III. Climate evolution of Earth, potential effects on life

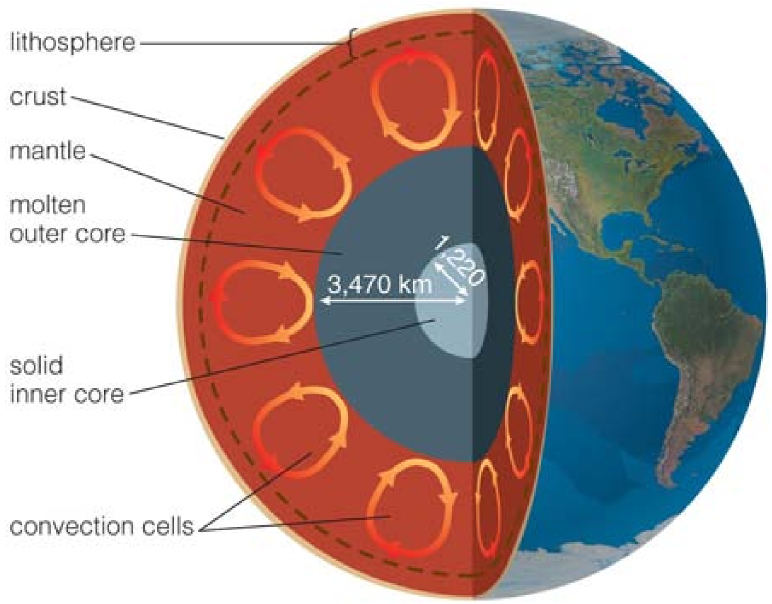
In order to stick with the textbook's presentation, this set of slides cover topics in sec. 4.4 and 4.5 in your book, which is a detailed discussion of climate control (CO_2 cycle), plate tectonics, runaway glaciations, and related geological phenomena. Don't worry too much about specifics, but do try to understand the main points, and how these processes ***might*** *have been crucial for the development of life on Earth.*

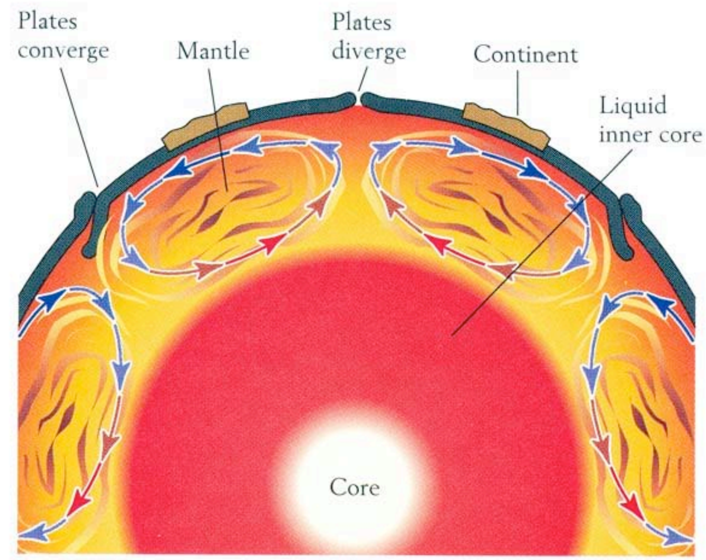
In order to appreciate how these climate considerations are tied to our *model* of what goes on deep within a planet's interior, a slide from a previous lecture is repeated next. Then we discuss:

1. Plate tectonics: "Outside" topic (not in textbook)--what kinds of exoplanets s should have tectonics?
2. CO_2 cycle: What it is, how it acts as a thermostat to keep the Earth's temperature from varying too much.
3. Some "paleosol" records of the temperture history of Earth: Hot/Cold cycles and how they might have driven the evolution of life. (Later we will explain how the genomes of organisms could be related to temperature changes or other environmental variations.)

Earth’s interior

Study the pictures. The most important feature: **convective motions** in the interior. They are required for
(a) Plate tectonics, volcanism, and other geological activity, and
(b) Generation of the Earth’s magnetic field (we won’t discuss here; read text section on your own.)
You should eventually be able to answer: Why might plate tectonics or a magnetic field be important for life?





