DEFINING AND QUANTIFYING FEEDBACKS IN EARTH'S CLIMATE SYSTEM

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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.

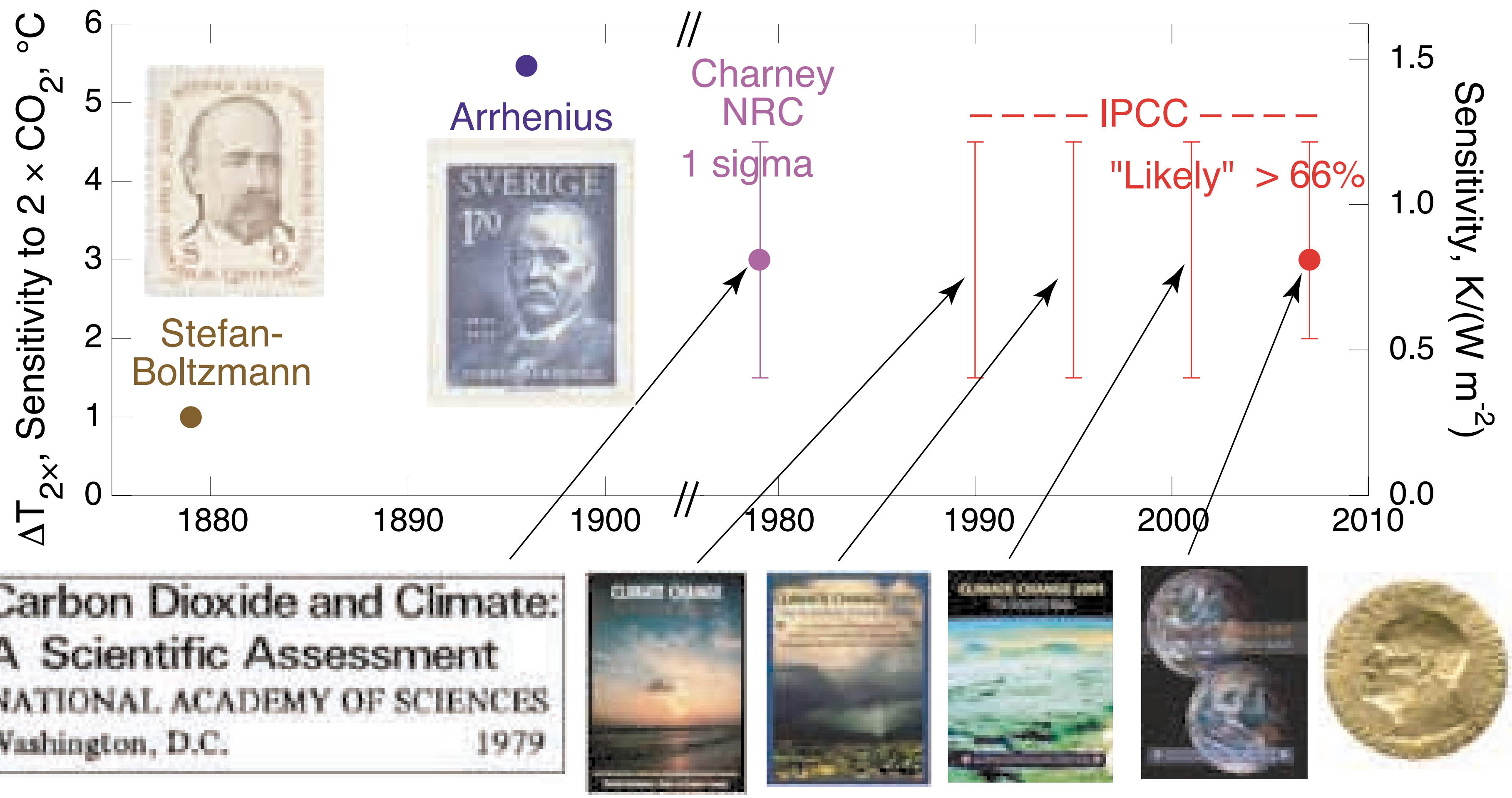
The reasons for differences in sensitivities between different climate models are ***hard to determine and interpret***.

