

# CO<sub>2</sub>, Hothouse and Snowball Earth

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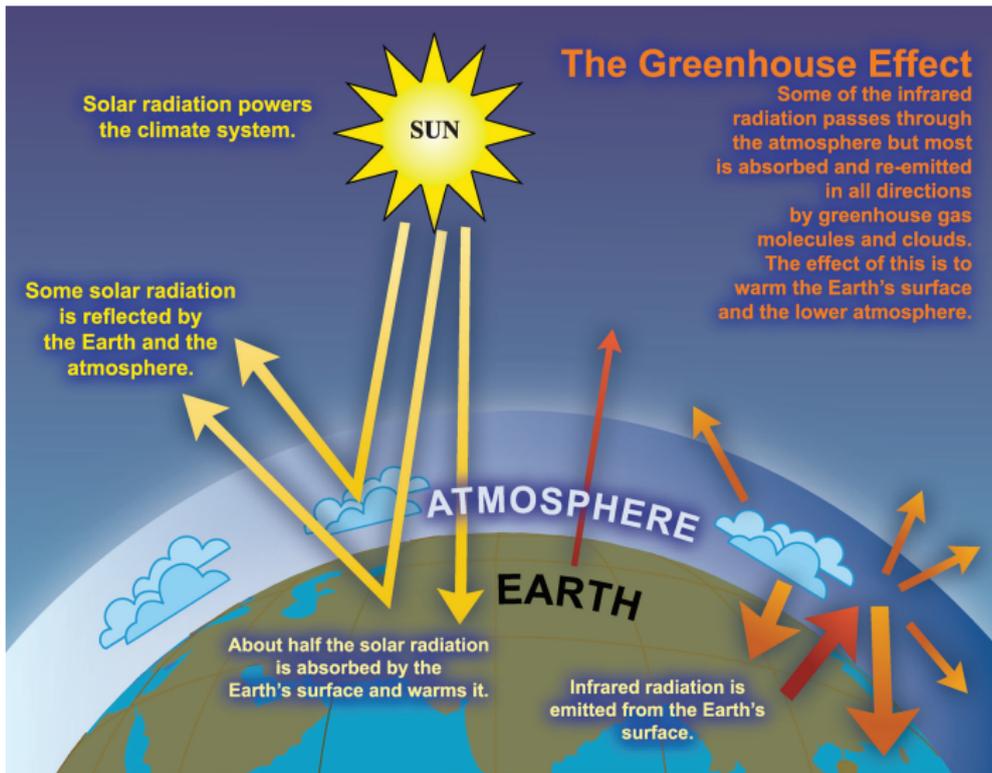
*Mathematical Models*

MATH 303 Fall 2018

November 12 and 14, 2018

## Lecture Outline

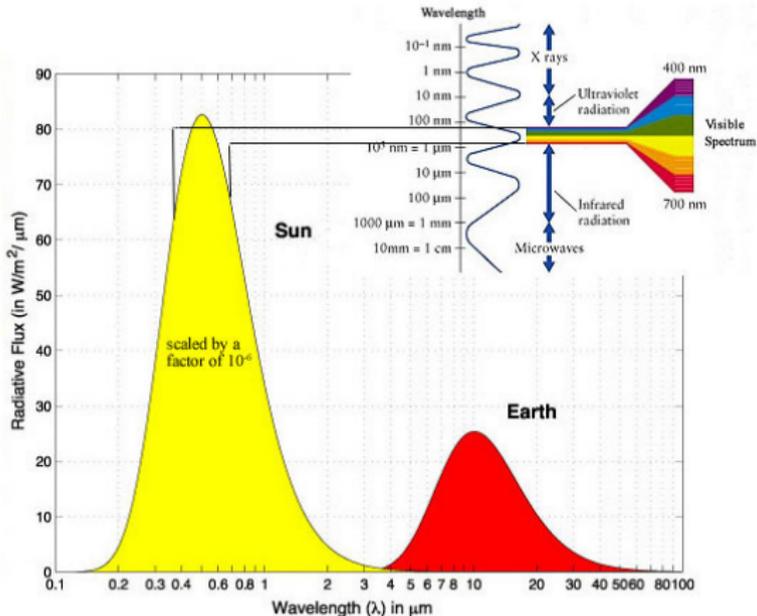
- The Greenhouse Effect
- The Keeling Curve and the Earth's climate history
- Consequences of Global Warming
- The long- and short-term carbon cycles and silicate weathering
- The Snowball Earth hypothesis



**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<sub>2</sub>, 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 from Lab #3 predicts  $-18.24^{\circ}\text{C}$ ).

