# DEFINING AND QUANTIFYING FEEDBACKS IN EARTH'S CLIMATE SYSTEM

Stephen E. Schwartz
Brookhaven National Laboratory Upton NY 11973
http://www.ecd.bnl.gov/steve ses@bnl.gov

American Geophysical Union, Fall Meeting, 2008, A21D-0195

# THE PROBLEM

***Climate sensitivity***, the equilibrium change in global mean near-surface air temperature per change in radiative flux $S = \Delta T_s / \Delta F$, ***remains highly uncertain***.

A key approach to determining climate sensitivity is through GCMs.

GCMs exhibit a ***wide range of sensitivity***.

Determining sensitivity of GCMs is not straightforward, requiring ***long integrations*** to reach equilibrium.

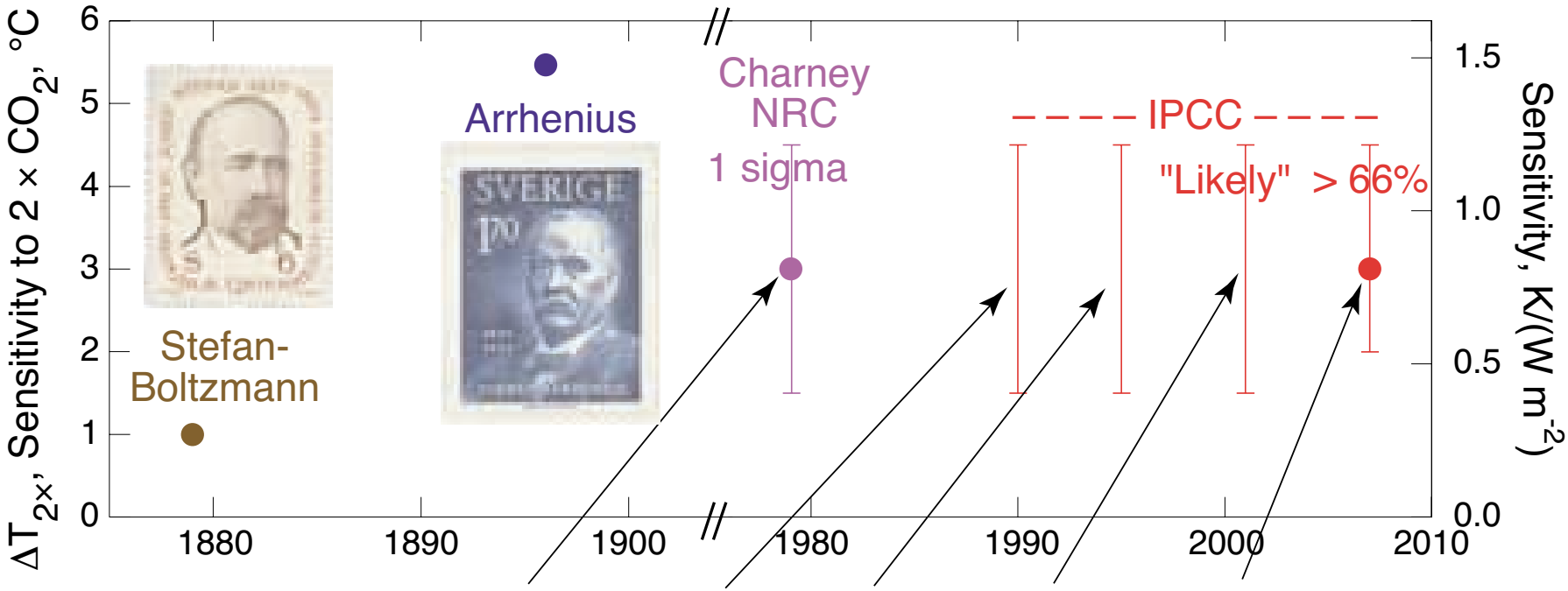
The reasons for differences in sensitivities between different climate models are ***hard to determine and interpret***.

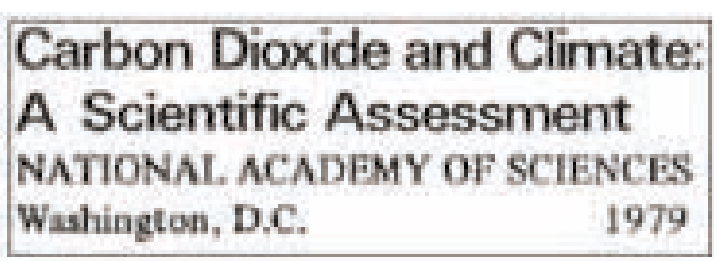
Climate sensitivity is often expressed as the equilibrium temperature that would result from a doubling of atmospheric $CO_2$, $\Delta T_{2\times}$, related by $\Delta T_{2\times} = \Delta F_{2\times} S$, where $\Delta F_{2\times}$ is the forcing from doubled $CO_2$, commonly taken as 3.7 W $m^{-2}$.

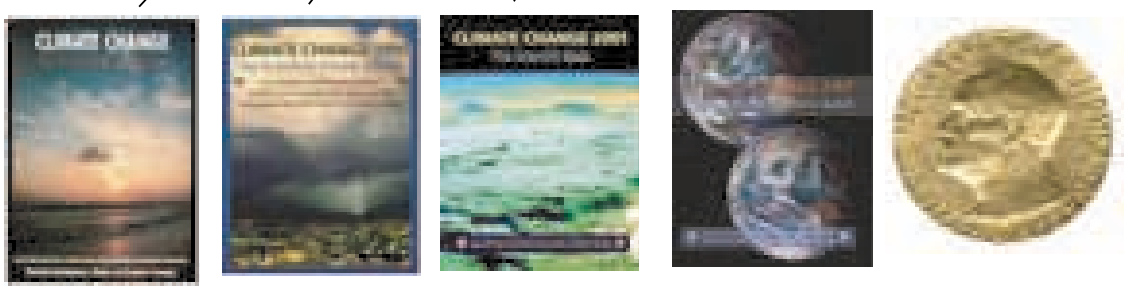
***This study introduces a new way of determining climate sensitivity of GCMs through analysis of shortwave and longwave feedbacks.***

# CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments



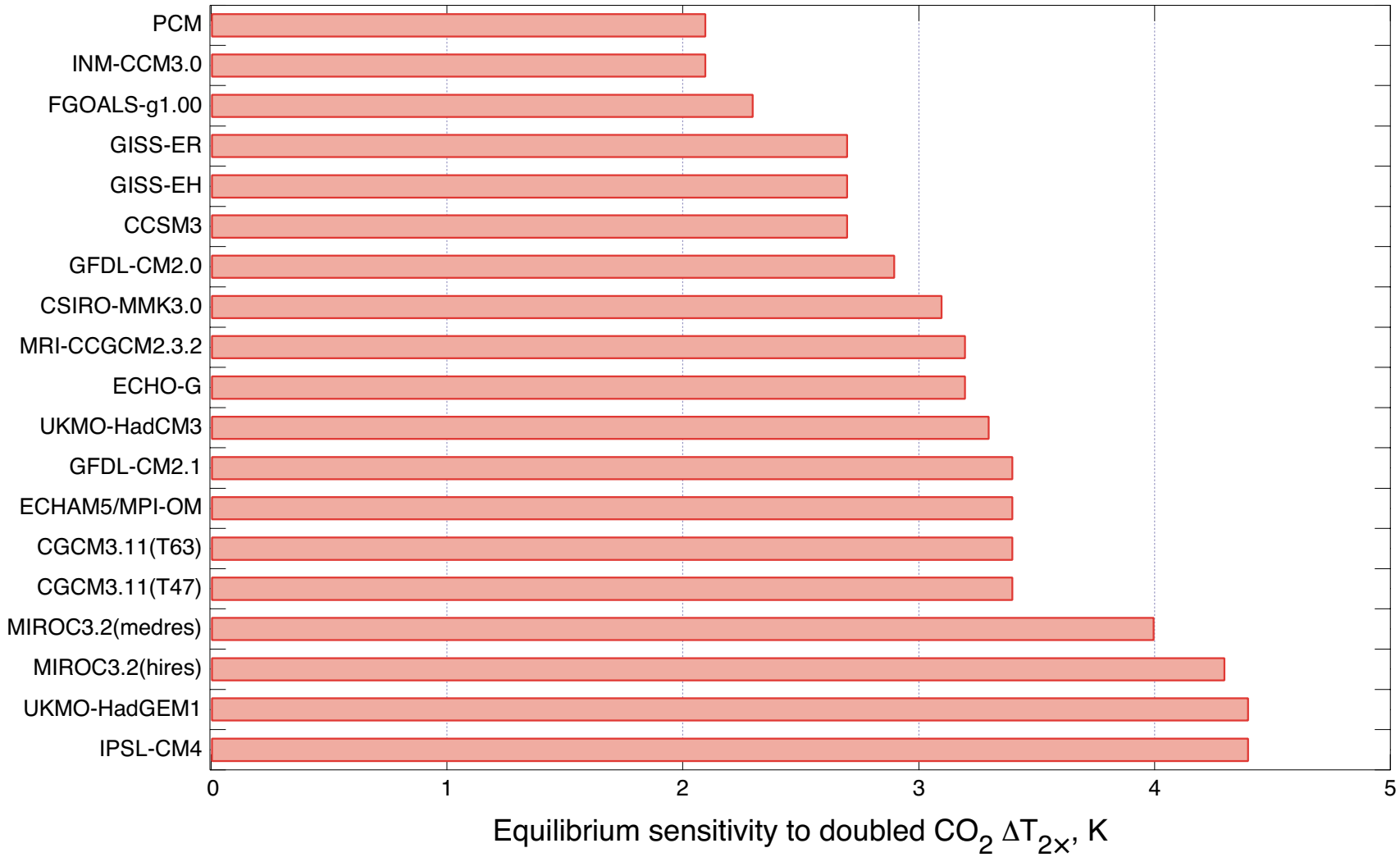



Despite extensive research, climate sensitivity remains ***highly uncertain***.

