CO_2, Hothouse and Snowball Earth

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Seminar in Mathematics and Climate

MATH 392-01 Spring 2018

February 6 and 8, 2018

Lecture Outline

- The Keeling Curve and the Earth's climate history
- The long- and short-term carbon cycles and silicate weathering
- The Snowball Earth hypothesis
- Modeling the transition between extreme climate states

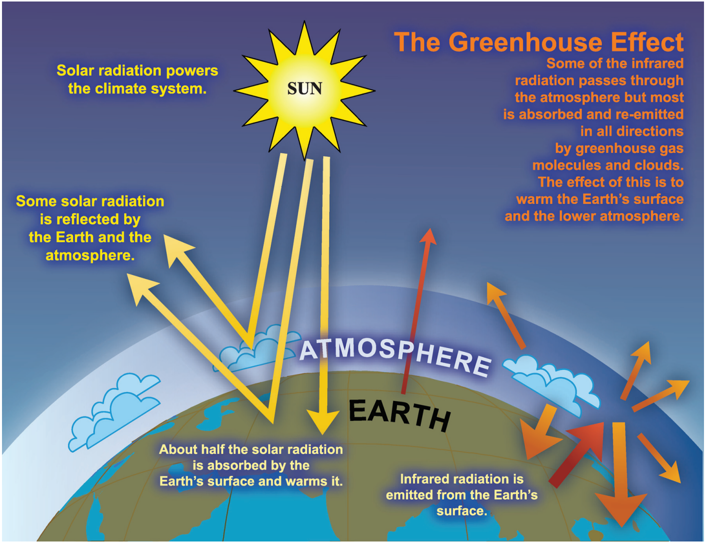

Figure: The Greenhouse Effect. Source: "Historical Overview of Climate Change Science," IPCC AR4, (2007) p. 115.

The Greenhouse Effect

- Energy from the Sun reaches the Earth in short wavelengths, mostly in the visible spectrum (e.g., ultraviolet). About half of this is absorbed by the Earth's surface (land and oceans).
- In order to achieve energy balance, the Earth radiates this energy back. But since the Earth is much colder than the Sun, it radiates energy in much longer wavelengths (infrared spectrum).
- Due to their chemical properties, greenhouse gases (water, CO_2, methane) increase the ability of the atmosphere to absorb radiation in the infrared spectrum. Parts of this radiation are then re-emitted back toward the Earth, warming the planet.
- Without the greenhouse effect, the Earth's average surface temperature would be well below the freezing point of water (Climate Model #2 predicts -18.25°C).

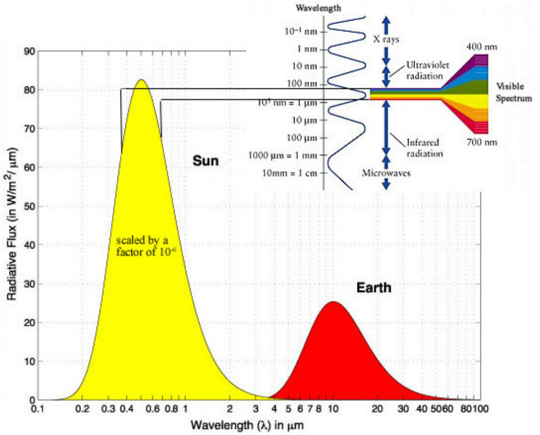

Figure: The electromagnetic spectrum indicating the frequency differences between the Earth and Sun. Source: Yochanan Kushnir
https://www.learner.org/courses/envsci/visual/visual.php?shortname=electromagnetic_spectrum