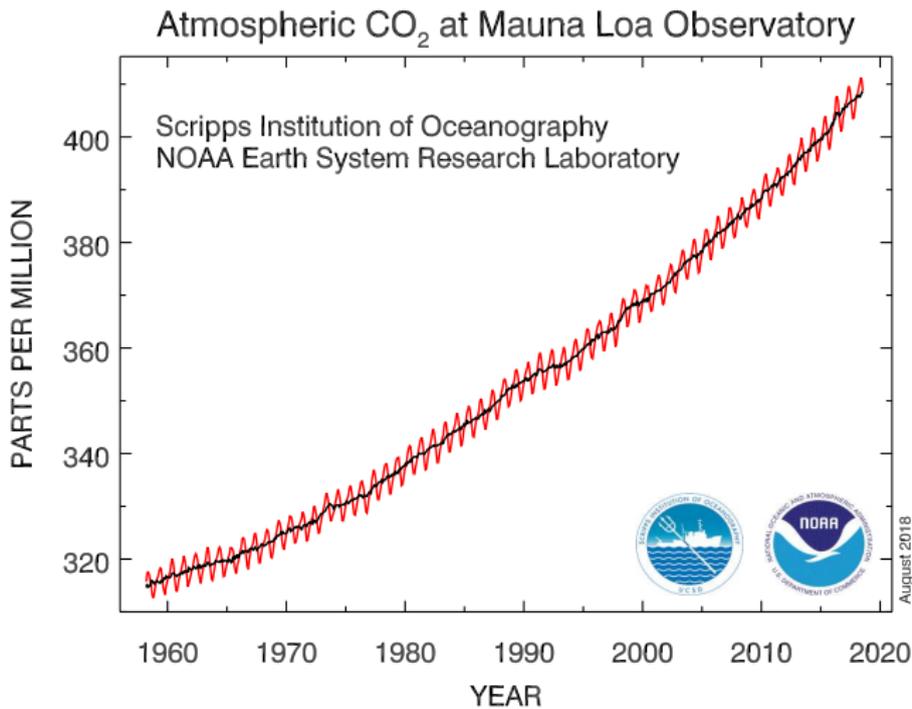


**Figure:** The electromagnetic spectrum indicating the frequency differences between the Earth and Sun. Source: Yochanan Kushnir

[https://www.learner.org/courses/envsci/visual/visual.php?shortname=electromagnetic\\_spectrum](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 group of 12 NOAA/ESRL and other agency scientists and engineers.



**Figure:** The Keeling Curve. CO<sub>2</sub> concentrations (red) measured from the Mauna Loa Observatory in Hawaii from March 1958 to August 2018. Seasonally corrected data shown in black.

## The Keeling Curve

- Measurements of carbon dioxide ( $\text{CO}_2$ ) 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  $\text{CO}_2$  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.”

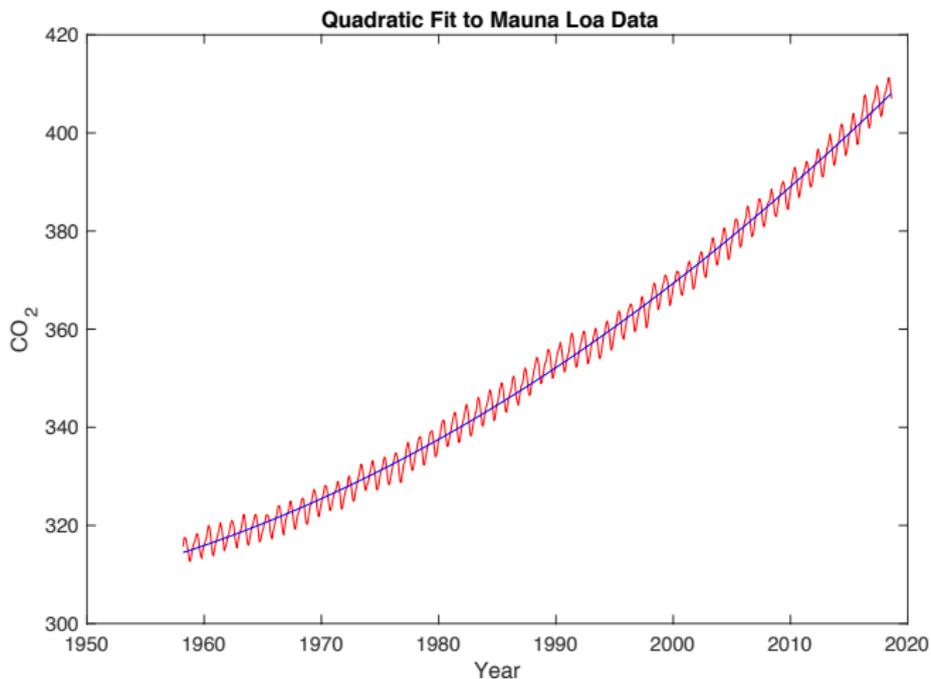
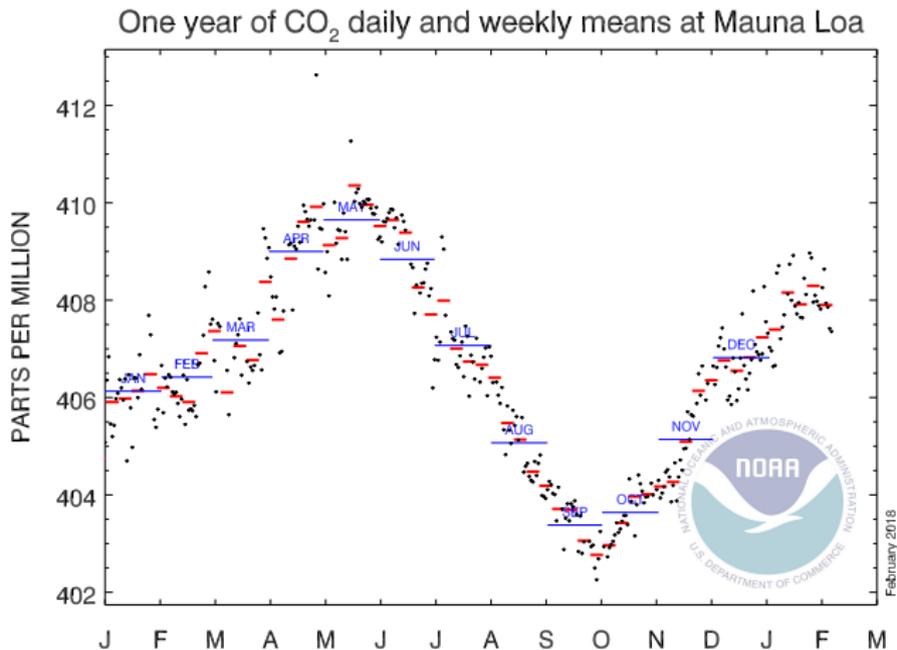
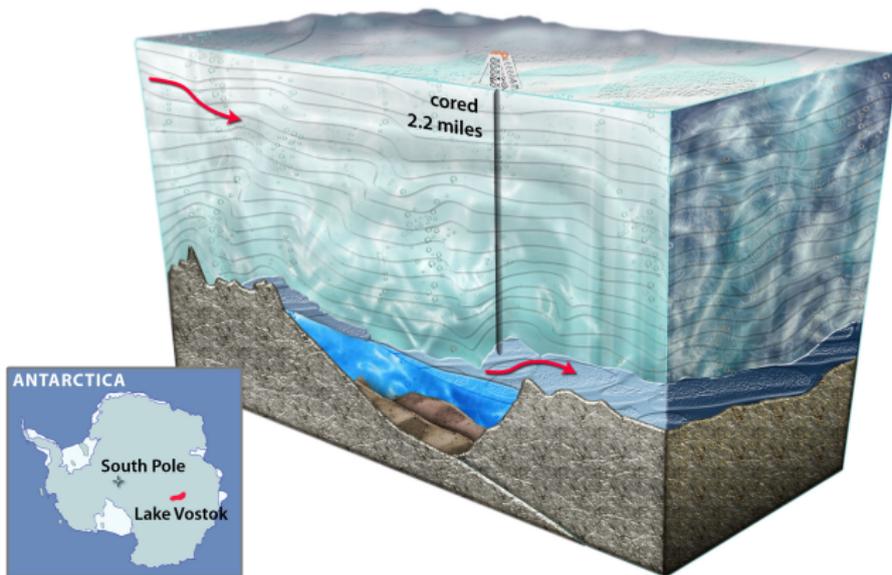