# EQUILIBRIUM SENSITIVITIES IN CURRENT CLIMATE MODELS

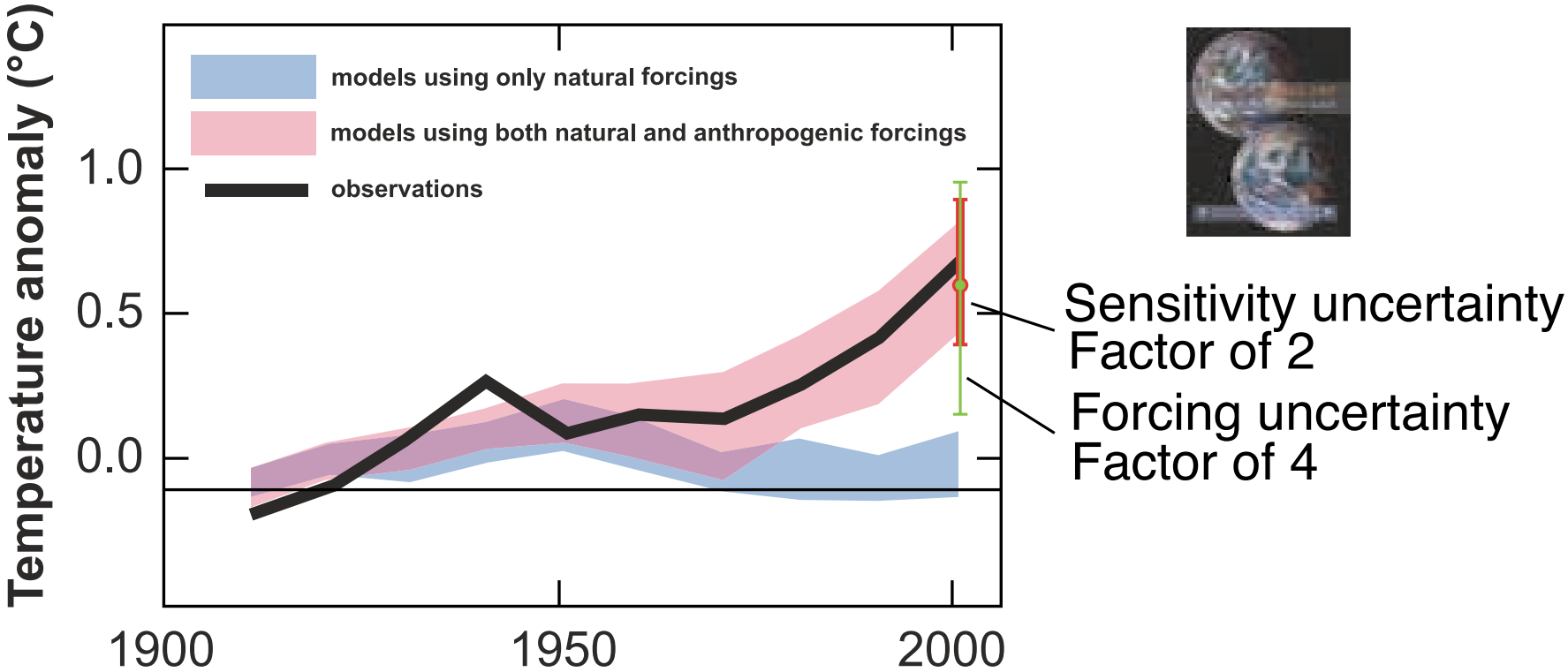
20 Models employed in IPCC AR4 simulations




Sensitivity varies by more than a factor of 2.

# TOO ROSY A PICTURE?

## Ensemble of 58 model runs with 14 global climate models




*Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007*

- Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.
- These simulations used models with ***different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings***.

Uncertainty in modeled temperature increase is less than the range of model sensitivity (factor of 2, red) and ***well less than the uncertainty in forcing*** (factor of 4, green).

***How can this be?!***

The models ***did not span the full range of the uncertainty*** and/or . . .

The forcings used in the model runs were ***anticorrelated with the sensitivities of the models***.

***Both!***

# THEORY

## CLIMATE SENSITIVITY AND ENERGY FLUXES

***Earth's energy balance***: $\dfrac{dH}{dt} = Q - E$

$H$ = planetary heat content at time $t$

$Q$ = absorbed shortwave power

$E$ = emitted longwave power

For climate initially at equilibrium at global mean near-surface air temperature $T_{s0}$,

$$Q(T_{s0}) - E(T_{s0}) = 0$$

***Apply forcing*** $\Delta F$ and allow the climate to come to a new equilibrium:

$$\Delta F + Q(T_{s0} + \Delta T_s) - E(T_{s0} + \Delta T_s) = 0$$

***Expand to first order*** in the perturbation in $Q$ and $E$:

$$\Delta F + Q(T_{s0}) + \frac{\partial Q}{\partial T_s}\Delta T_s - E(T_{s0}) - \frac{\partial E}{\partial T_s}\Delta T_s = 0$$

***Partial derivative***: Change due just to change in surface temperature, not including the effect of change in forcing itself.

***Rearrange*** to obtain equilibrium climate sensitivity $S$:

$$S \equiv \frac{\Delta T_s}{\Delta F} = \frac{1}{\left(\frac{\partial E}{\partial T_s} - \frac{\partial Q}{\partial T_s}\right)}$$

***Shortwave absorbed power***: $Q = \frac{1}{4}\gamma J_S$

$J_S$ is solar constant

$\gamma$ is planetary coalbedo

***Longwave emitted power***: $E = \varepsilon\sigma T_s^4$

$\sigma$ is Stefan-Boltzmann constant

$\varepsilon$ is effective planetary emissivity

***In absence of feedbacks***: $\frac{\partial Q}{\partial T_s} = 0$ and $\frac{\partial E}{\partial T_s} = 4\varepsilon\sigma T_{s0}^3 = \frac{\gamma J_S}{T_{s0}}$

***No-feedback sensitivity***: $S_{NF} = \frac{1}{4\varepsilon\sigma T_{s0}^3} = \frac{T_{s0}}{\gamma J_S} = 0.30\ \mathrm{K/(W\ m^{-2})}$

***Feedback factor f***: $$S = fS_{\mathrm{NF}}$$

***Feedback strength Φ***: $$f = \frac{1}{1-\Phi}$$

***Caution***: *These quantities are not consistently defined in the literature.*

Feedback factor increases greatly as feedback strength approaches unity.

***Rearrange***: $$f = \frac{1}{\frac{1}{4}\left(\frac{\partial \ln E}{\partial \ln T_{\mathrm{s}}} - \frac{\partial \ln Q}{\partial \ln T_{\mathrm{s}}}\right)}$$

***Substitute***: $$f = \frac{1}{1-\frac{1}{4}\left(\frac{\partial \ln \gamma}{\partial \ln T_{\mathrm{s}}} - \frac{\partial \ln \varepsilon}{\partial \ln T_{\mathrm{s}}}\right)}$$

$$\Phi = \frac{1}{4}\left(\frac{\partial \ln \gamma}{\partial \ln T_{\mathrm{s}}} - \frac{\partial \ln \varepsilon}{\partial \ln T_{\mathrm{s}}}\right)$$

$$S = \left(\frac{T_{s0}}{\gamma J_S}\right) \frac{1}{1 - \frac{1}{4}\left(\frac{\partial \ln \gamma}{\partial \ln T_s} - \frac{\partial \ln \varepsilon}{\partial \ln T_s}\right)}$$

***These expressions permit determination of Φ, f, and S from climate model output.***

$$\gamma = \frac{Q}{J_S / 4} \text{ and } \varepsilon = \frac{E}{\sigma T_s^4}$$

Partial derivatives $\frac{\partial \ln \gamma}{\partial \ln T_s}$ and $\frac{\partial \ln \varepsilon}{\partial \ln T_s}$ must be determined for constant forcing (or forcing must be known and subtracted).

