Climate Forcing and Feedback

Original slides provided by Dr. Daniel Holland

- We have looked at how to estimate the Earth's temperature and determined that it is increasing. Now what?.
- Suppose now that something in the system changes (e.g. more energy comes from the sun or more energy is trapped by the atmosphere.)
- How do we estimate the change in the equilibrium temperature?

Audio Link

Climate Forcing

- Any upset in the earth's energy balance is referred to as ***climate forcing***.
- The net effect should be much the same whether it is due to an increase in incoming energy or if it is due to increased trapping by greenhouse gasses.

In Equilibrium:

Energy in = Energy out

If we force the climate by adding additional energy in (ΔE) our equation would be

$$\textit{Energy in} + \Delta E = \textit{Energy out}$$

If we force the climate by reducing the energy out by an amount (ΔE) our equation would be

$$\textit{Energy in} = \textit{Energy out} - \Delta E$$

SAME EQUATION – DIFFERENT INTERPRETATION!

In the above we have talked in terms of energy flows. In our calculations, we have used power per unit area ($W/m^{2.}$). This is typical when discussing climate forcing.

Example: Estimate the change in temperature on earth due to a $5W/m^2$ energy forcing

- Use our simple model with ***NO*** atmosphere:
- Let the $5W/m^2$ be due to an increase in the solar input form $235W/m^2$ to $240\ W/m^2$. (2.1% increase).

$$240W/m^2 = e\sigma T^4$$

Or

$$T=255\ K$$

This is only an increase of 1°C

Climate Sensitivity

- Policy makers would like to have a simple measure of how a given climate forcing will change the temperature:

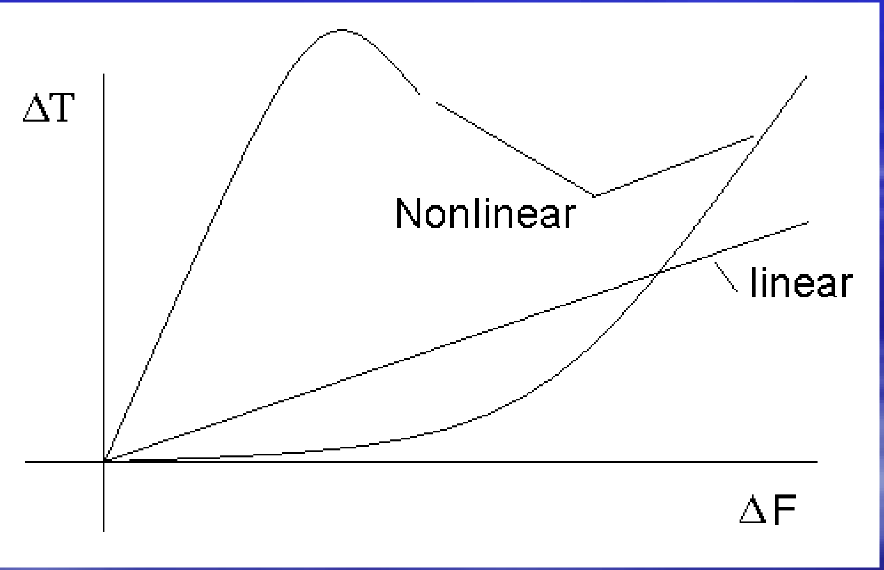
- climate sensitivity $G = \Delta T / \Delta F$

- Note: units are $^\circ C/(W/m^2)$

Linear vs. Nonlinear Response

Once we know the climate sensitivity, if the response is linear, we can multiply it by any forcing to get the change in temperature.

If the response in nonlinear, the problem is much harder.



First attempt at energy balance climate sensitivity

$$\frac{\Delta T}{\Delta F} = \frac{1}{e\sigma T^3}$$

$$\frac{1}{(1)(5.67\times10^{-8}\,W/m^2K^4)(254\,K)^3}$$

$$0.27\frac{°C}{W/m^2}$$

Notes: 1) derivation of this requires calculus

2) A 5W/m^2 forcing gives ΔT= (0.27)(5)=1.35°C

Feedback

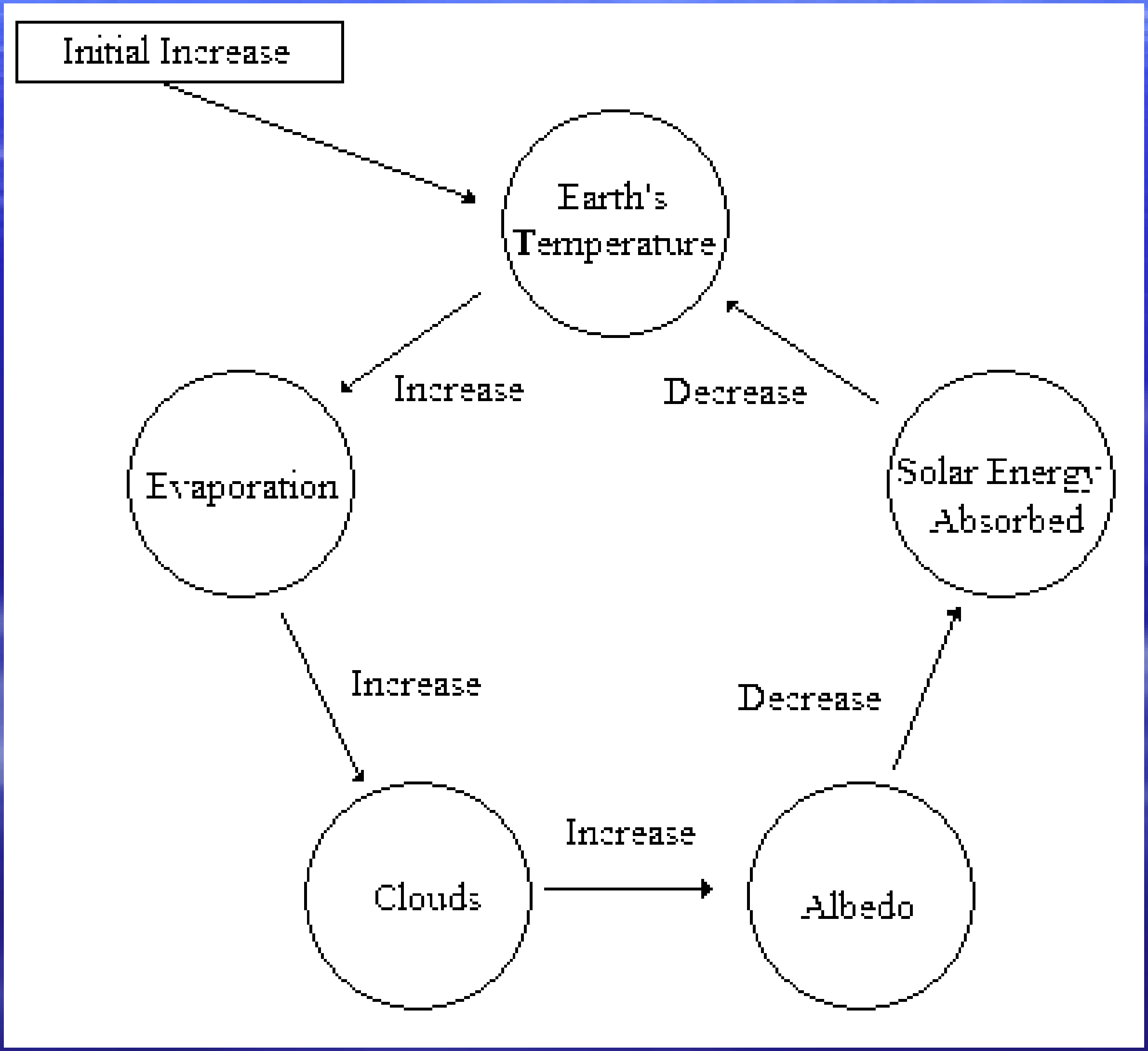
- Our value of G=0.27 °C/(W/m^2) is actually a bit low because we have left out some information, mostly feedback.
- Two type of feedback, negative and positive.