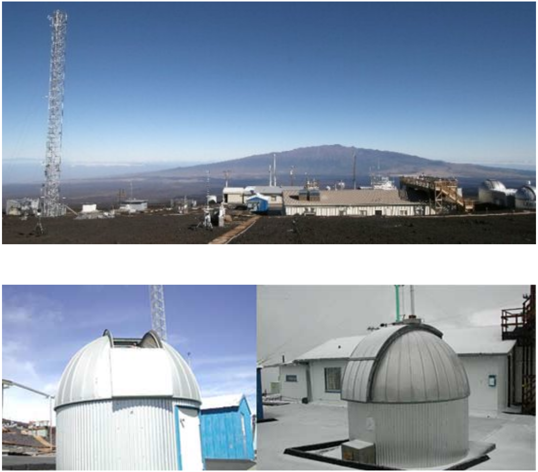

Figure: The Mauna Loa Observatory located on Mauna Loa Volcano on Hawaii Island. The observatory consists of 10 buildings from which up to 250 different atmospheric parameters are measured by a complement of 12 NOAA/ESRL and other agency scientists and engineers.

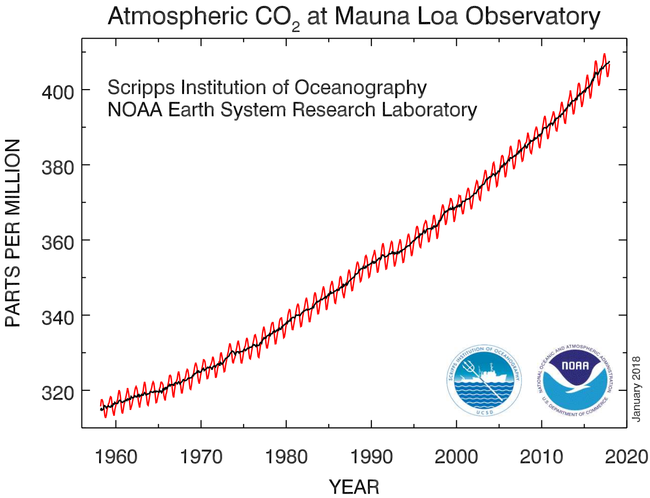

Figure: The Keeling Curve. CO_2 concentrations (red) measured from the Mauna Loa Observatory in Hawaii from March 1958 to January 2018. Seasonally corrected data shown in black.

The Keeling Curve

- Measurements of carbon dioxide (CO_2) concentrations in the atmosphere recorded at the Mauna Loa Observatory
- Study began by Charles David Keeling (1928–2005) of the Scripps Institution of Oceanography in 1958; now run by his son Ralph Keeling. Methane measurements began in 1983.
- Remote location ideal because measurements are not impacted by local vegetation or human activity, and wind patterns bring well-mixed air samples. Even though it is near a volcano (which would tend to increase CO_2 concentrations), the prevailing winds suppress this effect.
- Air samples taken hourly, every day, with the same measuring method, for 60 years. “The most important data set in modern climate research.”
- Regression analysis with a quadratic fit indicates a positive second derivative.

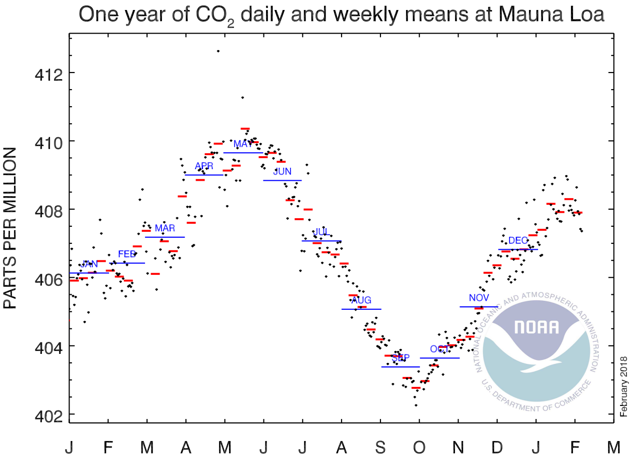

Figure: CO_2 concentrations over the course of 2017 indicate a maximum in May and a minimum at the end of September. Why? Red bars are weekly means; blue bars are monthly averages.

