CLIMATE CHANGE: A REALLY TOUGH SCIENTIFIC PROBLEM

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http://www.ecd.bnl.gov/steve
GLOBAL TEMPERATURE CHANGE SINCE 1850

Temperature anomaly vs. 1850-1900, K

Climatic Research Unit, East Anglia, UK

Departure from climatological average

0.8 K
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration over the last thousand years

Antarctic ice cores
- Law Dome
- Adelie Land
- Siple
- South Pole

Mauna Loa Hawaii

C. D. Keeling
EXPECTED AND OBSERVED TEMPERATURE CHANGE OVER THE TWENTIETH CENTURY

Expected warming for forcing by long-lived greenhouse gases only

Externally imposed change in Earth radiation budget

Decades to centuries: CO₂, CH₄, N₂O, CFCs

Expected increase substantially exceeds observed.

Observations: Climatic Research Unit, East Anglia, UK
2009 Copenhagen Accord agrees on 2°C maximum temperature rise

The Heads of State, Heads of Government, Ministers . . . present at the United Nations Climate Change Conference 2009 in Copenhagen:

Albania, Algeria, Armenia, Australia, Austria, . . . [106 countries] . . ., United States of America, Uruguay and Zambia, have agreed on this Copenhagen Accord. . . .

We underline that climate change is one of the greatest challenges of our time. We emphasise our strong political will to urgently combat climate change. . . .

To . . . stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius . . . enhance our long-term cooperative action to combat climate change.
Expected increase equals or exceeds 2 degree threshold.
KEY QUESTION

• How much more CO$_2$ can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?
The Greenhouse Effect

Some solar radiation is reflected by the Earth and the atmosphere.

Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

Solar radiation passes through the clear atmosphere

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

CO₂, Carbon Dioxide
ATMOSPHERIC RADIATION

Power per area

Unit: Watt per square meter
W m$^{-2}$

Photo: S. E. Schwartz
THE SOLAR SPECTRUM

Outside Earth’s atmosphere – Compare Planck spectrum at 255 K

Data source: Gueymard, Solar Energy, 2004

Short- and longwave spectra are nearly non-overlapping.
EARTH’S RADIATION BUDGET AND THE GREENHOUSE EFFECT

Radiative Fluxes in W m⁻²

1360 Solar constant

1/4 solar constant

240

340

Albedo \( \alpha = 29.4\% \)

J = \( \sigma T^4 \)

Stefan-Boltzmann Radiation law

T = \( (J/\sigma)^{1/4} \)

Stefan-Boltzmann Radiation law

H₂O, CO₂, CH₄ ···

\( \approx 287 \text{ K} \)

31

302

385

Greenhouse effect

Latent heat 88

Sensible heat 21

\( \approx 255 \text{ K} \)

70.6\% = 1 - \( \alpha \)

78

162

13

47

Aerosol 4

Rayleigh 36

Solar constant

Shortwave absorbed = Longwave emitted

100
WHAT IT REALLY LOOKS LIKE

Measurements for a single day, March 10, 2012, W m\(^{-2}\)

Shortwave upwelling

Net daytime, positive downward

Longwave upwelling

Net 24-hr, positive downward

NASA CERES Program, courtesy Norman Loeb
RADIATIVE FORCING

An externally imposed change in Earth’s radiation budget, W m\(^{-2}\).

**Working hypothesis:**

*Global temperature change is proportional to forcing.*

*On a global basis radiative forcings are additive and interchangeable.*
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration over the last thousand years
Greenhouse gas forcing is considered accurately known.
Gases are uniformly distributed; radiation transfer is well understood.
EARTH’S RADIATION BUDGET AND THE GREENHOUSE EFFECT

Shortwave absorbed = Longwave emitted

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1/4 solar constant

70.6% = 1 - \( \alpha \)

Albedo \( \alpha = 29.4\% \)

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Atmosphere

Radiative Fluxes in W m\(^{-2}\)

240

255 K

385

\( \approx 287 \) K

\( 78 \)

\( 302 \)

31

31

H\(_2\)O, CO\(_2\), CH\(_4\), \ldots

J = \sigma T^4

Stefan-Boltzmann Radiation law

\( T = (J/\sigma)^{1/4} \)

Stefan-Boltzmann Radiation law

1360
Solar constant

\( + 2.8 \) Forcing
HOW MUCH WARMING IS EXPECTED?