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

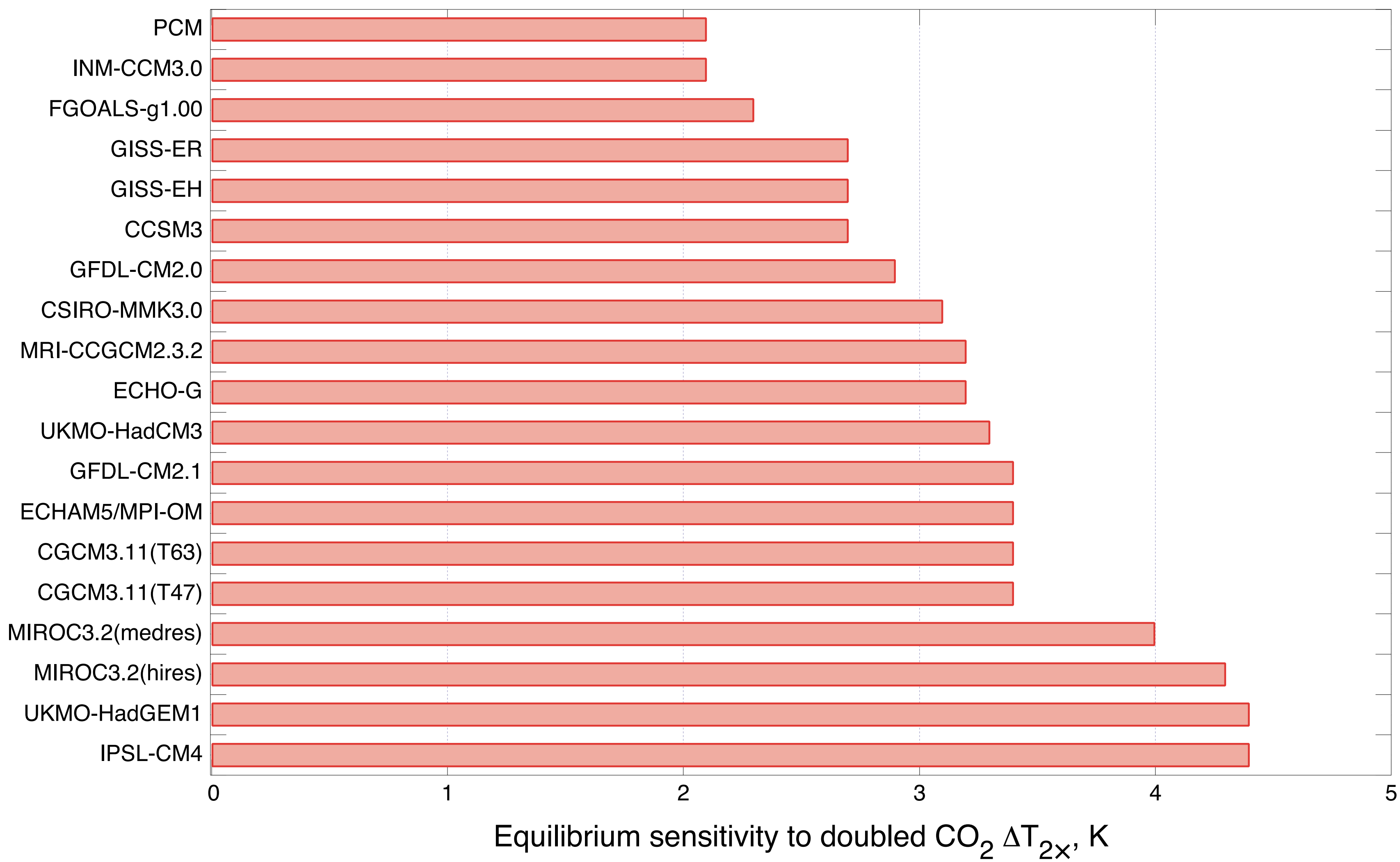
Estimates of central value and uncertainty range from major national and international assessments