Ice Cores

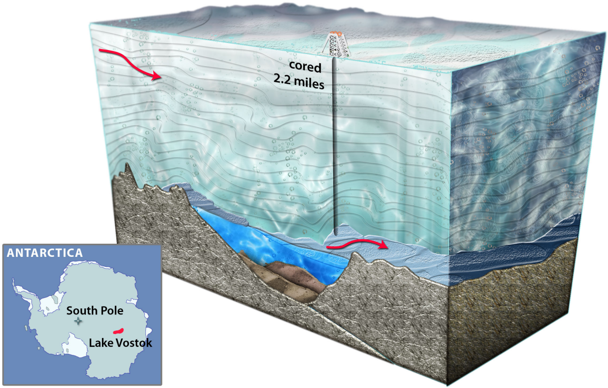

Figure: Some ice cores contain ice 800,000 years old (carbon dating). The proportions of different oxygen and hydrogen isotopes help reconstruct ancient temperatures; air trapped in bubbles can be analyzed to determine past levels of greenhouse gases.

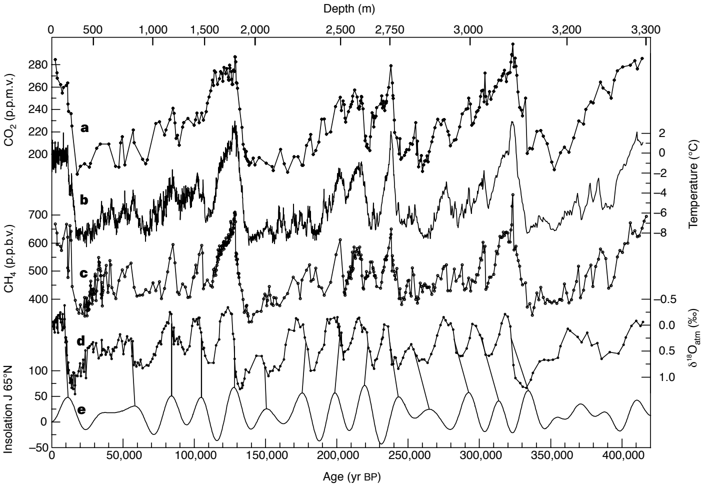

Figure: Time series data from ice core samples in Lake Vostok, Antarctica. **a** = CO2, **b** = Antarctic temp. changes , **c** = Methane. Source: “Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica,” Petit, et. al., *Nature* **399**, June 3, 1999, pp. 429–436.

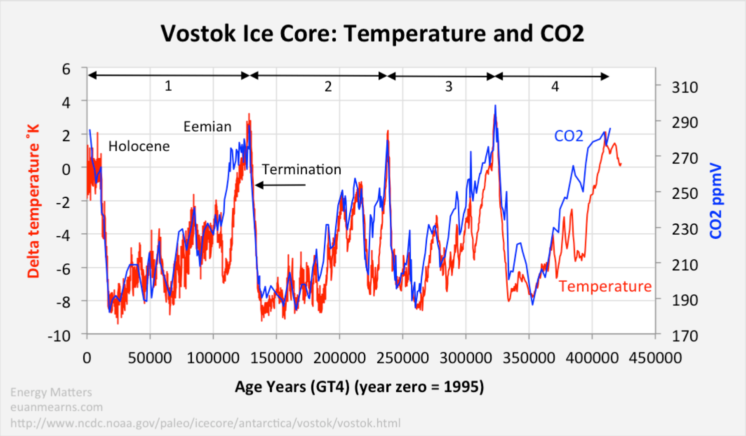

Figure: Very strong correlation between temperature and CO2 concentrations from the Vostok ice core data. Concentrations over the last 420,000 years range from 185 to 300 ppmV (parts per million by volume).

