Climate Change

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Chapters 17, 18

USGS Photo by M.P.Doukas, July 22, 1980
Climate can be defined as
- The accumulation of daily and seasonal weather events over a long period of time

Climate can change on various timescales
- Studies of ice cores, coral, tree rings, etc... document large variations in global and regional climate

Climate can change in response to different factors
- Natural
- Anthropogenic
Ice Cores

• By drilling long cores into the ice in places like Antarctica and Greenland, conditions in the past can be derived:
  – Atmospheric gas concentrations
  – Global temperatures through oxygen isotope data ($O^{18}/O^{16}$)
  – Sulfur concentrations from volcanoes and dust
  – Biological activity

• Some cores go back 800,000 years

Courtesy Montana State University
Tree Rings

- The width and density of growth rings in trees can give information about the temperature and precipitation during different years.
- Has been used to derive climate information for the last 10,000 years combining live and dead trees (e.g. Bristlecone Pines).
Observed climate through the ages

• Throughout much of earth’s history the temperature was warmer than today
  - Warm periods of hundreds of millions of years interrupted by glacial periods

• Most recent series of Ice Ages began about 2 million years ago
  - Recent N. American glaciers at maximum ~ 18,000 years ago
    • Sea level 125 m lower than present
    • Warming since, punctuated by shorter cold periods
      - “Younger Dryas” (~ 11k yrs ago)
      - Little Ice Age (~1550-1850) wiped out English vineyards and caused the demise of the Vikings in Greenland

![Graph showing temperature change through time]
Younger Dryas (12,700-10,000 years ago)

- It is thought that fresh meltwater and/or icebergs from a large glacial lake (Lake Agassiz) in a large region of Canada discharged into the North Atlantic.
- Recall that salty, cold, dense water sinks in the North Atlantic contributing to poleward oceanic heat transport (associated with formation of ice).
- It is thought that the freshwater flux made the North Atlantic water less dense, shutting downs sinking, and thus poleward heat transport subsequent cooling Europe.
- This contributed to a colder Northern Hemisphere during the Younger Dryas.
The big question: How much of this change is natural vs. man made?

Continental Ice Sheets

Present

20,000 years ago

Figure 1. Earth today (left) and during the last ice age (right). Twenty-thousand years ago, great ice sheets covered parts of North America, Europe, and Asia; surface waters of the Arctic and parts of the North Atlantic Oceans were frozen; and sea level was 350 feet lower than it is today. Many parts of the continental shelf, including a corridor between Asia and North America, became dry land. (Drawing by Anastasia Sotiropoulos, based on information compiled by George Denton and other members of the CLIMAP project.)
Let's look at the last millennium.
And even more recently... (TEMPERATURE ANOMALIES)

Global air temperature
2005 anomaly +0.47°C
equal 2nd warmest on record

PRONOUNCED WARMING
Climate Forcing Factors

• External Factors
  - Astronomical
    • Solar Output
    • Orbital Changes (Milankovitch theory)
    • Interplanetary dust
    • Collisions with other interplanetary bodies
      - comets
      - asteroids

• Internal Factors
  - Atmospheric composition
  - Surface Characteristics
  - Oceanic
    - Currents
  - Volcanic Activity
Milankovitch Theory

Astronomical variables account for climate fluctuations

Inspired by a study of glacial advances and ice ages

Periodicities:
  a) Ellipticity of orbit  
      100,000 years
  b) Changes in tilt (Obliquity)  
      41,000 years
  c) Precession  
      26,000 years (rotation of Earth’s spin axis; like a spinning top)

These time periods are roughly equal to the repeat time of ice ages
All other things being equal ...