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

EQUILIBRIUM SENSITIVITIES IN CURRENT CLIMATE MODELS

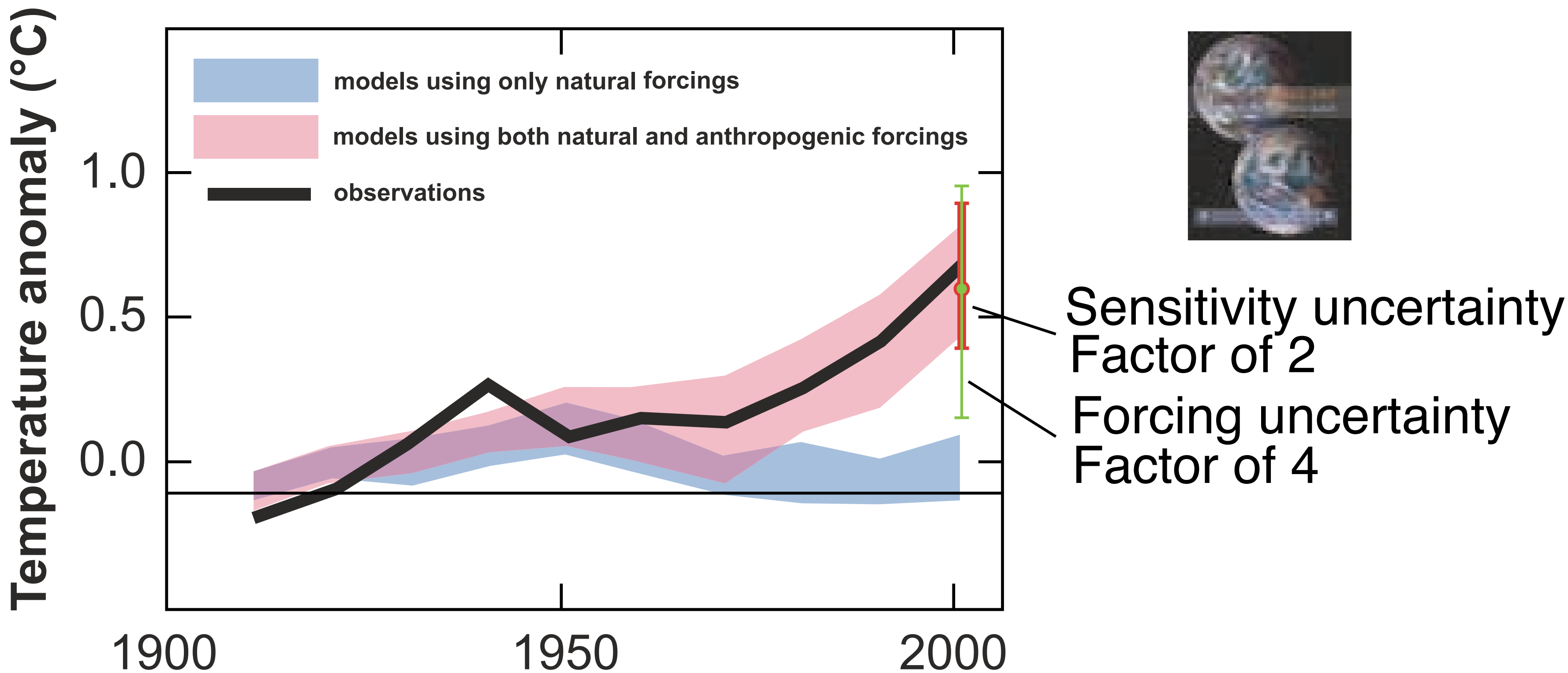
20 Models employed in IPCC AR4 simulations



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: $\frac{dH}{dt} = Q - E$

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 ΔF 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:

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

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

J_S is solar constant

γ is planetary coalbedo

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

σ is Stefan-Boltzmann constant

ε 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: $S_{NF} = \frac{1}{4\varepsilon\sigma T_{s0}^3} = \frac{T_{s0}}{\gamma J_S} = 0.30 \text{ K/(W m}^{-2}\text{)}$

***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.

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

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

Effective emissivity

$$\varepsilon = \frac{\overline{E}}{\sigma \overline{T_s}^4}$$

E = upwelling longwave irradiance at TOA:

