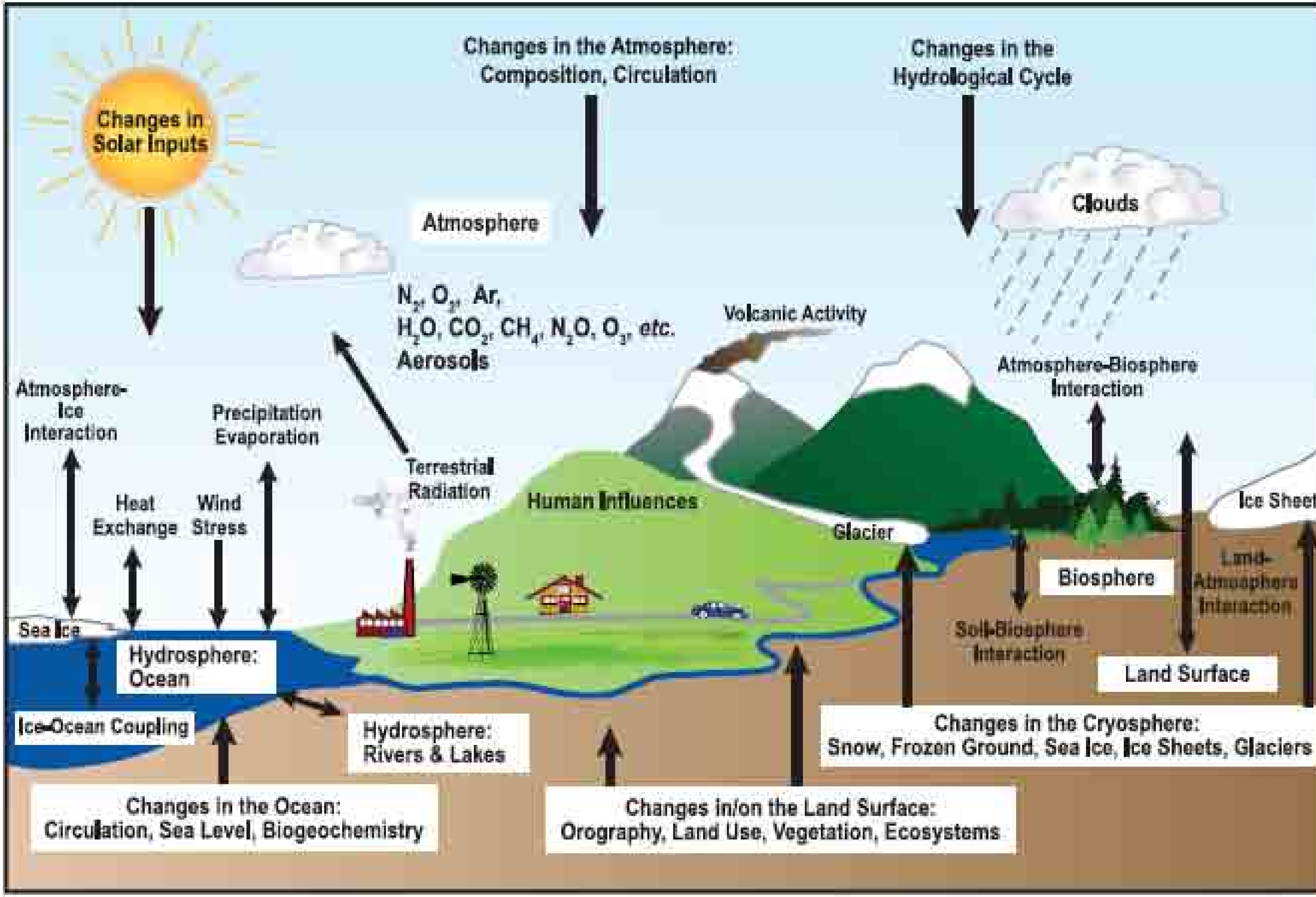
Climate Sensitivity, Forcings, And Feedbacks

Forcings and Feedbacks in the Climate System



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Forcings and Feedbacks

Consider the total flux of radiation through the top of the atmosphere:

$$F_{TOA} = F_{solar} - F_{IR}$$

Each term on the right can be regarded as function of the surface temperature, T_s, and many other variables x_i :

$$F_{TOA} = F_{TOA}\left(T_s, x_1, x_2, \ldots\ldots x_N\right)$$

By chain rule,

$$\delta F_{TOA} = 0 = \frac{\partial F_{TOA}}{\partial T_s}\delta T_s + \sum_{i=1}^{N}\frac{\partial F_{TOA}}{\partial x_i}\delta x_i$$

Now let's call the N^{th} process a "forcing", Q:

$$\delta F_{TOA} = 0 = \frac{\partial F_{TOA}}{\partial T_s}\delta T_s + \sum_{i=1}^{N-1}\frac{\partial F_{TOA}}{\partial x_i}\delta x_i + \delta Q$$

$$= \frac{\partial F_{TOA}}{\partial T_s}\delta T_s + \sum_{i=1}^{N-1}\frac{\partial F_{TOA}}{\partial x_i}\frac{\partial x_i}{\partial T_s}\delta T_s + \delta Q$$

Then

$$\frac{\partial T_s}{\partial Q} \equiv \lambda_R = -\frac{1}{\dfrac{\partial F_{TOA}}{\partial T_s} + \displaystyle\sum_{i=1}^{N-1}\frac{\partial F_{TOA}}{\partial x_i}\frac{\partial x_i}{\partial T_s}}$$

$$\text{Let}\quad S \equiv \left(-\frac{\partial F_{TOA}}{\partial T_s} \right)^{-1}$$

Climate sensitivity without feedbacks

$$\frac{\partial T_s}{\partial Q} \equiv \lambda_R = \frac{S}{1 - S\sum_{i=1}^{N-1} \frac{\partial F_{TOA}}{\partial x_i}\frac{\partial x_i}{\partial T_s}}$$

Climate sensitivity

Feedback factors; can be of either sign

Note that feedback factors do NOT add linearly in their collective effects on climate sensitivity

Examples of Forcing:

- Changing solar constant
- Orbital forcing
- Changing concentrations of non-interactive greenhouse gases
- Volcanic aerosols
- Manmade aerosols
- Land use changes