***Here this approach is applied to preindustrial control runs (no forcing) and to 21st century commitment runs for which forcing is constant.***

# APPLICATION

## DETERMINING EFFECTIVE EMISSIVITY AND PLANETARY ALBEDO FROM ARCHIVED GCM OUTPUT

***Planetary coalbedo***

$$\gamma = \frac{\overline{Q}}{J_S / 4}$$

$Q$ = net shortwave irradiance at Top of Atmosphere (TOA):

$$\overline{Q} = \overline{J_{sw}^{\downarrow \mathrm{toa}}} - \overline{J_{sw}^{\uparrow \mathrm{toa}}}$$

Overbar denotes average over space and time.

$$\gamma = \frac{\overline{J_{\mathrm{sw}}^{\downarrow\,\mathrm{toa}}} - \overline{J_{\mathrm{sw}}^{\uparrow\,\mathrm{toa}}}}{\overline{J_{\mathrm{sw}}^{\downarrow\,\mathrm{toa}}}} = 1 - \frac{\overline{J_{\mathrm{sw}}^{\uparrow\,\mathrm{toa}}}}{\overline{J_{\mathrm{sw}}^{\downarrow\,\mathrm{toa}}}}$$

Required quantities: $J_{\mathrm{sw}}^{\downarrow\,\mathrm{toa}}$, $J_{\mathrm{sw}}^{\uparrow\,\mathrm{toa}}$

***Effective emissivity***

$$\varepsilon = \frac{\overline{E}}{\sigma \overline{T_{\mathrm{s}}}^{4}}$$

$E$ = upwelling longwave irradiance at TOA:

$$\overline{E} = \overline{J_{\mathrm{lw}}^{\uparrow\,\mathrm{toa}}}$$

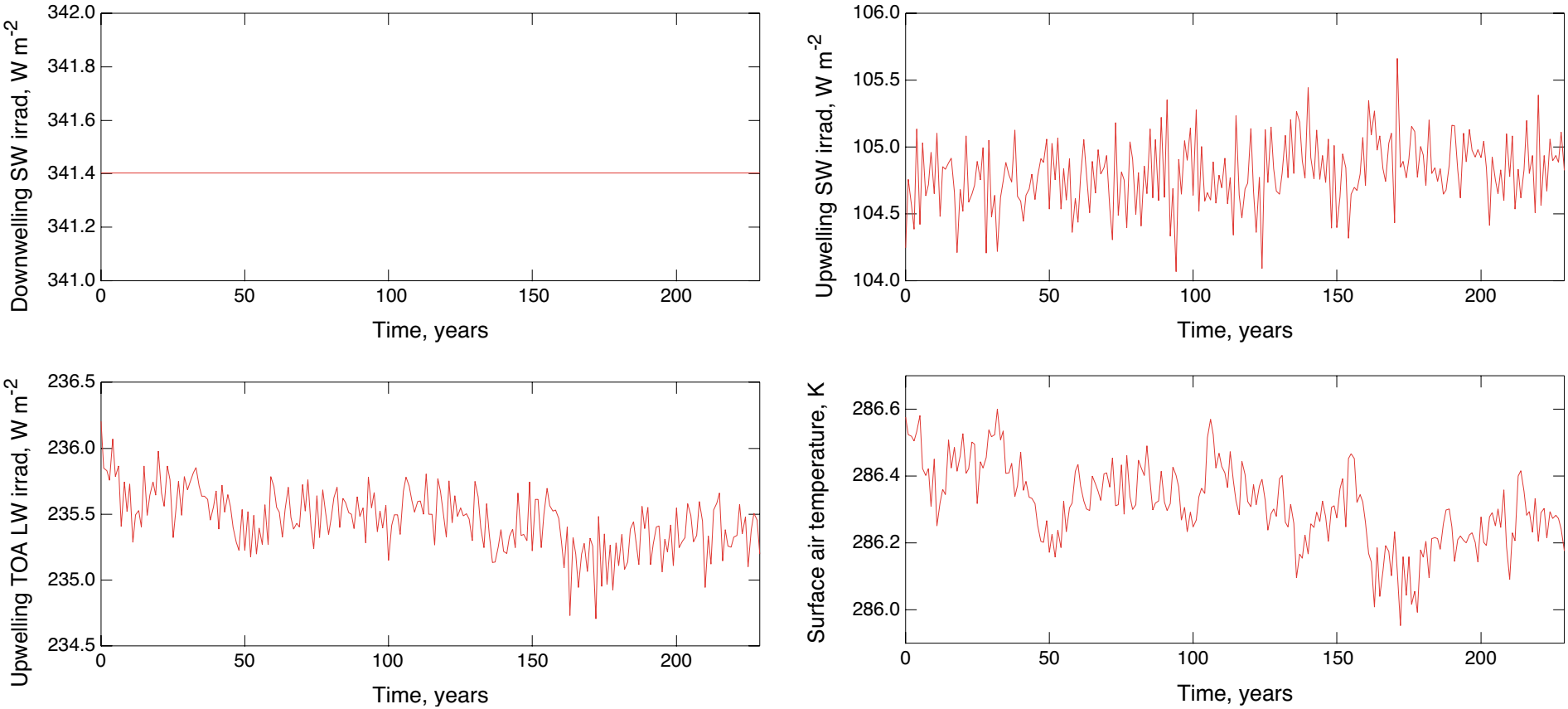
$$\varepsilon = \frac{\overline{J_{\mathrm{lw}}^{\uparrow\,\mathrm{toa}}}}{\sigma \overline{T_{\mathrm{s}}}^{4}}$$

Required quantities: $J_{\mathrm{lw}}^{\uparrow\,\mathrm{toa}}$, $T_{\mathrm{s}}$

All of these quantities are available in the PCMDI archive of model runs conducted for the IPCC Fourth Assessment Report (AR4).

