Climate Dynamics (PCC 587): Climate Forcings

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Outline of This Topic

- **Climate forcings**
  - Things that directly change global temperature
  - How to put different effects on the same ground
    - **Radiative forcing** will be a key concept
  - Forcings important for climate
    - Including greenhouse gases, volcanoes, air pollution, land cover changes, and others…
      - It's a long list!
      - Notion of "global warming" versus "climate change" will become more and more apparent

Radiative Forcings: Shortwave Forcings

- **Radiative forcing: change in shortwave in** or **longwave out** due to the particular forcing agent
  - For **shortwave forcings**, this is just the change in solar energy absorbed by the planet
    - Ex. 1: if the Sun increases in strength so 0.2 W/m^2 more is absorbed, the radiative forcing is 0.2 W/m^2
      - OK that was obvious…
    - Ex. 2: if a volcano blows up and reflects back an extra 0.3 W/m^2 of the Sun's rays, the radiative forcing is -0.3 W/m^2

Radiative Forcing: Longwave Forcings

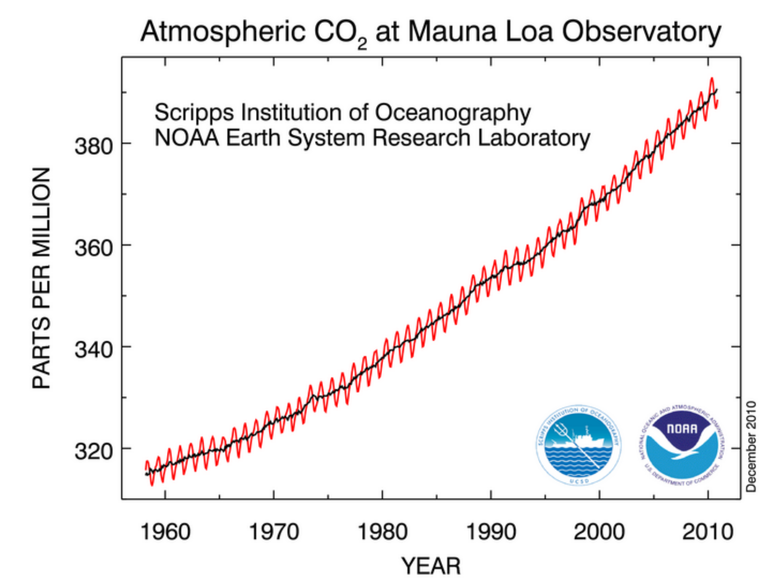
- What about gases that affect the **greenhouse effect**?
- Radiative forcing for greenhouse gases:
  - **Instantly change** the gas concentration as compared with a reference concentration (typically "preindustrial" values from the year 1750)
    - E.g., compare current CO_2 levels with preindustrial CO_2 levels
  - Calculate how much **longwave** radiation to space is **decreased**
    - Have to **assume temperature is unchanged** too
    - Ex: When increasing the concentration of a certain greenhouse gas, longwave radiation is decreased by 2 W/m^2 due to this gas

Radiative Forcings

- In response to a positive radiative forcing, the system will heat up
  - And therefore will radiate more to space
  - Thus radiative forcing for greenhouse gases is calculated assuming no change in temperature
- Ex: CO_2 levels are increased to decrease the longwave radiation to space by 4 W/m^2
  - The atmosphere will heat up in response (because shortwave is greater than longwave)
  - It will radiate away more, eventually getting into energy balance

Carbon Dioxide

- CO_2 is the primary contributor to the anthropogenic (human-caused) greenhouse effect
  - Over 60% of the anthropogenic greenhouse effect so far
- Increases primarily due to fossil fuel burning (80%) and deforestation (20%)
  - Preindustrial value: 280 ppm
  - Current value: 390 ppm



Carbon Dioxide

- CO_2 will also be the main problem in the future
- It's extremely **long-lived** in the atmosphere
  - Around 50% of what we emit quickly gets taken up by the ocean or land
    - We'll discuss this more later
  - Most of the rest sticks around for over **100 years**
  - Some of what we emit will still be in the atmosphere over **1000 years** from now!

Climate Forcing of CO_2

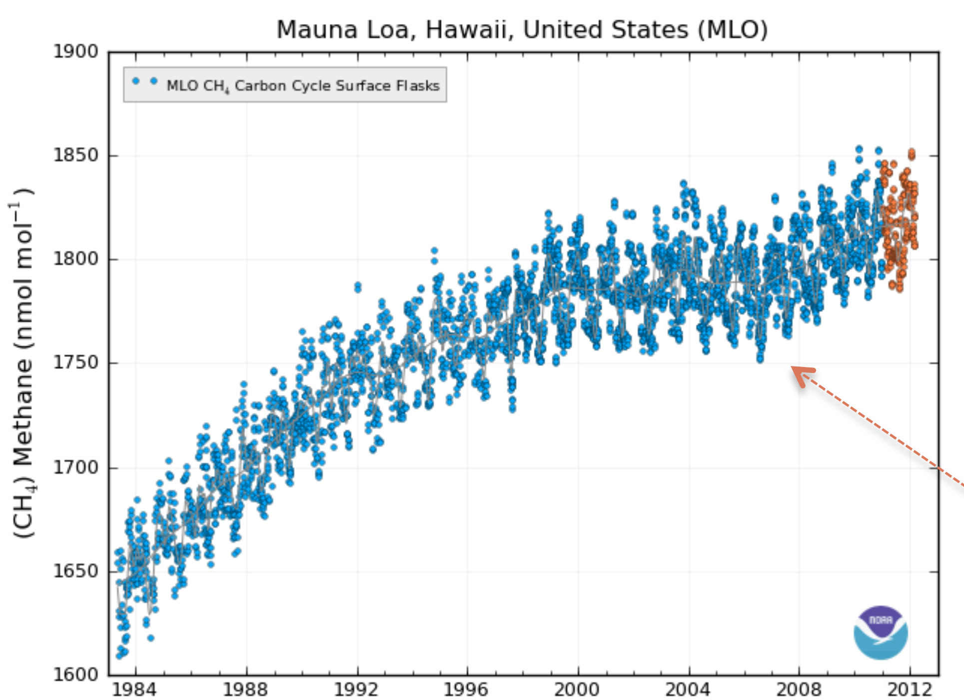
- Radiative forcing of CO_2 for current value versus preindustrial (year 1750) value: 1.66 W/m^2
- Radiative forcing for doubling CO_2: around 3.7 W/m^2
  - And the radiative forcing increase gets less as CO_2 increases more