Solar Sunspot Cycle

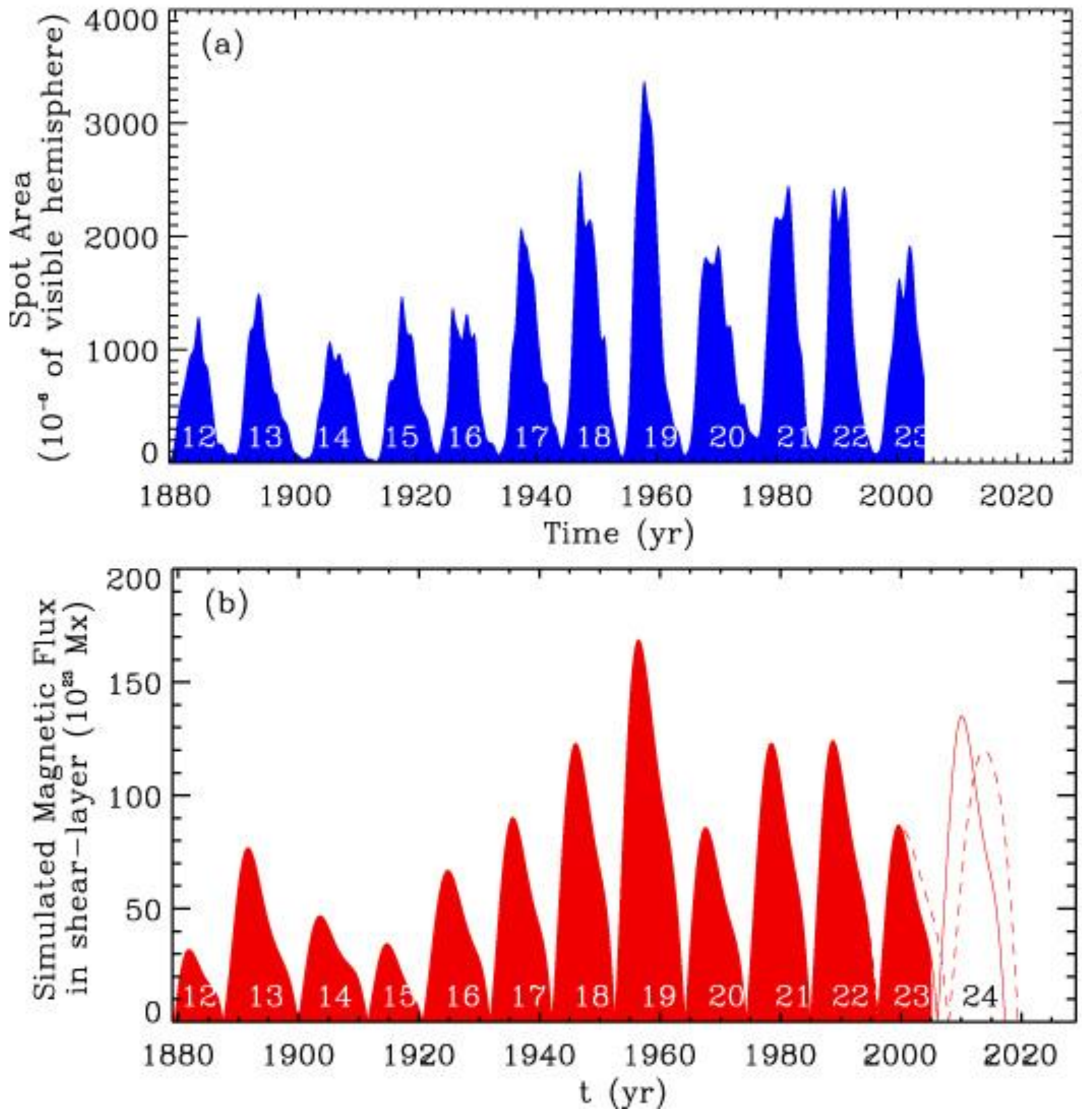
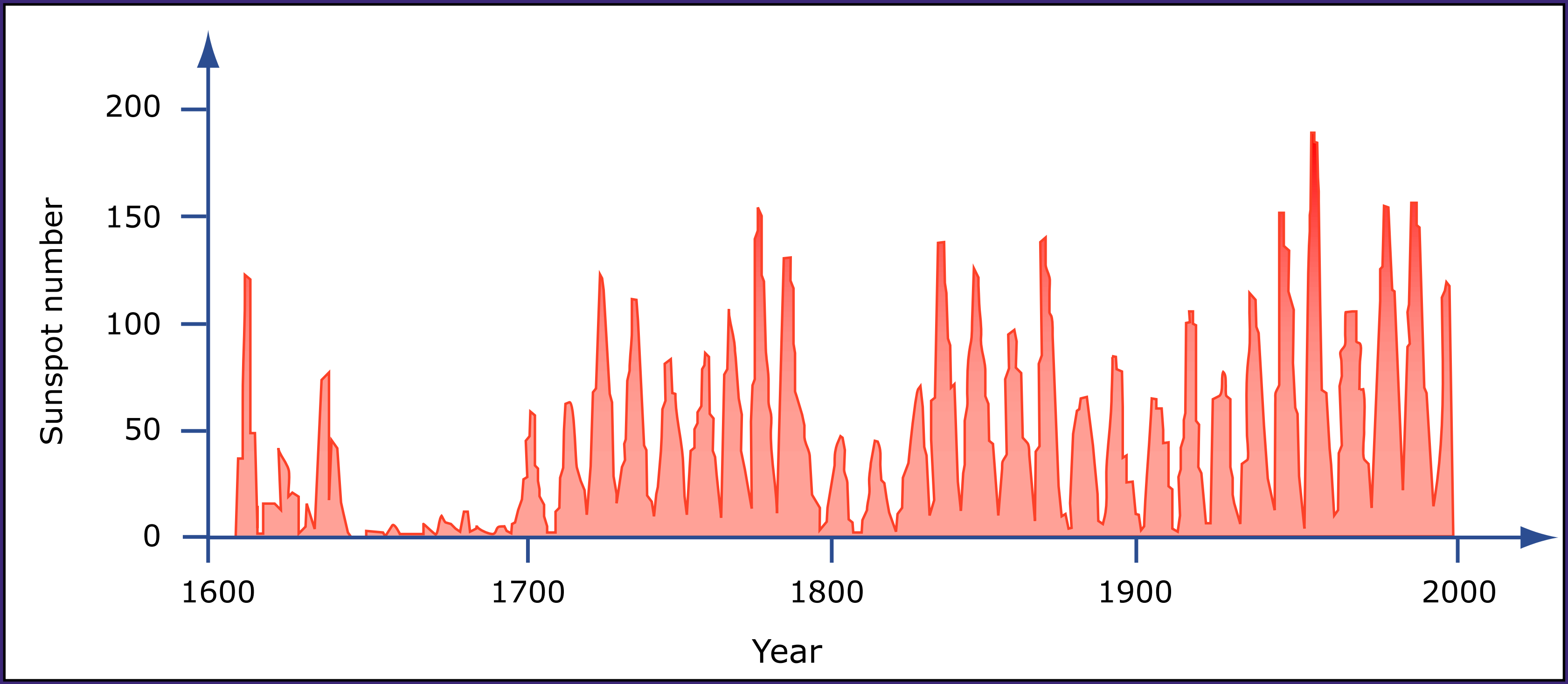
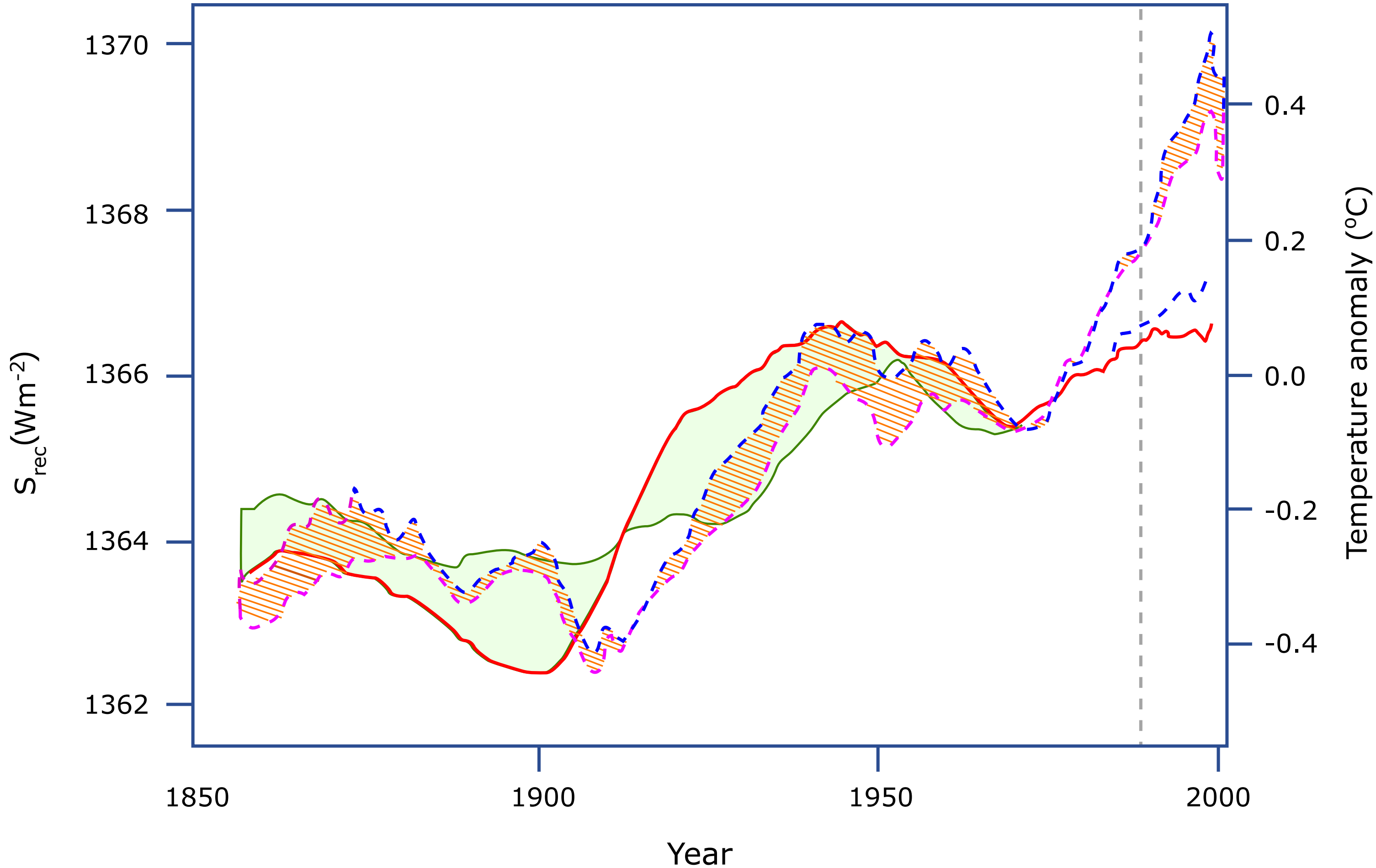


Image courtesy of NASA.


200
150
100
50
0
Sunspot number
1600
1700
1800
1900
2000
Year



Two reconstructions of total solar irradiance combined with measurements, where available (enclosing the greenshading) and two climate records (enclosing the orange shading) spanning roughly 150 years.