Figure: Regression analysis with a quadratic fit (blue) indicates a **positive** second derivative (recall Lab #1).  $R^2 = 0.9935$ .

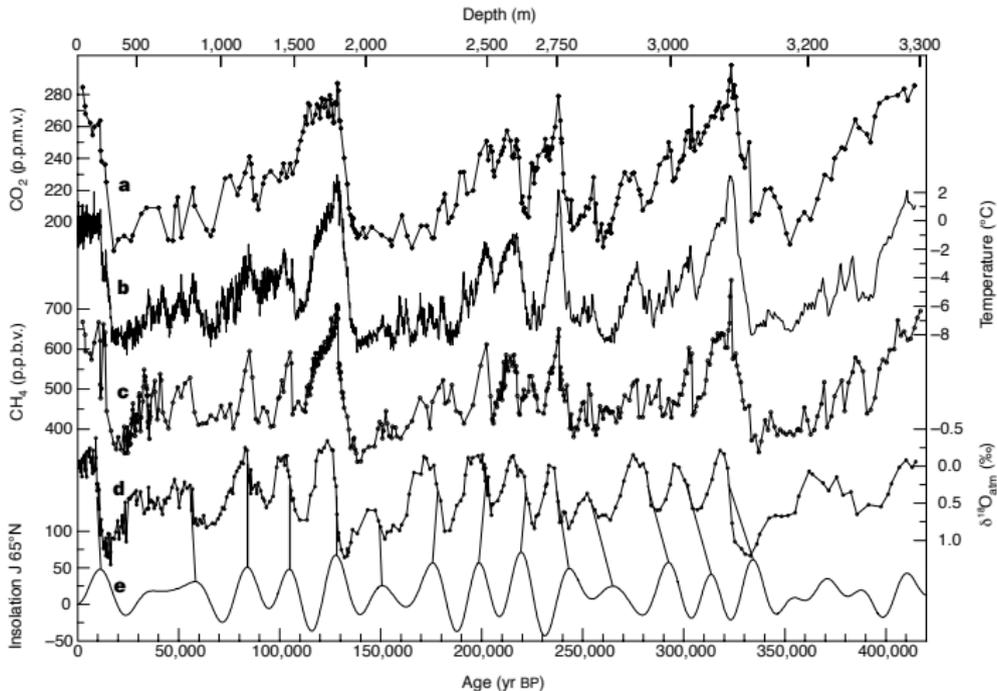


**Figure:** CO<sub>2</sub> concentrations over the course of 2017 indicate a maximum in May and a minimum at the end of September. Why? **Red bars** are weekly means; **blue bars** are monthly averages.