Methane

- CH_4
  - Natural gas like in stoves/heating systems
- Much more potent on a *per molecule* basis than CO_2
  - Only 1.7 ppm though – much smaller concentration than CO_2
- Natural sources from marshes (swamp gas) and other wetlands
  - Video of methane release from tundra lakes in Alaska & Siberia
- Increases anthropogenically due to farm animals (cow burps), landfills, coal mining, gas leakage, rice farming

Methane

- The lifetime of CH_4 is significantly shorter than carbon dioxide
  - Breaks down in the atmosphere in chemical reactions
  - Lifetime of methane is only 8 years



1984 2012

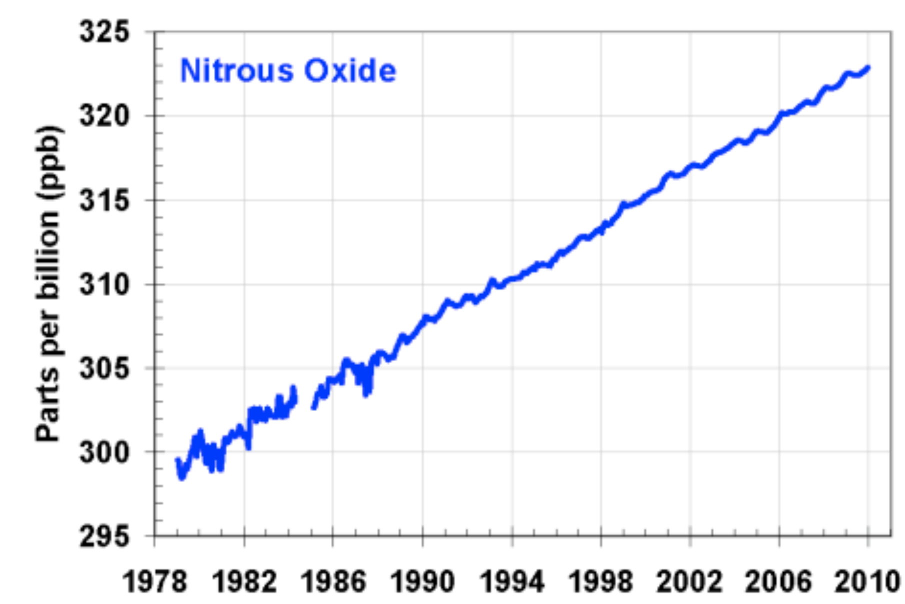
Methane leveled off for a few years (droughts in high latitude wetlands?) Starting to rise again though?

Global Warming Potential

- CO_2 lifetime > 100 years
- Methane lifetime = 8 years
  - But methane is a much stronger greenhouse gas
- How to put these on similar terms? **Global warming potential** (GWP)
  - **Global warming potential** is how much greenhouse effect emissions of a given gas causes over a fixed amount of time (usually 100 years)
    - Measured relative to CO_2 (so CO_2 = 1)
  - Methane's global warming potential is **25**
    - Much more potent than CO_2 even though it doesn't stay as long

Nitrous Oxide

- N_2O
  - Laughing gas
- Also more potent on a per molecule basis than CO_2
  - Global warming potential: **310**
- Comes from agriculture, chemical industry, deforestation
- Small concentrations of only 0.3 ppm