Satellite measurements of solar flux

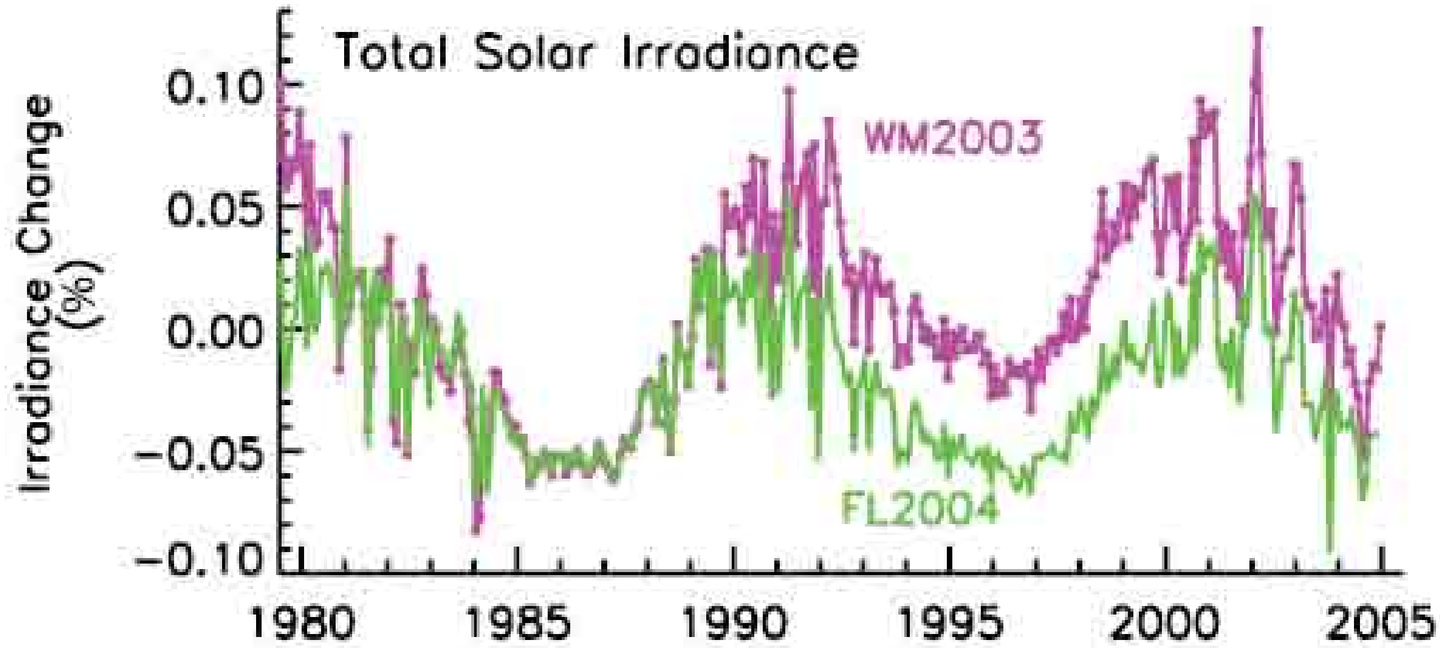


Figure 2.16. *Percentage change in monthly values of the total solar irradiance composites of Willson and Mordvinov (2003; WM2003, violet symbols and line) and Fröhlich and Lean (2004; FL2004, green solid line).*

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X-Ray Flux

Normal solar cycle variations in solar radiation

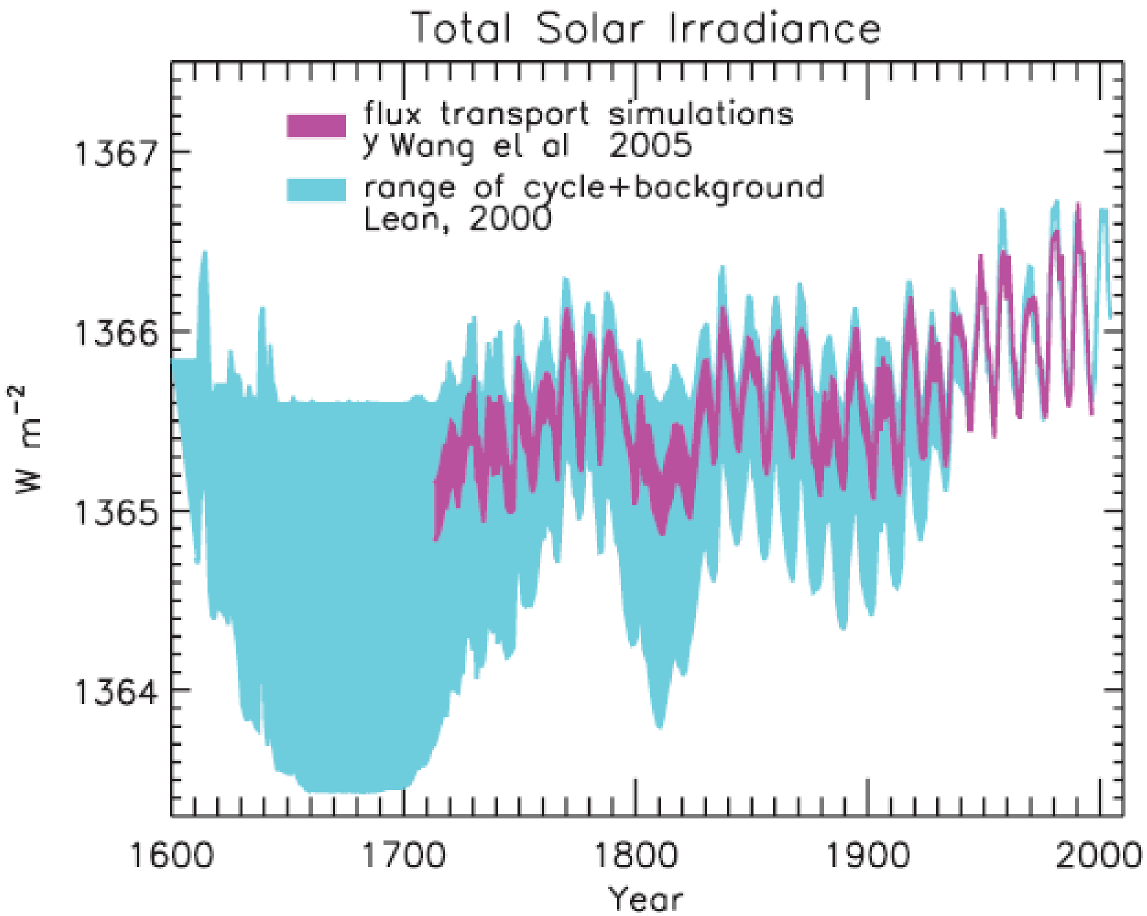

Figure 2.17. *Reconstructions of the total solar irradiance time series starting as early as 1600. The upper envelope of the shaded regions shows irradiance variations arising from the 11-year activity cycle. The lower envelope is the total irradiance reconstructed by Lean (2000), in which the long-term trend was inferred from brightness changes in Sun-like stars. In comparison, the recent reconstruction of Y. Wang et al. (2005) is based on solar considerations alone, using a flux transport model to simulate the long-term evolution of the closed flux that generates bright faculae.*

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Inferences based on Models of Solar Variability

Climate Forcing by Orbital Variations

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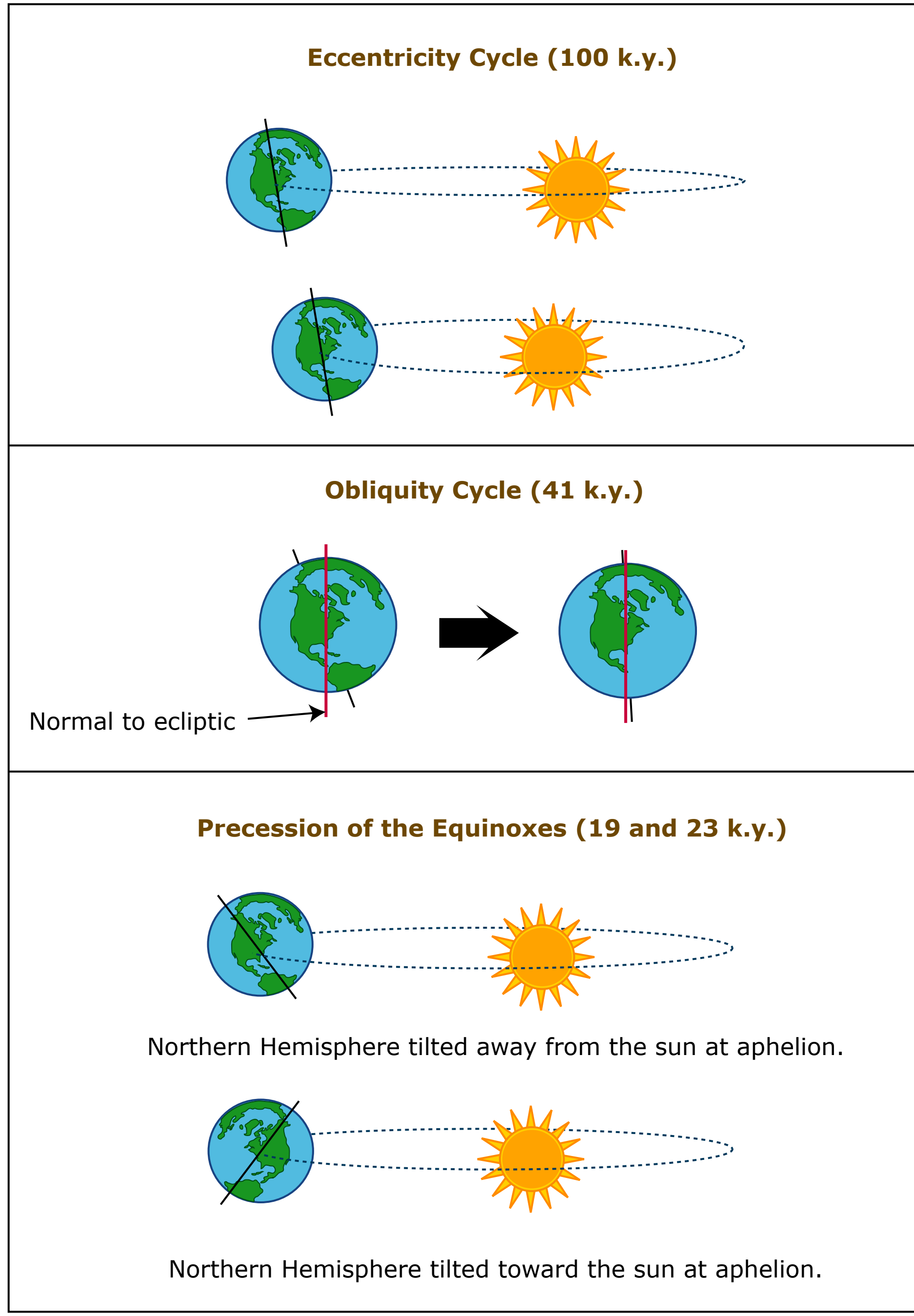
Please see the photo on page http://www.detectingdesign.com/milankovitch.html.

