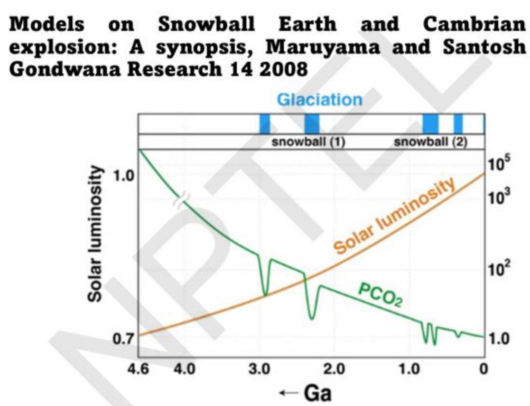
Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 41
Simulation of Snowball Earth

Around 600 million years ago, Earth experienced a remarkable climatic episode known as the Snowball Earth event, during which ice likely covered almost the entire planet, including equatorial regions. While simple energy balance models suggest such a scenario is theoretically possible, the idea was long considered implausible due to the assumption that global ice cover would make photosynthesis, and therefore life, unsustainable. However, geological evidence discovered in recent decades, such as glacial deposits on equatorial rocks, confirmed that this extreme glaciation indeed occurred.



To understand why Snowball Earth happened at that time and not during more recent glacial episodes such as the ten major ice ages of the last million years, it is important to consider two key variables: atmospheric carbon dioxide and incoming solar radiation. Carbon dioxide, though less abundant today than water vapor, is the primary driver of Earth's long-term climate because water vapor levels depend on temperature, which CO_2 regulates. In Earth's early history, CO_2 concentrations were extremely high but have since declined. Around 600 million years ago, they were still higher than today's 400 ppm.

The second factor is solar luminosity. The Sun, a fusion-powered star, has gradually increased its energy output since its formation 4.6 billion years ago. During the Snowball Earth period, solar radiation was weaker than it is today. Thus, a combination of lower solar luminosity and moderately high CO_2 could have tipped Earth into a fully glaciated state.

Although energy balance models can illustrate the possible combinations of CO_2 and solar radiation leading to such conditions, they oversimplify the climate system. They omit key dynamics such as the role of ice sheets, snow accumulation and melting, and ocean circulation. Therefore, to accurately assess the likelihood and mechanisms of Snowball Earth, more comprehensive climate models are required. These advanced models incorporate physical processes that are essential for simulating the conditions that triggered and ended such global-scale glaciation.

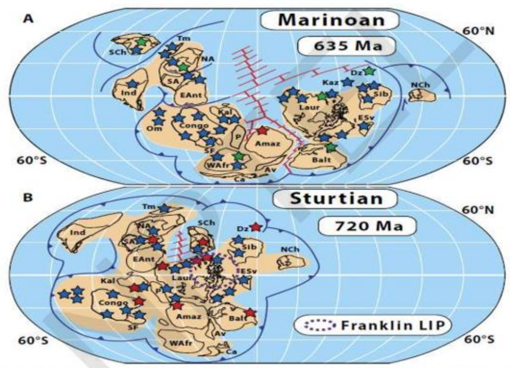


Fig. 5. Cryogenian paleogeography and the breakup of Rodinia. Global paleo-

Another important factor in the occurrence of Snowball Earth is the distribution of continents. If most continental landmasses are located near the equator, the likelihood of global glaciation increases. This is because the tropics receive the highest amount of incoming solar radiation. Land, having a higher albedo than ocean, reflects more of this radiation back into space. When large areas of the tropics are covered by land, the Earth's overall albedo increases, reducing the amount of absorbed solar energy and promoting cooling.

Therefore, the combination of reduced solar luminosity, elevated but declining CO_2 levels, and equatorially clustered continents created conditions favorable for global-scale glaciation. Modern climate models can now simulate such scenarios by incorporating these factors, helping us understand how Snowball Earth could have been triggered and maintained.

