

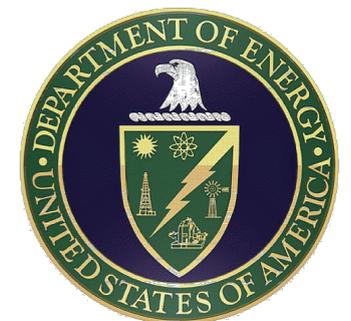
# Building emulators across model hierarchies

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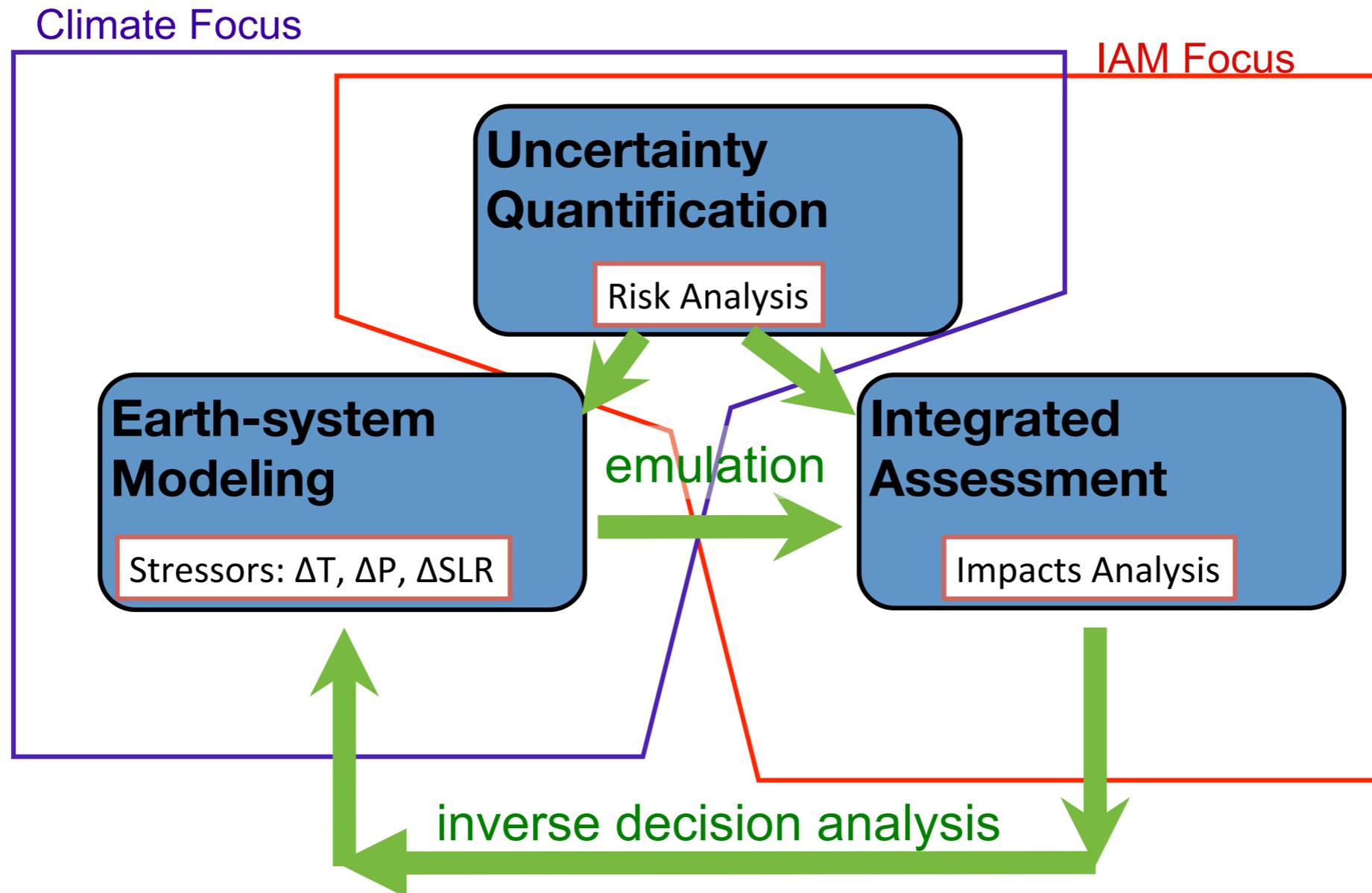
**Chris E Forest, Alex Libardoni, Ashley Warner, Randy Miller, Klaus Keller**  
The Pennsylvania State University

PIAMDDI Project Meeting  
Bechtel Conference Center  
Stanford University  
December 13, 2013

Primary Support  
from: DOE



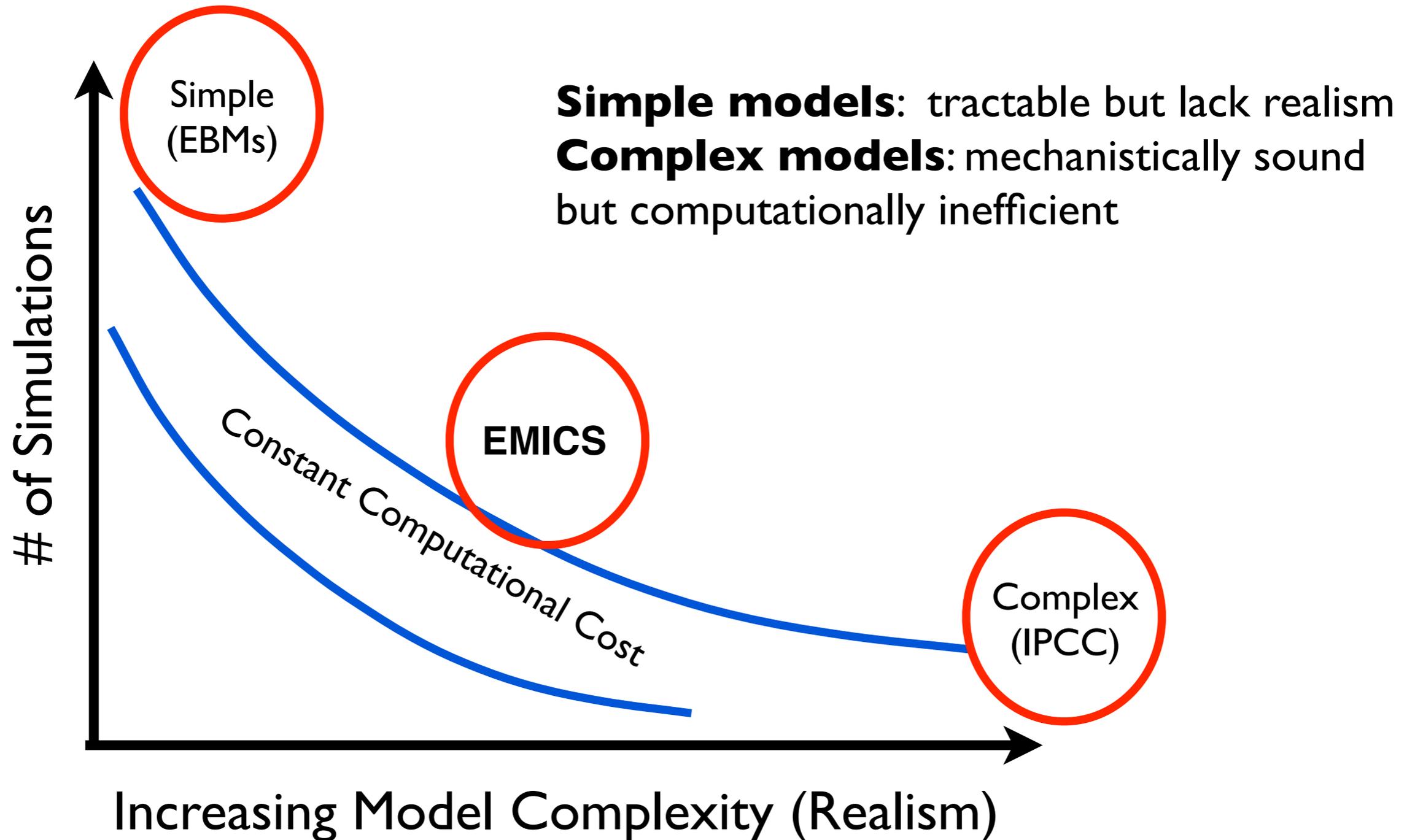
# Model emulators provide an important link between Earth-system modeling and Integrated Assessment, Risk Analysis and Impacts Analysis



## Questions:

1. What are emulators? What drives their design and efficacy?
2. How do we test them?
3. How do the emulator choices affect decision-relevant metrics and impacts?

# Tradeoff between model realism and computational tractability



- Integrated Assessment requires probabilistic predictions with full treatment of uncertainty
- How do we achieve this given the tradeoffs between realism and tractability?

# Emulators for Integrated Assessment (Jake Jacoby's Horses for Courses)

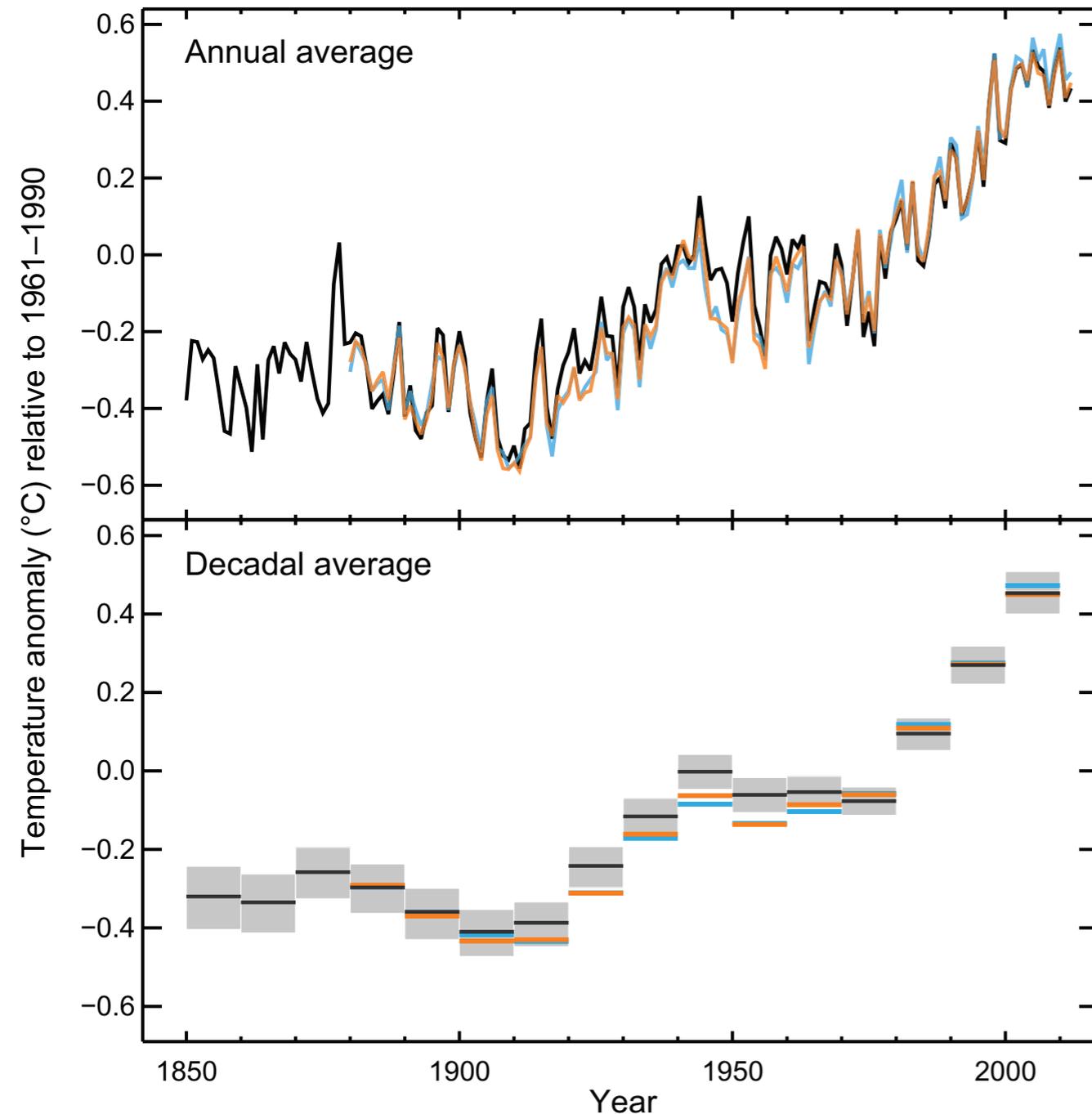
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- **Energy Balance-Carbon Balance Models**
  - **Basic model for Climate System Response; Few knobs**
- **Earth-system Models of Intermediate Complexity**
  - **Higher complexity with critical feedbacks in climate system; Many knobs**

# Reminder Question: What are we trying to emulate?

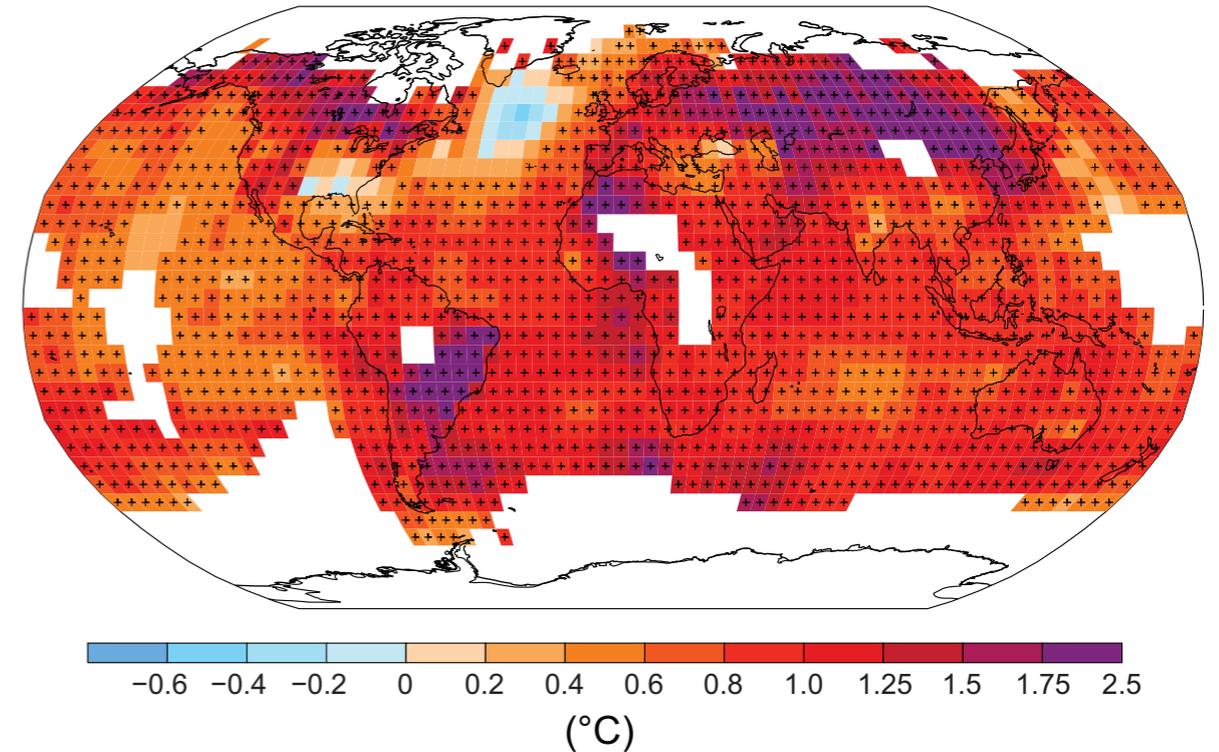
Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012

(a)



(b)