Milutin Milanković, 1879-1958



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Climate Forcing and Response

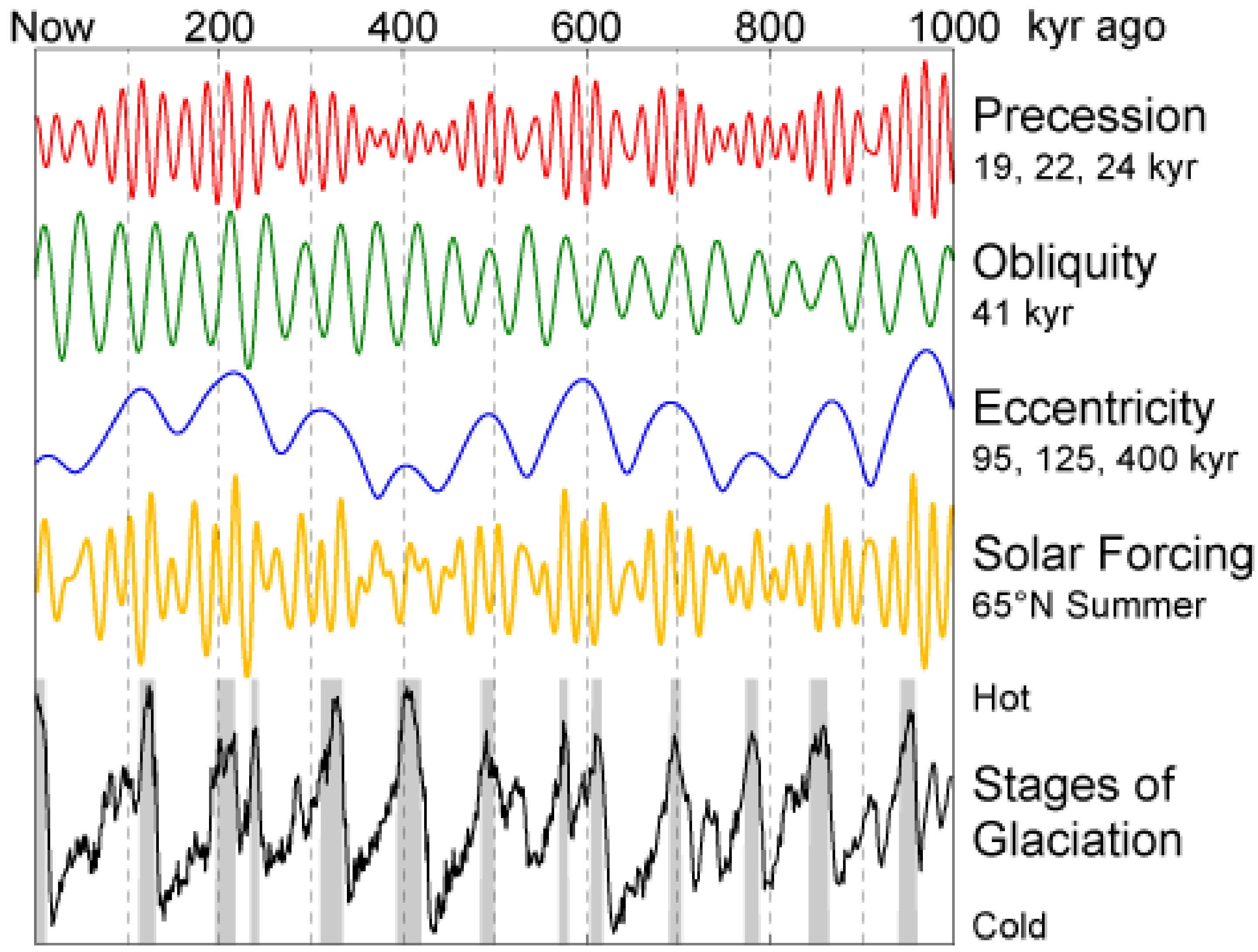

Image courtesy of Global Warming Art.

Strong Correlation between High Latitude Summer Insolation and Ice Volume

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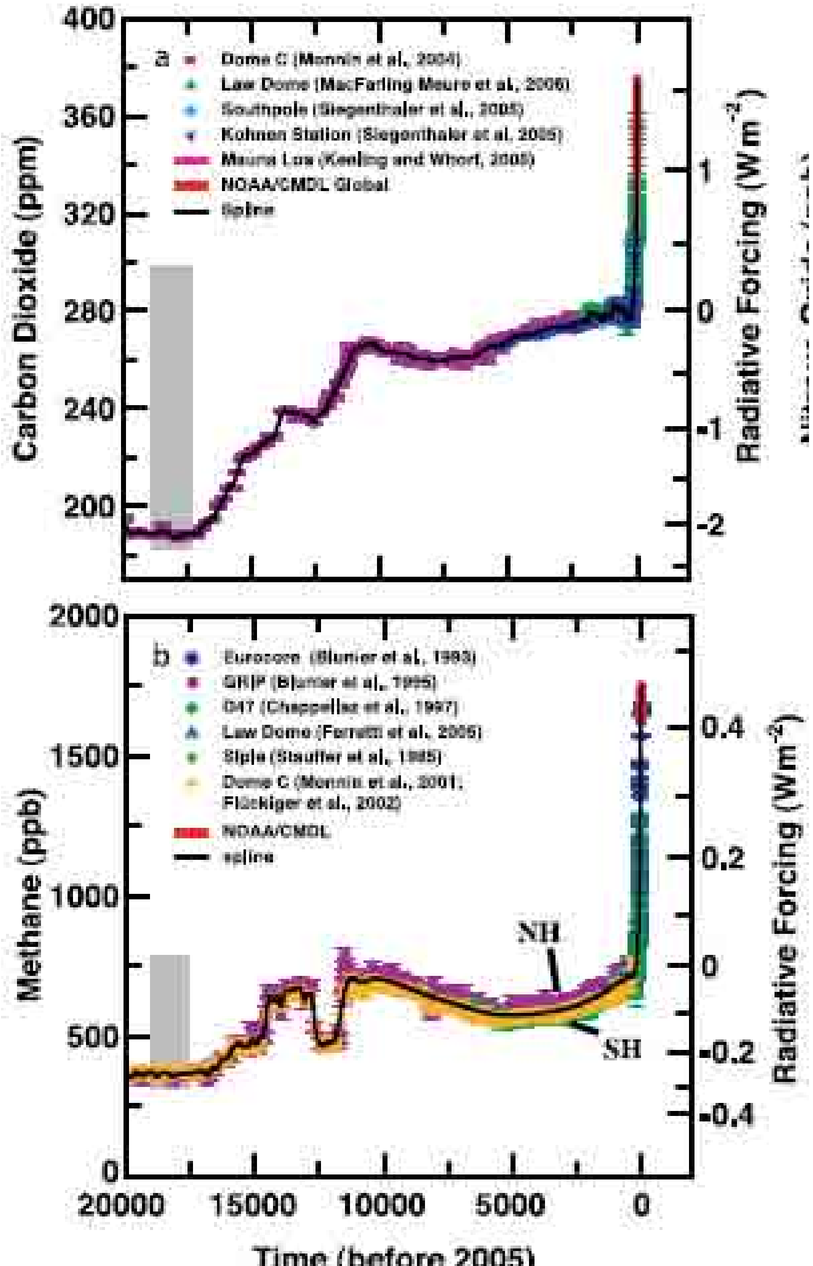

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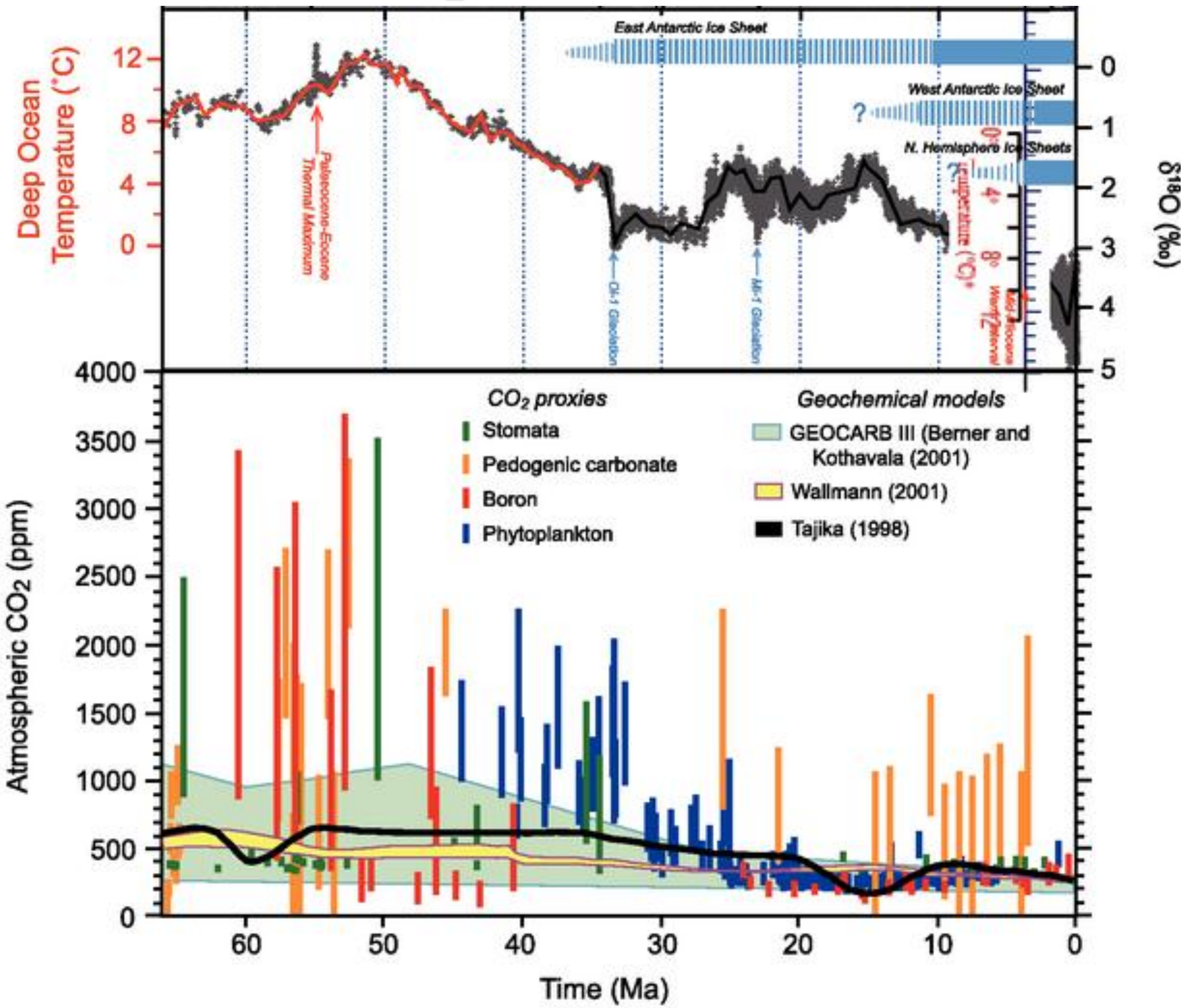
Variation in carbon dioxide and methane over the past 20,000 years, based on ice core and other records

