Summary of last lecture

- **Greenhouse gases**: H₂O, CO₂, and other GHG
  - capture outgoing IR radiation from earth
  - reradiate IR down to surface
  - raise surface temperature $T_s$

- **Radiative forcing**: net (down - up) tropopause flux change [W/m²]

- RF from CO₂ grows logarithmically

Global models $\Rightarrow F_{2x} \approx 3.7$ W/m² [IPCC 2001, 2007]

- All else fixed, $F_{2x} \approx 3.7$ W/m² $\Rightarrow \Delta T_s \approx 1.2^\circ$C
  
  feedbacks $\rightarrow \Delta T_{2x} \approx \sigma F_{2x}$, $\sigma$ “climate sensitivity parameter”

Today: consider feedbacks
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Today: consider feedbacks
Climate change: feedback, history, predictions and mitigation

Today:

• Carbon cycle and CO₂ emissions
• Feedbacks and modeling
• Paleoclimate data

Friday 11/30:

• Predictions and consequences of climate change
• Mitigation
Conclusive evidence: anthropogenic CO$_2$ increase

Pre-industrial: 280 ppm, Current: 391 ppm (by volume)

Increase: $\approx +2$ ppm/year
Carbon cycle and emission

Where is atmospheric CO$_2$ coming from?

2010 values: (carbon mass)
(http://www.globalcarbonproject.org/carbontrends/)

Net atmosphere:
$(5.14 \times 10^{18} \text{ kg}) \times \frac{12}{44} \times 588 \text{ ppm(m)}$
$\cong 824 \text{ Gt}$
(note: 588 ppmm $\cong 387 \text{ ppmv}$)

Fossil fuel + cement: $\sim 8.7 \text{ Gt}$

Land use: $\sim 1.5 \text{ Gt}$

Net ocean uptake: $\sim 2.3 \text{ Gt/year}$
(1000’s of years to equilibrate (?))

Net land uptake: $\sim 3 \text{ Gt/year}$

Atmosphere increase: $+ 5 \text{ Gt/year net}$
Estimated historical carbon emissions (fossil fuels + cement)

2010 land & ocean sinks removed 1/2 of added carbon

– How long will natural sinks continue?
Other sources of ± RF besides CO₂ (current $F_{CO2} \approx 1.7 \text{ W/m}^2$)
– Other sources generally relevant on shorter time scales

- **Methane:**
  Pre-industrial 400-700 ppb (last 650,000 years); current: 1800 ppb
  Sources: wetlands, biomass burning, cow gas, industrial processes
  $F_{CH4} \approx 0.5 \text{ W/m}^2$ (> CO₂ GHG effect per unit mass)
  Destroyed in atmosphere in $\sim 12$ years
  Possible large-scale nonlinear release from tundra

- **Nitrous oxide, CFC’s, ozone:**
  CFC’s: strong greenhouse gases (and destroy ozone) $F_{CFC} \approx 0.35 \text{ W/m}^2$
  Ozone in troposphere, $F_{ozone} \approx 0.35 \text{ W/m}^2$

- **Aerosol:**
  Small particles in atmosphere absorb + scatter sunlight
  Power plants (coal) $\rightarrow$ sulfur dioxide $\rightarrow$ sulphate particles
  Nucleate reflective clouds
  Difficult to estimate, maybe $F_{aerosol} \sim -1.2 \text{ W/m}^2$; recent estimate higher
  Particulates (black carbon) on ice accelerate melting (next lecture)
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Feedbacks + climate sensitivity

CO$_2$ radiative forcing $F_{2x} \simeq 3.7$ W/m$^2$ → $\Delta T \simeq 1.2^\circ$C direct → feedbacks

Many sources of $\pm$ feedbacks
- H$_2$O vapor: $T \uparrow \Rightarrow$ H$_2$O$\uparrow \Rightarrow +F$
- Lapse rate: H$_2$O$\uparrow \Rightarrow$ LR$\downarrow \Rightarrow -F$
- Ice albedo: $T \uparrow \Rightarrow$ ice$\downarrow \Rightarrow \alpha \downarrow \Rightarrow +F$
- Clouds: can be $\pm F$

... 

