Climate Change Science

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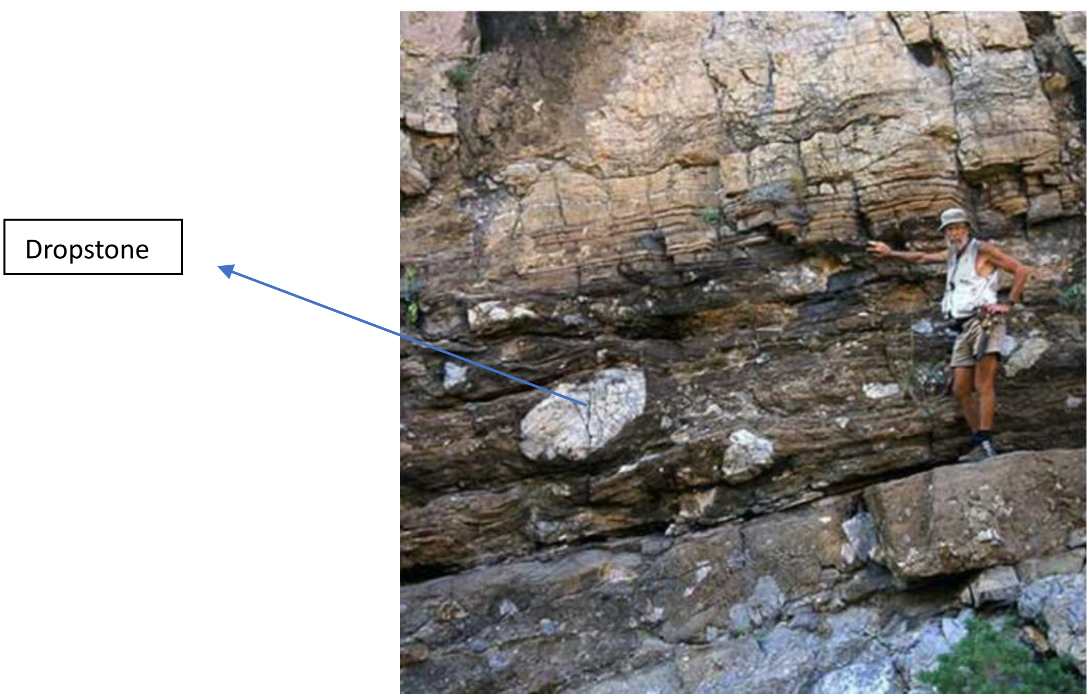
Lecture – 40
Snowball Earth (continued)

In the last lecture, we started our discussion on a very unusual phenomenon in Earth's history called Snowball Earth. We discussed the evidence that there was a time around 600 million years ago when Earth was probably covered completely with ice. If it is completely covered with ice, it is called a hard snowball, which many people find hard to believe because, if Earth were completely covered with ice, they believe photosynthetic life—life that depends on photosynthesis—cannot survive. Some people believe that there was a small region near the equator where it was not covered with ice. Now, we will not worry about whether it is hard or soft. We would argue that 90 to 95 percent of the Earth was covered with ice.

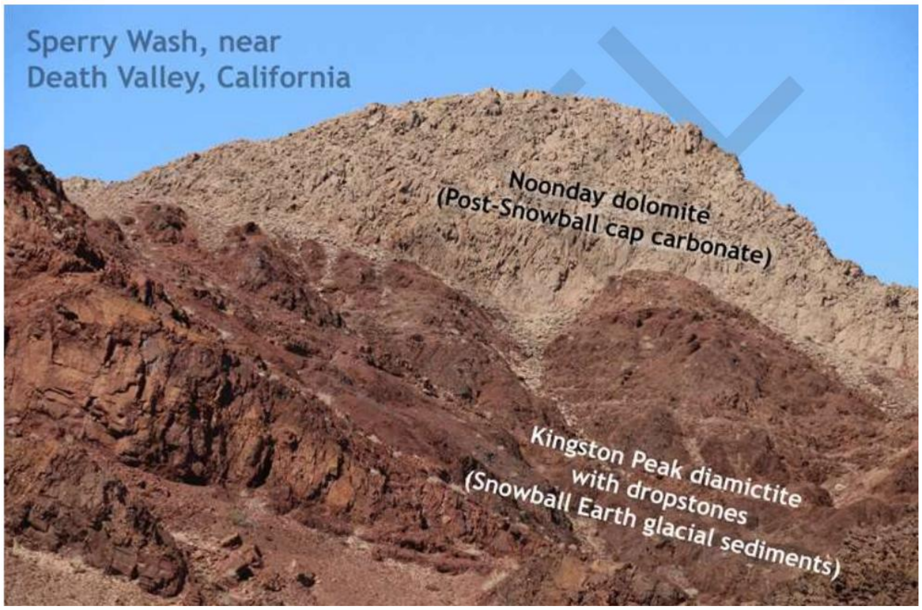
This is a very unusual phenomenon. It has not occurred in the last couple of hundred million years. It occurred only a long time ago. The evidence I showed in the last class includes glacial deposits, calcium carbonate occurring on top of those deposits due to the greenhouse effect, and banded-iron formation due to the fact that the ocean was either exposed to the atmosphere or completely not exposed because of ice and snow. And the carbon-13 isotope declined, which hinted that photosynthesis had almost stopped.

Here is Hoffman— I think in Namibia— showing a layer between two calcium-carbonate rock layers, in between a layer of glacial debris containing dropstones.

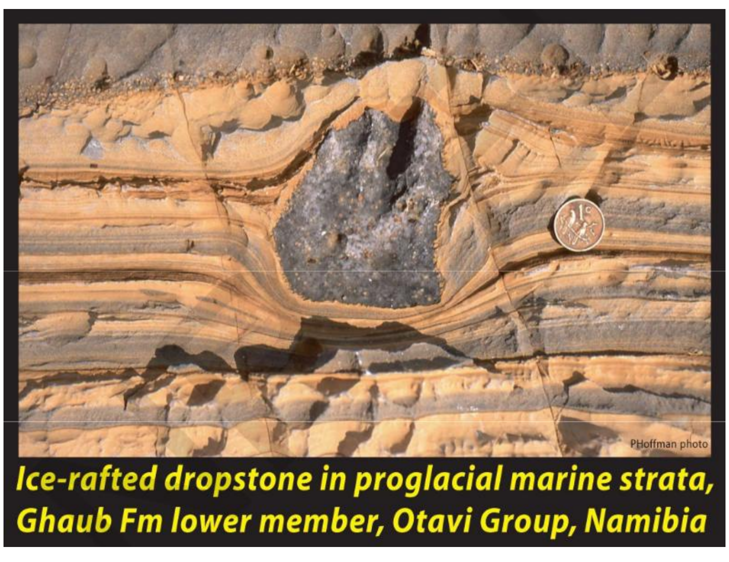


These dropstones are stones that were dropped into the ocean by an ice sheet. The above figure shows debris in the ocean, “ocean debris,” which was later solidified. So, these rocks (dropstones) are not similar to the surrounding rocks. They came from far away on the ice sheet. They were carried all the way and dropped into the ocean. This is real evidence of a large ice sheet moving into the ocean and dropping these unusual stones called dropstones.