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

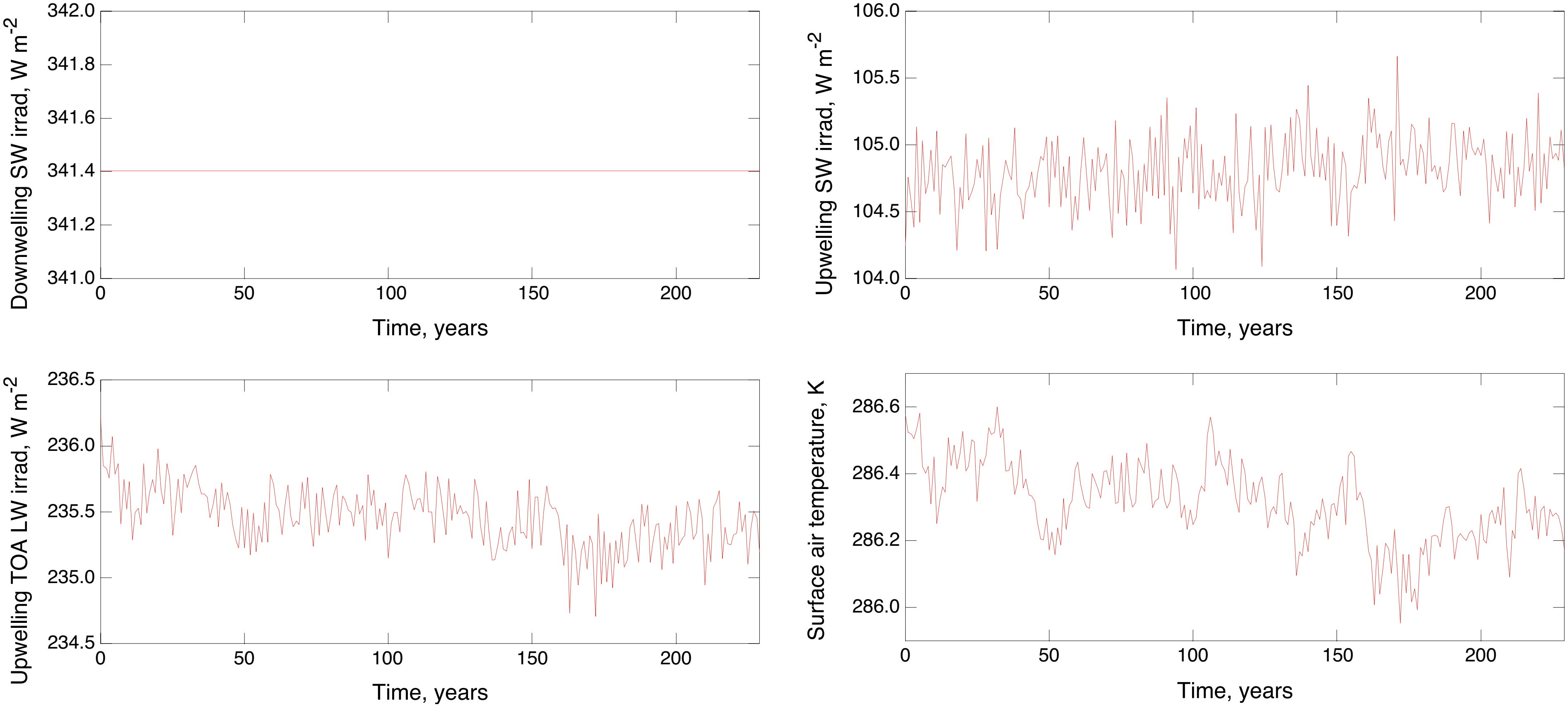
$$\varepsilon = \frac{\overline{J_{lw}^{\uparrow toa}}}{\sigma \overline{T_s}^4}$$

