Variation of Sun-Earth Distance

Eccentricity of Earth’s Orbit

Current N.H. summer (June)

N       152 million km

S

147 million km

Current S.H. summer (January)

The Greenhouse Effect

no atmosphere

Earth IR radiation

visible

Infrared

outgoing IR radiation is absorbed and emitted back to the ground

with atmosphere

visible

Infrared

Heat

The Greenhouse Effect

Some solar radiation penetrates the atmosphere. Some IR radiation is reflected by the Earth and its atmosphere. Some IR radiation is absorbed by ice in the atmosphere. Outgoing IR radiation is absorbed by the Earth's surface.
Why is predicting the climate so difficult?
The different effects:
• Greenhouse gases
• Clouds
• Rising temperatures
Above are not independent from another

Example:
more CO₂ ⇒ higher temperatures ⇒ more H₂O
⇒ stronger greenhouse effect due to H₂O

Negative Feedback

<table>
<thead>
<tr>
<th>Cause</th>
<th>Effect</th>
<th>Effect suppresses cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>suppress</td>
<td></td>
<td>decrease effect</td>
</tr>
<tr>
<td>&quot;self-regulation&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example: warmer → more clouds → higher albedo → cooling effect (negative feedback)
Positive Feedback

Effect enhances cause
→ increase effect
→ boom!!!

Ex: Water vapor feedback
Ex: warmer → melting land ice → lower albedo → further warming

Hydrological Cycle

from http://www.watersystems.co.nz/images/hydrologicalcycle.jpg

Carbon Dioxide (CO₂)

Source: http://www.esd.ornl.gov/education/5-1a-2-2.htm
Methane (CH₄)
- Termite
- Rice paddies
- Natural gas leakage
- Wetlands
- Ruminants

Nitrous Oxide, N₂O
- "Laughing gas"
- Biomass burning
- Industrial processes
- Nitrogen fertilizer
- Soils

Chlorofluorocarbons (CFCs), Hydrofluorocarbons (HCFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride (SF₆)
- Refrigeration
- Propellant
- Aluminum smelting
- Insulator for electrical equipment
Tropospheric Ozone ($O_3$)

$CO + OH + O_2 \rightarrow CO_2 + HO_2$

$NO + HO_2 \rightarrow NO_2$

$NO_2 + hv \rightarrow NO + O$

$O + O_2 \rightarrow O_3$

- **Tree rings**: changes in growing conditions that a tree might have encountered over its lifetime (temperature and rainfall) → *hundreds of years*

- **Pollen** from different plant species indicate shifts in vegetation patterns that occurred as a result of climate change → *millions of years*

- **Ice cores** record information about the conditions in which the ice was formed and trap ancient air → *hundreds of thousands of years*

- **Corals** give us indications on sea surface temperature → *hundreds of thousands of years*
• Shells of marine organisms found in marine sediments tell us about past temperatures and atmospheric CO2 hundreds of millions of years.

• Shape of the landscape (geomorphology) tells us about the extent of glaciers and ice sheets and sea level in the past billions of years.

Geologic Time Scale

Figure 12.13

Paleocene-Eocene Thermal Maximum (~55 million years ago)

65 Million Years of Climate Change

Rapid warming (10,000 years) lasting 100,000 years
Paleocene-Eocene Thermal Maximum
(~55 million years ago)

Geologic Time Scale

Figure 12.13

Climate History
Mid-Pliocene (~3.5 million years ago)

Configuration of continents and ocean basins close to present (good analogue for our near future?)
CO₂ concentrations: 360 – 400 ppm
Sea level: 15 – 25 m higher than modern
Global mean temperatures: 2 – 3°C above preindustrial
Estimated mid-Pliocene sea-level

http://geochange.er.usgs.gov/pub/sea_level/

The light blue color shows an estimate of the coastline of the eastern United States during the last glacial maximum, about 20,000 years ago. The dark green shows the modern coastline, and the lighter shades of green show the coastlines that may have existed during the warm climatic interval of the middle Pliocene epoch, about 3 million years ago.

Plate tectonics

Milankovitch cycles
Climate History
Temperature and Greenhouse Gases

Petit et al., 1999

Today: CO$_2$ = 370 ppm
CH$_4$ = 1800 ppb

Eccentricity: More to Less Circular

Obliquity: More or Less Seasonality
Precessional Cycle: Tilt and Eccentricity
Precession of the Equinoxes (19 and 23 k.y.)

