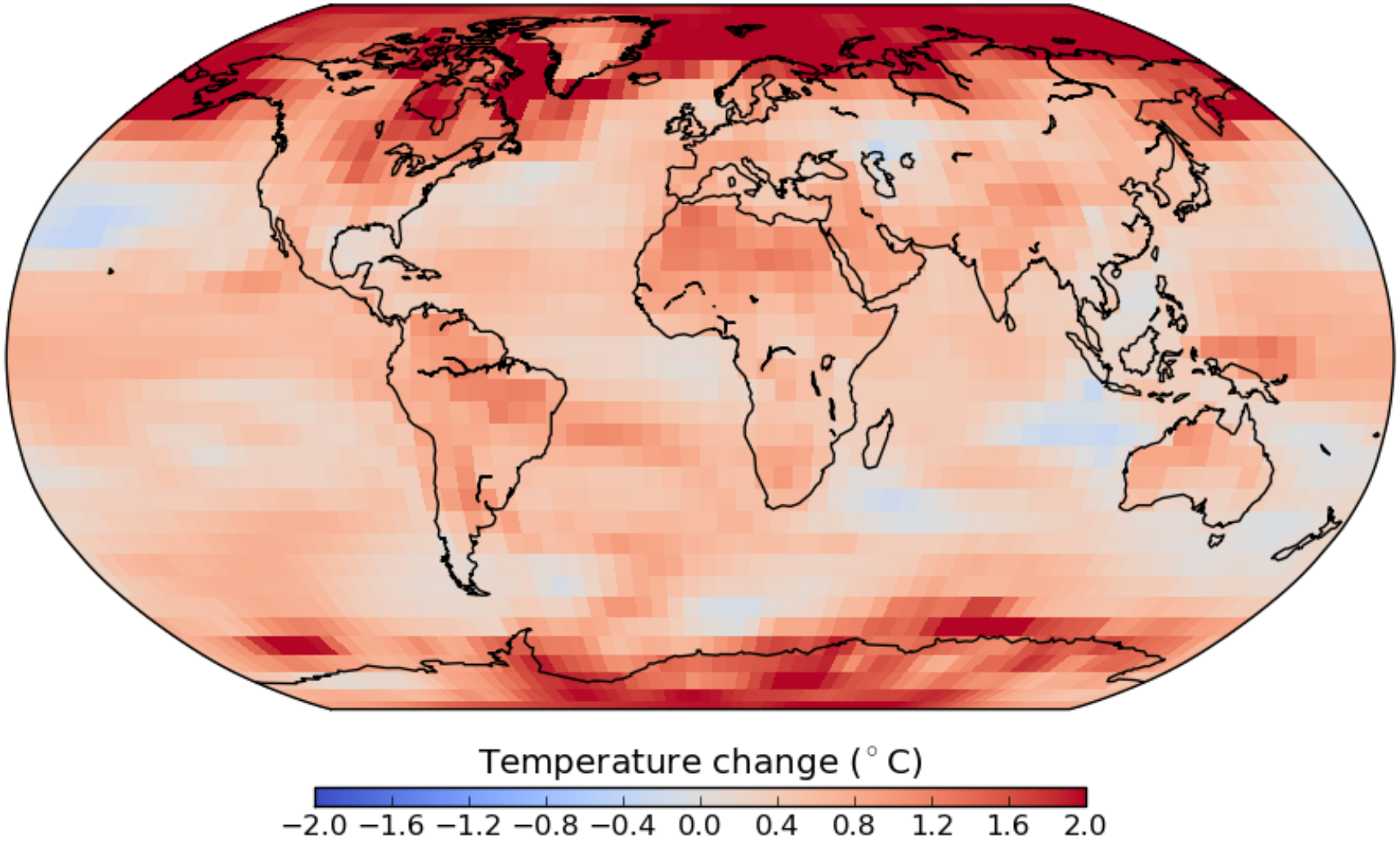


$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

1 Model:

1861—2005 warming:

0.66 °C

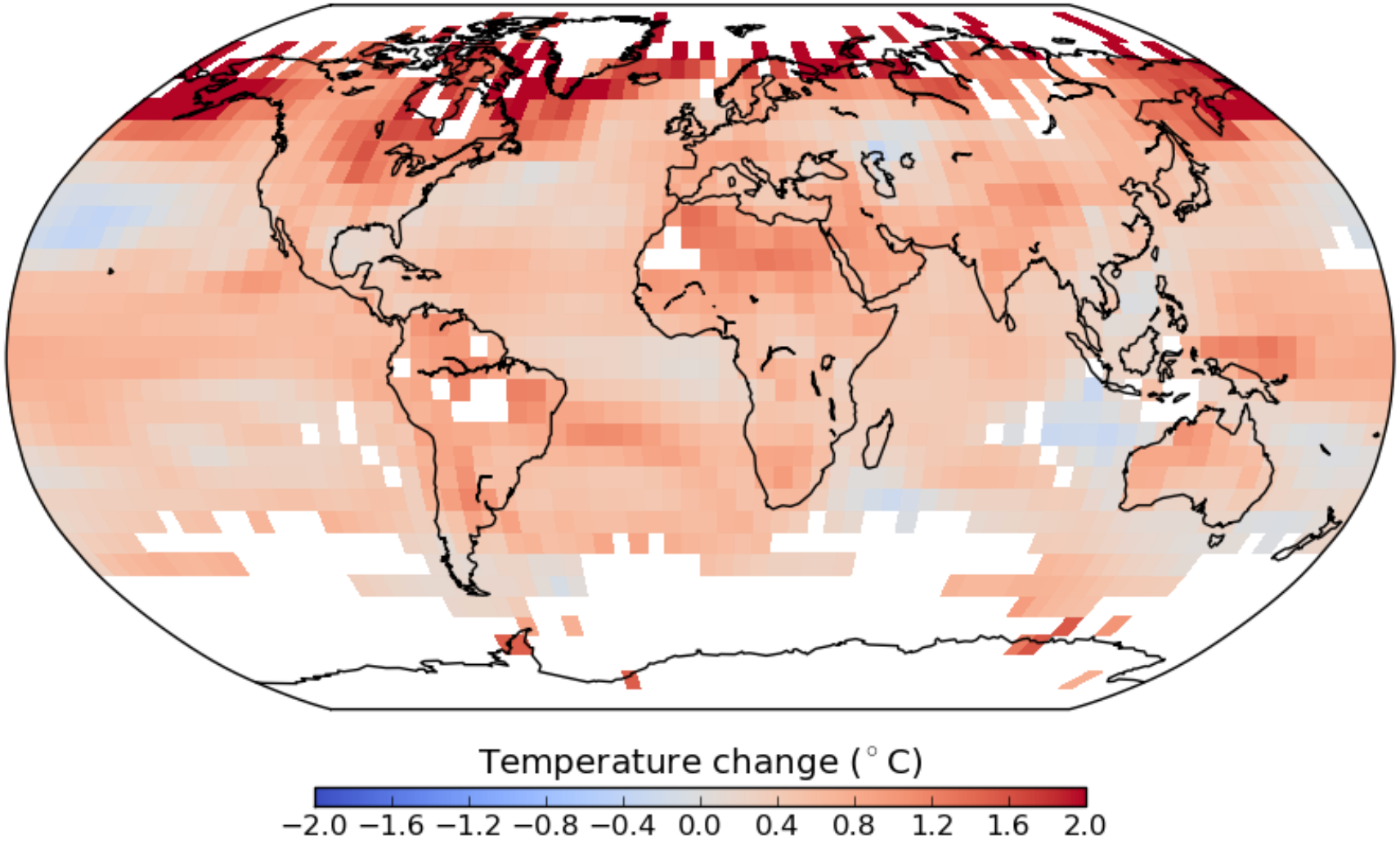


Measured areas 1996—2005

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

1861—2005 warming:

0.59 °C

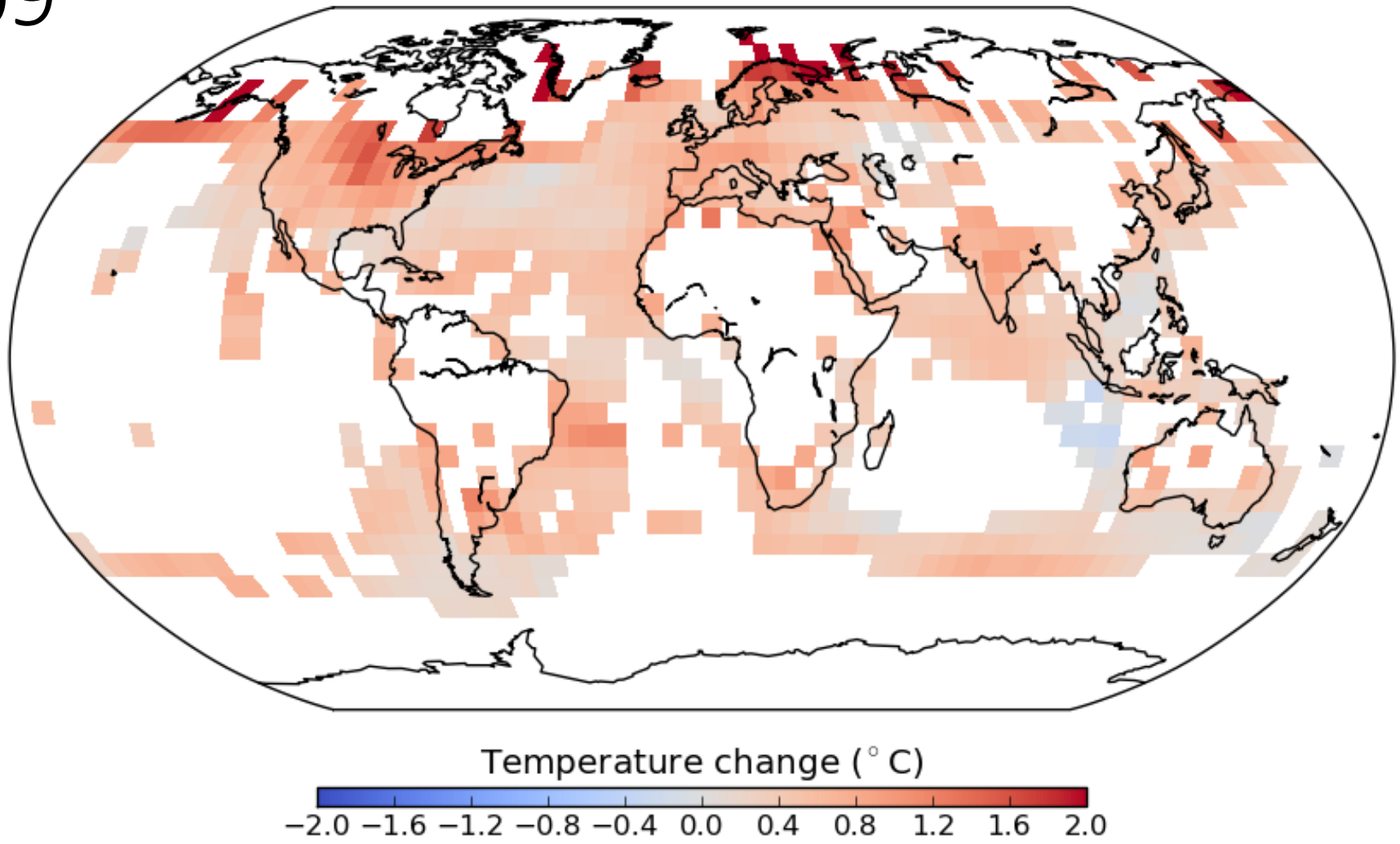


Measured areas 1900—1909

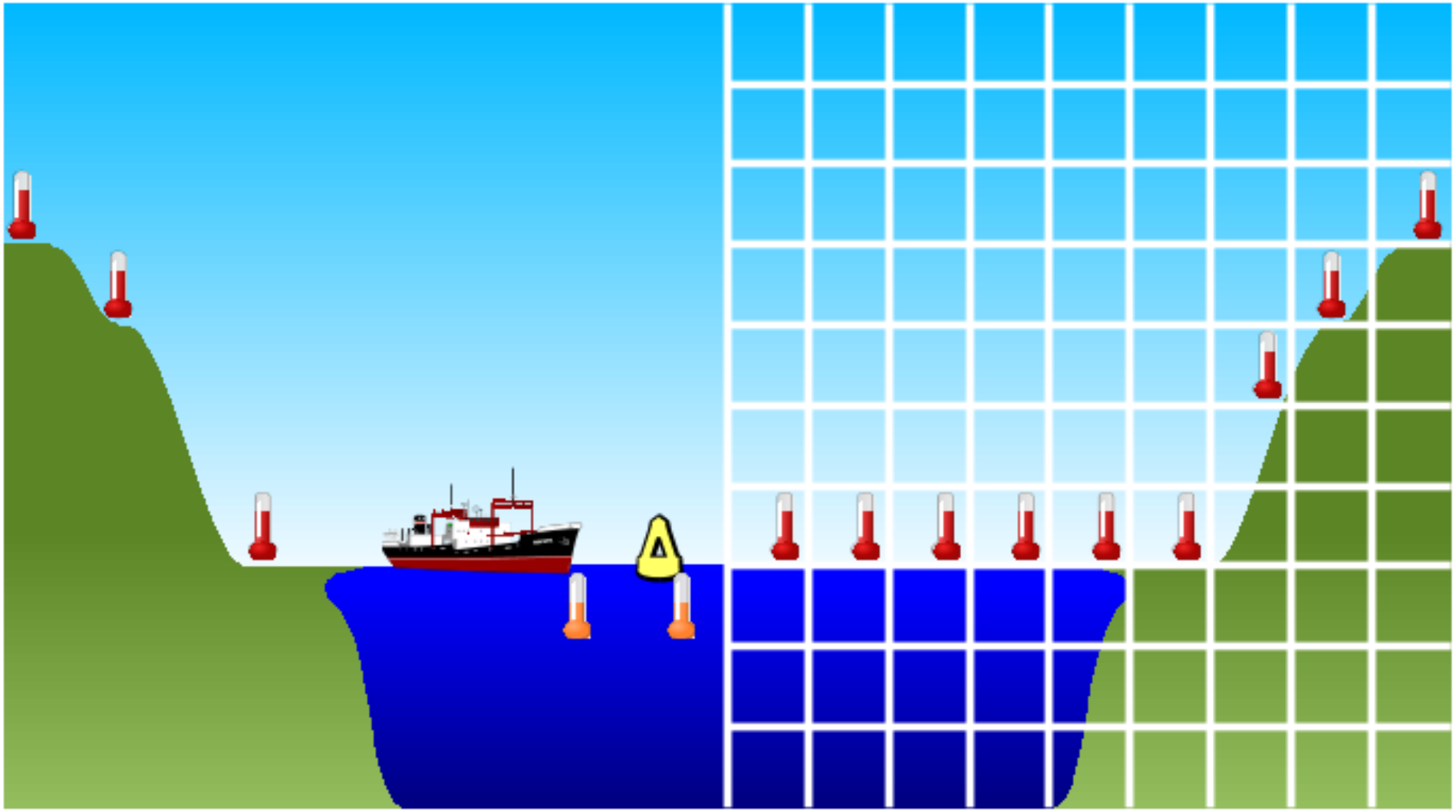
$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