Negative Feedback

- Negative feedback effects tend to counteract the changes that initially gave rise to them.
- Example: House thermostat: When the temperature drops, the furnace turns on and heats up. When the temperature goes too high, furnace turns off and the house will cool.

- When $C0_2$ goes up, plants grow more quickly and remove some of the CO_2.
- A warming earth tends to cause more clouds (evaporation increases) but the clouds increase the earth’s albedo so not as much energy enters the atmosphere and the earth cools.
- Increased temperature can reduce vegetation (deserts) which also increase the albedo.

Cloud Feedback Loop



- Note: negative feedback works in both directions.
- If the earth cools it results in a decrease in cloud cover. The albedo is reduced and the earth warms.

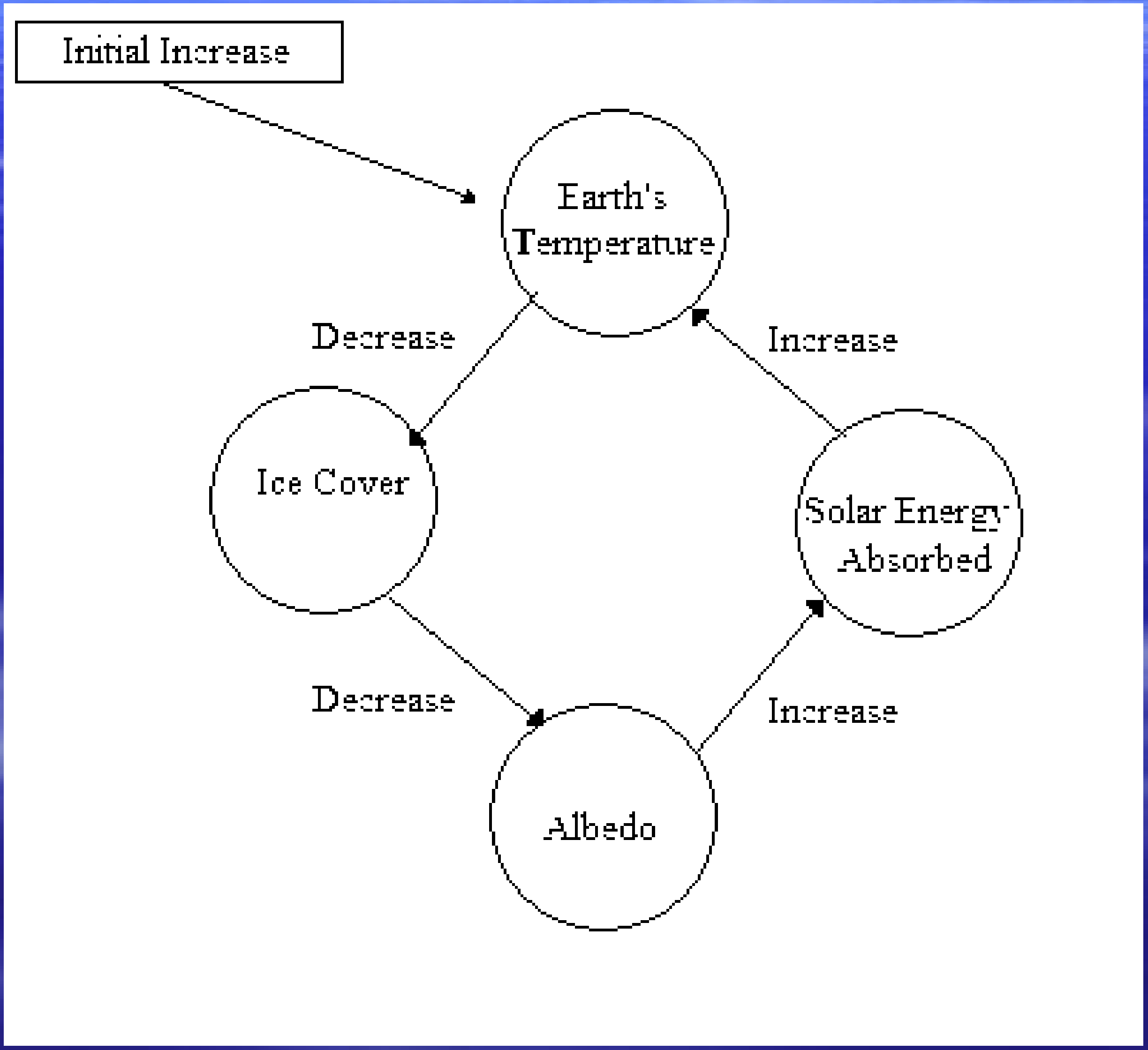
- Question: Can negative feedback reverse initial warming? More later.

Positive Feedback

- Positive feedback tends to increase the initial change.
- Imagine a thermostat that turns the furnace on when it gets hot.

- Water vapor is a powerful greenhouse gas. If we increase the temperature, more water evaporates. This adds more GHG to the atmosphere and traps more heat thus increasing the temperature more. (Note that water in clouds was a negative feedback, but water vapor is a positive feedback.)
- Ice-albedo effect: Increased temperature causes sea ice to melt. The darker water absorbs more energy thus causing additional warming which causes more sea ice to melt.

