Fundamentals of Global Climate Change Science
Erik Ramberg

• Temperature of the Earth
• Radiative balance in the atmosphere
• Forcings and the Ice Ages
• Direct measurements of the surface temperature
• Ice sheet melting
• Ocean sea level rise and acidification
• Predictions for the future
Radiative Balance on Earth
So – what temperature do we predict the Earth to have?

Use Stefan-Boltzmann equation to relate incoming power from the Sun to the temperature of the Earth:

\[ J(1-a) = \varepsilon \sigma T^4 \]

Where \( J \) is the incoming power per area from the Sun, \( a \) is the albedo of the Earth (or what fraction of the incoming power is simply reflected), \( \varepsilon \) is the ‘emissivity’ of the Earth (or how radiant it is compared to a blackbody), \( \sigma \) is the Boltzmann constant, and \( T \) is the temperature of the Earth.

Plug in the numbers:

- Average solar insolation at the Earth’s surface is \( J = 341 \text{ W/m}^2 \) (seasonally +/- 3.5%)
- Boltzmann constant is \( 5.67 \times 10^{-8} \text{ W/(m)}^2(\text{K})^4 \)
- Albedo is about 30%

If Earth is a perfect blackbody, with \( \varepsilon = 1 \), then:

- Predicted \( T = 255^\circ \text{K}, \text{or } 0^\circ \text{F} \)
- Actual \( T = 289^\circ \text{K}, \text{or } 60^\circ \text{F} \)

Difference must be due to details of emissivity of Earth
No True ‘Temperature’!

- There is no true ‘temperature of the Earth’ because there is an atmosphere.
- You can talk about the temperature at the surface, or at some height from the surface.
- The emissivity of the Earth depends on the composition of the gases in its atmosphere, their spectral properties and their distribution.
- The ocean plays a big role as well, as we shall see, but the time scale is much longer.
Radiation flow in the Earth system

Top-of-the-Atmosphere radiation balance, or “TOA”, can be readily calculated using these flows between the various layers of the atmosphere, without worrying about the topographical details of the surface. These calculations inform us of average behavior.

More general climate models use the intricacies of the Earth’s surface, including winds, cloud formation and interaction with the ocean, to predict what the globe will look like in the future.
CO₂ absorption lines

Resting State

Symmetric Stretch

Asymmetric Stretch

No Resting Dipole

IR Inactive

2349 cm⁻¹

660 cm⁻¹

H₂O absorption lines

Resting State

Symmetric Stretch

Bend

H
H
O

δ+ δ+

O

2δ-

3657 cm⁻¹

1594 cm⁻¹

Infrared radiation from the Earth’s surface will be absorbed by exciting these vibrations.
CO₂ and water absorb in the infrared region of 8-50 microns, which is the dominant wavelengths for a blackbody Earth.

This is the ‘Greenhouse effect’, which has been understood for more than 100 years.

Note how powerful water is as a greenhouse gas.

The main difference between H₂O and CO₂ is that the lifetime of water in the atmosphere is weeks, while the lifetime of CO₂ in the atmosphere is on the order of 1000 years.
Idealized Greenhouse Model – No Atmospheric GHG

$S_0$ is total solar insolation. $rac{1}{4} S_0$ is average over surface of Earth

Blue: Incoming and reflected shortwave radiation from the sun

Red: outgoing longwave radiation.
Idealized Greenhouse Model – With Nominal GHG

\[ S_0 \text{ is total solar insolation.} \]
\[ \frac{1}{4} S_0 \text{ is average over surface of Earth} \]

Blue: Incoming and reflected shortwave radiation from the sun

\[ \frac{1}{4} S_0 \alpha_p \]
\[ (100) \]

\[ \frac{1}{4} S_0 \alpha_p \]
\[ (30) \]

Red: outgoing longwave radiation.

\[ (1 - \epsilon) \sigma T_s^4 \]
\[ (25) \]

\[ \epsilon \sigma T_s^4 \]
\[ (45) \]

\[ \frac{1}{4} S_0 \alpha_p \]
\[ (55) \]

\[ T_a = 0.95 T_e \]

\[ \epsilon \sigma T_a^4 \]
\[ (45) \]

\[ T_s = 1.13 T_e \]

Note heating of surface and cooling of upper atmosphere
Idealized Greenhouse Model – Doubling of CO2

S₀ is total solar insolation. 
¼ S₀ is average over surface of Earth

Blue: Incoming and reflected shortwave radiation from the sun

Red: outgoing longwave radiation.

