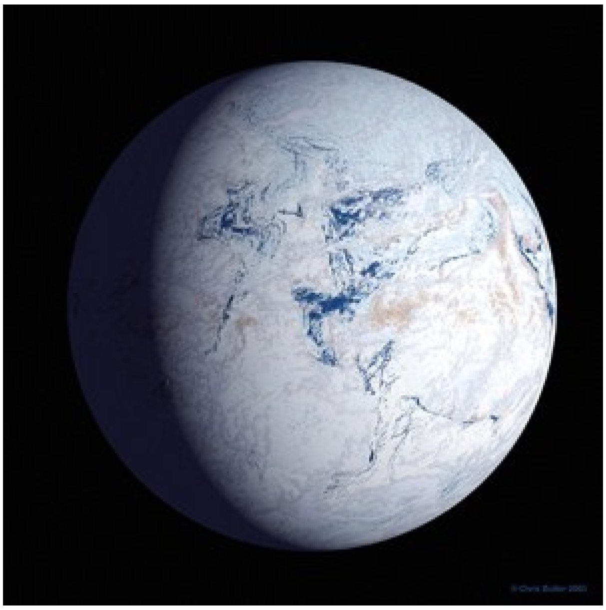
Snowball Earth



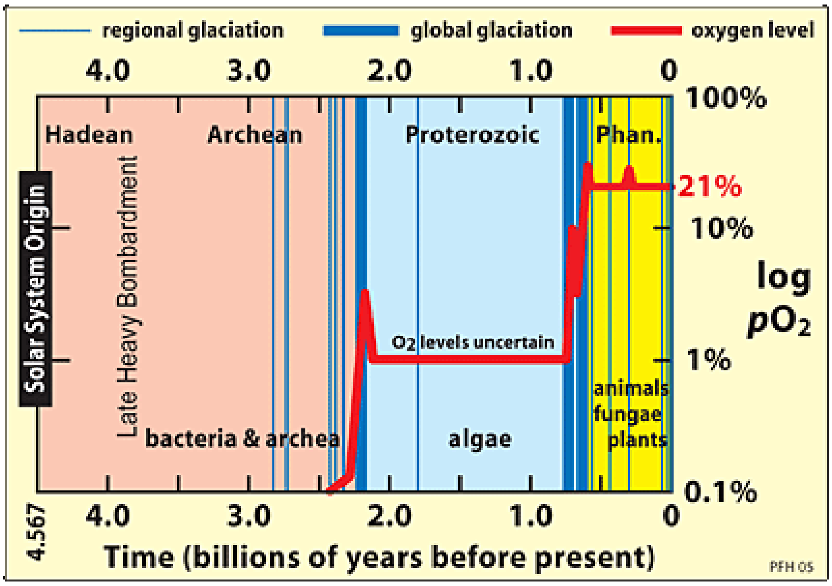
http://www.cosmosmagazine.com/features/print/2779/ice-world-catalyst-life

What is Snowball Earth?

Snowball Earth is a hypothesis created to offer an explanation about the climate during the Neoproterozoic period within the Proterozoic Ion. Snowball Earth hypothesis is that the Earth was once covered in snow and ice from pole to pole with an average temperature of -50°C for long periods of time. The surface albedo would reflect most of the sun´s radiation and the atmosphere would be cold and dry but it would still transfer some water vapour.

History

It has been estimated that there were 3 snowball earth´s within the Neoproterozoic era in the Proterozoic eon.



http://www.snowballearth.org/when.html

- The oldest snowball earth occurred about 2200 million years ago called Makganyene.
- The second snowball earth occurred approximately 710 Myrs ago called Sturtian.
- The last snowball earth was called Marinoan and ended 635 Myrs ago.

Causes

Since the three known, totally earth-covering glaciation periods appeared at different ages and therefore at different climatic and tectonic conditions of the earth, also the reasons for their development vary. The coupling of some of these processes is most likely to overcome the necessary limit for a snowball earth glaciation, which is estimated to be ice coverage up to 30° in latitude (Kirschvink 2002). From this point on, the ice albedo rises rapidly until even equatorial areas are ice sheeted and earth temperature reaches about -50°C. The analysis of geological data during the last few decades resulted in a couple of major causes for the massive glaciation. These causes are:

- Preponderant equatorial position of the continents at the respective period of time
- Unusually high volcanic activity in terms of supervolcano eruptions
- Highly reduced amount of atmospheric CO_2 concentration
- Drastic decline of CH_4 and corresponding increase of O_2 in the atmosphere

The influence of continental predominance at equatorial positions on the solar heat budget of the earth, at first possibly misleading, can be explained by the high absorbing power of tropical oceans. The albedo of tropical continents is generally high, whereas dark coloured tropical oceans absorb most of energy-rich equatorial radiation (Jacobsen 2001). If the continents accumulate at lower or mid latitudes, more tropical seawater is covered by landmass and the continental reflection is intensified. As the amount of solar radiation received by the sea water is reduced, also the heat transfer of the ocean is affected (Donnadieu *et al.* 2004). A further bearing of landmass preponderance at mid latitudes is the hot and dry climate condition, which triggers lifted rates of CO_2 or carbon deposition with respect to the carbon cycle (Hoffman *et al*. 2006).