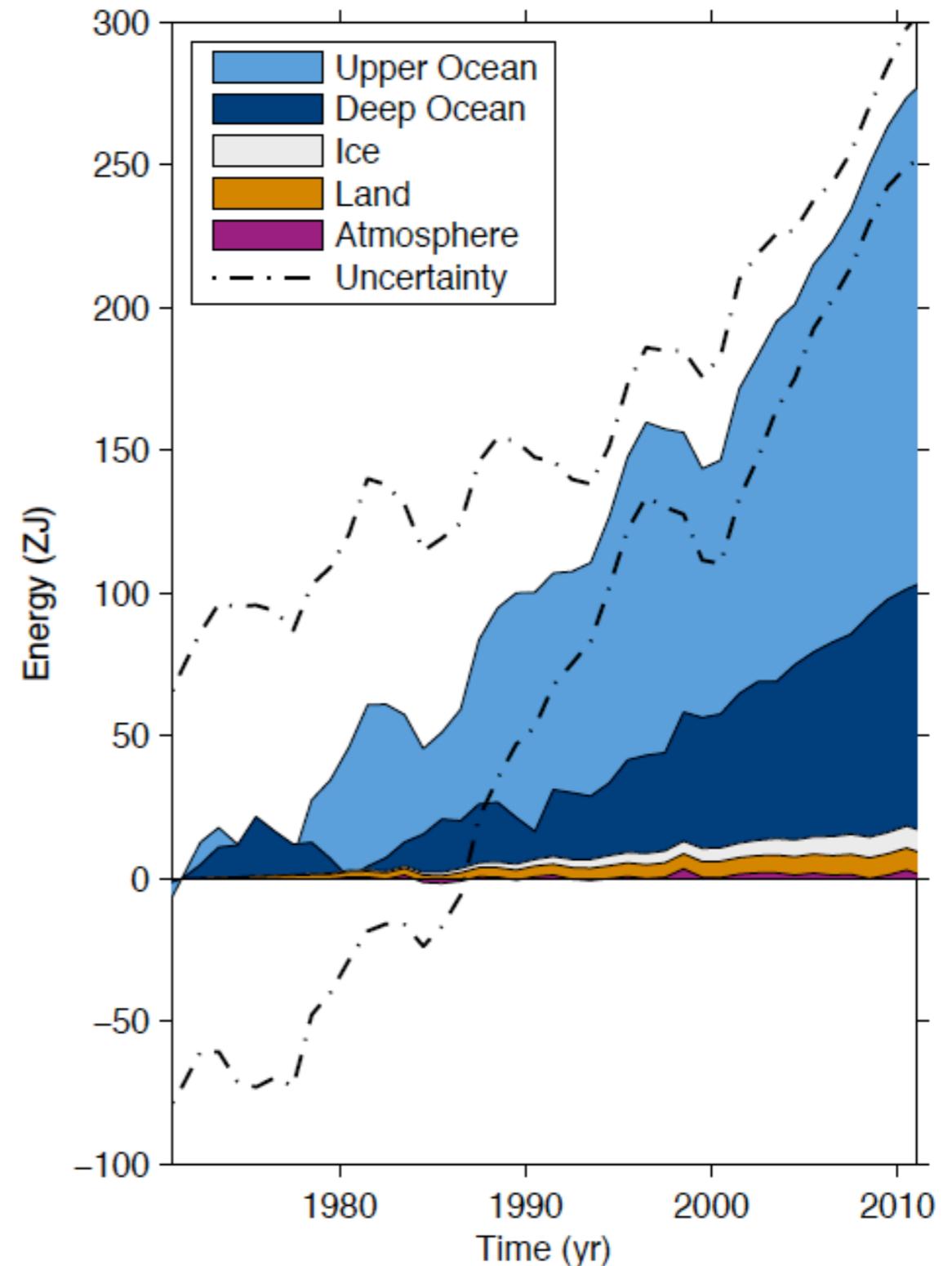
Observed change in surface temperature 1901–2012



**Note: high latitude warming  
& land-sea contrast**

# Ocean Heat Content changes based on Global Energy Budget (IPCC AR5 Box 3.1, Figure 1)

- Accumulated Energy Increase since 1970
- >90% of energy increase in ocean heat content
- ZJ =  $10^{21}$  Joules



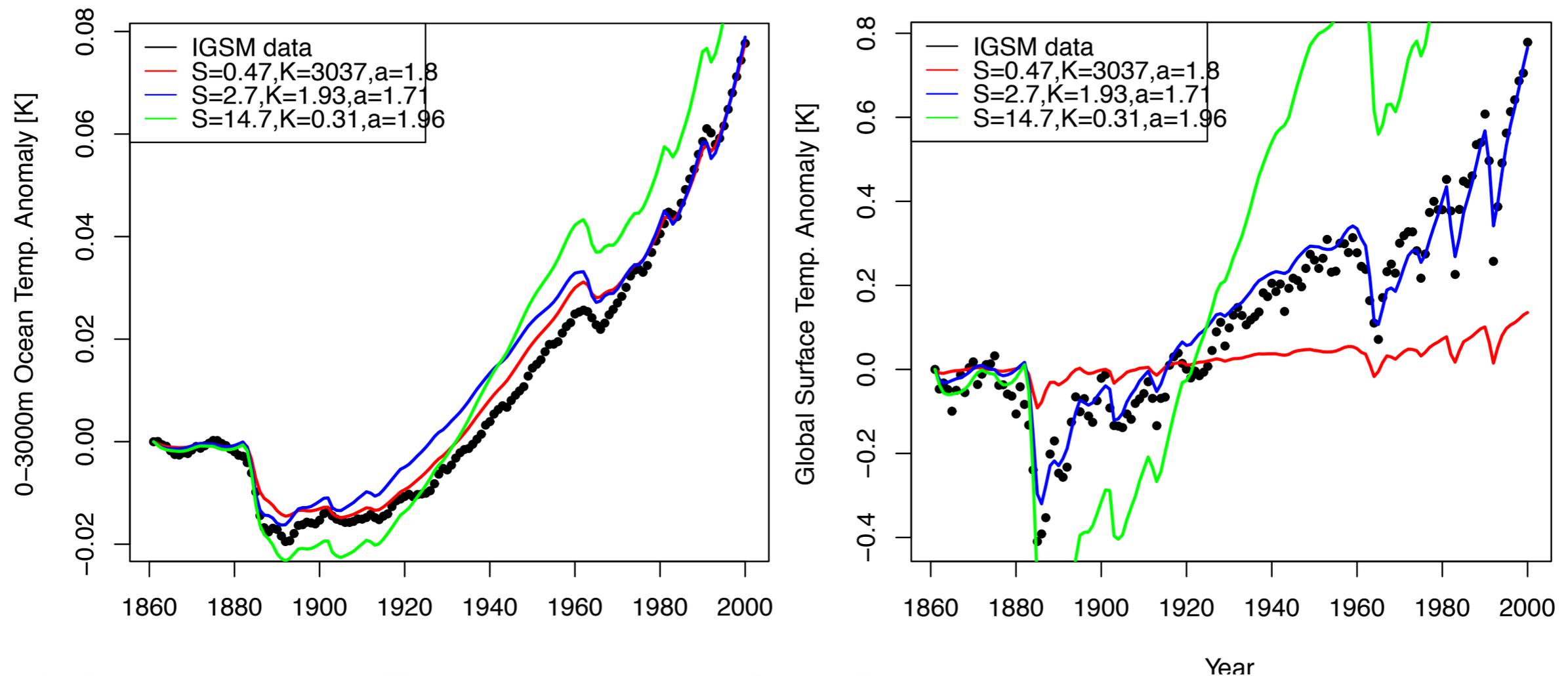
# Emulators for Integrated Assessment (Jake Jacoby's Horses for Courses)

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- **Statistical emulators**
  - **Gaussian Process Models; Hierarchical Bayesian**
- **Physically based Emulators**
  - **Simple Nonlinear EArth SYstem (SNEASY)**
  - **GLISTEN Ice Sheet Emulator (see Keller's talk later)**
- **Regional Climate emulation**
  - **Pattern Scaling (Static Response to Global Mean)**
  - **Beyond Pattern Scaling: Emulation of Atm. Dynamics (Account for variability in patterns on top of global pattern response; Teleconnections)**

# Emulation of an EMIC using an EBM: Trials and tribulations

- Using SNEASY (Urban and Keller, 2010) to emulate the MIT IGSM2.2 (Sokolov et al. 2005) with  $S = 3.0K$ ,  $K=4. \text{ cm}^2/\text{s}$ ,  $a = 1.7$



**Red: Deep Ocean Temperature only (AR1)**

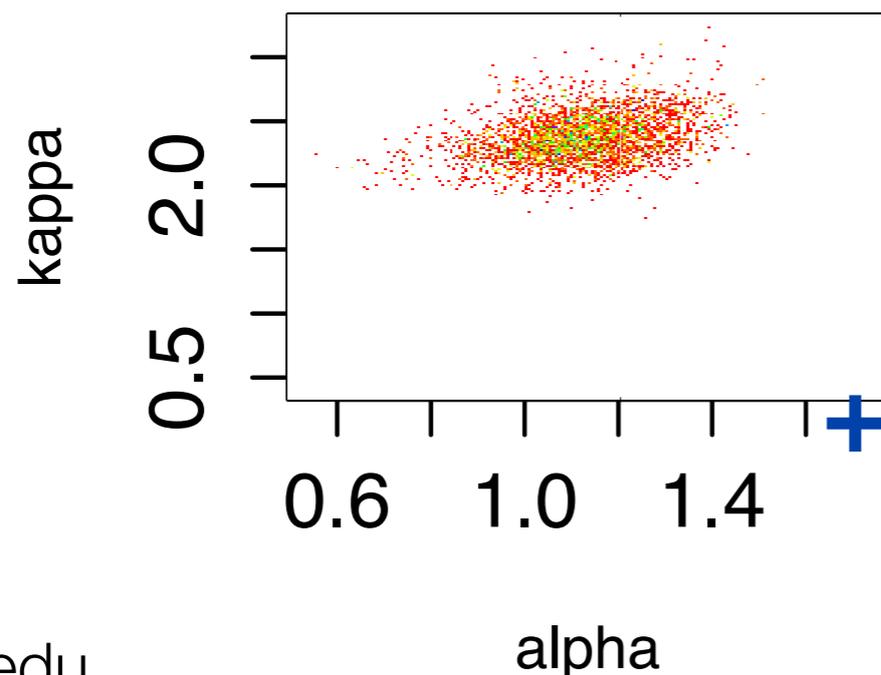
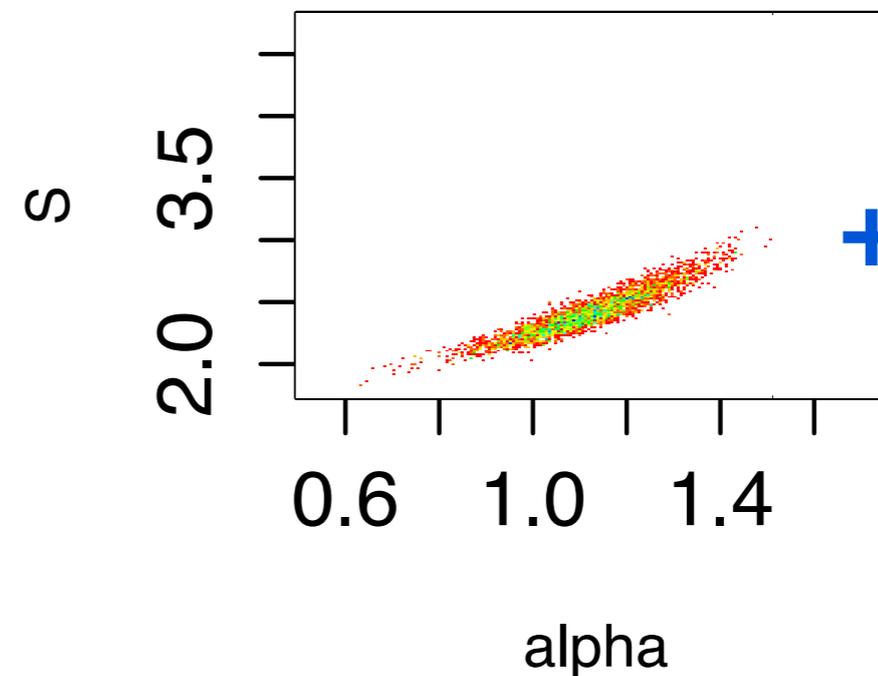
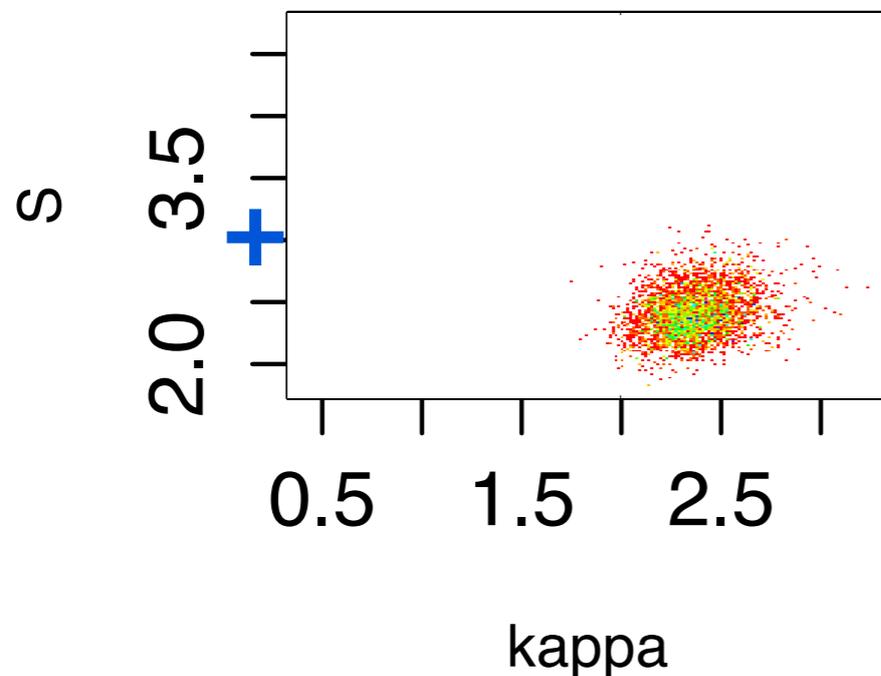
**Green: Deep Ocean Temperature only (AR0)**

**Blue: Deep Ocean and Surface Temperature (AR1)**

Year

Based on: Forest &  
Warner (in prep)

# Emulation gone bad: Wrong Volcanic Forcing SNEASY parameters estimated from IGSM2.2 run



**MIT IGSM (+)**

**S = 3.0 K**

**Alpha = 1.7**

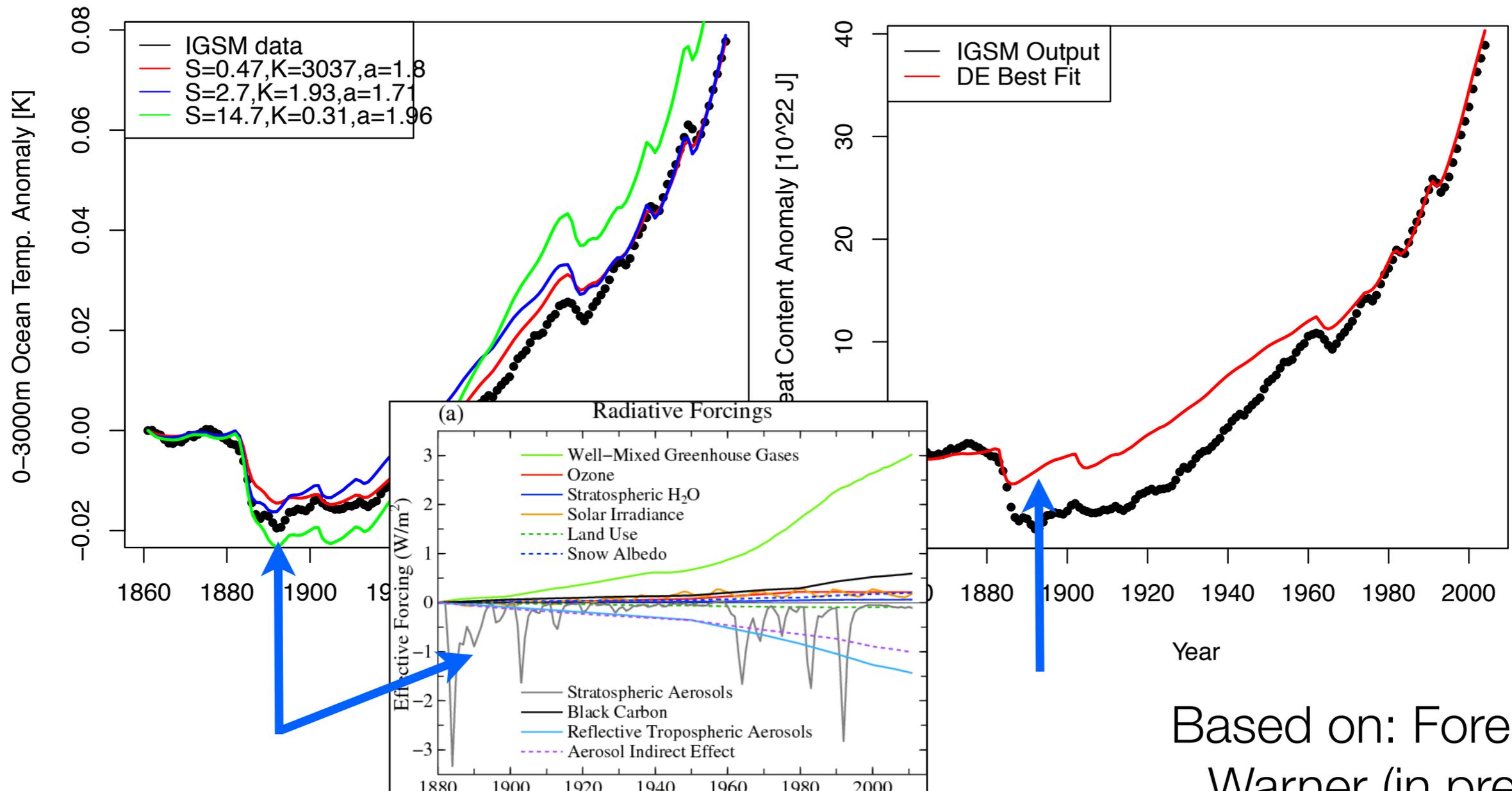
**kappa = ??**

Based on: Forest & Warner (in prep)