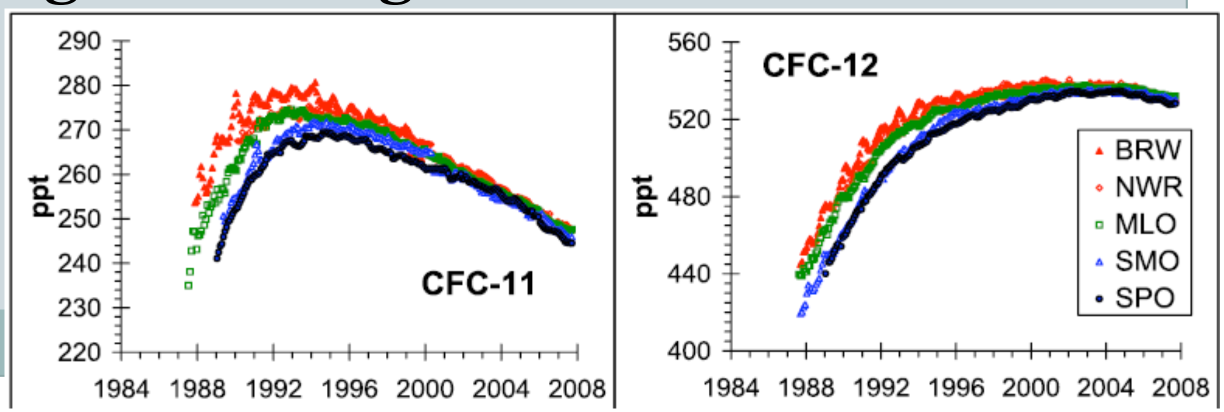


Ozone

- Ozone (O_3) occurs in two places in the atmosphere
  - In the **ozone layer** very high up
    - This is "**good ozone**" which protects us from ultraviolet radiation & skin cancer
  - Near the Earth's **surface**
    - "**Bad ozone**": caused by air pollution
- Bad ozone is a greenhouse gas, and is more potent on a per molecule basis than CO_2
  - But it's very very short-lived
    - Global warming potential for bad ozone is wrapped into the other gases which lead to its chemical creation

CFCs

- CFCs or chlorofluorocarbons are the **ozone depleting** chemicals
  - Have been almost entirely phased out
- CFCs are strong greenhouse gases
  - Their reduction likely saved significant global warming in addition to the ozone layer!
- Some replacements for CFCs (called **HFCs**) are strong greenhouse gases though
- Global warming potentials of up to 11,000!



Radiative Forcing of Other Greenhouse Gases

- These are all current values vs preindustrial values

Carbon dioxide: 1.66 W/m^2

Methane: 0.48 W/m^2

Nitrous oxide: 0.16 W/m^2

CFCs: 0.32 W/m^2

  - But CFCs are **decreasing** now (everything else is increasing)

Shortwave Forcings

- **Shortwave forcings** affect how much solar radiation is absorbed
- Examples of shortwave forcings:
  - Changes in **strength of the Sun**
  - Changes in the **surface albedo**
    - Not changes in ice coverage – that's a feedback
  - **Volcanoes**
  - **Air pollution**
    - This falls under the more general category of "**aerosols**"

Land Cover Changes

- Forests have low albedo (they're dark)
- **Cutting down forests** to create farmland/pastures tends to **raise the albedo**
  - This is actually a **negative** radiative forcing
    - Causes local **cooling** because there's more solar energy reflected
  - Remember that deforestation is an important source of carbon dioxide though
    - Deforestation can cause global warming but local cooling…

Soot on Snow

- A tiny amount of soot (AKA black carbon) in pure white snow can change the albedo dramatically!
  - Currently a very active area of research (Prof. Warren, Atmos Sci)

Fresh snow over Greenland from high above

Other Ways to Change Albedo

- Can change albedo **in the atmosphere** as well!
- ***Aerosols*** (fine particles suspended in air) make a large contribution to reflection of sunlight
  - Volcanoes!
  - Pollution (from coal burning or other types of burning)
  - Dust (e.g., from the Sahara)
  - And others

Air Pollution Aerosols

- Air pollution particles block out sunlight too
  - Sulfates from dirty coal burning are particularly important (**sulfate aerosols**)
    - This is the same stuff that causes acid rain
  - These are a **big effect**
    - One of the **main uncertainties** in our understanding of climate

Summary of Shortwave Climate Forcings

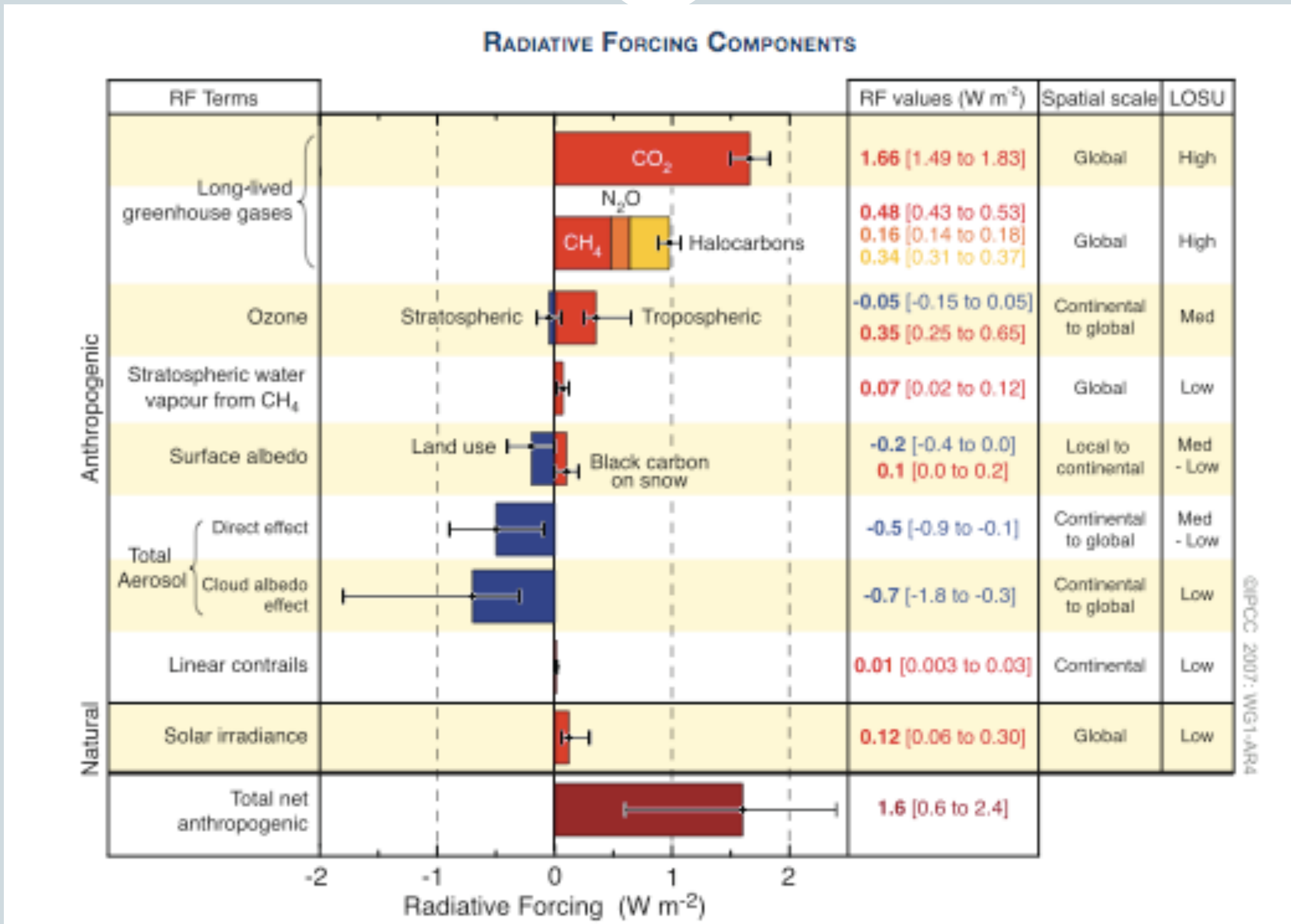
- **Radiative forcings** for shortwave agents in current climate vs preindustrial (best estimates)
  - Remember **CO_2** radiative forcing is currently: 1.66 W/m²
  - **Solar** radiation changes: 0.12 W/m²
  - **Land** cover changes: -0.20 W/m²
  - **Soot** on snow: 0.10 W/m²
  - **Aerosol direct** effect: -0.50 W/m²
  - **Aerosol indirect** effect (clouds): -0.70 W/m²
- Several of the above have significant scientific **uncertainty** associated with them though!
  - We just don't know these values very accurately