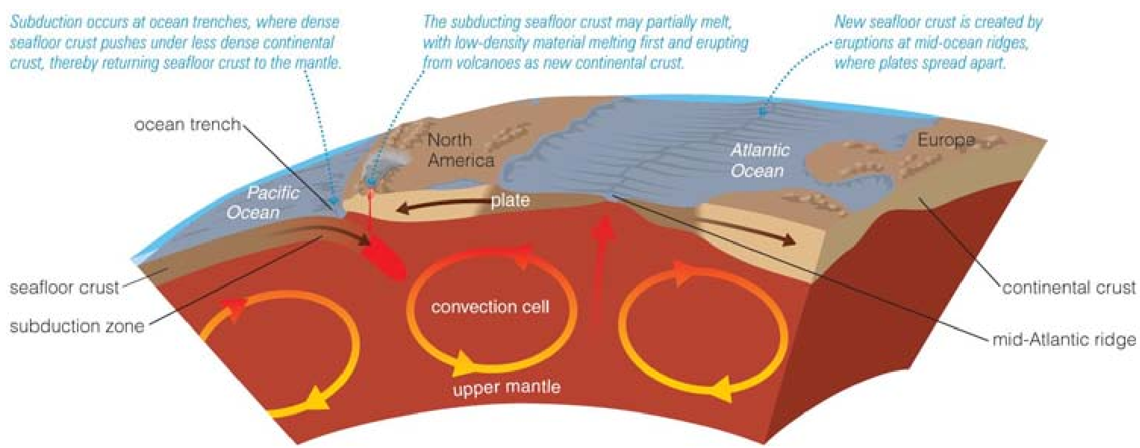
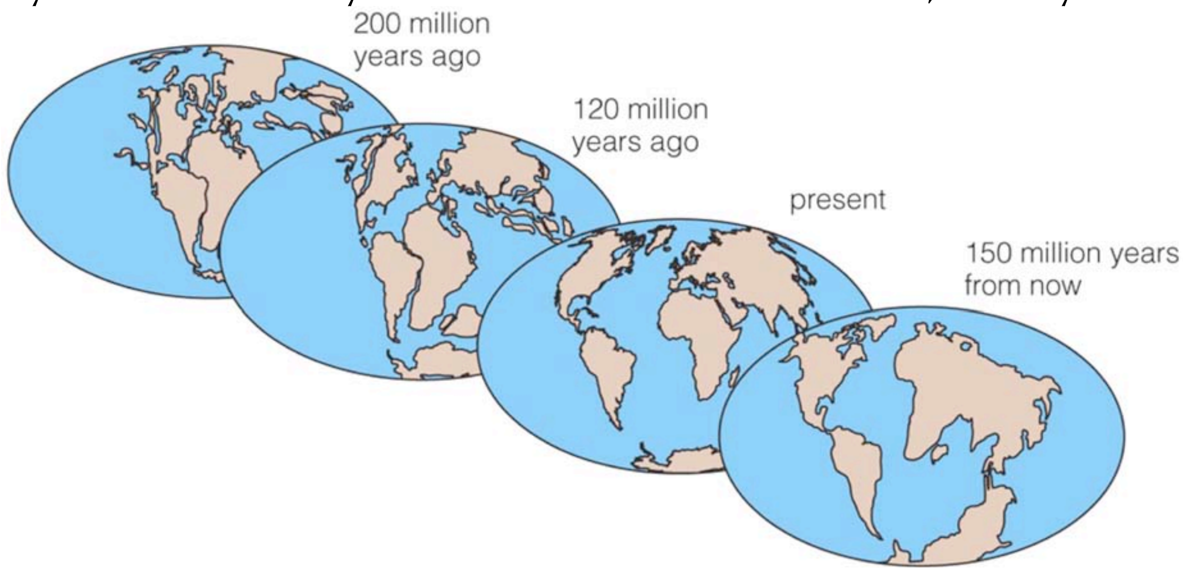


Plate tectonics: "Continental drift"

Throughout Earth's history the distribution of land mass has been changing radically: this leads to large changes in climate regulation that has affected life.

(We'll try to understand why. Textbook has excellent treatment, which you should read.)



A planet with active plate tectonics differs from one with a "stagnant lid" because of access of upper mantle material (and gases) to the atmosphere. For this reason, plate tectonics allows several global geochemical cycles to operate, like the CO2 cycle.

A planet with plate tectonism and a carbonate rock reservoir has an efficient built-in cycle that stabilizes climate at temperatures within the liquid water regime. (The CO2 cycle is discussed in your textbook, and two slides beyond this one.)

Plate tectonics on Earth-like planets?

If plate tectonics is necessary for life, we should ask what conditions are necessary to obtain tectonics on other Earth-like planets, say of different mass. Is the Earth's mass special in this regard? A recent paper says "yes," but not in the way you might think.

Inevitability of Plate Tectonics on Super-Earths
D. Valencia et al. 2007,

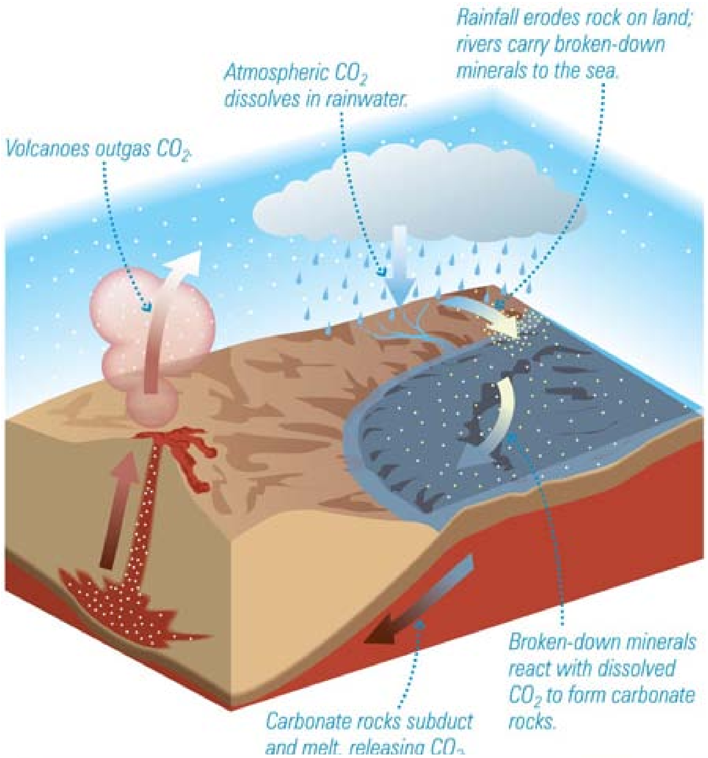
- With higher mass, interior heating and convection motions become stronger.
- This makes the shearing stresses on the plates stronger, and the plate thickness smaller, enhancing plate weakness.
- The net result is *subduction* of the lithosphere, which is essential for plate tectonics.

Valencia et al. find tectonics is easy for "super-Earths" (up to 10 Earth masses), even if they are dry (no ocean needed).
➞ They find that Earth is at the lower threshold for plate tectonics. If Earth were slightly less massive, then no tectonics. (Notice that Venus, just below Earth's mass, does not have tectonics. Their model also explains why Moon, Mercury, Mars do not exhibit plate tectonics.)