# EXAMPLE INPUT DATA

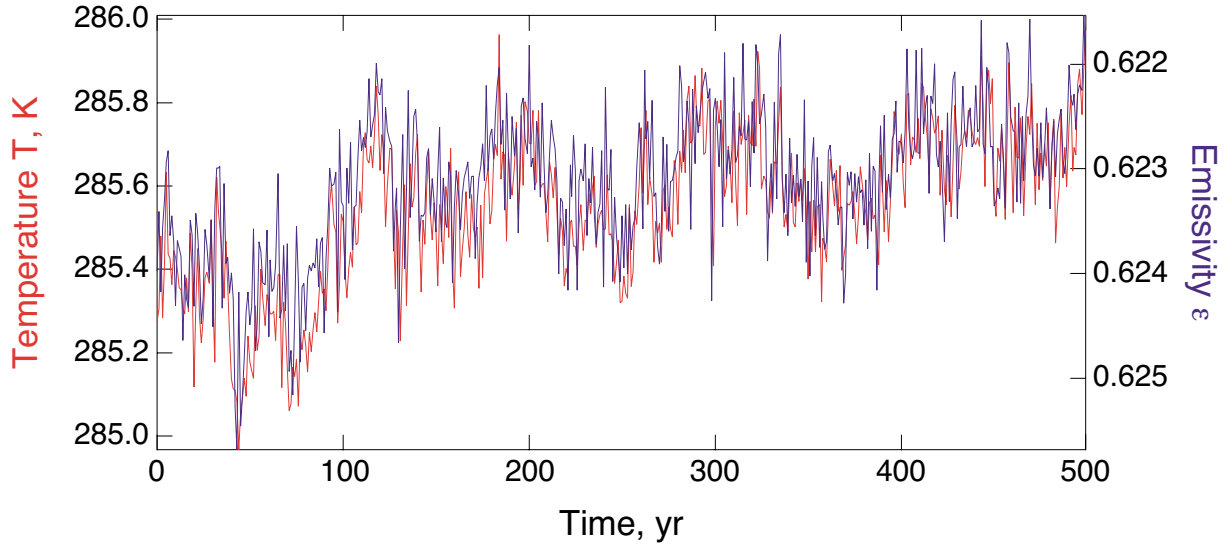
## Global-annual averages; NCAR-CCSM3.0 preindustrial control run