Total Radiative Forcing

- CO_2: 1.66 W/m^2
- Total GHG: about 3 W/m^2
- Shortwave forcings: about -1.3 W/m^2
  - With significant scientific uncertainty here
- Best guess of total forcing: **1.6 W/m^2**

- The Earth has been warming over the last 150 years
  - Not that hard to say that it's due to greenhouse gases
    - Greenhouse gases have dominated the radiative forcing
  - We'll discuss other methods of "attribution" later in the class
    - The patterns of warming also match that of GHG warming and not other causes

Radiative Forcing



Current radiative forcing due to different agents (relative to preindustrial era)

Local Aspects of Many Climate Forcings

- CO_2 is still the main problem
  - And it is global (essentially the same concentration everywhere)
  - Hence "**global warming**" is an appropriate name
- Many of the other climate forcings are much more localized though
  - Soot on snow, land use, aerosols all tend to be localized
  - Hence "**climate change**" is a better term when including these

Radiative Forcing and Temperature Response

- Temperatures must respond to a radiative forcing
  - Positive radiative forcing → temperatures must increase
  - This will then reduce the radiative imbalance
- How much temperature response depends on feedbacks though
  - Radiative forcing is defined so it doesn't depend on feedbacks

Climate Sensitivity

- Global warming theory:

$$\Delta T = \lambda \, \Delta F$$

ΔT = change in temperature (in degrees C)

ΔF = radiative forcing (in W/m^2)

λ = climate sensitivity

Feedbacks

- For instance, say lots of ice was on the verge of melting
  - Then any small warming would be strongly amplified
- On the other hand, say the lapse rate feedback could act strongly (warming the upper troposphere really quickly)
  - Then the surface temperature might only need to increase a tiny bit to respond to the forcing

Feedbacks

- Remember:
  - A positive temperature change is always required to balance a positive forcing
    - Could be very small though if there are many strong negative feedbacks
  - If there are many strong positive feedbacks, system could spiral out of control
    - “Runaway greenhouse effect”: Earth keeps getting hotter & hotter until all the oceans evaporate
    - Not going to happen on Earth, but happened on Venus?

