Looking back on the future of climate change

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Part 1: The early years of greenhouse theory.
A tale of ice ages and carbon dioxide

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In the beginning...

- There was an energy balance model
In steady state:

Energy IN = Energy OUT, Solve for surface temperature …
Incoming Solar Radiation

Solar energy $\perp$ to rays:

$$S_0 \approx 1367 \text{ W/m}^2$$

Average incident solar energy:

$$\frac{S_0}{4} \approx 342 \text{ W/m}^2$$
Albedo

\[ \text{Albedo} (\alpha) = \text{fraction of incoming solar radiation reflected} \]

Global mean albedo: \( \alpha \approx 30\% \)

<table>
<thead>
<tr>
<th>Type of surface</th>
<th>Albedo (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>2 – 10</td>
</tr>
<tr>
<td>Forest</td>
<td>6 – 18</td>
</tr>
<tr>
<td>Grass</td>
<td>7 – 25</td>
</tr>
<tr>
<td>Soil</td>
<td>10 – 20</td>
</tr>
<tr>
<td>Desert (sand)</td>
<td>35 – 45</td>
</tr>
<tr>
<td>Ice</td>
<td>20 – 70</td>
</tr>
<tr>
<td>Snow (fresh)</td>
<td>70 – 80</td>
</tr>
</tbody>
</table>

(Marshall, 2007)

(NASA MODIS)
Incoming Solar Radiation

Energy IN

= absorbed solar radiation

= \( (1 - \alpha) \frac{S_0}{4} \)

Energy OUT …
Outgoing Terrestrial Radiation

Stefan’s law for blackbody radiation:

\[ \text{Energy OUT} = \sigma T_e^4 \]
Global Energy Balance Model

Energy IN = Energy OUT \Rightarrow

\[ Te = \left( \frac{S_0(1 - \alpha_r)}{4\sigma} \right)^\frac{1}{4} \]

\[ Te = 255 \text{ K} \]

[Actual: \( T_s = 288 \text{ K} \)]
Joseph Fourier (1768-1830)

- First to recognize the concept of planetary energy balance (though infrared radiation had not yet been discovered)
- Calculated a radiative equilibrium temperature much too cold
- Inferred that the atmosphere interferes with the transmission of outgoing terrestrial heat
- This is what eventually came to be called the *greenhouse effect*
John Tyndall (1820-1893)
John Tyndall (1820-1893)

- Conducted laboratory experiments, showed that several atmospheric gases absorb heat, notably H\textsubscript{2}O and CO\textsubscript{2}
- Recognized the important implications for the energy balance of the earth:

  “As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth’s surface.” Tyndall, 1862
Water vapor “is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapour from the air… and the sun would rise upon an island held fast in the iron grip of frost.” Tyndall, 1863
Tyndall’s motivation

☐ An avid alpinist with first-hand knowledge of glaciers, he had become convinced by the evidence that all of northern Europe had once been covered by a colossal ice sheet

☐ He was looking for mechanisms to explain how the climate could change so radically!
Erratic boulders

Louis Agassiz (1807-1873)

- Argued to the Swiss Society of Natural Sciences in 1837 that an *immense polar ice sheet* had once blanketed the nearby Jura mountains, as well as all of northern Europe.
- A long dispute among geologists followed…
- 30 years later, the existence of the ice age was generally accepted.
Terminal moraines

Source: The Jesse Earl Hyde Collection, Case Western Reserve University (CWRU)
Figure 10. Professor T.C. Chamberlin's map was the first attempt to picture North America during the last ice age. (From J. Geikie, 1894.)

Not one ice age, but several!
But why and how did it happen?

- By the end of the 19th century, geologists had amassed a great deal of information about the ice ages.
- Multiple ice ages suggested that the climate had fluctuated enormously over time.
- Explaining the ice ages became the “holy grail” of climate studies (and still is!)
Svante Arrhenius (1859-1927)

- Swedish chemist, also interested in the ice age problem
- First attempt to calculate the temperature change resulting from adding or removing CO$_2$ from the atmosphere (what we now call climate sensitivity)
Calculating the greenhouse effect

- Atmosphere:
  - Does not absorb solar radiation
  - Absorbs terrestrial radiation
- Re-radiates energy in both directions
- 2 equations:
  - Top of atmosphere
  - Surface
- 2 unknowns ( $T_e$, $T_s$ )

$$T_s = 2 \frac{1}{4} T_e \quad T_s = 303 \, K$$

[ Actual: $T_s = 288 \, K$ ]

Source: Marshall 2007
A “leaky” greenhouse

Source: Goody and Young, 1989
Water vapor feedback

- Tyndall’s work had shown that H₂O is the dominant greenhouse gas in the atmosphere (was and still is much more abundant than CO₂).
- Warmer air can hold more water vapor
- Warmer ---> more H₂O ---> more greenhouse warming
- A positive feedback!
- Arrhenius recognized the crucial importance of this feedback and included it in his calculations
After months of pencil work…

- Arrhenius concluded that halving the atmospheric CO$_2$ would lead to a cooling of 4-5°C in Europe -- enough for an ice age!