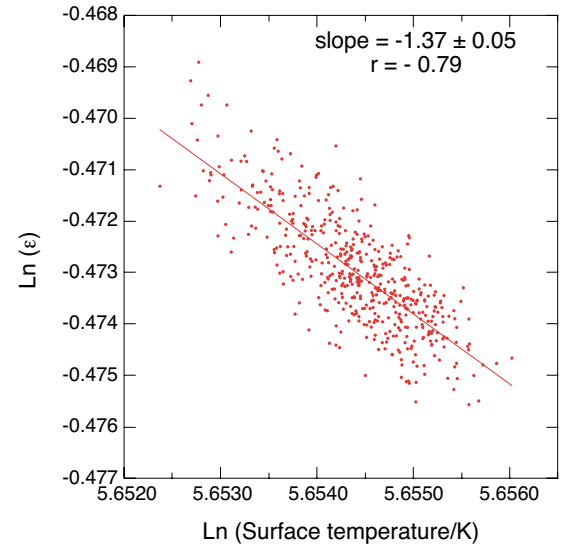


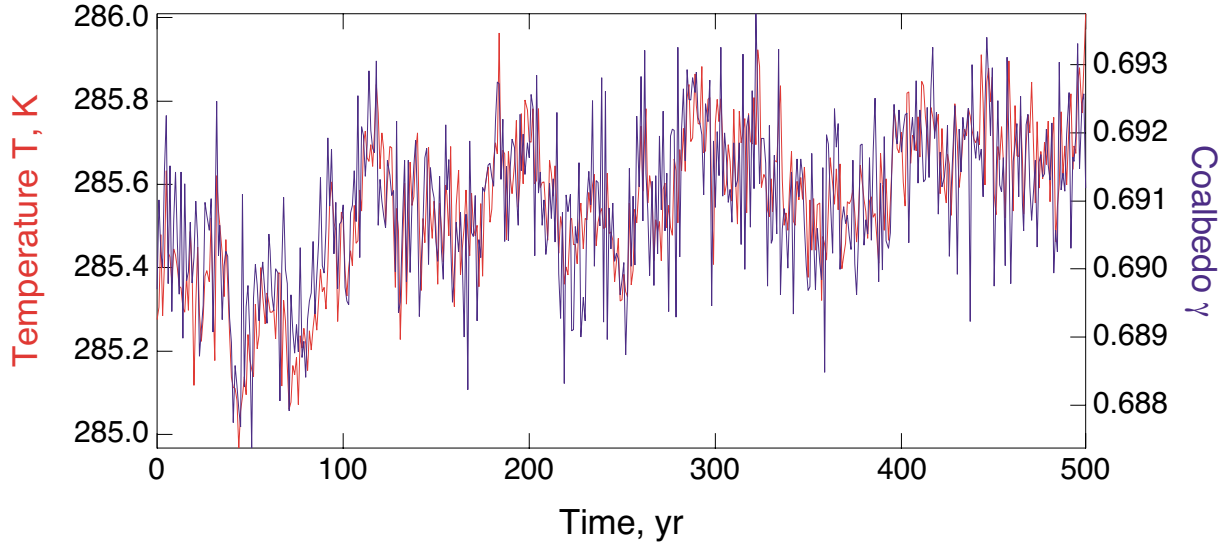

*Data source: PCMDI IPCC AR4 Archive*

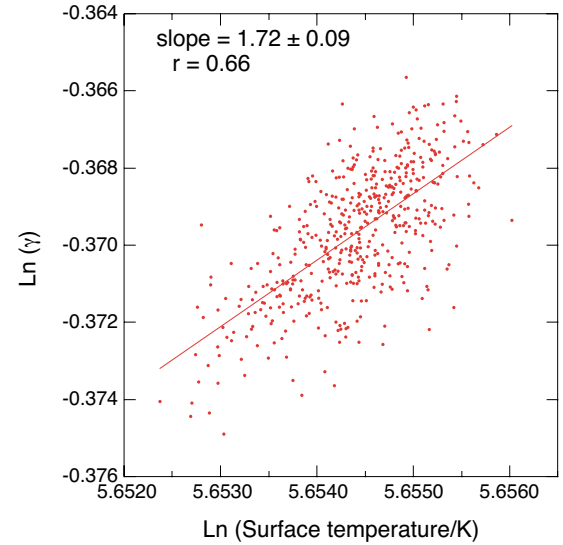
# CORRELATION OF EFFECTIVE EMISSIVITY AND COALBEDO WITH SURFACE TEMPERATURE

## GFDL-CM2.0 preindustrial control run – Global annual average



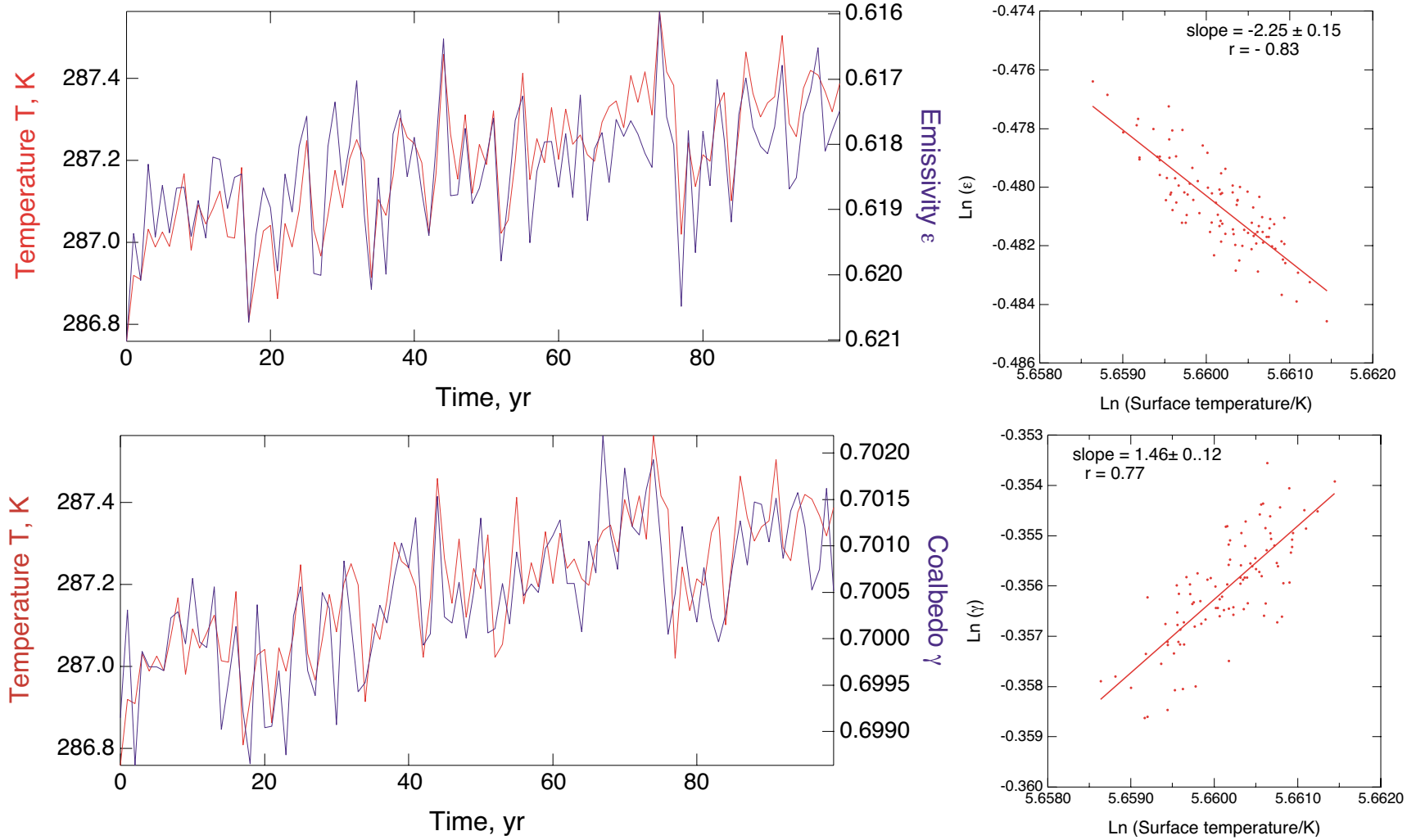




*Data source: PCMDI IPCC AR4 Archive*

# IPSL-CM4 21$^{st}$ century "commitment" run – Global annual average




*Data source: PCMDI IPCC AR4 Archive*

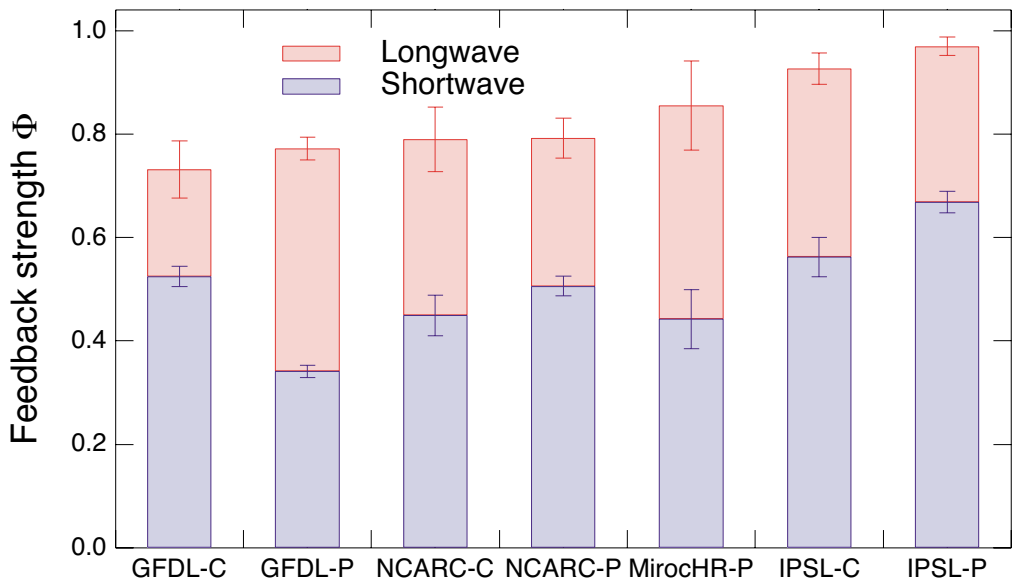
***Effective emissivity*** and ***planetary coalbedo*** are ***highly correlated*** with ***global-mean near-surface air temperature***.

Decrease of effective emissivity and increase of coalbedo with increasing surface temperature are ***both positive feedbacks***.