Climate Sensitivity

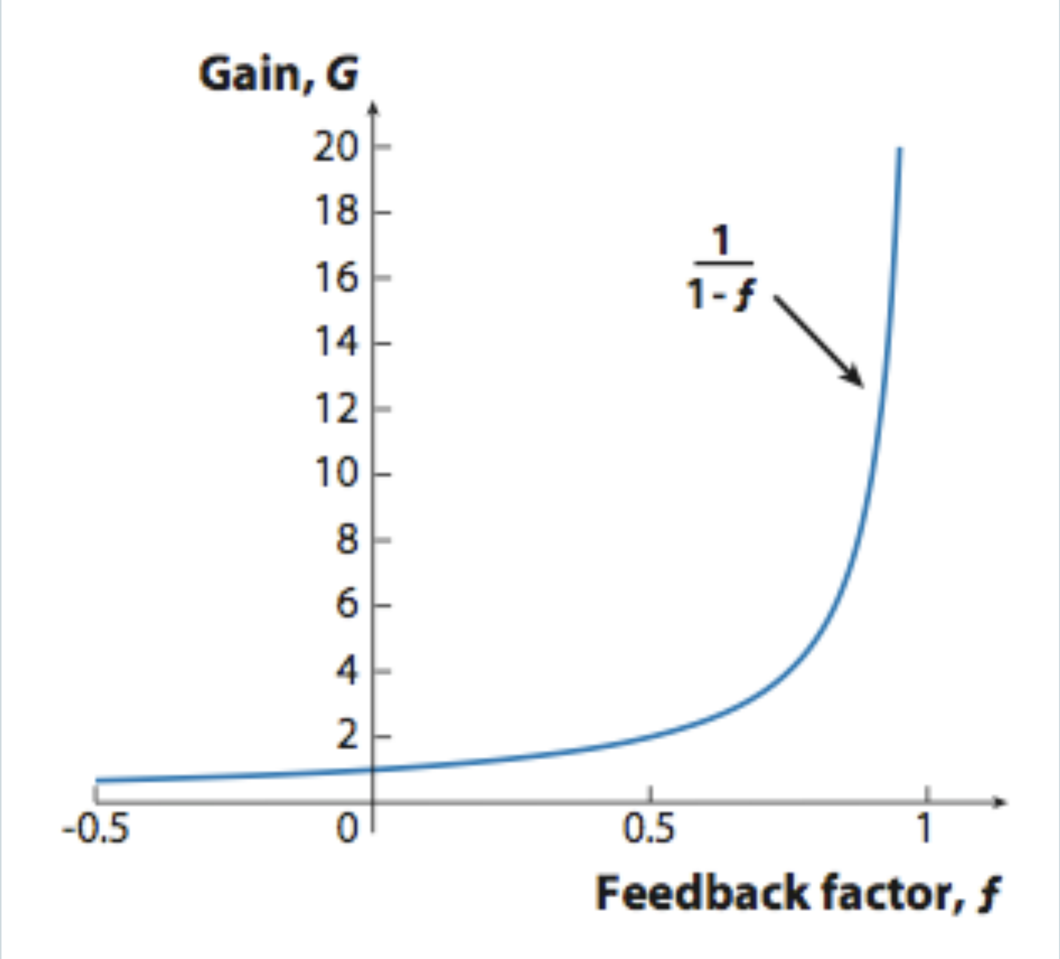
- Climate sensitivity:
  - The total temperature change required to reach equilibrium with the forcing
  - Depends on feedbacks! (unlike radiative forcing)
  - Refers to equilibrium state
    - Real climate change is transient: we'll discuss this later

- Have you ever noticed how often it's reported that the upper end of climate sensitivity is hard to rule out?
  - This is a fundamental property of systems with positive feedbacks

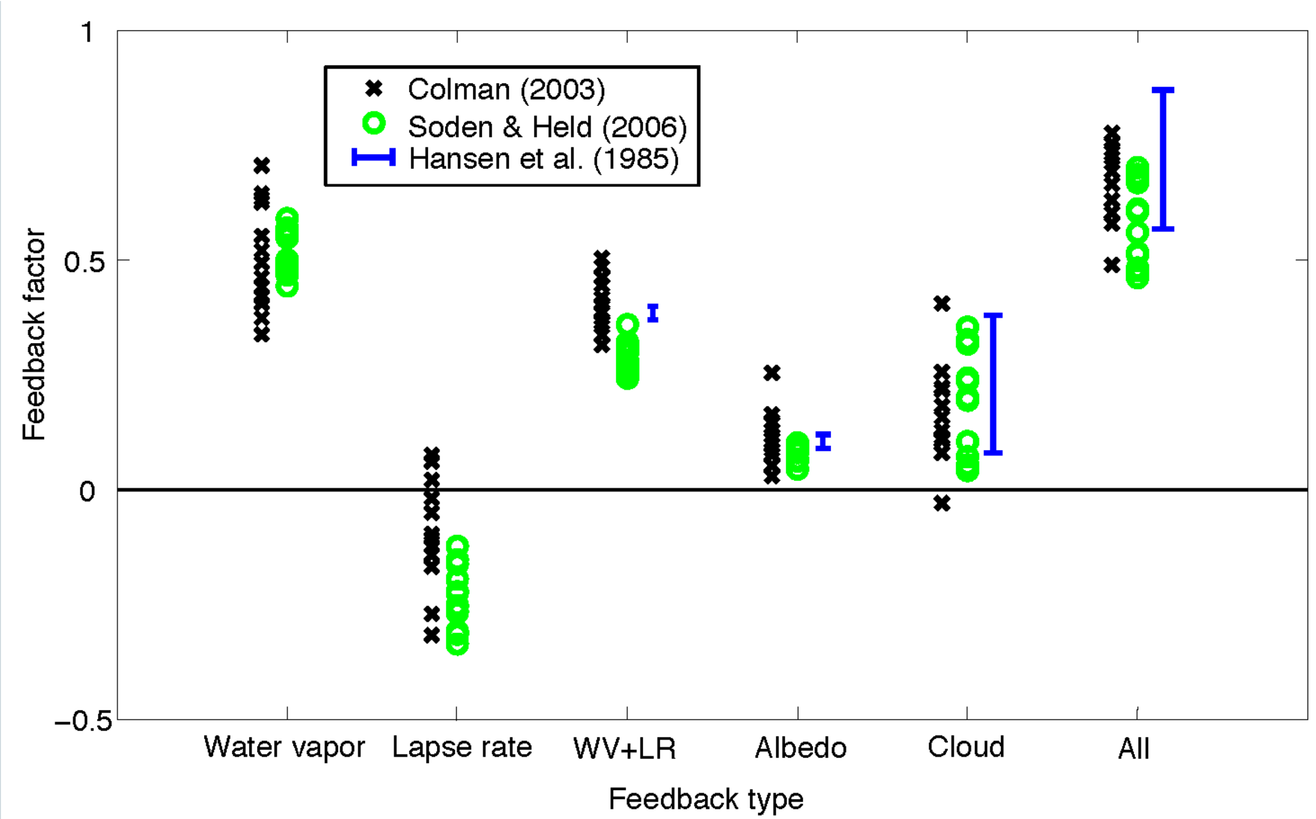
“Feedback Factor”

