Measuring CO$_2$ and Temperature

Climate Change
OLLI Summer 2013
Review: Essential Points I

• Temperature: average kinetic energy of system’s atoms

• Planets gain/lose energy through radiation

• Thermal radiation
  – Produced by above absolute zero temperature
  – Energy of photons determined by temperature
Review: Essential Points II

• Many gases occupy only certain energy levels

• Absorb photons with energy matching difference in energy levels

• Greenhouse gases: difference matches photons of Earth’s thermal radiation
MEASURING CO$_2$
Problem and Solution

• Early 1950s: no consensus on how much (or whether) CO₂ concentration was growing

• The problem
  – In long run, geographical source doesn’t matter
  – But does matter for months

• Two-part solution:
  – An isolated location: Manu Loa
  – Continuous careful measurements: David Keeling
The Keeling Curve

Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii

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

2005: Keeling dies
Three Carbon Cycles

• Geological: volcanoes vs. burial
  – Without us, determines total content of atmosphere-biosphere-ocean system
  – Time span: tens of millions of years

• The “Keeling cycles”
  – Biological:
    • Dominates intra-annual cycle
    • Little interannual impact
  – Fossil fuels: volcanoes on steroids
### CO₂ Emissions: Man vs. Volcanoes

<table>
<thead>
<tr>
<th>Description</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>
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</tbody>
</table>
Carbon emissions and sinks since 1750

Where our carbon emissions have come from: carbon emission sources 1750-2012 (Gt CO₂)

Coal*: 673 Gt
Oil: 496 Gt
Gas: 202 Gt
Land-use: 590 Gt

Current: 38 Gt

Where our carbon emissions have gone: carbon emission sinks 1750-2012 (Gt CO₂)

Atmosphere: 879 Gt
Ocean: 590 Gt
Land: 528 Gt

Notes: Both emissions and sinks sum to 1,997 Gt CO₂. Land, ocean and atmospheric sinks represent the increased carbon dioxide absorption due to human emissions between 1750 and 2012. *Coal emissions are mostly coal but also include significant biomass emissions. Gas emissions include a small volume of flaring emissions. Land use change emissions are the net change in carbon stocks resulting from human-induced land use, land use change and forestry activities.

Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA.
Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks

shrinkthatfootprint.com
The importance of carbon sinks

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

Notes: Carbon emissions and sinks are figures for 1750-2012. The 2012 concentration of 393 ppm reflects the global mean concentration which differs slightly from the more widely reported Mauna Loa figure. \(^*\)Coal emissions include significant biomass emissions. Land-use emissions are the change in carbon stocks resulting from human-induced land use, land-use change and forestry activities, with deforestation the major driver.

Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA.
Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks
Measures

• Most common today: metric tons or gigatons (Gt) of CO₂

• Alternative: tons of carbon
  – Molecular weight of carbon: 12
  – Molecular weight of CO₂: 12 + 2 x 16 = 44
    • CO₂ emissions = 3.67 x carbon emissions
    • Tax/ton on CO₂ = tax/ton on carbon/3.67
More Inclusive Measure: CO$_{2}$eq

• Definition
  – Global warming potential (GWP) per unit weight over 100 years
  – CO$_{2}$eq for CO$_2$ = 1

• 2010 atmospheric concentration (parts per million)
  – CO$_2$: 389
  – CO$_{2}$eq of the “Kyoto Six”: 444
Why it’s better to flare natural gas (CH₄)

• More powerful than CO₂ but shorter residence time: \( \text{CO}_2\text{eq} = 26 \)

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

• GWP of one carbon atom:
  – \( \text{ln CO}_2: \) 1
  – \( \text{ln CH}_4: \) \( 26 \times 16/44 = 9.5 \)
U.S. GHG Emissions 1990-2011

Overview of Greenhouse Gases

- Carbon Dioxide: 84%
- Methane: 9%
- Nitrous Oxide: 5%
- Fluorinated Gases: 2%

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Figure 4. Radiative forcing, relative to 1750, of all the long-lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis.

Click on image to view full size figure.
The Fourth Carbon Cycle

- http://www.youtube.com/user/CarbonTracker/p/a/u/2/H2mZyCblxS4
The Glacial Cycle: Cooling the Earth

• Declining atmospheric CO$_2$ from 50 MYA
  – Geologic burial > volcanic emissions
  – Arrhenius but change probably on burial side

• Temperature falls
  – By 10 MYA: permanent Antarctic ice sheet
  – From 2.75 MYA: alternating northern glaciation (most of the time) and interglacial periods (like now)
Temperature from 5 MYA

Warmer, Less ice

Colder, More ice

Millions of Years Ago
The Glacial Cycle: Earth’s Orbit

- **Eccentricity:** Cycle from more circular to less circular orbit – 100 thousand years
- **Precession:** Cyclical wobble changes 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
The Glacial Cycle: Feedbacks