1861—2009 warming:

0.53 °C



$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

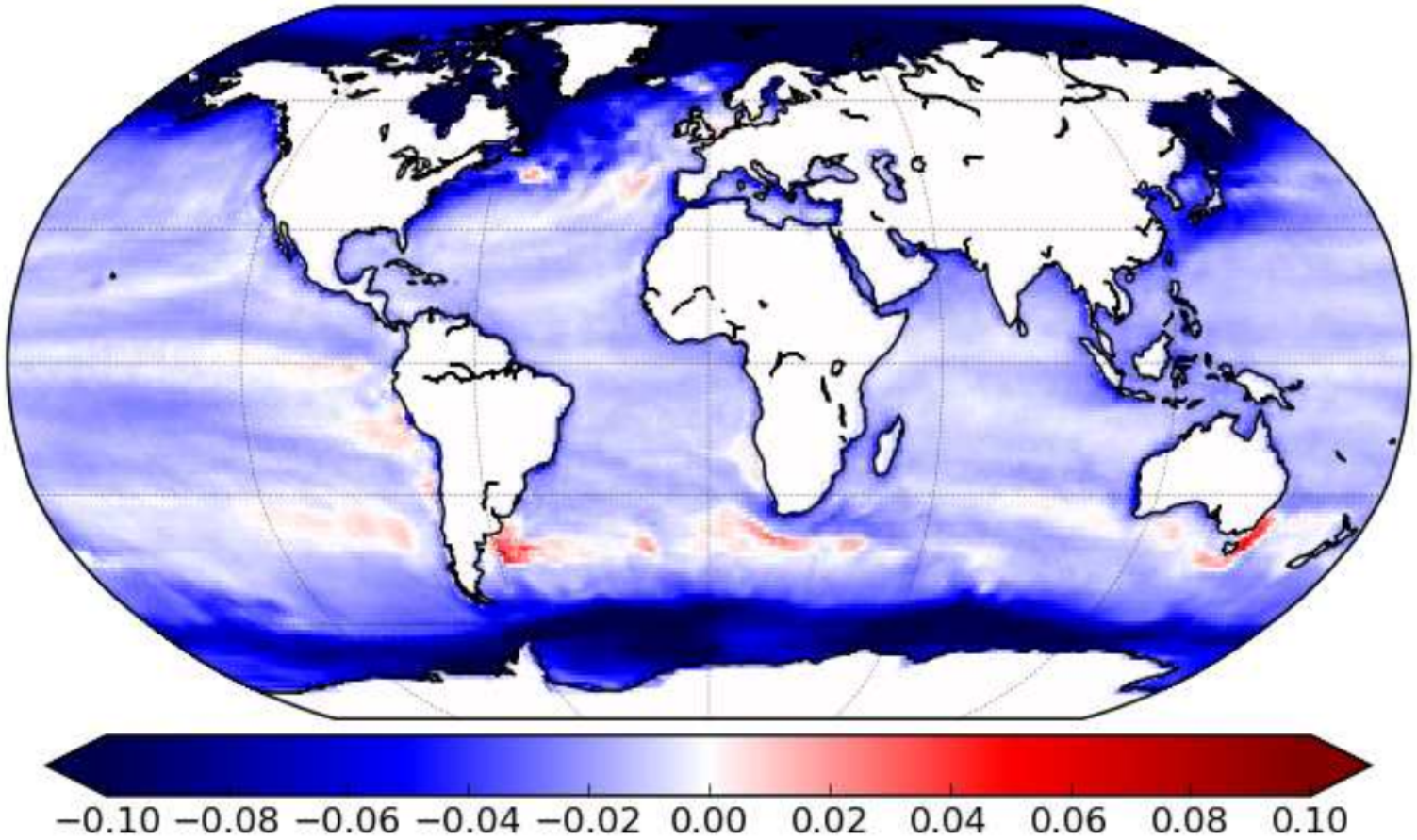


Observations **Models**

Credit: Kevin Cowtan

$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

(b) Trend difference, blended temperature anomalies

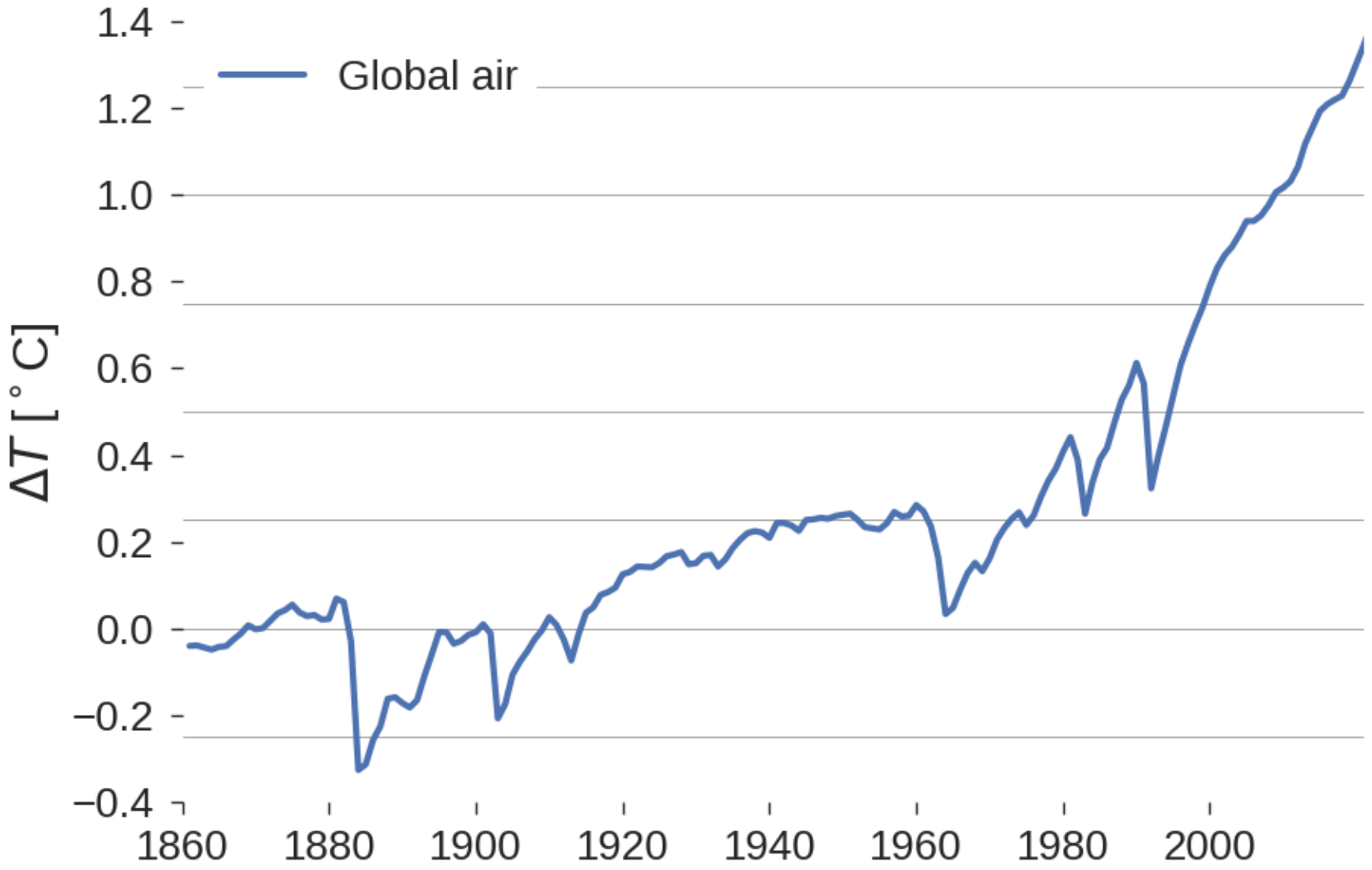


1985—2014 CMIP5 mean ocean minus air trend

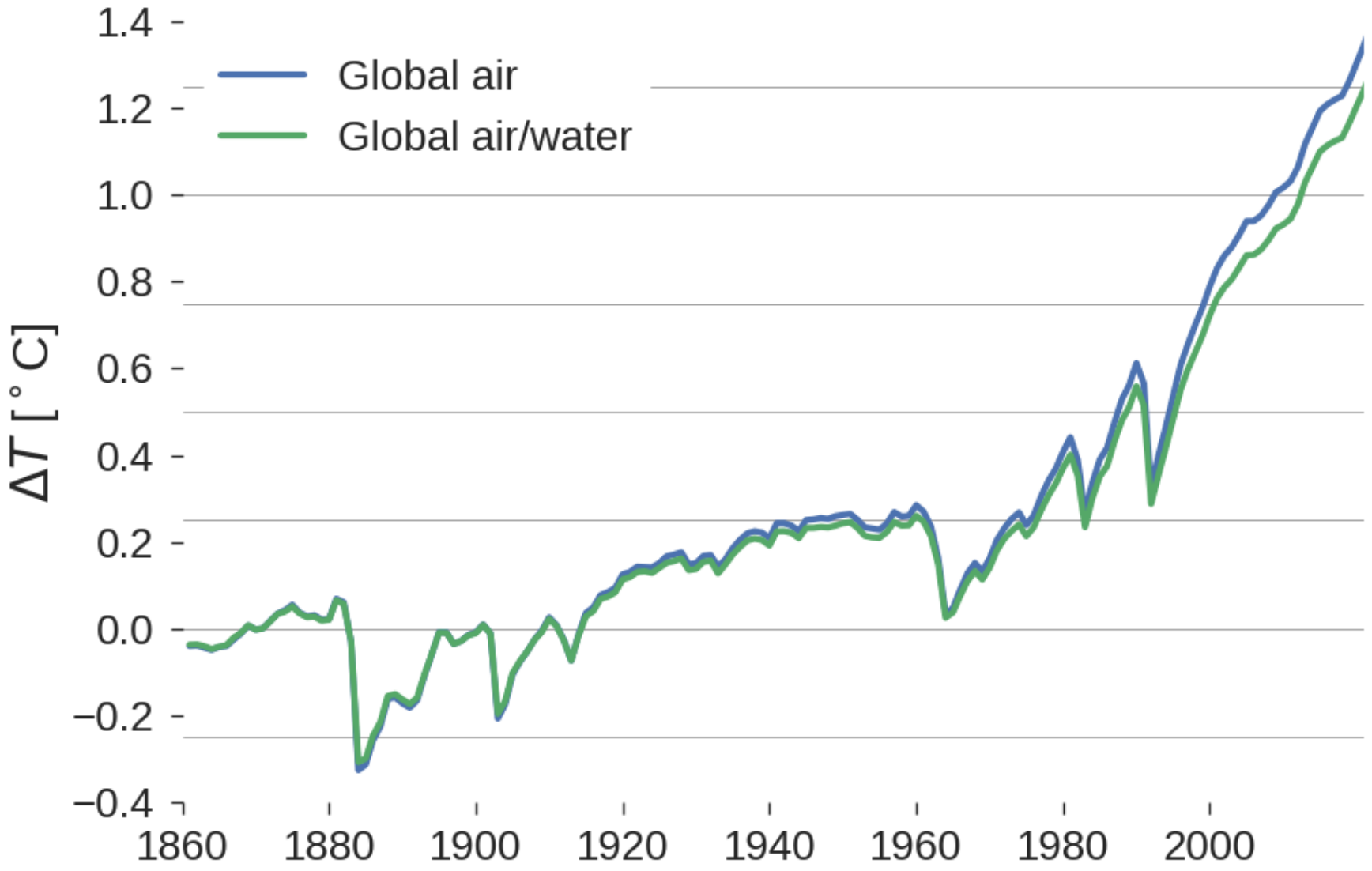
SSTs warm less.