But how vital is plate motion for life? We will see that there is strong evidence for alternating hot/cold cycles in the history of the Earth, mostly due to variation in CO2 greenhouse. The idea behind the importance of plate tectonics is that they prevent these variations in temperature from becoming too great--this "CO2 cycle" is a thermostat.

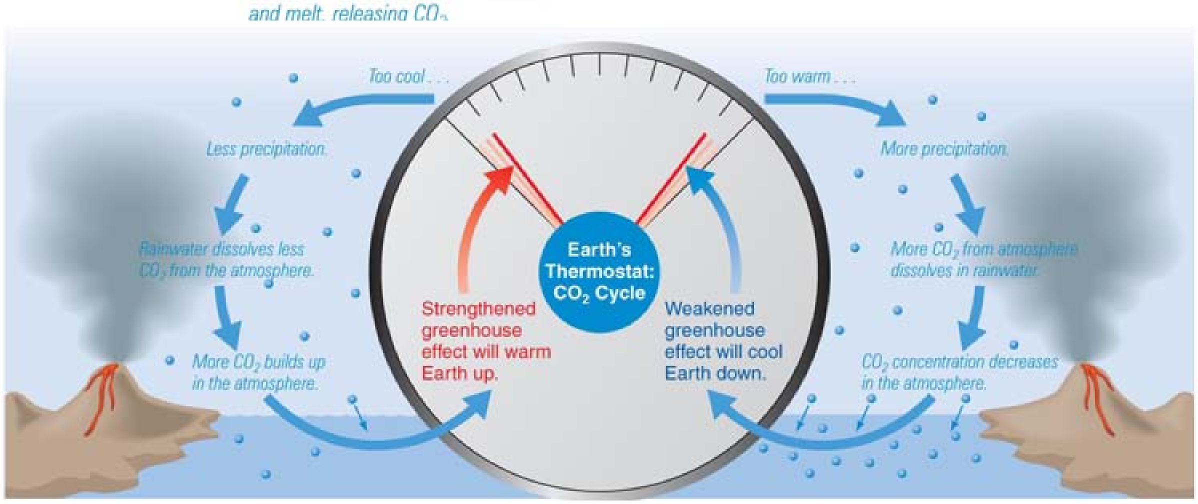
Climate regulation by the carbon dioxide, or carbonate-silicate, cycle

Illustrations from textbook--read about it there.



The basic principle illustrated to the left involves a coupling between CO_2, temperature, rainfall, erosion, and carbonate rock cycling. Say something warms the Earth's atmosphere:

- **Warmer** ➞ more water evaporates from oceans ➞ more rainfall.
- Rain contains atmospheric gases, like CO_2, ➞ **CO_2 concentration in atmosphere is reduced by the enhanced rainfall.**
- The enhanced rainfall also leads to enhanced **erosion** of rocks, which takes the form of "broken down minerals"; both these minerals and the CO_2 in the rainwater are washed into the sea.
- CO_2 is a greenhouse gas, so less ➞ cooler. So the **enhanced rainfall and erosion has *reduced* the warming.**



- In water, CO_2 reacts with the minerals to form carbonate rocks. Because the eroded rocks were silicates, and these rocks are carbonates, this process is sometimes called the "carbonate-silicate cycle." When these carbonate rocks are subducted and heated, the CO_2 is released, and eventually outgassed from volcanoes, which is the original source of CO_2.

➞ *Now you try to reason through the cycle in the case of an atmosphere that was initially getting colder than normal…*

Another important effect due to changing amount of a greenhouse gas: This time not a *regulator*, but instead leads to climate *catastrophe*.

(Note: we already covered this in sec. III on oxygenation of the atmosphere.)

- Recall that one of the most significant changes in the history of the Earth was the so-called "Great Oxidation Event," in which oxygen, from cyanobacteria which had developed aerobic (oxygen-releasing) photosynthesis, flooded the atmosphere.

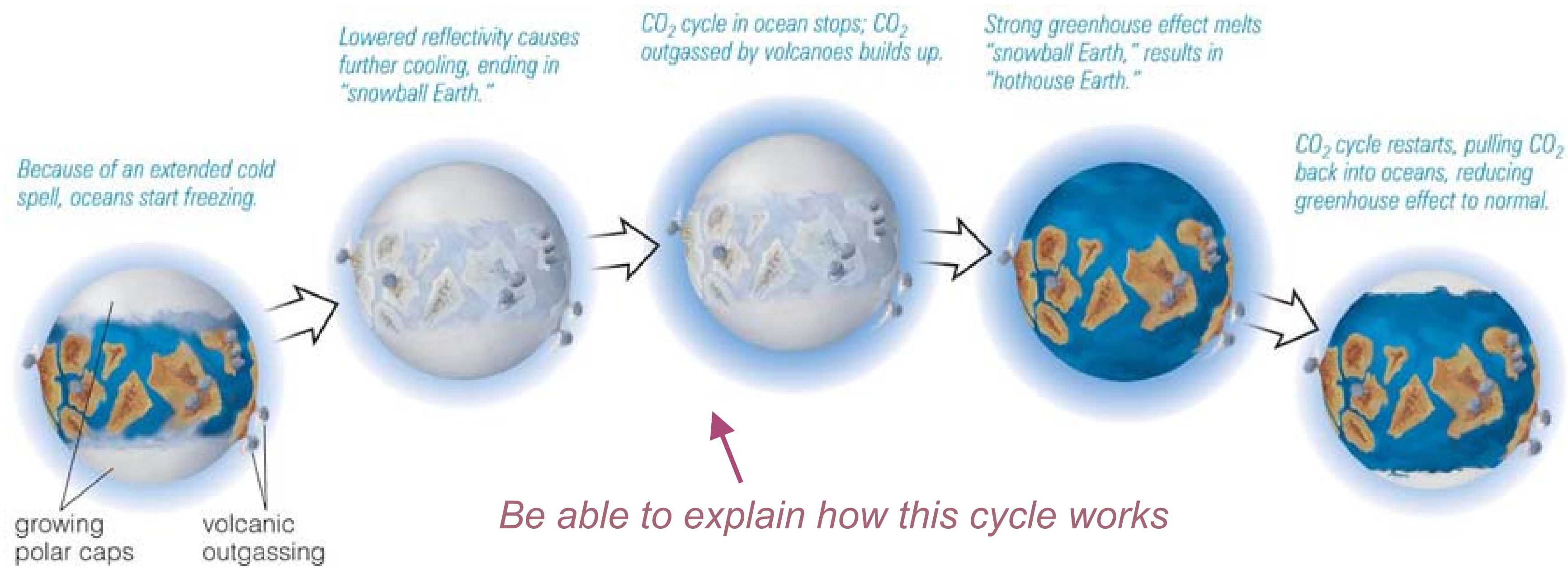
- Oxygen O_2 is *very* reactive, and easily destroys ammonia NH_3 in the atmosphere, a gas that had been contributed by another bacterium, the *methanogens*. (Note: The methanogens themselves may not be affected--they continue to pump out NH_3; that the NH_3 is destroyed rapidly by O_2 is the important point.)