Steady-state change in global mean surface temperature = Climate sensitivity × Forcing

\[ \Delta T = S \times F \]

S is “equilibrium” sensitivity. Units: K/(W m\(^{-2}\))

Sensitivity is commonly expressed as “CO\(_2\) doubling temperature”

\[ \Delta T_{2\times} \equiv S \times F_{2\times} \]

where \( F_{2\times} \) is the “CO\(_2\) doubling forcing” ca. 3.7 W m\(^{-2}\).
Earth’s Radiation Budget and the Greenhouse Effect

- **1360 Solar constant**
- **340 1/4 solar constant**
- **240 Radiative Fluxes in W m⁻²**
- **255 K**
- **70.6% = 1 - \( \alpha \)**
- **Emissivity \( \varepsilon = 240/385 = 0.61 \)**
- **J = \( \sigma T^4 \)**
- **T = (J/\( \sigma \))^{1/4}**
- **Stefan-Boltzmann Radiation law**
- **Albedo \( \alpha = 29.4\% \)**
- **Co-albedo \( \gamma = 1 - \alpha = 0.706 \)**
- **Greenhouse effect**
- **H₂O, CO₂, CH₄...**
- **385 \( \approx \) 287 K**
- **Latent heat 88**
- **Sensible heat 21**

Radiative Fluxes:
- **100**
- **47**
- **162**
- **13**
- **31**
- **302**

Atmosphere
ENERGY BALANCE MODEL OF EARTH’S CLIMATE SYSTEM

Global energy balance:
\[ \frac{dH}{dt} = Q - E = \frac{\gamma J_S}{4} - \varepsilon \sigma T_s^4 \]

- \( T_s \) is global mean surface temperature
- \( H \) is global heat content
- \( Q \) is absorbed solar energy
- \( E \) is emitted longwave flux
- \( J_S \) is solar constant
- \( \gamma \) is planetary co-albedo
- \( \sigma \) is Stefan-Boltzmann constant
- \( \varepsilon \) is effective emissivity

At radiative steady state:
\[ \frac{\gamma J_S}{4} = \varepsilon \sigma T_s^4 \]

- \( \gamma = 1 - \alpha \approx 0.7 \)
- \( \varepsilon = \frac{\gamma J_S}{\sigma T_s^4} \)

For \( T_s = 288 \) K, \( \varepsilon \approx 0.61 \)
NO FEEDBACK
CLIMATE SENSITIVITY

In absence of feedbacks $\gamma$ and $\varepsilon$ do not depend on $T_s$

Change in emitted flux per change in temperature:

$$\frac{dE}{dT_s} = \frac{d(\varepsilon \sigma T_s^4)}{dT_s} = 4 \varepsilon \sigma T_s^3 = \frac{4}{T_s} E = \frac{4}{T_s} \frac{\gamma J_s}{4} = \frac{\gamma J_s}{T_s}$$

No-feedback sensitivity: $S_{NF} \equiv \frac{dT_s}{dQ} = \frac{dT_s}{dE} = \left( \frac{dE}{dT_s} \right)^{-1} = \frac{T_s}{\gamma J_s}$

$J_s = 1360 \text{ Wm}^{-2}$; $T_s = 287 \text{ K}; \gamma = 0.7$;

$S_{NF} = 0.30 \text{ K/}(\text{Wm}^{-2})$

$$\Delta T_{2x} = F_{2x} S_{NF} = 3.7 \text{ Wm}^{-2} \times 0.30 \text{ K/}(\text{Wm}^{-2}) = 1.1 \text{ K}$$
Water Vapor Feedback: Pretty Well Understood

Higher temperature, More water vapor. More infrared is absorbed

Positive Feedback
Higher Sensitivity
Higher temperature, Clouds evaporate. More sunlight is absorbed

Higher temperature, More water vapor, More clouds. Less sunlight is absorbed

Positive Feedback Higher Sensitivity

Negative Feedback Lower Sensitivity
Despite extensive research, climate sensitivity remains \textit{highly uncertain}. 
Current estimates of Earth’s climate sensitivity are centered about a CO$_2$ doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty. Range of sensitivities of current models roughly coincides with IPCC “likely” range.
• Why is there such a large range of sensitivities in current climate models and why hasn’t this situation improved much in thirty years?

ANSWER

• This is a really tough scientific problem!
A REALLY TOUGH SCIENTIFIC PROBLEM

• Determine the consequences of a systematic change of less than 1% in a quantity that is highly variable in time and space applied to a noisy dynamic system.

• Right now we do not even know the sign of how much more CO₂ can be added to the atmosphere without committing Earth to a temperature increase ≥ 2° C.

• Even at the low end of the climate sensitivity range, expected temperature increase from long-lived greenhouse gases ~ 1.4 °C, the consequences would be severe.

• Why has Earth not warmed up the expected amount, 1.4 to 3.2 °C? We don’t know, but that’s another lecture.