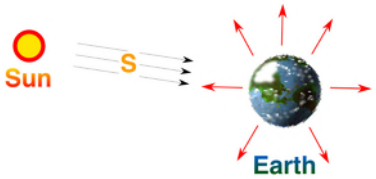
Climate Sensitivity

How Many Degrees of Warming per Watt/m^2 of Heating?

Please read Chapter 7 in Archer Textbook

Planetary Energy Balance



Energy In = Energy Out

$$S(1-\alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^\circ \mathrm{C}$$

But the observed T_s is about 15° C

Earth's Climate as a "Black Box"

$$F = \frac{S_0(1-\alpha)}{4}$$

240 W m^{-2} → **Climate System** → T_S 15 °C

Absorbed Sunshine In

Surface Temperature Out

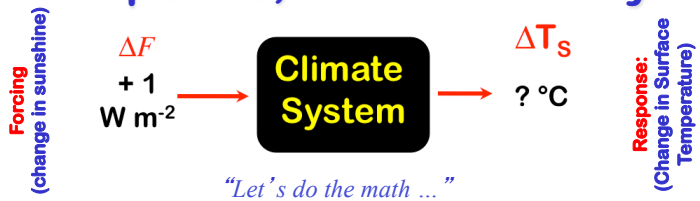
Climate Forcing, Response, and Sensitivity

ΔF + 1 W m^{-2} → **Climate System** → ΔT_S ? °C

Forcing (change in absorbed sunshine)

Response: (Change in Surface Temperature)

Climate Forcing, Response, and Sensitivity



"Let's do the math ..."

$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T^4$$

$$S_0(1-\alpha) = 4\sigma T^4$$

$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

Solve for ΔF that produces a given ΔT

Baseline Climate Sensitivity

"Let's do the math ..."

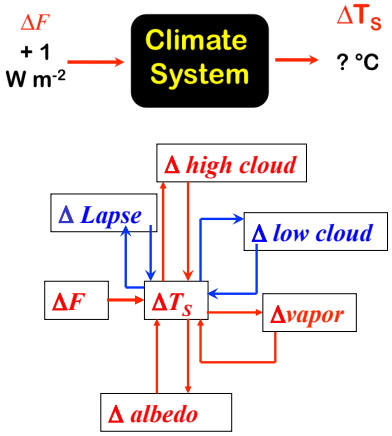
$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

$$\frac{dF}{dT} = 4\sigma T^3 = 4\sigma(255K)^3 = 3.8W\,m^{-2}K^{-1}$$

$$\Delta T = \frac{1}{3.8W\,m^{-2}K^{-1}}\Delta F = \frac{0.266\,K}{W\,m^{-2}}\Delta F$$

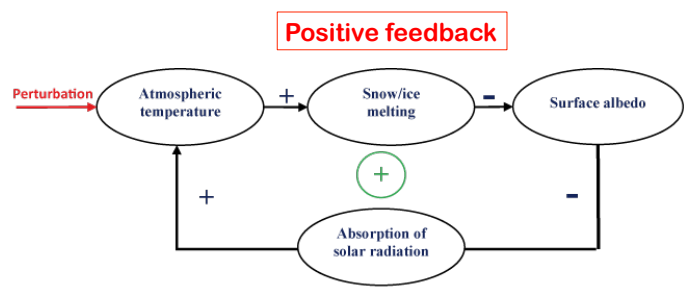
A 1 W m^{-2} change in absorbed sunshine produces about a 0.27 °C change in Earth's temperature

Climate Feedback Processes



- **Positive Feedbacks (amplify changes)**
  - Water vapor
  - Ice-albedo
  - High clouds
- **Negative feedbacks (damp changes)**
  - Lapse rate
  - Low clouds

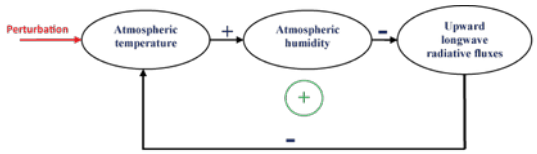
Ice Albedo Feedback



- Radiative forcing melts snow and ice
- Darker surface absorbs more radiation
- Amplifies warming or cooling