- But NH_3 was the greenhouse gas keeping the Earth above freezing, so as oxygen wipes it out through chemical reactions, the temperature must drop. Moderation by the CO_2 cycle is too weak to counteract this severe cooling. How severe was it?

- There ***was*** a very large glaciation that occurred shortly after the Great Oxidation Event: The evidence points toward the Earth becoming completely covered with ice ➙ ***Snowball Earth***

- ***Next slide*****: Notice how glaciation suppresses the CO_2 cycle, but then CO_2 from volcanoes *does* eventually come to the rescue, oceans restored, CO_2 cycle again operative.** This is a "cycle within a cycle" so don't get confused: one regulates temperature, the other makes it go from ice age to "hot house."

During glaciation, the CO_2 cycle is suppressed, leading to runaway glaciation (because of ice albedo): Snowball Earth episodes. Eventually so much CO_2 is pumped into the atmosphere (since if ice-covered there is no erosion to take out CO_2) that the Earth could un-freeze.



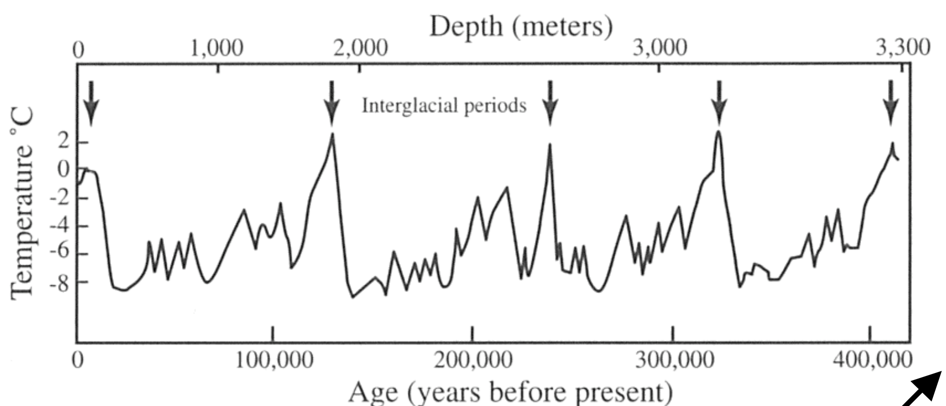
These episodes may be associated with important biological developments.

1. We already encountered the snowball that apparently followed the Great Oxidation Event. You should be able to explain why that Event led to severe cooling. In this case the major biological developments were probably more a response to the oxygen than the freeze-thaw.