The eruption of so-called supervolcanoes potentially changes earth's climate as well (Joseph 2010). Firstly, the emission of fine-grained ash distributed on the entire globe, especially in case of explosive eruption near the equator, leads to changes in the received solar energy budget (increased albedo value) and a corresponding cooling of the earth's surface. Secondly, the exposed gases may change the gas composition of the atmosphere, acidity of sea water and the biodiversity. Thirdly, basaltic lava weathers easily in the presence of acid rain, hence provides enhanced rates of atmospheric CO_2 depletion.

The radiative balance of the earth reflects the effect of albedo variations.

absorbed heat = emitted heat

$$E_s * (1 - \alpha) = 4 * f * \sigma * T_s^{\ 4}$$

With the received solar radiation E_s , earth albedo α, effective infrared transmission factor f (greenhouse effect), Stefan-Boltzmann constant $\sigma = 5.67*10^{-8}\ W/(m^2K^4)$ and the surface Temperature T_s. If the albedo value rises, e.g. due to ice sheet growth, suspended ash particles etc., less heat will be absorbed and a disequilibrium occurs. As a result the climate will change and the surface gradually cools down until a new equilibrium situation is reached (Hoffman *et al*. 2006).

As already mentioned, the carbon cycle is of prime importance for the climate conditions on earth. On geological timescales, CO_2 or carbon deposition and respective supply via volcanic activity and metamorphism is balanced. CO_2 molecules in the atmosphere accumulate in water droplets and precipitate as acid rain on the earth's surface. The surface runoff causes erosion and weathering of the bedrock material. The so-called silicate weathering reaction can generally be described by

$$\textit{Rock-mineral} + CO_2 + H_2O \rightarrow \textit{cation} + \textit{bicarbonate} + \textit{silicic acid}$$

The resulting solutes (cation and bicarbonate) are transported along rivers into the ocean where the solutes sediment finally. Under pressure sedimentary rocks are created and the originally atmospheric carbon is solidified. This deposition process is simply referred as "silicate weathering". The process is highly climate sensitive and indicates in reverse climatic changes in the past by analysing geological rock layering. With eruption of magmatic material the carbon redistributes in the atmosphere and the carbon cycle restarts (Hoffman *et al*. 2006).

In case of a breakdown of a tropical supercontinent, accelerated silicate weathering occurs. Under wet and dry continental conditions and the massive runoff distances, silicate weathering rates are diminished. Thus, the supercontinential disruption is likely to influence the atmospheric CO_2 content (Donnadieu *et al.* 2004). Huge amounts of basaltic lava originating out of an supervolcano eruption trigger similarly increased weathering rates as well, since basaltic lava is a rich source of Ca^{2+} cations and quite instable in the presence of acid rain. The accelerated silicate weathering causes a lowering of CO_2 in the atmosphere. This in turn implies a decreased greenhouse effect and an associated cooling, which results in sea water freezing. In the end the silicate weathering gains a new equilibrium situation (Hoffman *et al*. 2006).

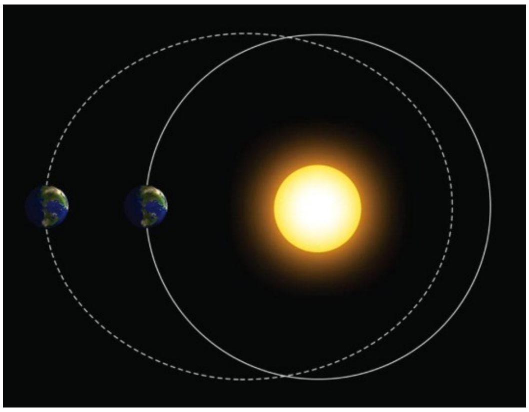
In the past, changes in the greenhouse effect severely affected the heat balance of the earth in comparison to present times, as the solar luminosity is increasing about 6% per billion years since the genesis of the sun. The solar energy constant was only about 1283 W m^{-2} one billion years ago and even lower at the earlier times of the earth, whereas it is 1367 W m^{-2} today. Variations in the value of the albedo and in the atmospheric composition therefore influenced the climate more strongly (Eyles and Januszczak 2004).