# Earth's Past Climate: Ice Cores

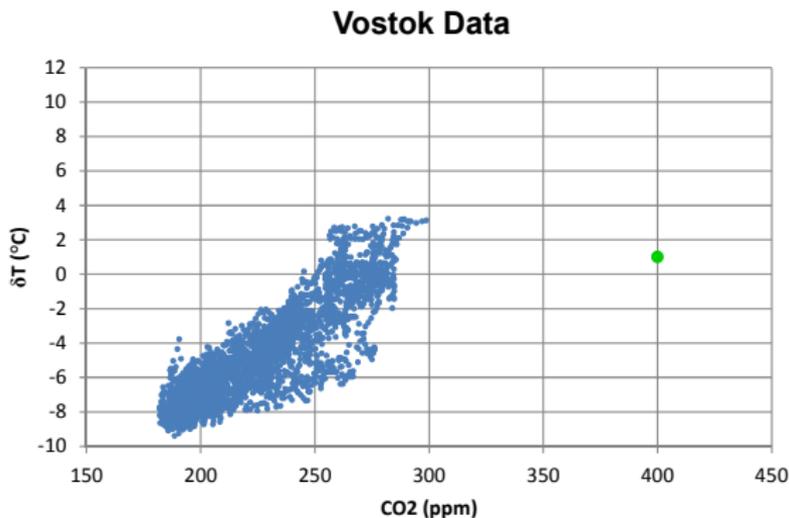


**Figure:** Some ice cores contain ice 800,000 years old (carbon dating). The proportions of different oxygen and hydrogen isotopes help reconstruct ancient temperatures; air trapped in bubbles can be analyzed to determine past levels of greenhouse gases.

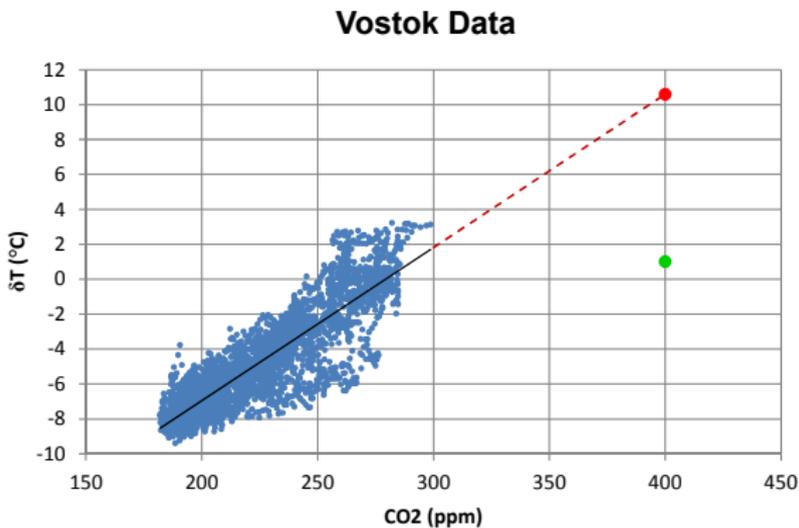


**Figure:** Time series data from ice core samples in Lake Vostok, Antarctica. **a** = CO<sub>2</sub>, **b** = Antarctic temp. changes, **c** = Methane. Source: “Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica,” Petit, et. al., *Nature* **399**, June 3, 1999, pp. 429–436.





**Figure:** A scatter plot of the temperature change versus CO<sub>2</sub> concentration for the Lake Vostok data, showing a clear correlation between temperature and CO<sub>2</sub> (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  $10^{\circ}\text{C}$ !  
Figure Source: Dick McGehee, Univ. of Minnesota and MCRN, lecture slides.

## CO<sub>2</sub> 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<sub>2</sub> and Methane averages, a Greenhouse Gas Index, CO<sub>2</sub> tracker, etc.

## Impacts of Global Warming

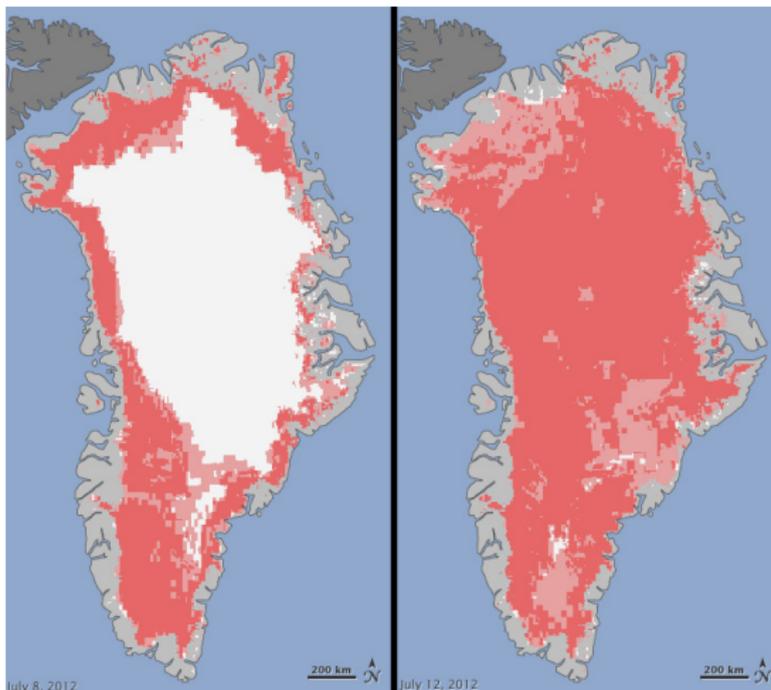
- 1 Rising sea level and increased coastal flooding.
- 2 Longer and more damaging wildfire seasons.
- 3 More powerful and damaging hurricanes largely caused by rising ocean temperatures.
- 4 Increase in extreme weather events (heat waves, coastal flooding, droughts). This has obvious impacts on our food supply.
- 5 Ocean acidification (higher acidity near surface due to excess carbon dioxide) and long-term damage to coral reefs.