CO_2 and Climate



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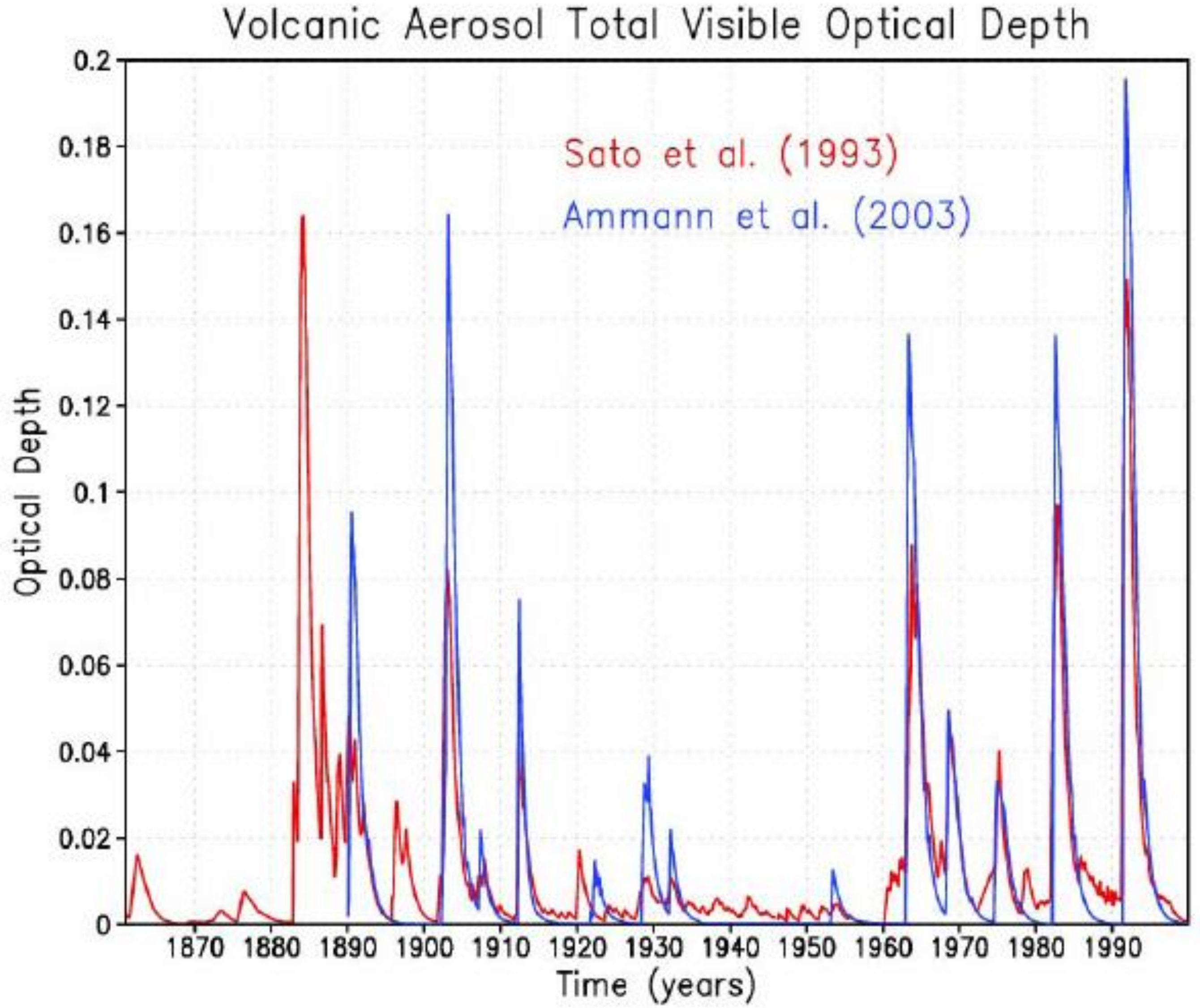
Recent History of Volcanic Eruptions



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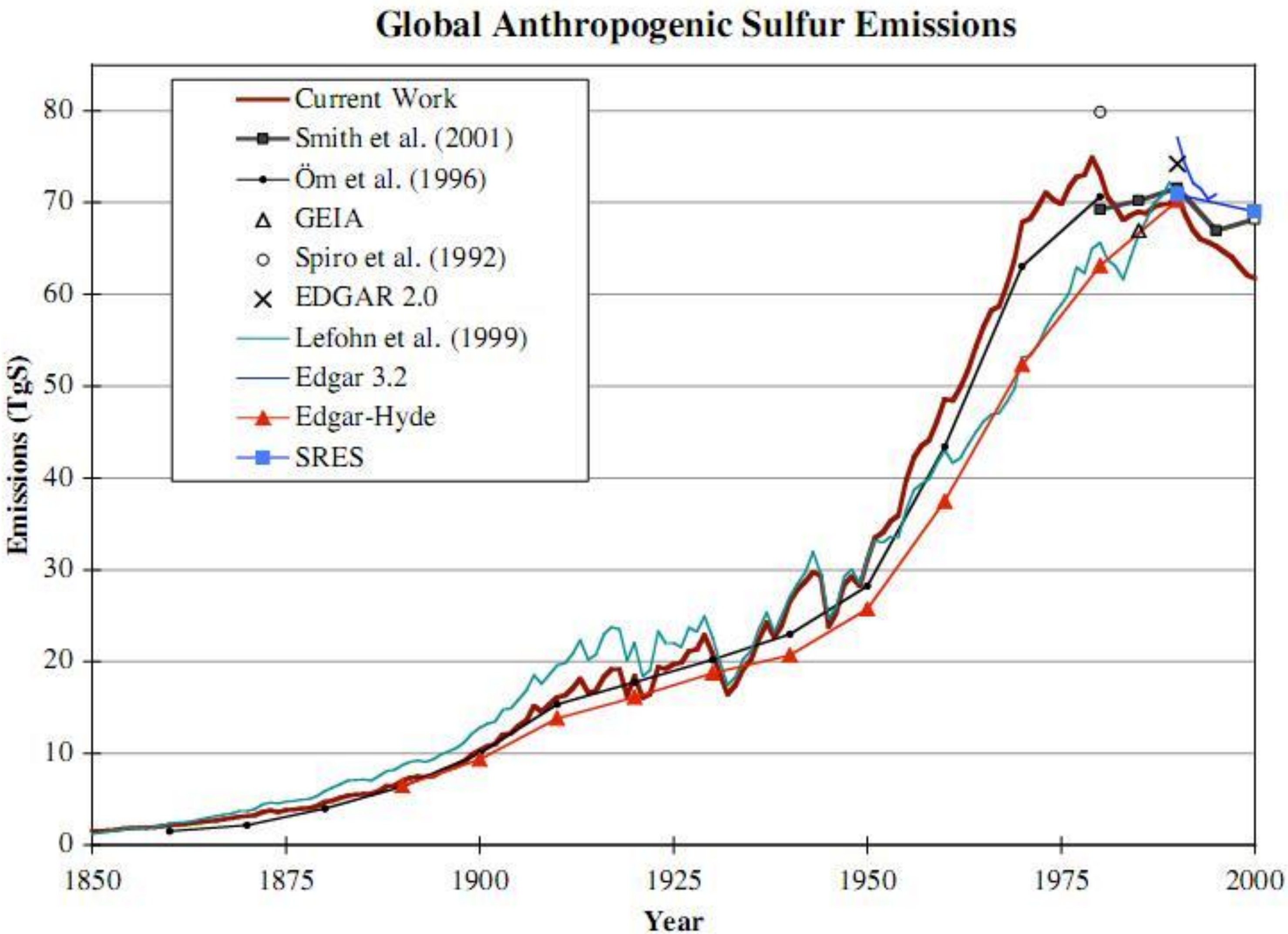
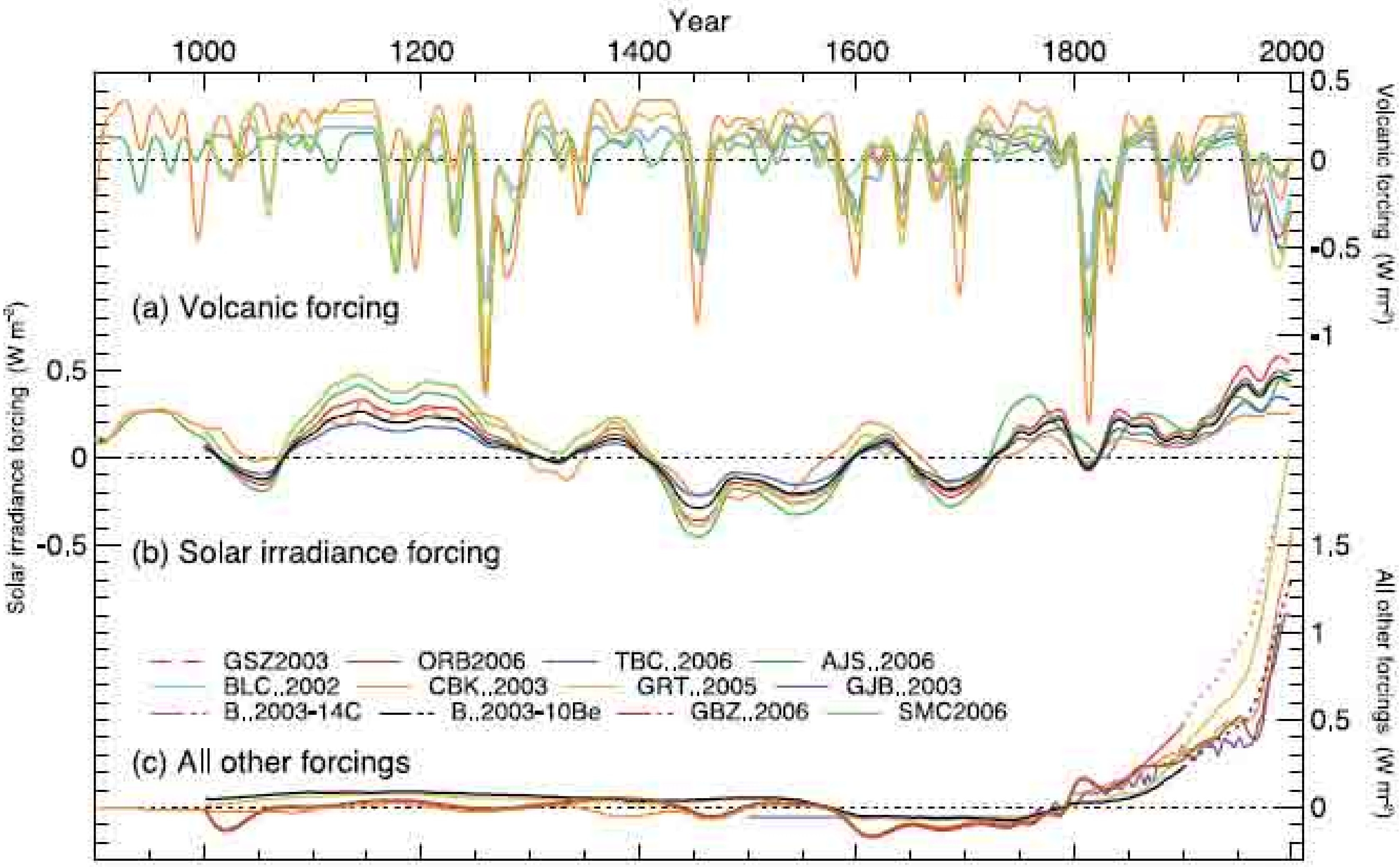


