Class 2
Measuring CO$_2$ and Temperature

OLLI
L809 Climate Change
January-February 2014
Carry-Over Issues

• Responding to climate change

• Oceans’ absorption of $\text{CO}_2$

• Potential future temperature increase
RESPONDING TO CLIMATE CHANGE:
AN OVERVIEW OF THE FRAMEWORK
Reducing Global Warming Harm

Mitigation

Increase* Albedo

Reduce* Atmospheric CO₂

Adaptation
Adaptation: The Thames Barrier
Characteristics of Adaptation And Their Implications

• Limited geographical and functional impact
  – Match between who pays and who benefits
  – Whom/what will we protect?

• Time: Most implementable in a few years

• Money: Comparison with mitigation
Reducing Global Warming Harm

Mitigation

Increase* Albedo

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Reduce* Atmospheric CO₂

* “Increase/reduce:” from current level or projected business-as-usual (BAU) level
Radiation Management

• Goal: Increased albedo $\rightarrow$ less thermal radiation $\rightarrow$ lower equilibrium temperature

• Scale: white roofs to global reflectivity (subset of geoengineering)

• Terraforming*: geoengineering on steroids

* See Kim Stanley Robinson’s Mars trilogy.
Low Cost – Big Impact

Low Cost – modest Impact

Enormous Cost – Big Impact (if it works)
Doing it with aerosols

• Fast-acting
  – Reduces surface temperature within months
  – Quickly stopped: short atmospheric residence time

• Effect well-established for one-two years: volcanoes

• Relatively low cost and low-tech: Lear jets
But . . .

• Effect of sustained use is unknown – begin small-scale experiments?

• Achieves lower average temperature, but
  – Different temperature and rainfall distribution
  – Different radiation spectrum
  – Doesn’t reduce ocean acidification

• Growing temperature overhang

• May undermine efforts to reduce emissions
General Pro-Geoengineering View

• Continue efforts to reduce emissions

• But need a SCRAM button

• SCRAM (apocryphal?) etymology: “safety control rod axe man”
Reducing Global Warming Harm

Mitigation

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US GHG Emissions 2010: Gigatons

- Fossil fuel combustion: 5,388
- Other CO2: 17
- Methane: 667
- N2O: 306
- HFCs: 123
- Other: 319
Reducing Emissions

• A quick way: the Soviet collapse

• The politically acceptable way: reduce emissions without reducing energy services

• Time: the paths
  – Reduce net anthropogenic emissions to ~0
  – From transient to equilibrium temperature

• Cost: Compare social cost of carbon (SCOC)
Alternatives

• **Reduce energy intensity:** supply service with less energy – LED bulbs

• **Reduce carbon intensity:** produce energy with fewer emissions: Coal emissions > natural gas > nuclear and renewables

• National emissions: GDP x EI x CI

• **Capture and store the emissions:** in effect reduces carbon intensity
CARBON DIOXIDE
Resolved:
Doubling CO$_2$ Would Raise Global Temperature

• Follows from mid-19$^{th}$ century science (Tyndall)

• Relevant boundary condition? (Angstrom)

• Ceteris paribus: Offsetting changes?
  – Reduced top-of-atmosphere solar radiation
  – Increased albedo

• The factual premise: Occurrence of doubling
CO$_2$ and GHG Metrics

• Atmospheric concentration: parts per million (ppm) or billion (ppb)

• Emissions
  – Most common: metric tons of CO$_2$
  – Alternatives
    • Metric tons of carbon = CO$_2$/3.67
    • CO$_2$ equivalent: 100-year global warming potential
      – CO$_2$ = 1.0
      – CH$_4$ = 26
Why it’s better to flare natural gas (CH$_4$)

• More powerful than CO$_2$ but shorter residence time: CO$_{2eq}$ = 26

• But also lighter: $12 + 4 \times 1 = 16$

• GWP of one carbon atom:
  – ln CO$_2$: 1
  – ln CH$_4$: $26 \times 16/44 = 9.5$
## Where’s the Carbon?