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

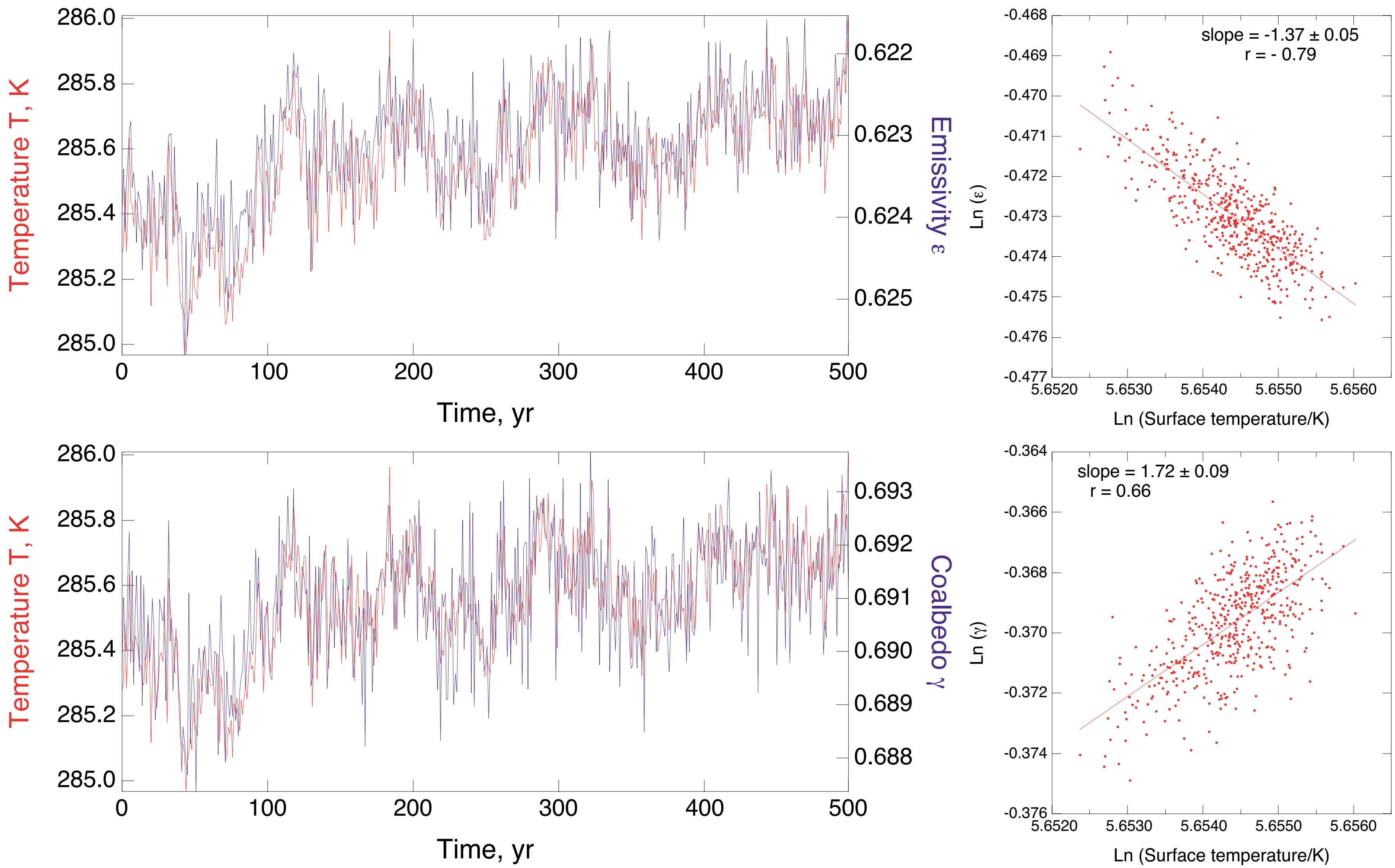
Global-annual averages; NCAR-CCSM3.0 preindustrial control run