Now, here is evidence from California’s Death Valley (shown below in the picture), where you would not expect to find evidence of a snowball. The darker color here shows soil that was ground to a very fine resolution, which is called diamictite, and on top of that you have calcium carbonate. So, this is where glaciers existed, and little later on, on top of the glacier, is a calcium-carbonate deposit indicating very strong photosynthesis and a greenhouse effect.

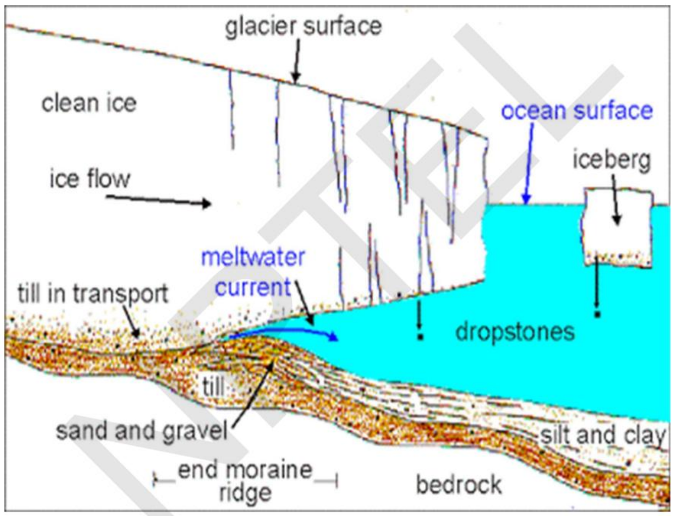


Again, the picture below shows another piece of evidence from Hoffman’s work- a rock deposited at the bottom of the ocean.



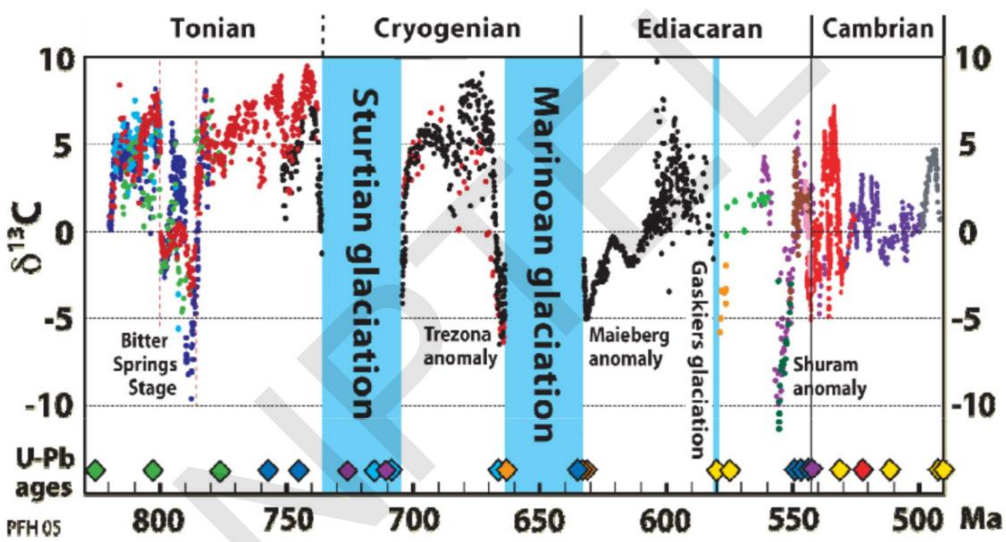
This is ocean floor sediment; in between is a rock from some completely different place. This is in Namibia. What I want you to realize is that evidence is there from all over the world, not just a few places.

Now, this is a cartoon showing how glaciers bring rocks and drop them into the ocean.



The picture above shows the ocean. At the bottom of the ocean, you have silt and clay. Ice carries rocks and debris, which ultimately drop into the ocean. These dropstones come from very far inland and do not belong to the local geology. That is how you recognize it as foreign material.

Here is the evidence (please refer to the image shown below) over the period between 500 and 800 million years of two intervals of almost complete ice cover on Earth, along with the carbon-13 isotope data showing that just before Earth was completely ice-covered, photosynthesis had stopped gradually.

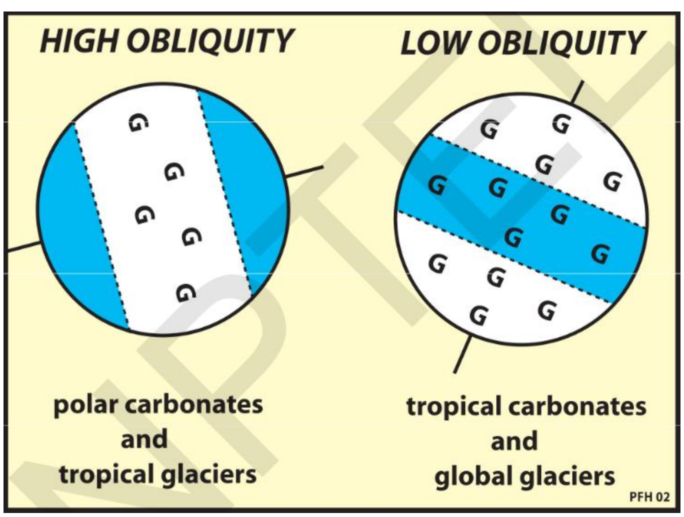


Gradually, photosynthesis declined, and during this time, there was virtually no photosynthesis; then, after the ice had melted and carbon dioxide had built up, photosynthesis again started. So, this is very powerful evidence of photosynthesis stopping due to ice sheets growing all over Earth, and during that time, the carbon-13 isotope value remained very low and negative for about 10 to 20 million years. The carbon-13 isotope value then recovered once the ice sheet was gone, and started increasing when there was a very warm condition in which photosynthesis occurred, and the carbon-13 isotope value reached a positive value.

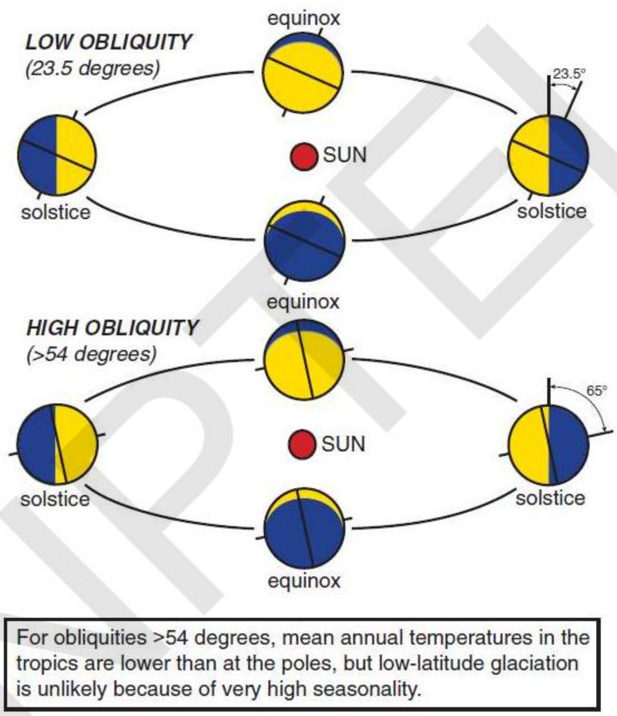
So, this is the evidence that ultimately convinced many people that Earth was once almost completely covered with ice. I have mentioned it in the picture shown below, so that you can read it carefully and understand how the carbon-13 isotope evidence, along with evidence of glaciers and dropstones, convinced many people that Earth was almost completely covered with ice.