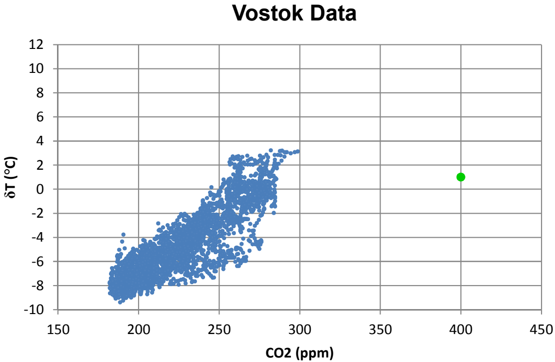

Figure: A scatter plot of the temperature change versus CO_2 concentration for the Lake Vostok data, showing a clear correlation between temperature and CO_2 (Petit, et. al., *Nature* **399**, June 3, 1999, pp. 429–436). The green dot represents current conditions. Figure Source: Dick McGehee, Univ. of Minnesota and MCRN, lecture slides.

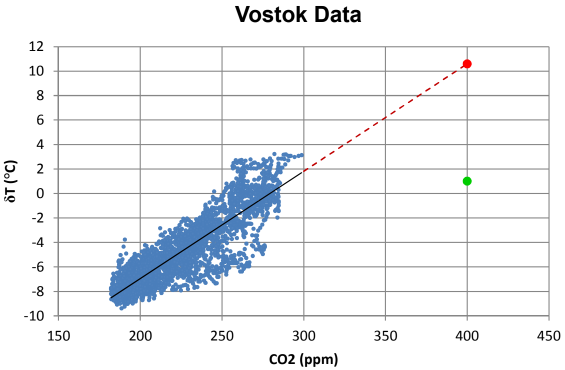

Figure: A naive linear extrapolation indicates a temperature rise of over 10°C!
Figure Source: Dick McGehee, Univ. of Minnesota and MCRN, lecture slides.

CO_2 concentrations over the last 800,000 years

Source: NOAA Earth System Research Library, Global Monitoring Division

https://www.esrl.noaa.gov/gmd/ccgg/data-products.html

Click Here

Excellent resource for data and graphs on CO_2 and Methane averages, a Greenhouse Gas Index, CO_2 tracker, etc.

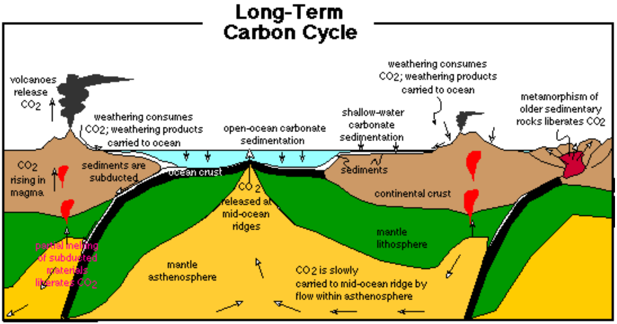

Figure 7.3. Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation exracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly — if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

Figure: Figure source: `http://www3.geosc.psu.edu/~dmb53/DaveSTELLA/Carbon/long_term_carbon.htm`

Long-Term Carbon Cycle

- Cycle occurs over time scales on the order of 100,000 to a million years.
- Carbon dioxide is added to atmosphere through volcanic activity on land and at mid-ocean ridges (e.g., Pacific rim, hot springs at Yellowstone National Park).
- Rain brings CO_2 down into the oceans forming carbonate sediments (limestone).
- Shifting of plate tectonics (continental drift) causes sediments to heat up, releasing CO_2 back into the atmosphere.