Note heating of surface and cooling of upper atmosphere

Note increase in surface temperature of <1%
Forcings
Forcing = imbalance in radiative equilibrium

Solar variations are small

Volcanic aerosols block sunlight for short periods of time – average forcing is low

Man-made aerosols are more systemic and have to be taken into account

Only greenhouse gas forcing looks like the recent temperature rise.

Crowley, 2000
Variations in Solar Output on the Short Time Scale are Irrelevant

CO2 in the Atmosphere

- Mankind’s use of fossil fuel is causing the CO₂ concentration in the atmosphere to rise significantly.
- Measurements of carbon isotopes confirm that the new CO₂ is deficient in Carbon-14 and is thus buried carbon being released.
- This increase is about half the amount of CO₂ that is calculated as being put into the atmosphere from industrial processes.
- Where is the other half?

The ‘Keeling curve’
CO₂ in the Ocean

- As shown by measuring the partial pressure of CO₂ in seawater, the ocean is absorbing about half of the industrial production of CO₂.
- The pH of the ocean is decreasing as a consequence. This acidification of the ocean is global in nature.
CO₂ and other GHG’s are now the dominant elements of climate forcing, and it is instantaneous on geological time scales.
Carbon cycle in the Earth/Atmosphere

• Note that the carbon resident in fossil fuels outweighs combined mass of carbon in atmosphere + soil + biomass + upper ocean
• Our impact on the atmosphere is about 0.7% per year, and rising

Illustration courtesy NASA Earth Science Enterprise.
Dependence of Temperature on Forcings, with No Feedbacks

Stefan Boltzmann:

\[ F = J(1-a) = \varepsilon \sigma T^4, \text{ or } T = \left(\frac{J(1-a)}{\varepsilon \sigma}\right)^{1/4} \]

Derivative w/r Temperature:

\[ \frac{dT}{dF} = \left(\frac{1}{4}\right)\left(\frac{1}{\varepsilon \sigma}\right)^{1/4}(F)^{-3/4} \]

So, ‘sensitivity’ is:

\[ dT = 0.3^\circ K \text{ per } 1 \text{ W/m}^2 \]

As we will see, the measured effective ‘sensitivity’ on Earth is more like 0.8^\circ C per 1 W/m^2. The difference is due to water vapor, which is a powerful greenhouse gas, but is considered a feedback, since it falls out of the atmosphere so readily.
Feedback effect of water vapor and clouds

The water vapor and cloud feedback are one of the bigger uncertainties in AGW theory. However, direct measurements from Ice Age analysis (as we’ll see) indicate the presence of positive feedbacks.
A Movie of the Earth’s Aerosols

The extinction optical thickness of aerosols from a free running 10-km GEOS-5 Nature-Run including dust (red), sea salt (blue), black and organic carbon (green) and sulphate (white) are depicted from August 2006 through April 2007. GEOS-5 was run with the GOCART model providing feedbacks of the direct radiative effects of aerosols within the model in addition to their advection by the weather within the simulation.
The Ice Ages
History of Earth’s Temperature

- Although people think of climate as always changing chaotically, the short story is that the Earth has very long and slow temperature changes and has been steadily cooling for the last 50 million years.
- There is an instability associated with glaciation that gives abrupt 5-7°C changes to the Earth’s temperature.
- Note the Paleocene-Eocene Thermal Maximum (PETM) during which CO₂ emission rates rivaled those of today.
As the planet has steadily cooled in the past 50 million years, an instability has resulted in an oscillatory behavior that has been evident in the last 3 million years. This is not the typical behavior of the Earth’s climate but rather a very special set of circumstances related to the albedo of ice sheets near their positive feedback tipping point.