> **Just before the glacial deposits, the amount of carbon 13 isotope plummets to levels equivalent to the volcanic source, a drop we think records decreasing biological productivity as ice encrusted the oceans at high latitudes and the earth teetered on the edge of a runaway freeze. Once the oceans iced over completely, productivity would have essentially ceased, but no carbon record of this time interval exists because calcium carbonate could not have formed in an ice-covered ocean.**
>
> **This drop in carbon 13 isotope persists through the cap carbonates atop the glacial deposits and then gradually rebounds to higher levels of carbon 13 isotope several hundred meters above, presumably recording the recovery of life at the end of the hothouse period**

Now, why did this happen? Some people believe that this could only happen if the tilt of Earth's axis suddenly changed from 23.5º to 45º or 50º. This is one hypothesis that is not accepted by everyone. The argument is that at the present tilt of 23.5º, polar regions are covered with glaciers, but if the tilt became very large, the equatorial region would also be covered with glaciers.



This is a very extreme hypothesis. You would need evidence of a large asteroid colliding with Earth, sufficiently big so that it would change the tilt. I do not think there is sufficient evidence to prove that, but some people still believe in this hypothesis.



The idea is that the tilt shifted suddenly from 23.5º to around 52º. This is only a hypothesis, and not enough evidence has been accumulated to prove it.

Impact-induced initiation of Snowball Earth: A model study
Fu et al., Science Advances, 2024

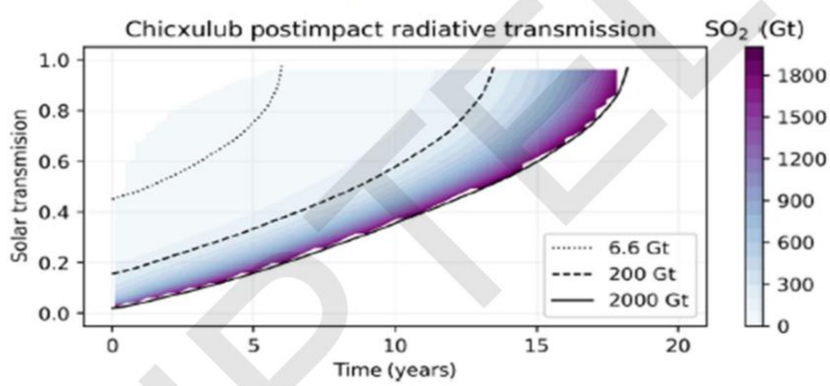
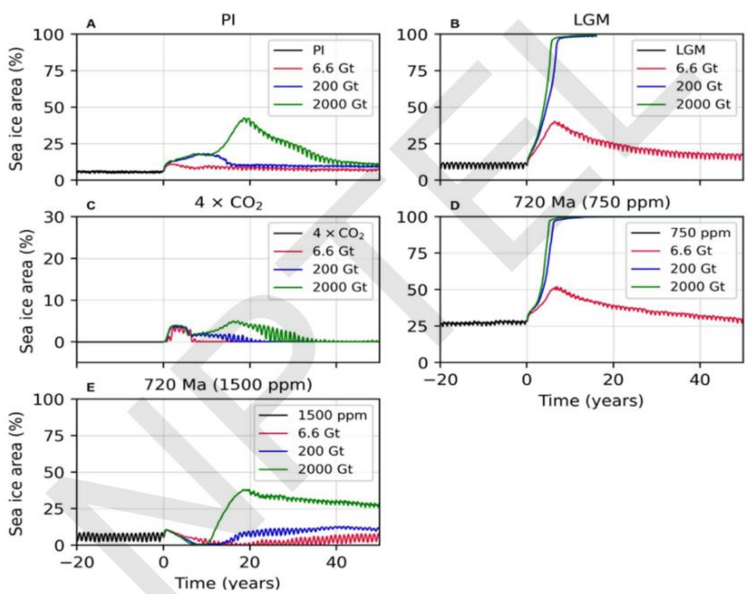


Fig. 1. Atmospheric transmission at a wavelength of 500 nm as a function of time after impact. Figure adapted from calculations of Pope *et al.* (46). Postimpact radiative transmission relative to preimpact is shown for three scenarios in black curves, with transmission curves for other volumes of SO_2 estimated through interpolation of the 6.6-, 200-, and 2000-Gt scenarios and shown in colored contours.

Now, one paper published this year looked at the impact of a large asteroid that changed the tilt. When the asteroid impact occurred, a huge amount of dust and sulfur dioxide was released by volcanic eruption, which cooled the Earth sufficiently. In the graph shown above, you can see how many gigatons of sulfur dioxide were released and how solar transmission declined, which led to the ice age.

In this paper, they did detailed calculations showing how many gigatons of sulfur dioxide would be needed, if released, for Earth to be almost completely covered with ice. So, that is a hypothesis, but the evidence is not strong enough to support it.



The author gave a table showing how temperature would change and whether a snowball would occur depending on the amount of CO_2. If CO_2 is very large—four times the pre-industrial level—there will be no snowball; but if CO_2 is small, like 190 ppm, for example, yes, a snowball could form. Or if CO_2 is large and the incoming radiation is small, then also a snowball Earth event can occur.

Table 1. Summary of all model experiments. Boundary conditions, preimpact global mean surface temperature, preimpact sea ice coverage, and whether Snowball Earth initiation occurs in response to the 200-Gt impact scenario are shown. PI, preindustrial.

Experiment	CO_2 (ppm)	Solar insolation	Preimpact surface temperature (°C)	Preimpact sea ice (%)	Snowball? (200-Gt SO_2)
PI	284.7	100%	15.1	5.5	No
LGM	190	100%	8.3	10.4	Yes
4 × CO_2	1138.8	100%	30.5	0.0	No
720 Ma (1500 ppm)	1500	94%	17.2	5.7	No
720 Ma (750 ppm)	750	94%	3.9	27.1	Yes

So, if there is a combination of incoming radiation and carbon dioxide, along with this impact, that could cause a Snowball Earth. This is a very unusual hypothesis, but it is not yet accepted universally.