Note: linear feedbacks assume $\exists$ continuous range of equilibria

Not necessarily true — abrupt/nonlinear changes possible
(e.g. 13 ka: draining of Lake Agassiz → shutdown MOC?)
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CO₂ radiative forcing \( F_{2x} \cong 3.7 \text{ W/m}^2 \rightarrow \Delta T \cong 1.2^\circ \text{C direct} \rightarrow \text{feedbacks} \)

\[
F \quad -F \quad F' = \lambda \Delta T
\]

Forcing

\[
F \Rightarrow \Delta T (= -F/\lambda_0) \\
\Delta T \Rightarrow \text{change } \lambda \Rightarrow F' \\
F' \Rightarrow \Delta T' \ldots
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\[
\lambda = \frac{\Delta T}{F - F'_0}
\]

\( F' \) is the climate feedback coefficient.

\[
\text{Forcing} \Rightarrow \text{Climate} \Rightarrow \text{Feedbacks} \Rightarrow \Delta T
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Carbon cycle
Feedbacks and climate models
Past and present climate

Feedbacks + climate sensitivity

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Feedback parameter $\lambda$ [W/m$^2$°C]: change in RF from change in $T_s$

$\lambda_0 \approx -3.2$ W/m$^2$°C “uniform temp.” radiative cooling response

Other feedbacks: water vapor, clouds, CO$_2$, ice albedo, . . .

Radiative equilibrium when $(\lambda_0 + \lambda_1 + \ldots \lambda_n)\Delta T + F = 0$

Iterative mechanism (1 $\lambda$): Forcing $F \Rightarrow (\Delta T)_0 = -F/\lambda_0 \Rightarrow \lambda$

$\lambda$ gives additional forcing $F_\lambda = \lambda \Delta T = -F\lambda/\lambda_0 \Rightarrow (\Delta T)_1 = F\lambda/\lambda^2$

$\Delta T = -\frac{F}{\lambda_0} \left[1 - \frac{\lambda}{\lambda_0} + \frac{\lambda^2}{\lambda^2_0} + \cdots \right] = -F/(\lambda_0 + \lambda)$

$\lambda > 0$ feedbacks $\Rightarrow$ amplify warming by $f = \lambda_0/(\lambda_0 + \lambda) = 1/(1 - \lambda/|\lambda_0|)$

Note that $\lambda > |\lambda_0| \Rightarrow$ runaway feedback!

(complete runaway unlikely– log forcing, paleo data: ok w/higher CO$_2$, $T$)
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General Circulation Models (GCM’s)

Compute dynamics of coupled atmosphere + ocean processes
many processes not modeled, parameterized to match observation

- **Atmosphere**
  - grid simulation well-developed
  - clouds parameterized, difficult

- **Oceans**
  - less well developed,
  - fewer observations available

- **Ice (cryosphere), land surface**
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- **Couplings (evap., wind stress, . . .)**
  - increase complexity

Currently, grids down to 1.25° latitude/longitude, 20 pts. vertical
Time steps 30m-1h, integrate years/decades → Tflop years

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Feedback estimates from general circulation models (∼ 20 GCM’s)

Upshot: estimate total $\lambda \approx 2 \text{ W/m}^2\text{°C}$

So $f = 1/(1 - \lambda/|\lambda_0|) \approx 1/(1 - 2/3.2) \approx 2.67, \quad \sigma = -f/\lambda_0$

So IPCC estimates $\Delta T_{2x} \approx \sigma F_{2x} \approx 3.2\text{°C} \pm 0.7\text{°C}$

Without cloud feedback (most uncertain): $\Delta T_{2x} \approx 1.9\text{°C} \pm 0.15\text{°C}$
Recent temperature data [Hadley climate centre, monthly data]

- Warming after little ice age → 1940, ~ flat to 1975
- Since 1975, believed warmest on record in > 1 million years
- Perhaps 0.1°C warming from “urban heat islands”
  (note: 500 EJ ≪ 50000 EJ/year from RF)
Temperature data, take 2

- Relatively flat since 2000, but 2010 second hottest (after 1998) (negative RF from sulphates from coal emissions?)