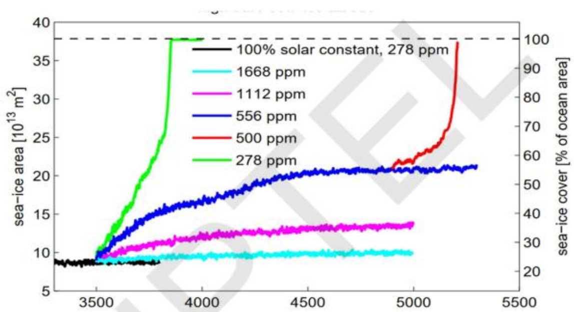
When fully coupled ocean-atmosphere climate models with interactive ice sheets were first used to simulate Snowball Earth conditions, they struggled to generate a completely ice-covered planet. In contrast, simpler models with a slab or mixed-layer ocean (i.e., lacking dynamic ocean circulation) could simulate global glaciation, including equatorial sea ice. However, more realistic models with full ocean circulation and basic sea ice physics often failed to achieve ice coverage at the equator.

This discrepancy raised two key challenges: first, ensuring that models could realistically simulate a fully glaciated Earth; and second, identifying the levels of atmospheric CO_2 required to melt out of such a frozen state. Some early models estimated that over

130,000 ppm of CO_2 would be necessary to deglaciate a Snowball Earth which are considered implausibly high values.

Despite modeling challenges, geological evidence indicates that Earth did emerge from Snowball conditions roughly 600 million years ago, followed by a significant burst in biological complexity. Many biologists view this Snowball event as a catalyst for the evolution of multicellular life. The extreme environmental stress may have driven organisms to evolve adaptive, more complex traits.

To better understand these transitions, one advanced model used was ECHAM5, coupled to the Max Planck Institute Ocean Model. This model could simulate Snowball Earth conditions during the Marinoan glaciation (about 635 million years ago) when solar insolation was approximately 1285 W/m² (lower than today), and CO_2 was reduced to 500 ppm. However, a major limitation is the lack of direct proxy data for atmospheric CO_2 levels from that far back in time. Unlike the last million years, for which ice cores provide detailed greenhouse gas records, the deep past relies on indirect reconstructions with significant uncertainties. Therefore, modelers must vary CO_2 inputs experimentally to examine possible climate states.

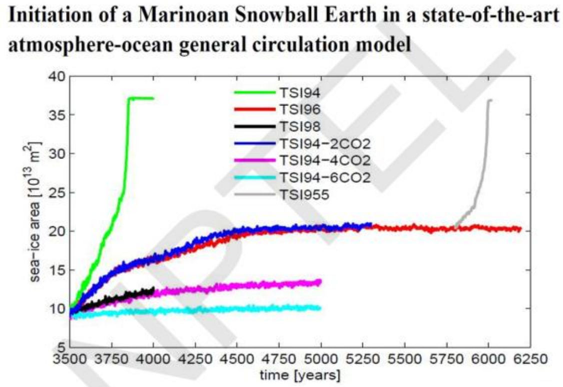


Initiation of a Marinoan Snowball Earth in ECHAM5/MPI-OM The evolution of annual-mean global sea-ice cover in response to an abrupt decrease of the solar constant from 100 % to 94 % and a simultaneous increase of atmospheric carbon dioxide.