Figure 1–Global sulfur dioxide emissions from this study (thick line) and several other recent estimates (see text). Note that the Lefohn *et al*. estimate does not include all anthropogenic emissions sources. References not shown on the cart are: GEIA (Benkovitz *et al.*1996); EDGAR 2.0 (Olivier *et al* 1996); EDGAR 3.2 (Olivier and Berdowski, 2001); EDGAR-HYDE (Van Aardenne *et al.* 2001); and SRES (Nakicenovic and Swart 2000).

Image courtesy of US government.

Variation with Time of Natural Climate Forcings:



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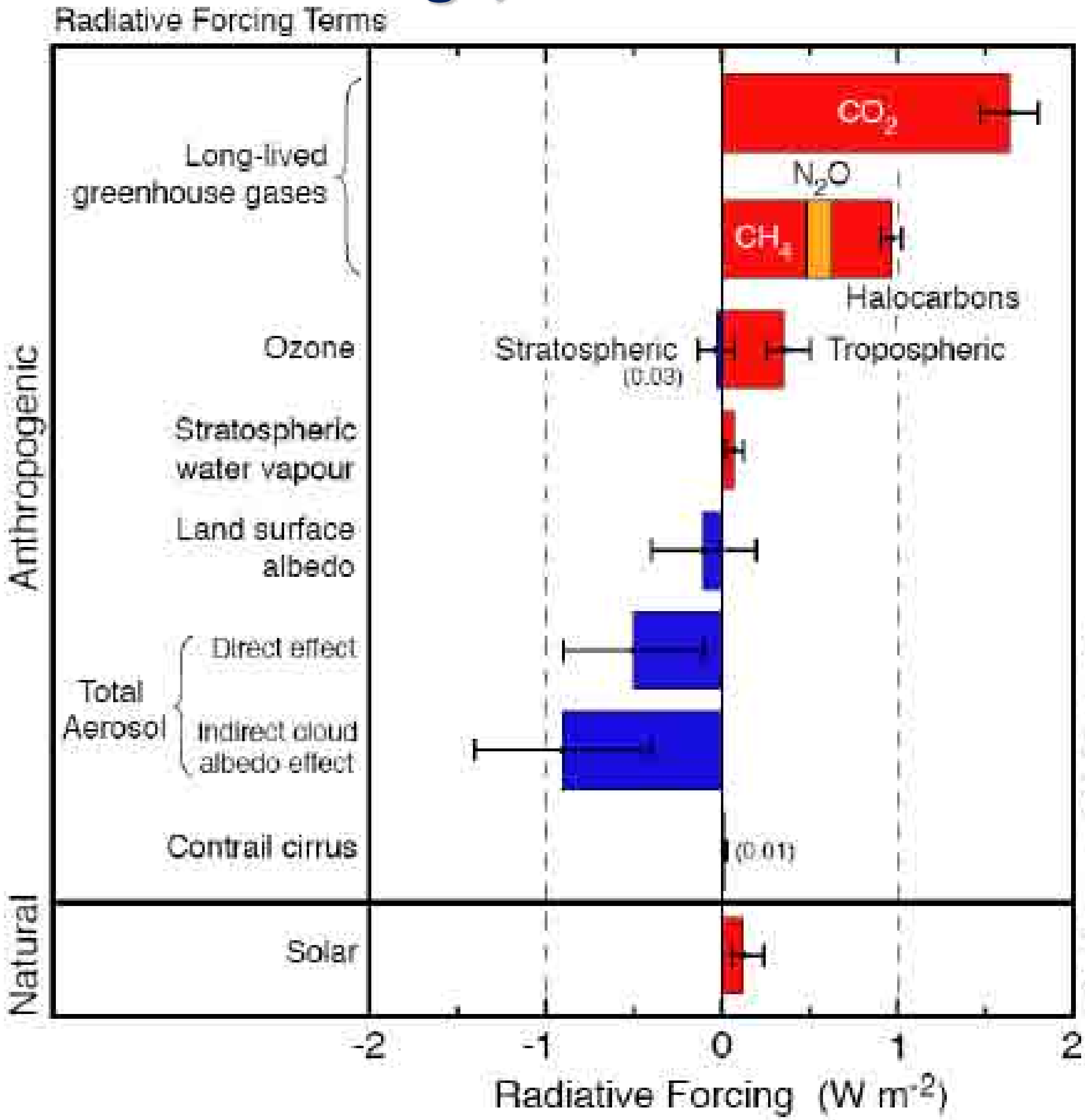
Examples of Forcing Magnitudes:

- A *1.6%* change in the solar constant, equivalent to $4\ Wm^{-2}$, would produce about 1^oC change in surface temperature

- Doubling CO_2, equivalent to $4\ Wm^{-2}$, would produce about 1^oC change in surface temperature

Contributions to net radiative forcing change, 1750-2004:



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Examples of Feedbacks:

- Water vapor
- Ice-albedo
- Clouds
- Surface evaporation
- Biogeochemical feedbacks

Estimates of Climate Sensitivity

$$\frac{\partial T_s}{\partial Q} \equiv \lambda_R = \frac{S}{1 - S\sum_{i=1}^{N-1} \frac{\partial F_{TOA}}{\partial x_i}\frac{\partial x_i}{\partial T_s}}$$

$$S \equiv \left(-\frac{\partial F_{TOA}}{\partial T_s} \right)^{-1}$$

Suppose that $T_s = T_e$ + *constant* and that shortwave radiation is insensitive to T_s:

$$F_{TOA} = -\sigma T_e^4, \quad \frac{\partial F_{TOA}}{\partial T_s} = -\frac{\partial}{\partial T_s}\sigma T_e^4 = -4\sigma T_e^3 = -3.8 Wm^{-2} K^{-1}$$

$$S = 0.26 K \left(Wm^{-2} \right)^{-1}$$

Examples of feedback magnitudes:

