Climate Sensitivity, Forcings, And Feedbacks
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 \( x_i \):

\[
F_{TOA} = F_{TOA}(T_s, x_1, x_2, \ldots, x_N)
\]

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

$$
\frac{\partial T_s}{\partial Q} \equiv \lambda_R = -\frac{1}{\frac{\partial F_{TOA}}{\partial T_s} + \sum_{i=1}^{N-1} \frac{\partial F_{TOA}}{\partial x_i} \frac{\partial x_i}{\partial T_s}}
$$
Let \( S \equiv \left( -\frac{\partial F\_{\text{TOA}}}{\partial T_s} \right)^{-1} \)  

\[
\frac{\partial T_s}{\partial Q} \equiv \lambda_R = \frac{S}{1 - S \sum_{i=1}^{N-1} \frac{\partial F\_{\text{TOA}}}{\partial x_i} \frac{\partial x_i}{\partial T_s}}
\]

Climate sensitivity without feedbacks

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.
Sunspot number

Year

Image by MIT OpenCourseWare.
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).

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2.16. Cambridge University Press. Used with permission.
X-Ray Flux

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Normal solar cycle variations in solar radiation

Inferences based on Models of Solar Variability

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.
Climate Forcing by Orbital Variations

Milutin Milanković, 1879-1958

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Eccentricity Cycle (100 k.y.)

Obliquity Cycle (41 k.y.)

Normal to ecliptic

Precession of the Equinoxes (19 and 23 k.y.)

Northern Hemisphere tilted away from the sun at aphelion.

Northern Hemisphere tilted toward the sun at aphelion.
Climate Forcing and Response

Image courtesy of Global Warming Art.
Strong Correlation between High Latitude Summer Insolation and Ice Volume

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This image has been removed due to copyright restrictions. Please see the image on page [http://en.wikipedia.org/wiki/File:Carbon_History_and_Flux_Rev.png](http://en.wikipedia.org/wiki/File:Carbon_History_and_Flux_Rev.png).
Variation in carbon dioxide and methane over the past 20,000 years, based on ice core and other records.
CO₂ and Climate

Recent History of Volcanic Eruptions

Volcanic Aerosol Total Visible Optical Depth

Sato et al. (1993)
Ammann et al. (2003)

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2.18. Cambridge University Press. Used with permission.
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).
Variation with Time of Natural Climate Forcings:

Examples of Forcing Magnitudes:

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

• Doubling $\text{CO}_2$, equivalent to $4 \text{ Wm}^{-2}$, would produce about $1^\circ\text{C}$ change in surface temperature
Contributions to net radiative forcing change, 1750-2004:
Examples of Feedbacks:

• Water vapor
• Ice-albedo
• Clouds
• Surface evaporation
• Biogeochemical feedbacks
Estimates of Climate Sensitivity

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

\[
S = \left( - \frac{\partial F_{TOA}}{\partial T_s} \right)^{-1}
\]

Suppose that \( T_s = T_e + constant \) and that shortwave radiation is insensitive to \( T_s \):

\[
F_{TOA} = -\sigma T_e^4, \quad \frac{\partial F_{TOA}}{\partial T_s} = -\frac{\partial}{\partial T_s} \sigma T_e^4 = -4\sigma T_e^3 = -3.8 W m^{-2} K^{-1}
\]

\[
S = 0.26 K \left( W m^{-2} \right)^{-1}
\]
Examples of feedback magnitudes:

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

\[
\left( \frac{\partial F_{\text{TOA}}}{\partial q} \right) \left( \frac{\partial q}{\partial T_s} \right)_{RH} \approx 2 \text{Wm}^{-2} \text{K}^{-1},
\]

\[
S \left( \frac{\partial F_{\text{TOA}}}{\partial q} \right) \left( \frac{\partial q}{\partial T_s} \right)_{RH} \approx 0.5
\]

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.
Budyko-Sellers type energy-balance model (1969)

Ice line latitude

Solar flux (x present)

0.9 1.0 1.1 1.2 1.3

Log \( p\text{CO}_2 \) (x present)

0.1 1 10 100 1000

No Ice

Present

All Ice

Neoproterozoic S = 0.93

Image by MIT OpenCourseWare.
Feedbacks in Climate Models

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

From Dufresne and Bony, J. Climate, 2008
Changes in global mean cloud radiative forcing (W m$^{-2}$) from individual models