With the inevitable doubling of atmospheric CO$_2$ due to anthropogenic emissions, and a 3° C temperature rise, then that means the Ice Ages are probably over. (Yay!)
Milankovitch Cycles

- There is good evidence that the Milankovitch cycles for average solar insolation dictate the timing of the Ice Ages.

- These cycles occur because of the details of the Earth’s orbit over a period of tens of thousands of years or so and their effect on solar insolation.

- The Ice Ages are then caused by an amplification mechanism. This amplification mechanism includes the loss of albedo as the ice sheets melt, and the release of greenhouse gases, specifically CO$_2$, from the ocean.
Very consistent model: when northern latitude average insolation falls below 450 W/m$^2$, then ice volume starts increasing. Positive feedback mechanisms cause very large temperature excursions.
Simple empirical calculation for last 800,000 years (no simulations)

(a) Measured CO$_2$, CH$_4$ and sea level for past 800 kiloyears.

(b) Calculated climate forcings due to changes of GHGs and ice sheet area,

(c) Predicted (blue) and observed (red) global temperature change based on above forcings and climate sensitivity of ¾°C per W/m$^2$. Observations are Antarctic T change divided by two.
Ice Age Climate Forcings (W/m²)

Forcing $\sim 6.5 \pm 1.5$ W/m²

Observed $\Delta T \sim 5 \pm 1$°C

$\rightarrow \frac{3}{4} \pm \frac{1}{4}$°C per W/m²

Implied Climate Sensitivity: $\sim \frac{3}{4}$°C per W/m²
Forcing during the Industrial era has been about 1.9 W/m². For a sensitivity of 3/4°C per W/m², as just shown from Ice Age data, we expect a 1.4°C rise in temperature – which is what we have experienced.

Expected total forcing from doubled CO₂ concentration is 3.7 W/m². We can expect a total of at least 2.5°C rise in global temperature compared to pre-industrial times. Other feedbacks may start up (CH₄ clathrates?)
Greenhouse effect is not linear

- There is a saturation effect for adding CO\(_2\) and the response is ultimately logarithmic.
- However, this effect is not a substantial correction until well beyond 550 ppm (doubling the pre-industrial concentration)
Measurements of Earth’s Temperature
Global Historical Climate Network (GHCN)

- Managed by National Climatic Data Center
- ~7000 temperature stations
- Used for reconstructions of global temperatures by NCDC and GISS (Goddard Institute for Space Studies)
- Oldest continuous record started in 1701.
- Ocean data supplemented by ship records.
- Major enhancements in 1997 to allow for inclusion of max/min data and regional information.
- Time of observation during the day is a significant correction.
Satellite measurements

- University of Alabama in Huntsville (UAH) and MSU have made extensive analyses from an ever changing array of satellite measurements of the radiance ($W/m^2/\text{steradian}$) of the Earth and atmosphere.
- Significant corrections need to be made to these data, causing a lot of disagreements and confusion. (Note 1998 orbital decay correction)
2001-2007 Mean Surface Temperature Anomaly (°C)

Base Period = 1951-80, Global Mean = 0.54

- 5 x 5 degree grids are laid on the surface
- Each temperature record is changed to an ‘anomaly’ series, after making various corrections
- Anomalies are averaged within the grid boxes
- Anomalies from without the grid box are weighted by their distance
- Empty grid boxes are interpolated from surrounding boxes
Are There Systematic Effects Biasing the Recent Temperature Record?