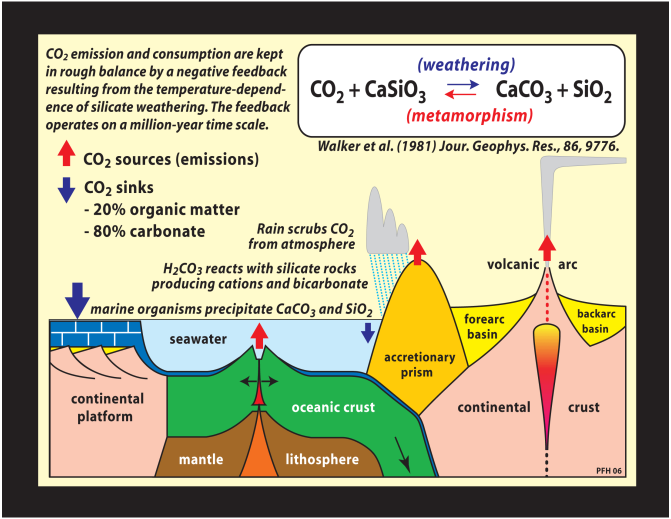

Figure: The long-term Carbon cycle — a million-year feedback loop.

Silicate Weathering

A negative feedback loop or thermostat to help control the Earth's temperature

- Rainwater containing dissolved CO_2 falling on silicate rocks (granite, feldspar) replaces a silicon atom with a carbon atom, eventually producing calcium carbonate (limestone, marble) and silicon dioxide (quartz). This is known as silicate weathering.

$$CO_2 + CaSiO_3 \longrightarrow CaCO_3 + SiO_2$$

  CO_2 (gas) replaced by SiO_2 (rock)

- Due to volcanic activity and intense heat, the carbon atom in calcium carbonate gets replaced by the silicon atom and the CO_2 gets released, completing the long-term carbon cycle.

$$CaCO_3 + SiO_2 \longrightarrow CO_2 + CaSiO_3$$

- The entire process is temperature dependent: speeds up for warmer temp.; slows down for cooler temp.

Earth's Climate in the Cenozoic Era

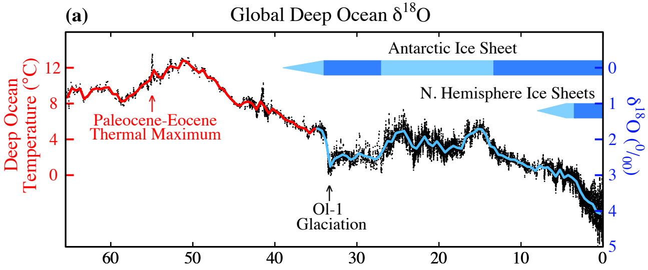

Figure: Oxygen isotope records for foraminifera shells found in deep ocean sediment cores provide a temperature record for the past 65 million years (Cenozoic era). Source: Hansen, et. al., "Target Atmospheric CO_2: Where Should Humanity Aim?" *The Open Atmospheric Science Journal* **2** (2008), pp. 217–231.

Earth's Climate in the Cenozoic Era

- We have good geological records of the Earth's climate (100 mya) from measuring oxygen isotopes (δ^{18}O) in the deep ocean sediment cores. CO_2 records only date back 800,000 years.
- From 65–35 mya, the Earth was a hothouse with no polar ice caps. Small mammals and rodents exist, (e.g., mice, rabbits). Warm period confirmed by the spread of warm-adapted plants and mammals into high latitudes, as well as magnesium/calcium ratios in marine fossil shells.
- About 35 mya, for reasons not well understood, Earth shifted dramatically into a glacial cooling period. One theory is that Asia and India collided, forming the Himalayas and Tibetan plateau. The newly formed mountains absorbed huge amounts of CO_2 through silicate weathering, thus reducing the greenhouse effect dramatically and cooling the planet enough for ice sheets to begin to form.

Target CO_2 Level?

"Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects." — Hansen, et. al., "Target Atmospheric CO_2: Where Should Humanity Aim?" *The Open Atmospheric Science Journal* **2** (2008), pp. 217–231.