Ice Albedo Effect

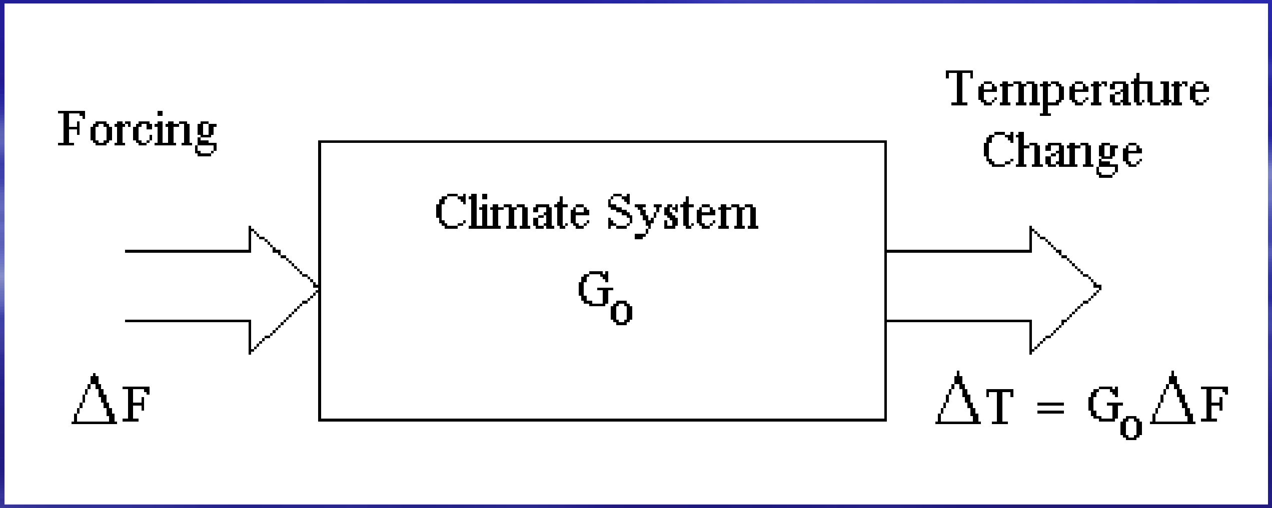


- Just like negative feedback, positive feedback works both ways.
- If the earth cools, more sea ice forms. This increases the albedo which reduces the amount of energy absorbed. The reduced energy absorption causes further cooling which in turn causes more sea ice.

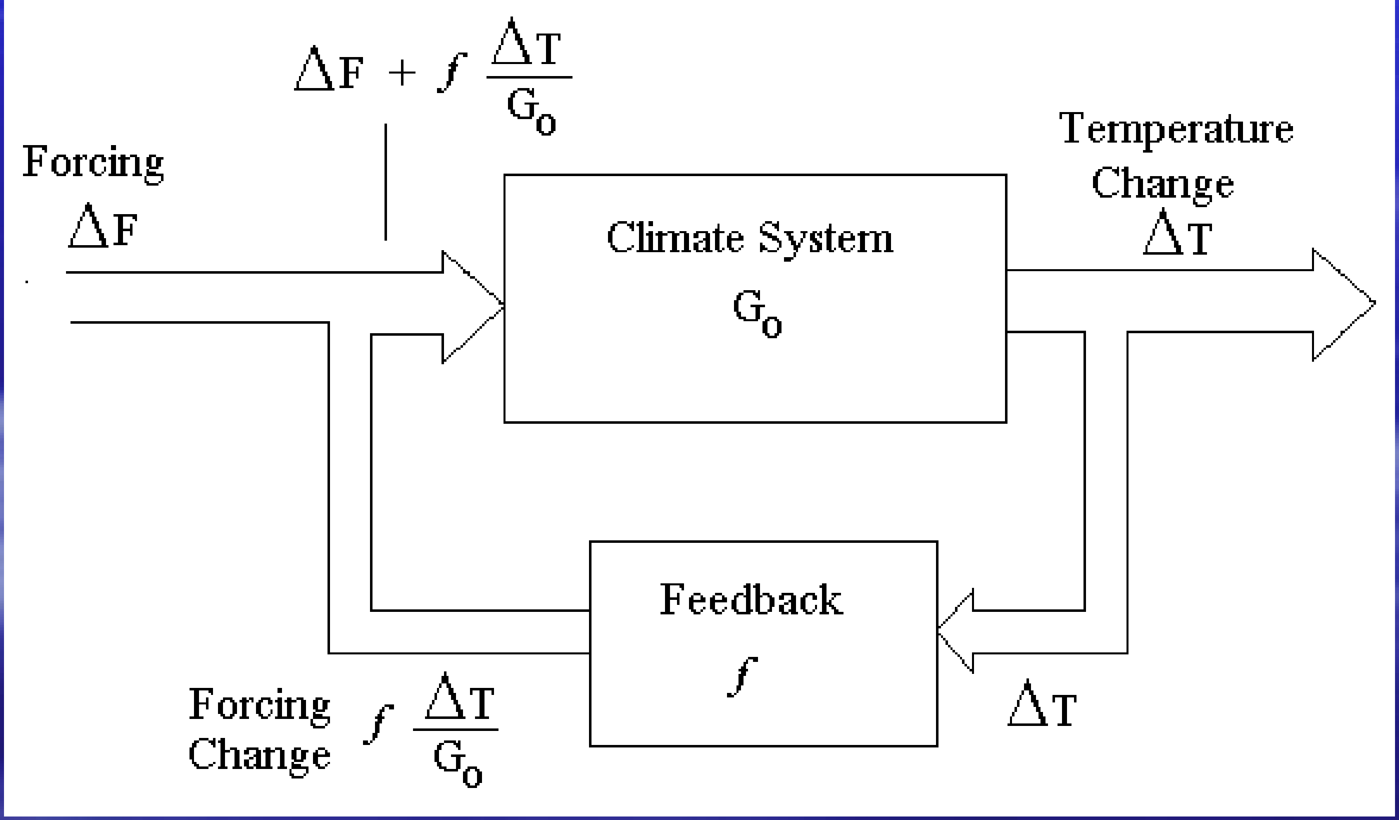
- The effects of feedback are active areas of research. Of particular interest are the effects of clouds and water vapor.