Water Vapor Feedback

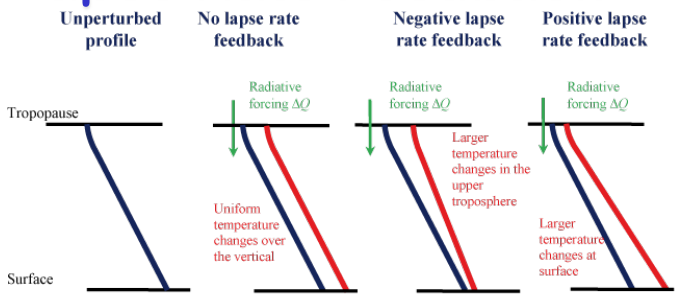
Positive feedback



- Radiative forcing warms surface
- Warmer surface evaporates more water
- Warmer air can "hold more water"
- Increased water vapor (GHG) absorbs more outgoing radiation, amplifying warming

Lapse Rate Feedback

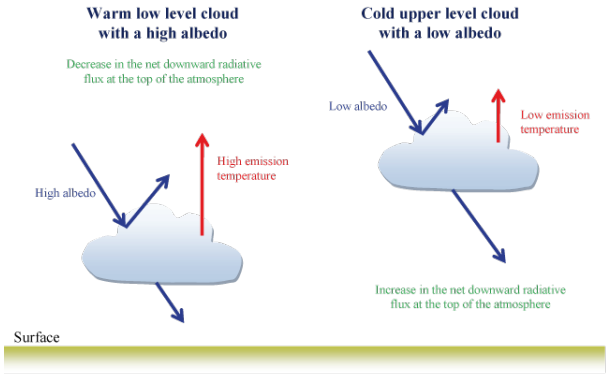
Positive OR negative feedback!



- Greenhouse effect depends on emission to space from higher (colder) levels of the atmosphere
- If radiative forcing produces increased vertical mixing by convection, then more heat is mixed to higher levels
- Warm air aloft emits more radiation to space, compensating for original forcing

Cloud Feedbacks

Positive OR negative feedback!



- Additional water vapor makes more clouds
- Low clouds cool, but high clouds warm

Estimating Total Climate Sensitivity

1. Paleoclimate analogs: how much has climate changed in the past when forcing of known strength was applied?
   - Advantage: all feedbacks included
   - Disadvantage: hard to know exactly how much forcing & global temperature response
2. Calculation from physical principles including feedback processes (complex global climate models)
   - Advantage: Physical insight
   - Disadvantage: "All models are wrong …"

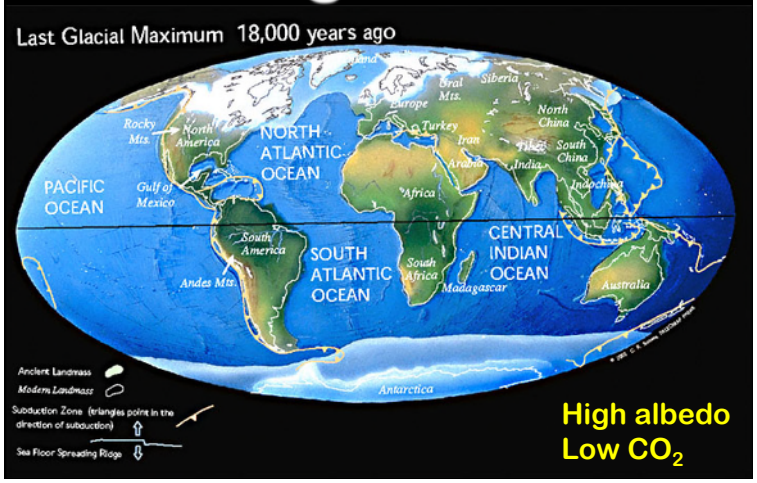
Learning from the Past

1. Geologic past (100's of millions of years)
2. Deglaciation analog (18,000 years ago to preindustrial time)
3. Last Millennium analog (Medieval Warm Period to Little Ice Age)
4. Modern Climate Record (20th Century changes)

The further back we go, the less data we have to work with.