<table>
<thead>
<tr>
<th>Sink</th>
<th>Amount in Billions of Metric Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>578 (as of 1700) - 766 (as of 1999)</td>
</tr>
<tr>
<td>Soil Organic Matter</td>
<td>1500 to 1600</td>
</tr>
<tr>
<td>Ocean</td>
<td>38,000 to 40,000</td>
</tr>
<tr>
<td>Marine Sediments and Sedimentary Rocks</td>
<td>66,000,000 to 100,000,000</td>
</tr>
<tr>
<td>Terrestrial Plants</td>
<td>540 to 610</td>
</tr>
<tr>
<td>Fossil Fuel Deposits</td>
<td>4000</td>
</tr>
</tbody>
</table>

*Note: Quantities are in tons of carbon*
Carbon Flows
Measuring CO$_2$ Concentration

• Changed by difference between flows into/out of atmosphere

• Early 1950s: no consensus on size (or even sign) of the difference

• The problems
  – Lack of continuous measurements
  – Existing measurements affected by local sources and sinks
The Solution

• Monitor at isolated location: Mauna Loa
  – Mauna Loa Observatory at 3,397 meters
  – No nearby industry or motorized vehicle traffic
  – In barren lava field

• Monitor frequently and continuously: Begun by David Keeling in 1956 and continues to date
The Keeling Curve

Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii

NSF stops supporting “routine” research – Revelle to the rescue

2013: 396 ppm CO₂ and 478 ppm CO₂eq

2005: Keeling dies
The Keeling Carbon Cycles

• Biological:
  – Dominates intra-annual cycle
  – Little interannual impact

• Fossil fuels dominate interannual changes

• Carbon sinks moderate fossil fuel impact
The importance of carbon sinks

Increased absorption by land and ocean sinks since 1750 has ensured atmospheric carbon dioxide concentrations have not risen more.

Source: Carbon emissions and sinks figures for 1740-2012. The 2012 concentration of 393 ppm reflects the global forest concentration which has stabilized. From the more widely reported Mawana Loa figures, *Coal emissions* include significant biomass emissions. Land use emissions are the change in carbon storage resulting from human-induced land use and land-use change and forestry activities, with deforestation the primary driver.

Sources: IPCC (2007) WG1, Global Carbon Project, CDiac, NOAA.

Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks
Longer Term

• Geological cycle: millions of years
  – Volcanoes add CO$_2$ to surface-atmosphere-ocean system
  – Rock weathering and burial of biogenic sediment remove CO$_2$ from system

• Glacial cycle: tens of thousands of years
Pre-Industrial Geological Cycle

Volcanoes

Weathering and Seafloor Burial

Biosphere

Atmosphere

Ocean
Post-Industrial Revolution

Volcanoes
Fossil Fuels
Weathering and Seafloor burial

Biosphere
Atmosphere
Ocean

Climate Change - OLLI Jan-feb 14
## CO₂ Emissions: Man vs. Volcanoes

<table>
<thead>
<tr>
<th>Category</th>
<th>tons per year (Gt/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global volcanic emissions (highest preferred estimate)</td>
<td>0.26</td>
</tr>
<tr>
<td>Anthropogenic CO₂ in 2010 (projected)</td>
<td>35.0</td>
</tr>
<tr>
<td>Light-duty vehicles (cars/trucks)</td>
<td>3.0</td>
</tr>
<tr>
<td>Approximately 24 1000-megawatt coal-fired power stations *</td>
<td>0.22</td>
</tr>
<tr>
<td>Argentina</td>
<td>0.20</td>
</tr>
<tr>
<td>Pakistan</td>
<td>0.18</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>0.44</td>
</tr>
</tbody>
</table>
The Glacial Cycle: Cooling the Earth

- From 50 MYA geologic burial exceeds volcanic emissions $\rightarrow$ declining CO$_2$

- Temperature falls
  - By 10 MYA: permanent Antarctic ice sheet
  - From 2.75 MYA: alternating northern glaciation (most of the time) and interglacials (like now)
Mechanisms

• Orbital cycles periodically cause cool northern summers
• More snow remains at beginning of following winter $\rightarrow$ year-by-year growth of snow cover
• Increased albedo $\rightarrow$ cooling but not enough for glacial cycle
• $\text{CO}_2$ transferred from atmosphere to deep ocean
  – Begins after initial temperature decline: a feedback
  – Causes large further decline in global temperatures
• Land mass alignment allows spread of glaciers
The Glacial Cycle: Earth’s Orbit

