Energy and Climate III:
Projections, consequences, and mitigation

November 30, 2012
Summary of previous lectures

- Radiative forcing from CO$_2$:
  
  Logarithmic growth, $F_{2x} \cong 3.7$ W/m$^2$

- Without feedbacks: $\Delta T_s \cong 1.2^\circ$C

- Including feedbacks: water vapor, lapse rate, albedo, clouds, …
  
  IPCC estimates $\Delta T_{2x} = \sigma F_{2x} \cong 3.2^\circ \pm 0.7^\circ$C

- Current CO$_2$, global temperature likely highest in $\sim 125,000$ years

  Current CO$_2$: 391 ppm, pre-industrial 280 ppm, around 180 ppm at glacial maxima over last 650,000 y (CO$_2$ lagged temperature during orbital cycles)

  Eocene (50 Ma): probably $\geq 3$-12x current CO$_2$, much warmer
Today: projections, consequences, and mitigation

Climate projections and consequences of warming

- IPCC scenarios
- Warming climate
- Ice melt, sea level rise, etc.

Mitigation:

- Change fuel source
- Carbon capture and storage
- Geoengineering
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.”
What is time scale of warming?

\[ F_{2x} = 3.7 \text{ W/m}^2 \]

Compute time to warm oceanic mixed layer (Complete shift to new equilibrium takes significantly longer)

\[ V = 350 \text{ Mkm}^2 \times 200 \text{ m} \approx 7 \times 10^{16} \text{ m}^3 \]

\[ M = \rho V \approx 7 \times 10^{19} \text{ kg} \]

\[ Q = c_p M \Delta T \approx (4.186 \text{ kJ/kg K}) \times 7 \times 10^{19} \text{ kg} \times 3.2 \text{ K} \approx 10^{24} \text{ J} \]

Rate of energy input \( R = 3.7 \text{ W/m}^2 \times 500 \text{ M km}^2 \approx 2 \times 10^{15} \text{ W} \)

Time constant \( \sim Q/R \approx 17 \text{ years} \)

[Assumes radiative forcing constant; really, decreases with warming]

⇒ expect convergence to new equilibrium over many decades (really much > 17 years since only fraction of \( E \rightarrow \) mixed layer)
What happens next?

IPCC scenario categories I-VI:

I: cap emissions, decrease after ∼ 2010

VI: “business as usual” until ∼ 2050

IPCC: “Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels”
Kyoto protocol:

- 1997 agreement on greenhouse emissions
- Ratified by 191 nations/states (not including U.S.)
- Legally binding
- CO₂ 5% below 1990 by 2012 for 38 Annex I members
- Need new treaty by 2012

Copenhagen conference 2009: Countries outlined stronger targets

U.S., 2020: 17%, 2030: 42%, 2050: 83% (below 2005 levels)

EU, 2020: 20% (below 1990 levels)

Japan, 2020: 25% (below 1990 levels, with conditions)

China, 2020: 40-45% (below 2005 levels, GDP indexed)

Accord not legally binding; aims at ΔT < 2°C, 138 countries signed.

IEA 2012: 80% of 2°C is already “locked in” (existing cars, factories, plants)
Further climate negotiations

Last year: Durban, South Africa
   Disagreements between developed and developing countries
   Some agreement: legally binding agreement by 2015, implement 2020+

This year: Doha, Qatar – conference finishes Friday 12/7
Consequences of climate change

• Gets warmer!

— More warming over land, high northern latitudes
— Diurnal fluctuations decrease— increase daily minima > maxima (higher fraction of downward radiation from atmosphere)
— More very hot days, heat waves; fewer cold episodes (Doubling CO$_2$ $\rightarrow$ $\sim$ 1 month shift in climate)
— Increased precipitation, precipitation intensity

• Uncertainties

— Extent of warming (depends on feedback)
— Latitude distribution [GCM and paleo data disagree; ocean transport?]
Mean surface warming projections in 3 scenarios [IPCC]

2090-1990 Global mean $\Delta T = 1.1-2.9$ (B1), 1.7-4.4 (A1B), 2-5.4 (A2)
Projections and consequences

Mitigation

Annual mean surface warming, precipitation as function of latitude [IPCC]
Consequences of climate change, continued

- **Glacial ice melt: mountains, Greenland, Antarctica:**
  Caused by warming, ice albedo feedback, direct effect of “black soot”
  Melting faster than most models predicted
  Yesterday in Science article: Greenland 55 Gt/y in ’90s $\rightarrow$ 290 Gt/y

- **Sea level rise:** highly uncertain, will probably continue for centuries
  IPCC 2007: $\Delta T \sim 3.5^\circ C \rightarrow \delta h \sim 0.25$ – 0.5 m this century
  [note: change 0.2 m in 20th century mostly thermal expansion]
  (general agreement: IPCC prediction is underestimate, 1 m plausible)
  Recent antarctic report: 1.4m by 2100 from West Antarctic ice melt (?)
  Ice loss $\rightarrow$ 7 m from Greenland but only over 100’s of years
  Possible collapse West Antarctic Ice Sheet $\rightarrow$ 5-6m rise
Consequences of climate change, continued

- Arctic ice melting:

  - September 2012: Arctic sea ice extent lowest ever (3.6 Mkm$^2$)
  - Ice loss significantly faster than expected by IPCC, other models
  - Possibly ice free Arctic during summer months by 2020
Arctic ice melting, continued

Why is Arctic ice melting so quickly?