“I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them.” Arrhenius, 1896
Could CO$_2$ vary that much?

- Arrhenius turned to a colleague named Arvid Högbom who was studying how CO$_2$ cycles through natural geochemical processes (e.g. volcanoes, oceans)

- Högbom found something remarkable: industrial sources were emitting CO$_2$ at a rate comparable to geochemical sources!

- They realized that given enough time there was a possibility for artificial warming of the climate.
So Arrhenius did another calculation

- Now curious about the warming question, he calculated the effect of \textit{doubling} the CO$_2$ in atmosphere.
- Answer: 5-6°C warming
- With the rate of coal consumption in 1896, this doubling would take 3000 years (revised in 1908 to hundreds of years)
- Arrhenius had demonstrated anthropogenic global warming… as a curious theoretical concept.
Meanwhile, the climate was warming…

Northern hemisphere surface temperature (expressed as deviation from 1946-1960 mean in °C)

P.D. Jones et al (1982), MWR 110, p.67
“The Northern Hemisphere is still recovering from the last great glaciation of the Ice Age, though for chronological purposes this period is considered to have ended some 20,000 years ago. The continental ice sheet which once covered the northern United States still exists in Greenland where it is still retreating. Despite various speculations, the reason for such climate changes is obscure.

In 1932 the U.S. Weather Bureau assembled all available records covering a century or more, found that they showed a trend towards warmth.”
Is the World Getting Warmer?

By ALBERT MARBANEL and THORP MCCLUSKEY

Was this past mild winter just part of a natural cycle? Will the old-fashioned blizzards someday disappear? Here are the startling facts revealed by worldwide weather surveys now going on...

For the past three decades a galaxy of scientists, meteorologists, and observers have been investigating the weather. The American National Weather Service, the U.S. Weather Bureau, the U.S. Department of Agriculture, the U.S. Geological Survey, and many private organizations and scientists have been collecting and analyzing what some call the "weather chains" that circle the globe.

The American Meteorological Society, through the cooperation of the National Science Foundation, has been sending out weather observers to the most remote corners of the world. They have been collecting, recording, and analyzing the data from these remote stations. The results are startling. The past three decades have shown a trend toward warmer weather throughout the world.
Guy Stewart Callendar (1898-1964)

- English steam engineer, dabbled in meteorology as a hobby
- Curious about the apparent warming trend
- Also interested in Arrhenius’ CO₂ warming theory
- Compiled many old temperature observations, found a warming
- Compiled available data on atmospheric CO₂ concentration, and found it was increasing
- Used an energy balance argument to calculate the effect of the CO₂ increase on temperature, found it consistent with observations
- Stood before the Royal Meteorological Society in London in 1938 and delivered his paper “The Artificial Production of Carbon Dioxide and its Influence on Temperature”

Image source: http://www.aip.org/history/climate/
"Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale.

In the following paper I hope to show that such influence is not only possible, but is actually occurring at the present time.

Callendar, 1938

Callendar (1968), QJRMS 64, p. 233
“In conclusion it may be said that the combustion of fossil fuel, whether it be peat from the surface or oil from 10,000 feet below, is likely to prove beneficial for mankind in several ways, besides the provision of heat and power. For instance the above mentioned small increases of mean temperature would be important at the northern margin of cultivation… In any case the return of the deadly glaciers should be delayed indefinitely.”

Callendar, 1938
Guy Stewart Callendar

- Continued to argue for the next 20 years that CO$_2$-induced greenhouse warming was occurring.
- Sometimes called the “Callendar Effect”
- However, few people were convinced at the time.
A few persistent arguments against CO₂ greenhouse warming

- Lab results showed CO₂ absorption already saturated
- Oceans are a huge carbon sink, probably taking up excess emissions
- Simple calculations by Arrhenius, Callendar and others completely neglected many important meteorological processes, including changes in cloud cover
Whither the carbon?

- As late as 1950’s, reliable measurements of atmospheric CO₂ were lacking. Were emissions accumulating in the atmosphere, or being quickly taken up by the oceans?
- Meanwhile, radiometric ¹⁴C dating was invented.
- In 1955 Hans Suess was measuring carbon isotopes in tree rings to better calibrate ¹⁴C dates.
- He found “old” carbon in recent growth rings.
Whither the carbon?

