Earth’s Energy Balance: Climate Change Workshops

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Earth’s Radiative Energy Budget Related to SORCE
20-22 Sept 2006, Orcas Island, WA
Energy Balance Workshops

We are developing a progressive series of workshops for calculating Earth’s radiative energy budget in a climate change classroom. A solar physicist and a biological oceanographer will co-teach an integrated undergraduate program in fall 2006. In Fire and Water, teams of students will analyze classical and open questions to better understand mechanisms regulating Earth’s climate. What would Earth’s equilibrium temperature be without a greenhouse effect? What is the effect of clouds on the atmospheric radiation budget? How does inclusion of ocean and ice albedo change this equilibrium? How do variables such as phytoplankton abundance and growth contribute to climate regulation? How can effects of the biosphere be quantified for radiation budget calculations?

We hope to include data and methods learned at this meeting in some of our more advanced workshops.
Over geologic time the Earth has experienced wide fluctuations in climate, such as ice ages. Earth is currently experiencing a rapid warming trend. A major factor determining global climate is the intensity of the Sun's energy reaching the Earth. However, climate changes cannot be explained by variations in solar radiation alone. Climate changes involve complex interactions between astronomical and Earth-bound processes. This program will examine some of these interactions. Specifically, we will examine how the Sun's output has varied over geologic time and recently. We will also examine how the oceans impact global climate by redistributing the Sun's energy and affecting the composition of the atmosphere. We will discuss how changes in ocean circulation may explain climatic changes over geologic time. We will also study how marine microorganisms play a major role in the cycling of gases that affect climate. Finally, we will discuss contemporary global warming, examining the contribution of human activities and fluctuations in solar output. We will critique proposed schemes to engineer solutions to global warming such as the sequestration of anthropogenic carbon into the deep sea.

Our study will examine various physical, chemical, geological and biological processes. This requires a basic understanding of biology and chemistry as well as facility with algebra and an ability to learn pre-calculus. The material will be presented through lectures, workshops, laboratories and seminars. We will draw on the primary literature whenever possible for a rigorous scientific treatment of this topic. Students will do significant teamwork and will research in depth questions of particular interest. We will have weekly online assignments, so students should be comfortable using computers and the Internet.

Credit awarded in introductory physics, earth science, marine science, and environmental studies.

http://academic.evergreen.edu/curricular/fireandwater/

Climate Change Workshops, Zita + Chin-Leo, SORCE, Sept 2006, Orcas Island, WA
Goldilock Hypothesis: Earth is just the right distance from Sun?

Venus is close to Sun

Earth is intermediate distance from Sun

Mars is far from Sun

TOO HOT

JUST RIGHT

TOO COLD

(distances not to scale!)
Q0: What would be Earth’s equilibrium temperature without an atmosphere?

Thermal equilibrium:

Power received from Sun = Power emitted by Earth

\[ \pi R_{\text{Earth}}^2 S = 4\pi R_{\text{Earth}}^2 \sigma T^4 \]

where \( S \) = solar intensity at Earth = 1370 W/m\(^2\) and the Boltzmann constant \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \)

\[ \sigma T^4 = S/4 \]

Q0: What would be Earth’s equilibrium temperature without an atmosphere?

\[ s \, T^4 = \frac{S}{4} \rightarrow T = \sqrt[4]{\frac{S}{4\sigma}} = \sqrt[4]{\frac{1370 \, \frac{W}{m^2}}{4 \times 5.67 \times 10^{-8} \, \frac{W}{m^2 K^4}}} = 279 K \sim -6^\circ C \]

Reality check: This is very cold! And we have neglected a big effect – Earth’s atmosphere reflects a significant amount of the Sun’s incoming radiation. What do you predict we will find for the Earth’s equilibrium temperature if we take cloud reflection into account? A warmer or colder planet?
Hypothesis 1: Clouds warm Earth
Hypothesis 2: Clouds cool Earth

Both are partly right…
Q1: What would be Earth’s equilibrium temperature with reflective clouds?

Power absorbed by Earth = Power emitted by Earth

Power emitted by Earth = $4\pi R_{\text{Earth}}^2 \sigma T^4$

Power absorbed by Earth =

Power received from Sun – Power reflected by clouds, …

Power received from Sun = $\pi R_{\text{Earth}}^2 S$
Q1: What would be Earth’s equilibrium temperature with reflective clouds?