- Many insist that as cities and their ‘urban heat islands’ have grown in size, any local temperature sensors will record an artificial increase.
- There are many temperature sensor locations that are obviously flawed (near air conditioning exhausts, parking lots, etc.), but most aren’t.
- A self-described ‘skeptic’ Berkeley professor – Richard Muller – embarked on a complete reanalysis of the temperature record:

  ‘BEST’ = ‘Berkeley Earth Surface Temperature project’

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Berkeley Earth</th>
<th>GHCN-M v3</th>
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<tbody>
<tr>
<td>Number of Stations</td>
<td>39,028</td>
<td>7,280</td>
</tr>
<tr>
<td>Monthly Observations</td>
<td>14,786,160</td>
<td>5,150,496</td>
</tr>
<tr>
<td>Median Record Length</td>
<td>25.8 Years</td>
<td>58.5 Years</td>
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</table>
Assembling the Record

Local factors such as latitude and elevation have a very large effect on the mean climate at each site.

- Each partial record is corrected for latitude and elevation
- Partial records are stitched together by other partial records
- Standard statistical tests are made on each record and obvious outliers are deweighted
- No gridding is performed, but global average is calculated

Integrated Outlier / Reliability Assessment

- Highly anomalous series are also deweighted
Correlations of temperature span huge distances!

- BEST measurements confirm that temperature sensors are highly correlated, even on the scale of 1000 km.
- For any point on the globe, you can weight the data averaging using this correlation.
- As little as 200 sensors, placed strategically around the globe, could give an accurate measure of the global average temperature.
No urban vs rural systematic effect exists

Rural sited meteorological station

Urban sited meteorological station

Urban Heat Island Influence

Red envelope indicates 95% consistent with no change
BEST final result

Decadal Land-Surface Average Temperature

10-year moving average of surface temperatures over land
Anomalies relative to the Jan 1950 - Dec 1979 mean
Gray band indicates 95% statistical/spatial uncertainty interval

1940-1970 was a time of heavy aerosols in the atmosphere

(HadCRU does not include Arctic regions!)
Corrections to the global average temperature record

Table 2: Trends in °C/decade of the signal components due to MEI, AOD and TSI in the regression of global temperature, for each of the five temperature records from 1979 to 2010.

<table>
<thead>
<tr>
<th></th>
<th>MEI</th>
<th>AOD</th>
<th>TSI</th>
</tr>
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<tbody>
<tr>
<td>GISS</td>
<td>-0.014</td>
<td>0.025</td>
<td>-0.014</td>
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<tr>
<td>NCDC</td>
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<tr>
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<td>-0.022</td>
<td>0.038</td>
<td>-0.023</td>
</tr>
<tr>
<td>UAH</td>
<td>-0.023</td>
<td>0.041</td>
<td>-0.018</td>
</tr>
</tbody>
</table>

Foster and Rahmstorf (2011)

MEI = Multivariate ENSO Index
(ENSO=El Nino Southern Oscillation)

AOD = Aerosol Optical Thickness

TSI = Total Solar Irradiance

Figure 2: Influence of exogenous factors on global temperature for GISS (blue) and RSS data (red). (a) MEI; (b) AOD; (c) TSI.
El Nino & La Nina –
The Southern Pacific Oscillation

El Nino: High atmospheric pressure in the western Pacific causes heat flow eastward. La Nina is the reverse.

These oscillations are not related to global warming, (first observed in the 1600’s) but do introduce a noise source.

These episodes are correlated to global temperatures at the 0.2°C level and can be corrected for in global averages.
Has Global Warming Stopped in the last 15 years?
Anthropogenic Global Warming is Continuing at a Steady Pace
Calculation of Anomaly Distributions by Decade

- Baseline the temperatures in 1951-1961 to Gaussian
- Plot average temperature anomalies with respect to this base period.
- As shown, extreme heat events have become much more common – at the 4-5 \( \sigma \) level.
- Heat waves that are causing tens of thousands of people to die are, indeed, a direct result of AGW.

Ref: J. Hansen (2011)
Water and Ice
The ocean is absorbing a large fraction of the warming.

What happens when the deep ocean equilibrates with the surface?