# Emulation gone bad: Wrong Volcanic Forcing SNEASY parameters estimated from IGSM2.2 run

**Left: Correct Volcanic forcing for MIT IGSM2.2 run**

**Right: Volcanic forcing events missing in 1880-1920 period**



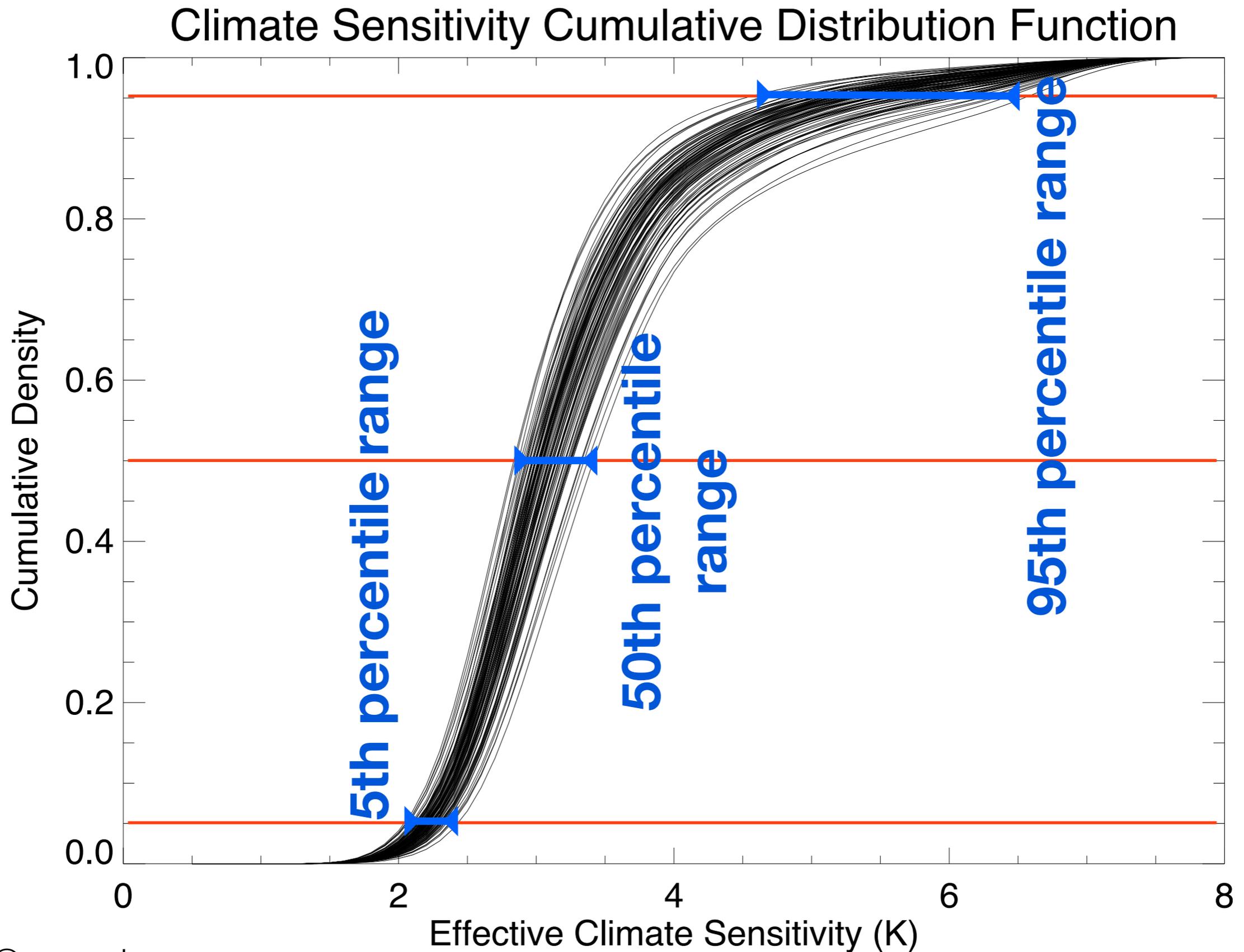
Based on: Forest & Warner (in prep)

# Results testing impact of Uncertainty in Observations

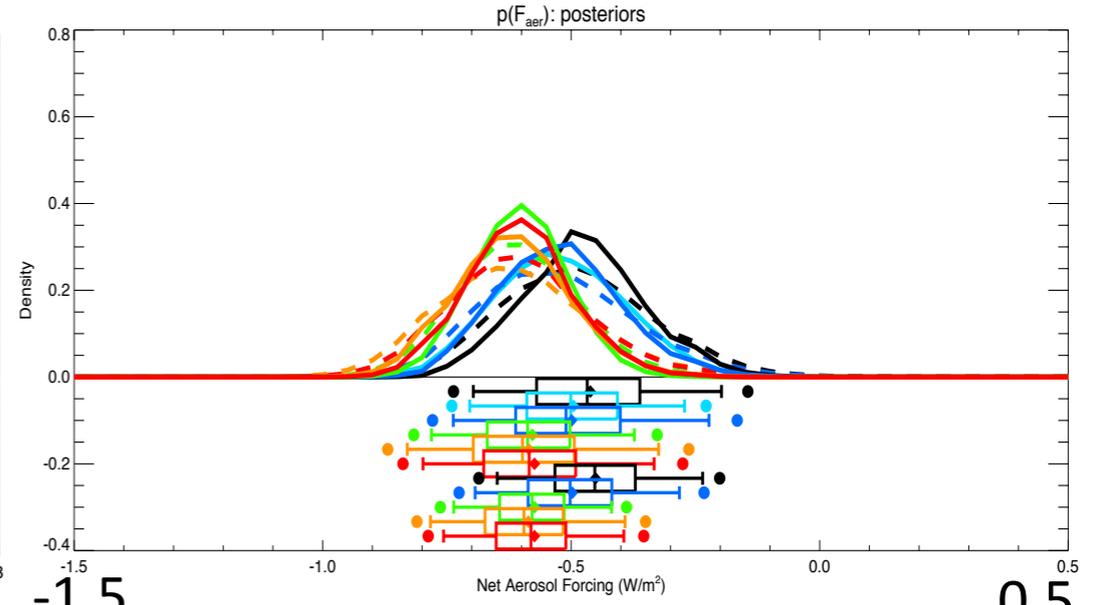
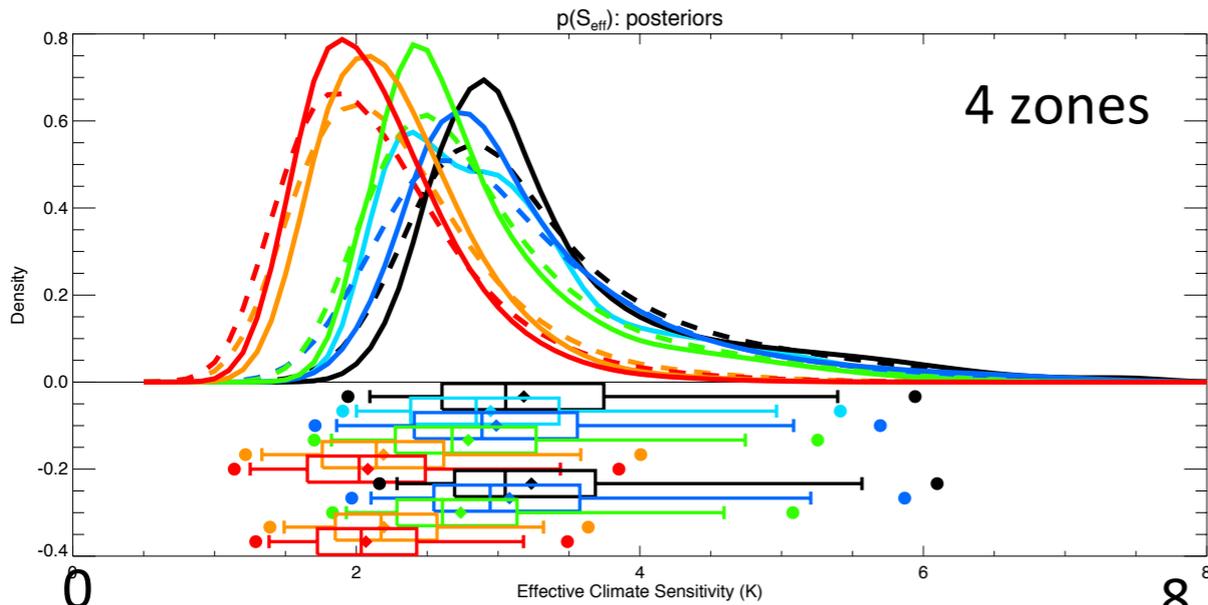
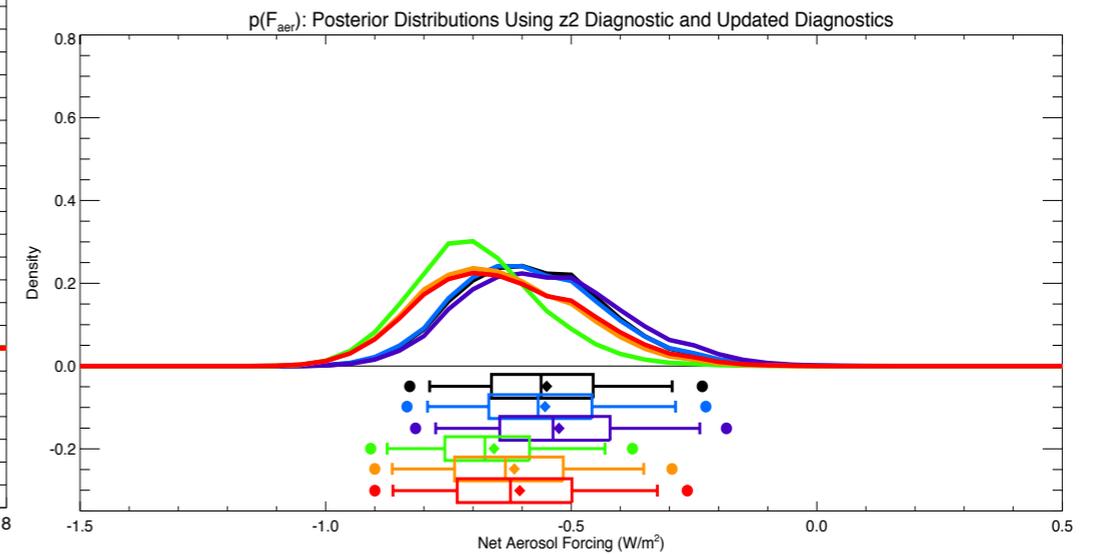
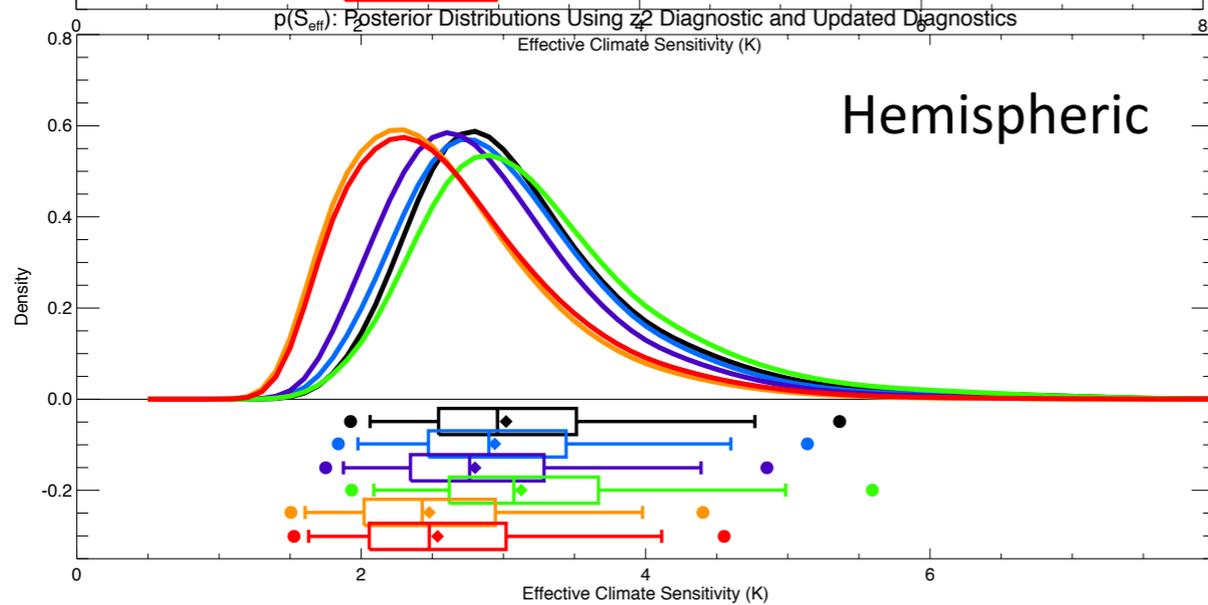
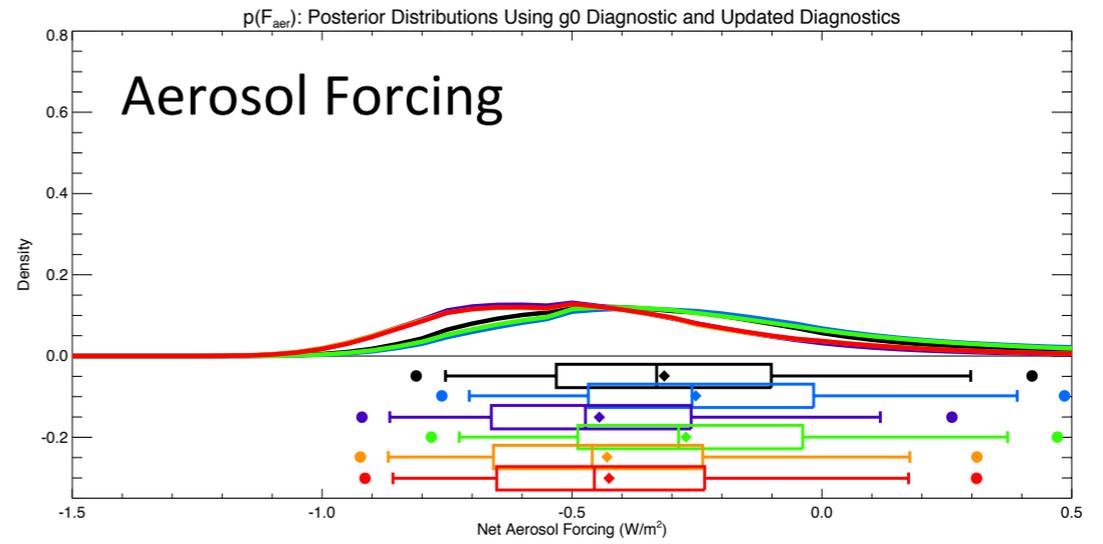
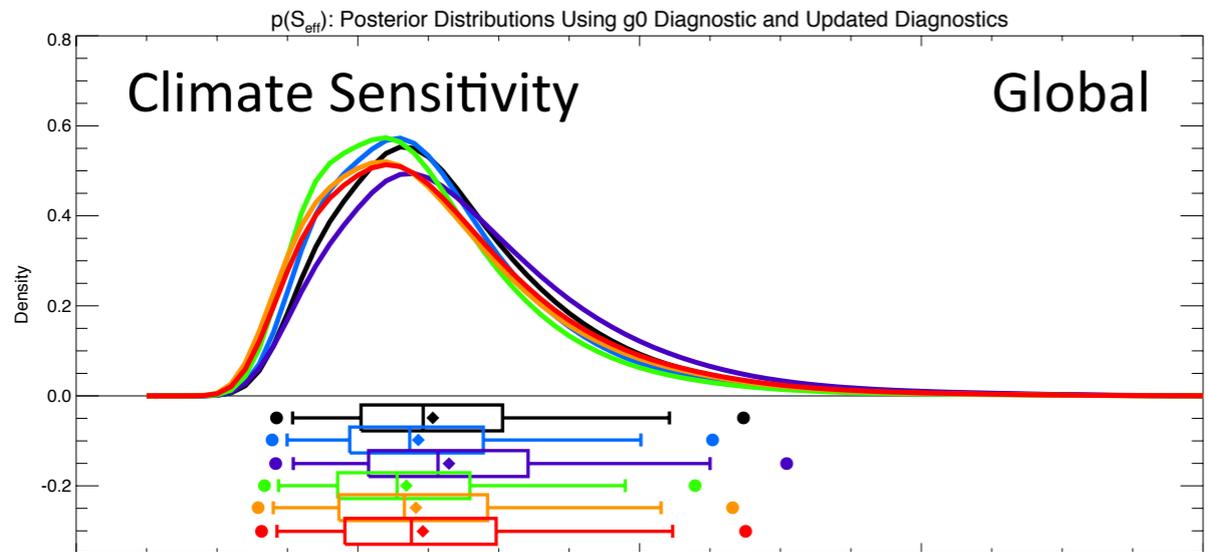
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- Surface Temperature
  - Add HadCRUT4 dataset into the analysis (100 member ensemble)
  - **Shift diagnostic period** to include an additional decade of data (**1945-2004**)
- Ocean Heat Content
  - New data sources (Domingues et al., 2008 and Levitus et al. 2009)
  - **Shift diagnostic period to 1968-2003/4 to coincide with the use of ARGO float data and observational/model data limits**
  - Add warming trend in the 700-3000 m layer of  $1.9 \times 10^{21}$  J/yr inferred by Domingues et al. (2008) and consistent with IPCC Global Energy Budget
- Upper Air Temperature
  - **HadAT2 data replaced HadRT2 up to 2004.**