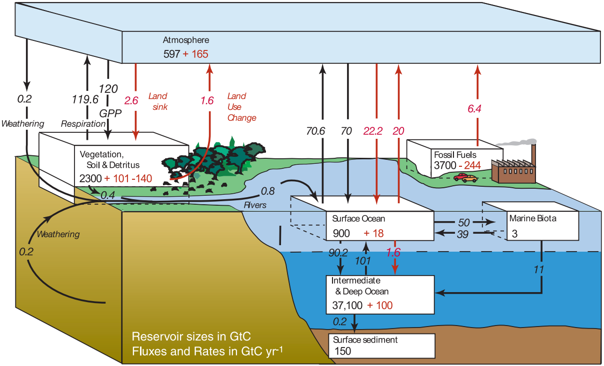

Figure: The short-term carbon cycle indicating anthropogenic (human) impacts (red) versus the natural biological and chemical weathering processes (black). Rates are given in gigatons of carbon per year. Source: Couplings between changes in the climate system and biogeochemistry, IPCC AR4 (2007), p. 515.

How Do We Know Human's Are Responsible?

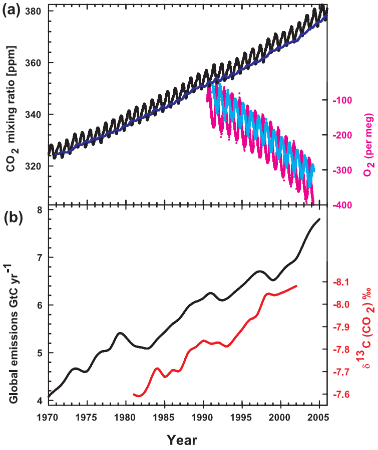

Figure: Carbon isotope ratios and atmospheric oxygen depletion (as a result of oxidizing carbon) indicates that increases in CO_2 in the atmosphere are caused by the burning of fossil fuels. Source: Changes in atmospheric constituents and in radiative forcing, IPCC AR4 (2007), p. 138.

How Do We Know Human's Are Responsible?

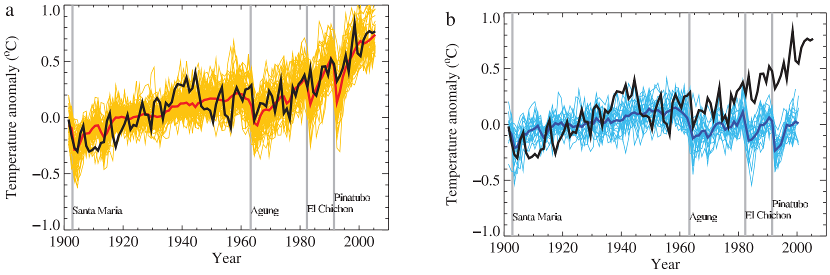

Figure: Results of Atmoshpere-Ocean General Circulation Model (AOGCM) simulations with (a) and without (b) human activity. Actual data is in black; anthropogenic and natural forcings are in red; natural forcings alone are in blue. All data represent global mean temperature anomalies relative to 1901–1950. Results in (a) are from 58 simulations from 14 models; (b) contains 19 simulations from 5 models. Major volcanic activity indicated by vertical gray lines. Source: Understanding and attributing climate change, IPCC AR4 (2007), p. 684.

Summary

- The greenhouse effect is required to keep the Earth at a habitable temperature.
- We have excellent records of CO_2 concentrations over the past 800,000 years, recently from observatories such as Mauna Loa, and historically from ice core data. The ice core data reveal a strong correlation between the amount of greenhouse gases in the atmosphere and the temperature.
- A long-term carbon cycle exists from natural processes (volcanoes, silicate weathering) that serves as a thermostat for global temperature. It acts on very long time scales.
- Over the past 420,000 years, CO_2 concentrations have been in the range 185–310 ppmV. Now they are over 400 ppmV and climbing, resulting in a 1°C rise in temperature over the 20th century mean. There is very strong evidence that human activity (e.g., burning of fossil fuels) is responsible for this.