Then the forcing from GHG’s will have a more intense effect.
Sea ice area reached a new absolute minimum in 2012
- Antarctica is buffered by an extremely large land ice mass
- There is a modest increase in sea ice area, but this does not match Arctic losses
We are rapidly transitioning to a world without permanent Arctic Ice.

Note the reduction in albedo for this large area.
To understand the drastic nature of what is happening in the Arctic regions, it’s important to concentrate on volume, not area!

PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System – U. Washington) is a model that uses estimates for sea ice thickness and then calculates ice volume.

20,000 km³
Determining Ice Sheet Mass by Satellite

GRACE is a pair of polar orbiting satellites, monitored by GPS, which can make systematic studies of the gravity field of the Earth. This has been an extraordinarily useful facility, in many fields of study, one of which is studying the amount of ice that is resident in Greenland and Antarctica.
Results from the GRACE satellites

Loss in Arctic icecap averaged over the last 30 years is of the same order
The Future
Predicted sensitivities from climate models. A $5^\circ$ C sensitivity would be on the order of a $15\sigma$ effect.
σ is interannual standard deviation of observed seasonal mean temperature for period 1900-2000.

Much of the land surface will experience extreme floods or drought
Sea Level Rise: Storm Surges are Highly Sensitive to this Value

Rate = 2.5 meters/millennium, and accelerating.
Much of this rise currently is due to thermal expansion.

Re: Robert Rohde, U.C. Berkeley
Simple Sea Level Extrapolation, Using Historical Data, Not Models

Sea Level, m

Global T Change, °C

Last Glacial Maximum 20 kyr ago

Pliocene 3 Myr ago

Eocene 40 Myr ago

Eventual Sea Level Rise = 50 m?!

Source: David Archer, U.C.
20 meter Rise of Sea Level
Facing the Problem
[If we continue on our present course...]

“Over the next several decades, the Western United States and the semi-arid region from North Dakota to Texas will develop semi-permanent drought, with rain, when it does come, occurring in extreme events with heavy flooding. Economic losses would be incalculable.

... “Every major national science academy in the world has reported that global warming is real, caused mostly by humans, and requires urgent action. The cost of acting goes far higher the longer we wait — we can’t wait any longer to avoid the worst and be judged immoral by coming generations.”
The Economic Imperative for Burning Carbon

Gapminder.org
The Economic Imperative for Burning Carbon

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A 20-Year Low in U.S. Carbon Emissions

By RACHEL NUWER

Energy-related carbon dioxide emissions in the United States from January through March were the lowest of any recorded for the first quarter of the year since 1992, the federal Energy Information Administration reports.

The agency attributed the decline to a combination of three factors: a mild winter, reduced demand for gasoline and, most significant, a drop in coal-fired electricity generation because of historically low natural gas prices. Whether emissions will continue to drop or begin to rise again, however, remains to be seen, experts said Friday.
A Summary

- Climate on Earth is predictable
- One of the biggest ‘knobs’ that controls our climate is CO₂ in the atmosphere. Water vapor in the atmosphere follows the CO₂
- The Ice Ages give us a handle on exactly how sensitive the global temperature is with respect to changes in forcing (0.75° for +1 Watt/m²).
- The anthropogenic CO₂ emission from fossil fuels is a very significant forcing component and doubling the concentration of it in the atmosphere is predicted to lead to at least a 2.7° C rise in temperature compared to pre-industrial times.
- The temperature sensor record is very clear that the global temperature has risen already about 1.5° C. There have been no significant systematic errors brought to light in this measurement in some time.
- All major ice sheets are dramatically decreasing in mass. The complete melting of the summer Arctic polar ice cap will very likely occur within this decade.
- Predictions show severe consequences if we do not curtail our CO₂ emission.
- United States emissions of CO₂ have dropped in the last 20 years, so change is possible.
- Every physicist should be familiar with the details of global climate change and be able to confidently speak to the public about them.
Thank you for your attention!

If you are interested in talking about the solutions to anthropogenic global warming, please join the:

Fermilab Sustainable Energy Club!
Meeting tonight at 5:30 at User’s Center