# CDF Uncertainty based on HadCRUT4 ensemble distribution

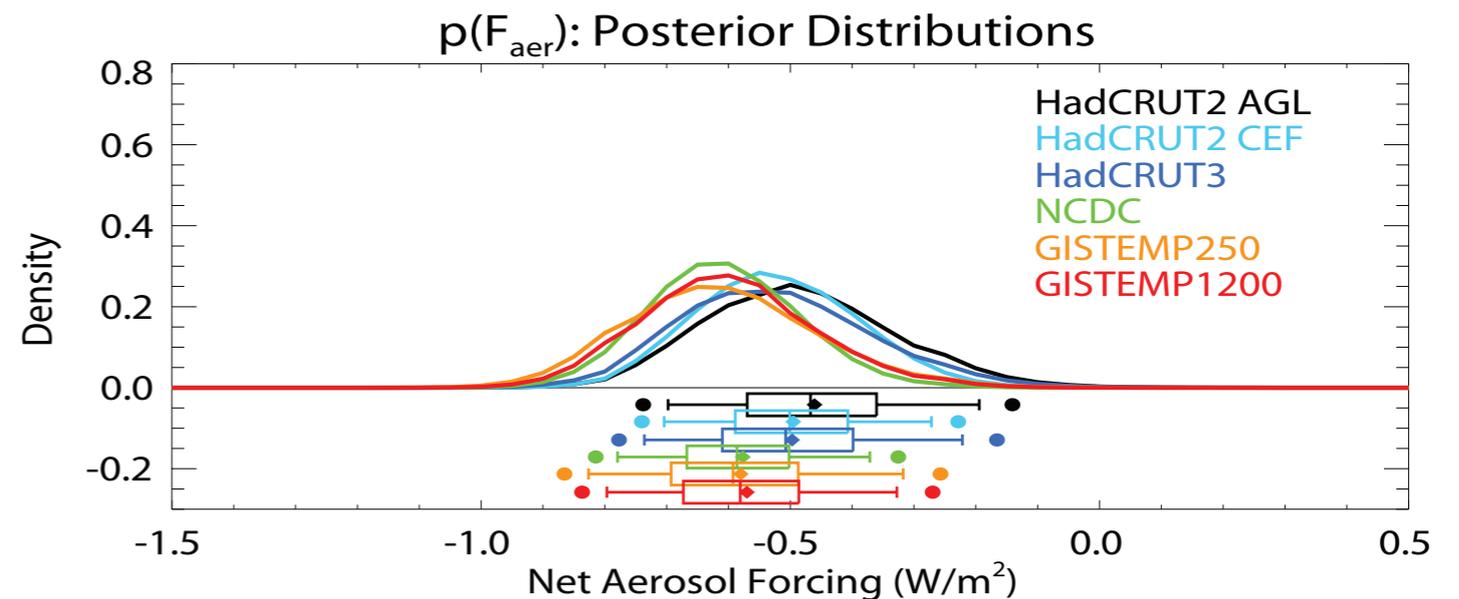
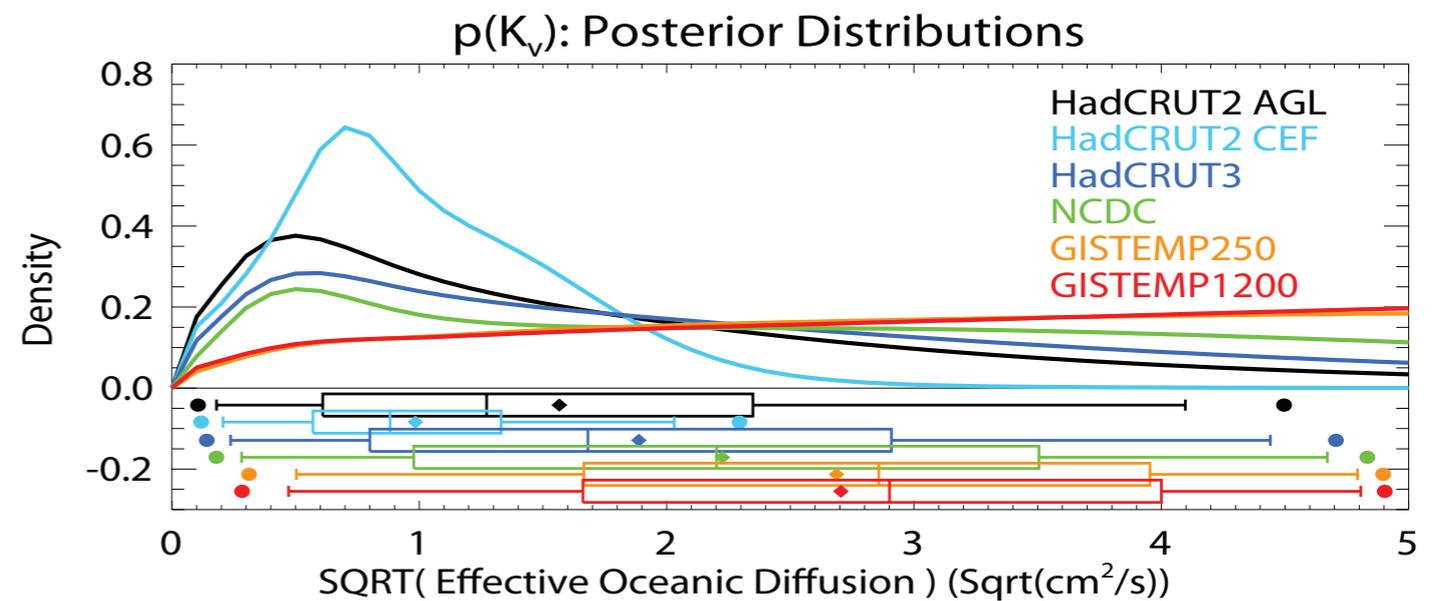
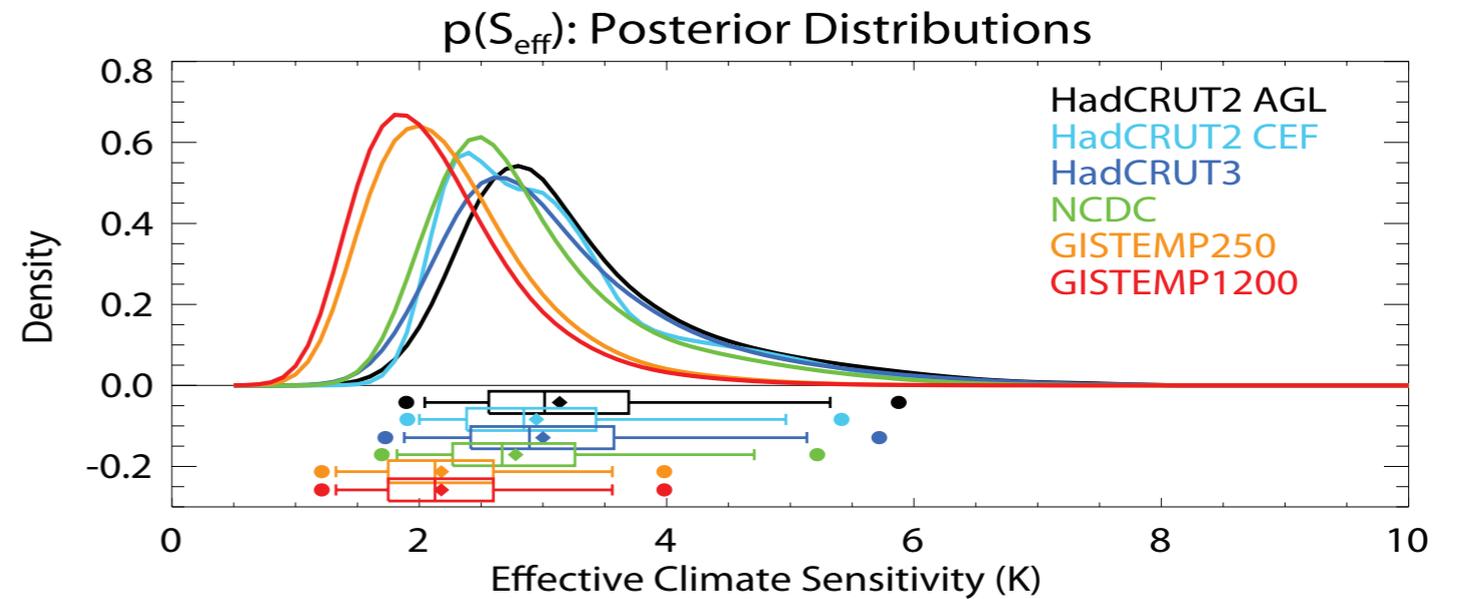


# Adding Spatial Information Matters



# Impact of Observational Uncertainty

- Libardoni and Forest (2011,2013)
- Based on MIT Integrated Global System Model climate model. (EMIC)
- Constraints based on surface temperature, deep ocean heat content, and upper air temperature observations in the 20th century.



# Summary

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# Summary

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- Where do emulators fit into the Integrated Assessment framework?

# Summary

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  - Front and center!

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---

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# Summary

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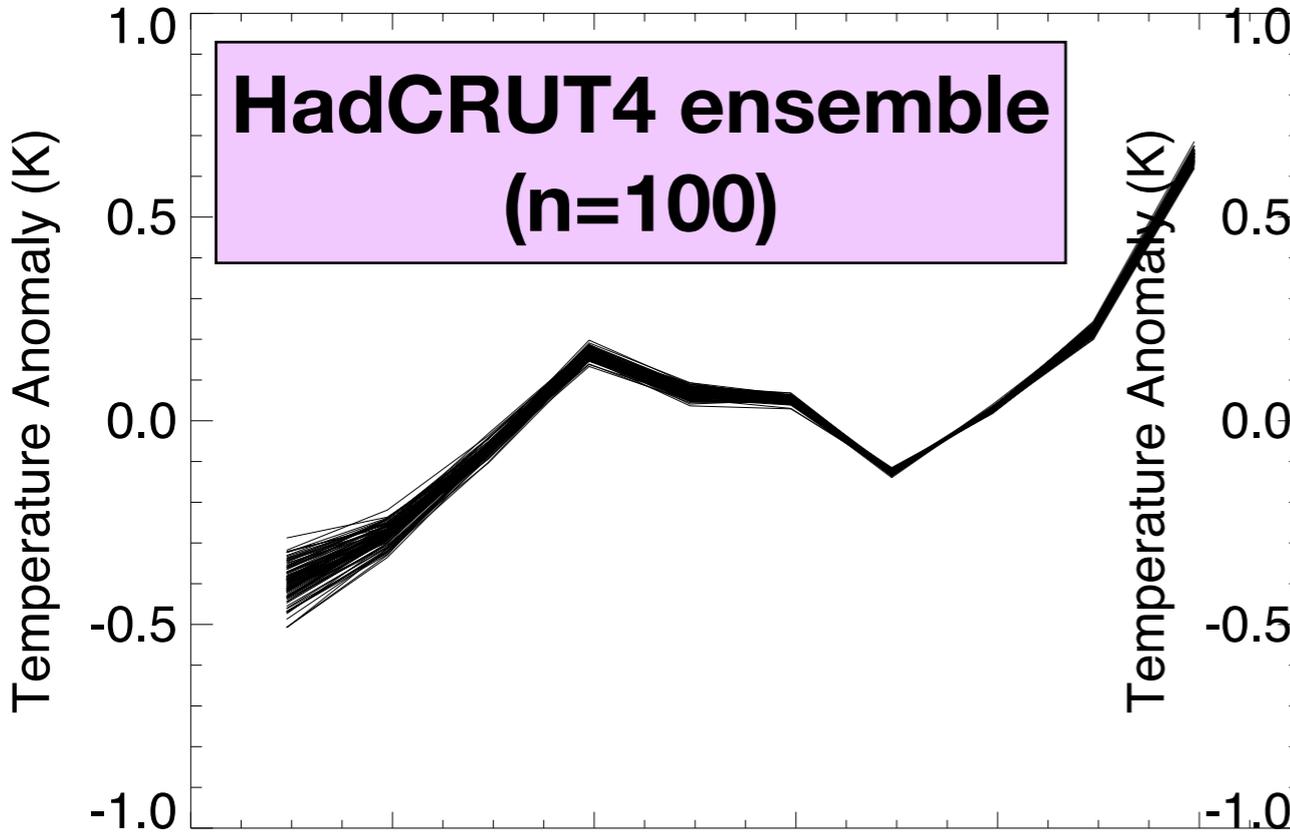
- Where do emulators fit into the Integrated Assessment framework?
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- Statistical emulators v. Physically based emulators

# Summary

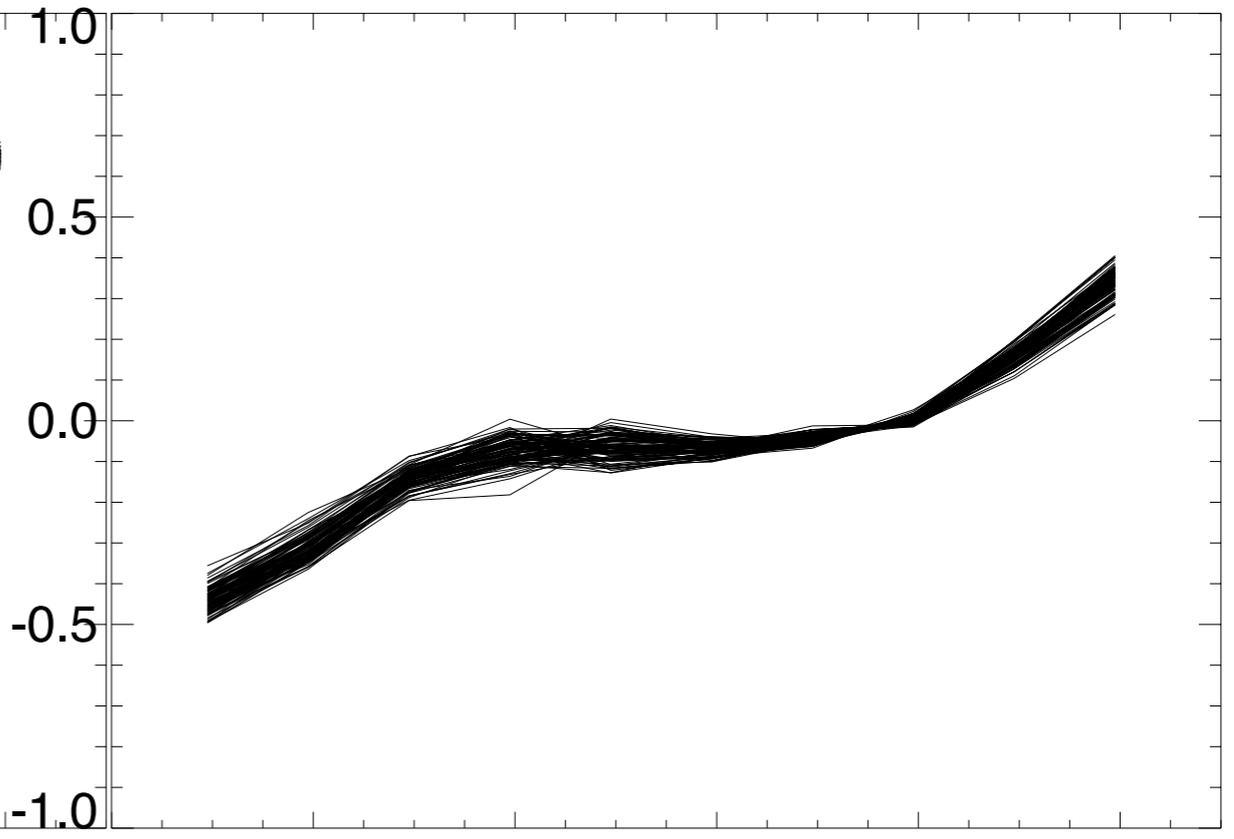
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- Where do emulators fit into the Integrated Assessment framework?
  - Front and center!
  - Need to define the relevant climate variables
- Caution: Mismatch between parameters in emulator and higher complexity models
  - As said in Maine, “You just can’t get there from here...”
- Statistical emulators v. Physically based emulators
  - Much more discussion on this today