• Cooler periods associated with:
  - more circular (less eccentric) earth orbit
    - cooler in general
      » period 100,000 years
  - smaller tilt (inclination of earth’s axis)
    • closer to minimum of 22.1°
      - less range of seasonal variation - cooler in general
        » period 41,000 years
    • current tilt 23.5°

• Warmer periods associated with:
  - more eccentric earth orbit
    - warmer in general
      - period 100,000 years
  - larger tilt
    • closer to maximum 24.5°
      - more range in seasonal variation - warmer in general
        » period 41,000 years
Eccentricity (100,000 year cycle)

- The Earth’s orbit around the Sun is not circular, but rather an ellipse. The Sun is at one of the foci of the ellipse.
- Thus, the Earth is closer to the Sun at one part of the orbit (year) than another, affecting the amount of insolation.
- Coupled with precession, eccentricity controls the amount of sunlight reaching the top of atmosphere during Northern Hemisphere summer.
- Higher eccentricity seems to be associated with ice ages, but scientists don’t really know why.
Obliquity (41,000 year cycle)

- The tilt of the Earth on its axis, which varies from $24.5^\circ$ to $22^\circ$. It is presently $23.5^\circ$.
- Higher tilts lead to warmer summers and colder winters.
- Lower tilts lead to cooler summers and warmer winters.
- Ice ages would be favored during periods of lower tilt when NH summer insolation is lower.
Precession (23,000 Year Cycle)

- The Earth wobbles around on its axis like a top
- For the Earth to do one complete wobble takes about 23,000 year
- Ice ages are favored when NH summer occurs (Earth’s axis tilted away from the Sun) when the Earth is furthest in its elliptical orbit from the Sun (lowest summertime insolation)
Solar Variability

• The output of the Sun is not exactly constant at 1366 W m\(^{-2}\)), and does show some modest variations in time.

• For example, the Sun does have an 11-year solar cycle in output, corresponding to variations in sunspots. Large numbers of sunspots=high solar output
Solar Variability

- A minimum in sunspots occurred in the 1600’s, thought by some to be responsible for the Little Ice Age. Both the causes (and existence) of the Little Ice Age are still debated, including whether there actually was a significant reduction in solar output in the 1600’s and 1700’s.

IPCC 2007

Figure 2.17. Reconstructions of the total solar irradiance time series starting as early as 1600. The upper envelope of the shaded regions shows irradiance variations arising from the 11-year activity cycle. The lower envelope is the total irradiance reconstructed by Lean (2000), in which the long-term trend was inferred from brightness changes in Sun-like stars. In comparison, the recent reconstruction of Y Wang et al. (2005) is based on solar considerations alone, using a flux transport model to simulate the long-term evolution of the closed flux that generates bright faculae.
Volcanoes

- Volcanoes emit sulfur dioxide that become aerosols (airborne solids) in the stratosphere that reflect sunlight and increase the albedo of the Earth, reducing the solar radiation absorbed by the climate system.
- For example, this plot (ignore the multiple lines) shows the globally-averaged reduction in absorbed solar radiation after the eruption of Mt. Pinatubo in summer 1991.
  - The reduction in solar absorption peaked at about 4.5 W m⁻².
  - Some are advocating man-made stratospheric injections of aerosols to mitigate anthropogenic climate warming.
Volcanoes

- This reduction is solar radiation led to a cooling of the global-averaged temperature on the order of 0.5-0.7 °C, depending on what temperature estimate is used.
- The distribution of sulfate particles emitted into the stratosphere after the eruption is shown on the left. The volcanic emissions spread rather uniformly throughout the tropics.

Global Temperature Change After Pinatubo
Now let’s turn to anthropogenic mechanisms for climate change...
Greenhouse gas concentrations (pass solar and absorb/re-emit infrared)

- Concentrations have increased dramatically since Industrial Revolution
- Increases since 1750
  - $\text{CO}_2$ -- 31%
  - $\text{CH}_4$ -- 151%
  - $\text{N}_2\text{O}$ -- 17%

Courtesy: NOAA
Greenhouse gas ($CO_2$) emitters

World fossil carbon dioxide emission 1970-2018

- Other countries
- China
- United States
- EU28
- India
- Russia
- Japan
- International shipping and aviation

Million tonnes CO2/year


Wikipedia
Recent Warming

- The global average surface temperature increased by 0.6 °C during the 20th century
  - 1998 was probably warmest year in last 1000 years in N.H.
- Widespread retreat of mountain glaciers seen in non-polar regions in 20th century
  - Snow cover extent decreased ~10% in last 30 years
- Decrease in sea ice thickness in latter 20th century
Can natural factors explain recent warming?