Credit: Cowtan et al. (2015)

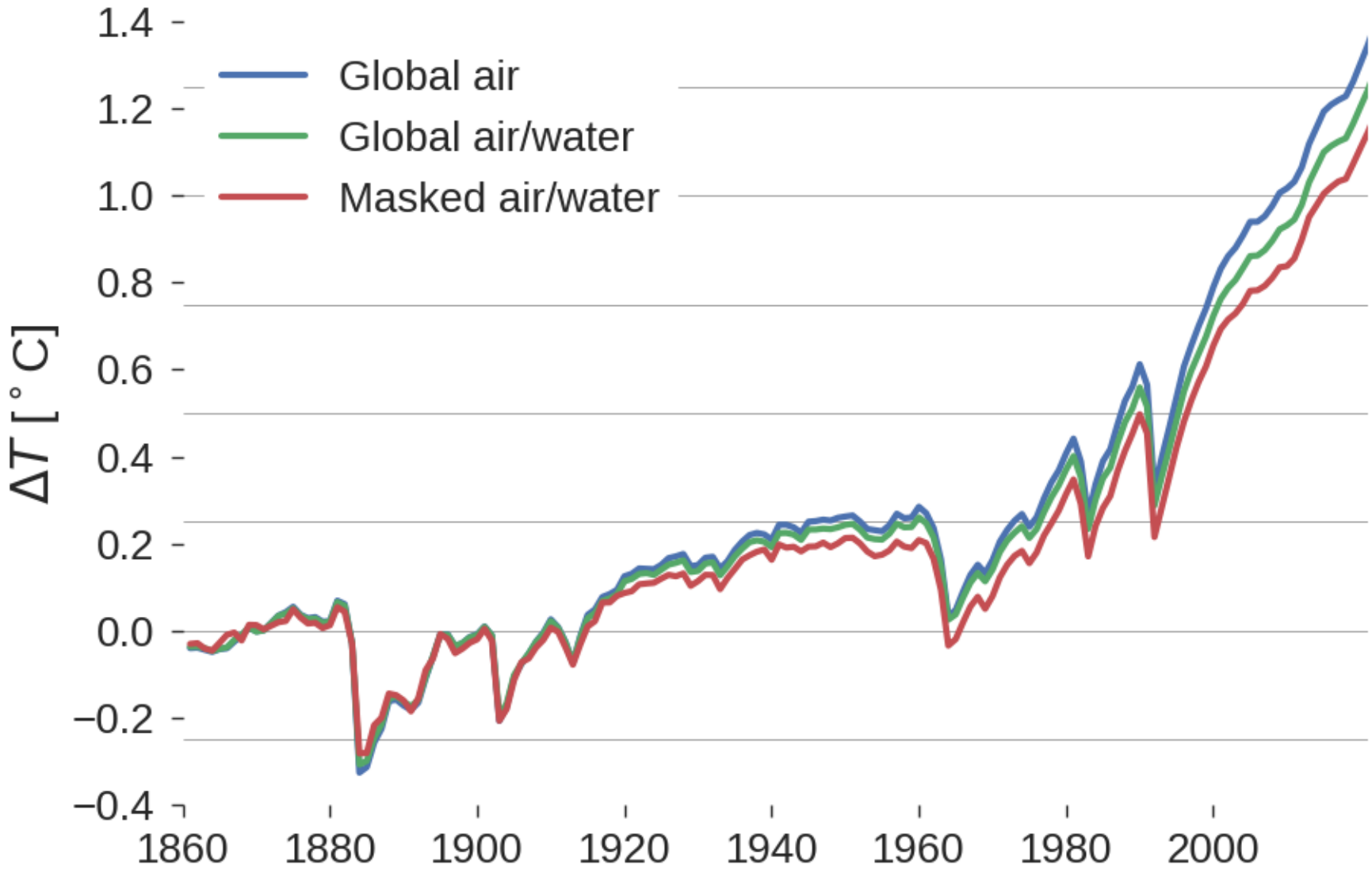
$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$



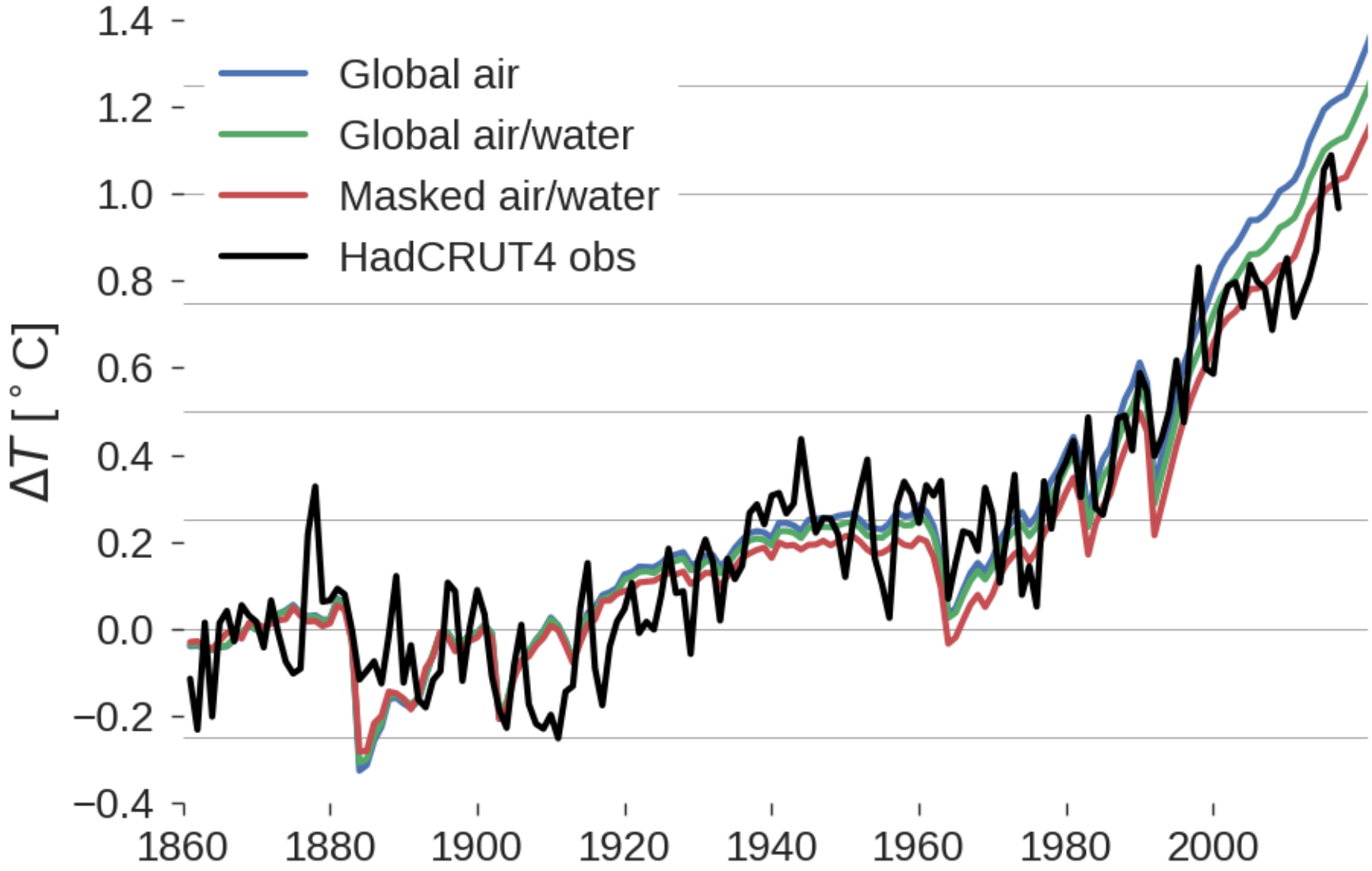
$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$



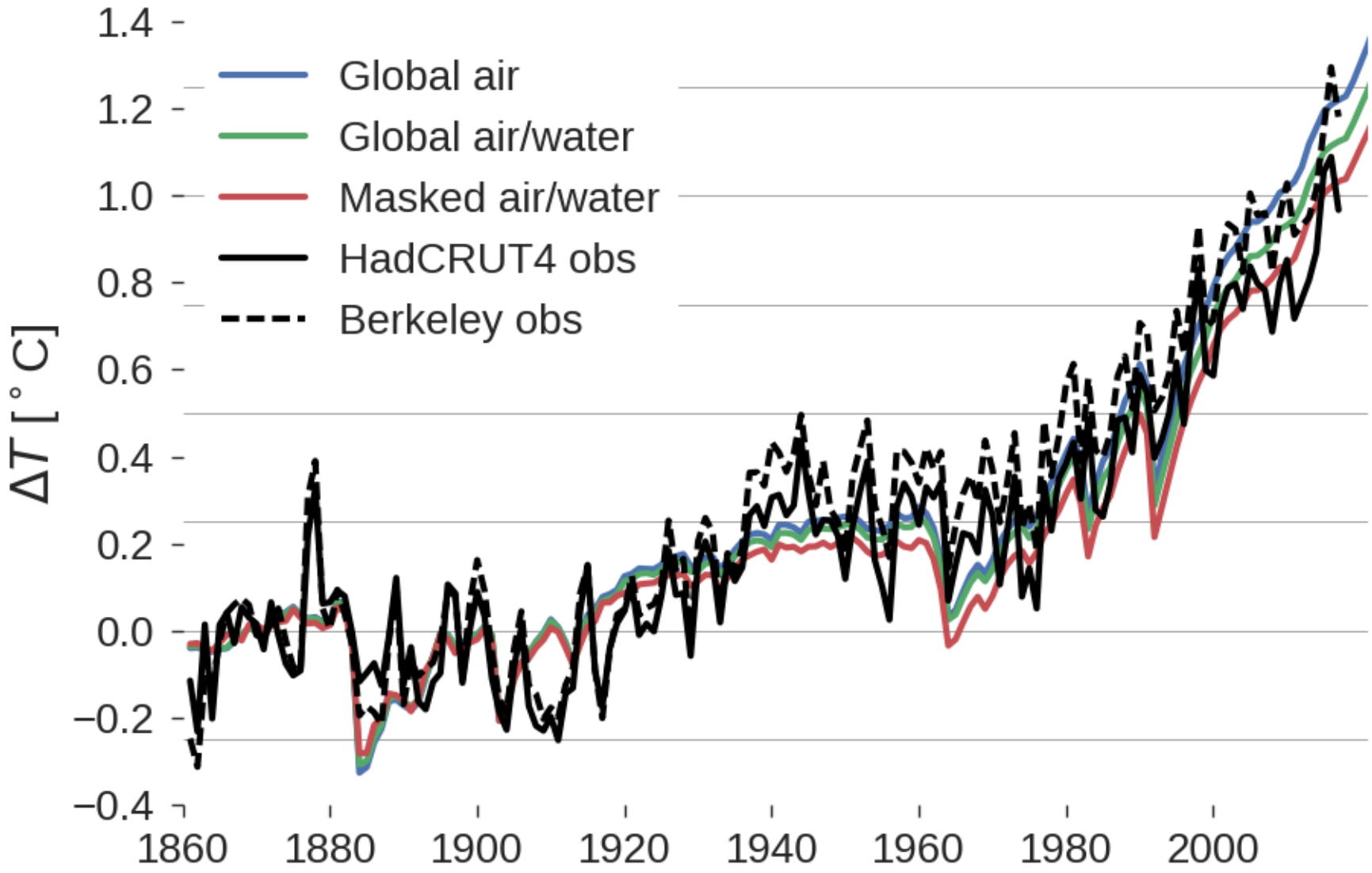
$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$



$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

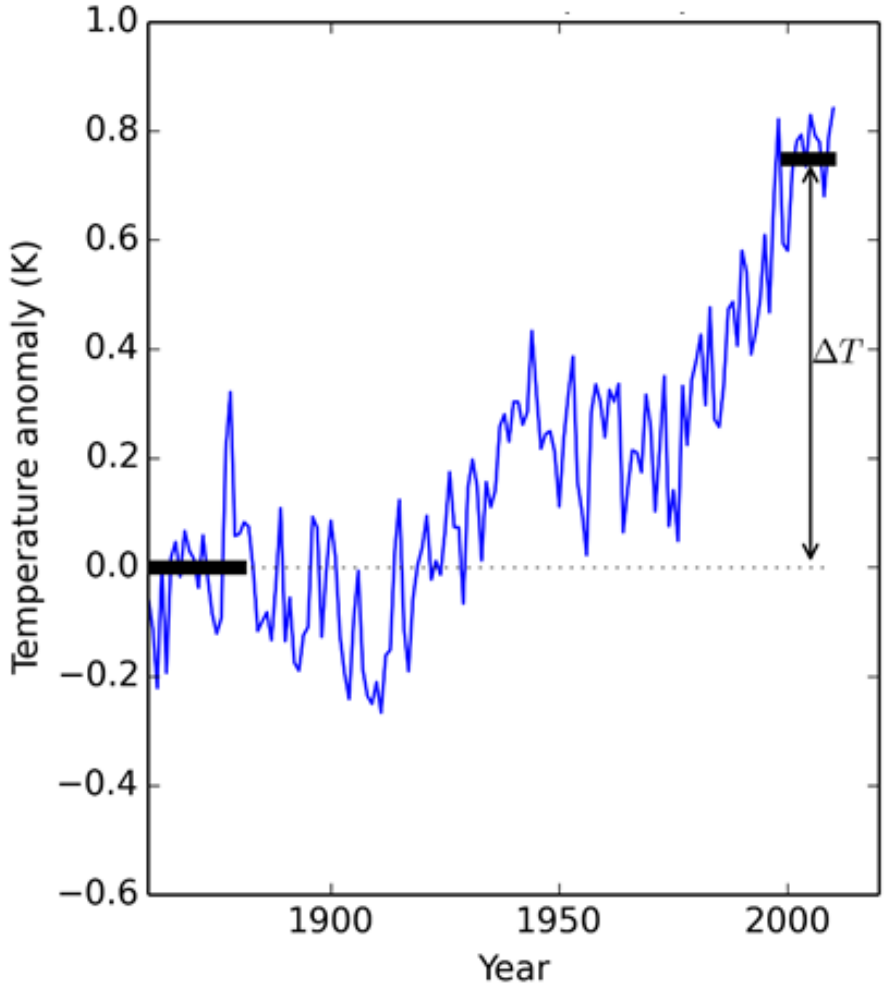


$$ECS = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$



Consistent comparison

- ΔT ~20 % higher with global coverage + reduced air/water blending bias
- Berkeley Earth minimizes these and says 0.95 °C
- Lewis & Curry used HadCRUT4 0.80 °C for main result