Power reflected = Power received * (reflectivity, or albedo)

\[ = \pi R_{\text{Earth}}^2 S * (A= \text{albedo}) \]

So **Power absorbed** = Power received – Power reflected

\[ = \pi R_{\text{Earth}}^2 S - \pi R_{\text{Earth}}^2 S * A = \pi R_{\text{Earth}}^2 S (1-A) \]

Put it all together:  Power absorbed = Power emitted

\[ \pi R_{\text{Earth}}^2 S (1-A) = 4\pi R_{\text{Earth}}^2 \sigma T^4 \]

Simplify:

\[ \sigma T^4 = S (1-A) / 4 \]
Q1: What would be Earth’s equilibrium temperature with reflective clouds? \( \sigma T^4 = S \frac{(1-A)}{4} \)

\[
T = \sqrt[4]{\frac{S}{4\sigma}} (1 - A) = \sqrt[4]{\frac{1370 \frac{W}{m^2}}{4 \times 5.67 \times 10^{-8} \frac{W}{m^2 K^4}}} \left(1 - 0.3\right) = 255 K \sim -18^\circ C = 0^\circ F
\]

Reality check: The Earth is not really this cold! Its average surface temperature is actually about \( T = 15^\circ C \). What’s missing from this model? Brainstorm ideas, and we will analyze some of them quantitatively.
Q2: What effect do greenhouse gases have on Earth’s equilibrium temperature?

Clouds do not merely reflect and transmit solar radiation – they also absorb Earth’s thermal radiation and re-radiate, especially in longer wavelengths.

One-layer model: Assume the atmosphere absorbs all the Earth’s radiation, and re-radiates half of it back down to Earth (and half out to space), at an equilibrium temperature \( T_e \).

Find Earth’s Surface temperature \( T_s \).
Q2: What effect do greenhouse gases have on Earth’s equilibrium temperature?

At Earth’s surface,
\[ \sigma T_s^4 = S' + \sigma T_e^4 \]

radiated by Earth = received from Sun + received from Atmosphere
Q2: What effect do greenhouse gases have on Earth’s equilibrium temperature?

Eliminate $\sigma \, T_e^4$ from the two equations and solve for Earth’s $T_s$:

$$\sigma \, T_s^4 = 2 \, S' \quad \rightarrow$$

$$T_s = 4 \sqrt[4]{\frac{2S}{4\sigma}} (1 - A) = 4 \sqrt[4]{\frac{1370 \frac{W}{m^2}}{2 \times 5.67 \times 10^{-8} \frac{W}{m^2 K^4}}} (1 - 0.3) = 303K = 30^\circ C$$

Reality check: This is certainly warmer – in fact it is about 15º C too warm.

What’s missing from this improved model? Brainstorm ideas, and we will analyze some of them quantitatively. This is how science progresses – by gradually improving simple models and getting closer and closer approximations to nature’s reality.
Q3: What if the atmosphere also transmits some of Earth’s radiation?

We found that the Earth is too cold without greenhouse gases, and too warm with them. What’s missing?

Two-layer model: The atmosphere actually does not absorb all of Earth’s radiation – it transmits some of it out into space. This imperfect insulator should result in a slightly cooler surface temperature for the planet.

We can quantify this effect by saying the atmosphere absorbs a fraction $a$ of the Earth’s radiation ($E = \sigma T_s^4$), and transmits the rest $(1-a)$. Meanwhile, the atmosphere continues to radiate with an intensity $R = \sigma T_e^4$. Let’s see how this changes the results of our thermal equilibrium energy balance analysis.
Solving any two equations, we find that

\[
a = 2 \left(1 - \frac{S'}{E}\right) = 2 \left(1 - \frac{240}{390}\right) = 0.77
\]

assuming \(T_s = 288K\).

This means that 23% of Earth’s radiation must be transmitted out into space by the insulating atmosphere, if this two-layer model fully explains why the Earth’s surface temperature currently averages about 288K. What other factors might be involved?
Q4: What is the effect of ocean and ice albedo on Earth’s global energy balance?