- Some saw in Suess’s discovery a great new opportunity to study the circulation of the ocean and the gas exchange with the atmosphere.
- Suess collaborated with Roger Revelle at the Scripps Institution of Oceanography.
- They calculated an average lifetime of 10 years for a molecule of CO$_2$ in the atmosphere.
- Along the way, Revelle discovered a peculiar buffering mechanism in seawater: to equilibrate with a given increase in atmospheric CO$_2$, the amount of dissolved carbon need only increase by about 1/10th as much.
Roger Revelle (1909-1991)

- Oceanographer, Al Gore’s hero
- Instrumental in setting up the International Geophysical Year, 1957
- Many important contributions as researcher, teacher and administrator
- Was aware of Callendar’s arguments, and became personally interested in the fate of fossil carbon emissions.
- His demonstration of the “Revelle factor” suggested that the oceans were probably not taking up carbon at a sufficient rate to prevent a build-up in the atmosphere.
- It was clear that better measurements were needed.

Image source: http://www.aip.org/history/climate/
Roger Revelle

“Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future.”

Revelle and Suess, 1957
C. David Keeling (1928-2005)

- Geochemist, became interested in atmospheric CO$_2$ as a post-doc at CalTech (1954-1956)
- First to develop reliable instruments and techniques to measure the baseline atmospheric CO$_2$ concentration
- Measurements motivated in part by the CO$_2$-greenhouse theory of climate change
- With IGY funds, Revelle hired Keeling to conduct a short-term global CO$_2$ survey

Image source: http://sio.ucsd.edu/keeling/
Keeling’s Antarctic measurements

C. D. Keeling, Tellus 12, (1960), p. 200
The Mauna Loa observatory

- Built in 1956 atop Mauna Loa, Hawaii, at 3397 m above sea level
- High elevation, remote ocean location - far from most anthropogenic sources
- Keeling started a CO$_2$ measurement campaign here during IGY, that has continued to the present.
The Keeling Curve (1971)

Reproduced from The Discovery of Global Warming at http://www.aip.org/history/climate/xKeeling71.htm

The Keeling Curve (now)

Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii

Image:Mauna_Loa_Carbon_Dioxide_png
So now we know

- As Keeling’s measurements continued, there could no longer be any doubt that anthropogenic CO$_2$ was accumulating in the atmosphere.
- The possibility of a greenhouse warming had to be taken seriously.
- Meanwhile, progress was being made on the theoretical side, helped tremendously by the invention of computers.
Why is the energy balance calculation so difficult?

Source: Goody and Young, 1989

Source: Marshall 2007
Why is the energy balance calculation so difficult?

- Details of absorption spectra depended on quantum mechanics; not worked out until WWII era.
  - 1956: Gilbert Plass made the first accurate calculation of vertical radiative transfer; CO₂ shown to have warming effect

- Need to know vertical distribution of absorbing gases, which depends on temperature (water vapor feedback)
  - 1963: Fritz Möller publishes a similar calculation, but taking account of the water vapor feedback; model is extremely sensitive to CO₂
Why is the energy balance calculation so difficult?

- Radiative equilibrium temperature profile is unstable to vertical motion
  - 1967: Manabe and Wetherald publish an energy balance calculation with both water vapor feedback and vertical redistribution of heat through convection
  - Doubling CO$_2$ --> about 2°C warming
  - Considered by many to be the first convincing demonstration that CO$_2$ greenhouse warming was a real possibility.

Manabe & Wetherald (1967), JAS 24 p. 244
The story so far, circa 1967

- Most of the technical details of the greenhouse effect were understood by the 1960s, a century after its discovery by Tyndall.
- We had convincing evidence that CO$_2$ of fossil origin was accumulating in the atmosphere.
- Increasingly sophisticated model calculations were beginning to convince many scientists that greenhouse warming was a distinct possibility.
- Meanwhile, the climate was cooling.

P.D. Jones et al (1982), MWR 110, p.67
CO$_2$ and the ice age story

- In 1897, inspired by Arrhenius’ calculation, T.C. Chamberlin publishes a theory of the ice ages as a self-oscillating cycle driven by CO$_2$ feedbacks (involving, among other things, the temperature dependence of the chemical weathering of rocks and the increased solubility of CO$_2$ in cold oceans).

- This sort of CO$_2$ ice age theory was pitted against the astronomical theory championed first by James Croll in the 1860s, and later by Milutin Milankovic in the early 20th century.

- In more recent times, ice cores and ocean sediment cores have given us a very detailed picture of the ice ages.

- The debate has not gone away: CO$_2$ and orbital changes both seem to be involved in ice age cycles.
CO₂ and the ice age story

Source: Global Warming Art, http://www.globalwarmingart.com
James Croll (1821-1890) and Milutin Milankovic (1879-1958)


For more information

- Weart’s excellent website http://www.aip.org/history/climate/
- “Ice Ages: Solving the Mystery” by Imbrie and Imbrie, Harvard University Press, 1986
Please join us tomorrow for Part 2

Daniel Enderton will talk about the observations of climate change, and what can and can’t say about the role of greenhouse warming in those changes.

1 pm, E40-298