Now, if you want to understand why a snowball didn't occur before 750 million years ago or after 600 million years ago, you need to know the conditions that made it possible. The first condition for Earth to be completely ice-covered is equatorially distributed continents. If the continents are near the equator, land has a higher albedo than the ocean, and most of the sunlight falls in the tropics. So, if the tropics are mostly covered with land, Earth's albedo is much higher, the global mean temperature is much lower, and the formation of glaciers and ice sheets is more probable.

Why didn't these Snowball Earth events occur all the time?

1. **Need an equatorial distribution of continents**
   Equatorially-distributed continents inevitably results in a colder Earth. Normally, land in the tropics has higher weathering rates, resulting in CO2 levels dropping and temperatures dropping, which is a check on weathering rates.
2. **In addition to albedo effects, equatorially distributed continents results in extensive polar ice caps. Then, the atmosphere will be drier (less latent heat in it), and atmospheric energy is reduced, and circulation is less effective in transporting heat from low latitudes to high latitudes. The tropics will be warmer but the poles will be colder, and will be more susceptible to albedo runaway.**

If most of the land regions are near the equator, then the atmosphere would also be drier. There would be less circulation to transport heat to the polar regions. Polar regions would start becoming ice-covered, although it would take time because the ocean has thermal inertia. So, the requirement is that most of the land must lie around the equator, which is not true today.

The Marinoan and Sturtian ice ages appeared because of the following three reasons:

1. Carbon dioxide was not very high. If it had been very high, ice would not have formed.
2. Incoming radiation was lower than today. It was about 94 percent of today's value because, as all of you know, solar radiation was about 70 percent of the present value when Earth formed 4.5 billion years ago. The nuclear reactions in the Sun have gradually increased solar output to the present value. Astronomers studied millions of stars like the Sun and, based on their age and radiation output, predicted that after a star's formation, its radiation output increases almost linearly until late in its life. So, we can say that 600 million years ago, incoming radiation was about 94 percent of the present value.
3. There had to be a supercontinent around the tropics.

All three of those conditions—low CO_2, reduced solar radiation, and a supercontinent in the tropics—were satisfied only between 600 and 750 million years ago.

Marinoan Ice age (- ~600 m.y.) and Sturtian Ice age(~750m.y)appear to be the most severe Ice Ages ever on Earth.

Why did such extreme ice ages did not appear before?

1. Role of CO_2

2. Role of solar insolation

3. Role of super continent in the tropics

So, the argument was that if Earth was completely frozen, then the carbon cycle would not work. How did carbon build up again? For this, we depend on plate tectonics: even when Earth is completely ice-covered, plate tectonics will continue to operate because it depends on heat from Earth's interior, which comes from radioactive decay, not sunlight. Molten rock inside the Earth continues to move because of radioactive decay. So, plate tectonics continues, and volcanism continues. Volcanoes eventually release CO_2 through the ice layer. Volcanic eruptions are violent. When they occur, they break open the ice and release CO_2 into the atmosphere. Therefore, a snowball Earth cannot last forever, because volcanoes will keep erupting occasionally and releasing CO_2. That CO_2 builds up, since CO_2 cannot become calcium carbonate because the carbon cycle cannot operate without photosynthesis.

But if the planet freezes over and its rocks are blanketed with ice, the CO2 thermostat switches off. Now there is all give and no take. Volcanoes keep giving out carbon dioxide, but the ice-covered rocks can no longer soak it back up again. Left unchecked in this way, the greenhouse effect of the CO2 will build and build until it's ten times, even a hundred times, what we have today

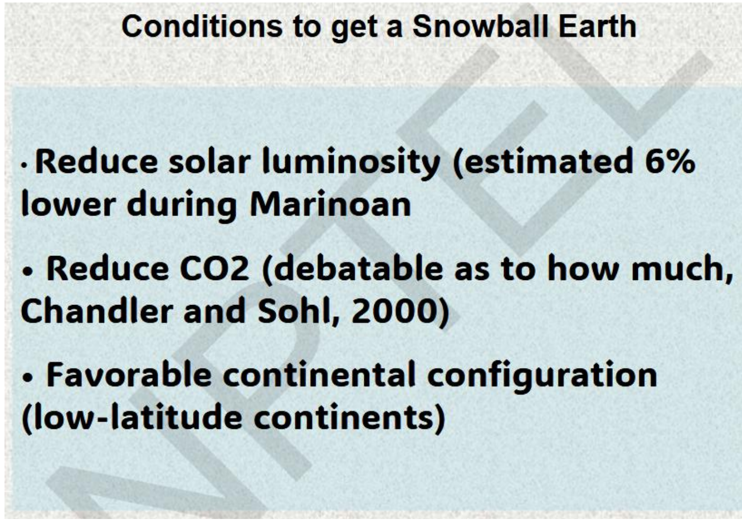
Plate tectonics is driven by energy from from Earth's internal heat. So under the sea ice and under the glaciers, the plates continued their slow lateral movement and volcanism. During the Snowball Earth, volcanoes continued to erupt and release CO2

So, the conditions to get a Snowball Earth are as follows:

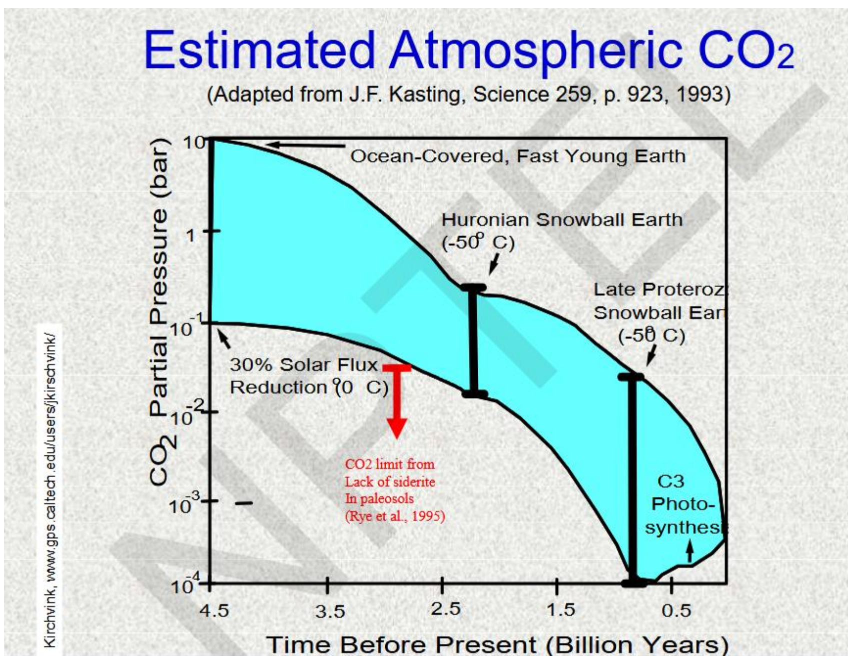
1. Reduced solar radiation, about 6 percent lower than present.
2. Reduced CO_2— although the exact amount is debated, because we do not have actual measurements of CO_2 600 million years ago, we have to guess.

3. Low-latitude continents (equatorially distributed land).

With these three factors, one can show that ice can cover almost the entire Earth.