- IPCC (2000) says “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.”

- Both anthropogenic greenhouse gas and aerosol emissions are important players.
IPCC (2000) expects a global average temperature rise of 1.4 to 5.8 °C from 1990-2100.

- Amount varies with emission scenario and computer model.
- Some scientists argue the system is not predictable given current knowledge.

Projected warming rate is much larger than observed in the 20th century and probably unprecedented in the last 10,000 years.

Most land areas will warm faster than the global average.
Future temperature changes are expected to be non-uniform

- Figure below shows one projection of change in surface temperatures due to a doubling of CO$_2$ concentrations and anthropogenic sulfur emissions
- Most land areas will warm faster than the global average
Potential Climate Change Impacts

Climate Changes
- Temperature
- Precipitation
- Sea Level Rise

Health Impacts
- Weather-related Mortality
- Infectious Diseases
- Air Quality-Respiratory Illnesses

Agriculture Impacts
- Crop yields
- Irrigation demands

Forest Impacts
- Change in forest composition
- Shift geographic range of forests
- Forest Health and Productivity

Water Resource Impacts
- Changes in water supply
- Water quality
- Increased Competition for water

Impacts on Coastal Areas
- Erosion of beaches
- Inundate coastal lands
- Costs to defend coastal communities

Species and Natural Areas
- Shift in ecological zones
- Loss of habitat and species
Precipitation and sea level effects

- More evaporation (due to warmer temperatures) implies more precipitation
  - Precipitation increases expected over northern mid- to high latitudes and over Antarctica in winter
  - Regional decreases and increases at low latitudes
  - Larger year to year variations in precipitation
  - More intense, episodic precipitation events (more intense hurricanes)
- Thermal expansion of seas and melting of land ice expected to cause significant sea level rise
  - 0.1-0.9 m rise expected by 2100
  - This rise will put many at risk
Sea level rise

- Global average sea level rose 0.1-0.2 m during 20th century
- Warmer temperatures associated with sea level rise due to
  - Thermal expansion
  - Melting of continental and Greenland ice
  - Break-up and melting of Antarctic ice sheet
Possible responses to climate change threat

• Wait and see
• Take action
  - Reduce greenhouse gas emissions
    • Global approach required
    • Economic costs not unthinkable
      - Economists suggest a 20% reduction in GHG emissions would require a GDP cost of <1% (loss of 6 months economic growth or less) and indicate the costs may even be negative
      - Past air pollution regulations suggest costs are often much lower than claimed by industry (e.g., catalytic converters, CFC elimination, SO₂ emissions reductions)
    - Engineer to mitigate possible climate consequences
      • e.g., sea walls, agricultural adaptation,…
• Study the problem further before taking action
Anthropogenic climate change will persist for a long time

- Emissions of long-lived greenhouse gases have a long-lasting effect on atmospheric composition

<table>
<thead>
<tr>
<th>Species</th>
<th>$CO_2$</th>
<th>$CH_4$</th>
<th>$N_2O$</th>
<th>CFC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric lifetime (yrs)</td>
<td>1000’s</td>
<td>12</td>
<td>120</td>
<td>50-300</td>
</tr>
</tbody>
</table>

- Temperature increases and rising sea level from thermal expansion are projected to continue for hundreds of years after stabilization of GHG concentrations (IPCC, 2000)
  - Due to long timescale for deep ocean to adjust to climate change

- Ice sheets will react to warming and contribute to sea level rise for thousands of years after climate has been stabilized (IPCC, 2000)
  - A local warming > 3 °C, if sustained for millenia, would lead to essentially a complete melting of the Greenland ice sheet and a resulting sea level rise of 7 m
  - Collapse of West Antarctic ice sheet would raise sea level ~ 70 m!
Climate Feedbacks
Feedbacks

• What we have discussed so far are forcing agents external to the climate system (e.g. orbital parameter changes, volcanoes, greenhouse gas emissions) that want to push the temperature of the climate system in one direction or another.