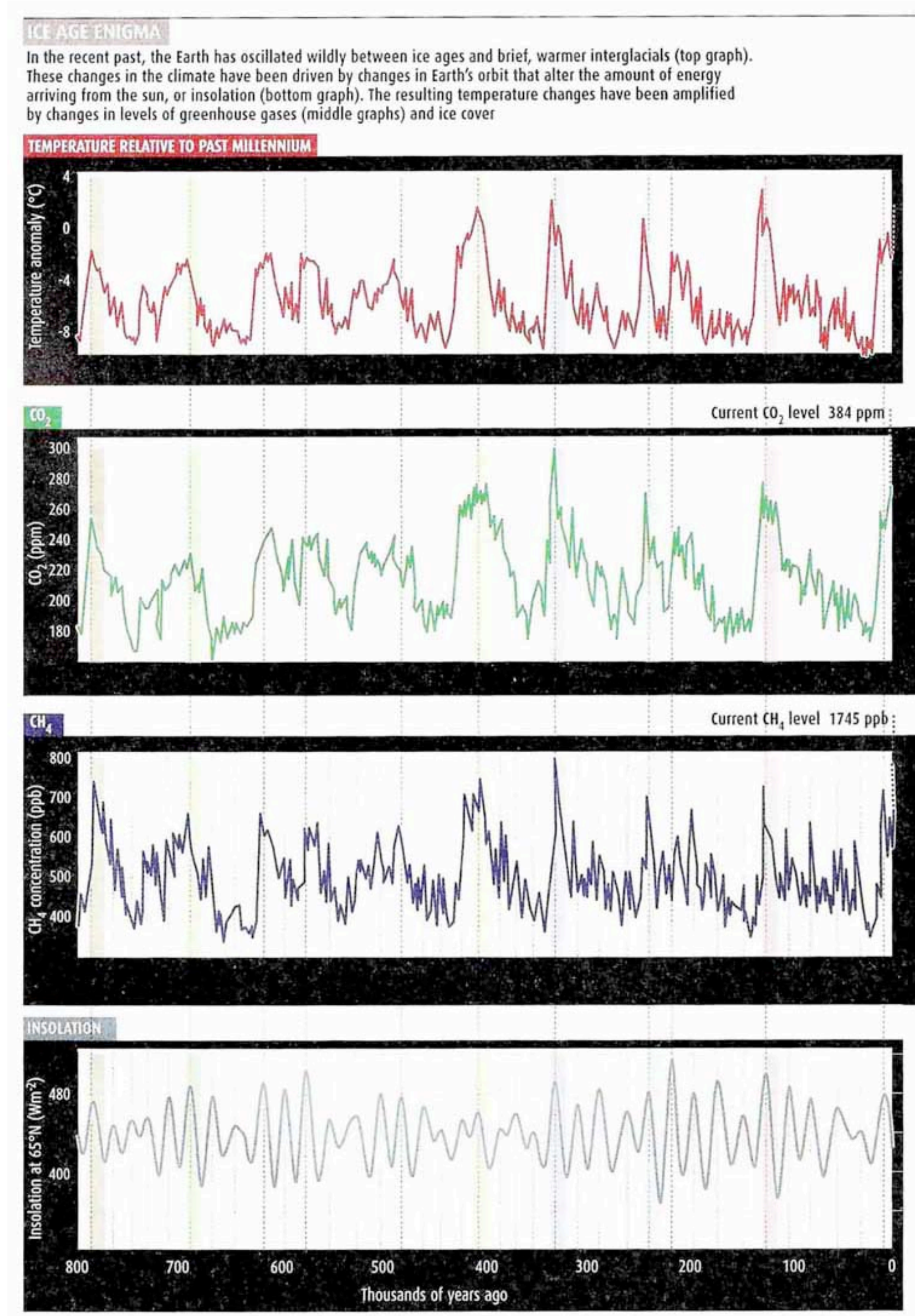
2. There is evidence for a second Snowball Earth episode right around the time of the Precambrian-Cambrian transition, the most important and rapid increase in the complexity of life. Some claim there is a causal connection, but no agreement on how…

Earth's climate history: Repeated pattern of warm/humid and cool/dry: "interglacials" and glaciations. These probably due to "Milankovitch cycle" involving Earth's orbital changes with time, amplified by greenhouse gases.

"Snowball Earth" episodes are just extreme versions of what is apparently a persistent feature: Earth's history alternated between glacial and interglacial periods back to at least 400,000 yr ("Snowball Earth" episode probably occurred a little earlier--illustration below from textbook. **More illustrations follow, only in case you are interested, not on exam.)**

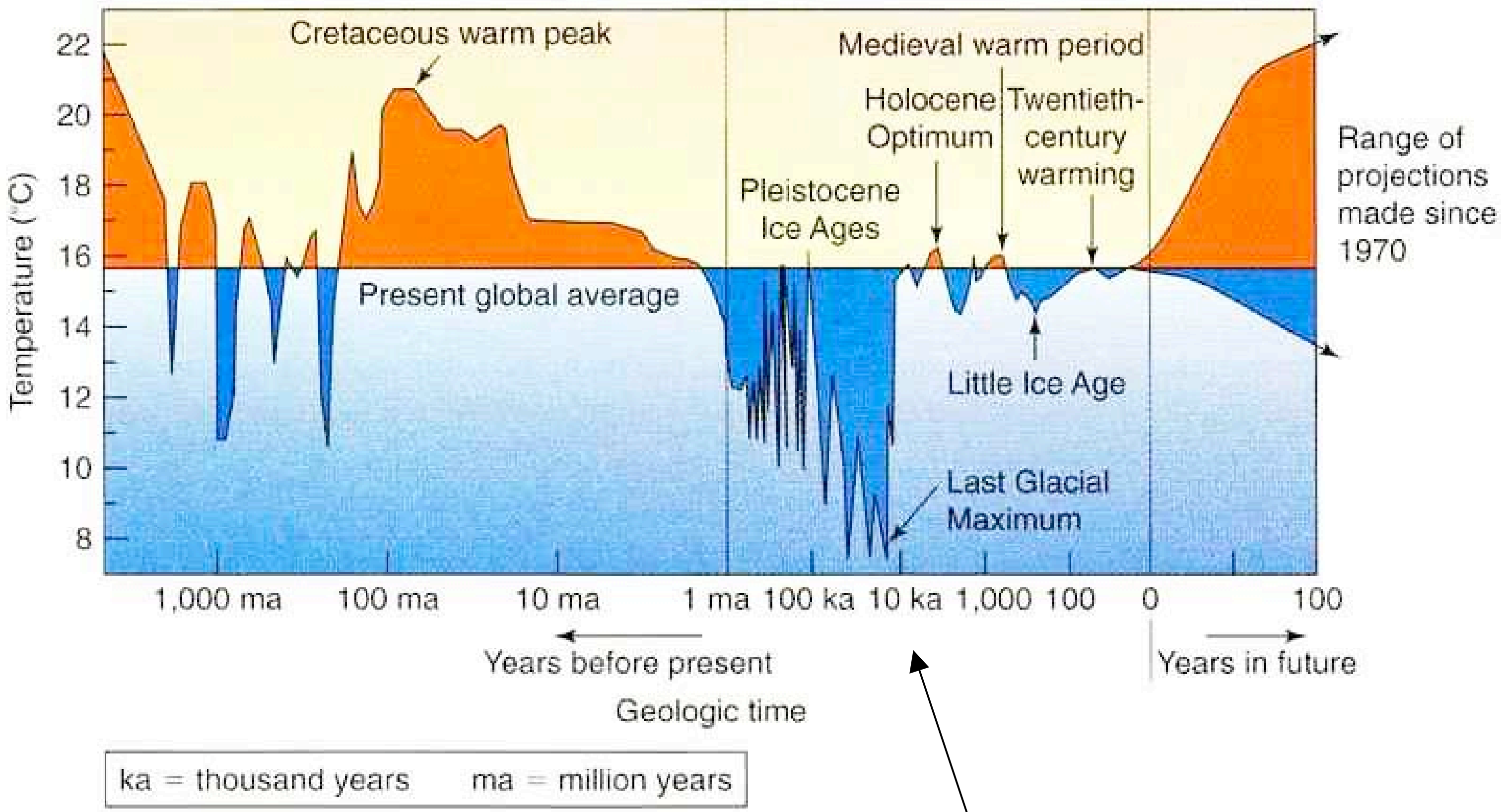


Records for temp., CO_2, CH_4, and solar flux incident on the Earth, as a function of time.