## The Destructive 2017 Hurricane Season



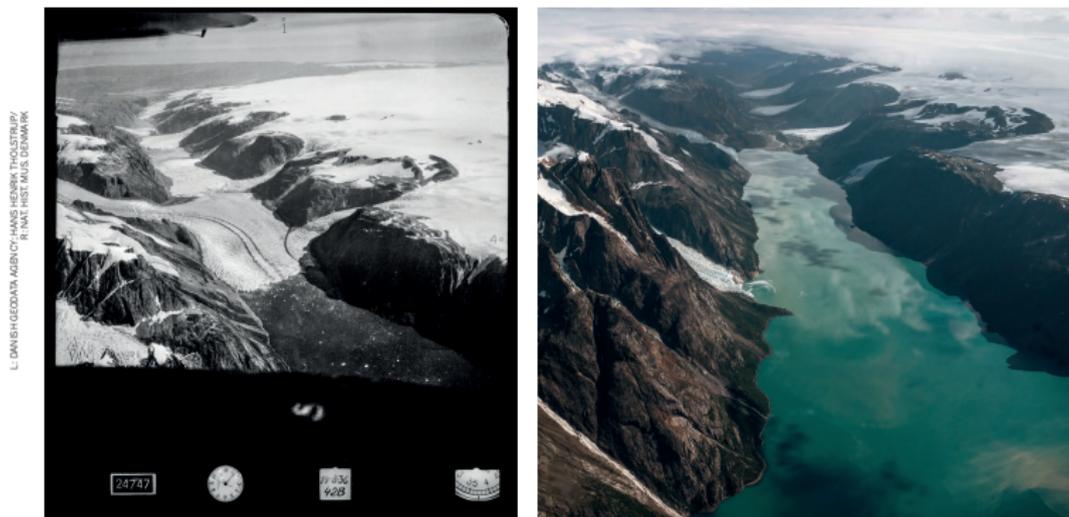
**Figure:** Three simultaneous hurricanes on Sept. 8, 2017: Katia (left), Irma (center) and Jose (right). The year 2017 saw 17 storms and 10 hurricanes, 6 of which were Category 3 or higher. Image Source: NOAA Suomi NPP satellite

# The Great Greenland Thaw in July 2012



**Figure:** Around 97% of the Greenland ice sheet experienced melting during the middle of July in 2012 (pink and red), up from a usual average of 50%. Most of the melt water refreezes; however, if the entire sheet were to melt, sea level could rise 24 feet!

## Disappearing Glaciers in Greenland

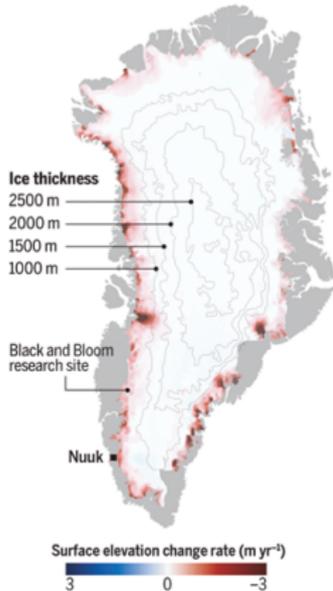


**Figure:** Aerial photos of the Ujarannaq Valley (southwest Greenland) taken in the summer of 1936 (left) and in 2013 (right) showing severe glacier loss. Source: “The ice historians,” Q. Schiermeier, *Nature* **535**, July 28, 2016, pp. 480–483.

# Decline of the Greenland Ice Sheet

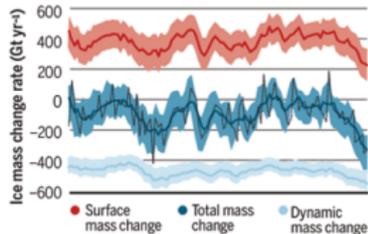
## Fraying edges

Satellite altimeters show that the ice sheet's margins are dropping as surface snow and ice melt and glaciers shed icebergs.



## Tallying the losses

Because of increasing melt, surface mass gain from snowfall no longer offsets "dynamic" losses from iceberg calving, greatly increasing total mass loss.



Cumulative mass loss has risen in recent years, along with Greenland's contribution to sea level rise.

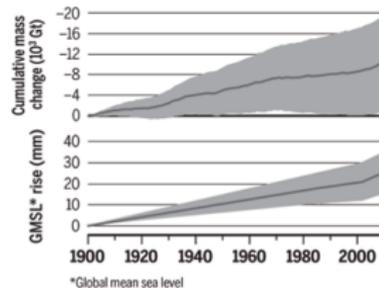


Figure: "Nobody expected the ice sheet to lose so much mass so quickly," Isabella Velicogna, geophysicist at the University of California, Irvine. Source: "The great Greenland meltdown," E. Kintisch, *Science*, Feb. 23, 2017, doi:10.1126/science.aal0810