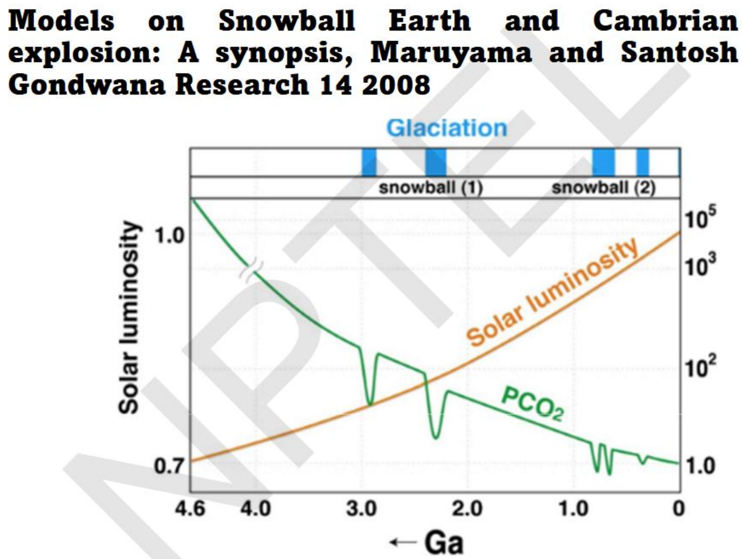


Here is an approximate estimate of Earth's CO_2 from its origin 4.5 billion years ago to the present.



In the beginning, Earth's atmosphere contained mostly CO_2—how much is uncertain, and values span a wide range. As photosynthesis began, CO_2 declined until we reached values quite low today, around 400 ppm. This is based on a model, so uncertainties are large; we have not measured actual values, and this is guesswork based on planetary evolution models.

It is important to understand why a snowball occurred in a certain period. For a snowball to occur, solar radiation must be low, not as high as present value, and CO_2 also must be low. Early on, CO_2 was high but solar radiation was low, so greenhouse warming dominated and Earth was not completely frozen. As CO_2 declined due to photosynthesis and solar radiation increased as the Sun brightened, there came a time around 600 million years ago when the combination of low solar radiation and low CO_2 was sufficient to initiate a Snowball Earth.



In the above cartoon, they mention four potential events, but we have good evidence for only two of them. Evidence for the other two is weaker.

Here is the configuration of the continents 635 million years ago and 720 million years ago, as inferred by geologists.

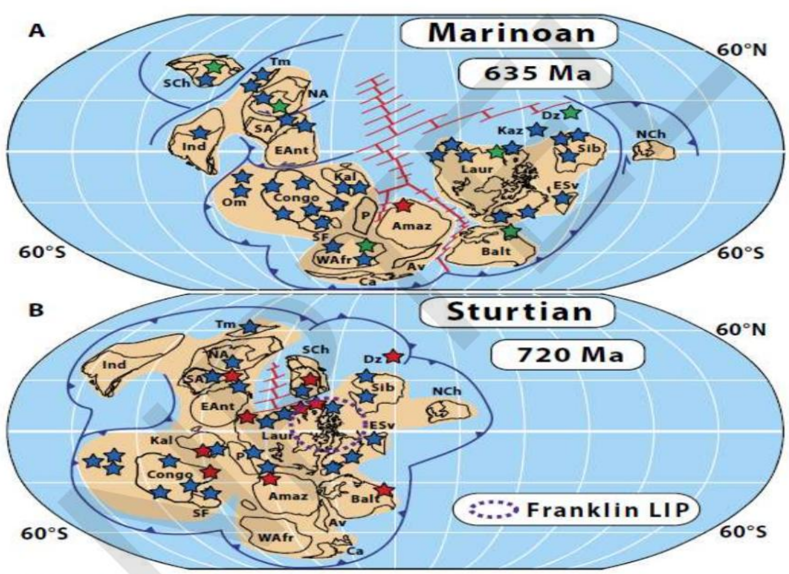


Fig. 5. Cryogenian paleogeography and the breakup of Rodinia. Global paleo-

You can see that at those times, most of the continents lay between 30° N and 30° S. India was at the equator 635 million years ago—and even at 720 million years ago, India was still near the equator. This is paleogeographic evidence from rocks. When the supercontinent Rodinia broke up, it led to this configuration.

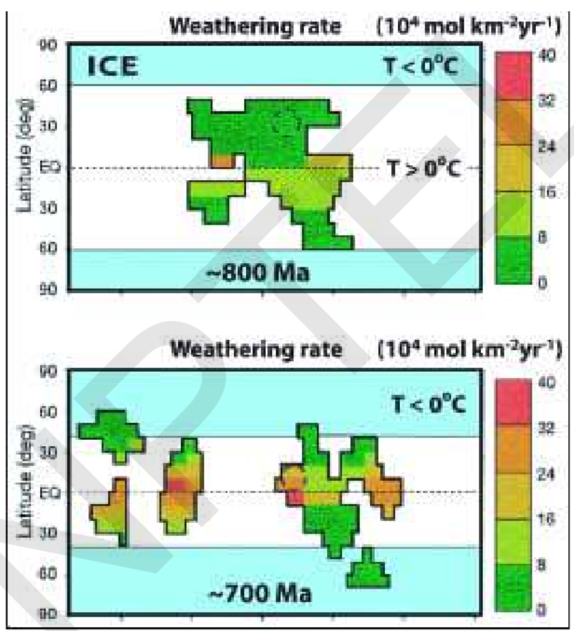
The most accepted model for the initiation of the Snowball Earth glaciations depends exquisitely on the level of the greenhouse gas carbon dioxide, CO2 in Earth's atmosphere.

A supercontinent called Rodinia formed in Earth's equatorial region. On account of warm, wet conditions there would have been enhanced chemical weathering of the rocks in that belt. The reactions of chemical weathering consume CO2

As chemical weathering proceeded, CO2 levels in the atmosphere would have fallen. Typically, weathering-induced CO2 drawdown is balanced by volcanic CO2emissions. But if the rate of tropical-weathering-induced CO2 drawdown was greater than the volcanoes could compensate for

The most accepted model for initiating Snowball Earth depends very sensitively on three factors: greenhouse-gas levels (like CO_2), the presence of continents around the equator, and incoming solar radiation. All three must align. It cannot happen often. If CO_2 becomes too high, snow will melt away. If continents shift away from the equator, it's gone. And if solar radiation is too high, then it is also not good. It requires a very special combination.