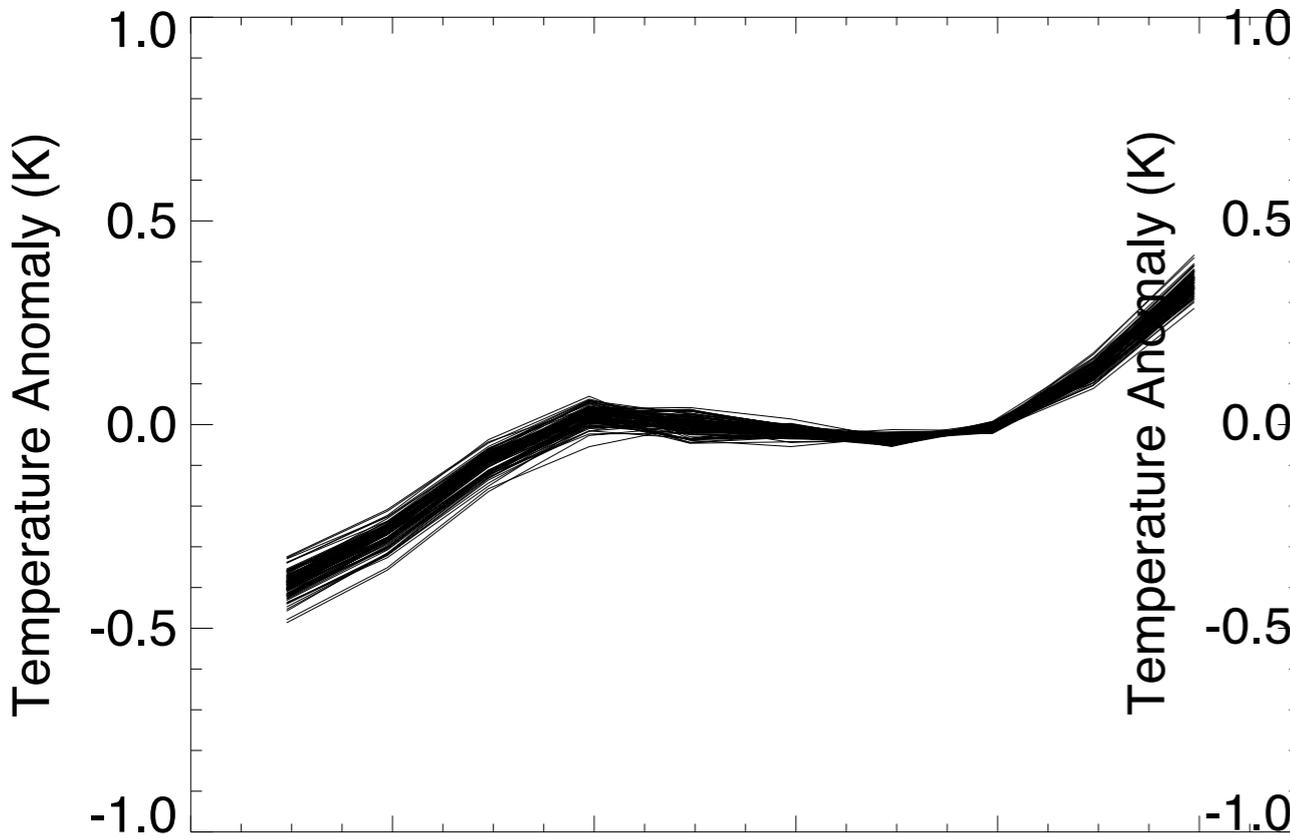
30-90 N



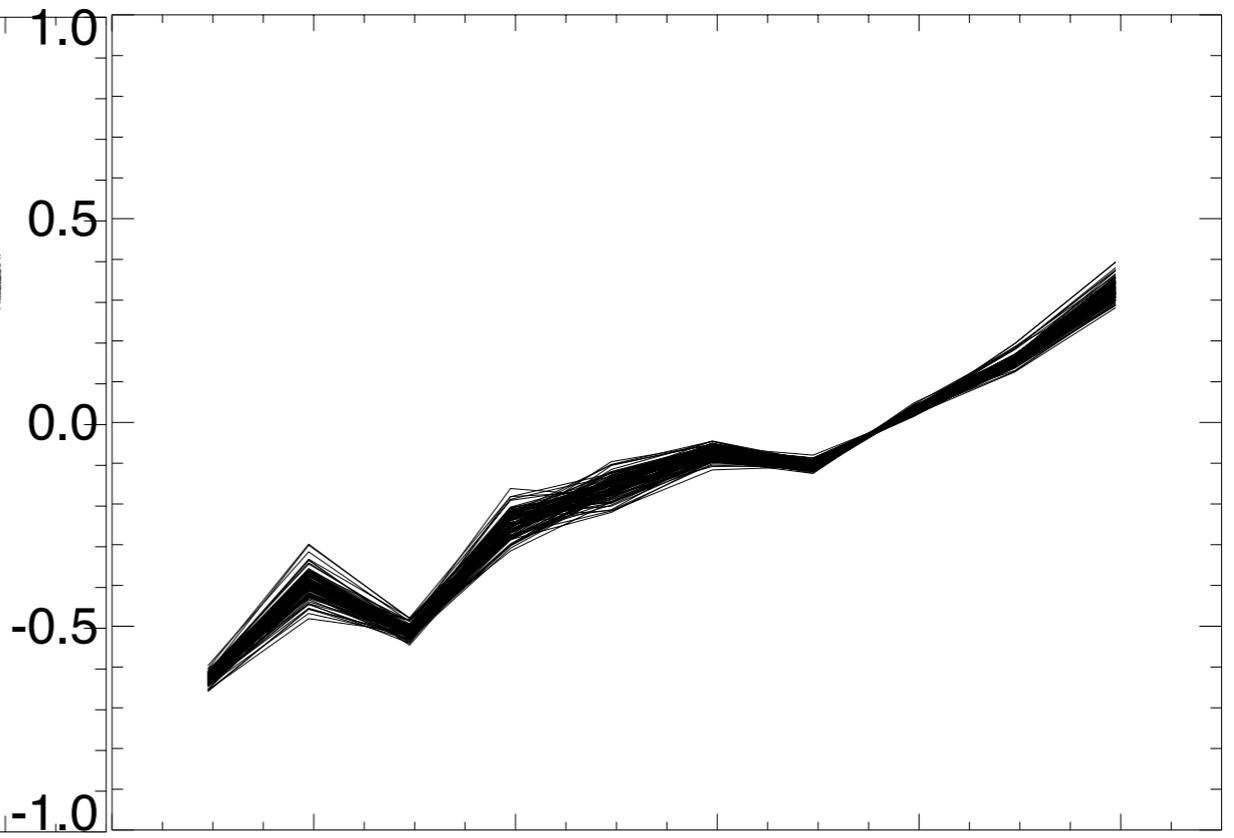
0-30 S



0-30 N

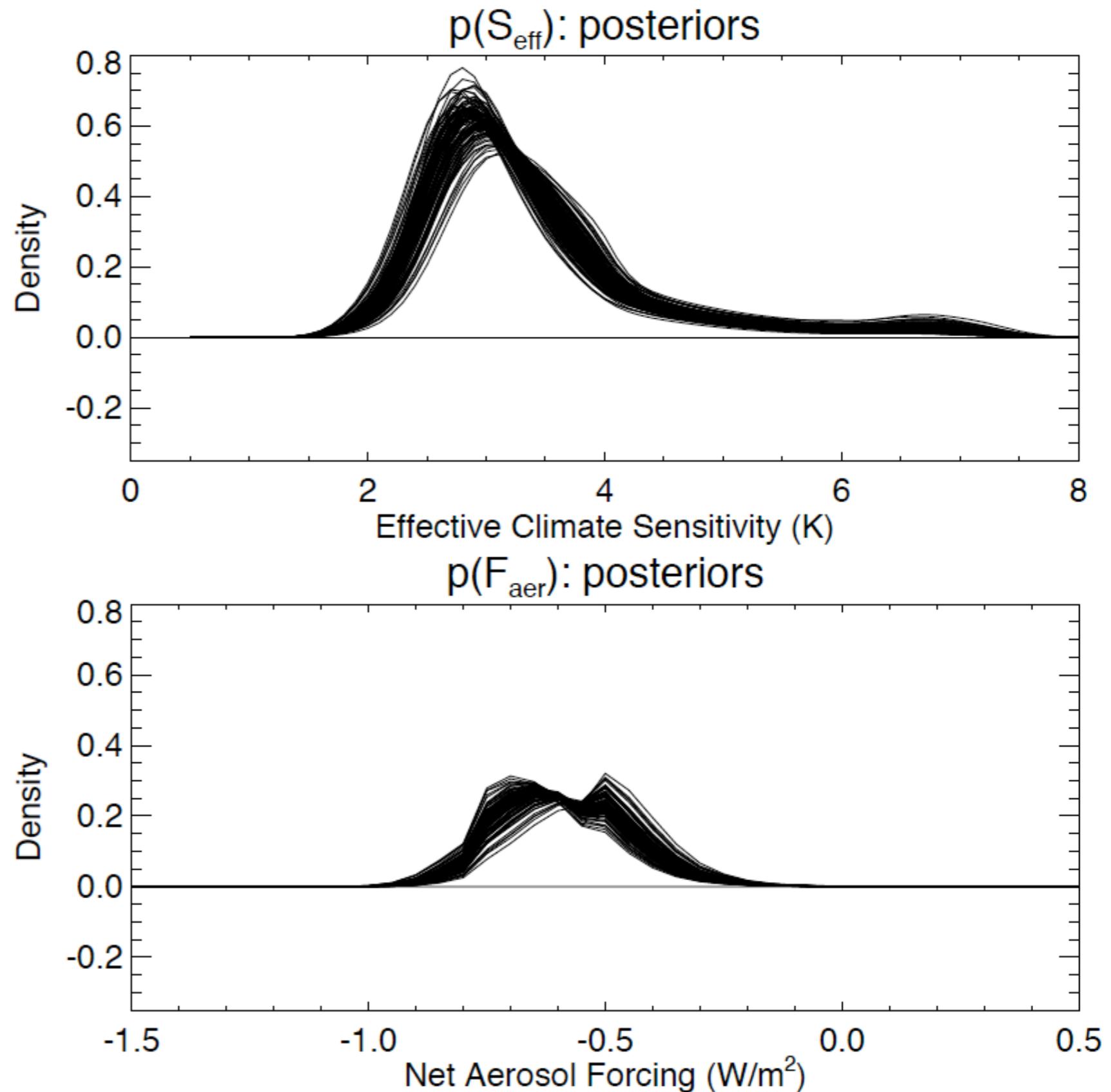


30-90 S

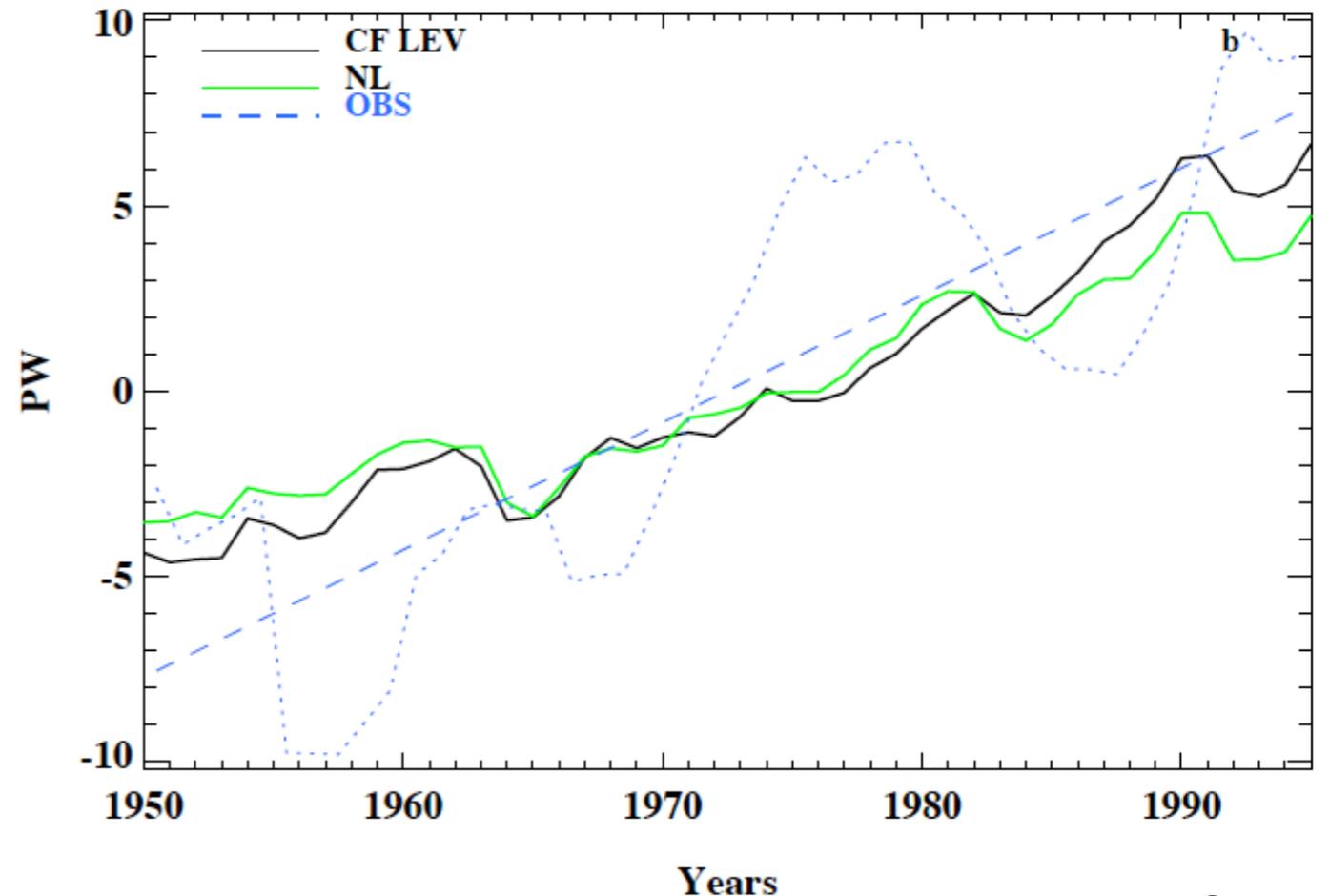
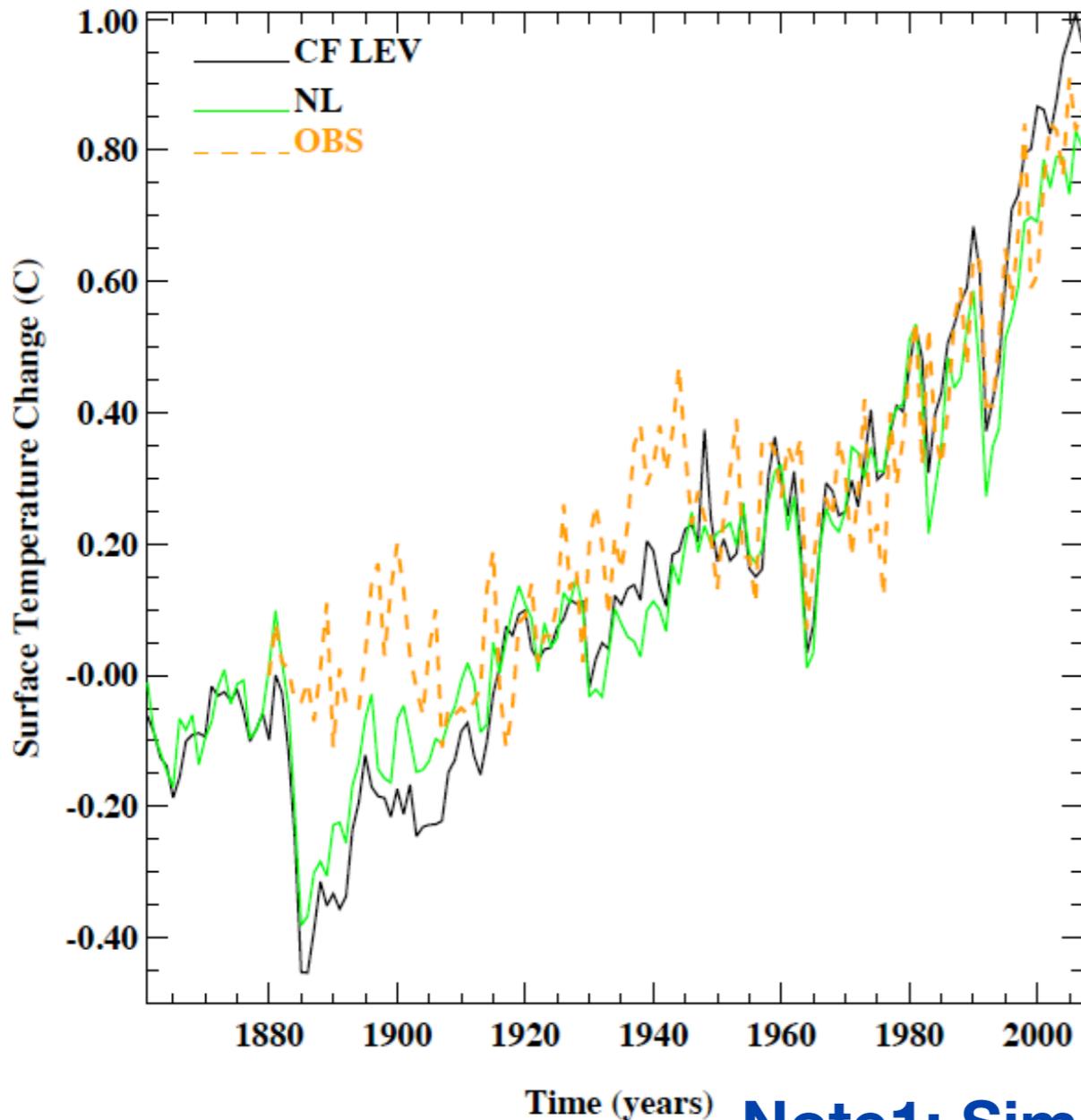