Southern Hemisphere tilted toward the Sun at aphelion

Current situation

Northern Hemisphere tilted toward the Sun at aphelion

Milankovitch Cycles

Milankovitch cycles

Example of how Milankovitch Cycles impact climate: NH Glaciation
Solar insolation in NH summer appears to be key maintaining glaciation. Ice sensitive to melting!

Positive Feedback—Destabilizing Climate

Initial Forcing
Weaker NH summer insolation

Same old ice-albedo feedback, just different initial forcing
Carbon dioxide (CO₂) variability over the past 400,000 years

Reconstructed Temperatures in NH over last 1000 years

- 20th century increase largest in any century over last 1,000 years
- 1990s and 1998 warmest decade and year of the millennium

Surface Temperature Measurement Stations

GHCN v2.0 Mean Temperature Stations
Recent Changes in Surface Temperature

Variations of the Earth’s surface temperature for:

- Increase in global-average surface temperature over the 20th century by about 0.6°C
- 1990s warmest decade and 1998 warmest year in instrumental record since 1861

Aerosols Increase Earth’s Albedo

Aerosols scatter a fraction of incoming solar radiation back to space
This is known as the “direct forcing” of aerosols.

Smoke particles from biomass burning in Southeast Asia appear as white haze

ΔF ~ - 0.9 W/m² from direct effect of aerosol

Ship Tracks and Contrails

Examples of Aerosol Indirect Effects on Clouds
"Sulfate Forcing" Mid 20th Century

Aerosol direct effect thought to explain temporary hiatus in T increase

Regional pattern of warming

- Near global increase in temperatures
- Largest increases in mid- and high-latitudes over continents in Northern hemisphere

Solar output varies, but not much

Change of solar intensity ~0.1%

Figure courtesy of NOAA National Geophysical Data Center
Sunspots – Cyclic Changes in Solar Output

~11 year Sunspot Cycle

Mount Pinatubo Eruption
Carbon Dioxide: up 32%

Anthropogenic sources: fossil fuel burning, deforestation

Methane, CH$_4$ up 150%

Anthropogenic sources: rice paddies, cows, natural gas leakage, landfills/waste, biomass burning
Natural sources: Wetlands, termites
Nitrous oxide, N\textsubscript{2}O up 15\%

**Anthropogenic sources:** fertilized agriculture, biomass burning

**Natural sources:** Oceans, natural soils

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**Human influence fingerprints on global warming**

**Natural Climate Influence**

**Human Climate Influence**

**IPCC, 2001**
Do all Greenhouse gases have the same effect?

Global Warming Potential (GWP)
Related to amount of predicted warming from a unit increase in concentration

GWP’s relative to CO₂:

- CO₂ ⇒ 1
- CH₄ ⇒ 21
- N₂O ⇒ 310
- CFC ⇒ 4000-12000

Common Myths and Misconceptions

Myths and Misconceptions (1)

"It's 70º today, in January? Global warming is real."

"Hurricane Katrina was the strongest hurricane in decades. Global warming must be real."
Weather Change vs. Climate

- A single hurricane is an example of weather.
- An increase in the number per year or average strength is a climate problem.

Myths and Misconceptions (2)

“The decrease in pirates anti-correlates with global temperature. Thus, global warming is caused by fewer pirates (or it is causing there to be fewer pirates).”

Myths and Misconceptions (3)

“The recent warming is just part of a natural cycle.”
Myths and Misconceptions (4)

“Is global warming really such a big deal? A few degrees warmer seems harmless.”

What difference does a few degrees make?

Seattle ice free

ΔT_{ice-no ice} \sim -5-8^\circ

Seattle under mile of ice
The light blue color shows an estimate of the coastline of the eastern United States during the last glacial maximum, about 20,000 years ago. The dark green shows the modern coastline, and the lighter shades of green show the coastlines that may have existed during the warm climatic interval of the middle Pliocene epoch, about 3 million years ago.