- Feedback factor: nondimensional measure of feedback amplification
  - Negative for negative feedbacks, positive for positive feedbacks
  - 1 for a positive feedback that makes the system blow up (so feedbacks must be < 1 for stability)
  - Feedback factors are **additive** (can just sum the impact of different agents)

Feedback Factor vs Gain



Feedback Factors for Global Warming



Individual feedbacks uncorrelated among models, so can be simply combined:

Soden & Held (2006):

$\bar{f} = 0.62; \sigma_f = 0.13$

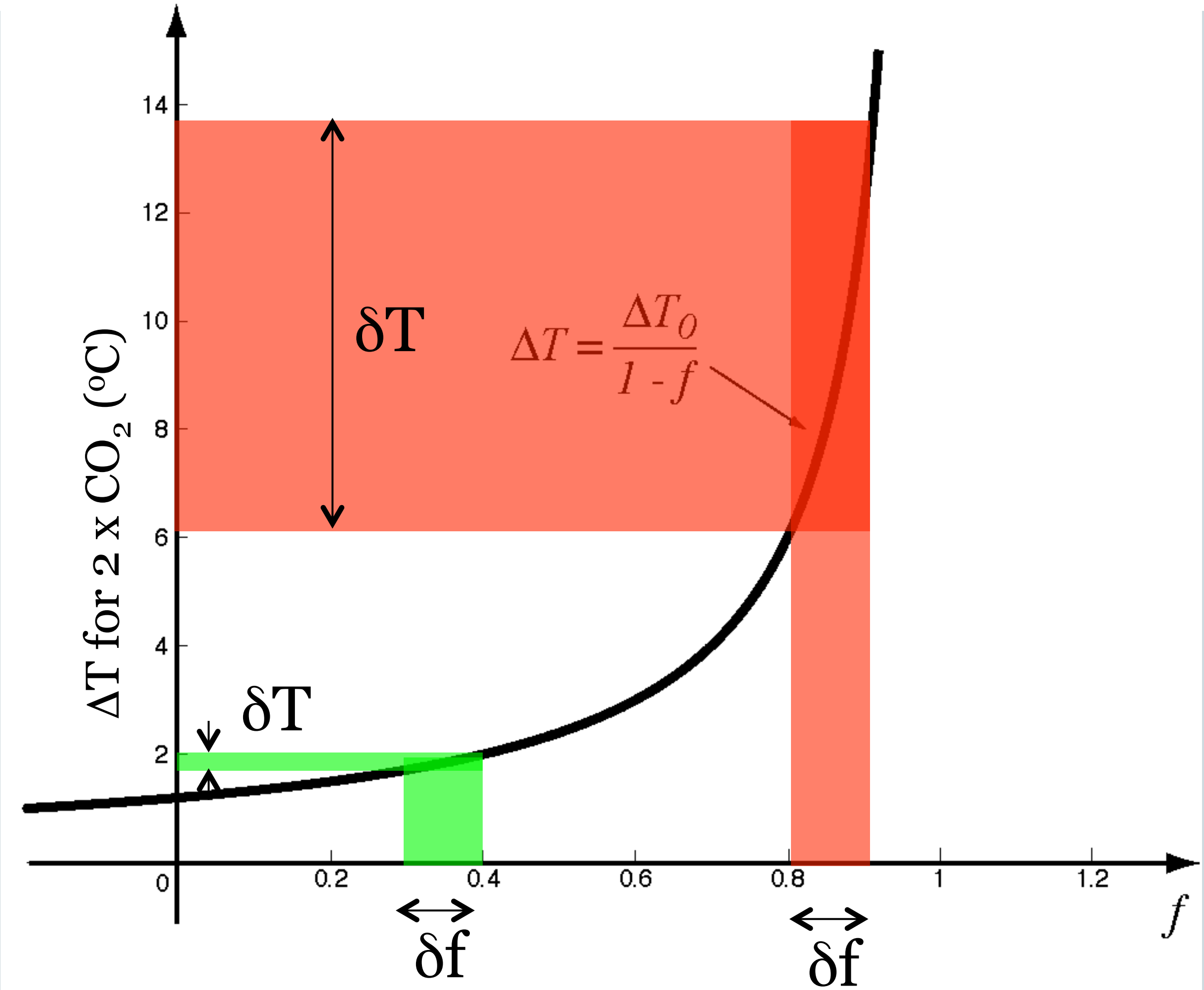
Colman (2003):

$\bar{f} = 0.70; \sigma_f = 0.14$

Clouds have largest uncertainty by far (when water vapor and lapse rate are combined)

Cloud LW forcing is expected to be slightly positive (depth of high clouds to increase)