Using modern data, we have only brief transients to study.

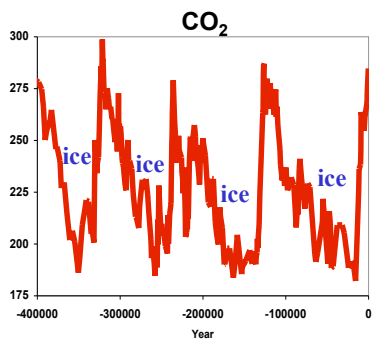
Ice Age World



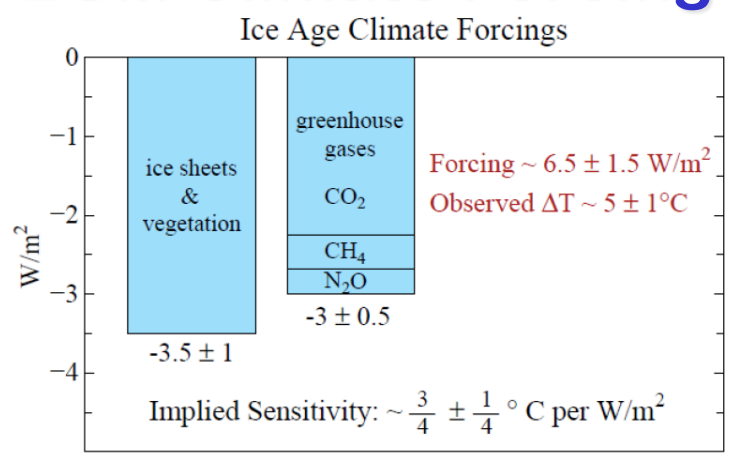
High albedo
Low CO_2

CO_2 and the Ice Ages

- Over the past 420,000 years atmospheric CO_2 has varied between 180 and 280 ppm, beating in time with the last four glacial cycles

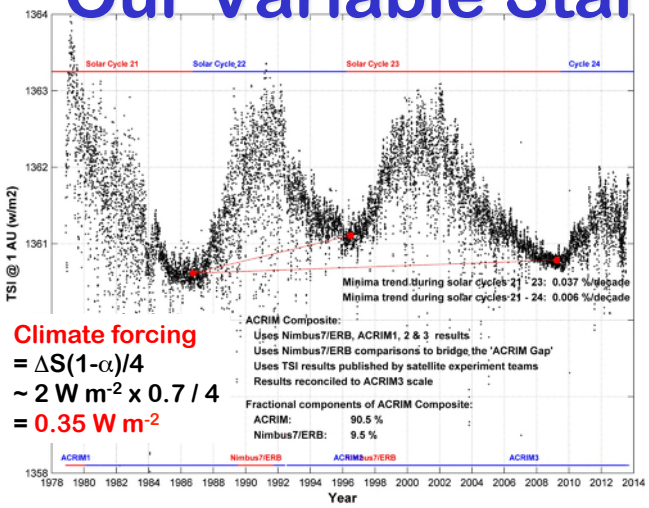


LGM Climate Forcing



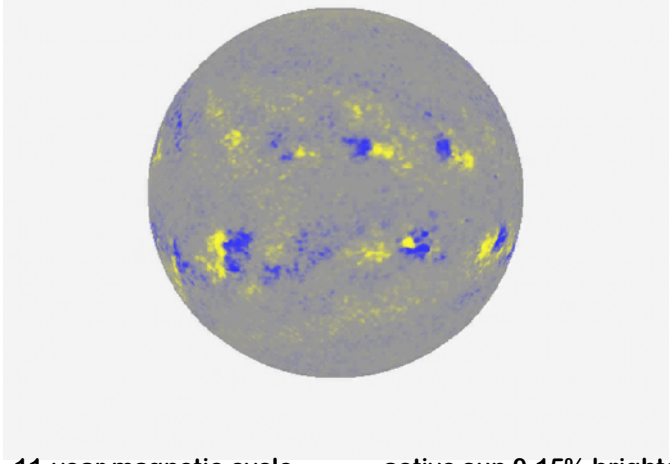
Source: Hansen and Sato (2011)