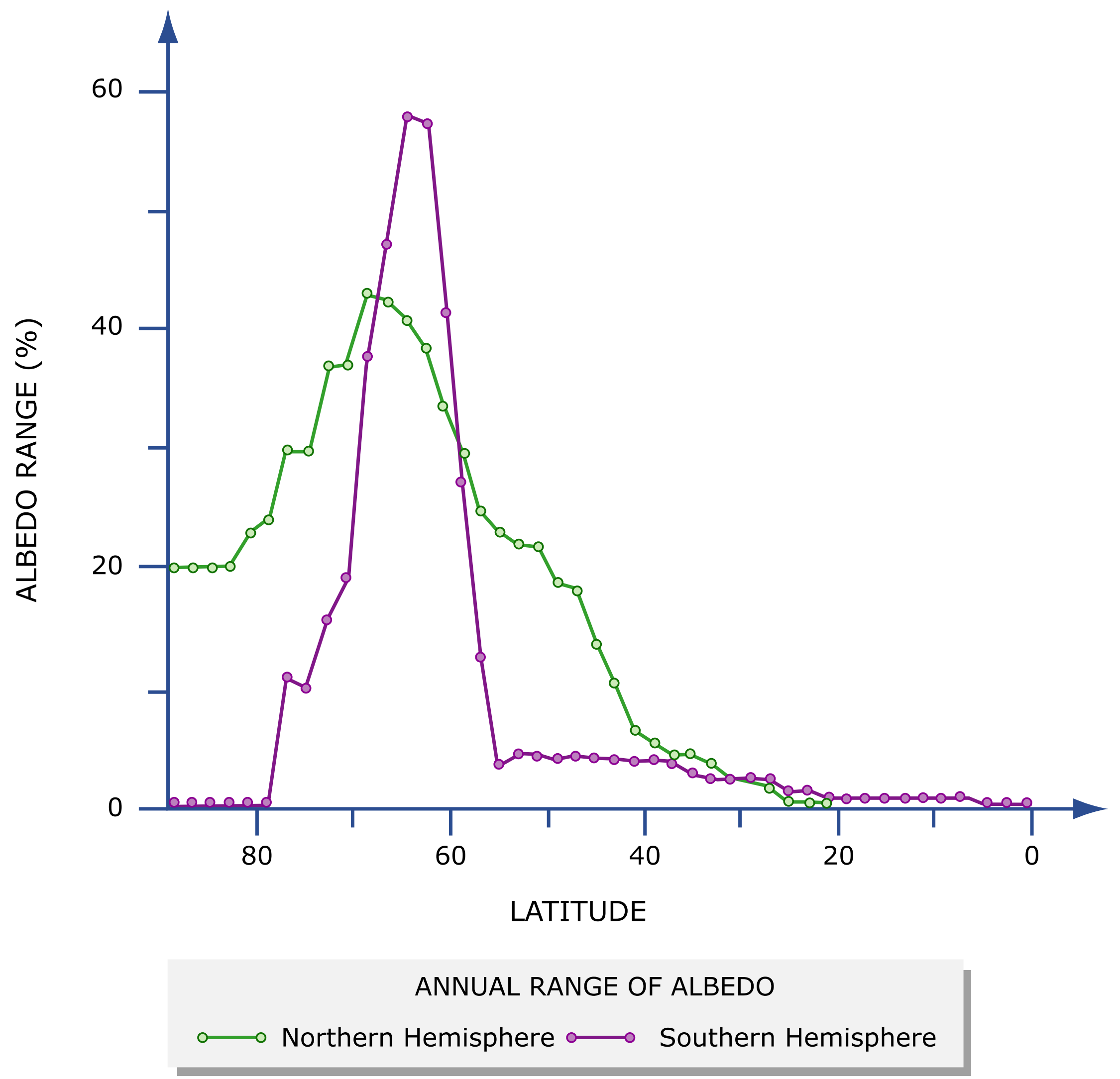
- Experiments with one-dimensional radiative-convective models suggest that holding the relative humidity fixed,

$$\left(\frac{\partial F_{TOA}}{\partial q}\right)\left(\frac{\partial q}{\partial T_s}\right)_{RH} \cong 2\,Wm^{-2}K^{-1},$$

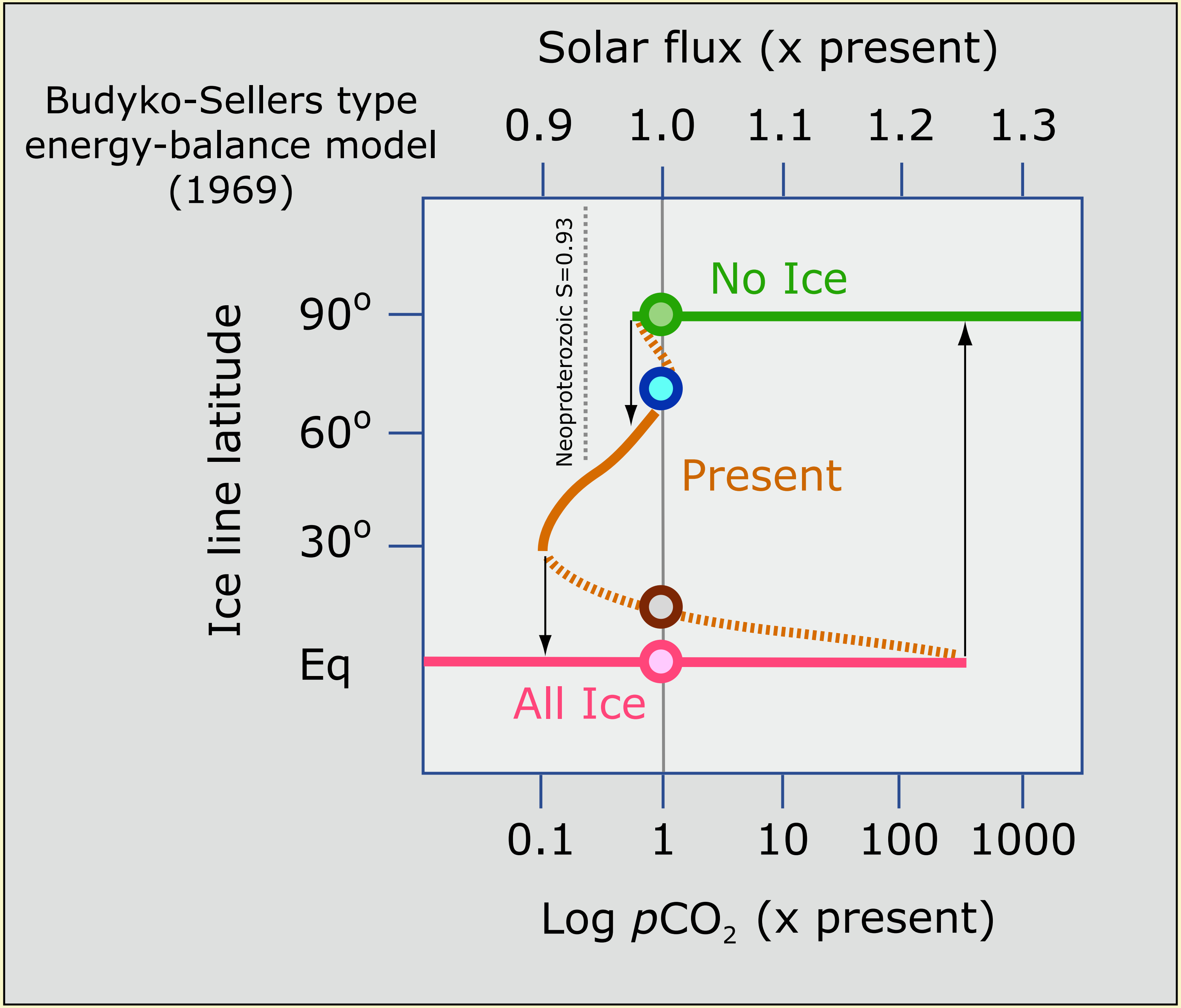
$$S\left(\frac{\partial F_{TOA}}{\partial q}\right)\left(\frac{\partial q}{\partial T_s}\right)_{RH} \cong 0.5$$

This, by itself, doubles climate sensitivity; with other positive feedbacks, effect on sensitivity is even larger

Ice-Albedo Feedback



Annual range of zonal monthly surface albedo estimates by 2° latitudinal belts.



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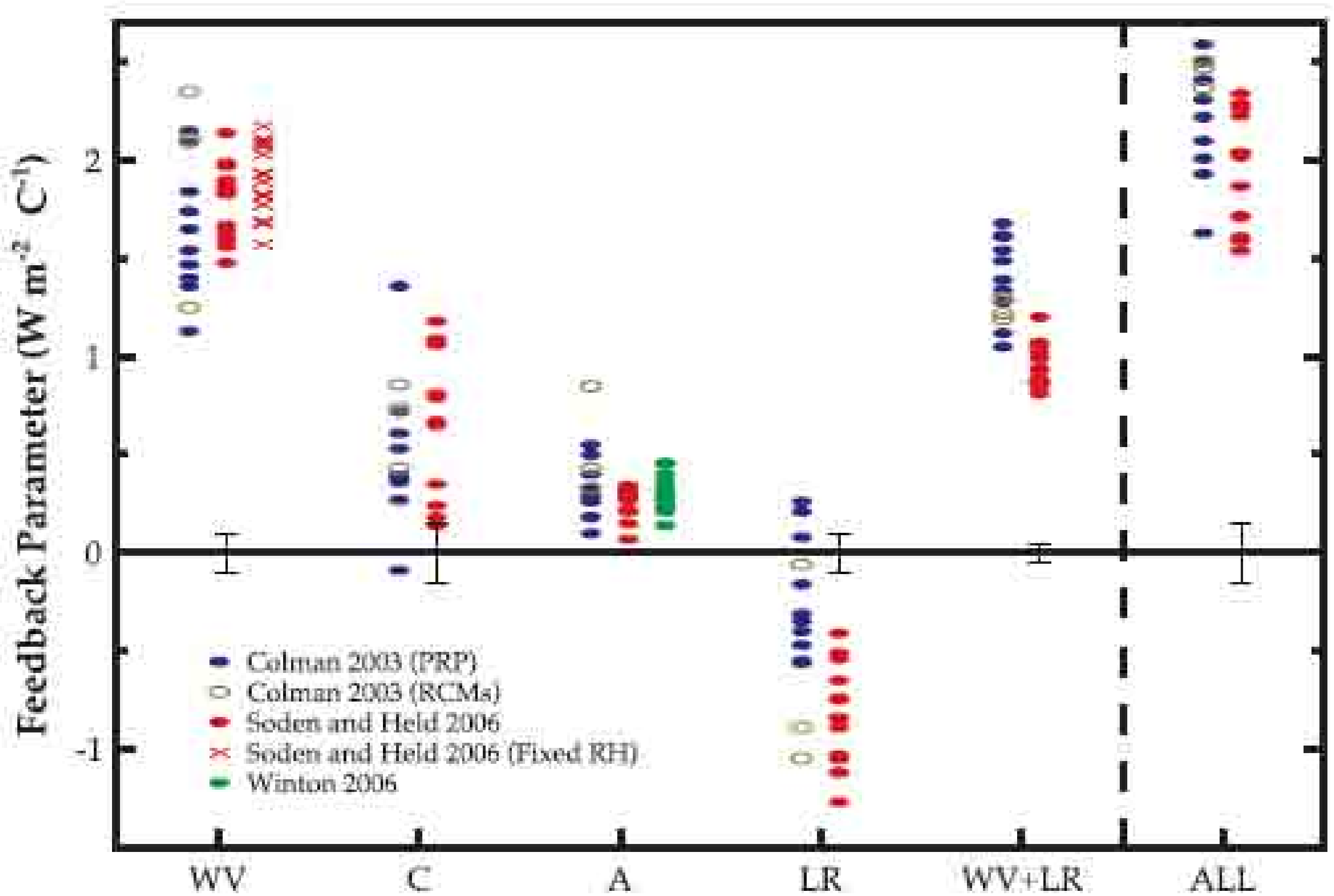
Feedbacks in Climate Models