Modeling Feedback

- Use the "Black Box" approach. Without feedback, we take an initial forcing, put it into our black box and out comes the temperature change. For our linear system $\Delta T=0.27\Delta F$ or $G_0=0.27$



- The feedback is a response to the initial forcing and modifies the forcing itself



Mathematics of Feedback

$$\Delta T = G_0 \left(\Delta F + f \frac{\Delta T}{G_0} \right)$$

$$\Delta T = G_0 \Delta F + f \Delta T$$

$$(1 - f) \Delta T = G_0 \Delta F$$

$$\Delta T = \left(\frac{G_0}{1 - f} \right) \Delta F$$

New Climate Sensitivity

Since we found

$$\Delta T = \left(\frac{G_0}{1-f} \right) \Delta F$$

We may define a new climate sensitivity

$$G = \left(\frac{G_0}{1-f} \right)$$

- Note: For positive feedback *f* is positive and $G>G_0$
- For negative feedback *f* is negative and $G<G_0$.
- No matter how large the magnitude of negative *f*, *G is still positive.*

Example

- The IPCC best estimate is that climate sensitivity is approximately G=0.67˚C/(W/m²). Our simple model had a value of G_0=0.27 ˚C/(W/m²). What is the value for the net feedback, *f* ?

$$G = \frac{G_0}{1 - f}$$

$$G - fG = G_0$$

$$G - G_0 = fG$$

$$f = \frac{G - G_0}{G}$$

$$f = \frac{0.67 - 0.27}{0.67} = 0.597$$

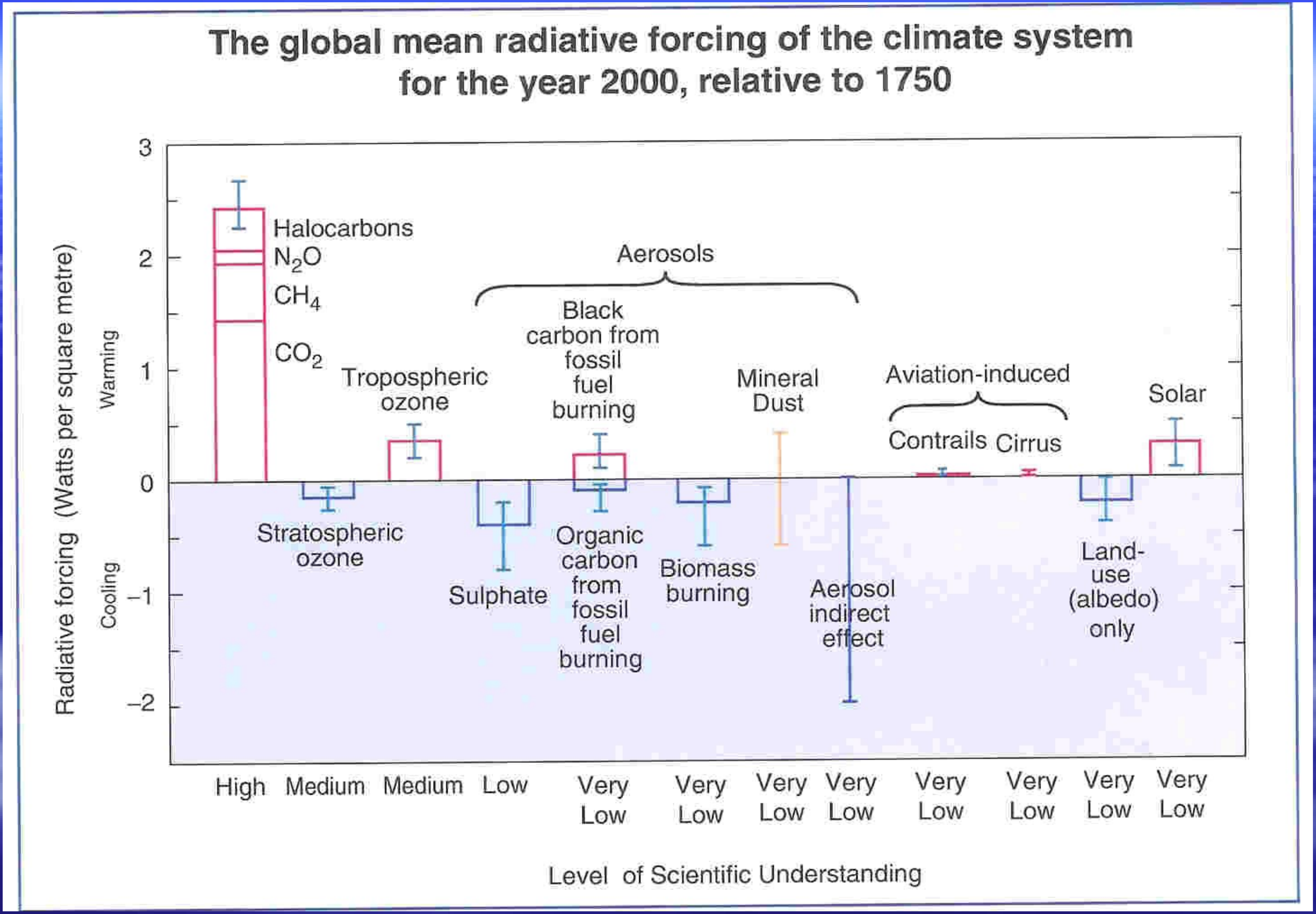
Real Forcings.

- For a baseline, we will use conditions in the pre-industrial era (250 yrs ago.)
- Note: There is definitely natural changes that occur in climate. We want to know the size of the changes that we are causing.