Temperature Trends

IPCC 2007

Relative to 1961-1990 mean

IPCC 2007
**Northern Hemisphere Spring Snow Cover**

March - April NH snow-covered area


10^4 km^2

IPCC 2007

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**Melting Glaciers**

Glacier Ururashraju, Peru in 1986

1999
Glacier retreated around 500m

---

Glacier National Park - 1911

2000
South Cascade Glacier

Mt. Kilimanjaro Ice Area

Changes in sea level

- Global average sea level rose by 0.1-0.2 meters during the 20th century (~1.5 mm/year; 10 times higher than average over last 3000 years)
- Global ocean heat content has increased

Factors causing sea-level change:
- Thermal expansion, as ocean water warms it expands: main reason for change over last century and for coming few centuries
- Melting of ice on land (glaciers and ice sheets): main reason for change in sea-level between glacials and interglacials (~120m since 20,000 years ago)
Sea-level rise
Relative to 1961-1990 mean IPCC 2007

Sea-level rise
Relative to 1993-2001 mean IPCC 2007

Attributing sea-level rise
Island of Fualopa, Tuvalu

Highest point is 4 m above sea level

Many people on Tuvalu are now looking at migrating; indeed New Zealand has offered to take in 75 Tuvaluans every year.

Arctic Minimum Sea-Ice Extent

IPCC 2007

The oceans take up / release CO₂
Ocean currents redistribute heat/thermal energy
Extreme Weather Events

Droughts

Hurricanes

Human Health - Malaria

Prediction of Malaria Transmission rates in 2002 relative to the average risks between 1961-1990

Epstein, 2000
Regional climate change and impacts

Climate change in the Pacific Northwest – past and future

Temperature trends (°F per century) since 1920

PNW warmed +1.5°F during the 20th century
Projected warming: 0.2-1.0°F per decade
(compared to 1.5°F over 20th century)
Precipitation: wet season gets wetter, dry season gets drier

Trends in timing of spring snowmelt (1948-2000)

Washington’s economy and natural resources are sensitive to climate changes
- we know this from experience
- the water cycle plays an especially prominent role in transmitting climate impacts into resource impacts
  - skiing
  - water supplies
  - hydropower
  - aquatic ecosystems
  - flooding
  - forests
- “drought” – a water supply shortage – is our region’s greatest climate vulnerability
Climate Change Policy

• 1st international negotiations to combat climate change began in 1992 at the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro, Brazil.
• Called on signatory nations to:
  1. develop current and projected emissions inventories for greenhouse gases
  2. Devise policies for reducing emissions
  3. Promote technologies for reducing emissions
Set no mandatory limits on greenhouse gas emissions for individual nations and contains no enforcement provisions (legally non-binding)
Included provisions for updates, called protocols, that would set mandatory emissions limits
154 nations signed the UNFCCC (including the U.S.)

Kyoto Protocol (1997)

• Called on industrialized nations to reduce greenhouse gas emissions by 2008-2012 by a certain percentage relative to their 1990 emissions (for CO₂, CH₄, N₂O) or 1995 emissions (all other greenhouse gases).
• The net change in emissions would be 5.2% below 1990 levels

Percent Change in 1990 Emissions Required Under Kyoto Protocol

<table>
<thead>
<tr>
<th>Country</th>
<th>Percent Change in Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland, central Europe, European Union</td>
<td>-8</td>
</tr>
<tr>
<td>United States</td>
<td>-7</td>
</tr>
<tr>
<td>Canada, Hungary, Japan, Poland</td>
<td>-6</td>
</tr>
<tr>
<td>Russia, New Zealand, Ukraine</td>
<td>0</td>
</tr>
<tr>
<td>Norway</td>
<td>+1</td>
</tr>
<tr>
<td>Australia</td>
<td>+8</td>
</tr>
<tr>
<td>Iceland</td>
<td>+10</td>
</tr>
</tbody>
</table>

Table 12.5
Countries can meet their Kyoto targets by:

1. Reducing their own emissions and increasing their own sinks (e.g. forests)
2. Clean Development Mechanism: Financing emission-reduction projects in developing countries that are not subject to the Kyoto Protocol (e.g. planting forests, improving energy efficiency, alternative energy sources)
3. Emissions trading with other developed countries