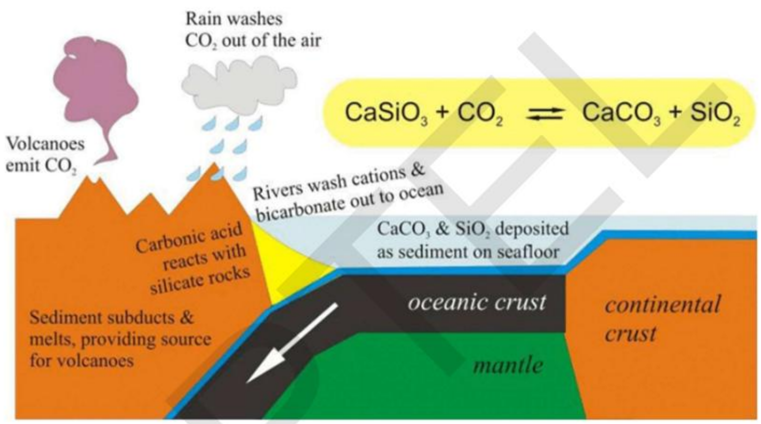
Another important factor is weathering.



Weathering is the chemical reaction of CO_2 with calcium silicate, for example. As you know from the Arrhenius equation, chemical reactions proceed much faster at high temperatures. Weathering is therefore strongest in the tropics, where temperatures are above freezing. When the temperature is low, chemical reactions proceed more slowly. On paleogeographic reconstructions from a little less than 800 million years ago, you can see orange and red areas (in the figure shown above) indicating where weathering was most intense. Weathering is critical for understanding atmospheric CO_2 because equatorially distributed continents result in a colder Earth and higher tropical weathering rates, which cause CO_2 to drop. Thus, with low CO_2, continents around the equator, and increasing albedo as ice forms, Earth can move toward a Snowball Earth state.

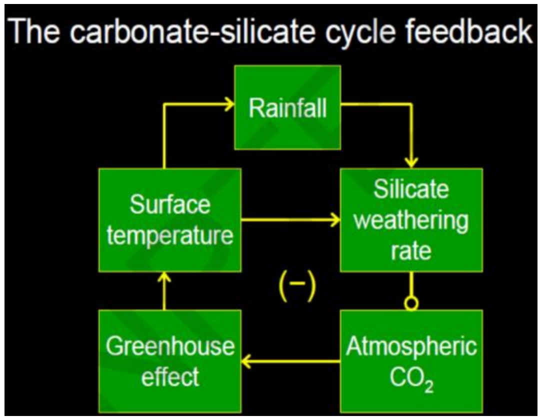
Equatorially-distributed continents inevitably results in a colder Earth. Tropics have higher weathering rates, resulting in CO2 levels dropping and hence temperatures dropping.
In addition to albedo effects, equatorially distributed continents results in extensive polar ice caps. The atmosphere is less effective in transporting heat from low latitudes to high latitudes. The tropics will be warmer but the poles will be colder, and will be more susceptible to albedo runaway.

Here is a cartoon showing the calcium-silicate reaction with CO_2, producing calcium carbonate.

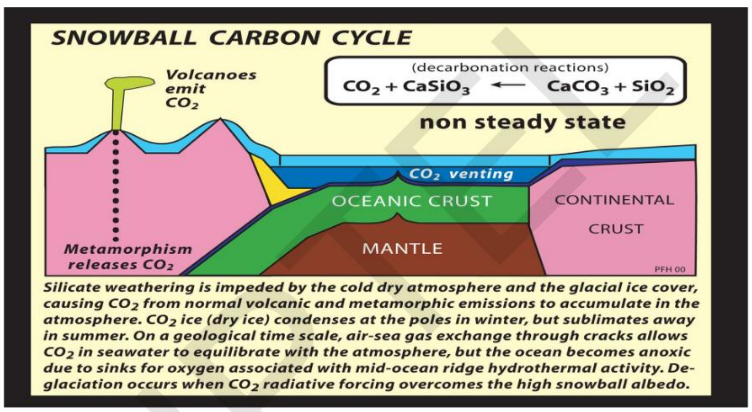


More land in the tropics will lead to more weathering (more rain and higher reaction rate) and lead to the reduction of CO_2

This is the long-term carbon cycle operating over a billion-year timescale—until recently, we weren't fully aware of its importance. More land in the tropics leads to more weathering, more rain, and higher reaction rates due to high temperatures. Rainwater dissolves CO_2 to form carbonic acid, which weathers silicate rocks and deposits calcium carbonate, controlling atmospheric CO_2. It's a delicate cycle: high temperature → high weathering → CO_2 removal → temperature drops → slower weathering → CO_2 builds up again. It is a very interesting cycle mediated by weathering, albedo, and the greenhouse effect.

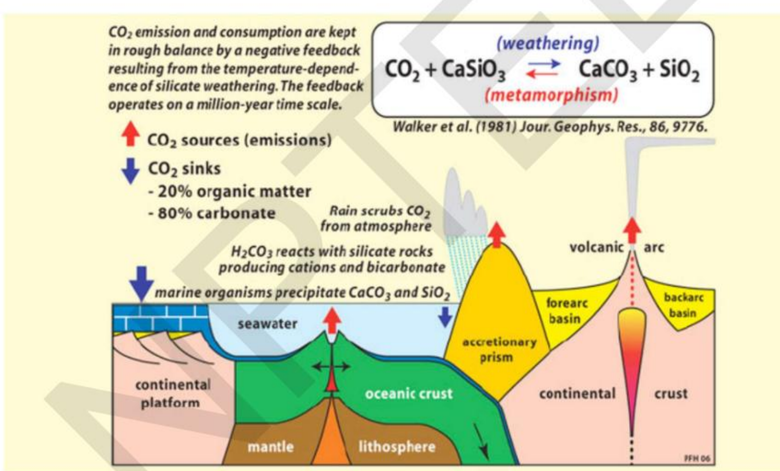


Here is another cartoon (from a Science article) showing how temperature-dependent silicate weathering acts as a geological thermostat. Before humans, Earth's carbon cycle maintained a fairly constant climate for long periods by keeping CO_2 reasonably stable.



How temperature-dependent silicate weathering acts as Earth's geological thermostat
Brantley et al., Science,379,2023

Silicate weathering reduces when the temperature is low, which increases CO_2 to form a negative feedback.



When Kirschvink and Hoffman first proposed the Snowball Earth hypothesis, many climate modelers over the next 40 years tried to demonstrate it. In a simple energy-balance model, it was possible, but that model is very simplified, so doubts remained. So, unless one demonstrates it in a complex general circulation model (GCM) with dynamic ocean, atmosphere, and land components, many scientists would not believe it.

There have been difficulties in recreating a snowball Earth with global climate models.

Simple GCMs with mixed-layer oceans can be made to freeze to the equator; a more sophisticated model with a full dynamic ocean (with a primitive sea ice model) failed to form sea ice to the equator.

The levels of CO2 necessary to melt a global ice cover have been calculated to be 130,000 ppm, which is considered by to be unreasonably large.