# Selected Significant Climate Anomalies and Events in 2017

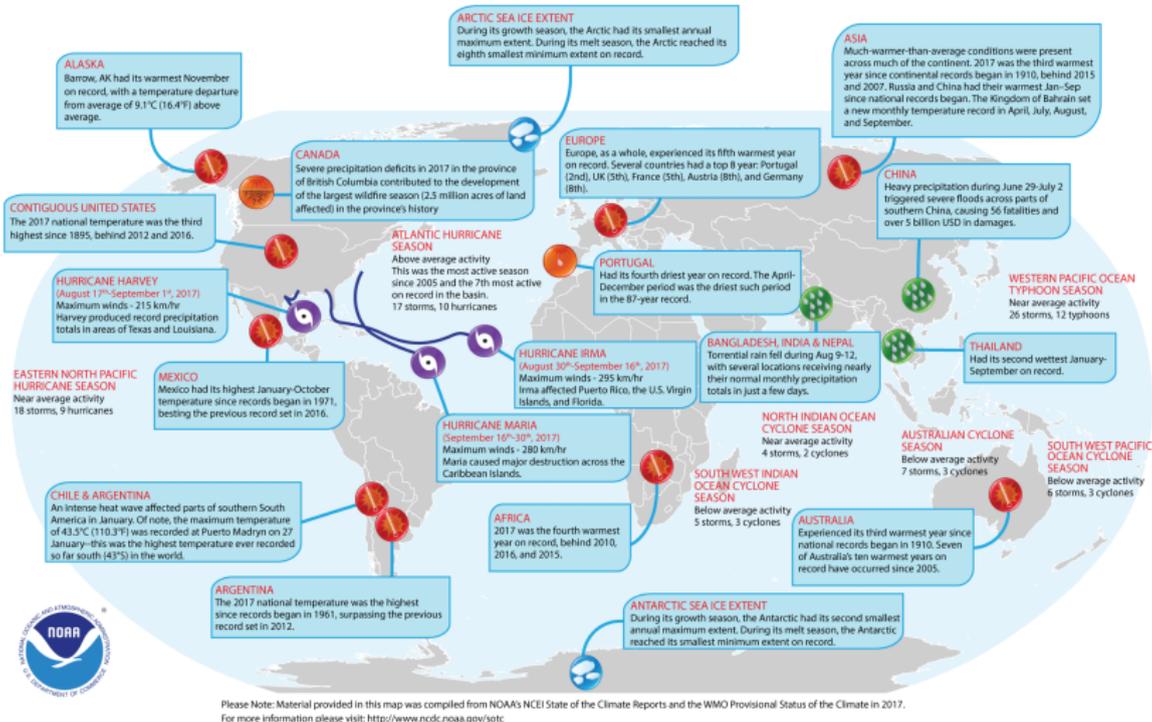


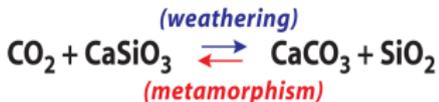
Figure: 2017 Global Significant Weather and Climate Events. Source: NOAA Global Climate Report <https://www.ncdc.noaa.gov/sotc/global/201713>



## 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  $\text{CO}_2$  down into the oceans forming carbonate sediments (limestone).
- Shifting of plate tectonics (continental drift) causes sediments to heat up, releasing  $\text{CO}_2$  back into the atmosphere.

CO<sub>2</sub> emission and consumption are kept in rough balance by a negative feedback resulting from the temperature-dependence of silicate weathering. The feedback operates on a million-year time scale.



Walker et al. (1981) *Jour. Geophys. Res.*, 86, 9776.

↑ CO<sub>2</sub> sources (emissions)

↓ CO<sub>2</sub> sinks  
 - 20% organic matter  
 - 80% carbonate

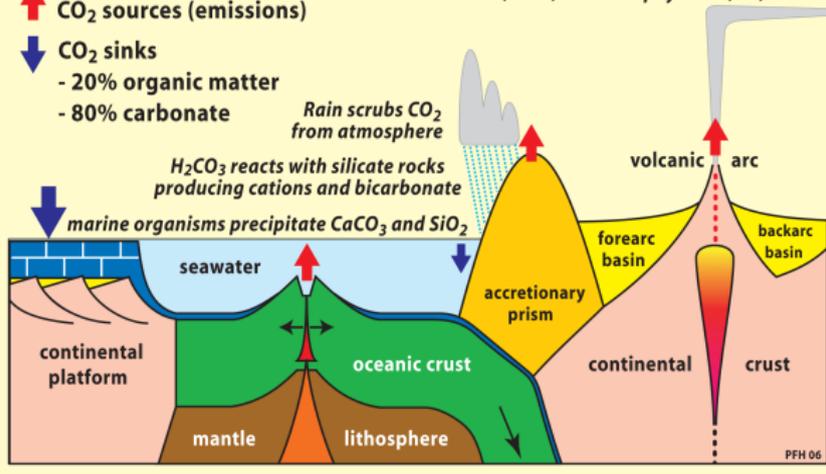


Figure: The long-term Carbon cycle — a million-year feedback loop.

## Silicate Weathering

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

- Rainwater containing dissolved  $\text{CO}_2$  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**.