Data source: PCMDI IPCC AR4 Archive

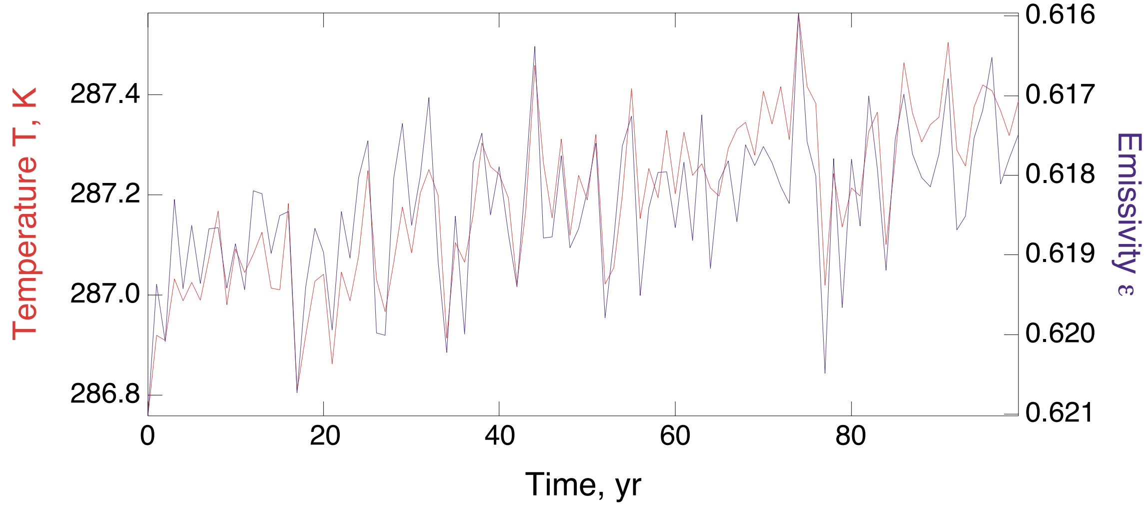
CORRELATION OF EFFECTIVE EMISSIVITY AND COALBEDO WITH SURFACE TEMPERATURE

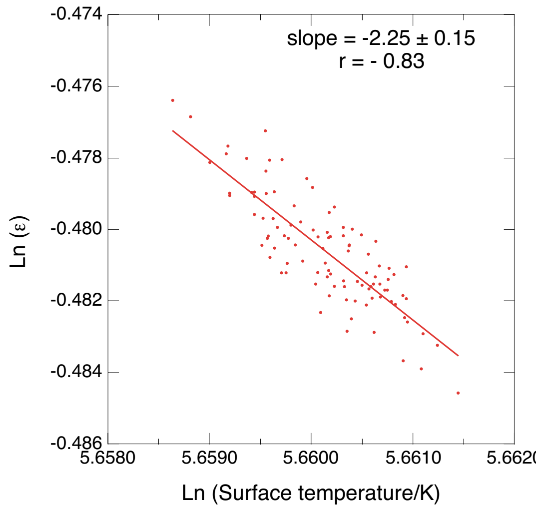
GFDL-CM2.0 preindustrial control run – Global annual average