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>-17%</td>
<td>-8%</td>
<td>-18.2</td>
<td>-8%</td>
</tr>
<tr>
<td>Canada</td>
<td>+27%</td>
<td>-8%</td>
<td>+26.6</td>
<td>+6%</td>
</tr>
<tr>
<td>Australia</td>
<td>+23%</td>
<td>-8%</td>
<td>+23.3</td>
<td>-8%</td>
</tr>
<tr>
<td>Spain</td>
<td>+46%</td>
<td>-8%</td>
<td>+52.4</td>
<td>-8%</td>
</tr>
<tr>
<td>Norway</td>
<td>+150%</td>
<td>+1%</td>
<td>+18.7</td>
<td>+11%</td>
</tr>
<tr>
<td>New Zealand</td>
<td>+21%</td>
<td>+1%</td>
<td>+11.9</td>
<td>+1%</td>
</tr>
<tr>
<td>France</td>
<td>0.8%</td>
<td>-1%</td>
<td>0.7%</td>
<td>-1%</td>
</tr>
<tr>
<td>Greece</td>
<td>0.7%</td>
<td>0.8%</td>
<td>0.7%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Ireland</td>
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<td>+1%</td>
<td>+25.3</td>
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</tr>
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<td>Japan</td>
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<td>-1%</td>
<td>+2.2</td>
<td>+1%</td>
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<td>United Kingdom</td>
<td>-16%</td>
<td>-8%</td>
<td>-16.6</td>
<td>+1%</td>
</tr>
<tr>
<td>Portugal</td>
<td>+41%</td>
<td>+1%</td>
<td>+28.9</td>
<td>-1%</td>
</tr>
</tbody>
</table>

LULUCF = Land Use, Land Use Change, and Forestry
Worldwide CO$_2$ emissions

http://www.epa.gov/climatechange/emissions/globalghg.html

CO$_2$ emissions in developed and developing countries

http://www.epa.gov/climatechange/emissions/globalghg.html

Post-Kyoto: What happens next?

- Kyoto to expire in 2012
- 2009 UN conference in Copenhagen, Denmark: Goal to come up with post-2012 plan
- Resulted in (weak) “Copenhagen accord”: Actions should be taken to keep any temperature increases to below 2°C. The document is not legally binding and does not contain any legally binding commitments for reducing CO$_2$ emissions.
- Copenhagen accord pledges US$30 billion to the developing world over the next three years, rising to US$100 billion per year by 2020, to help poor countries adapt to climate change. An agreement was also reached that would set up a deal to reduce deforestation in return for cash from developed countries.
What is happening currently in the US with respect to greenhouse gas emissions?

Emissions of CO₂ equivalents in the U.S.

Recent decrease driven by 1) decrease in economic activity, decrease in energy consumption, and 2) fuel switching for electricity generation (price of coal increased, price of natural gas decreased).

Greenhouse gas emissions in the U.S. relative to 1990
Greenhouse gas sources in the U.S. in 2009

2009 U.S. CO₂ emissions by sector and fuel type

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of GDP
Supreme Court ruling April 2007: Massachusetts vs EPA

- U.S. Supreme Court case decided 5-4 in which twelve states and several cities of the United States brought suit against the EPA to force that federal agency to regulate carbon dioxide and other greenhouse gases as pollutants.
- The Clean Air Act requires the EPA to set emission standards for "any air pollutant" from motor vehicles or motor vehicle engines "which in his judgment cause[s], or contribute[s] to, air pollution which may reasonably be anticipated to endanger public health or welfare."
- The ruling does not force the Environmental Protection Agency to regulate auto emissions, but the agency would almost certainly face further legal action if it fails to do so.

So what is the EPA doing?

- EPA determined that CO\textsubscript{2} and five other greenhouse gases "endanger public health and welfare" giving the EPA a mandate to regulate ghg emissions.
- EPA can implement new guidelines under the Clean Air Act, or wait for congress to pass more comprehensive legislation such as a "cap and trade" program (proposed legislation failed in senate in 2010)
- So, EPA will use its regulatory power to set limits on CO\textsubscript{2} emissions from factories, power plants and refineries (responsible for ~40% of ghg emissions) by requiring federal permits that cap ghg emissions.

How will EPA regulate greenhouse gases?

- Beginning Jan. 2, 2011, the EPA requires large new projects or plant upgrades that emit more than 75,000 tons of greenhouse gases to have a permit.
- After that, in July, the EPA will begin to include other "regulated" sources that emit more than 100,000 tons. By July 2012, it will begin to weigh smaller emitters, but none under 50,000 tons.
- House trying to block EPA from regulating greenhouse gases via federal spending legislation (as of February 18, 2011)
What will it take to stabilize CO₂ levels?

- Stabilization at 550 ppm = twice pre-industrial levels
- Need to start reducing emissions by 2030, and will need to drop well below current emissions by mid-22nd century