# Impact of Observational Uncertainty

- 100 Member Ensemble of HadCRUT4
  - Based on defensible/plausible methods for correcting SST biases
- Data comparison period: 1945-2004 (limited by model runs)
- Updated Upper-air Temperatures to 2004 using HadAT2



# Lewis (2013, J. Climate) estimates v. Forest et al. (2008, Tellus) estimates



**NL: CS = 1.6K,  $K_v = 0.6 \text{ cm}^2/\text{s}$**   
**CF LEV: CS = 2.9,  $K_v = 1. \text{ cm}^2/\text{s}$**

**Note1: Simulations using Lewis (2013) do not reproduce observed ocean heat content trends**

**Note2: Levitus et al. (2009) trends (above) are weaker than other estimated trends**

# Estimating Uncertainty in Climate System

**Properties:  $p(S, K_v, F_{aer} \mid \Delta T_{obs}, C_N)$**

---

- **Simulate 20th century climate using anthropogenic and natural forcings while systematically varying the choices of climate system properties ( $S$ ,  $K_v$ , and  $F_{aer}$ ) in the MIT Integrated Global System Model (IGSM2.2) (Sokolov et al., 2005)**
- **Compare each model response against observed  $\Delta T$  as in optimal fingerprint detection algorithm (Requires Estimate of Climate Variability,  $C_N$ )**
- **Compare goodness-of-fit statistics to estimate likelihood function  $L(S, K_v, F_{aer} \mid \Delta T_{obs}, C_N)$  for individual  $\Delta T$  diagnostics**
- **Estimate  $p(S, K_v, F_{aer} \mid \Delta T_{obs})$  for multiple diagnostics and combine Likelihood Estimates using Bayes' Theorem**

**Latest results summarized in: Libardoni & Forest (2013, GRL)**

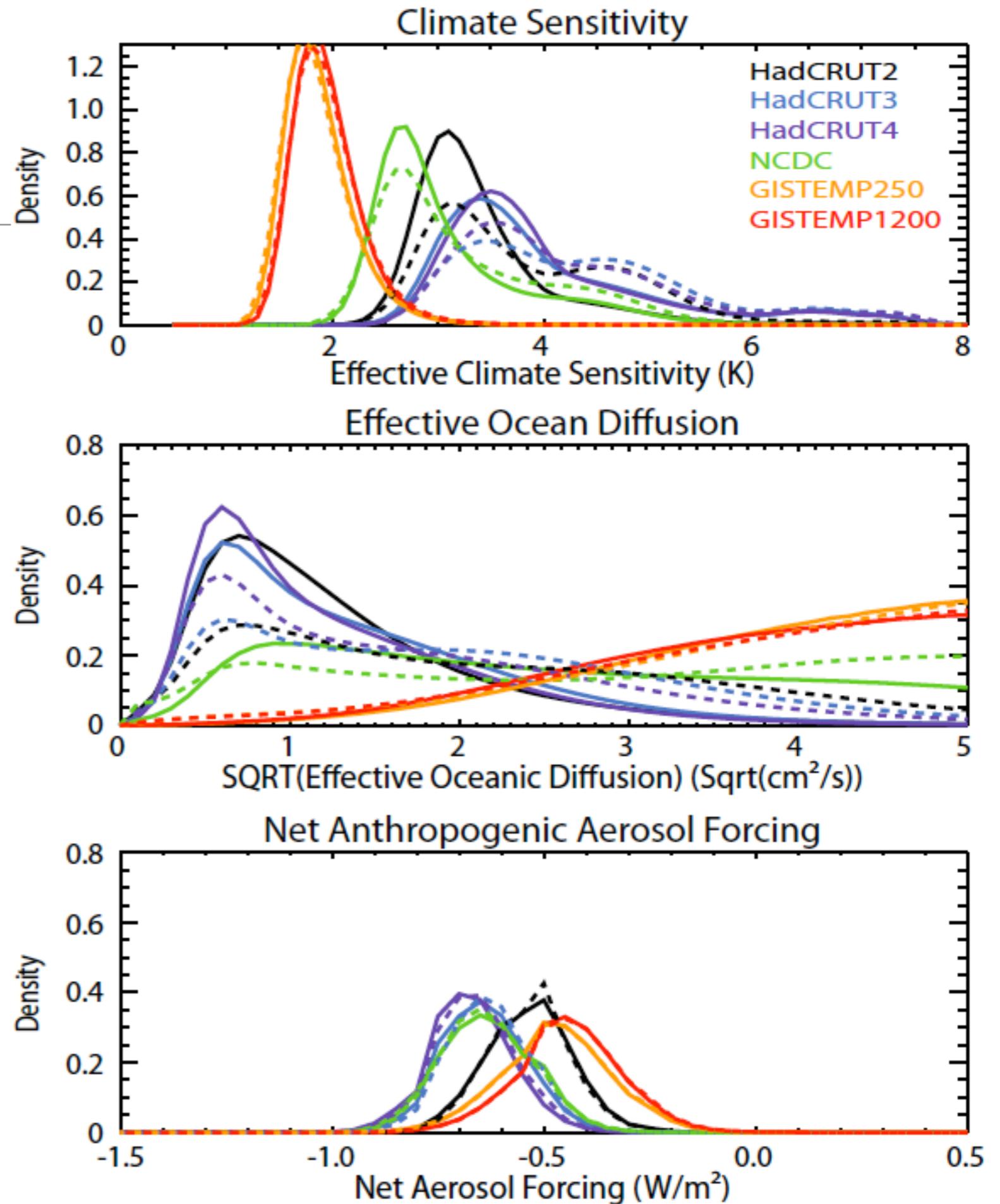
# Main Differences: data interpolation

See Poster for Details:  
Libardoni and Forest  
GC43E-1083

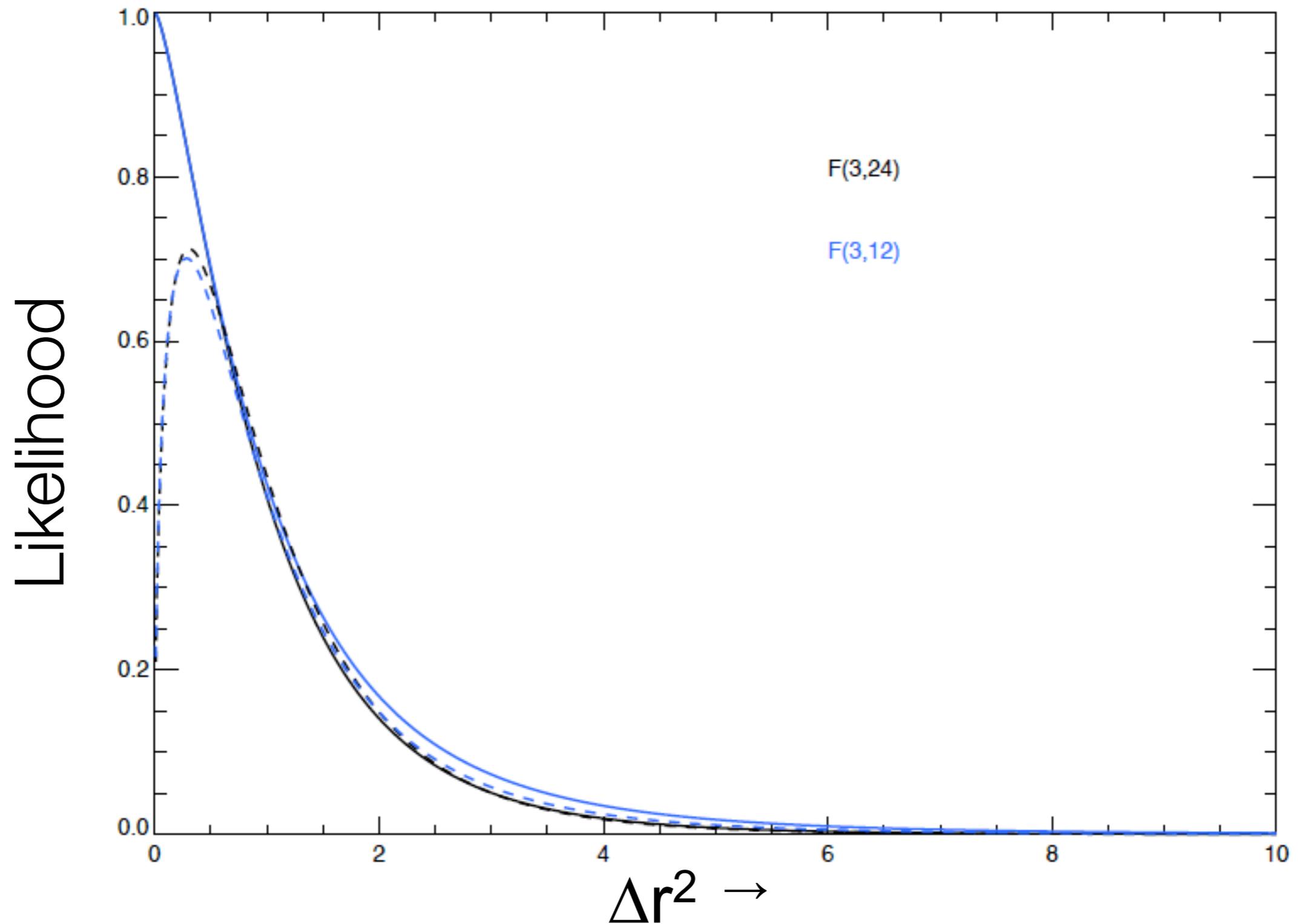
S. Hemisphere SST  
interpolation and  
smoothing

Extended to: 1946-2004

Ocean data:  
Levitus et al. (2009)  
Domingues et al. (2008)