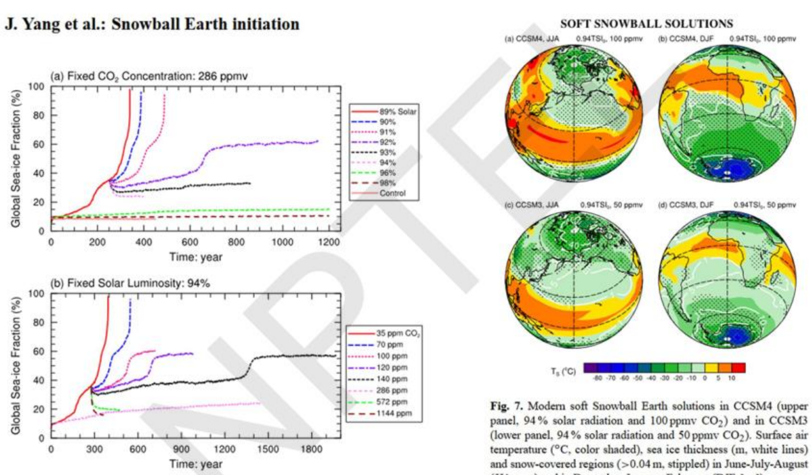
Simulations using the ECHAM5 atmospheric model coupled with the Max Planck Institute Ocean Model reveal how global sea ice cover responds to changes in solar radiation and atmospheric CO_2 levels, exploring conditions relevant to the Snowball Earth hypothesis. In these simulations, the solar constant was abruptly reduced from 100% to 94% of its present value, reflecting the lower solar output believed to have existed around 600 million years ago.

When CO_2 was set at 278 ppm (pre-industrial levels), the Earth rapidly developed complete sea ice coverage, indicating a transition to Snowball Earth conditions. When CO_2 was increased to 556 ppm (double the pre-industrial level), the system remained ice-free for nearly 5,000 years before a rapid ice expansion occurred after lowering CO_2 to 500 ppm. For even higher CO_2 concentrations, such as 1,112 ppm and 1,668 ppm, the model showed no significant sea ice growth.

These results suggest that, within this model framework, a Snowball Earth state can be triggered only when the solar constant is reduced to about 94% of its current value and atmospheric CO_2 is at or below 500 ppm. This illustrates the delicate balance between solar input and greenhouse gas levels in determining global glaciation thresholds.



Additional simulations using the ECHAM5–MPIOM model further highlight the sensitivity of Snowball Earth initiation to both solar radiation and atmospheric CO_2 levels. When the solar constant is reduced by 6% (to 94% of present levels) and CO_2 is set at 278 ppm, the Earth rapidly transitions into a fully ice-covered state. However, if the solar constant is reduced by only 4.5%, even with the same CO_2 concentration, the transition to a Snowball Earth takes significantly longer. This clearly demonstrates that the onset of global glaciation is highly sensitive to even small changes in solar input, indicating that both CO_2 and solar radiation thresholds must be crossed simultaneously to trigger a Snowball Earth scenario.



Further simulations explored the individual roles of solar radiation and atmospheric CO_2 in triggering Snowball Earth. Keeping CO_2 fixed and reducing solar radiation confirmed that a ~6% reduction from present-day insolation is necessary to induce global glaciation. Conversely, holding the solar radiation 6% below present and varying CO_2 levels revealed that full Snowball conditions occur only when CO_2 drops to around 70 ppm. Examining seasonal effects, the equatorial region in these simulations showed no ice cover during June–August, but ice did form during December–February. When CO_2 was reduced to 50 ppm, the Earth remained largely ice-covered in winter, though brief summer melting persisted. This implies that Snowball Earth may not have been fully glaciated year-round, offering a possible refuge for life during summer months - an interpretation many biologists favour, as it allows photosynthetic life to survive even under severe glaciation.

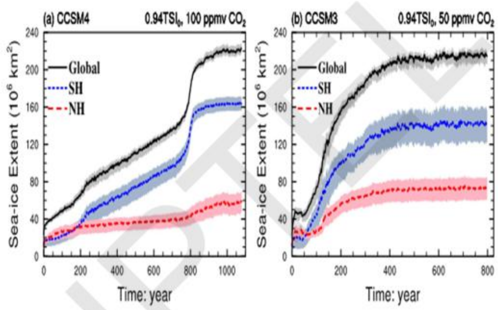
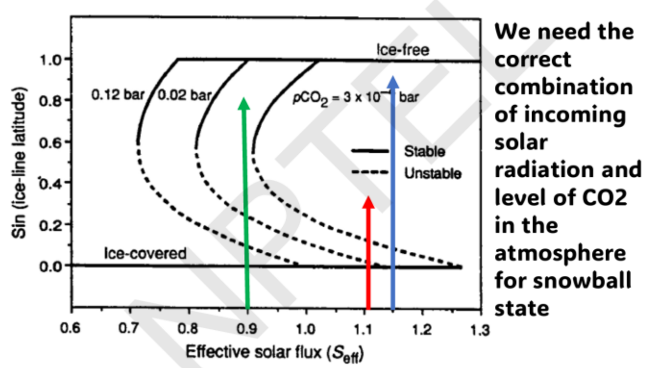