# FINDINGS

# FEEDBACK STRENGTHS OF GCMS

Diagnosed from correlation of planetary coalbedo and effective emissivity with surface temperature in unforced model runs

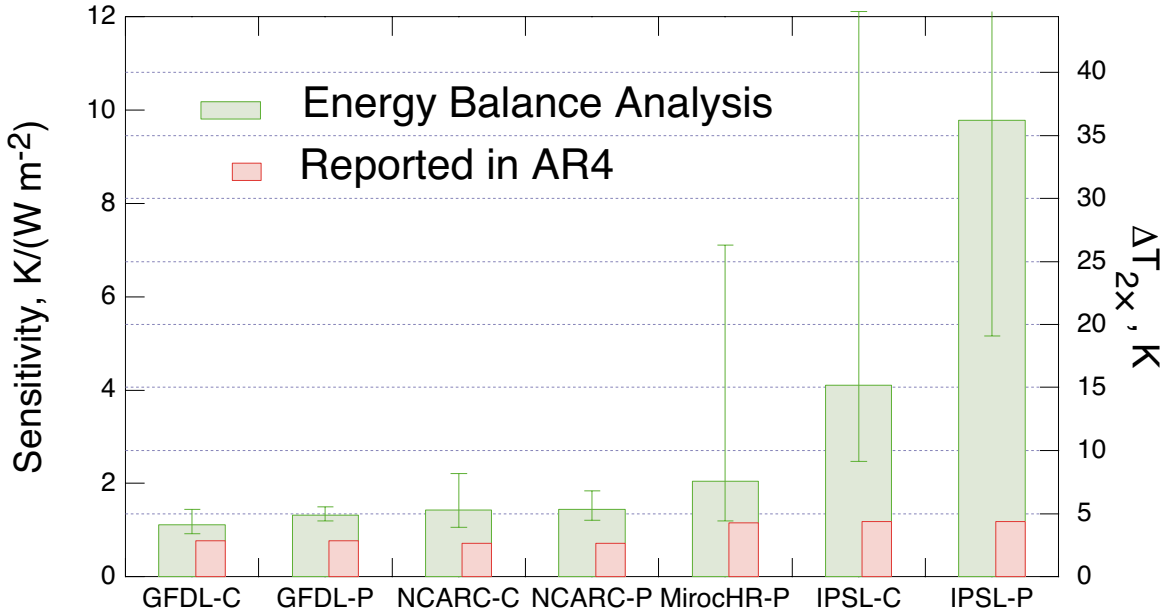



*Data source: PCMDI IPCC AR4 Archive*

| | | |
|---|---|---|
| GFDL | Geophysical Fluid Dynamics Laboratory, Princeton, NJ | CM2.0 |
| NCAR | National Center for Atmospheric Research, Boulder, CO | CCSM3.0 |
| MIROC | Frontier Research Center for Global Change in Japan | 3.2 HIRES |
| IPSL | Institut Pierre Simon Laplace, Paris France | CM4 |

C denotes 21$^{st}$ century commitment runs with constant (year-2000) forcing; P denotes preindustrial control run.

# SENSITIVITIES OF GCMS




*Data source: PCMDI IPCC AR4 Archive*

Diagnosed sensitivities are greater than sensitivities reported for these models.

Sensitivity and uncertainty are greatly amplified as feedback strength approaches unity.