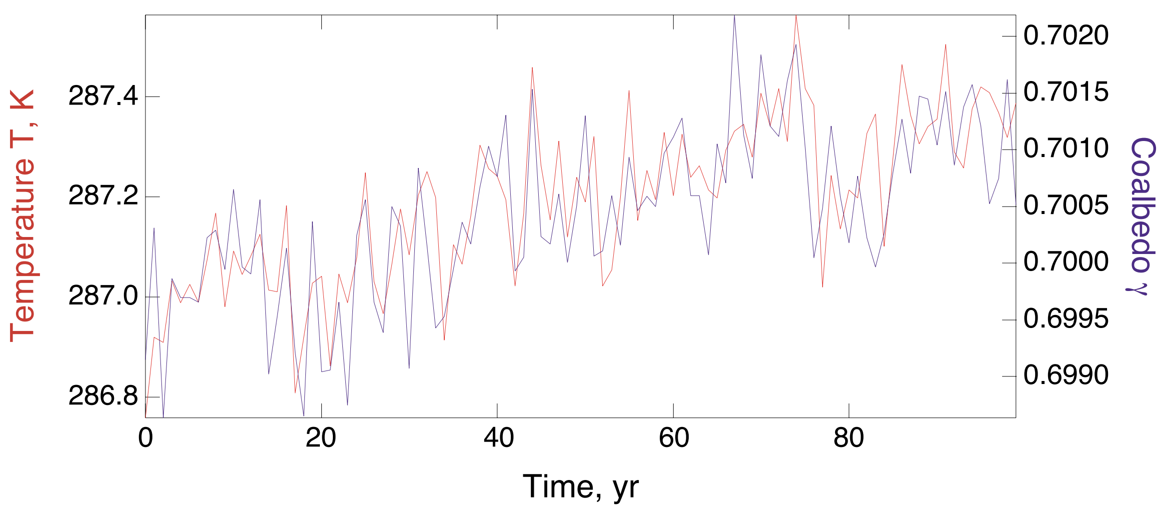


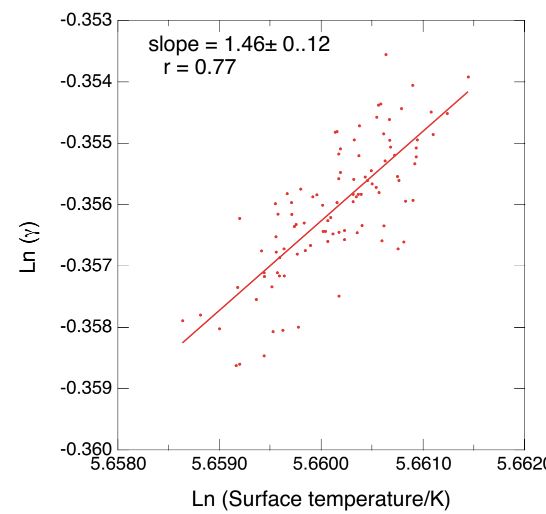
Data source: PCMDI IPCC AR4 Archive

IPSL-CM4 21st century “commitment” run – Global annual average









Data source: PCMDI IPCC AR4 Archive

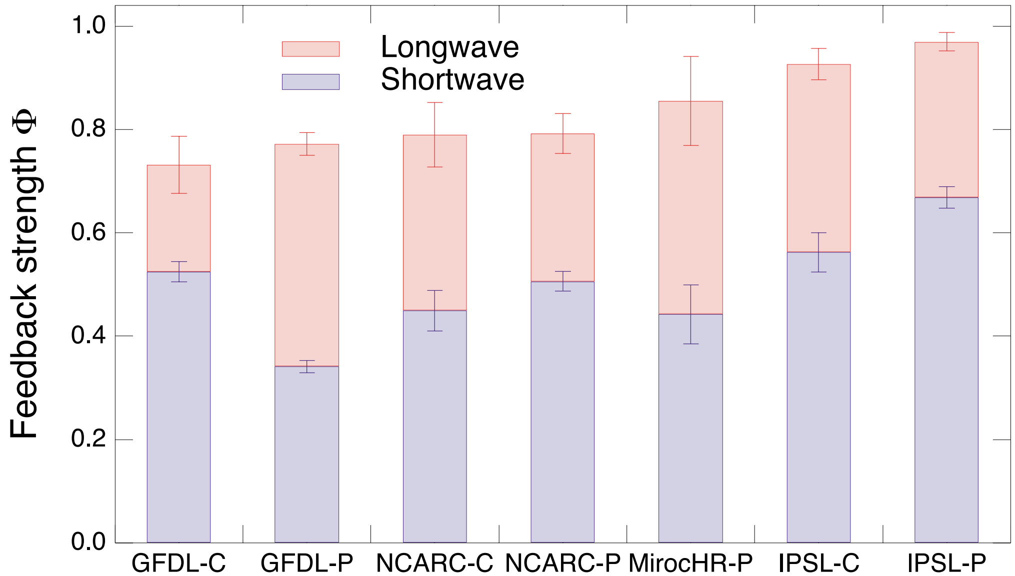
Effective emissivity and ***planetary coalbedo*** are ***highly correlated*** with ***global-mean near-surface air temperature***.

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

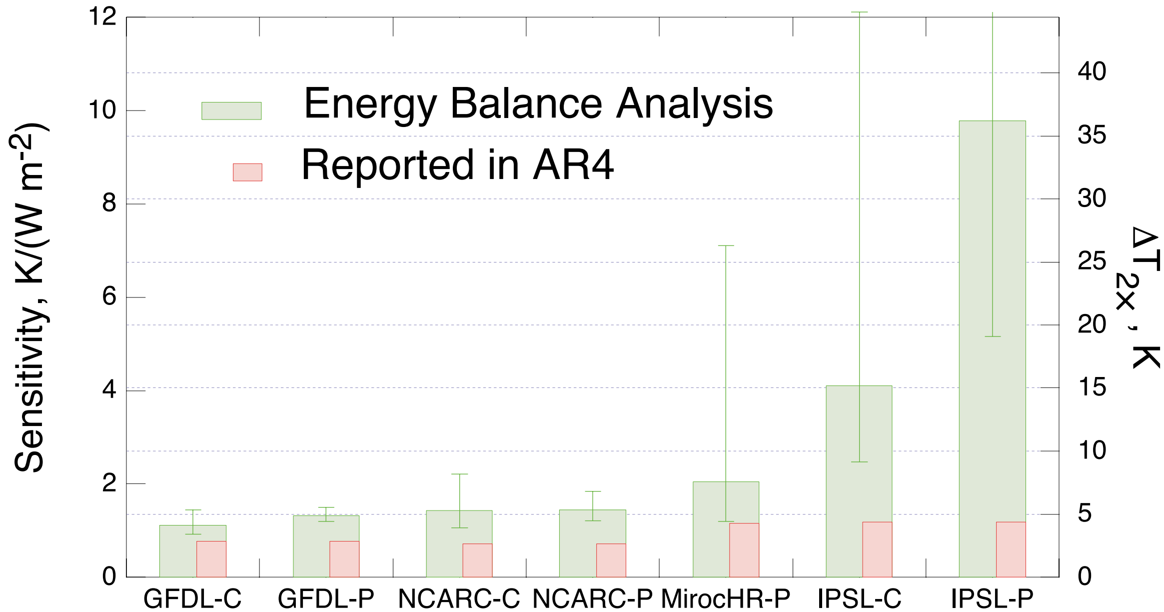


Data source: PCMDI IPCC AR4 Archive

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.

