Future Climate Change

Please read IPCC Working Group 1: 5th Assessment Report Technical Summary (download from class website)

Historical Trends

- CO₂ increased by about 33% (295 ppm in 1900, 397 ppm in 2012)
- Warming almost everywhere
- Most warming
  - on land
  - In NH
  - In Arctic
- Global average warming of about 0.8 °C (1.3 °F)
- Land warming ~ 50% more

Historical Precipitation Trends

- Warmer air evaporates more water
- Overall precipitation must therefore also increase
- Wet places get wetter, and dry places get drier
Ice Mass Loss (observed)

- Good data only since the 1990s (sat)
- Smaller glaciers are losing mass faster than ice sheets
- Greenland and West Antarctic Ice Sheets are losing mass
- East Antarctic Ice Sheet (much bigger) is gaining mass

Empirical Models

- Generalized mathematical formulation with adjustable coefficients
- Combinations of polynomials, exponential growth & decay, periodic sines and cosines
- Coefficients fit to data (e.g., least squares)

Deterministic Models

- Formulated as “cause and effect”
- Common in physics and chemistry
- Usually take the form of differential equations
- Initial & boundary-value problems
- May still have adjustable coefficients

“General Circulation Models” (GCMs)

- Deterministic, not empirical
- “F = ma of a compressible fluid on a rotating sphere with radiation, thermodynamics, and phase transitions”
- Allow detailed prediction of future states at high resolution in both space and time
- Same equations:
  - Weather forecasting (initial value problem)
  - Climate simulation (boundary value problem)
Climate Model Processes

Climate Model Grids

Typical climate model $\Delta x \sim 100$ km

Typical weather forecast model $\Delta x \sim 12$ km

Topography at Different Resolutions

Climate Models circa early 1990s

Global coupled climate models in 2006

Regional models

Global models in 5-10 yrs

Flux Coupler
20th Century

Red line shows model average

3 observation sets
36 GCMs
Observations almost identical
Lots of model variations

Warming under Cooling

stratospheric cooling

tropospheric warming

Manabe and Wetherald (1967)

20th Century

Predicted Vertical Structure

- Greenhouse “signature” is tropospheric warming and stratospheric cooling
- Predicted in mid-1980’s by climate models

Balloons, Satellites, and Surface Obs

\[
\varepsilon = \rho_{CO_2} k_{CO_2} \frac{dz}{d} \]

\[
\varepsilon \sigma T^4_{strat} 
\]
• Models without greenhouse forcing don’t predict enough warming
• Models with only greenhouse forcing predict too much warming
• Models with all forcing do a good job of predicting past climate change

• Surface warming required to re-establish thermal equilibrium at top of atmosphere
• Many lines of paleoclimate evidence and most GCMs find about 3 °C warming for 3.7 W m⁻² forcing

• Warming takes a long time because much of the heat is absorbed by the oceans
• TCR is warming at time when CO₂ reaches 560 ppm
• Models and obs show TCR ~ 1 to 2.5 °C

No GHG forcing
Only GHG forcing
all forcing

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Modern Climate Forcing
Radiative forcing of climate between 1750 and 2011

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Hindcasts of 20th Century

Equilibrium Climate Sensitivity
**Anthropogenic Forcing**

- Cooling from reflective air pollution is harder to estimate
- Greenhouse gases
- Total anthropogenic cooling

**Scenarios**

- Not predictions … “what if” experiments
- None are more or less likely
- Depends on economics and policy (politics)
- Emissions peak in
  - 2020 (RCP2.6)
  - 2040 (RCP4.5)
  - 2070 (RCP6.0)
  - 2150 (RCP8.5)

**Radiative Forcing**

- Observations
  - General patterns and magnitudes very well simulated
  - Problems with mountain ranges and some finer-scale patterns

- Model Evaluation: Precipitation
  - Precipitation • General patterns and magnitudes very well simulated • Problems with mountain ranges and some finer-scale patterns

**Emissions peak in**

- 2020 (RCP2.6)
- 2040 (RCP4.5)
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Global Warming

Maps of Warming

Precipitation Changes

Changing Hydrologic Cycle

- Wet places get wetter
- Dry places get drier
- More evaporation everywhere that there’s water to evaporate
- Less runoff for reservoirs in many places
Snow & Permafrost

- Reduced snow and ice under all scenarios
- Reduced snow cover increases absorbed solar radiation (positive albedo feedback)
- Loss of permafrost has special risks …
  - Drainage
  - Methane and CO₂

Sea Ice Changes

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<tr>
<th>RCP 2.6</th>
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Evaluation: Sea-Level

- Most models underpredict recent sea-level rise
- They completely lack ice sheet dynamics

Future Sea-Level

- All models show substantial and accelerating rise in sea-level
- Big differences depending on future emissions
- Equilibrium sea level will take many centuries
Carbon Sources and Sinks

- Half the carbon from fossil fuels goes into the atmosphere.
- The other half goes into land and oceans.
- The land part is unexpected and unreliable.
- Future of carbon sinks is harder to predict than temperatures.

Where Has All the Carbon Gone?

- Into the oceans
  - Solubility pump (CO₂ very soluble in cold water, but rates are limited by slow physical mixing).
  - Biological pump (slow "rain" of organic debris).
- Into the land
  - CO₂ Fertilization (plants eat CO₂... is more better?).
  - Nutrient fertilization (N-deposition and fertilizers).
  - Land-use change (forest regrowth, fire suppression, woody encroachment... but what about Wal-Marts?).
  - Response to changing climate (e.g., Boreal warming).

Vertical Structure of the Oceans

- Warm buoyant "raft" floats at surface.
- Cold deep water is only "formed" at high latitudes.
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn’t know we’re here yet!
The Long Tail

- Fossil CO₂ dissolves into the oceans
- Chemistry limits the amount the oceans can hold
- Mixing with deep oceans is very slow
- Removal of CO₂ depends on how much we add to atmosphere
- For a big pulse, 40% is still in the air after 1000 years