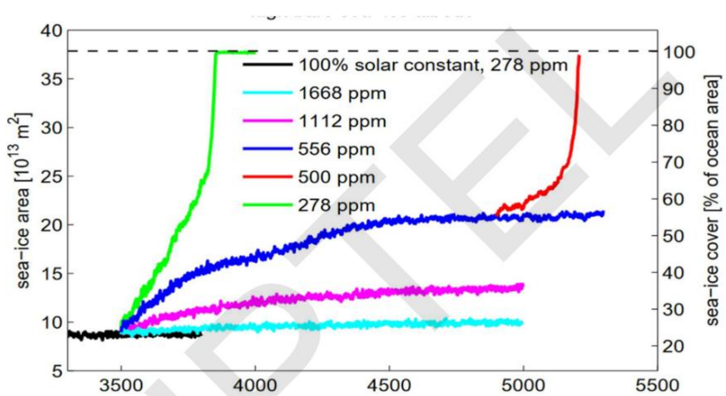
Some simple general circulation models with a mixed-layer ocean were able to show freezing at the equator; more sophisticated models with a dynamic ocean failed to form a snowball, raising questions. The level of CO_2 required in those models to melt the snowball after it formed was extremely high, raising further doubts. However, over the last 20 years, these issues have been largely resolved with improved modeling.

Results from complex climate models

The atmosphere-ocean general circulation model ECHAM5/MPI-OM initiates a Snowball Earth for Marinoan (~635 Ma) continents and solar insolation 1285 W/m^2 when CO2 is decreased to 500 ppm

For example, the ECHAM-5 model coupled with the MPI ocean model (a fully coupled ocean-atmosphere-land GCM) produced a snowball when incoming radiation was 1,285 W/m^2 (lower than today) and CO_2 was about 500 ppm. Thus, it is possible to generate a snowball in today's climate models, given the right combination of solar radiation and CO_2.

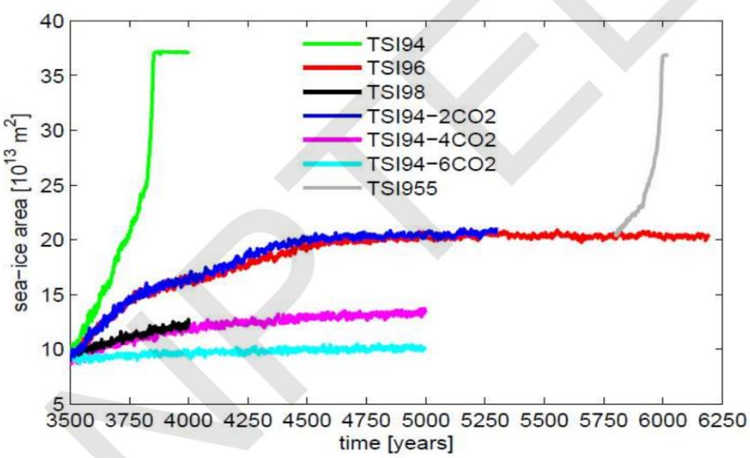
I have discussed this earlier in the course, but to recap: in the above model, it initiates a Marinoan Snowball Earth if you decrease the solar constant from today's value to 94 percent (the value 600 million years ago) and lower CO_2 to 278 ppm, within about 500 years, the ocean becomes completely sea ice covered. But if CO_2 is as high as 1,668 ppm, it does not form a snowball. Thus, snowball conditions only occur when CO_2 is sufficiently low. So, they argued that for Snowball Earth to occur, the CO_2 concentration should be below 500 ppm. If the CO_2 concentration was 278 ppm, it formed very quickly, even at 100% solar constant. So it showed that some combination of CO_2 concentration and solar constant gives the Snowball Earth.



Initiation of a Marinoan Snowball Earth in ECHAM5/MPI-OM The evolution of annual-mean global sea-ice cover in response to an abrupt decrease of the solar constant from 100 % to 94 % and a simultaneous increase of atmospheric carbon dioxide.

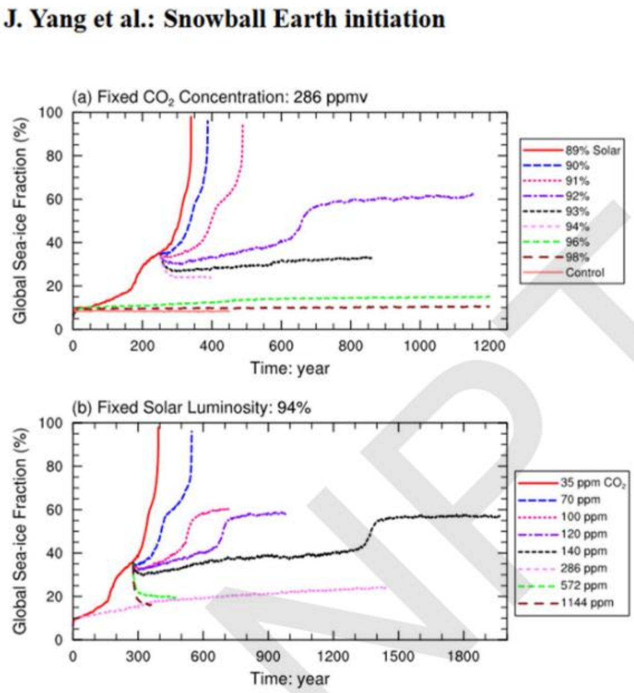
More data show a combination of total solar irradiance at 95 percent, 96 percent, etc, and the solar constant value resulting in the formation of sea-ice.

Initiation of a Marinoan Snowball Earth in a state-of-the-art atmosphere-ocean general circulation model



You see that only at certain combinations—like 95 percent solar value and present CO_2 concentration, or 95.5 percent solar value—does sea ice approach global coverage, though it takes longer for 95.5 percent solar value. In most cases, sea ice remains limited in extent.

A paper by Yang et al. simulated Snowball Earth for fixed CO_2 concentrations with varying incoming radiation. At 94 percent solar constant (which is correct for 600 million years ago), CO_2 had to be extremely low—around 70 ppm—for a snowball to form. At 140 ppm, it did not form. We don't know the exact CO_2 600 million years ago, so this is uncertain. Their model shows two solution regimes: one with snow at the equator (hard snowball) and one where equatorial temperature exceeds 10 °C (soft snowball).



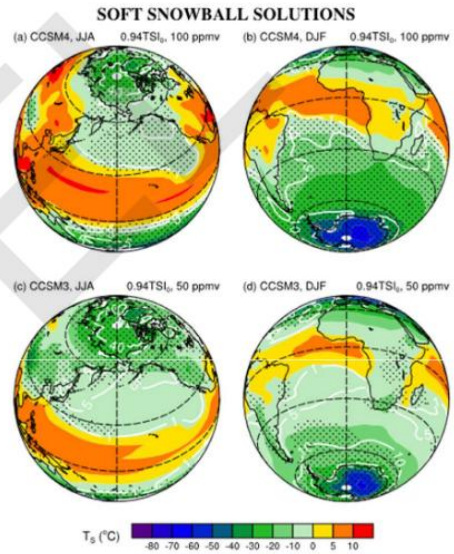


Fig. 7. Modern soft Snowball Earth solutions in CCSM4 (upper panel, 94 % solar radiation and 100 ppmv CO_2) and in CCSM3 (lower panel, 94 % solar radiation and 50 ppmv CO_2). Surface air temperature (°C, color shaded), sea ice thickness (m, white lines) and snow-covered regions (>0.04 m, stippled) in June-July-August (JJA, **a**, **c**) and in December-January-February (DJF, **b**, **d**).