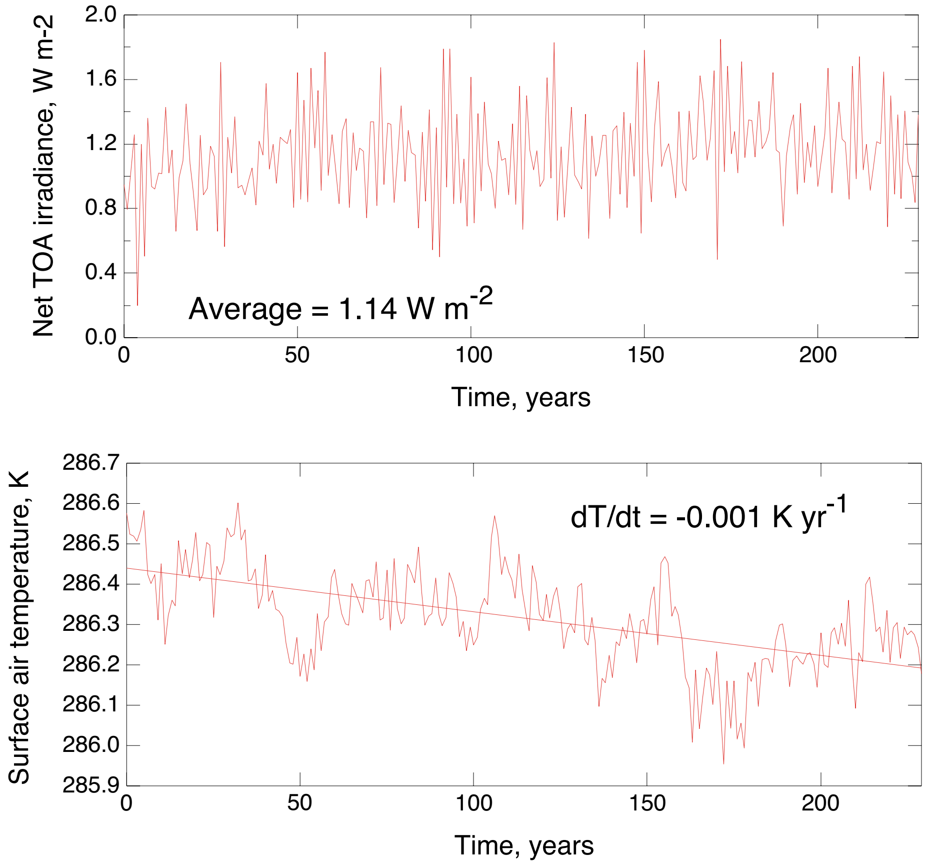
Uncertainties are propagated from 1-σ standard error in regression slope.

ENERGY IMBALANCE IN CLIMATE MODELS

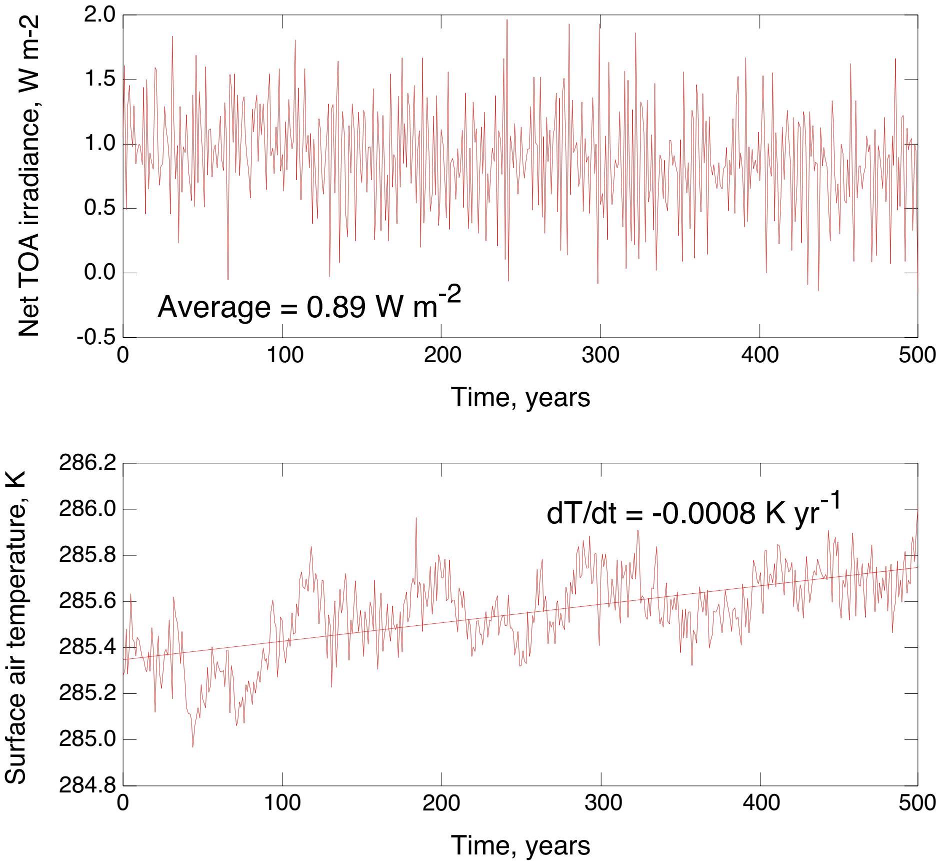
Global-annual average net flux and temperature, preindustrial control runs

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

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***.