• Eccentricity: Cycle from more circular to less circular orbit – 100 thousand years

• Precession: Cyclical change in relationship between season and distance from sun – 22 thousand years

• Obliquity: Cyclical rocking of Earth’s angle to rotation plane – 41 thousand years
The Glacial Cycle: Cooler Northern Summers

• More elliptical orbit (eccentricity) and northern summer at aphelion (precession), or

• Smaller tilt (obliquity), or

• Both
Northern summer
Glaciers Spread
Videos

• Animated video of 800,000 years of CO₂:
  
  http://www.youtube.com/user/CarbonTracker#p/a/u/2/H2mZyCblxS4

• Video on temperature-carbon relationship in glaciation/deglaciation:
  http://www.youtube.com/watch?v=hWJeqqG3Tl8&t=16
Questions

• Why the change from 41,000 years (obliquity) to weaker 100,000 years (precession) cycle?

• Details of CO₂ feedback mechanism: possible elements
  – Colder water absorbs more CO₂
  – Cooler → drier → dustier → increased micronutrients to Southern Ocean
41,000 Year – 100,000 Year Shift
So Why Believe?

• Sustained correlation with orbital cycles and plausible link to initial cooling

• Need for additional forcing and lagged temperature-CO$_2$

• Changing isotopic composition of CO$_2$
14Carbon and Its Implications

- 12Carbon: Six protons and six neutrons
  - 99% of carbon
- 14Nitrogen: seven protons and seven neutrons
  - Cosmic rays (and nuclear tests) transform into
    14Carbon: six protons and 8 neutrons
- Atom decays back to 12C – half-life of 5730 years
  - In atmosphere, constant new supply of 14C maintains concentration
  - Isolated from atmosphere, concentration declines
Cosmic ray

$^{14}\text{N}$

270 PPM CO$_2$ with <1% $^{14}$C

170 PPM CO$_2$ with <1% $^{14}$C

270 PPM CO$_2$ with depleted $^{14}$C

Decay of $^{14}$C

CO$_2$ with <1% $^{14}$C

CO$_2$ with no $^{14}$C

Ocean
MEASURING TEMPERATURE
Temperature and CO$_2$

- Atmospheric concentration of CO$_2$ is rising
- Science: Should produce rising temperature
- Is it?
Measuring Temperature: Problems

• Spatial
  – Large gaps: Arctic and central Africa
  – No spot represents global temperature: No Mauna Loa

• Temporal
  – Wide-spread instrument record only from ~1850
  – Temperature (unlike chemical composition) not retained in ice cores
Tasks

• Develop algorithms for combining instrument readings into global average

• Use proxies to estimate temperatures for pre-instrument period

• Deal with (or not) the Arctic gap
Milestones: 1980 to mid-2013

• ~1980: NASA, NOAA and Hadley Center develop estimates of global temperature from 1880

• 1998-99: Mann and co-authors estimate temperatures from 1000 AD primarily from tree rings

• 2011-2012: Berkeley Earth Project publishes reanalysis of temperature data from 1750

• 2013 Marcott and co-authors reconstruct temperatures for Holocene (past 11,300 years)
Berkeley Earth Project Reanalysis

Annual Land-Surface Average Temperature

12-month moving average of surface temperature over land
Gray band indicates 95% uncertainty interval

Temperature Anomaly (°C)

1750 1800 1850 1900 1950 2000

NASA GISS
NOAA / NCDC
Hadley / CRU
Berkeley Earth
An Updated Hockey Stick

Green dots show the 30-year average of the new PAGES 2k reconstruction. The red curve shows the global mean temperature, according HadCRUT4 data from 1850 onwards. In blue is the original hockey stick of Mann, Bradley and Hughes (1999) with its uncertainty range (light blue). Graph by Klaus Bitterman.
1961-1990 equals 0. Due to smoothing, graph cannot resolve changes for periods shorter than 300 years.
Data Sources
MEASUREMENTS AND POLICY
1960s-1980s: Three Linked Elements

• Increased scientific understanding

• Understanding + computer power: Improved (but still inadequate) computer models