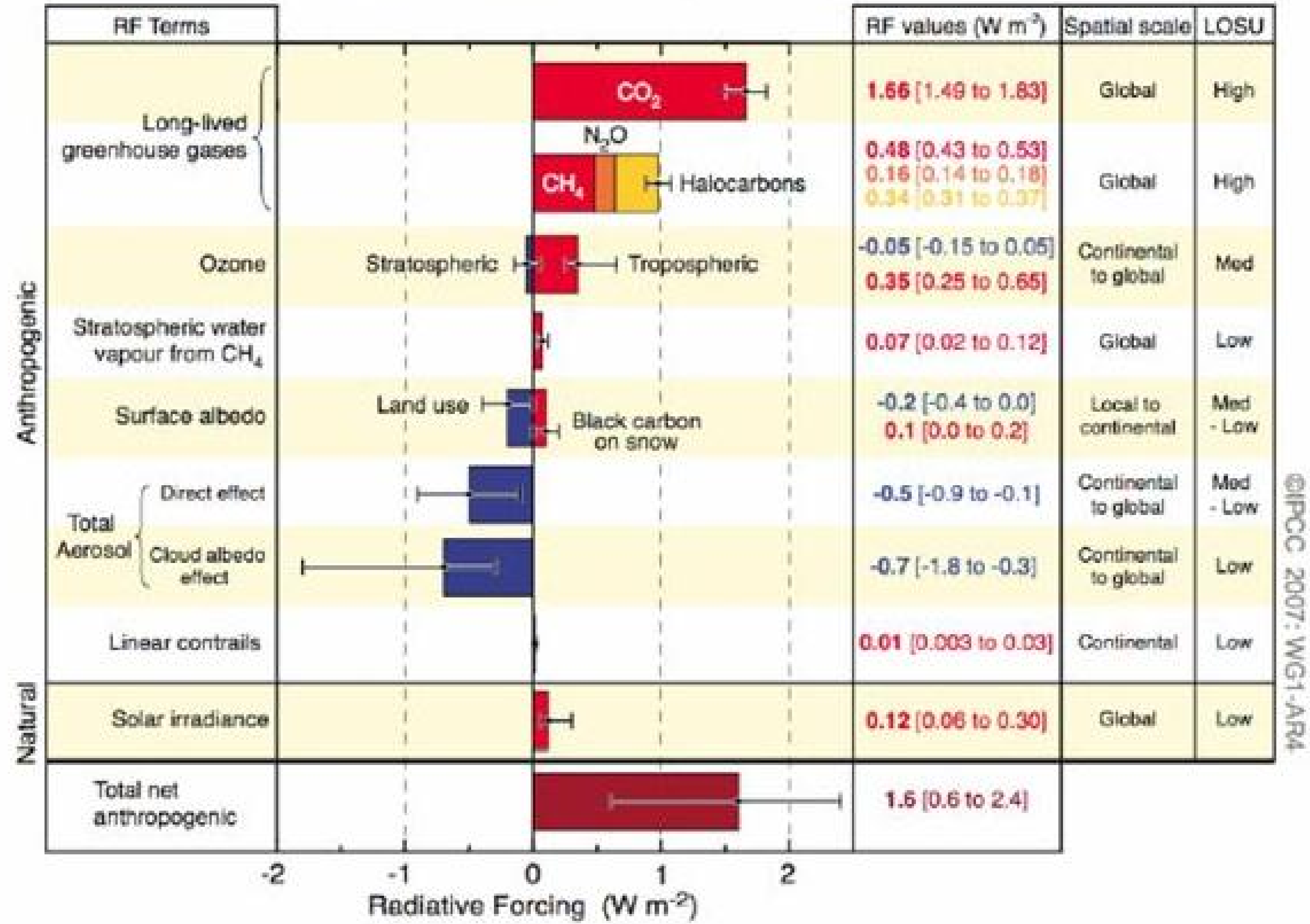
Real Forcings.

- For a baseline, we will use conditions in the pre-industrial era (250 yrs ago.)
- Note: There is definitely natural changes that occur in climate. What we want to know is are we causing additional change.

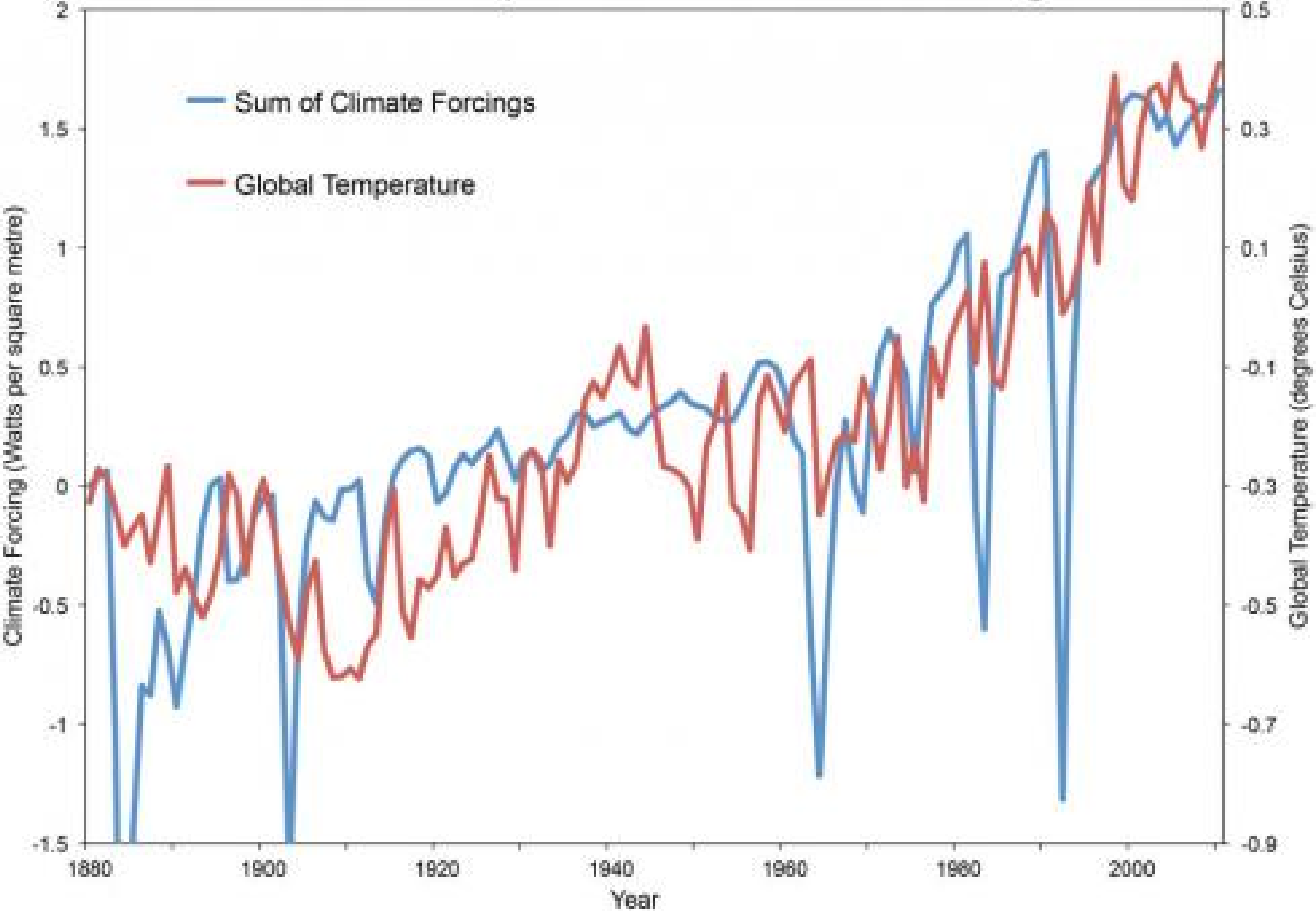
Audio Link


The global mean radiative forcing of the climate system
for the year 2000, relative to 1750
Radiative forcing (Watts per square metre)
Warming
Cooling
3
2
1
0
−1
−2
Halocarbons
N_2O
CH_4
CO_2
Tropospheric ozone
Stratospheric ozone
Aerosols
Black carbon from fossil fuel burning
Mineral Dust
Aviation-induced
Contrails
Cirrus
Solar
Sulphate
Organic carbon from fossil fuel burning
Biomass burning
Aerosol indirect effect
Land-use (albedo) only
High
Medium
Medium
Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Level of Scientific Understanding

Radiative Forcing Components



Global Temperature vs Climate Forcings



- Note that all but the possible change in solar output are anthropogenic
- Volcanic activity is another but highly variable forcing.