# Difference in F-distribution likelihood v. likelihood function in Forest et al. (2002)

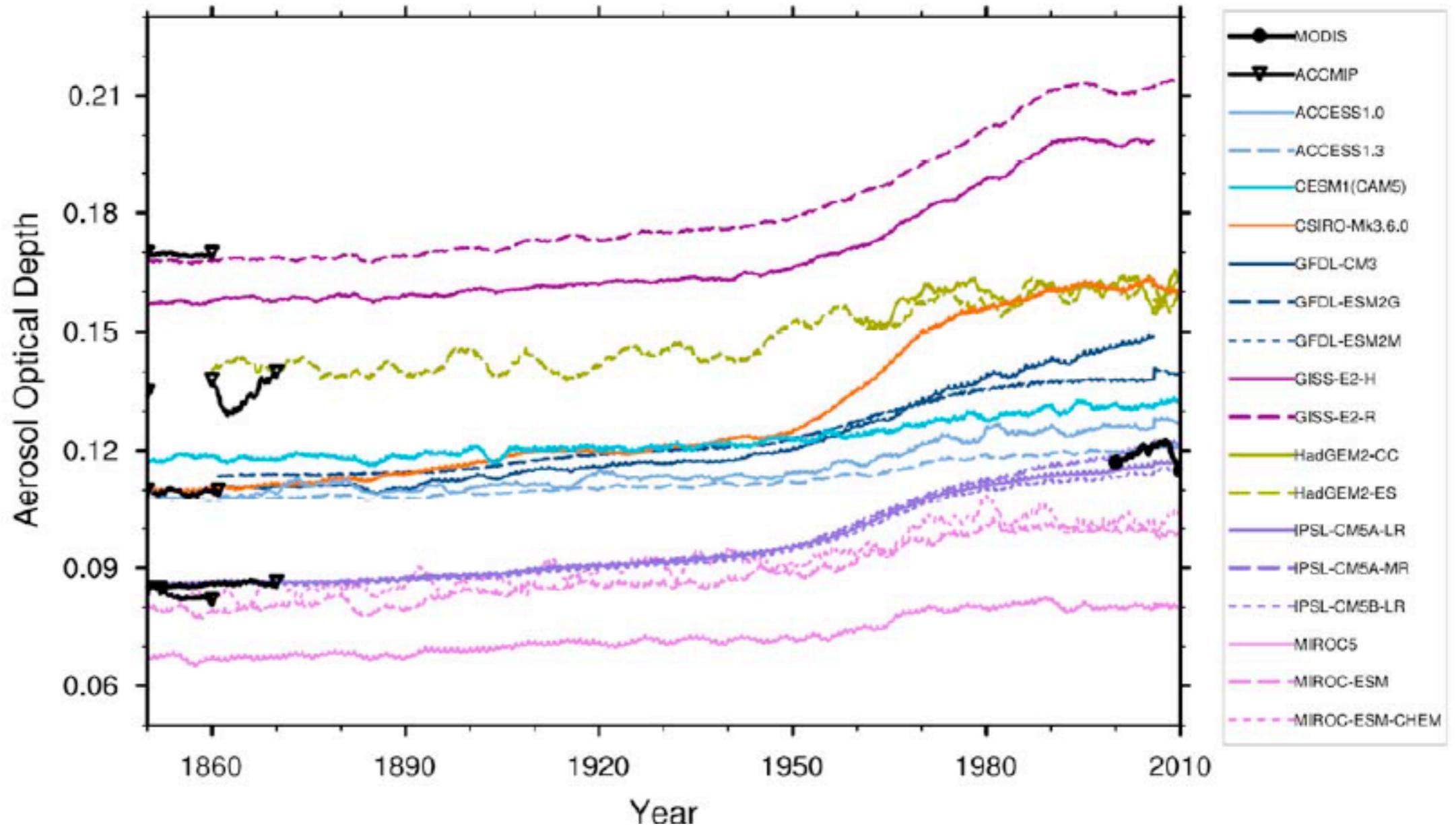


# Three basic methods to estimate Climate System Properties using observed climate changes

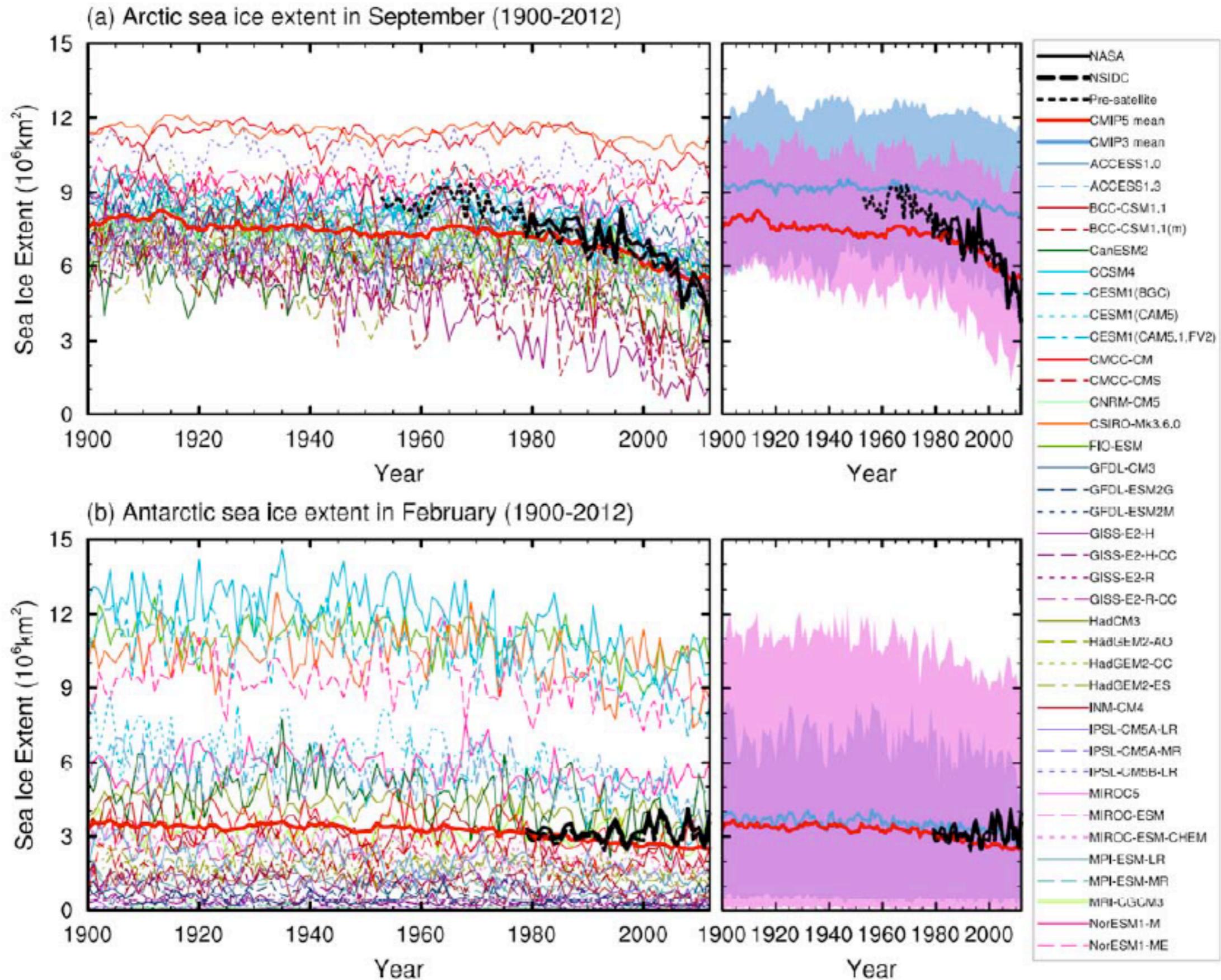
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- **The Goal: Match 20th century climate change with a model**
- **Model Options:**
  - **Earth System Models (or Atmosphere-Ocean GCMs):**
    - “Scale” individual model simulations (or ensemble of simulations)
  - **Earth-system Models of Intermediate Complexity (EMICs)**
    - **Calibrate parameters that control climate system feedbacks**
  - **Energy Balance Models**
    - **Calibrate Equilibrium Climate Sensitivity parameter in**

# Ch09: Aerosol Optical Depth (Fig 9.29)

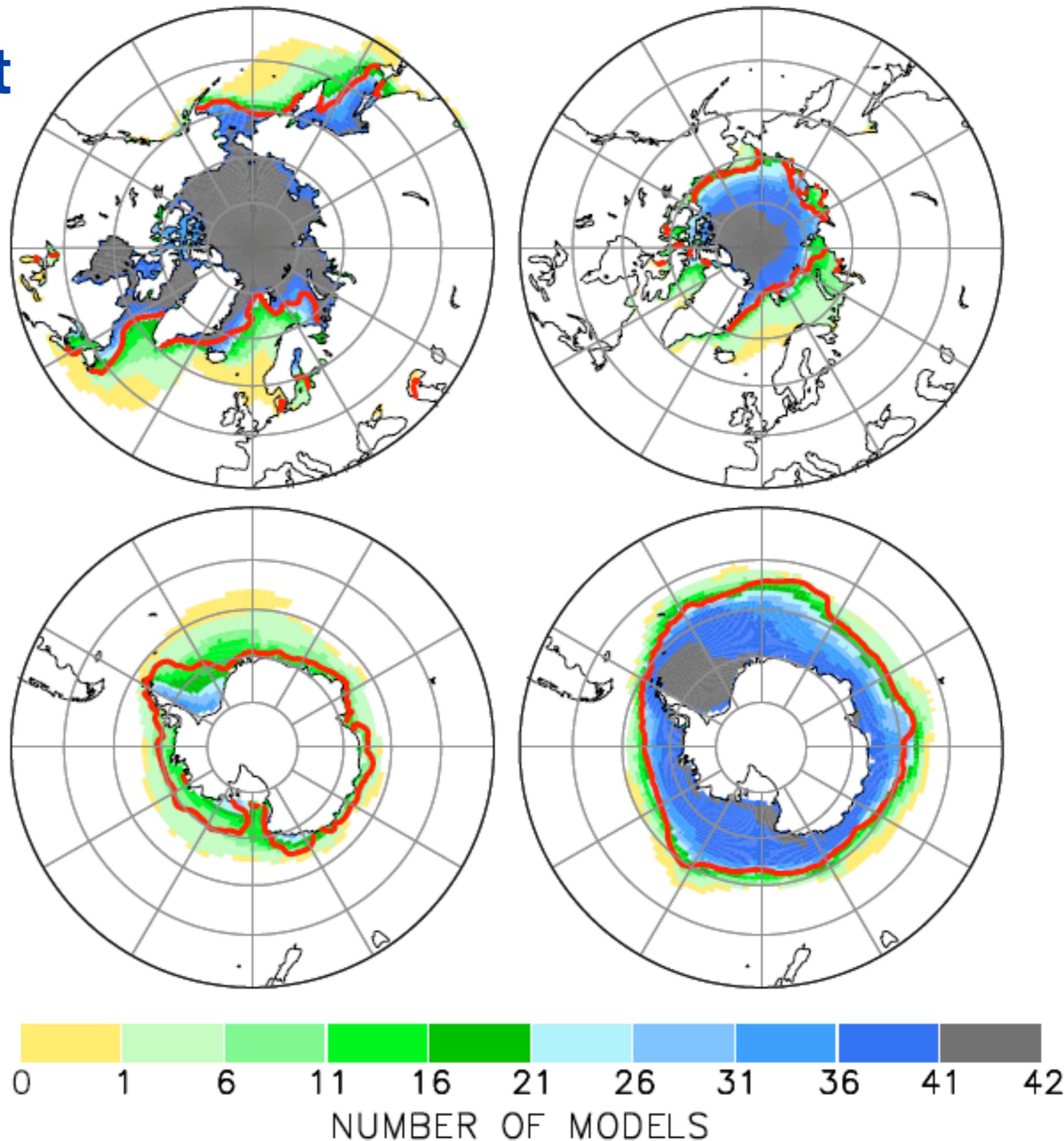


# Ice Albedo feedbacks? Sea Ice (Figure 9.24)

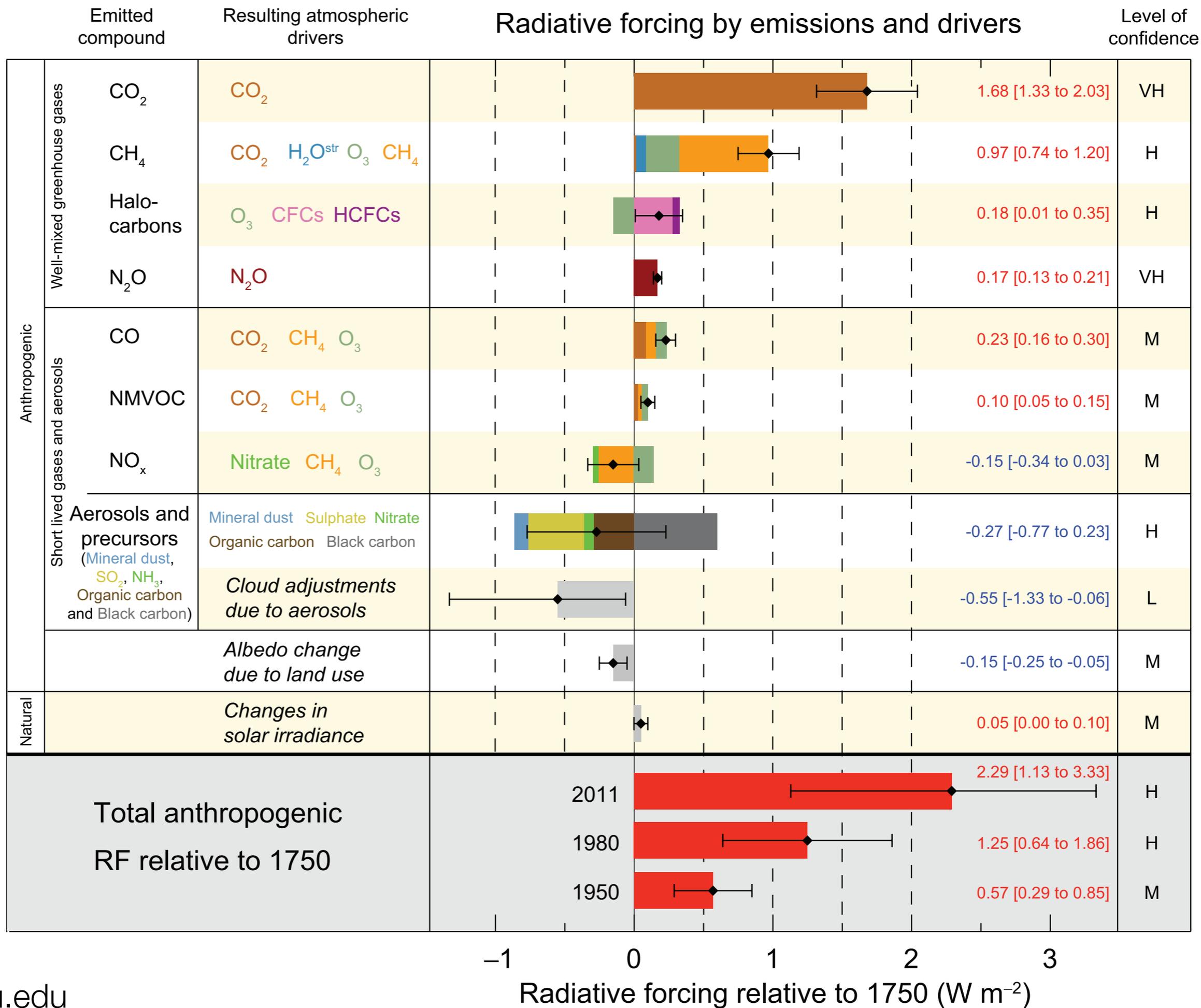


# Sea Ice Extent (Figure 9.23)

- Left: February
- Right: September
- Top: Arctic
- Bottom: Antarctic
- Colors: # of Models simulating sea ice with “at least 15%” of coverage
- Red contour: HadISST

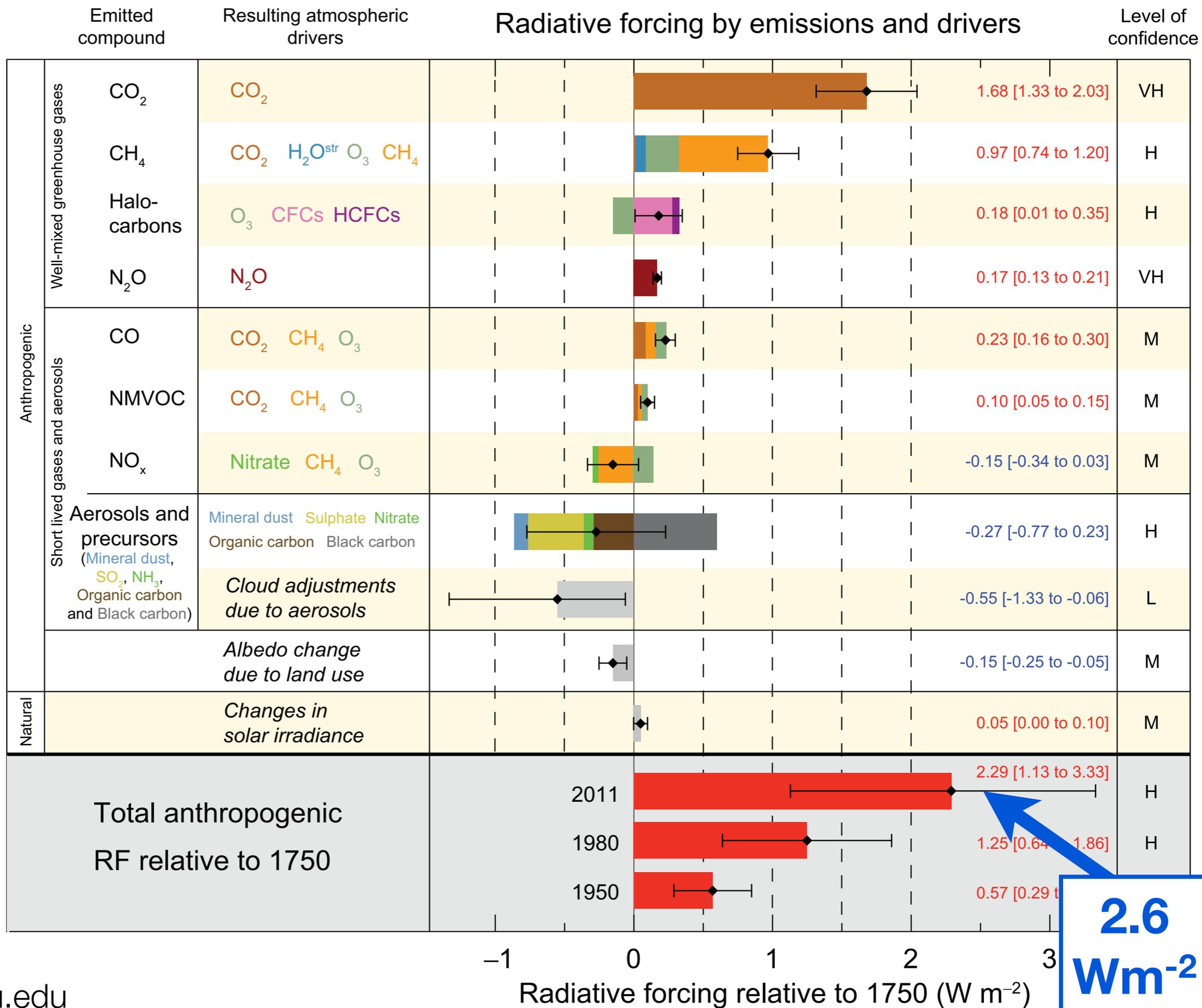


# Radiative Forcing: Figure SPM.5



-1 0 1 2 3  
Radiative forcing relative to 1750 (W m<sup>-2</sup>)