• Feedback 1
  – Cool summer → more snow remains → increased albedo → More cooling
  – Not enough

• Feedback 2: Transfer of CO$_2$ to deep ocean
  – Begins after temperature decline begins
  – Implication: a feedback
Carbon Dioxide vs Temperature: past 400,000 years
Glaciers Spread

Glacier starting point

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Concluding Points

• Video on temperature-carbon relationship in glaciation/deglaciation:
  http://www.youtube.com/watch?v=8nrvrkVBt24

• Questions
  – Why the change from 41,000 years (obliquity) to weaker 100,000 years (precession)?
  – Details of CO$_2$ feedback mechanism
  – So why believe?
    • Implications of science
    • Carbon isotopes
14 Carbon and Its Implications

- **12 Carbon:** Six protons and six neutrons
  - 99% of carbon
- **14 Nitrogen:** Seven protons and seven neutrons
  - Cosmic rays constantly transform into 14 Carbon: six protons and 8 neutrons
  - Decays back to 12C – half-life of 5730 years
- **Depleted 14 C:** isolated from cosmic rays
Cosmic ray → $^{14}\text{N}$ → $^{14}\text{C}$ → Leaving “ice age” → $^{14}\text{N}$ → $^{14}\text{N}$ → Entering “ice age” → $^{14}\text{C}$ → Ocean
MEASURING TEMPERATURE
Temperature and CO$_2$

• Atmospheric concentration of CO$_2$ is rising

• Science: Should produce rising temperature

• Is it?
Measuring Temperature Compared with $\text{CO}_2$
Problems I: Since Mid-Late 19$^{\text{th}}$ Century

- Longer instrument record, but--

- Reliability of individual readings – examples
  - Development of heat islands
  - U.S. vs. British maritime measurements

- Temperature unevenly distributed: No Manu Loa
Measuring Temperature Compared with CO$_2$
Problems II: Before Mid-19$^{th}$ Century

• No pre-instrument direct measurement

• Temperature not retained: no ice cores

• Reliance on proxies

• Manu Loa problem again
  – Global Medieval Warm Period?
  – Global Little Ice Age?
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 to 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.
Data Sources
Note: Due to smoothing, graph cannot resolve changes for periods shorter than 300 years.
The Future With and Without Anthropogenic Warming

![Graph showing temperature changes over time with and without anthropogenic warming.](image)
1960s-1980s: Three Linked Elements

• Increased scientific understanding

• Understanding + computer power: Improved (but still inadequate) computer models
  – One product: Explanation for lack of temperature increase 1930-1970

• Temperature observations
1988-1992: Moves to Policy Agenda

- **Domestic** 1988: James Hansen testimony
  - “[G]lobal 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 UNFCC
  - 1992: United Nations Framework Convention on Climate Change (UNFCCC)
    - U.S. ratification: October 15, 2002
Departures from 20th Century Average to 1980
(NOAA Early 2013 Data Set)

1944-1980: 0.02\degree increase
What’s Happening?

• Science is wrong

• Science is correct but by 1940 atmosphere was saturated with CO₂

• CO₂ radiative forcing is offset by changes in albedo and/or solar insolation
Offsets?

• Need “experiment”: Compare observed temperature with effect of combinations of CO$_2$, insolation, and volcanoes/ pollution

• Problem:
  – Can’t conduct physical experiment
  – No adequate computer models in 1980
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...
Figure 4: Simulating the Earth’s temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.
Departures from 20th Century Average to 1987
(NOAA Early 2013 Data Set)
1988-1992:
Climate Change Moves to Policy Agenda

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

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Departures from 20th Century Average to 2012
(NOAA Early 2013 Data Set)
Temperature Change to 2012 from:

- 1996: 0.25
- 1997: 0.10
- 1998: -0.05
- 1999: 0.15
- 2000: 0.15
10-Year Average Temperature Increase 1980-2012
10-Year Average Temperature 1889-2012
We’ve Been Here Before – But Why This Time?
Three Possibilities Plus a Fourth

• Science is wrong

• Atmosphere is saturated with greenhouse gases

• GHG radiative forcing is being offset by increased albedo or reduced insolation

• Change 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-Manu Loa problem

• Vertical: surface and deep ocean
Volcanoes

Strong El Nino

Figure 1: Ocean Heat Content from 0 to 300 meters (grey), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members.
Role of the Oceans

- Absorbs about a quarter of CO$_2$ emissions
- 90% of warming goes to heating the oceans
- El Niño-La Niña change rate of warming by redistributing heat between ocean and atmosphere
“Missing” Heat and Its Implications

• Since 2004 measured warming less than implied by measured radiative forcing
• New studies: increased warming in deep ocean
• Issues
  – Accounts for much but not all “missing heat”
  – Which future
    • Additional heat comes back into the atmosphere
    • Reversion to former apportionment of incremental thermal energy
    • Continued larger apportionment to deep ocean