• However, understanding the full response of the climate system to a forcing agent requires understanding of feedbacks.

• Feedback: A process that changes the sensitivity of the climate response to an external forcing.
Feedbacks

• **Positive Feedback:** Increases the magnitude of the response to the forcing
  – Ice/snow-albedo feedback (less ice, lower albedo, increased heating of Earth)
  – Water vapor feedback (more water vapor in atmosphere due to higher temperatures, therefore increased absorption of outgoing longwave radiation)
  – Ocean carbon cycle feedbacks (warmer oceans hold less CO$_2$, increasing atmospheric CO$_2$ levels)

• **Negative Feedback:** Decreases the magnitude of the response to the forcing
  – Stephan-Boltzmann feedback (i.e. warmer Earth emits more radiation out to space)
**Ice-Albedo Feedback (Positive)**

- **Albedo Decreases**
  - Increased solar absorption

- **Surface Temperature Warms**

- **Snow/Ice Decreases**
  - High surface albedo
  - Low absorption of sunlight
  - Gradual surface warming

- **Lower surface albedo**
  - Higher absorption of sunlight
  - Surface warming increases

- **Very low surface albedo**
  - Much higher absorption of sunlight
  - Surface warming enhanced
Water Vapor Feedback (Positive)

- The most important feedback in the climate system
- Remember that water vapor is a greenhouse gas
- As the climate warms, the atmosphere can hold more water vapor (saturation vapor pressure increases)
- As water vapor increases, its radiative effects warm the climate system more
- As the climate warms it can hold more water vapor, and so on.
Stephan-Boltzmann Feedback (Negative)

• Remember that the total possible rate of radiation emission by an object is given by:

\[ E = \sigma T^4 \]

• Hence, a warmer Earth will emit more radiation to space, eventually stabilizing the climate system and capping the rise in temperature. Likewise, a cooler globe will emit less radiation to space.

• In order to realize this negative feedback though, temperature needs to increase.
Cloud Feedbacks (Maybe Positive?)

- The effect of clouds on climate depend on whether they are high or low clouds, thick or thin
- High, very thin clouds have a warming influence on climate (let most sunlight through, but emit at low temps to space)
- Low, thick clouds have a strong cooling influence (emit a lot of infrared radiation, and reflect a lot of solar radiation)
- Adding it all together, **clouds have a net cooling influence on climate** and contribute to the Earth’s albedo
- However, the cloud feedback in a warming climate will depend on how much high clouds change, how much low clouds change, and the relative magnitudes of these two effects
- Right now, clouds are thought to be a slight positive feedback, but really there is a lot of uncertainty as to the role of clouds in the climate sensitivity—it is a big unknown.
Aerosol-Cloud Albedo Feedback

- Ship tracks off US west coast
- Atmospheric aerosol serve as CCN
- Brighter clouds reflect more sunlight

Fig. 12.6  GOES 1-km visible image of stratocumulus clouds over the Pacific Ocean on July 1, 1987 at 1615 UTC (Universal Time Coordinate). The scale of the image is approximately 5° square. The continental outline in the upper right is the Olympic Peninsula of Washington, and the one in the lower right is Cape Blanco on the Oregon coast. The linear features in the center of the image are ship tracks, enhancements of otherwise thin stratocumulus clouds caused by sulfur gas and particulate emissions of passing ships. The gray scale on the right indicates the visible albedo. (Image courtesy of Robert Pincus.)