Consistent comparison ΔN

- ΔN is the energy imbalance

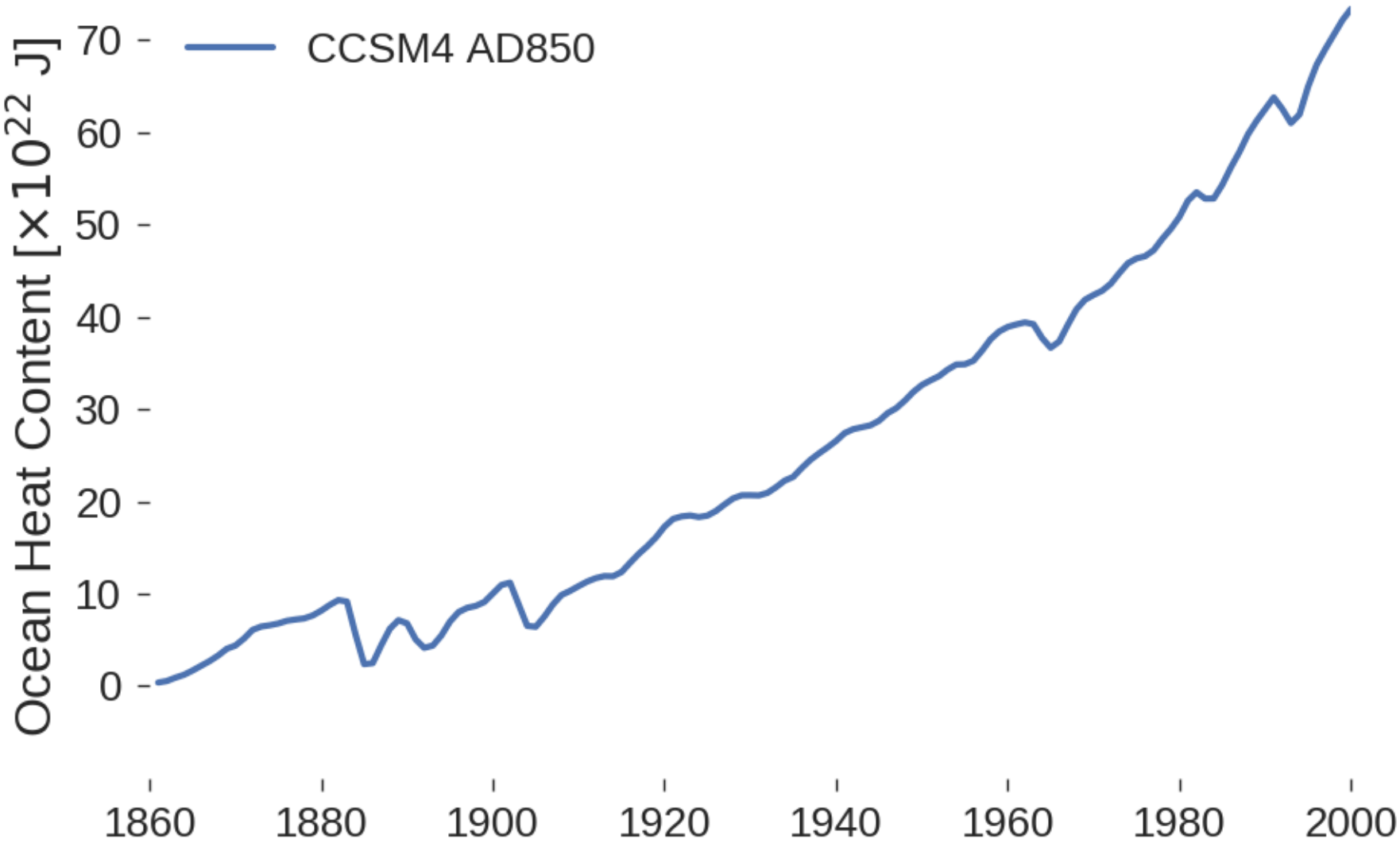
- Mostly ocean heat, generally from Argo floats.

- **WE DO NOT HAVE 1869—1882 DATA… where does it come from?**

Early period heat uptake

- Lewis & Curry take $\overline{N_{1869-1882}}$ from a CCSM4 model run that began in AD850.
- Climate models are “spun up” in a control run, often without volcanoes
- Small, missing volcanic cooling so ocean is *slightly* out of balance
- The moment volcanoes erupt, deep ocean cools.