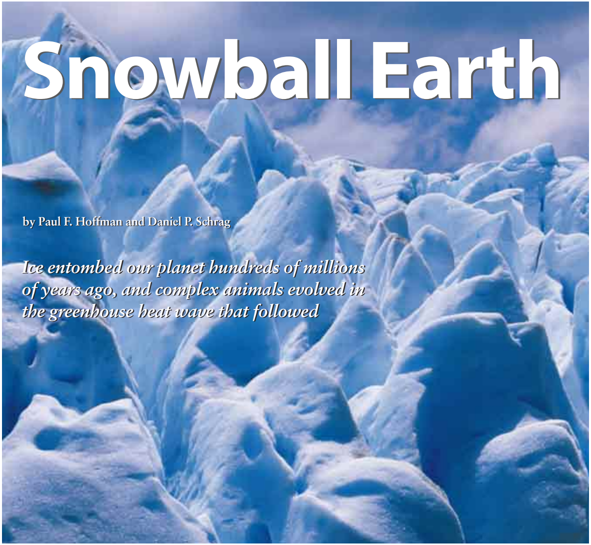

Figure: Paul F. Hoffman and Daniel P. Schrag, *Scientific American*, January 2000, pp. 68–75.

Fire and Ice

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

—Robert Frost,
Fire and Ice (1923)

Snowball Earth Champions

Figure: Hoffman (right) and Schrag (left) at their field site in Namibia studying rocks from the Neoproterozic era (1000–540 Mya). The light-colored boulder likely traveled within a glacier during a runaway snowball event and fell to the muddy seafloor when the ice melted. Both at Harvard, Hoffman is a field geologist with a long and storied career of studying ancient rocks while Schrag is a geochemical oceanographer who studies the chemical and isotopic variations of coral reefs, deep-ocean sediments, and carbonate rocks. (Hoffman and Schrag, “Snowball Earth,” *Scientific American*, Jan. 2000, p. 70)

Snowball Earth Theory

- Around 740 and 635 Mya, glaciers covered nearly all of the Earth's surface. Evidence comes from ancient rocks and glacial debris found near sea level in the tropics. Glaciers near the equator can only exist at 5,000 meters above sea level (or higher).
- Ice and snow have a much higher rate of reflectivity (albedo) than do water and land. The more ice on the planet, the higher the albedo and thus less energy is received by the Earth (less E_{in}). This creates an ice-albedo feedback that can overwhelm the greenhouse effect and drive the planet toward a snowball state.
- During this time period, the continents were clustered around the equator. Thus, silicate weathering was allowed to continue unabated as the glaciers slowly moved towards the equator. This meant CO_2 was continually being pulled from the atmosphere as the temperatures dropped.

EARTH'S LANDMASSES were most likely clustered near the equator during the global glaciations that took place around 600 million years ago. Although the continents have since shifted position, relics of the debris left behind when the ice melted are exposed at dozens of points on the present land surface, including what is now Namibia (*red dot*).

Figure: During the runaway snowball events, Earth's continents were clustered around the equator. (Hoffman and Schrag, "Snowball Earth," *Scientific American*, Jan. 2000, p. 70)