Water vapor | **Cloud** | **Surface albedo** | **Lapse rate** | **Water vapor + lapse rate**

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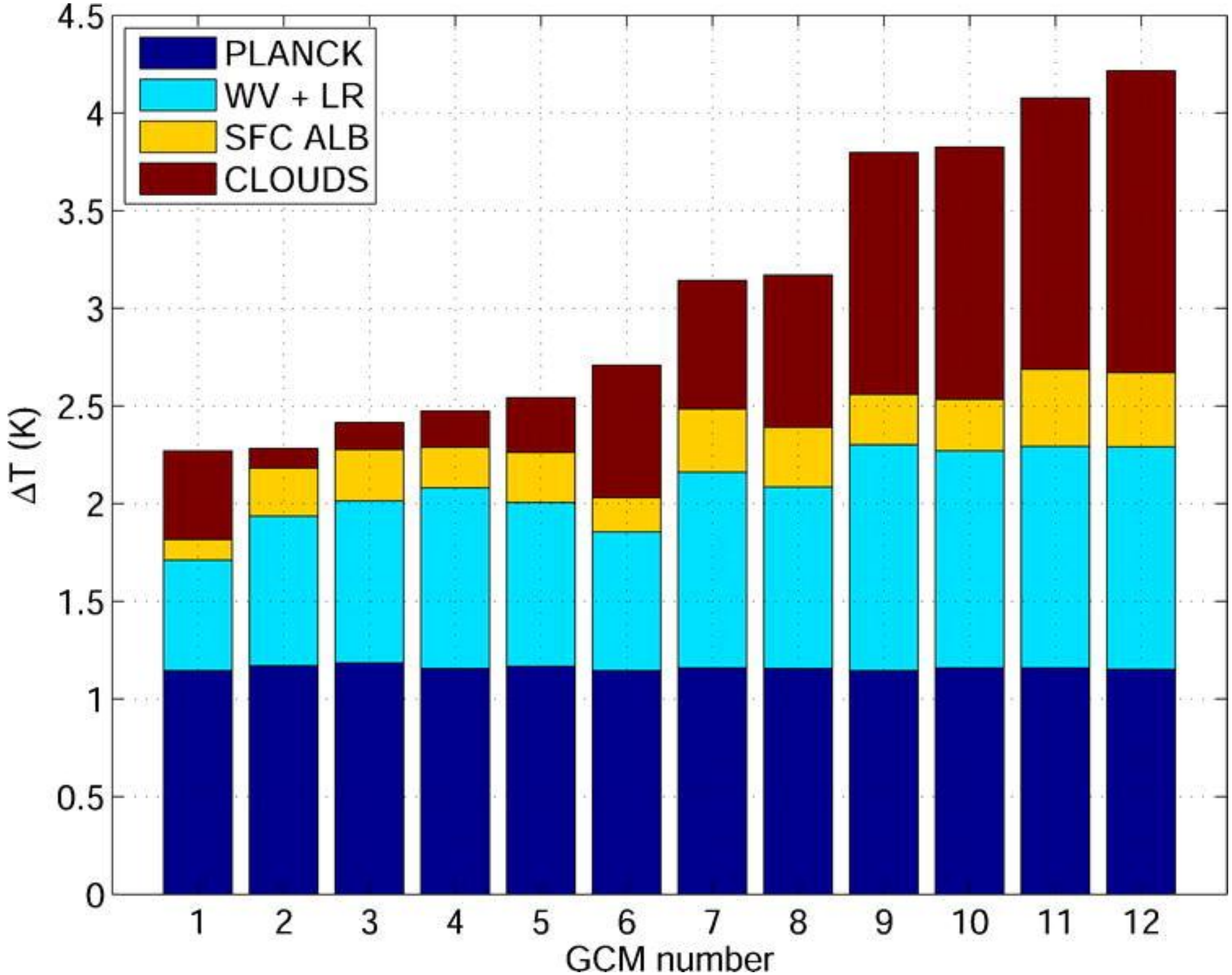
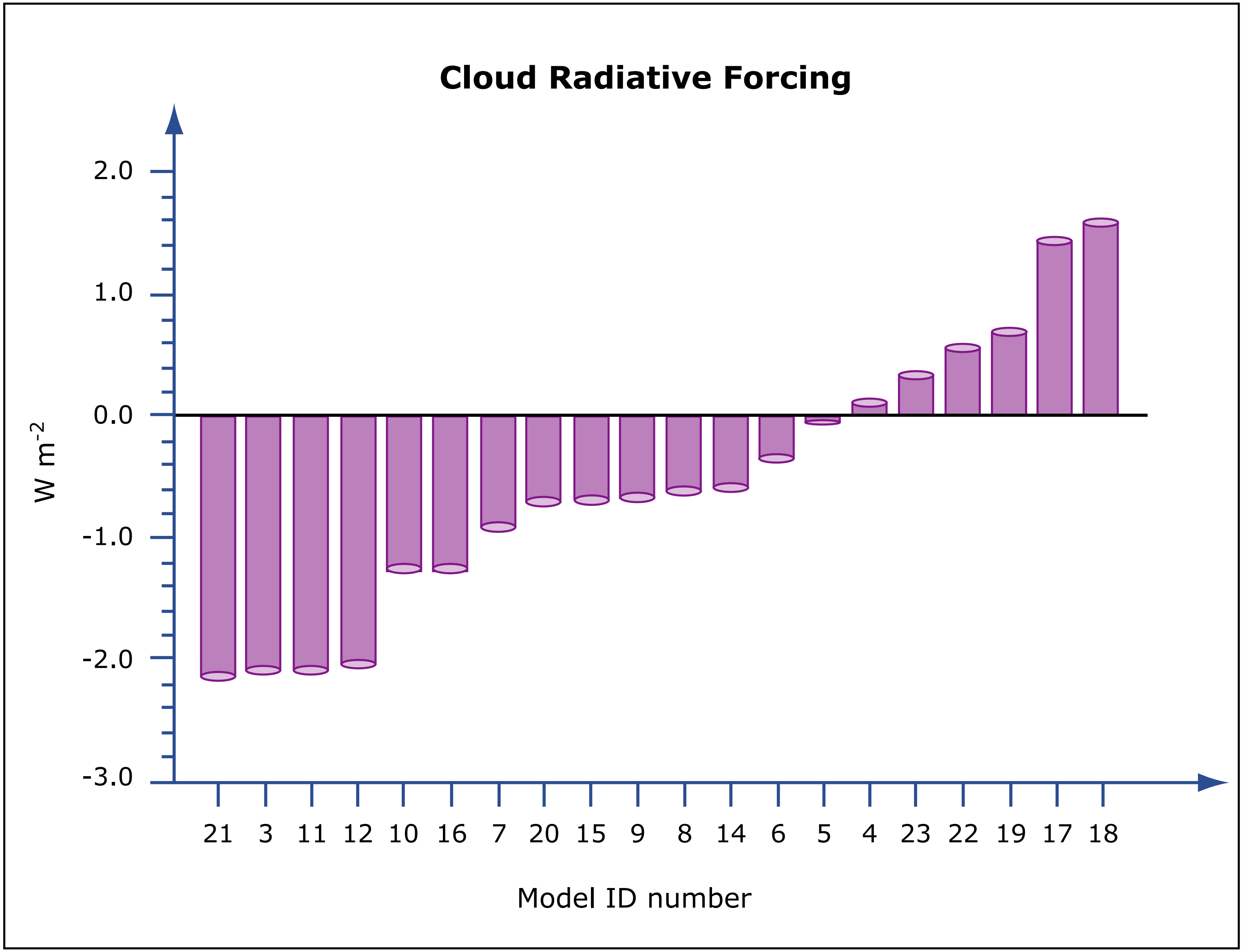


Equilibrium temperature change associated with the Planck response and the various feedbacks, computed for 12 CMIP3/AR4 AOGCMs for a 2 × CO_2 forcing of reference (3.71 W m^{-2}). The GCMs are sorted according to ΔT^e_s.

From Dufresne and Bony, J. Climate, 2008



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Changes in global mean cloud radiative forcing (W m–2) from individual models

12.340 Global Warming Science
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