Greenhouse Gasses

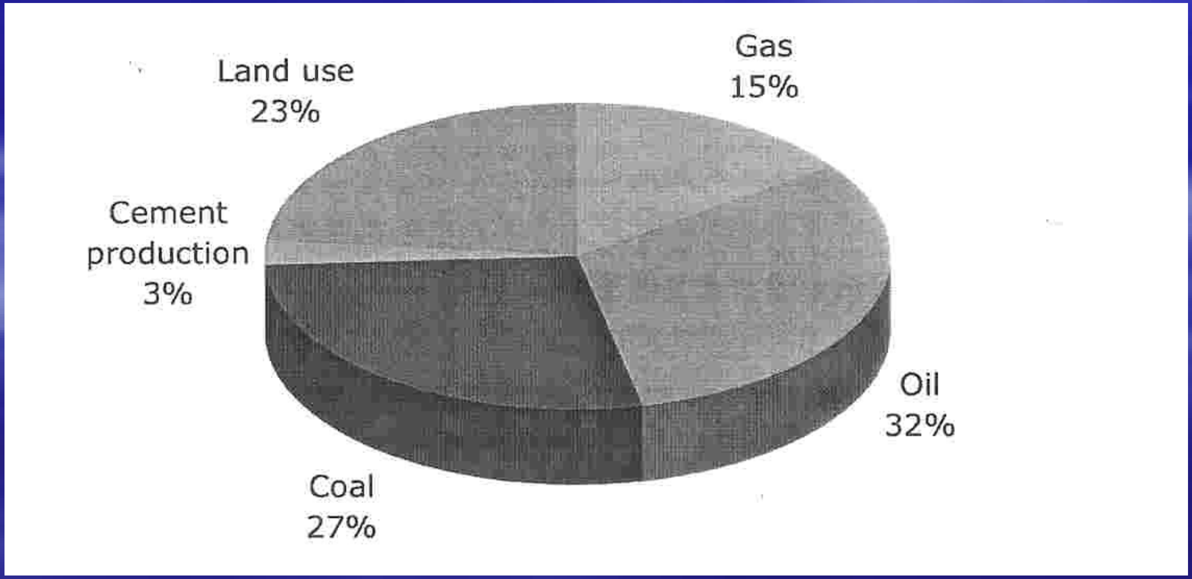
- GHG (CO_2, Methane, N_2O and Halocarbons) are the dominant forcing.
- The GHG remain in the atmosphere long enough that they are well mixed

Sources of GHG

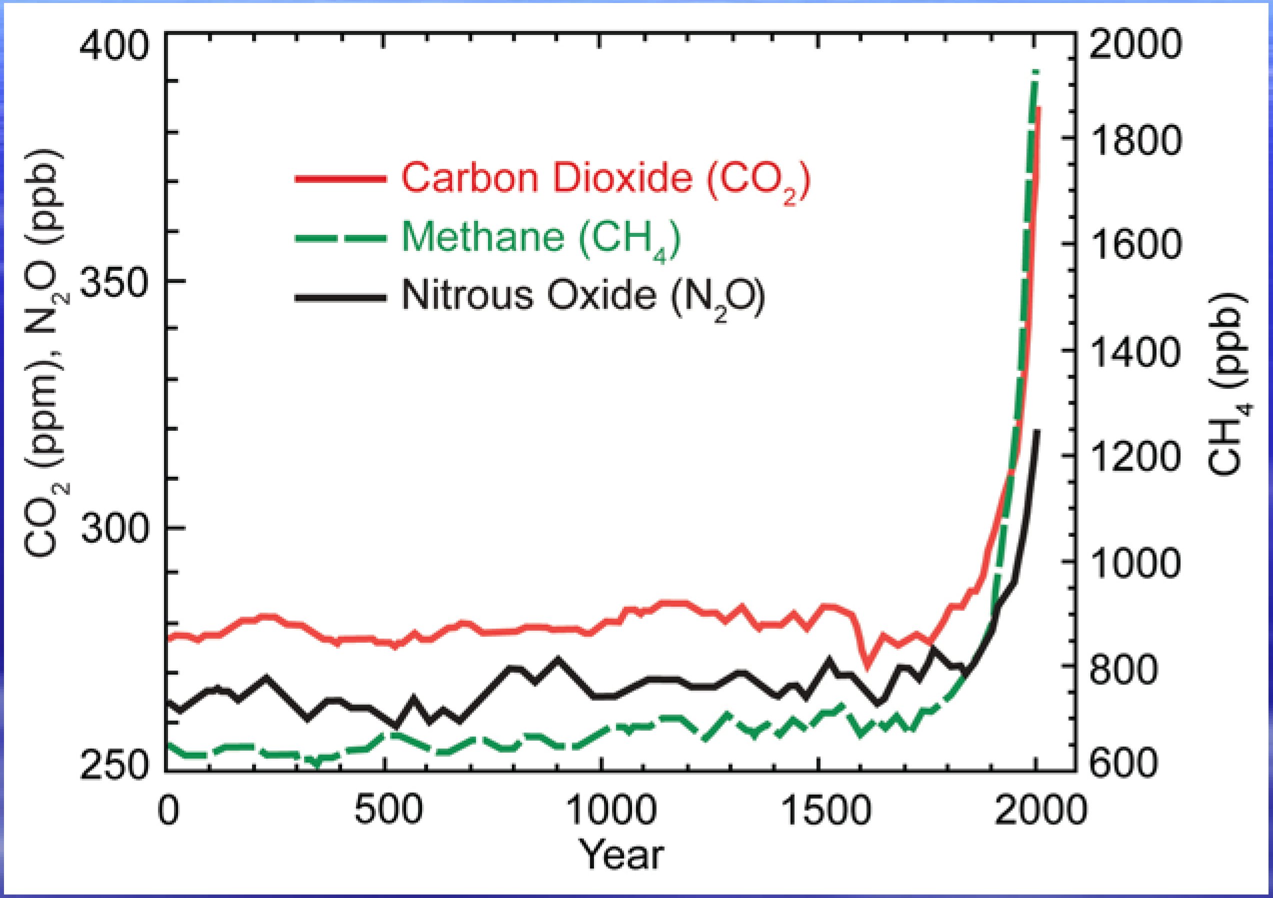
- N_2O comes from combustion of fuels and more importantly form from fertilizers.
- Halocarbons are products such as CFCs (now banned because of ozone depletion) and HCFCs (hydrochlorofluorocarbons,safe for ozone, but still a greenhouse gas.) How many times did I mis-pronounce them in the lecture?
- Methane comes from natural gas releases, coal mining, sewage treatment plants, landfills, cows, rice paddies, etc.