We actually included some reflection (r) from the Earth’s surface in our original albedo term (A). Surface albedo is complicated, however, by several factors, including (1) seasonal changes and (2) positive feedback effects.
Planetary albedo changes through the seasons

by Sanjay Limaye and Rosalyn Pertzborn, University of Wisconsin (http://www.earthscape.org/t1/lis01/lis01aa.html)
Earth’s longwave radiation

by Sanjay Limaye and Rosalyn Pertzborn, University of Wisconsin (http://www.earthscape.org/t1/lis01/lis01aa.html)
Net Radiation Balance

by Sanjay Limaye and Rosalyn Pertzborn, University of Wisconsin (http://www.earthscape.org/t1/lis01/lis01aa.html)
Ice-albedo feedback

http://www.bbc.co.uk/portuguese/especial/1126_clima/page4.shtml
Positive feedback destabilizes Earth system

Negative feedback stabilizes Earth system
Global energy balance:
a partial summary

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Gaia hypotheses: Biota help regulate Earth’s climate

Ex: Faint young Sun Paradox
Q5: How do phytoplankton contribute to climate regulation?

Plankton contribute to absorption and emission of CO$_2$, cloud formation, ocean albedo, and more.

Coccolithophores under the Scanning Electron Microscope

http://oceanworld.tamu.edu/NMEA_Talk/
Phytoplankton → ocean albedo

Coccolithophore bloom off the Coast of Brittany: Due to their unusually high reflectivity, “special algorithms have been developed specifically for the remote-sensing detection of coccolithophorid blooms in the ocean. If the data indicates the presence of such a bloom, the data is [flagged to note] this anomalous condition.”

http://visibleearth.nasa.gov/view_rec.php?id=705

http://disc.gsfc.nasa.gov/oceancolor/scifocus/classic_scenes/12_classics_blooms.shtml
Phytoplankton production is an important sink of atmospheric CO$_2$. Sinking of phytoplankton biomass below the pycnocline ("biological pump") removes CO$_2$ from atmospheric circulation.

Biological factors (production, predation, decomposition) and physical/chemical factors (density stratification, acidity of the ocean, wind speed, etc.) affect the efficiency of the biological pump. [www.msre.sunysb.edu/octet/BP_Fig_1.gif](www.msre.sunysb.edu/octet/BP_Fig_1.gif)
Phytoplankton → sulfur compounds → cloud formation

Marine algae produce dimethylsulfoniopropionate (DMSP), which is converted to dimethylsulfide (DMS) by phytoplankton and bacterial enzymes during decomposition. DMS then enters the atmosphere where it is photo-oxidized to sulfate aerosols. DMS accounts for 95% of the natural marine input of sulfur gases to the atmosphere, and about 50% of the total global biogenic source of sulfur to the atmosphere. Sulfur compounds act as cloud condensation nuclei.
Solar/atmosphere/ocean/biota interactions
SUMMARY

• In Q0, we found that **without an atmosphere**, Earth’s equilibrium temperature would be about 279 K, or 9º C **too cold**.

• In Q1, we found that an Earth with **reflective clouds** but no greenhouse gas trapping was about 255 K, or 33º C too cold.

• In Q2, we found that an Earth with reflective clouds and an insulating layer of **greenhouse gas** atmosphere was about 15º C **too warm**. (One-layer model)

• Two-layer model: If the atmosphere is an **imperfect insulator**, transmitting about 23% of Earth’s radiation into space, this yields Earth’s **observed temperature** of 288 K.

• **Positive feedback** tends to warm Earth: melting ice decreases albedo; increased water vapor increases greenhouse effect.

• **Negative feedback** stabilizes: warmer Earth radiates more.

• **Biota** such as plankton also contribute to ocean albedo, atmospheric composition, and cloud formation, all of which **have impacts on the global energy balance**.
Energy balance and climate change workshops


Evergreeners studying phytoplankton in local estuaries
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References and sources of figures

Shindell et al. (http://www.people.virginia.edu/~Emem6u/ssmrw02.html)


ETE team (http://www.cotf.edu/ete/modules/coralreef/CRatmo.html)


Atelier Changement Climatique, ENPC (http://www.enpc.fr/fr/formations/ecole_virt/trav-eleves/cc/cc0304/cycle-carbone/cycle-carbone.htm)


Scott Rutherford, Roger Williams Univ., RI, Milankovitch Cycles in Paleoclimate, (http://deschutes.gso.uri.edu/~rutherfo/milankovitch.html)

E.J. Zita, solar physics research at Evergreen and HAO/NCAR http://academic.evergreen.edu/z/zita/research.htm, http://www.hao.ucar.edu/
Background concepts

Thermohaline cycle

Fluid flows and energy flux

Milankovitch cycle

- Eccentricity Cycle (100 k.y.)
- Obliquity Cycle (41 k.y.)
- Precession of the Equinoxes (19 and 23 k.y.)