Our Variable Star



Climate forcing
$= \Delta S(1-\alpha)/4$
$\sim 2\ W\ m^{-2} \times 0.7 / 4$
$= 0.35\ W\ m^{-2}$

Cycle of Solar Variability

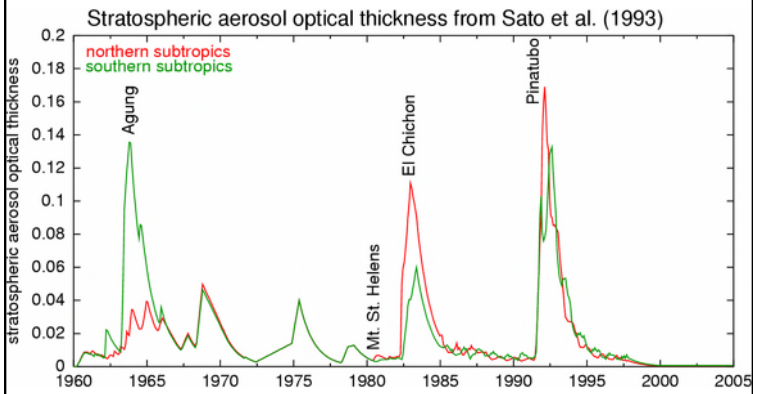


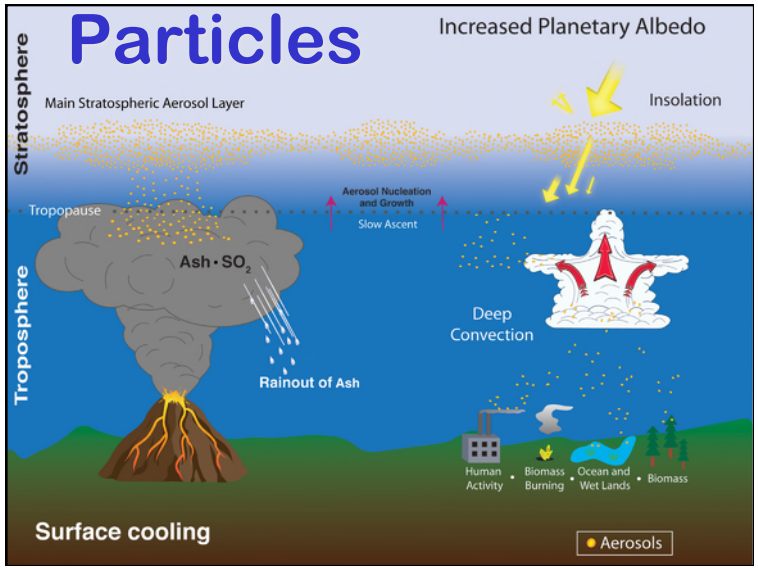
11-year magnetic cycle active sun 0.15% brighter

BOOM!

- Volcanoes release huge amounts of SO_2 gas and heat
- SO_2 oxidizes to SO_4 particles ("aerosol") and penetrates to stratosphere
- SO_4 aerosol scatters solar radiation back to space