# Radiative Forcing: Figure SPM.5

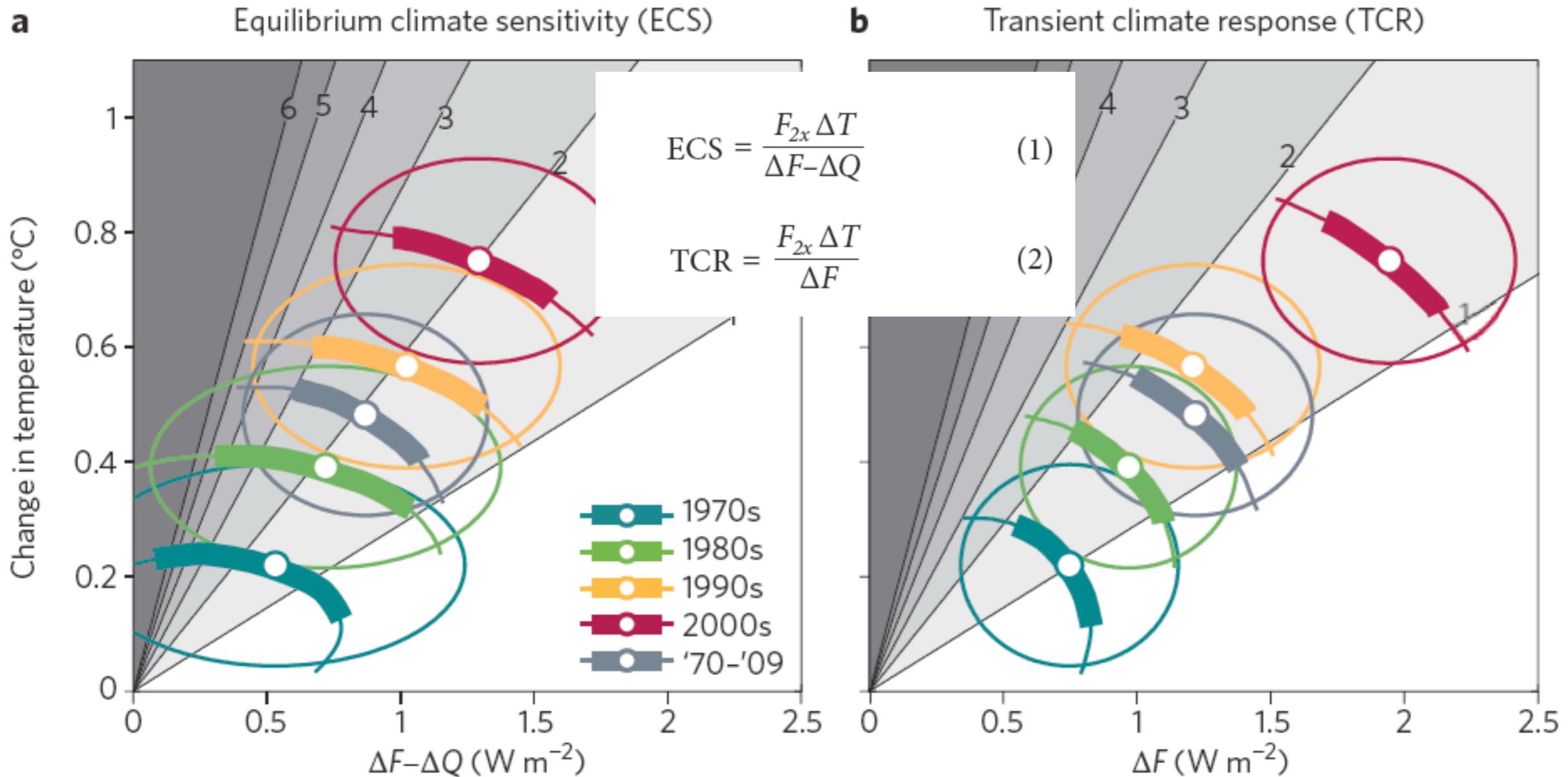


# Radiative Forcing Summary

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- Effective Radiative Forcing for Cloud Adjustments to Aerosols
  - Permits rapid adjustments to cloud/environment
  - Eliminates direct/indirect/semi-direct forcing nomenclature
- Total Radiative Forcing is Larger
  - Increased GHG forcing & Reduced Aerosol forcing
  - Implies smaller “climate sensitivity”
  - Both Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR) are impacted by this

# Constraints including recent data up to 2009.

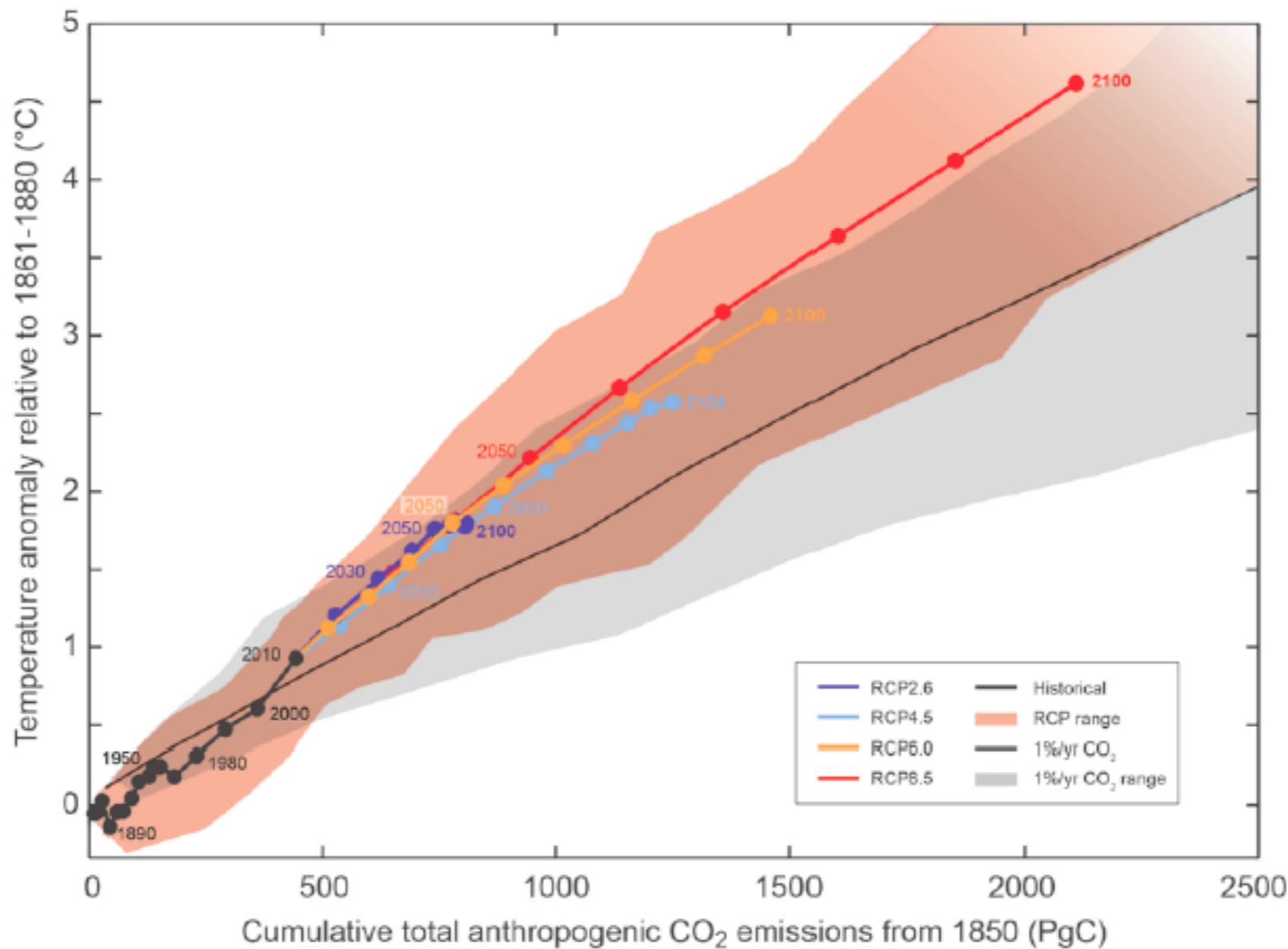


## Energy budget constraints on climate response

NATURE GEOSCIENCE | VOL 6 | JUNE 2013

Alexander Otto<sup>1\*</sup>, Friederike E. L. Otto<sup>1</sup>,  
 Olivier Boucher<sup>2</sup>, John Church<sup>3</sup>, Gabi Hegerl<sup>4</sup>,  
 Piers M. Forster<sup>5</sup>, Nathan P. Gillett<sup>6</sup>,  
 Jonathan Gregory<sup>7</sup>, Gregory C. Johnson<sup>8</sup>,  
 Reto Knutti<sup>9</sup>, Nicholas Lewis<sup>10</sup>, Ulrike Lohmann<sup>9</sup>,  
 Jochem Marotzke<sup>11</sup>, Gunnar Myhre<sup>12</sup>,  
 Drew Shindell<sup>13</sup>, Bjorn Stevens<sup>11</sup>  
 and Myles R. Allen<sup>1,14</sup>

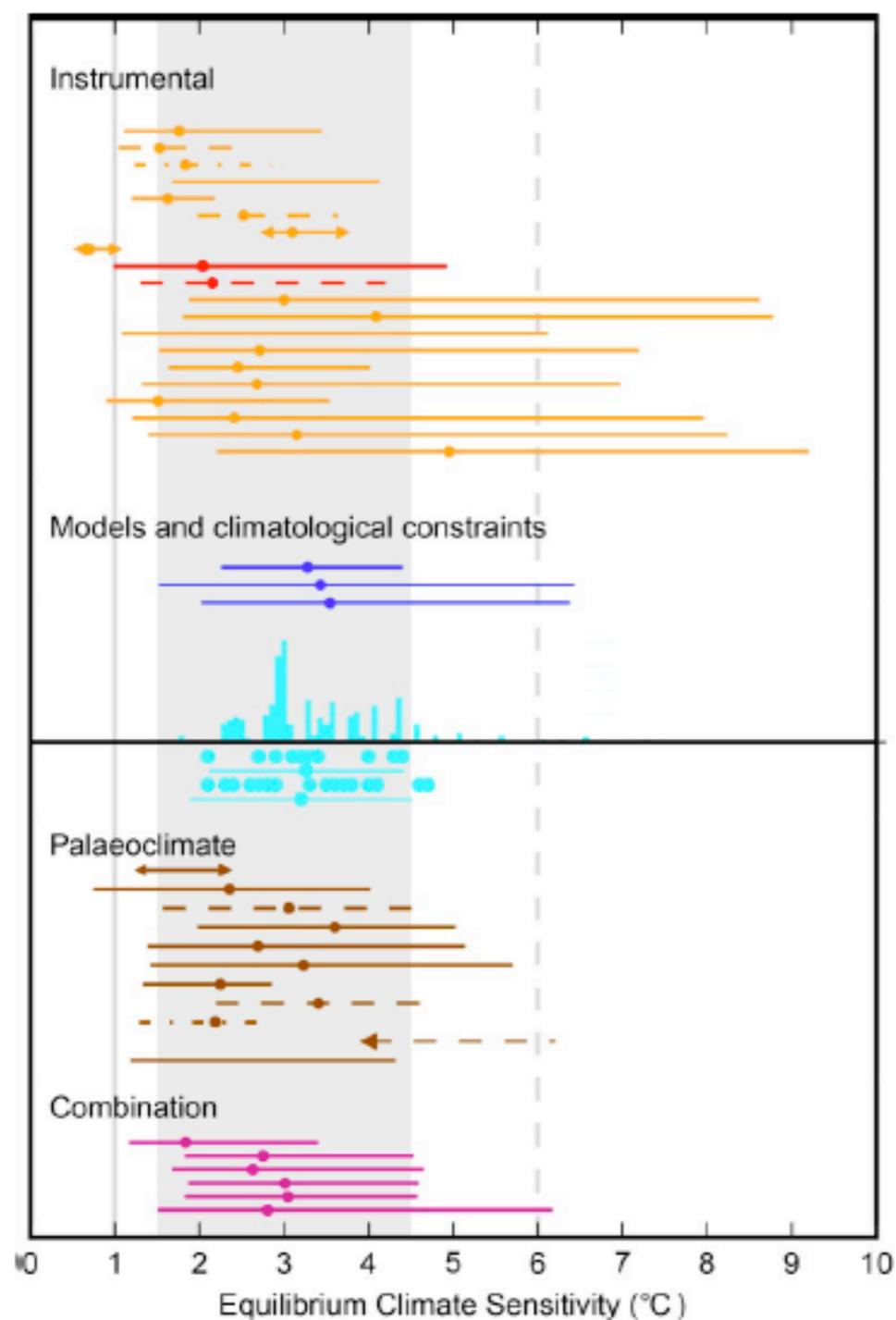
	TAR	AR4	AR5
ECS	Likely range: 1.5 to 4.5°C	<i>likely</i> range: 2.0 to 4.5°C  <i>very unlikely</i> <1.5°C  —  best estimate about 3°C	<i>likely</i> range: 1.5 to 4.5°C  <i>extremely unlikely</i> <1.0°C  <i>very unlikely</i> >6.0°C  —
TCR	Model range 1.1 to 3.1°C	<i>very likely</i> >1.0°C  <i>very unlikely</i> >3.0°C	<i>likely</i> range: 1.0 to 2.5°C  <i>extremely unlikely</i> >3.0°C
TCRE			<i>likely</i> range: 0.8 to 2.5 °C/1000 PgC



(IPCC 2013, Fig. SPM.10)

Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions

# Equilibrium climate sensitivity estimates



*Likely* range supported by all lines of evidence

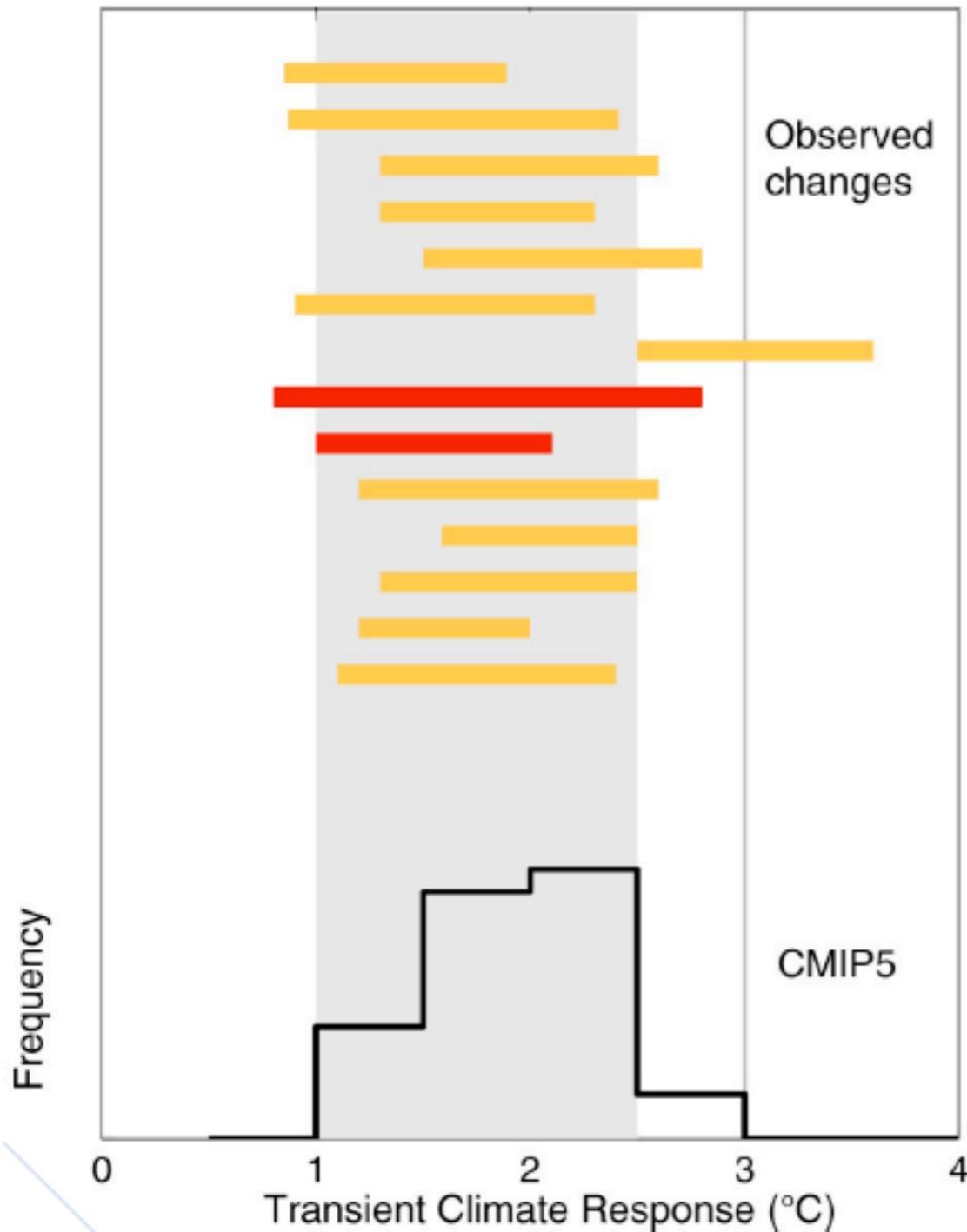
Model fit to observed warming in **lower part of likely range**; model estimates constrained by mean climate in **upper part of the likely range**)

=> No best estimate possible

ECS is

- *likely* in the range 1.5°C to 4.5°C (high confidence)
- *extremely unlikely* less than 1°C (high confidence)
- *very unlikely* greater than 6°C (medium confidence).

# Transient Climate Response: more relevant for next century



The transient climate response (TCR) is *likely* in the range of 1.0°C to 2.5°C (*high confidence*) and *extremely unlikely* greater than 3°C

- ⇒ tightening of upper limit compared to earlier estimates,
- ⇒ slight downward adjustment of lower limit

# Transient Climate Response