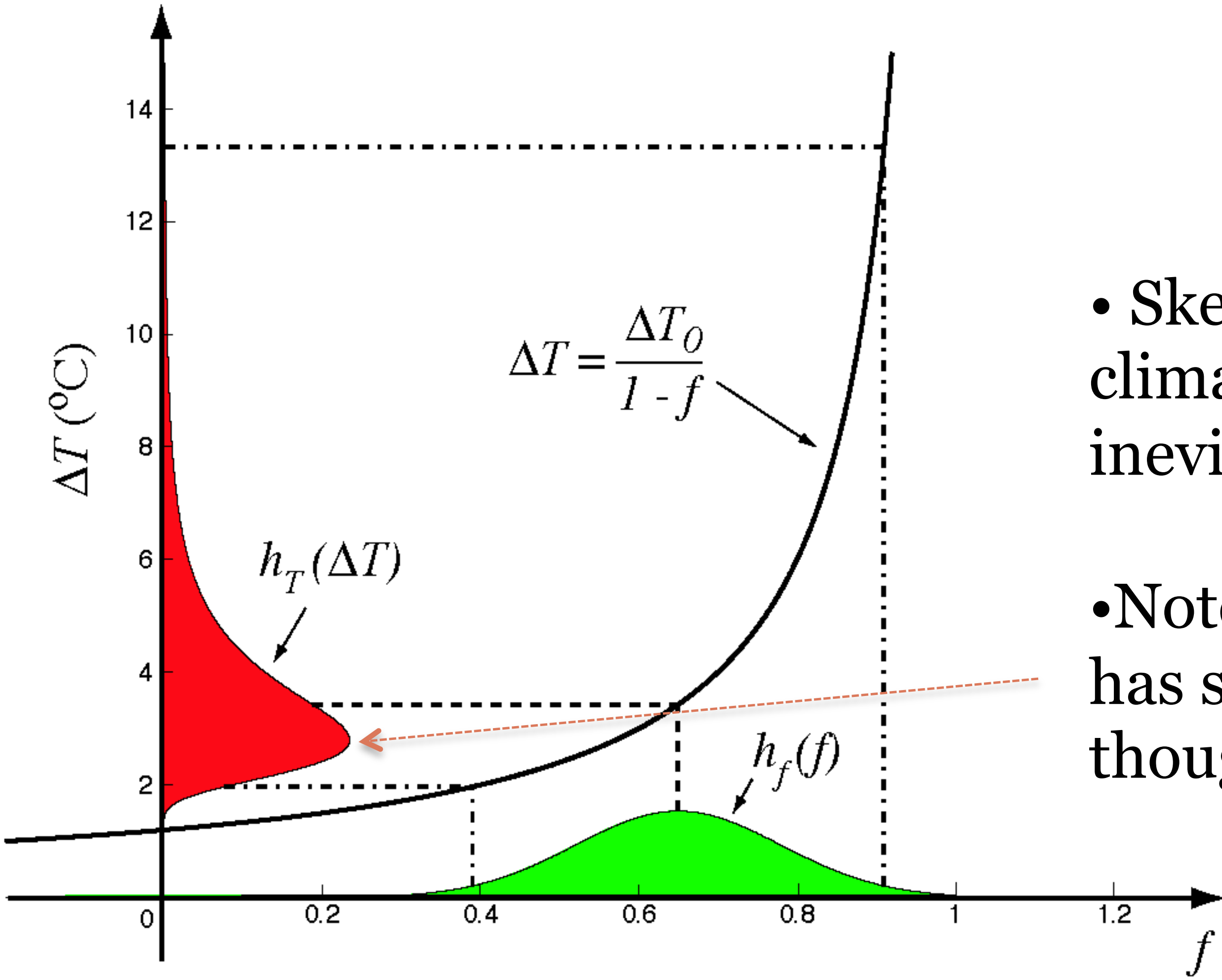
Uncertainty in Sensitivity



Same uncertainty in feedback strength (δf) for a *high sensitivity* climate leads to **much more** uncertainty in temperature (δT)!

- Uncertainty in climate sensitivity strongly dependent on the gain.

Distributions of Sensitivity



for:

$\bar{f} = 0.65$

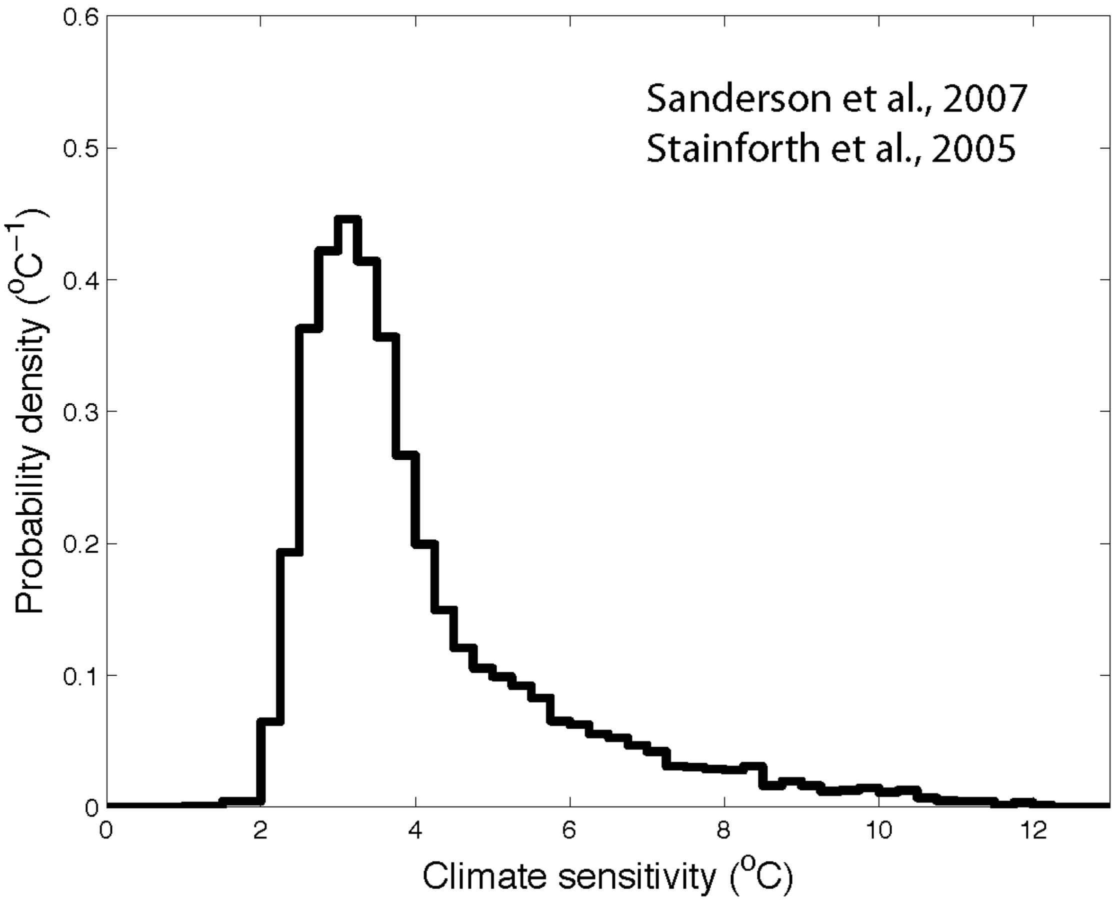
$\sigma_f = 0.14$

- Skewed tail of high climate sensitivity is inevitable!

- Note the expected value has slightly less warming though

Climate sensitivity: an envelope of uncertainty

climateprediction.net 250,000+ integrations, 36,000,000+ yrs model time(!);



Equil. response of global, annual mean sfc. T to 2 x CO_2.

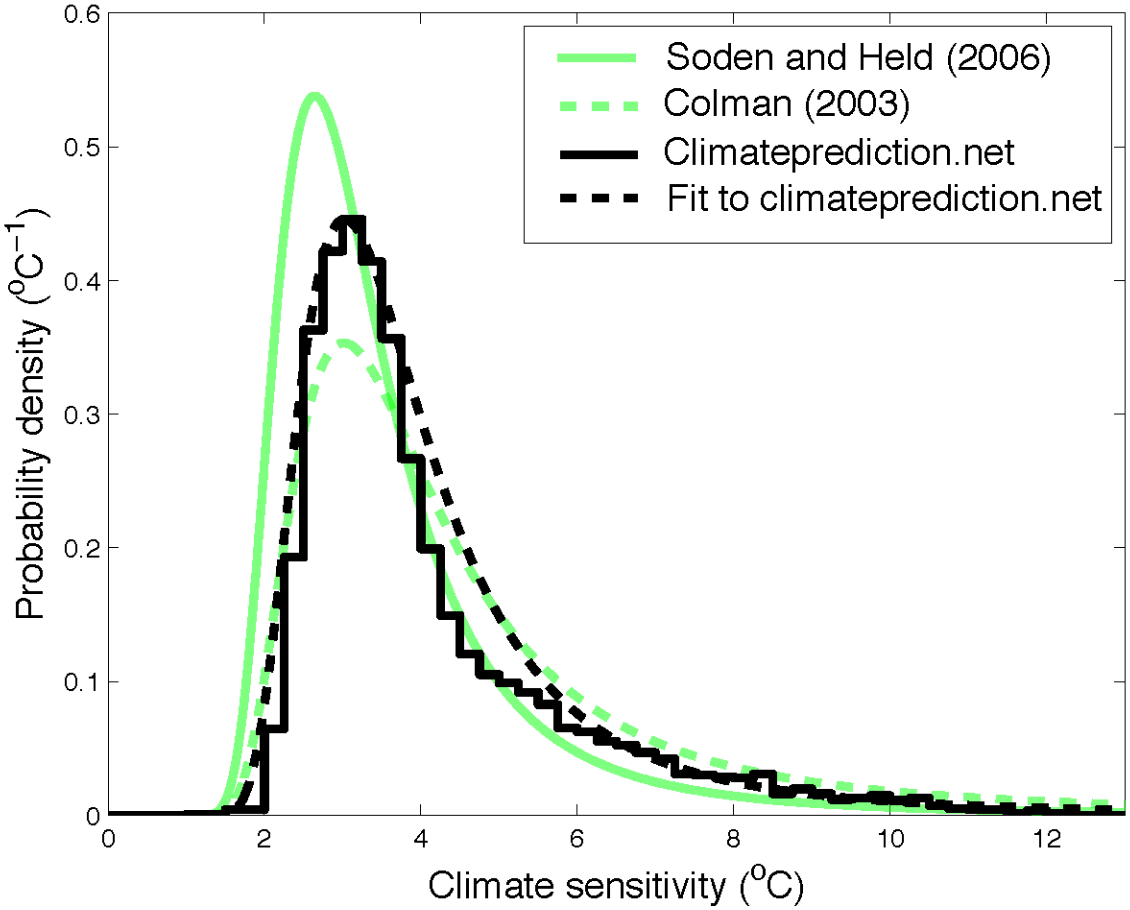
6,000 model runs, perturbed physics

Slab ocean, Q-flux
12 model params. varied

- Two questions:
  1. What governs the shape of this distribution?
  2. How does uncertainty in physical processes translate into uncertainty in climate sensitivity?

Climate sensitivity: GCMs

Work of Gerard Roe, ESS & Marcia Baker (emeritus, Atmos & ESS)



- GCMs produce climate sensitivity consistent with the compounding effect of essentially-linear feedbacks.