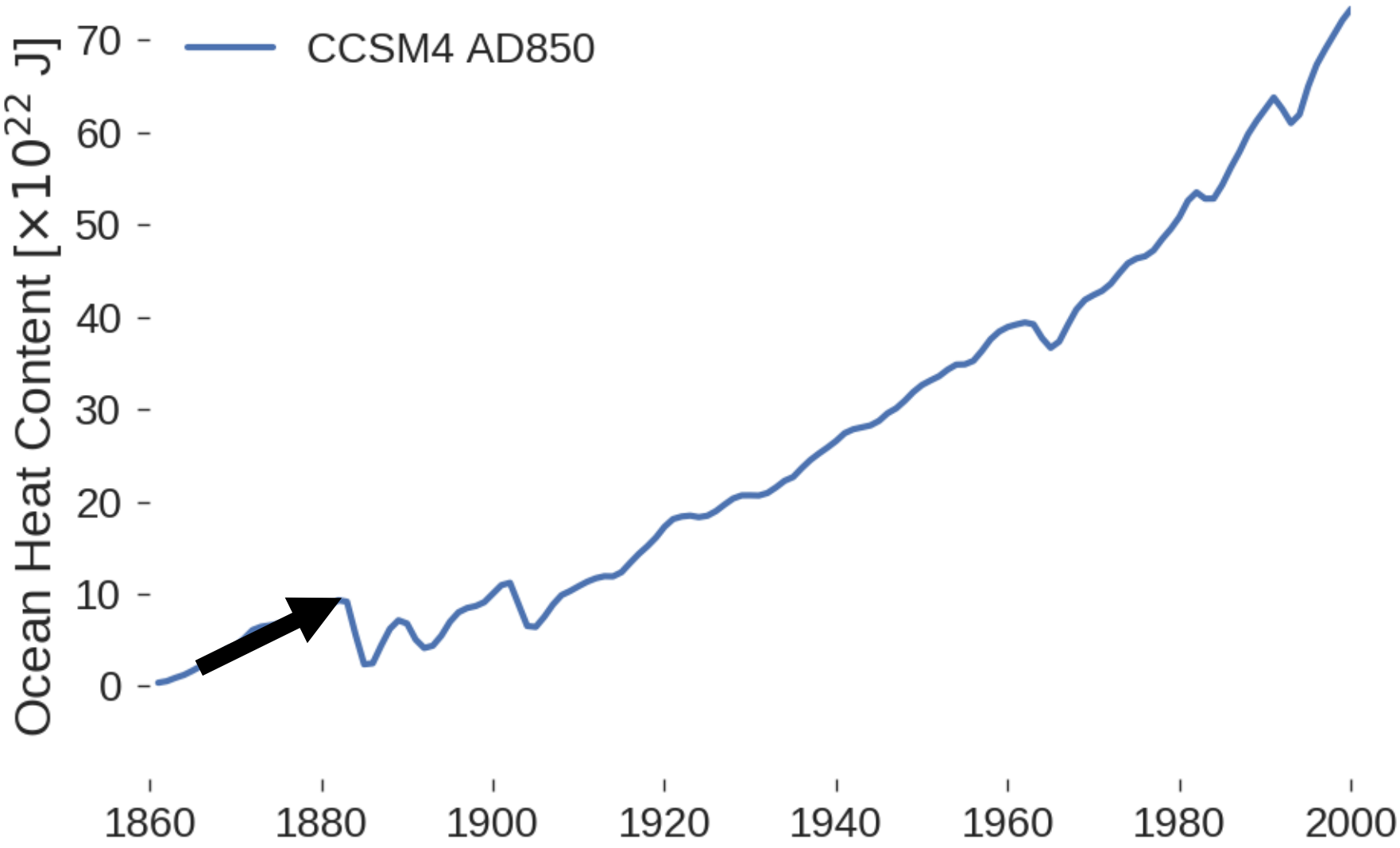
Source of Lewis & Curry early *N*



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

doi: 10.1029/2010GL045507

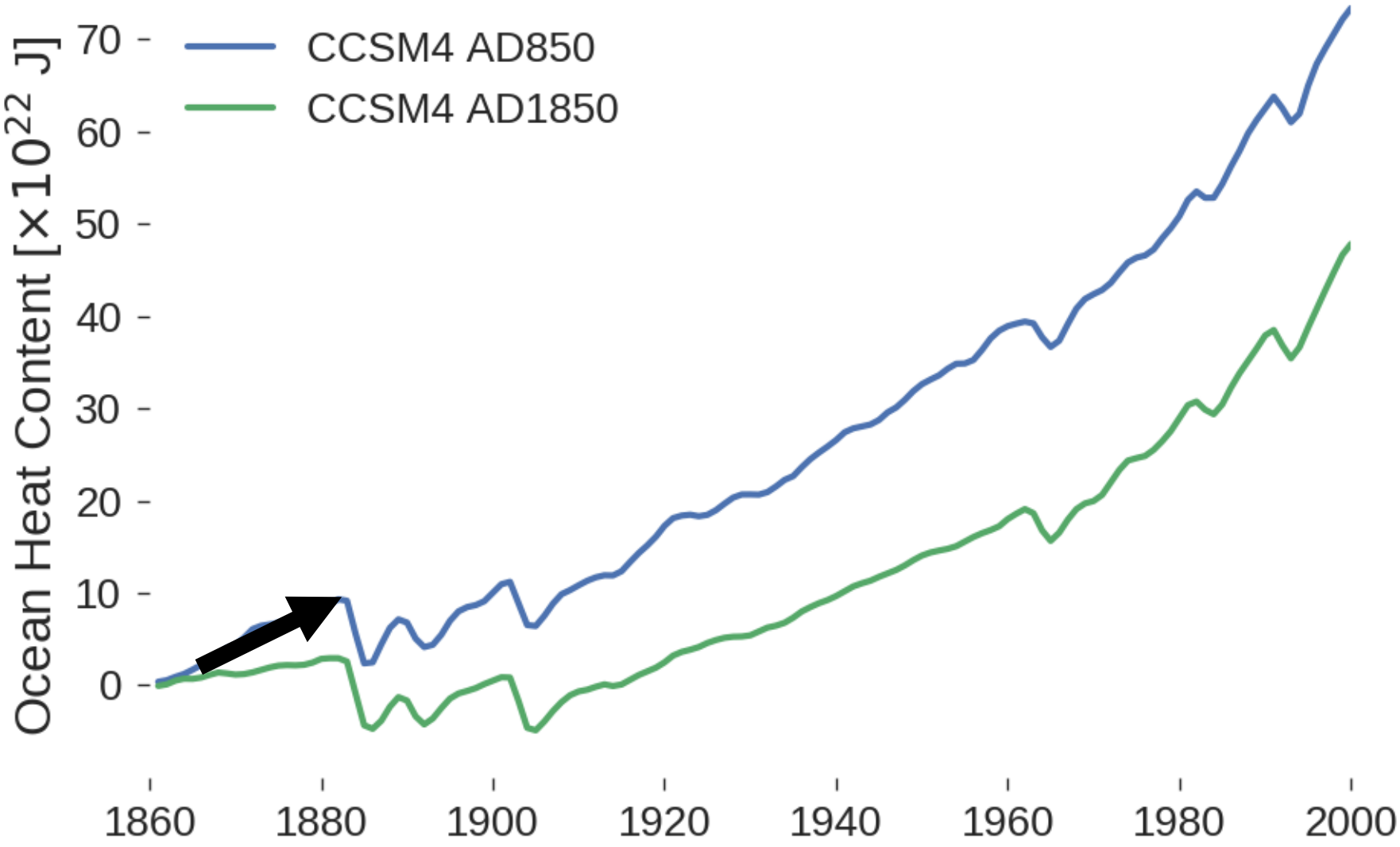
Source of Lewis & Curry early *N*



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

doi: 10.1029/2010GL045507

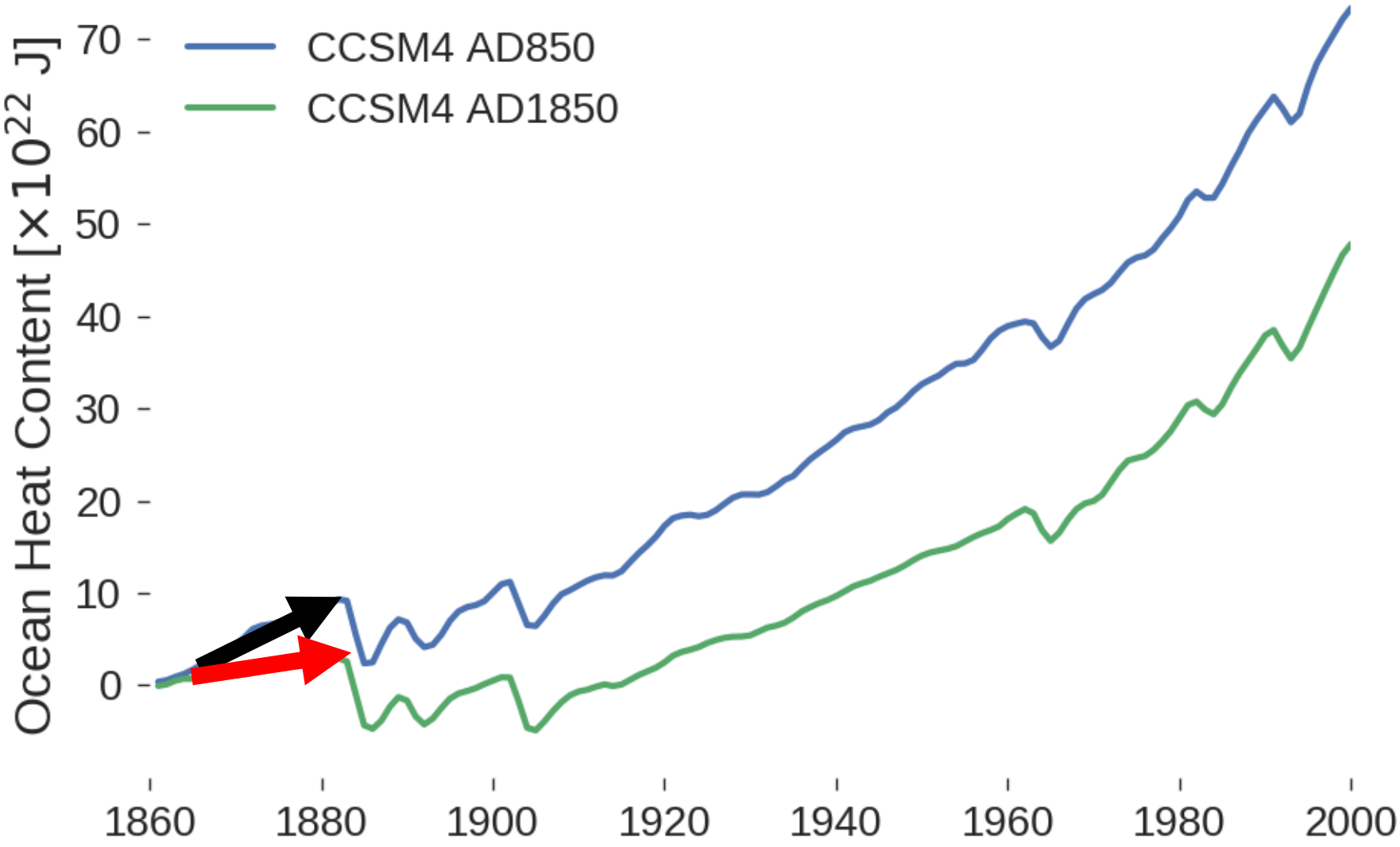
Source of Lewis & Curry early *N*



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

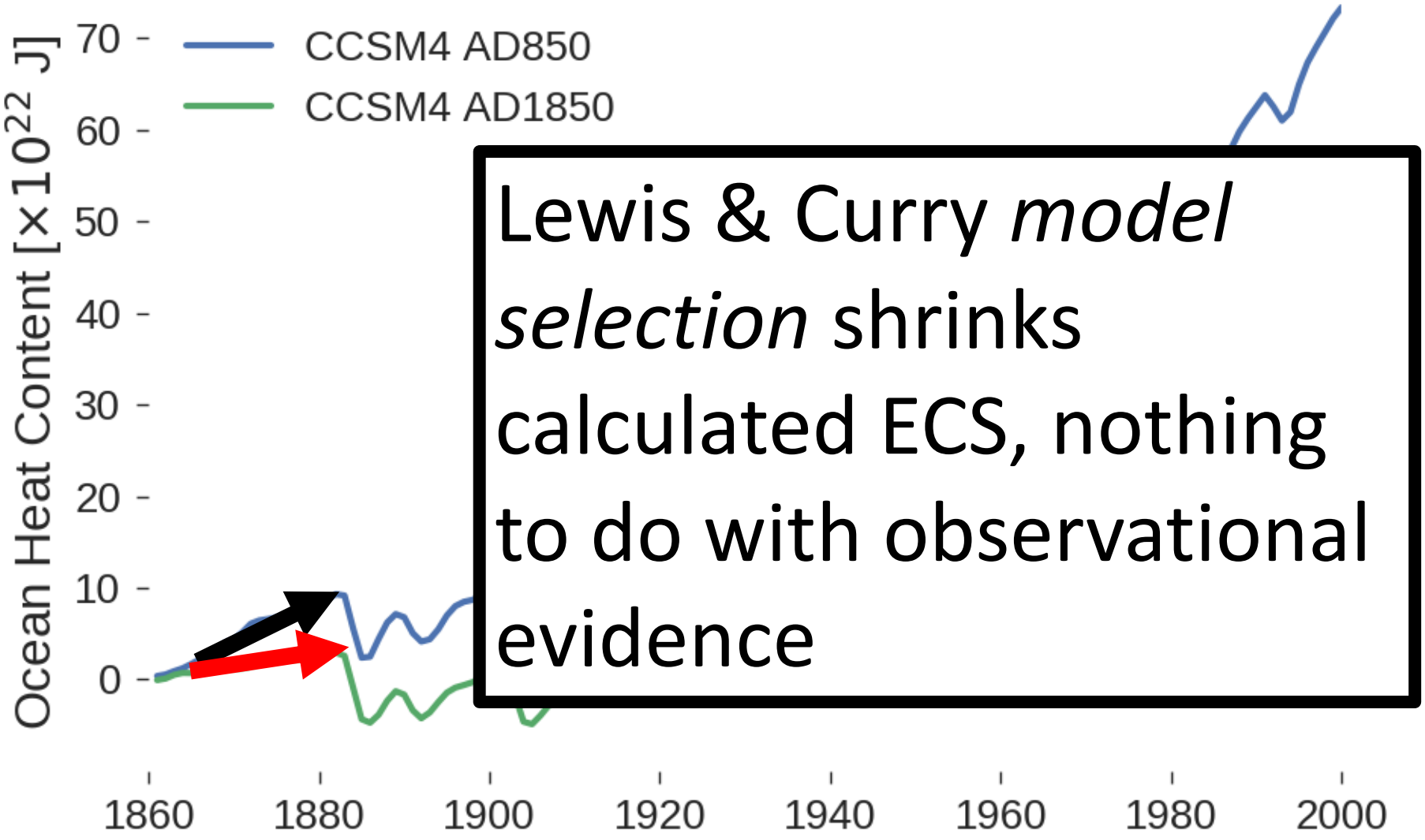
doi: 10.1029/2010GL045507

Source of Lewis & Curry early *N*



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

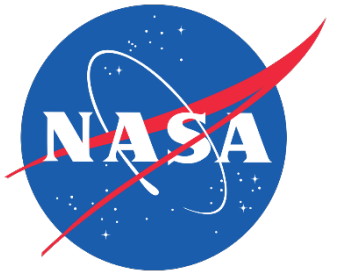
Source of Lewis & Curry early *N*



Lewis & Curry *model selection* shrinks calculated ECS, nothing to do with observational evidence

$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

Let's do emergent constraint



- Use Lewis & Curry (2018) method on every CMIP5 model that has outputs

$$ECS_{hist} = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

Let's do emergent constraint

- Use Lewis & Curry (2018) method on every CMIP5 model that has outputs

$$ECS_{hist} = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

Forster et al. (2013)

Let's do emergent constraint

- Use Lewis & Curry (2018) method on every CMIP5 model that has outputs

CMIP5 sampled like observations

$$ECS_{hist} = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

Forster et al. (2013)

Let's do emergent constraint

- Use Lewis & Curry (2018) method on every CMIP5 model that has outputs

CMIP5 sampled like observations

$$ECS_{hist} = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

2007—2016 = CMIP5 output

Forster et al. (2013)