Sources of Carbon Dioxide

- Major source for carbon dioxide forcing come from burning fossil fuels. (75%)
- Other major contribution is land use, mostly tropical deforestation.

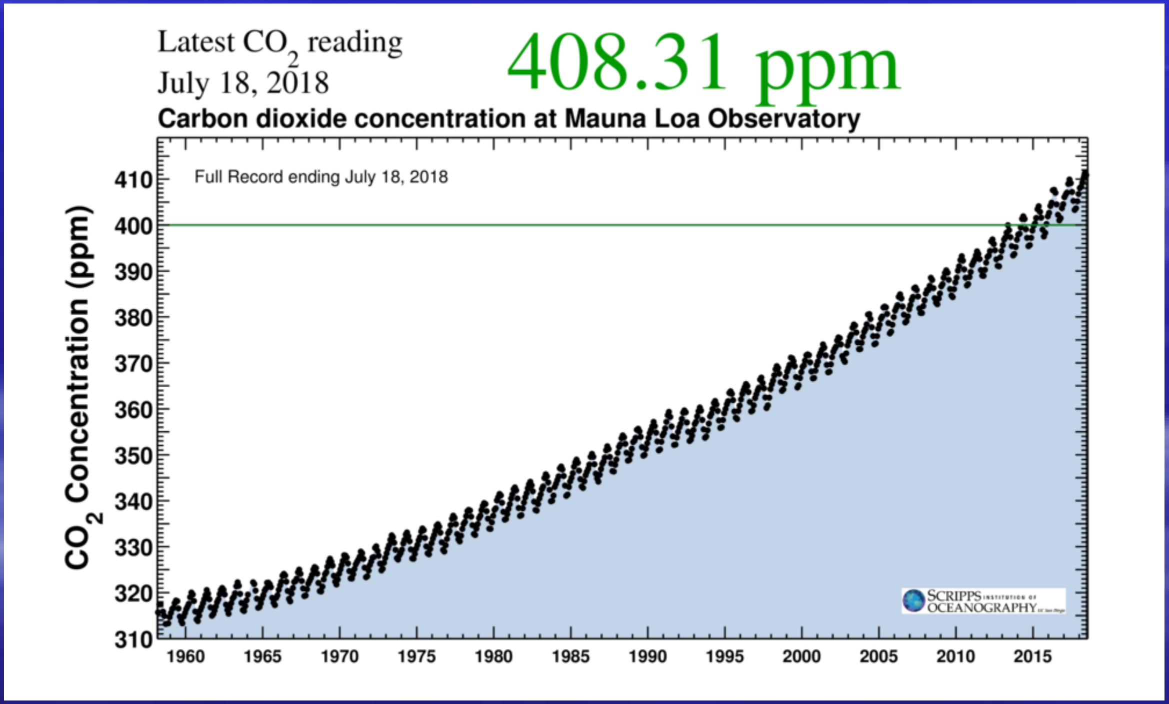


GHG Concentrations



https://nca2009.globalchange.gov/2000-years-greenhouse-gas-concentrations/index.html

- CO_2 Concentration at Mauna Loa observatory in Hawaii. Note the annual oscillation caused by the seasonal growth of plants.



https://scripps.ucsd.edu/programs/keelingcurve/

How do we know the CO_2 is anthropogenic in origin.

- It tracks the known emission from the burning of fossil fuels.
- CO_2 is well mixed in the atmosphere, but its concentration in the northern hemisphere is slightly higher than in the southern,
- The ratio of carbon-14 to carbon-12 is decreasing due the burning of fossil fuels. (C-14 would have decayed long ago in the fossil fuels.)

Global Warming Potential

- GHG vary in their ability to trap IR radiation,
- One molecule of Methane is 26 times more effective at IR absorption then one molecule of CO_2.
- Effectiveness also depends on the lifetime in the atmosphere.
- Methane remains in the atmosphere for about a decade, CO_2 has an effective lifetime of ~1000 years.

- In the near term a given amount of Methane cause a much greater forcing than the equivalent amount of CO_2, but wait 100 years and the CO_2 is still there warming while the Methane is long gone.
- We define the effectiveness of a greenhouse gas relative to CO_2 as its global warming potential (GWP).

GWP on a per kilogram basis

Table 13-1 Global Warming Potentials				
Gas	**Atmospheric lifetime, years**	**Global Warming Potential relative to CO_2 Time Scale**		
		20 years	100 years	500 years
Carbon dioxide, CO_2	~1000*	1	1	1
Methane, CH_4	~10	62	23	7
Nitrous oxide, N_2O	114	275	296	156
CFC-11, CCl_3F	45	6300	4600	1600
HCFC-22, $CHClF_2$	12	4800	1700	540
HFC-23, CHF_3	260	9400	12000	10000

* The lifetime of CO_2 is ambiguous; see Section 5

Data source: IPCC 2001, *Climate Change 2002: The Scientific Basis*, Table 6.7, p. 388 [xxx list here or with data source listing?]

Concentration and Forcing

- In general, the higher the concentration of a GHG, the more IR it absorbs, ***BUT*** if all of the IR at the wavelength in question is being absorbed, the addition of more GHG don't really matter.

OZONE – O_3

- Listed separately because it is not evenly mixed throughout atmosphere.
- Different effects near ground and higher up
- Near ground it is a nasty pollution
- In the stratosphere it protects us from UV radiation

Aerosols—fine particulate matter.

- Overall there is a high degree of uncertainty in the effects of aerosols.
- Sulfates from burning coal tend to reflect more incoming light (Negative Forcing)
- Some forms of carbon aerosols contribute positive forcing while others contribute negative.