**Global average temperature 1850-2011**
Based on Brohan et al. 2006

Smoothed yearly temperature data [Hadley climate centre]
Paleoclimate data

Comparison to historical record useful in many ways —

- Compare current era to historical
- Isolate anthropogenic/natural sources of change
- Check GCM’s

Sources of data

Instrumental data: back 150-200 years max

Tree rings (dendrochronology): several 1000’s years data

Ice cores, deep sea sediment cores: back 100,000’s of years
  CO₂ data, $^{18}$O → ice mass, temperature back ~ 600,000 years

Further back, challenging but some data
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Further back, challenging but some data
Reconstructions of surface temperature over 2000 years

Medieval climatic optimum 1000-1300 AD
Little ice age: 1400-1900 AD (incl. Maunder, Sporer sunspot minima)
Ice core data: Vostok and EPICA

Antarctic ice cores: 700,000 year climate record
– Ice cores > 3 km long
– Trapped air bubbles: information about atmosphere
– Levels of deuterium (in HDO) proxy for temperature
Paleo data — last 650,000 years

- CO$_2$ 180-300 ppm, varies with (following) $T$.
- $\sim$ 100 kyr glacial cycle, warm interglacials $\sim$ 10 – 30 kyr
- Last glacial max $\sim$ 20 kyrs ago. $\Delta T \sim -5^\circ$C (sea level -120m)
- 9ka-1200 AD relatively warm, very stable; 1250-1850 little ice age
Natural causes of climate change

Many natural phenomena influence climate

- Solar variation (sunspots, gradual intensity increase)
- Configuration of land masses on earth
- Particulate matter in atmosphere (e.g. volcanos, meteor impact)

Generally agreed, main factor over last 0.5 Myrs is orbital geometry

Milankovitch (orbital parameter) theory

Obliquity (tilt) $\Phi$: tilt of axis relative to ecliptic plane

Eccentricity $e$: ellipticity, departure of orbit from circle

Axial precession $\Lambda$: tilt direction vs. perihelion
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Orbital parameters and ice ages

Orbital parameters vary with characteristic periods.

\( e \): 100 ky, 400 ky \( \rightarrow \) small (~ 0.18\%) total insolation variation

\( \Phi \): 22.1°-24.5°, cycle \( \sim 41,000 \) y \( \rightarrow \) latitudinal insolation variation

\( e \sin \Lambda \): \( \sim 26,000 \) y \( \rightarrow \) latitudinal insolation variation

Minimum northern summer insolation when \( \Phi \) small, \( e \sin \Lambda \) negative

Small effects but with feedbacks, believed drive ice ages
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Further back ... Cretaceous period

145-65 million years ago

- Quite warm in Cretaceous/Eocene
  - dinosaurs near (then) South Pole
  - seas 100-200m > now; deep sea 10-15°C > now

- Estimated 3x-12x current CO$_2$
  - poorly understood: GCM’s indicate higher tropical $T$ than data

- Continents configured differently, different ocean flow

- Life abundant, 60% current oil reserves from Cretaceous
55 million years ago: CO$_2$~5x current, mammals proliferated

Cooling over last 50 million years:

CO$_2$ removal by weathering from Tibetan Plateau (?)

35 Ma: permanent glaciation in Antarctica, major growth 13 Ma

7-3 Ma: permanent ice sheets in Greenland, 2.75 Ma: northern glaciation
Causes of recent warming

- IPCC: “Most of the observed increase in global average temperatures since the mid-20th-century is very likely [> 90%] due to the observed increase in anthropogenic GHG concentrations”.