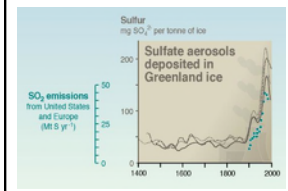
Volcanic Aerosol

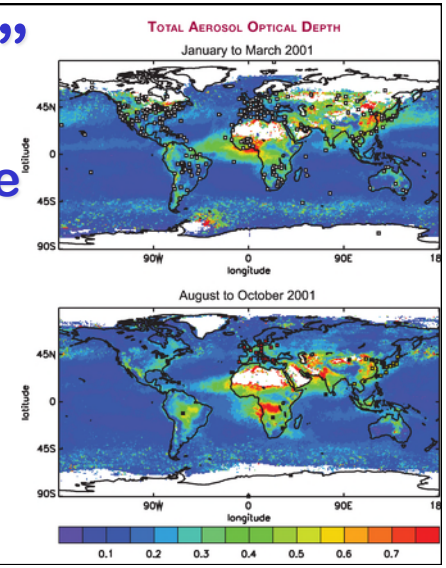




"Aerosol"

Particles in Troposphere from air pollution





Tropospheric Aerosol

Enhance Cloud Albedo

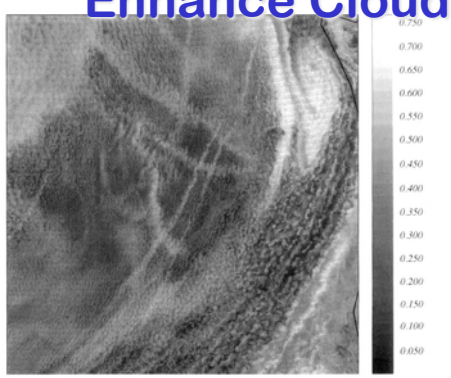
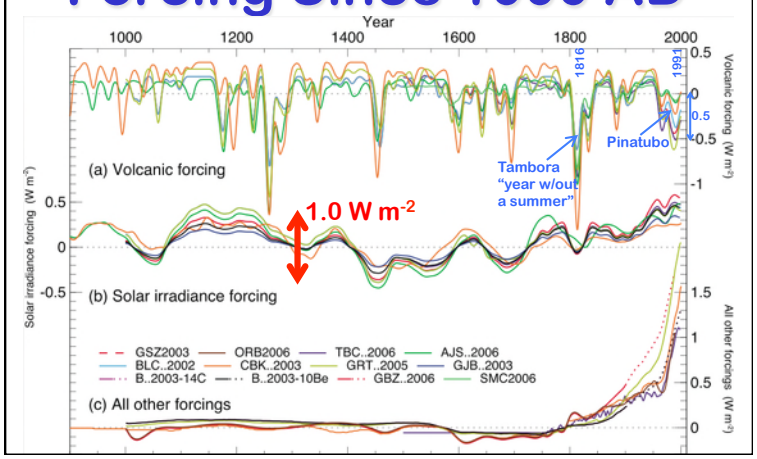


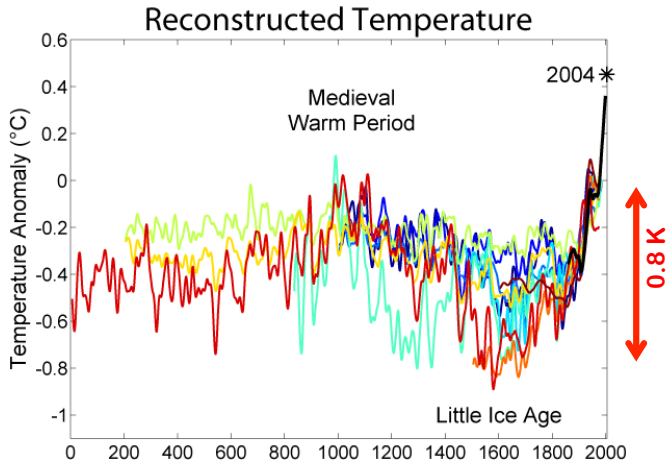
Fig. 12.6 GOES 1-km visible image of stratocumulus clouds over the Pacific Ocean on July 1, 1987 at 1615 UTC (Universal Time Coordinate). The scale of the image is approximately 5° square. The continental outline in the upper right is the Olympic Peninsula of Washington, and the one in the lower right is Cape Blanco on the Oregon coast. The linear features in the center of the image are ship tracks, enhancements of otherwise thin stratocumulus clouds caused by sulfur gas and particulate emissions of passing ships. The gray scale on the right indicates the visible albedo. (Image courtesy of Robert Pincus.)