Climate evolution: A major driver of diversity of life on Earth?

Notice that temperature changes shown here are mostly from 4 to 8 degrees above or below the present global average. These are *huge* changes in average temperature.



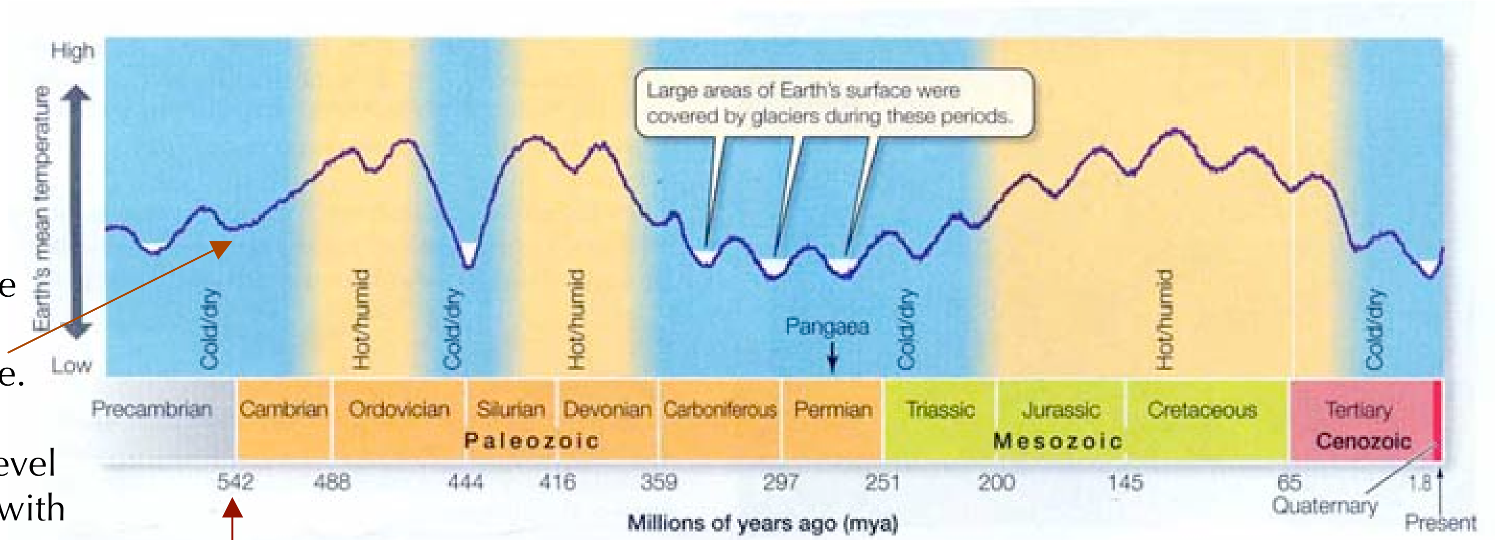
Note: The time axis is logarithmic in order to show details for all times

Climate variations during Phanaerozoic Eon (from Precambrian to present): Mean Temperature and Sea Level

Notice glaciations (top) and mass extinctions (bottom) marked.

Temperature

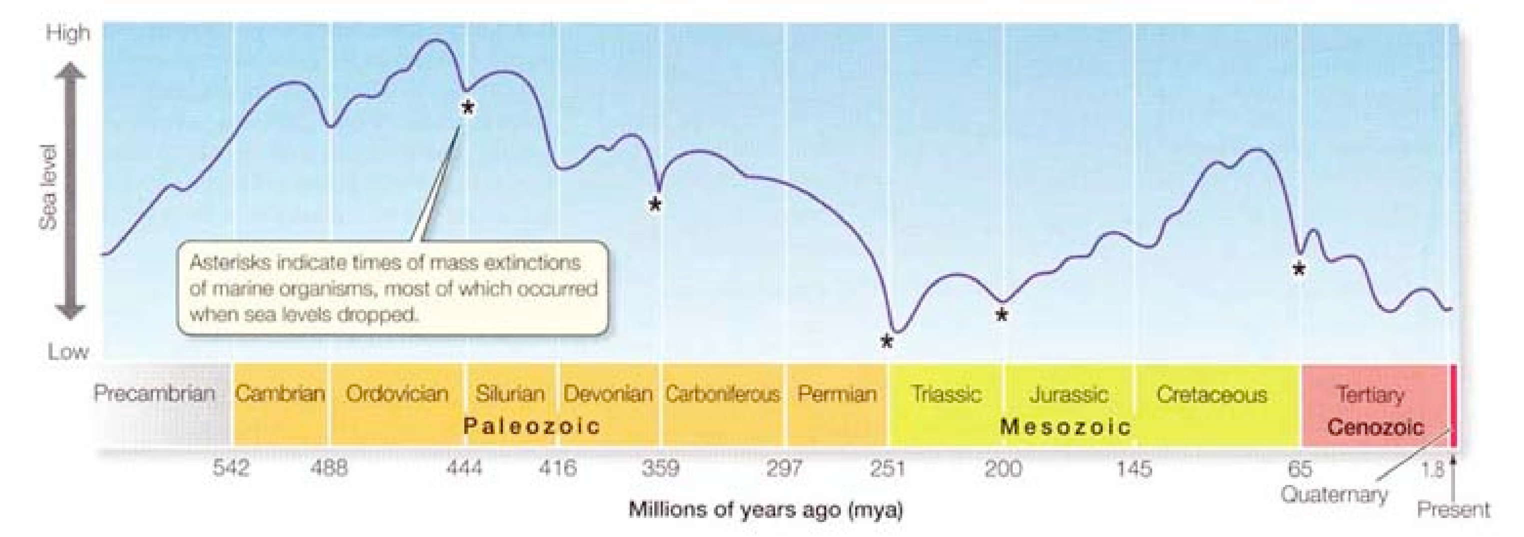
Note that there is no "snowball Earth" episode shown at the Cambrian explosion in this timeline.