At 50 ppm CO_2, most equatorial regions are snow-covered, but in summer (June–July–August), there are some warm conditions. Life can still survive if only a few months per year are ice-covered at the equator. Life on Earth is resilient: both soft-snowball (or slush ball) and hard-snowball states may allow survival.

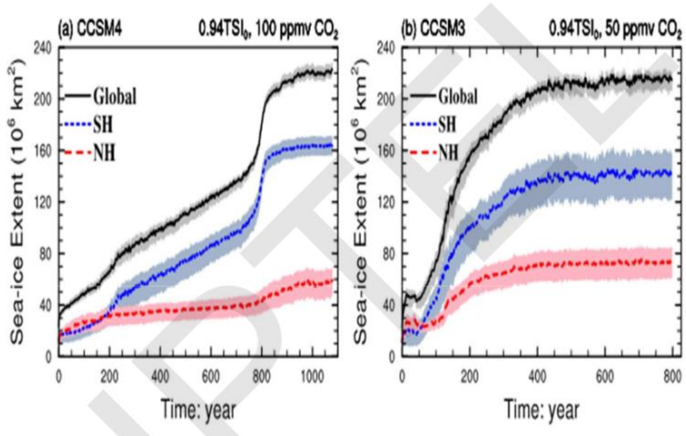


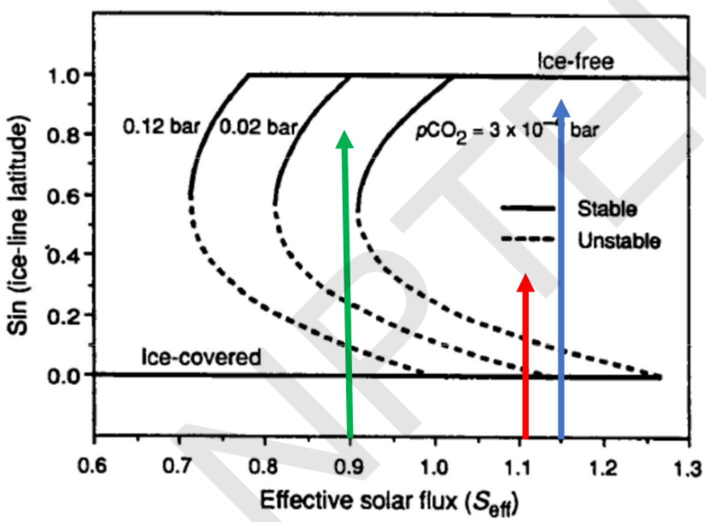
Fig. 8. CCSM4 **(a)** vs. CCSM3 **(b)**: sea ice evolution in the Northern Hemisphere (NH, red line), in the Southern Hemisphere (SH, blue line) and for total (Global, black line). Shaded area shows the range of the seasonal cycle. Note: the ocean area is 205×10^6 km^2 in the SH and 154×10^6 km^2 in the NH, and the entire Earth's surface area is 510×10^6 km^2.

Shown above is a simulation of sea-ice coverage in two versions of the CCSM model (CCSM3 vs. CCSM4). There are slight differences in how sea ice evolves, but in both cases, the global ice cover approaches its maximum. Notice that the Southern Hemisphere, having more ocean, shows a different curve (blue) versus the Northern Hemisphere with less ocean, but the overall outcome is similar.

Modelers still debate the albedo of sea ice—values for thick sea ice (>1 m) range from 0.4–0.5 in CCSM3 to 0.6–0.65 in CCSM4; observed variations are closer to CCSM3 values. For snow only on top of the glacier, CCSM4's values are more realistic, but uncertainties remain. There is still some doubt about the exact value of snow albedo that will trigger Snowball Earth.

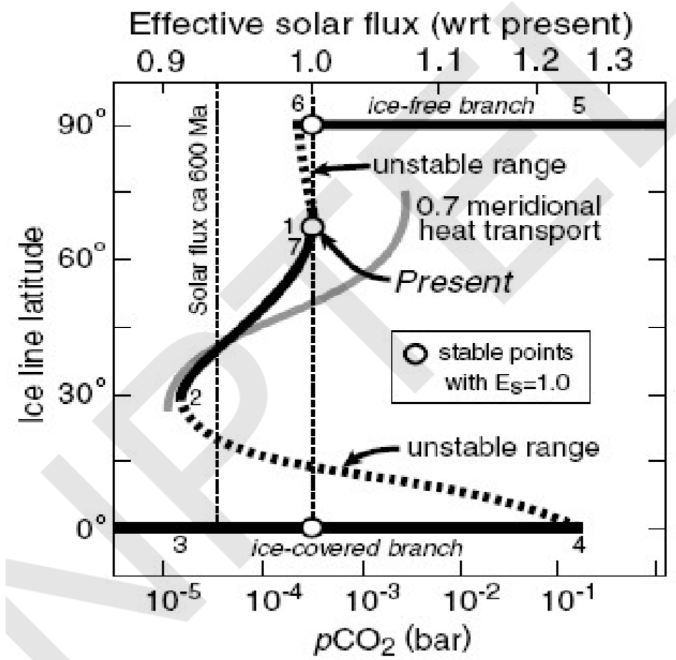
Table 1. Typical albedos for sea ice (>1 m), sea glacier (compressed snow over ocean), snow and melt pond in CCSM3, CCSM4 (see Briegleb and Light, 2007; Yang et al., 2012a) and observations (see Perovich, 1996; Warren et al., 2002; Warren and Brandt, 2006).

Surface type	CCSM3	CCSM4	Observation
Sea ice	0.43–0.50	0.61–0.65	0.47–0.52
Sea glacier			0.55–0.66
Snow	0.66–0.78	0.71–0.91	0.75–0.87
Melt pond		0.10–0.52	0.15–0.40



We need the correct combination of incoming solar radiation and level of CO2 in the atmosphere for snowball state

Let us understand this based on the simple energy-balance model we studied earlier: if incoming radiation is quite low (below one in the graph shown above) and CO_2 is sufficiently low (e.g., ~0.02 bar, which is higher than today), Earth tends toward ice free state; if it is little lower, Earth remains largely ice-covered. Thus, we need a correct combination of incoming solar radiation and CO_2 to yield a snowball state. Both simple energy-balance models and GCMs agree on this.



Finally, let us look at the work of Hoffman (a well-known Science paper), which uses a more complicated picture. The black line is stable, and the dotted line is unstable. He is showing that there is an ice-free branch and an ice-covered branch, which is stable depending on the amount of CO_2 and the amount of incoming radiation.

So, with these things we know that under certain conditions, Snowball Earth could have existed 600 million years ago. I will continue the discussion in the next lecture to give you some more evidence to show that Snowball Earth did indeed occur.

With that, we will close our discussion in the next lecture on the paleoclimate of the Earth. All these were given to convince you that the Earth's climate went through various phases, ice-free Earth, ice-covered Earth, and in between. So, one has to be careful about what can happen in the future. Thank you.