- Ship tracks off west coast
- Cloud droplets condense on tiny particles
- Makes more/ smaller cloud drops
- Clouds are brighter (higher albedo)

Reconstructed Climate Forcing Since 1000 AD



The Past 2000 Years



Second Millennium Analog

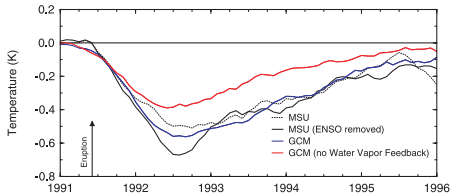
- Cooling from Medieval Warm Period to Little Ice Age ~ 0.8 K
- Solar forcing ~ 1.0 W m^{-2} (somewhat complicated by volcanic forcing)

A frost fair on the Thames at Temple Stairs, c 1684. Abraham Hondius Museum of London

Total climate sensitivity (including feedback)
0.8 K per (W m^{-2})

Volcanic Analog

- Cooling following eruption of Mount Pinatubo in 1991 ~ 0.5 K
- Volcanic forcing ~ 0.7 W m^{-2}



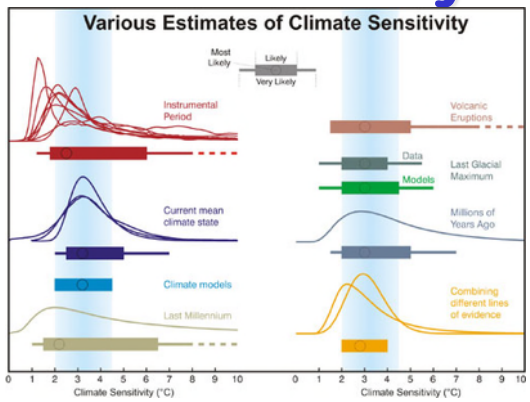
Total climate sensitivity (including feedback)
0.7 K per (W m^{-2})

Climate Sensitivity to enhanced CO_2

- Many lines of evidence suggest about 0.8 °C of warming per (W m^{-2})
- Remember each doubling of CO_2 adds 3.7 Watts per square meter
- So expect about (3.7 W m^{-2}) x (0.8 °C (W m^{-2})$^{-1}$) = 3 °C per doubling of CO_2

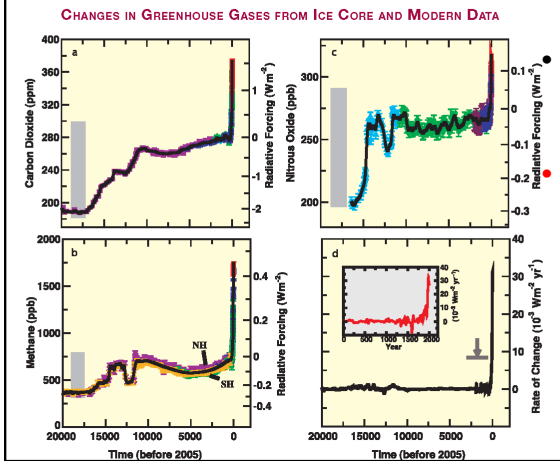
Climate Sensitivity

Dozens of studies using many different methods agree that climate sensitivity is about 3 C per doubling of CO_2



Distributions and ranges for climate sensitivity from different lines of evidence. The circle indicates the most likely value. The thin colored bars indicate very likely value (more than 90% probability). The thicker colored bars indicate likely values (more than 66% probability). Dashed lines indicate no robust constraint on an upper bound. The IPCC likely range (2 to 4.5°C) and most likely value (3°C) are indicated by the vertical grey bar and black line, respectively (Source: Knutti & Hegerl, Nature, 2008)

GHG Radiative Forcing



- Note different scales
- Modern changes comparable to postglacial, but much faster!

Since Last Ice Age