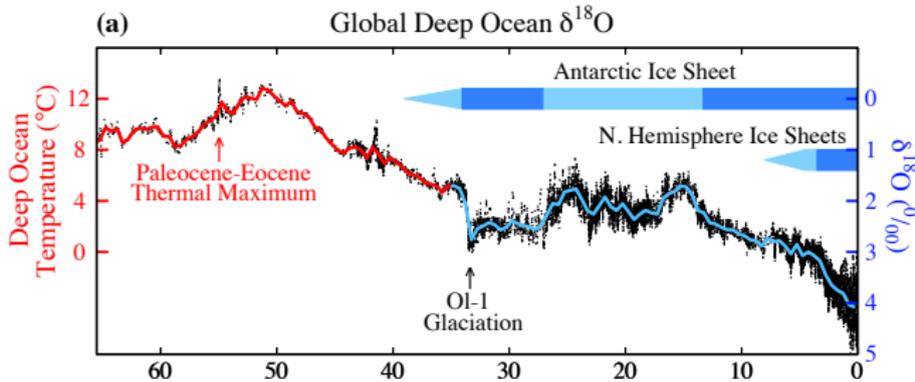
$\text{CO}_2$  (gas) replaced by  $\text{SiO}_2$  (rock)

- Due to volcanic activity and intense heat, the carbon atom in calcium carbonate gets replaced by the silicon atom and the  $\text{CO}_2$  gets released, completing the long-term carbon cycle.



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

## Earth's Climate in the Cenozoic Era



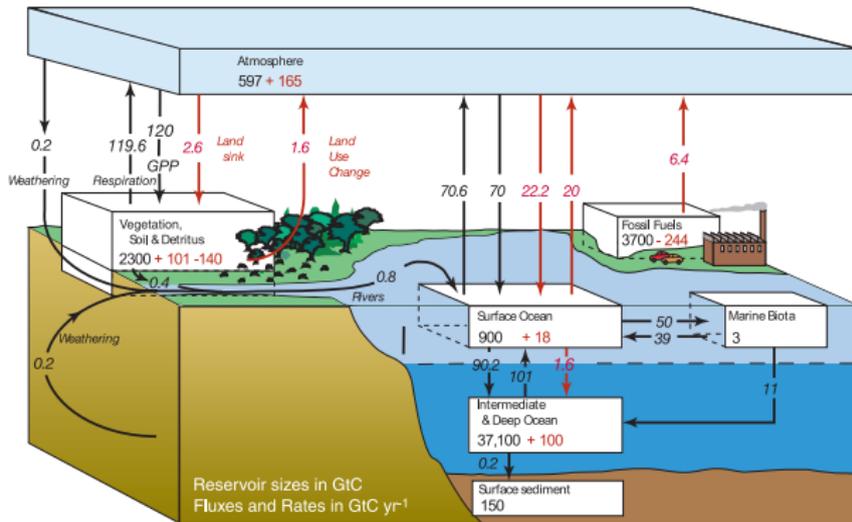
**Figure:** Oxygen isotope records for foraminifera shells found in deep ocean sediment cores provide a temperature record for the past 65 million years (Cenozoic era). Source: Hansen, et. al., “Target Atmospheric  $\text{CO}_2$ : Where Should Humanity Aim?” *The Open Atmospheric Science Journal* **2** (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 ( $\delta^{18}\text{O}$ ) in the deep ocean sediment cores.  $\text{CO}_2$  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  $\text{CO}_2$  through silicate weathering, thus reducing the greenhouse effect dramatically and cooling the planet enough for ice sheets to begin to form.

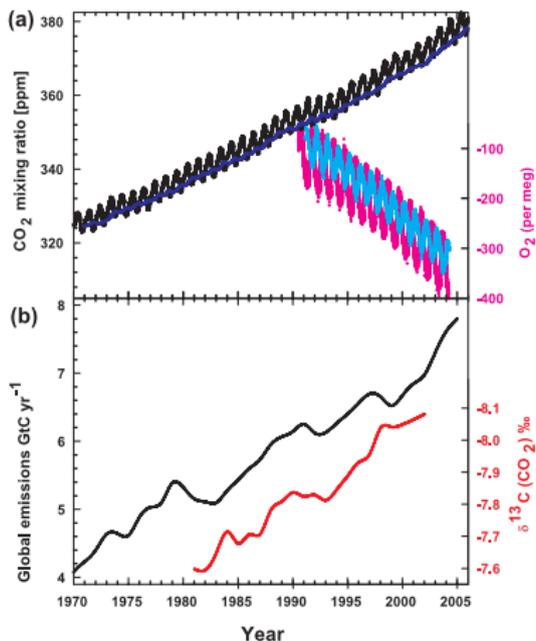
## Target CO<sub>2</sub> Level?

“Decreasing CO<sub>2</sub> was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO<sub>2</sub> fell to  $450 \pm 100$  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<sub>2</sub> 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<sub>2</sub> forcings. An initial 350 ppm CO<sub>2</sub> target may be achievable by phasing out coal use except where CO<sub>2</sub> is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO<sub>2</sub> is not brief, there is a possibility of seeding irreversible catastrophic effects.” — Hansen, et. al., “Target Atmospheric CO<sub>2</sub>: Where Should Humanity Aim?” *The Open Atmospheric Science Journal* **2** (2008), pp. 217–231.