"Cambrian explosion"

Unexplained: why sea level drops seem to coincide with mass extinctions.

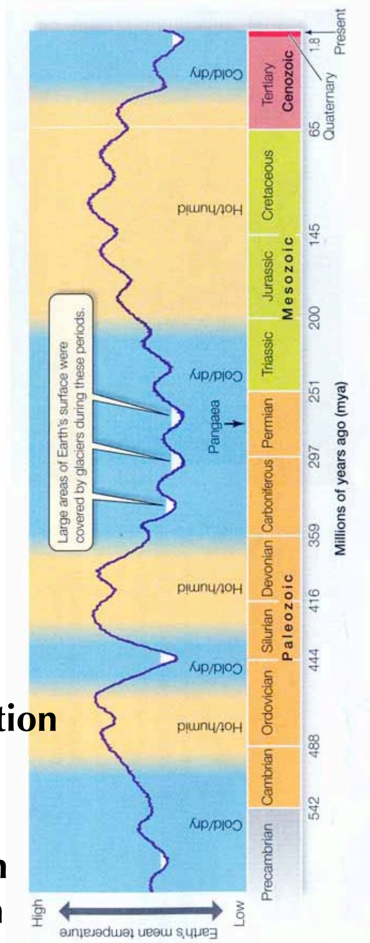
Sea level



Temperature Variations from Oxygen Isotope Ratios

550, 50, 2, 0.1 Myr time intervals, "zooming in" on smaller time intervals. Can see alternating glacial-interglacial (cold-warm) periods as persistent features in the climate record. How much of the development of the biosphere has been due to this quasi-periodic environmental variation?