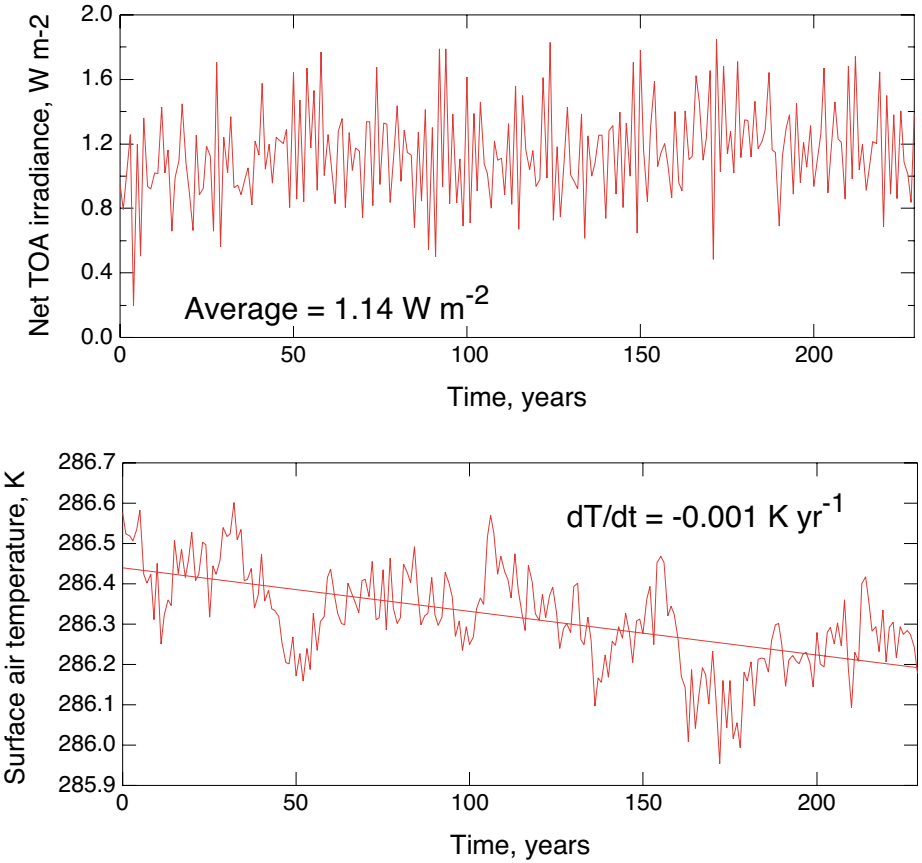
Uncertainties are propagated from 1-σ standard error in regression slope.

# ENERGY IMBALANCE IN CLIMATE MODELS

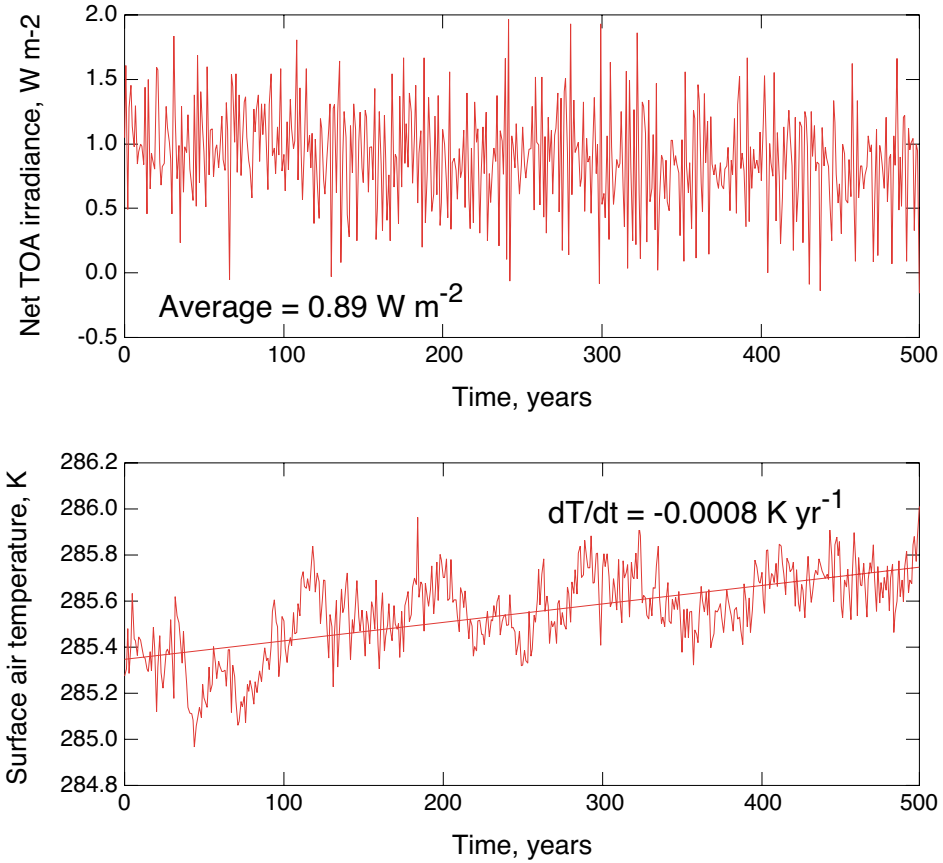
## Global-annual average net flux and temperature, preindustrial control runs

Net TOA flux evaluated as $J_{\text{net}}^{\downarrow\,\text{toa}} = J_{\text{sw}}^{\downarrow\,\text{toa}} - J_{\text{sw}}^{\uparrow\,\text{toa}} - J_{\text{lw}}^{\uparrow\,\text{toa}}$

### NCAR-CCSM3.0




### GFDL-CM2.0




*Data source: PCMDI IPCC AR4 Archive*

Net TOA flux is ***distinctly and substantially non-zero*** for preindustrial control runs, implying substantial imbalance (heating) of the climate system.

This flux ***greatly exceeds average heat flux into oceans*** even during global warming (second half of twentieth century; Levitus *et. al.* , GRL, 2005), 0.2 W $m^{-2}$.

This flux is comparable to forcings of concern over the industrial period.

Global mean temperature over the model run changes only slightly.

# CONCLUSIONS

Whole-Earth energy-balance considerations readily lead to expressions for shortwave and longwave ***feedback strengths***, overall ***feedback factor***, and ***climate sensitivity***.

Climate model feedback strengths and sensitivity can be deduced from archived near-surface air temperature and TOA fluxes for ***unforced model runs***.

This approach ***does not require model to be run out to equilibrium***.

Modeled ***planetary albedo and effective emissivity are highly correlated*** with annual-average near-surface ***global mean temperature***.

Application to archived AR4 runs suggests ***greater model sensitivities*** than previously reported.

Examination of preindustrial control runs suggests ***substantial energy imbalance in some models***.