Let's do emergent constraint

- Use Lewis & Curry (2018) method on every CMIP5 model that has outputs

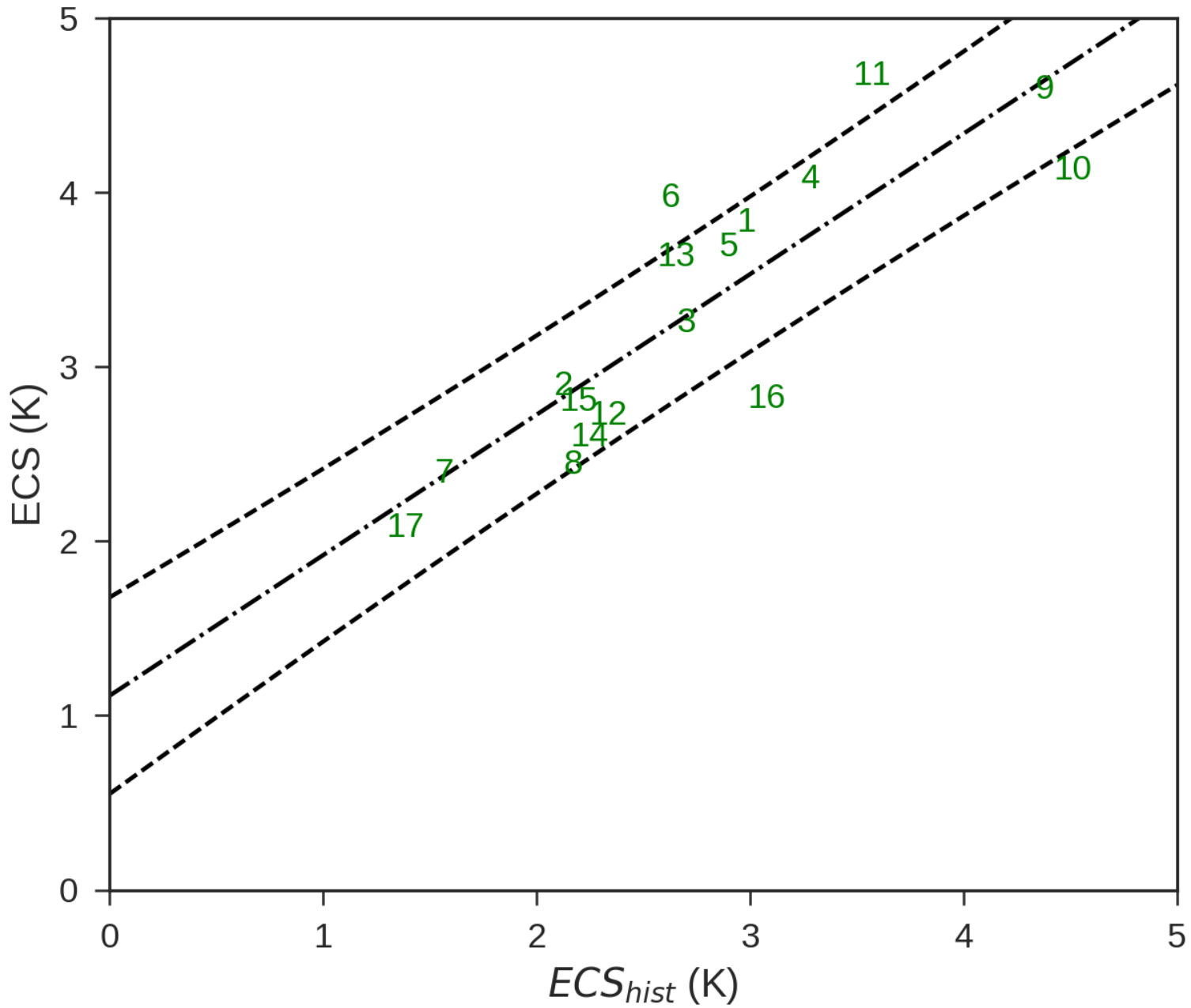
CMIP5 sampled like observations

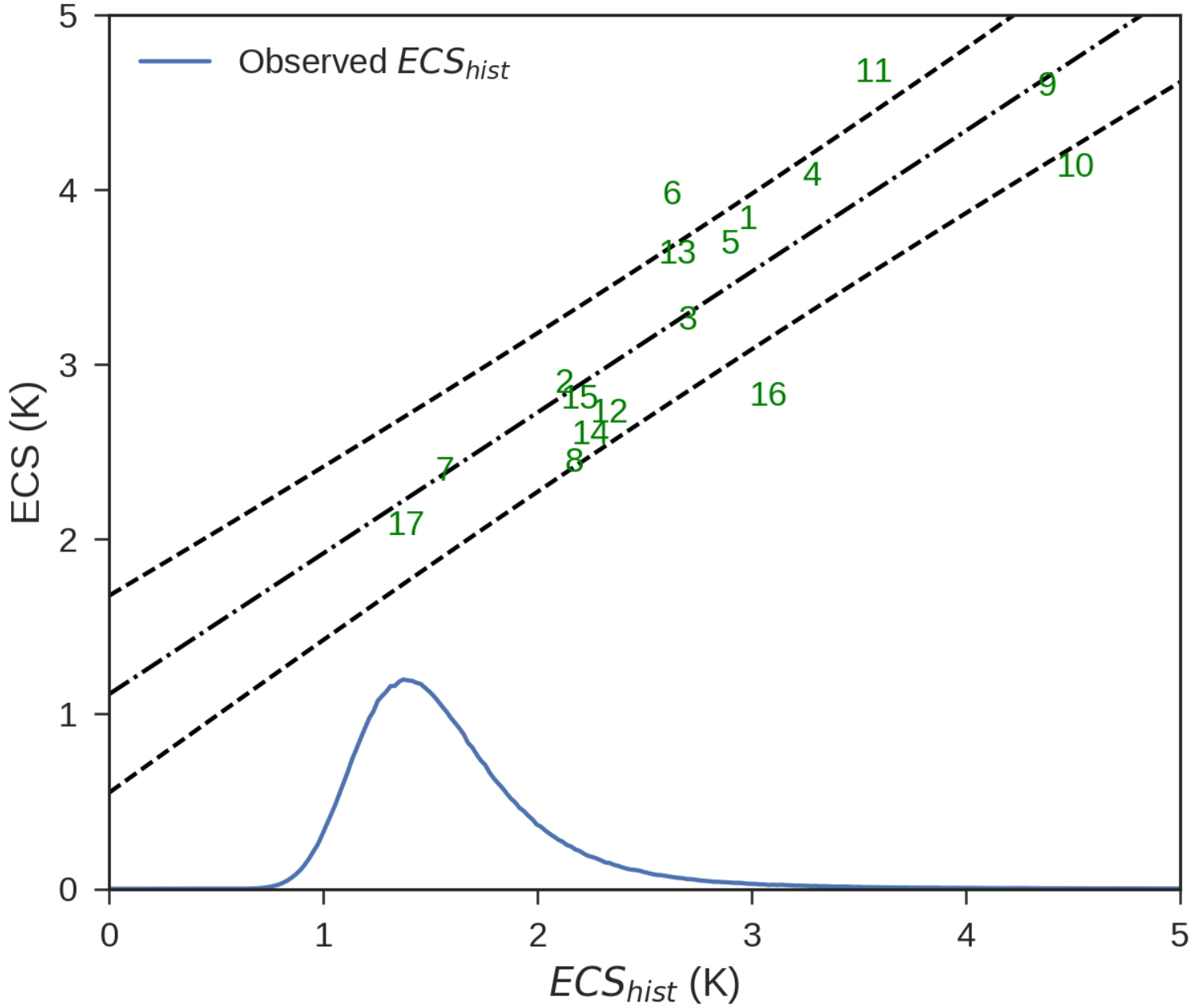
$$ECS_{hist} = \Delta F_{2\times CO2} \frac{\Delta T}{\Delta F - \Delta N}$$

2007—2016 = CMIP5 output

1869—1882 = Scaled CCSM4, like in Lewis & Curry

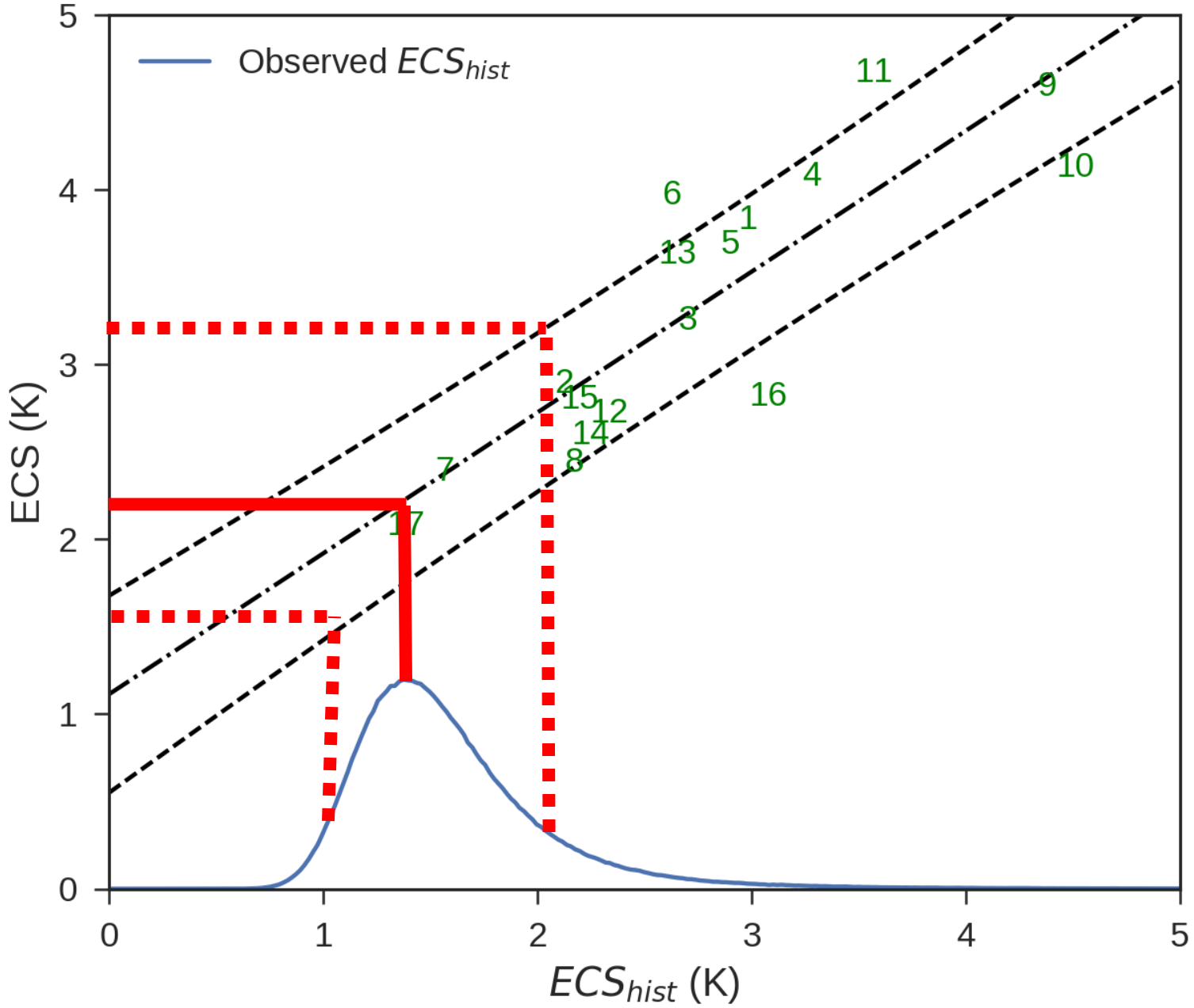
Forster et al. (2013)


ECS (K)
ECS_{hist} (K)
0
1
2
3
4
5
11
9
6
4
10
1
5
13
3
2
15
12
16
14
8
7
17

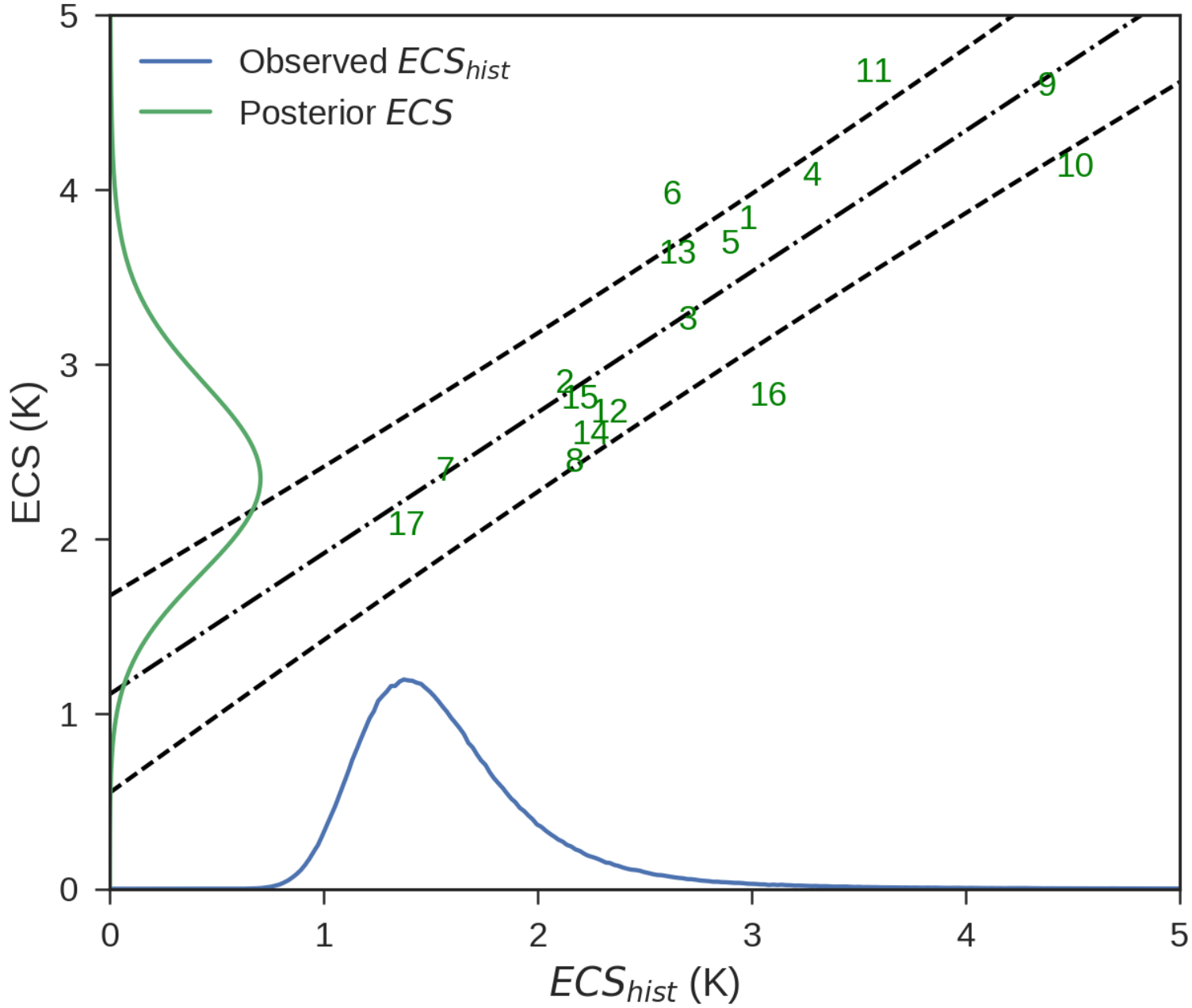


HadCRUT4 ECS_{hist}

1.5 ° (1.1—2.4 °C)



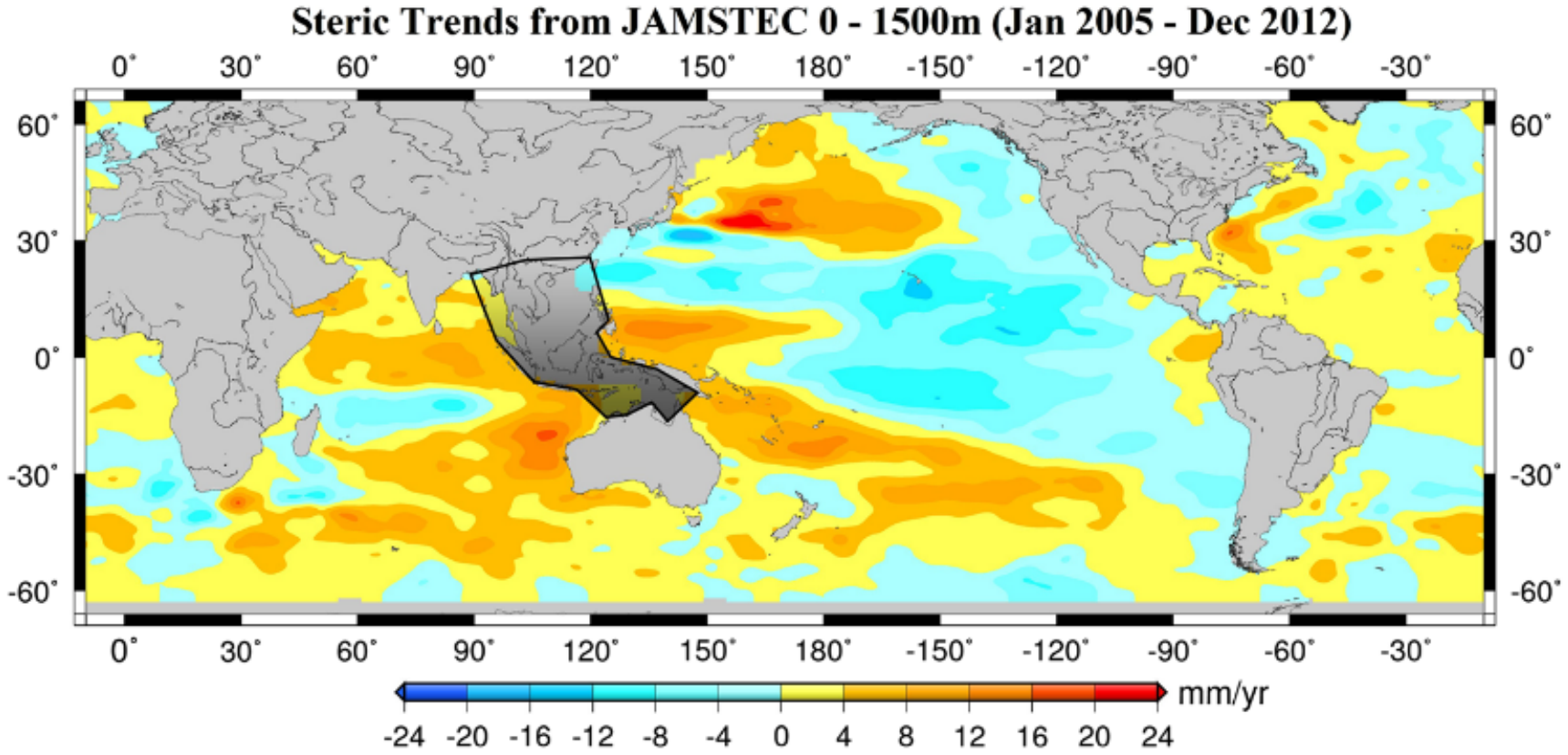
Apply Bayes' theorem with $P(ECS|ECS_{hist})$ from CMIP5 fit