Warming of atmosphere, oceans; black soot on ice

Ice thickness gradually decreasing from 1980-2000

Change in atmospheric circulation patterns

Decrease in multi-year ice → weaker ice, faster flow, breakup

∼ 2000: past threshold for substantial ↓ in ice extent, albedo change
Consequences of climate change, continued

- **Ecosystem impact:**
  - Many ecosystems resiliency “likely” to be exceeded
  - IPCC: up 1.5 to 2.5°, 20% to 30% species higher extinction risk
  - 3.5°C rise, maybe 40-70% species extinct
    [note: currently 25% mammals threatened by habitat loss etc.]

- **Increased growth** and food production at mid-latitudes

- **Increased desertification** in dry/tropical regions, H₂O supply ↓

- **Increased range for some disease vectors**

- **Increased floods, extreme weather events**

- **Possible slowing of MOC**
With emissions controls, perhaps 2100 ~ mid-Pliocene (3.3-3 Ma)

- Atmospheric CO$_2$ levels ~ 360-400 ppm
- Similar geography (continents, ocean basins)
- Mean global temperatures 2°-3°C above present
- Sea levels were ~ 15-25m above current (prob. not ~ 2100)
- High latitudes much warmer, tropics maybe similar? (GCM disagree)

**Further back:** gradual cooling from Eocene (50-30 Ma, $\Delta T$ ~ 7°C)

Eocene $\rightarrow$ Oligocene $\rightarrow$ Miocene $\rightarrow$ Pliocene
Mitigation Options:

What are our options for reducing total radiative forcing?

- **Conservation/Energy efficiency**  [Lecture 37]
  Use less energy → emit less CO₂

- **Renewable sources**
  Use solar, wind, ... instead of FF → eliminate CO₂ emissions

- **Non-carbon sources**
  Nuclear, geothermal in place of fossil fuels → eliminate CO₂ emissions

- **Fuel switch**
  Natural gas, biofuel in place of coal, petroleum → reduce CO₂ emissions

- **Capture and sequester CO₂**  [this lecture]
  Store in gas form (huge volume). Solid form?

- **Geoengineering**  [this lecture]
  Reduce radiative forcing independent of CO₂
Carbon capture and storage/sequestration

**Basic concept:** Capture CO$_2$ at large point sources $\rightarrow$ long-term storage

- Large point sources: currently $\sim 40\%$ of CO$_2$ emissions
- At some point may consider capture from atmosphere

**Storage options:**
- Geological [oil/gas fields, ... ]
- Ocean storage
- Fixation into solid carbonates

Sleipner Vest natural gas field, Norway
First large-scale CO$_2$ sequestration
1 Mt/year, began 1996 (Statoil)
Carbon capture costs energy

Energy of separation
from entropy of mixing

Mix \bullet \text{ at concentration } c \ll 1

\[ \Delta S \approx -Nk_B \ln \frac{1}{c} \]

separation: requires \( \Delta E \)

\[ \frac{1}{T} = \frac{\Delta S}{\Delta E} \Rightarrow \Delta E \approx T \Delta S \]

[Gibbs free energy: \( G = H - TS \) ]

Energy needed for capture/storage

Capture 1 kg of CO\(_2\):
(from atmosphere)

\[ N \approx 1 \text{ kg}/44u \approx 1.4 \times 10^{25} \]

\[ T \Delta S \approx (300K)Nk_B \ln \frac{10^6}{387} \]

\[ \Delta E = T \Delta S \approx 460 \text{ kJ} \]

Store at 100 atm., \(+Nk_BT\log 100\)

\[ \Delta E_{cs} = 730 \text{ kJ} \]

Coal plant (\( \eta =30\% \)):
10 MJ/kg\(_C\) \approx 2.7 MJ/kg\(_{CO_2}\)

E to capture and store 37 Gt CO\(_2\):

27 EJ

(> 40\% of electricity production)
Carbon capture at source:

Capture in plant easier (post/pre-combustion)
but still substantial energy cost

• Basic approach (pulverized coal plant) capture from flue gases
  \[ c \sim 1/10 \Rightarrow E_{cs} \approx 25\% - 40\% \text{ plant output} \]

• IGCC: gasify \rightarrow syngas, capture carbon pre-combustion
  — Only need 11-22\% output E
  — Difficult chemical engineering to capture at high \( p, T \)
  — Few plants build so far

• Currently CO\(_2\) production in gasification facilities

• CCS may be crucial for meeting climate goals, key in China
Geoengineering: Many ideas suggested for cooling without reducing carbon

— Giant mirrors (in space?)
— Inject atmosphere with sulphates, reduce RF
— Iron → plankton, increased growth, CO₂ → ocean bottom
— Seed low lying clouds, inject particulate matter into air

Most of these approaches have serious issues. In particular:

• CO₂ not removed, mitigation must be continued for 100’s of years
• Other side effects of CO₂: ocean acidification, etc.
• Other side effects of mechanisms (e.g. sulphates → acid rain, … )
SUMMARY

- Radiative forcing from CO₂ will cause warming over many decades.
- The longer CO₂ emissions go unchecked, the greater the warming.
  Maximum CO₂ levels probably decades after max. emissions.
  Maximum temperature/climate effect decades after max CO₂.

- Many alternative energy sources exist.
- Carbon capture and sequestration possible but costs energy + money.

What should we do?