Fig. 8. CCSM4 **(a)** vs. CCSM3 **(b)**: sea ice evolution in the Northern Hemisphere (NH, red line), in the Southern Hemisphere (SH, blue line) and for total (Global, black line). Shaded area shows the range of the seasonal cycle. Note: the ocean area is 205 x 10^6 km^2 in the SH and 154 x 10^6 km^2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

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).

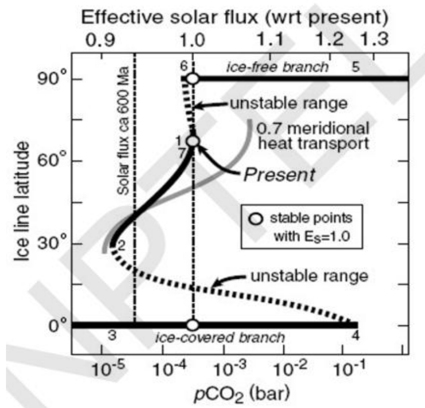
Surface type	CCSM3	CCSM4	Observation
Sea ice	0.43–0.50	0.61–0.65	0.47–0.52
Sea glacier			0.55–0.66
Snow	0.66–0.78	0.71–0.91	0.75–0.87
Melt pond		0.10–0.52	0.15–0.40

Comparisons between simulations using CCSM4 and CCSM3 reveal notable differences, highlighting the sensitivity of Snowball Earth results to the climate model used. These differences arise largely from how each model handles surface albedo, particularly of sea ice and snow. Sea ice albedo is influenced by snow cover. Bare ice is more transparent and absorbs more solar radiation, while snow-covered ice is much more reflective. CCSM4 assumes a higher sea ice albedo than CCSM3, leading to enhanced cooling and a greater likelihood of achieving full ice cover. Since we lack direct observational data on past albedo values, especially during Snowball Earth conditions, such assumptions introduce uncertainties into model outcomes. Observations from the modern Arctic show a wide range of albedo values, with fresh snow consistently reflecting more sunlight than bare ice.



The occurrence of Snowball Earth can also be interpreted using a simple energy balance model that explores the relationship between solar flux and atmospheric CO_2 concentration. In the above figure, the latitude of the ice line (where ice ends and open surface begins) is plotted against solar radiation, with different curves representing various CO_2 levels (e.g., 0.12 bar, 0.02 bar, etc.). If the ice line is at 90°, the Earth is ice-free; if at 0°, the Earth is completely ice-covered.

This model shows that for a wide range of CO_2 concentrations, both ice-free and fully ice-covered states are possible, two stable solutions. The key insight is that as ice expands and crosses a critical latitude (around 30°, or arcsin(0.5)), the feedback from increasing albedo becomes strong enough to trigger a runaway effect. Once the ice line moves past this threshold, partial ice cover becomes unstable, and the Earth rapidly transitions to full glaciation. This bi-stability and critical tipping behaviour are central to understanding how Snowball Earth could initiate under certain combinations of low solar input and CO_2 levels.



Hoffman's model on Snowball Earth similarly illustrates three types of climate solutions: fully ice-free, fully ice-covered, and a partially glaciated state. However, for conditions representative of ~600 million years ago, particularly lower solar insolation, only two stable outcomes emerge where either the planet remains ice-covered up to about 40° latitude or it becomes fully ice-covered. There is a critical instability around 30° latitude; once ice advances past this point, the system rapidly transitions to complete glaciation due to albedo feedbacks.