Posterior *ECS* from HadCRUT4:
2.4 °C (1.5—3.4 °C)

(i.e. +60 % from methodology)

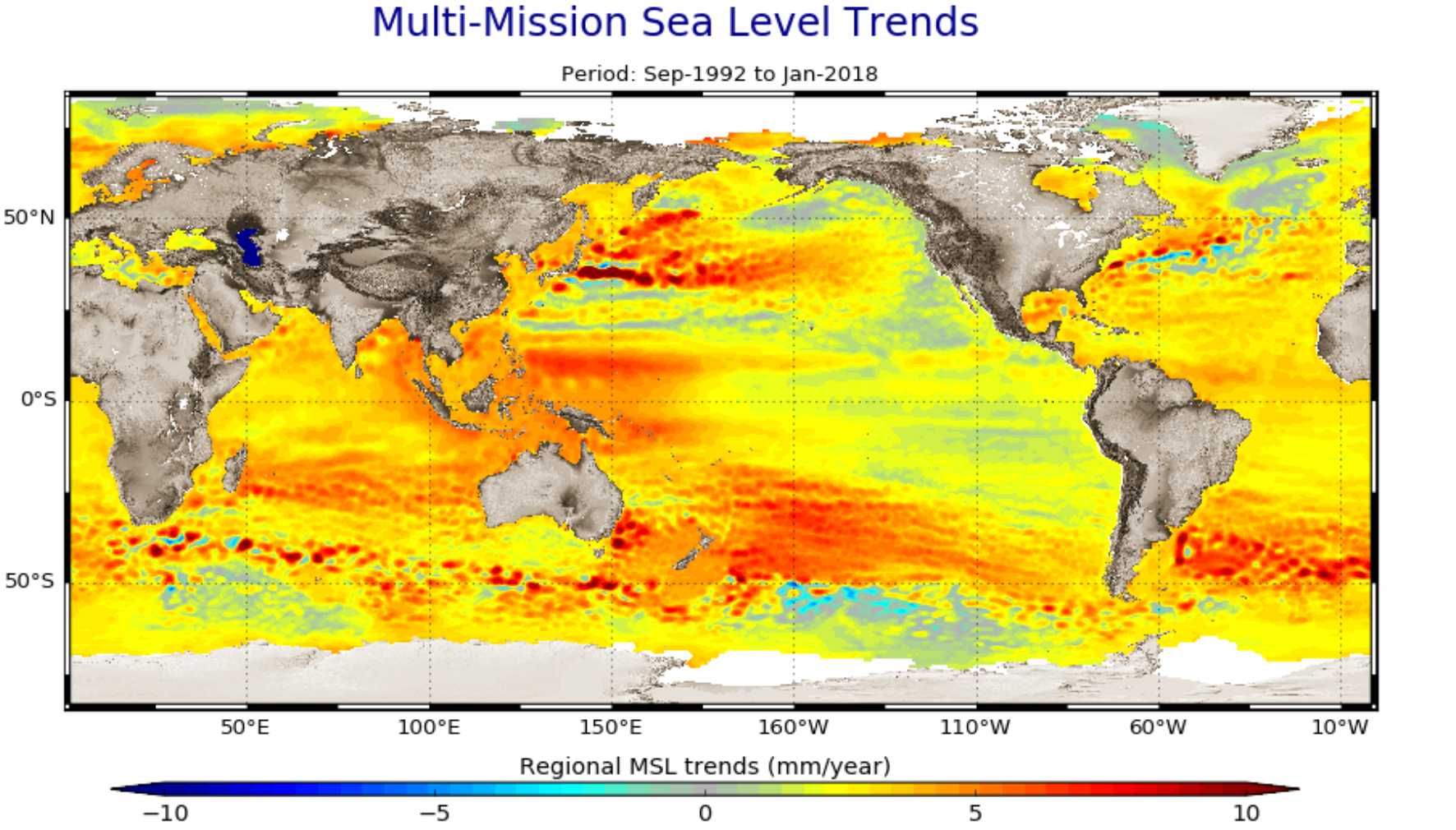
Recent heat imbalance from Argo floats



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

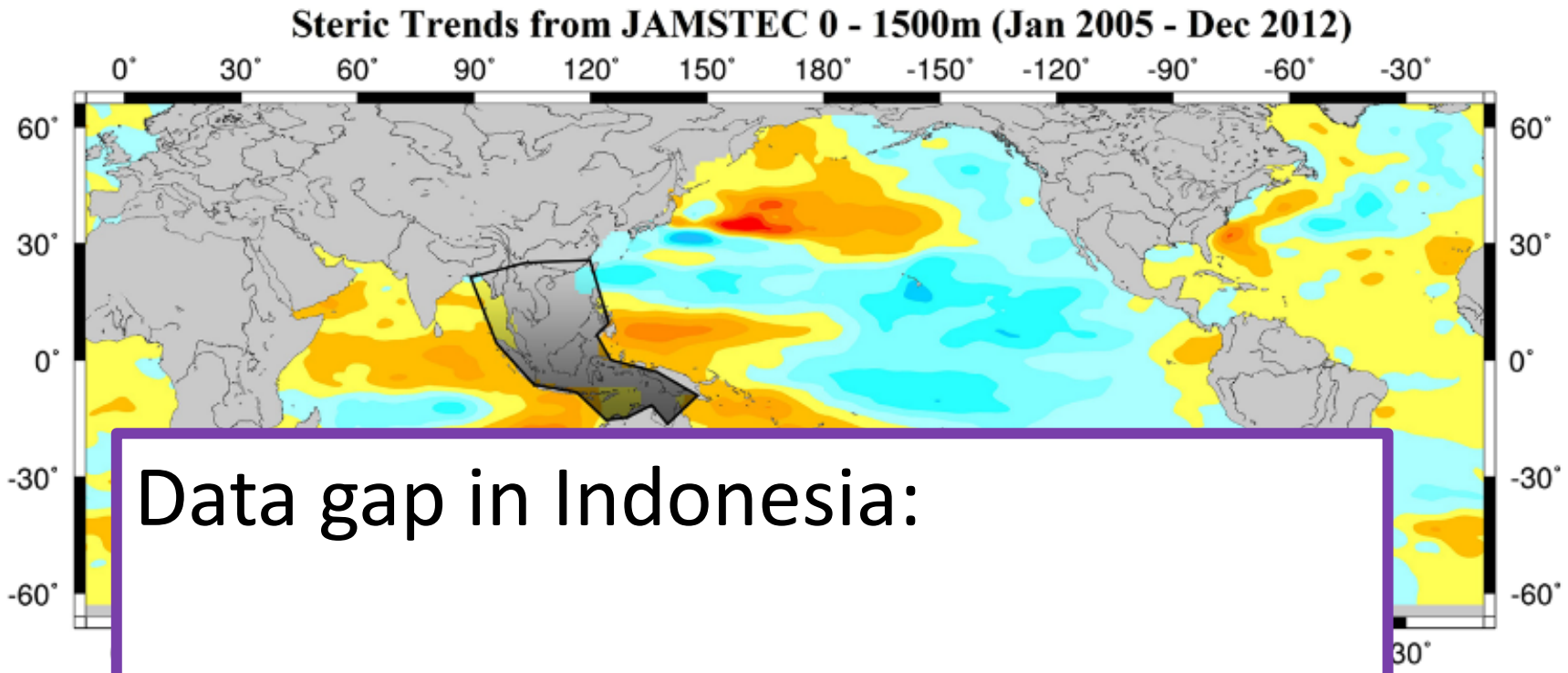
Fig. 10 Steric trend map based on Jamstec data over January 2005–December 2012 showing the Argo data gap in the Indonesian region and the contours (*black line*) of the area considered in this study to estimate—using the ORAS4 reanalysis—its contribution to the global mean steric trend

Sea level trends from altimetry ‘91—18



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

Recent heat imbalance from Argo floats



$$ECS \propto \frac{\Delta T}{\Delta F - \Delta N}$$

Data gap in Indonesia:

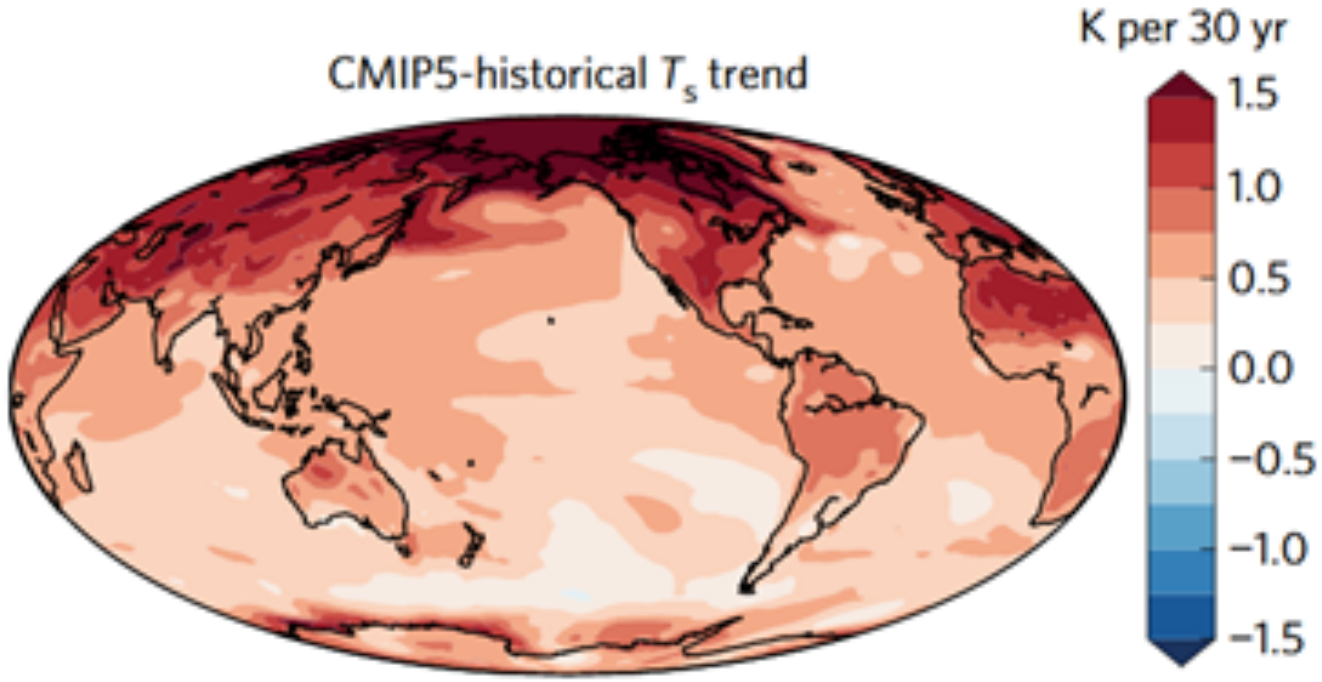
Gravimetry + altimetry suggests heat uptake here worth ~0.13 W m^{-2} globally

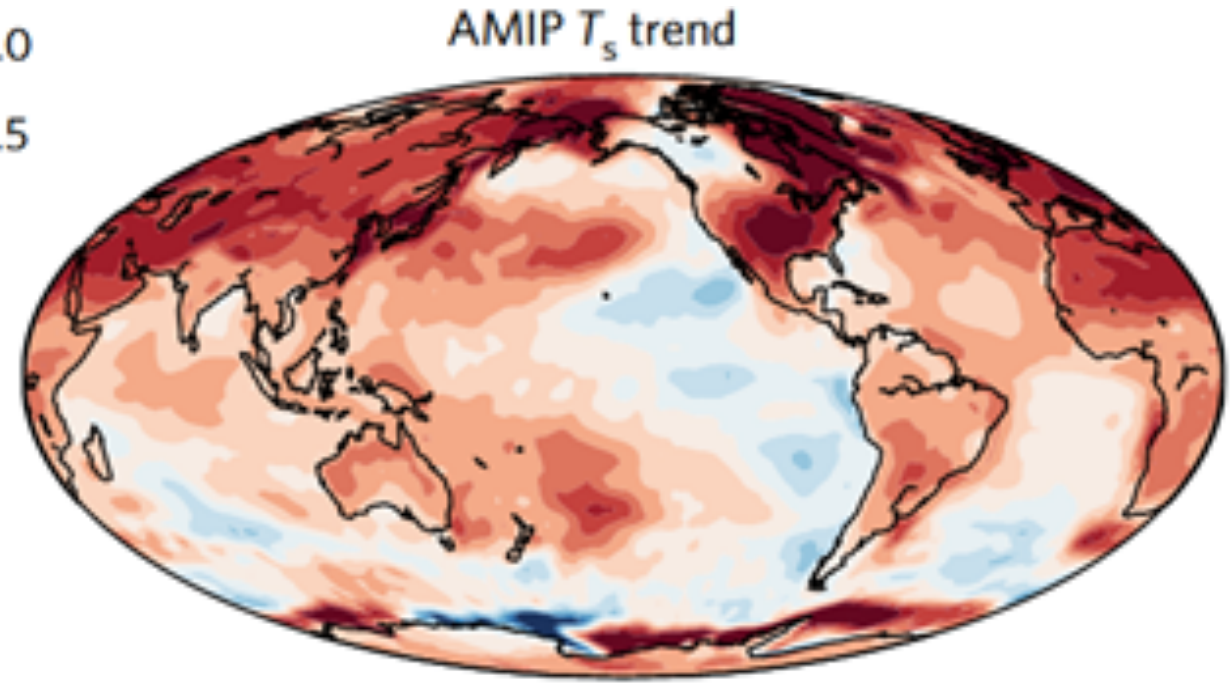
Fig. 10 gap in th using th ...he Argo data ...o estimate—