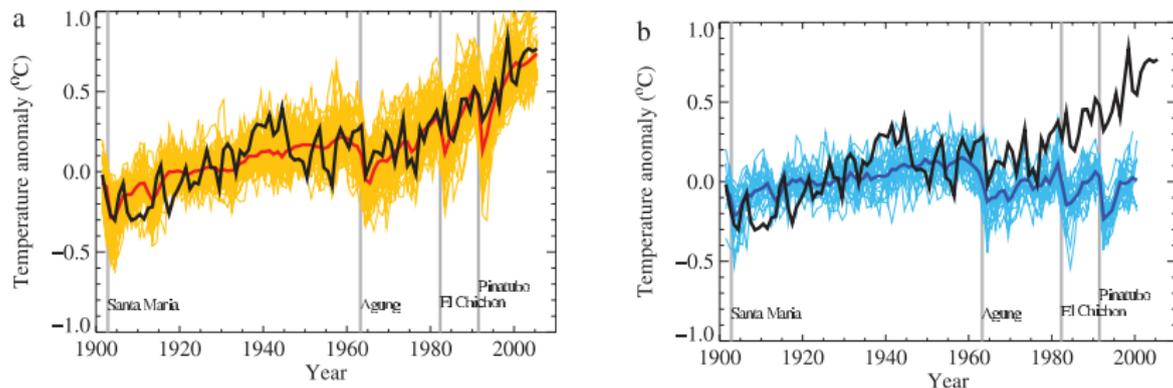
**Figure:** The short-term carbon cycle indicating anthropogenic (human) impacts (red) versus the natural biological and chemical weathering processes (black). Rates are given in gigatons of carbon per year. Source: Couplings between changes in the climate system and biogeochemistry, IPCC AR4 (2007), 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<sub>2</sub> 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.

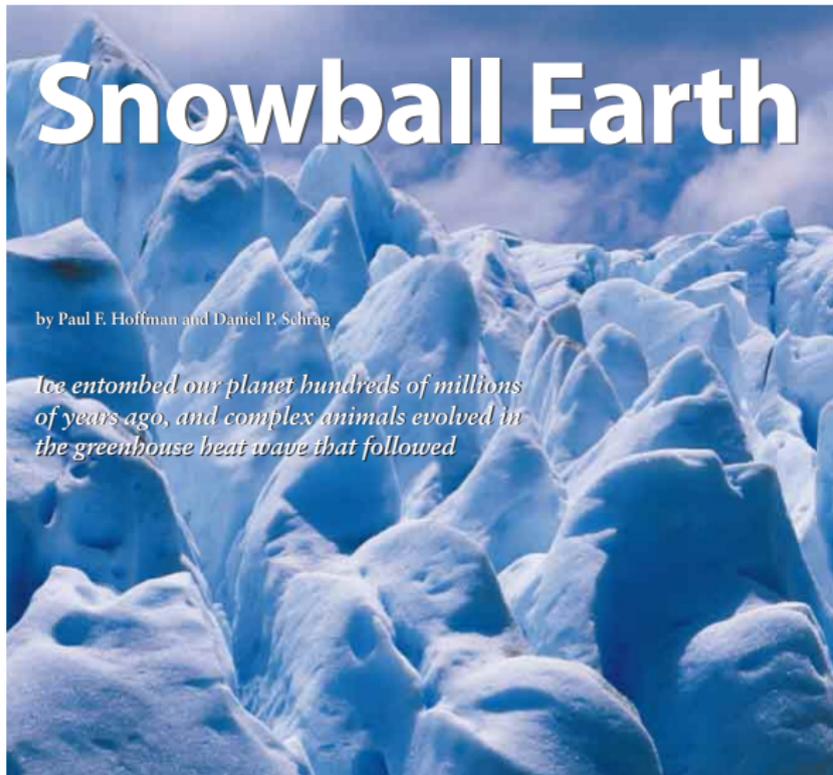
## How Do We Know Human's Are Responsible?



**Figure:** Results of Atmosphere-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.

## Recap

- The greenhouse effect is required to keep the Earth at a habitable temperature.
- We have excellent records of CO<sub>2</sub> 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<sub>2</sub> 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 Neoproterozoic 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

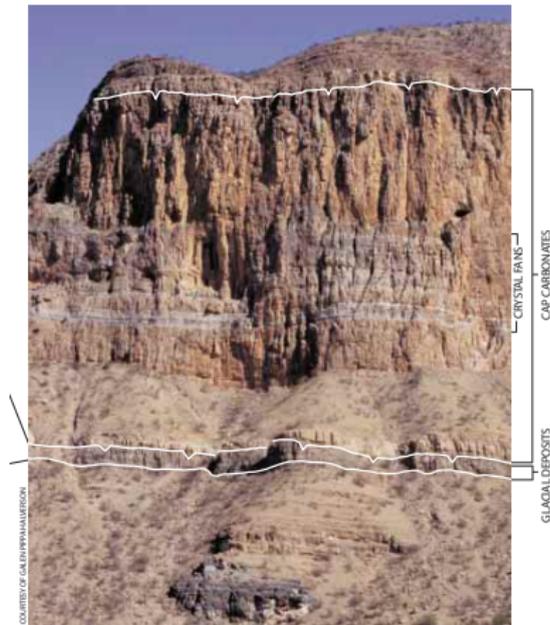
- Around 740 and 635 Mya, glaciers covered nearly all of the Earth's surface. Evidence comes from ancient rocks and glacial debris found near sea level in the tropics. Glaciers near the equator can only exist at 5,000 meters above sea level (or higher).
- Ice and snow have a much higher rate of reflectivity (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  $\text{CO}_2$  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)





**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  $\text{CO}_2$  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