550 Myr
"Cambrian explosion"

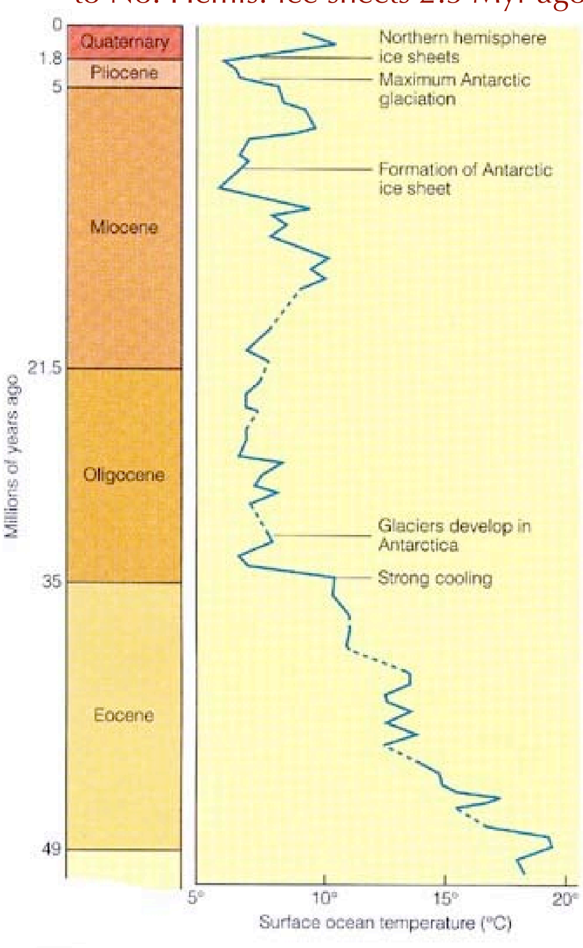


Land Colonization

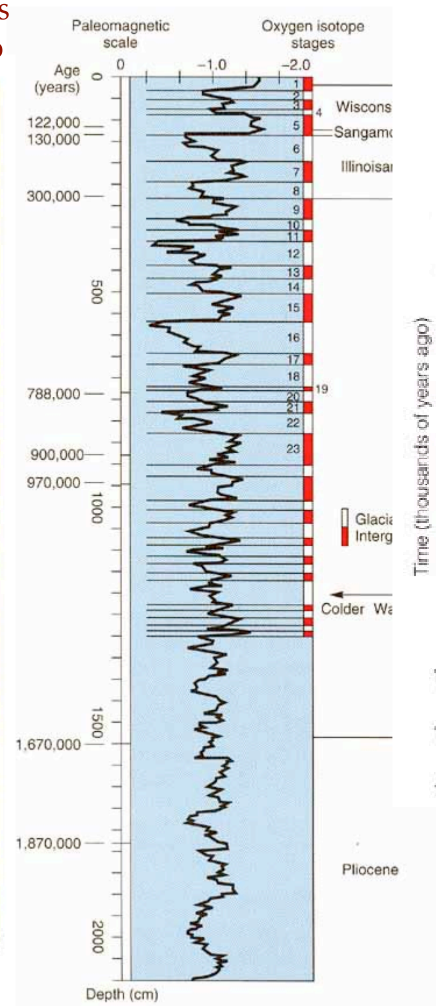
Cambrian explosion

50 Myr sediment core Western Pacific ocean surface

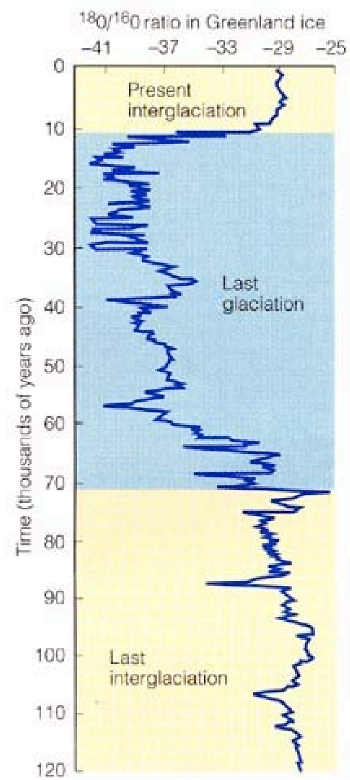
35 Myr drop leads to buildup of Antarctic glaciers, then ice sheets by 15 Myr. More recent cooling leads to No. Hemis. ice sheets 2.5 Myr ago



2 Myr ice cores
Glacial/interglacial



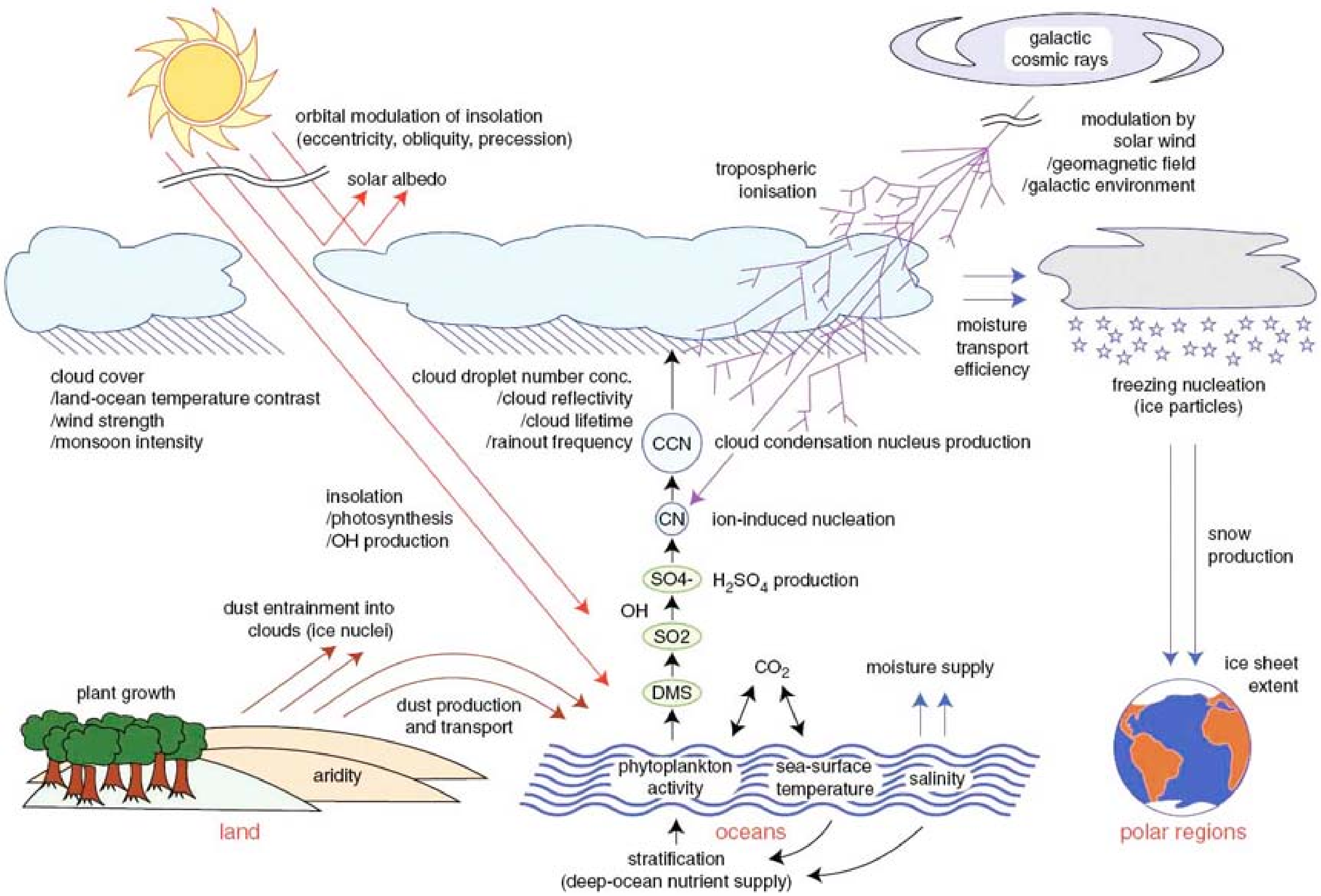
0.1 Myr Greenland
Ice Sheet



Evolutionary development might be driven in part by glacial/interglacial cycles on Earth. Then our question is: *Should we expect similar cycles on extraterrestrial Earth-like planets?*

A. Glacial/interglacials driven by Milankovitch cycle: all planets are likely to have the same kinds of *orbital* features (precession, elliptical orbit, …). So *yes!*

B. Whether changes in orbital parameters leads to glaciation is much more complex than we have admitted. The picture below illustrates some of the factors that we would have to take into account. So this suggests: *Maybe not!*



Controversial: Climate partly controlled by cosmic ray flux variations, not CO_2?