Climate and ocean circulation in the aftermath of a Marinoan snowball Earth
Clim. Past, 18, 759–774, 2022

Figure 1. Topography of the Marinoan setup. Land areas (dark grey) have an elevation of 300 m above sea level, and the ocean (white) has a depth of 3500 m. The distribution of continents follows Li et al. (2013) and Merdith et al. (2017) and is simplified

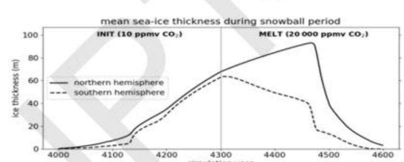


Figure 3. Evolution of the mean sea-ice thickness in the hemispheres during the snowball period. The vertical line denotes the transition from a low CO_2 concentration in INIT to a high CO_2 concentration in MELT.

The results are sensitive not only to incoming solar radiation and CO_2 concentration but also to the arrangement of continents. For example, placing continents in their Marinoan positions influences the resulting climate state. Hoffman's simulations using very low CO_2 levels (e.g., 10 ppm) show extensive and thick global ice coverage. However, at higher CO_2 levels (e.g., 20,000 ppm), melting begins and ice thins significantly, which could allow for limited photosynthetic life to survive. Additionally, hemispheric asymmetries due to differences in landmass distribution can also impact regional glaciation and ice thickness.

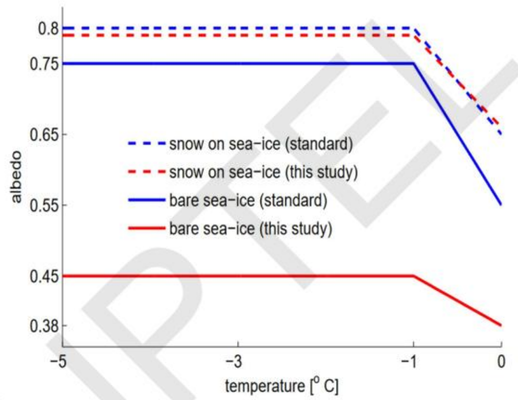


Fig. 2. Albedo of snow on sea ice (dashed) and bare sea ice (solid) of the standard setup of ECHAM5/MPI-OM used in Voigt et al. (2011) and Voigt and Marotzke (2010) (blue) and the values adopted from the Community Atmosphere Model version 3 used in this study (red).

One major challenge in Snowball Earth modeling lies in assumptions about surface albedo: high for snow-covered ice, lower for bare ice, and very low for open ocean. These fixed values heavily influence model outcomes. In the study by Voigt et al., albedo changes dynamically with temperature where ice begins melting once temperatures rise above -1°C. To address concerns about the survivability of life, an alternative hypothesis called the Slushball Earth has been proposed, suggesting that while most of the planet was ice-covered, open water may have persisted near the equator.

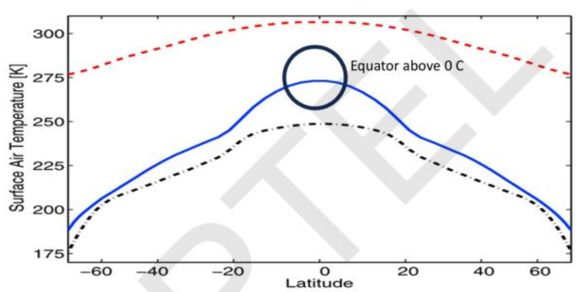


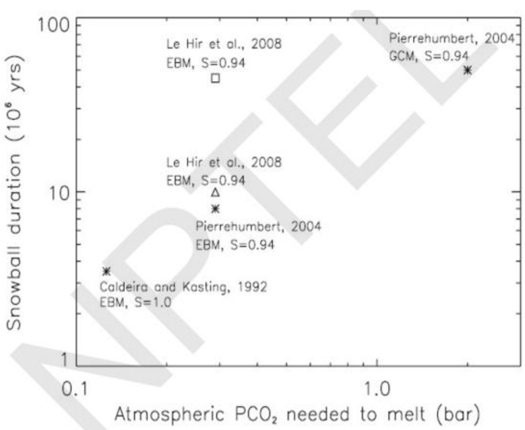
Figure 3. Annual and zonal mean surface air temperature for the ice-free state (red dashed), Jormungand state (blue), and Snowball state (black dash-dotted) with $pCO_2 = 5000$ ppm.