Dieng et al. (2015)

1980—2005

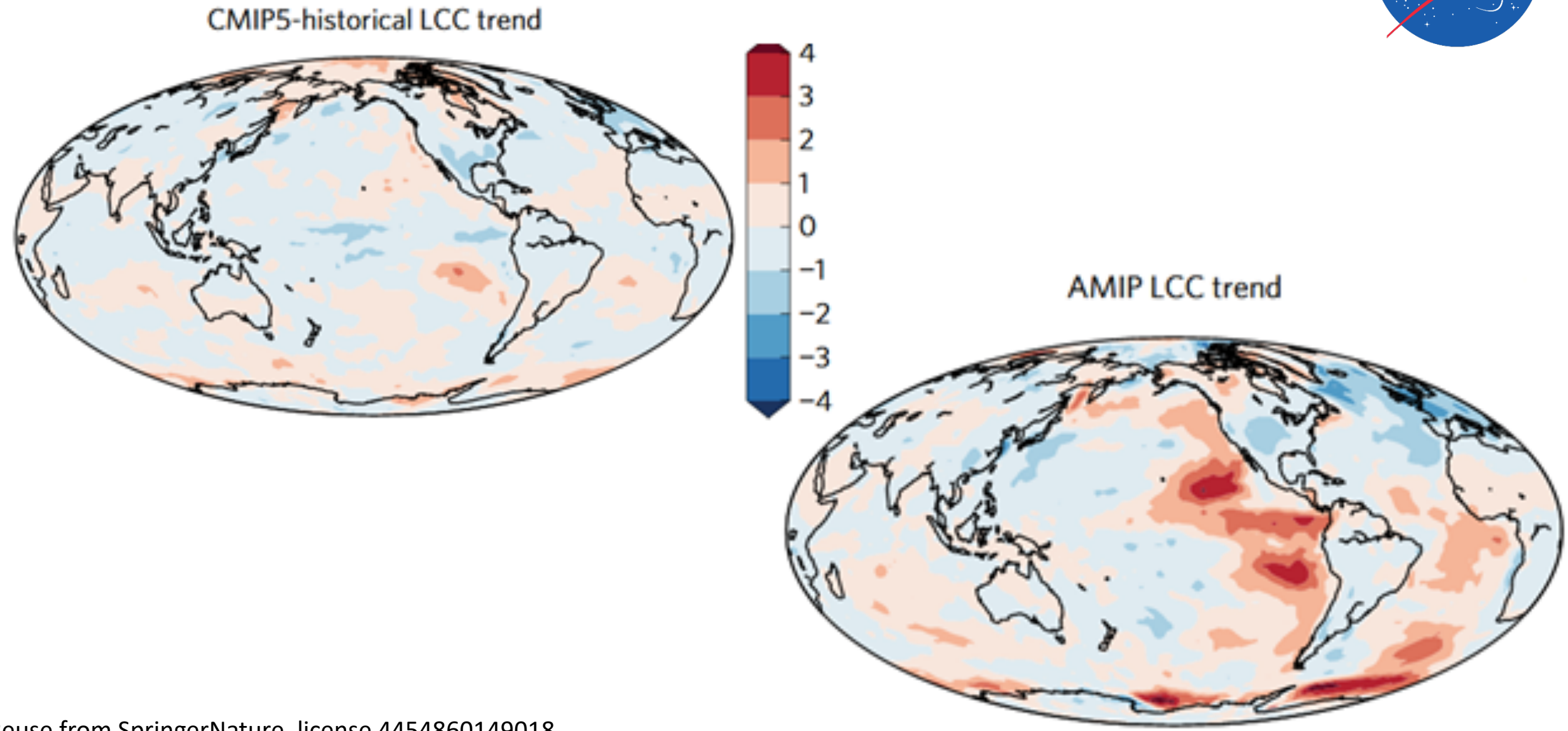
Zhou, Zelinka & Klein http://dx.doi.org/10.1038/ngeo2828





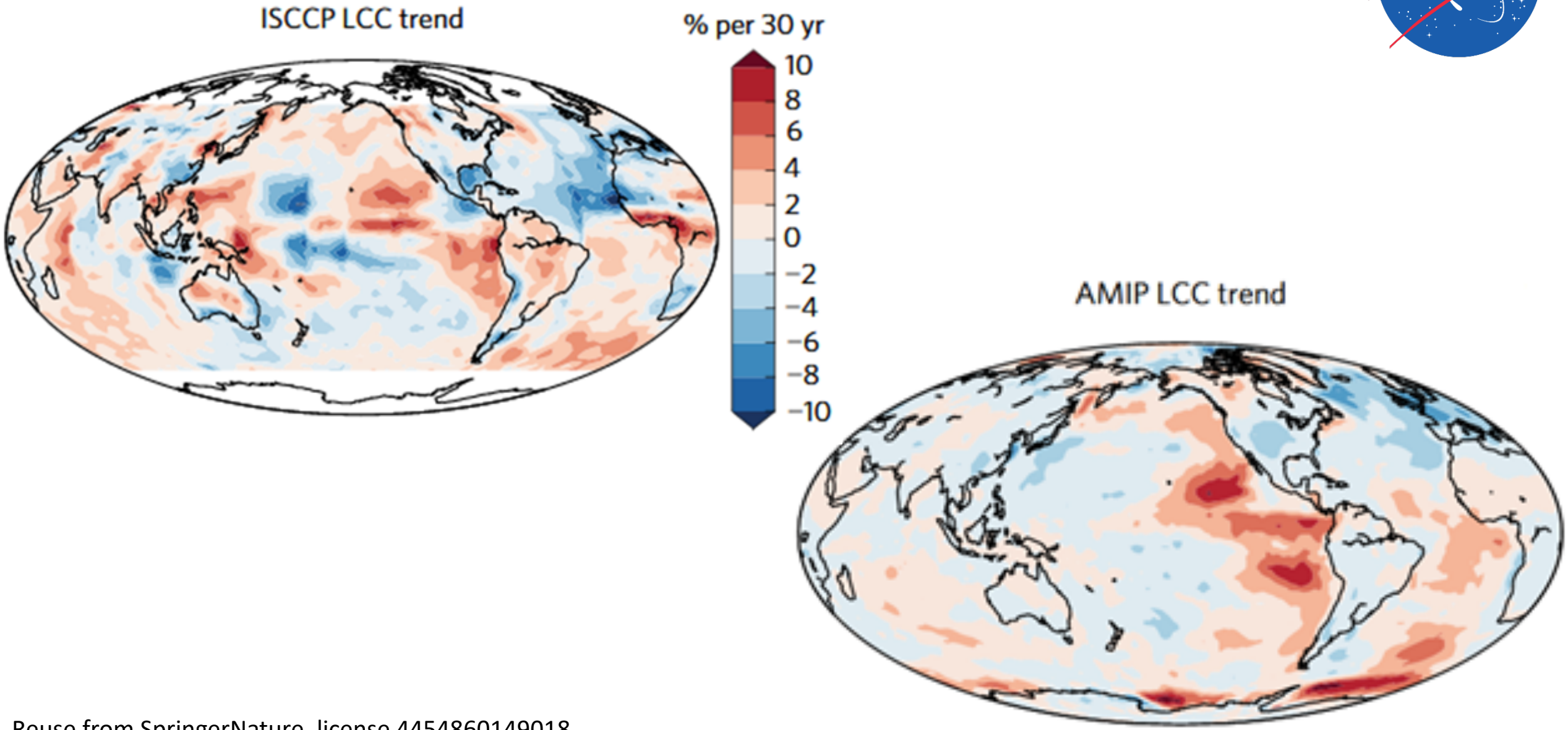
1980—2005

Zhou, Zelinka & Klein http://dx.doi.org/10.1038/ngeo2828

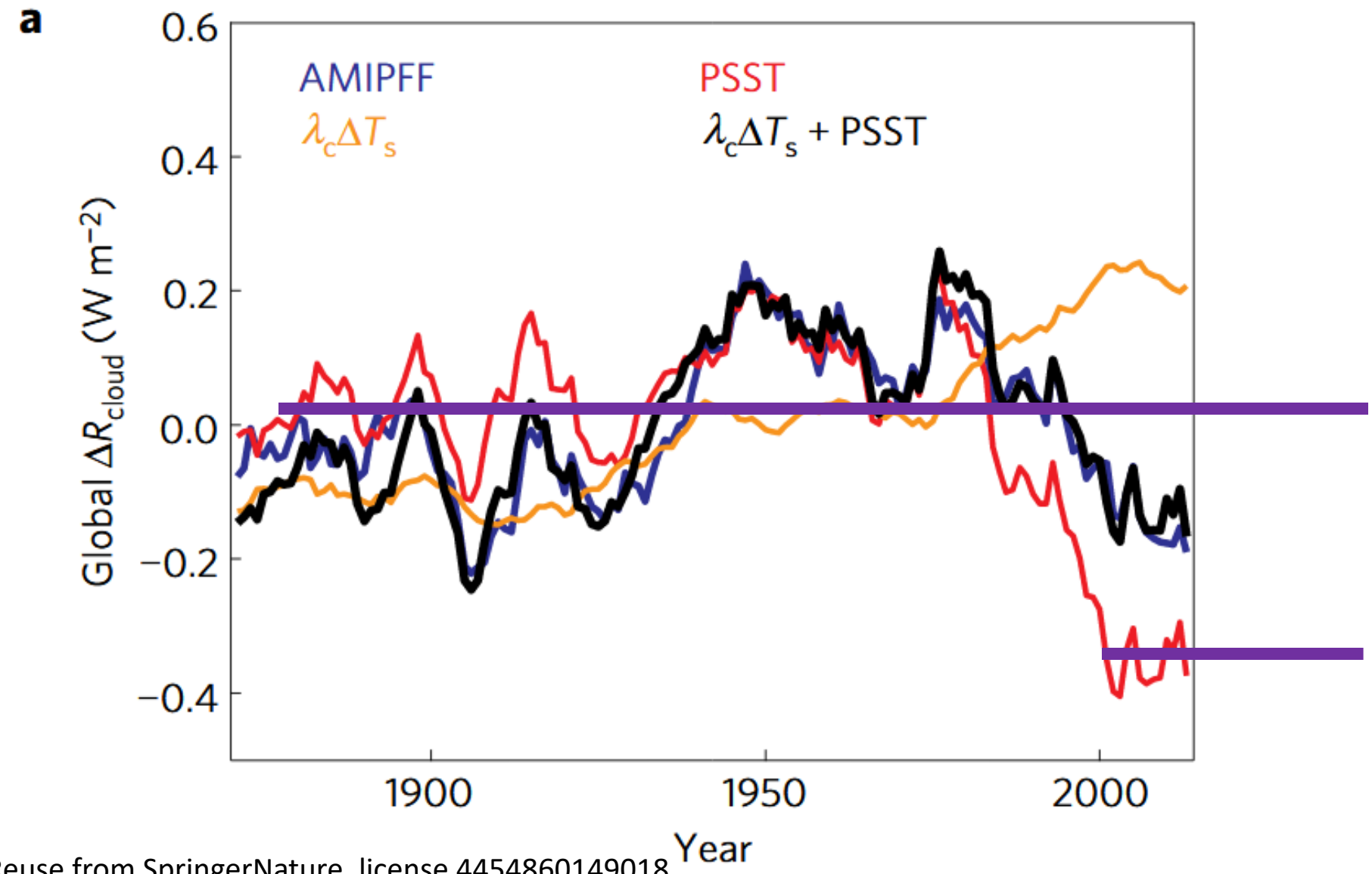


1980—2005

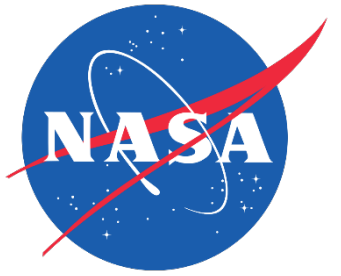
Zhou, Zelinka & Klein http://dx.doi.org/10.1038/ngeo2828



RED is “pattern difference from average”



ΔN due to cloud pattern >0.35 W m^{-2}

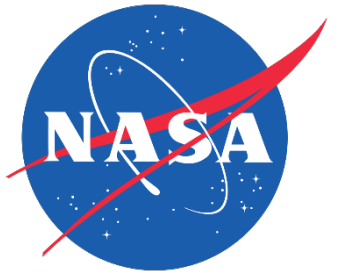


- Lewis & Curry ECS_{hist} = 1.5 °C maps to ECS_{true} = 2.4 °C
- We must:
    1) Make sure heat uptake data aren't biased
    2) Work out cloud pattern effects
    3) Improve ΔF comparison

Dieng or Zhou ΔN effects change ECS_{true} to 2.5—3.0 °C

ΔF could be bigger shift.

Conclusions



- When you see an energy budget study on ECS, look for three things:
  - How do they select their data and time periods?
  - Do they assume λ = constant?
  - Do they test their *exact calculation* on climate models and check if it works when we know answer?
- Doing this for Lewis & Curry suggests 2.4 °C+, not 1.5 °C