Escaping Snowball

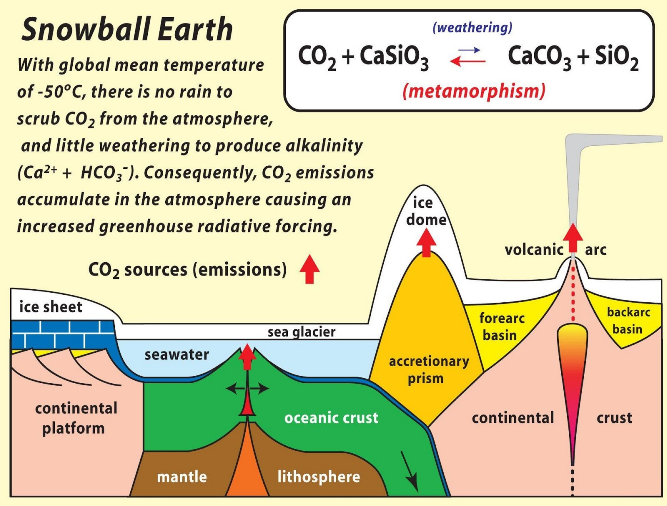

Figure: Koh Xuan Yang, Beyond Earthly Skies (Blog), http://beyondearthlyskies.blogspot.com/2013/09/snowball-earth-thawing-snowball.html

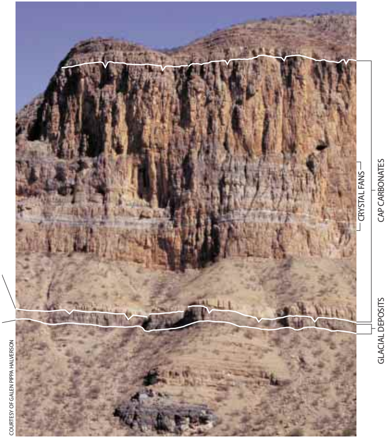

Figure: Pure carbonate layers, typically found in shallow, warm waters, situated directly above the glacier rocks are evidence of an ensuing hothouse. The crystal fans suggest a rapid carbonate accumulation. Sudden variation in the carbon isotopes also supports the relatively rapid transition from snowball to hothouse.

Escaping Snowball

- The snowball state would last around 10 million years! Huge amounts of CO_2 would build up from volcanoes enabling the greenhouse effect to warm the planet enough for the ice to melt near the equator.
- Open water forming in the tropics absorbs more solar energy, helping to accelerate the increase in global temperatures. Now the ice-albedo effect works in the opposite direction: less ice and more water means a lower albedo and more solar radiation being absorbed by the planet.
- Global temperatures rise so quickly ("in a matter of centuries?!") that the effect of silicate weathering is not enough to halt a runaway path to a hothouse planet.

Life Finds a Way

- One of the major objections to Snowball Earth comes from biologists: how could life have survived?
- Microbes have been discovered on seafloor hot springs that thrive on chemicals rather than sunlight. Cold-loving organisms have been found in cold and dry mountain valleys in East Antarctica. Cyanobacteria and some types of algae can survive in snow, porous rock, and in dust particles.
- The 11 animal phyla (our genetic ancestors) all emerged from the time period of the last snowball event, known as the Cambrian explosion.
- "Ironically, the long periods of isolation and extreme environments on a snowball earth would most likely have spurred on genetic change and could help account for this evolutionary burst." — Hoffman and Schrag

Dynamical Systems View of the Transition Between Climate States

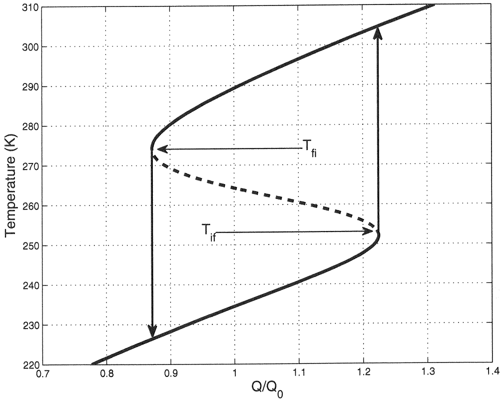

Figure 2.6. *Mean surface temperatures at equilibrium as a function of the solar constant (in units of its present value).*

Figure: Bifurcation diagram indicating possible transition scenarios between steady states. Source: Kaper and Engler, *Mathematics and Climate*, SIAM (2013), p. 22.