CAM aquaplanet model (no continents) with an ocean mixed layer of depth 50 m, a thermodynamic sea ice scheme, no ocean heat transport, no aerosols, and with diurnal and annual cycles, but a solar constant that is 94% of its modern value

Voigt's model introduces the "Jormungand" state, a version of Snowball Earth in which ocean water remains ice-free between 20°N and 20°S, with ice covering the rest of the globe. Although this model omits continents (aqua-planet setup), it includes a full annual and diurnal cycle. With a solar constant reduced to 94% of the present value and CO_2 levels set at 5,000 ppm, the model generates a narrow equatorial band of open ocean just enough to potentially support photosynthetic life. This result highlights the system's sensitivity to ice-ocean albedo contrast and suggests that complete ice coverage may not have been inevitable, especially under elevated greenhouse gas levels.

There remains active debate regarding whether Earth was ever completely ice-covered during Snowball Earth episodes. Some recent studies challenge the total glaciation hypothesis by pointing to sedimentary records from these periods that suggest the presence of dynamic glaciers and flowing ice streams entering the ocean, indicating at least partial open water and undermining the idea of a fully frozen planet.

A key limitation in many early Snowball Earth simulations is the absence of explicit ice sheet dynamics. Simpler models account for sea ice and snow but lack the physics of thick, deformable ice sheets that can flow, depress landmasses, and affect isostatic rebound. Some researchers now argue that simulating full glaciation requires models that include realistic ice sheet behaviour to capture the extent and feedbacks of glacial coverage.



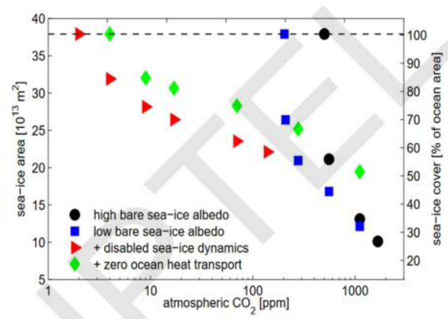
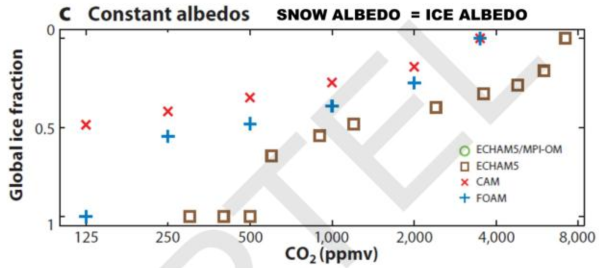


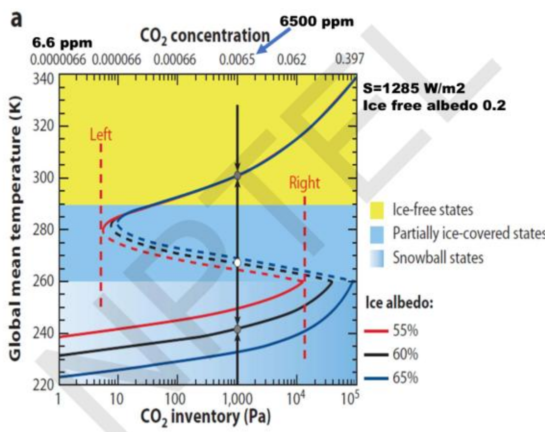
Fig. 10. Sea-ice cover as a function of CO_2 for simulations with high bare sea-ice albedo (black circles; Voigt et al., 2011), simulations with low bare sea-ice albedo (blue squares), simulations with low bare sea-ice albedo and disabled sea-ice dynamics (red triangles), and simulations with low bare sea-ice albedo, disabled sea-ice dynamics and zero ocean heat transport (green diamonds). All simulations use 94 % solar insolation.