• Temperature observations
The Development of Climate models, Past, Present and Future

| Mid-1970s | Mid-1980s | Early 1990s | Late 1990s | Present day | Early 2000s+
|-----------|-----------|-------------|------------|-------------|-----------
| Atmosphere | Atmosphere | Atmosphere | Atmosphere | Atmosphere | Atmosphere |
| Land surface | Land surface | Land surface | Land surface | Land surface | Land surface |
| Sulphate aerosol | Sulphate aerosol | Sulphate aerosol | Sulphate aerosol | Sulphate aerosol | Sulphate aerosol |
| Carbon cycle | Carbon cycle | Carbon cycle | Carbon cycle | Carbon cycle | Carbon cycle |
| Dynamic vegetation | Dynamic vegetation | Dynamic vegetation | Dynamic vegetation | Dynamic vegetation | Dynamic vegetation |
| Atmospheric chemistry | Atmospheric chemistry | Atmospheric chemistry | Atmospheric chemistry | Atmospheric chemistry | Atmospheric chemistry |
| Ocean & sea-ice model | Sulphur cycle model | Non-sulphate aerosols | Ocean carbon cycle model | Carbon cycle model | Dynamic vegetation |

Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive.
Departures from 20th Century Average to 1980
(NOAA Early 2013 Data Set)

1880 1900 1920 1940 1960 1980

1944-1980: 0.02° increase

Departures from 20th Century Average to 1987
(NOAA Early 2013 Data Set)

• Domestic: James Hansen 1988
  – “Global warming is now large enough that we can ascribe, with a high degree of confidence, a cause-and-effect relationship to the greenhouse effect.”

• International
  – 1991: First assessment report from IPCC
  – 1992: UNFCCC
A Guide to the Alphabet

• IPCC: Intergovernmental Panel on Climate Change
  – Does not promote/implement policy or conduct research
  – Issues assessment reports based on existing literature

• UNFCCC: United Nations Framework Convention on Climate Change
  – Ratified by U.S.
  – Framework for protocols with national commitments
  – Kyoto Protocol (not ratified by U.S.)
  – U.S. participating in negotiation of post-Kyoto protocol
THE CURRENT ISSUE:
GLOBAL WARMING HAS/HAS NOT STOPPED/PAUSED/SLOWED
Who Did It?
NOAA 2/14 Download

1998: 0.63°

2010: 0.66°
The Suspects

• Reduced radiative forcing
  – No pause in growth of CO₂ concentration
  – Plausible contributors but not large enough
    • Reduced solar radiation: below-average solar cycle
    • Increased albedo: tropical volcanoes and Asian factories

• Distribution of thermal energy within Earth system
Distribution of Earth’s Thermal Energy

• Vertical: surface and upper atmosphere
  – Measurement issue but little effect

• Horizontal: distribution over surface
  – The no-Mauna Loa problem

• Vertical: surface and deep ocean
Role of the Oceans

• >90% of warming goes to heating the oceans

• El Niño-La Niña change rate of warming by affecting distribution of between ocean and atmosphere
THE PACIFIC’S GLOBAL REACH

As researchers have investigated why global temperatures have not risen much since 1998, many have focused on an ocean cycle known as the Pacific Decadal Oscillation (PDO). During periods when the PDO index is positive and the eastern Pacific is warm, global temperatures have risen quickly. During spells when the PDO index is negative, the warming has stagnated.
But is there a problem?

• The Arctic weather station gap
  – Hadley: assumes Arctic temperature changes at global rate
  – NASA: fills gaps by interpolation
  – NOAA: like Hadley?

• Cowtan and Way
  – Begin with satellite data
  – Develop algorithm for relating satellite data to surface temperature
  – Test algorithm for known surface temperatures
## Rank of Highest Recorded Temperatures

<table>
<thead>
<tr>
<th>Rank</th>
<th>NASA</th>
<th>NOAA</th>
<th>HADLEY</th>
<th>COWTAN and WAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2010</td>
<td>2010</td>
<td>2010</td>
<td>2010</td>
</tr>
<tr>
<td>2</td>
<td>2005</td>
<td>2005</td>
<td>2005</td>
<td>2005</td>
</tr>
<tr>
<td>4</td>
<td>2002</td>
<td>2013</td>
<td>2003</td>
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