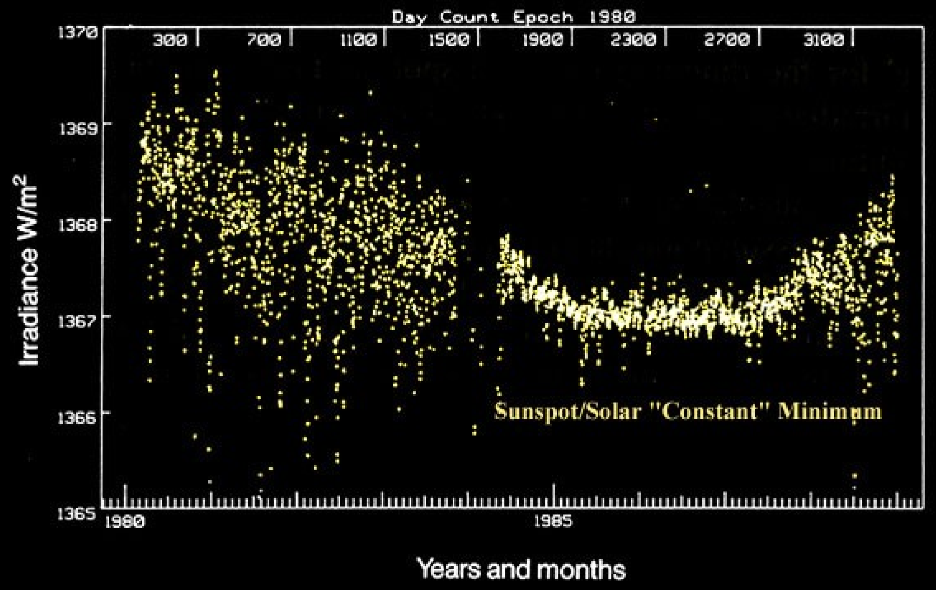
- Aerosols contribute to cloud formation which are complex in themselves, thus the indirect effects of aerosols are really poorly understood.

Other Anthropogenic Forcing

- Land use changes affect albedo. Relatively small but most likely negative.
- Aviation induced clouds. When planes were grounded after 9/11/01, there was a clear (but small) signature of altered climate

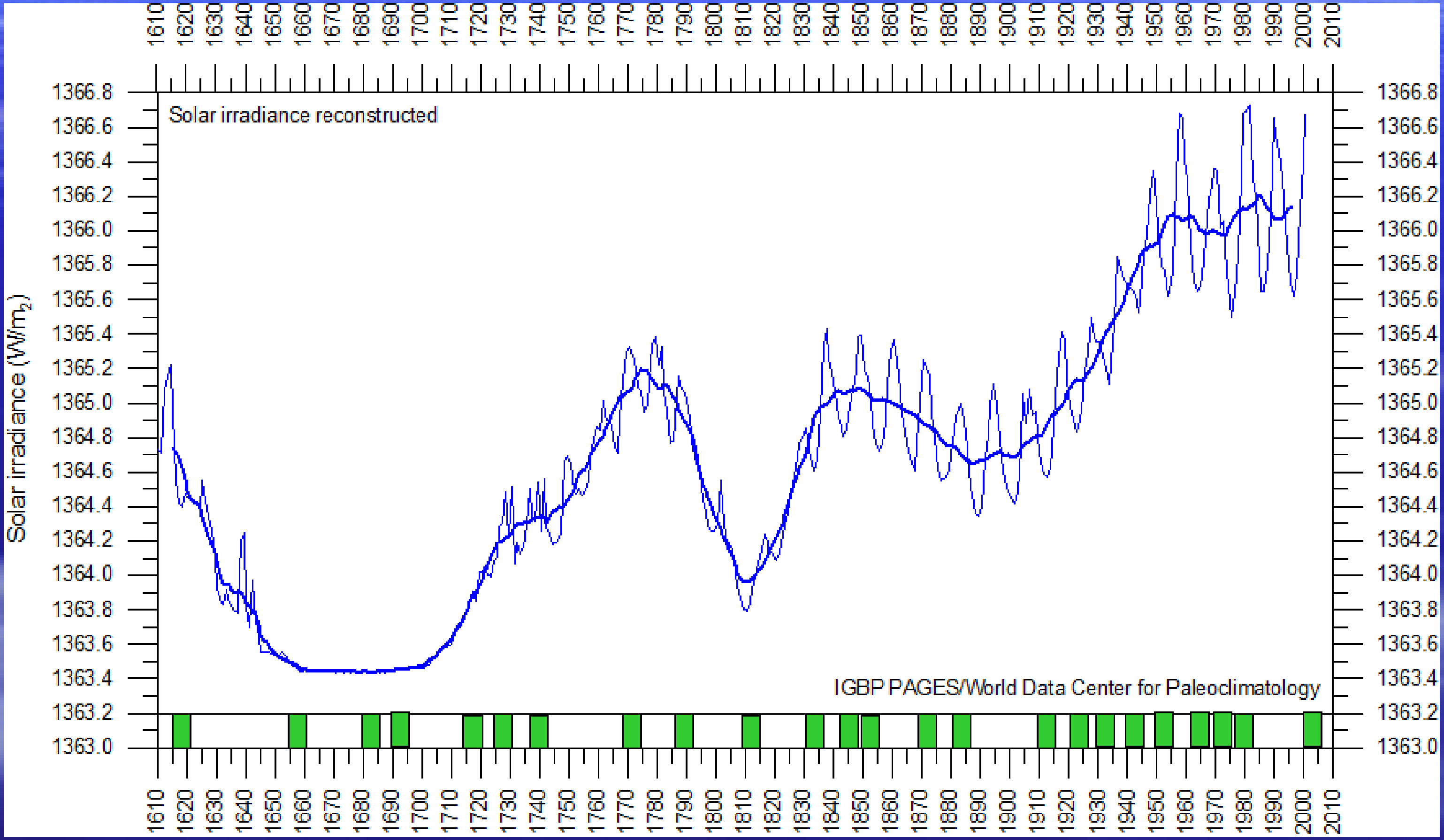
Solar Variability

- Small variation in solar output during a solar cycle.
- Varies by approximately 1W/m^2.



The solar irradiance measured by ACRIM over the period 1980–88, showing sunspot-associated dips at times of large spot activity (1980–84 and 1988 onwards) and the prolonged minimum (1985–87) when solar activity was low. The observational errors are larger for the period between the end of 1980 and the beginning of 1984 because of a lower rate of data acquisition and the coarse pointing of the *SMM* spacecraft in this interval. (Courtesy R. C. Willson and H. S. Hudson)

Reconstructed Solar Constant Note ~1W/m² Increase Since 1840



http://www.climate4you.com/Sun.htm

Example

- Over the last 100 years the solar constant has increased by approximately 1 W/m^2, whereas the average surface temperature has gone up approximately 0.6°C. How much of this warming is due to the increased solar output. Remember that the solar constant is 4 time the average sunlight on the surface and that 31% gets reflected.

Solution

- Actual Increase $(0.69)\times(1 W/m^2)/4 = 0.1725 W/m^2$.
- Change in temperature:
- $\Delta T = G\Delta F$

$$= [.67^\circ C/(W/m^2)][0.1725 W/m^2] = 0.116^\circ C$$

Thus only about 19% of temp increase can be attributed to increased solar output…we probably did the rest.