Another major question concerns how Earth escaped from a Snowball state. In the absence of photosynthesis and weathering, volcanic CO_2 emissions would accumulate in the atmosphere unchecked. Over time, this would lead to significant greenhouse warming. Model simulations suggest that atmospheric CO_2 levels would need to rise to around 1000 ppm to reduce sea ice coverage from 100% to about 30%, similar to levels seen during past interglacial periods. The rate at which CO_2 accumulates depends on volcanic outgassing rates, and estimates can be made for the time it would take for concentrations to rise from ~500 ppm to ~1000 ppm. This process of CO_2-driven deglaciation is widely considered the most plausible mechanism by which Earth emerged from Snowball conditions.



The equilibrated sea-ice fraction as a function of CO_2 for the Snowball model intercomparison (SNOWMIP) model runs in each albedo case: (*a*) default albedos, (*b*) SNOWMIP albedos, and (*c*) constant albedos. In the SNOWMIP albedo case, the sea-ice albedo is 0.6 and the snow albedo is 0.9. In the constant-albedo case, both the sea-ice and snow albedos are 0.6. Abbreviations: CAM, National Center for Atmospheric Research's Community Atmosphere Model v3.1; ECHAM5, Max Planck Institute's atmospheric model v5.3.02p; ECHAM5/MPI-OM, ECHAM5 coupled to the Max Planck Institute Ocean Model v.1.2.3p2; FOAM, Fast Ocean Atmosphere Model v1.5.

Model simulations, such as those using the ECHAM5 model, show that as atmospheric CO_2 levels increase, the global ice fraction steadily decreases until complete deglaciation occurs. In this model, the Earth remains entirely ice-covered up to CO_2 concentrations of around 500 ppm. Beyond this threshold, ice cover begins to decline, and by approximately 4,000 ppm, the ice fraction reduces to about 30%, a value comparable to conditions during the last million years. This abrupt transition from full glaciation to partial or ice-free states highlights the nonlinear response of the climate system. These simulations help estimate how long a Snowball Earth state could persist before being terminated by the gradual buildup of volcanic CO_2 in the atmosphere.



The onset and termination of Snowball Earth conditions can also be examined using a simple energy balance model by analysing the relationship between atmospheric CO_2 concentration and global mean temperature under different ice albedo assumptions. Ice albedo plays a crucial role: bare ice reflects about 55% of incoming radiation, while snow-covered ice can reflect up to 65%. For a solar constant of 1285 W/m², representative of the late Precambrian, complete global glaciation occurs when CO_2 levels drop below ~50 ppm. Conversely, when CO_2 exceeds ~62,000 ppm, the Earth becomes ice-free. Between these extremes, partial ice cover solutions exist.

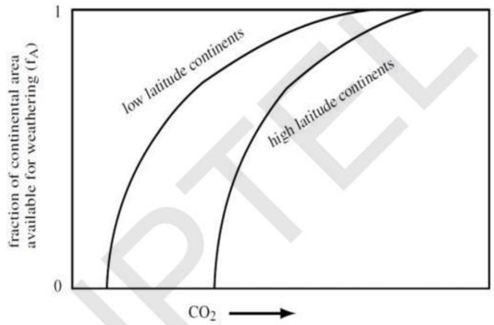
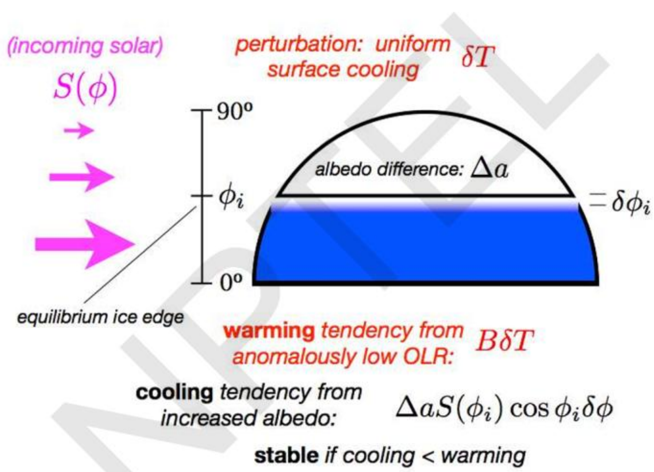


Figure 1. A schematic representation of the fraction of land area available for silicate weathering as a function of the partial pressure of atmospheric carbon dioxide for high- and low-latitude continental distributions. As carbon dioxide drops, glaciation commences on high-latitude continents, reducing the rate of silicate weathering in those areas and stabilizing the atmospheric CO_2. If most of the continents were in the tropics, this effect would not commence until CO_2 levels were substantially lower.

Additionally, continental configuration significantly affects climate stability. When continents are concentrated near the equator, their higher albedo increases the likelihood of glaciation due to greater solar reflection in low-latitude regions where insolation is highest. In such cases, deglaciation requires higher CO_2 levels compared to configurations with more polar continents. Thus, both CO_2 concentration and land distribution critically determine the onset and termination of Snowball Earth events.



From the energy balance perspective, the distribution of incoming solar radiation across latitudes plays a central role in the dynamics of ice sheet growth. Annual mean insolation is highest in the tropics and much lower at the poles, primarily due to the polar regions experiencing long periods without sunlight. If ice extends equatorward to a certain latitude (ϕ_i), the area covered by ice increases significantly, raising the planet's overall albedo. A higher albedo leads to more reflection of solar radiation and thus promotes further cooling, encouraging continued ice growth in a positive feedback loop.

However, this tendency is moderated by the meridional transport of heat from low to high latitudes. In simplified energy balance models, this heat transport is often represented by a diffusive or linear approximation, where the heat flux is proportional to the temperature difference between a given latitude and the global mean, scaled by a constant 'C'. This equator-to-pole heat transport works to warm the polar regions and melt ice, thereby opposing the albedo-driven cooling. The interplay between the albedo feedback (promoting ice growth) and poleward heat transport (promoting melting) ultimately governs the stability of partial ice cover and the potential transition to a Snowball Earth state.

In the context of Earth's spherical geometry, the progression of ice sheets toward the equator leads to a tipping point beyond which the growth becomes self-reinforcing and irreversible. This concept is known as large ice cap instability. As ice extends equatorward, the planetary albedo increases significantly due to the expanding high-albedo ice cover replacing lower-albedo surfaces like ocean or land. The increased albedo reduces absorbed solar radiation, enhancing cooling and thus further ice growth - a positive feedback loop.

To analyse this, consider a balance between two competing processes:

1. Cooling due to increased albedo, quantified by the change in absorbed solar radiation as a function of latitude, adjusted for surface area (cos(ϕ) weighting) and the linear approximation of outgoing longwave radiation (OLR = A + BT).
2. Warming due to meridional (poleward) heat transport, often modelled as proportional to the meridional temperature gradient: -C(dT/dϕ), which is positive since dT/dϕ is negative (temperature decreases from equator to pole).

The condition for ice growth can be shown as below:

$$\frac{\delta\alpha \times S(\varphi_i) \times \cos(\varphi_i)}{B} < -\left.\frac{dT}{d\varphi}\right|_{\varphi_i} \delta\varphi$$

If the cooling effect exceeds the warming from heat transport (LHS > RHS), then ice will continue to grow. This leads to a critical latitude, typically around 30–33° from the equator, beyond which ice growth becomes unstable and rapidly expands to cover the entire globe.

This threshold has important implications: in the last million years, ice sheets during glacial maxima extended to ~40°N but did not cross the critical latitude, thus avoiding a transition to a full Snowball Earth. If they had extended further equatorward beyond this threshold, a runaway glaciation might have ensued. This dynamic explains why Snowball Earth events are rare and require specific combinations of solar luminosity, atmospheric CO_2, and continental configuration to occur.