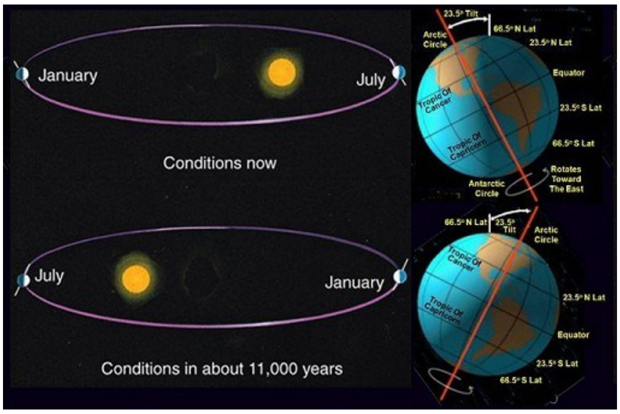
Examination of CH_4 also has a bearing on snowball earth glaciation. Even in consideration of the rather short lifetime of methane of about 12 years at present atmospheric level (PAL) in comparison to CO_2, the greenhouse potential of CH_4 is 25 to 30 times higher than the potential of CO_2. The accumulated methane in the atmosphere may be metabolised by methanotroph microorganisms, which cause a lowered greenhouse effect and possibly increased amount of sunlight at the earth´s surface. This in turn may increase the photosynthetic activity and an associated production of O_2 collected in the atmosphere. The O_2 enrichment enhances, on the other hand, the chemical reduction of methane, which implicates further descent of the greenhouse effect (Joseph 2010).

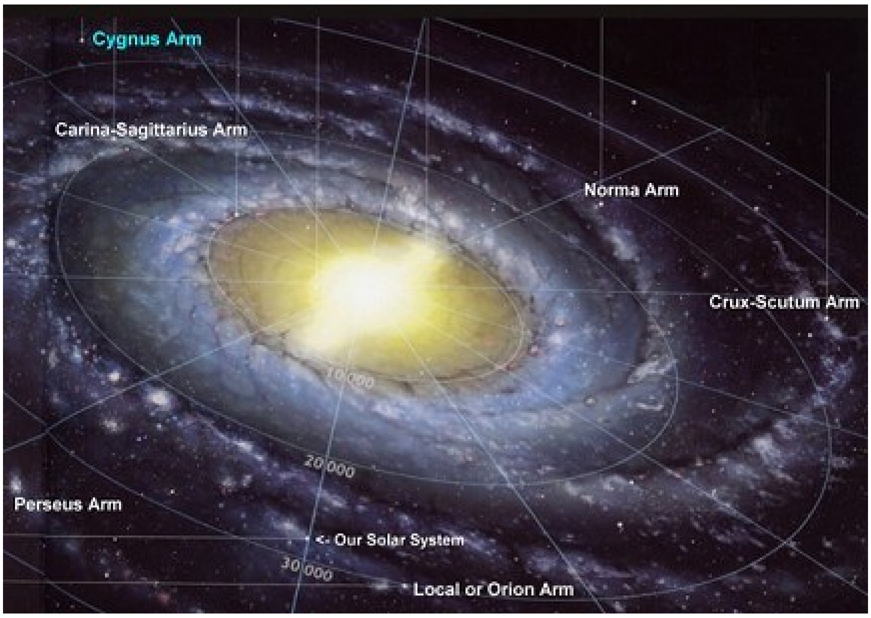
Scientists concluded that the Makganyene (1.) glaciation occurred due to atmospheric decline of CH_4, in a period between 2.5 and 2.2 Byrs, in combination with decreased CO_2. The Sturtian (2.) glaciation is likely to be caused by the continued breakup of the supercontinent Rodinia and increased atmospheric O_2 concentrations, accompanied by a dropping of CO_2 and CH_4 concentration levels. The Marinoan snowball earth was possibly triggered by an eruption of a supervolcano in conjunction with respective O_2, CO_2 and CH_4 interactions (Joseph 2010).

Beside these major relationships also other reasons contribute to changes in solar energy radiation and, through their effects on seasonality**,** potentially caused or enhanced snowball development. According to Joseph 2010, these are:

- Milankovitch cycles: eccentricity (upper left figure), axial tilt and precession (upper right figure)
- Perturbation of the Earth’s orbit in the early times of the solar system due to uncertain planetary orbits and additional space material
- Elliptical orbit of the solar system in the milky way galaxy (still in exploration; lower figure)



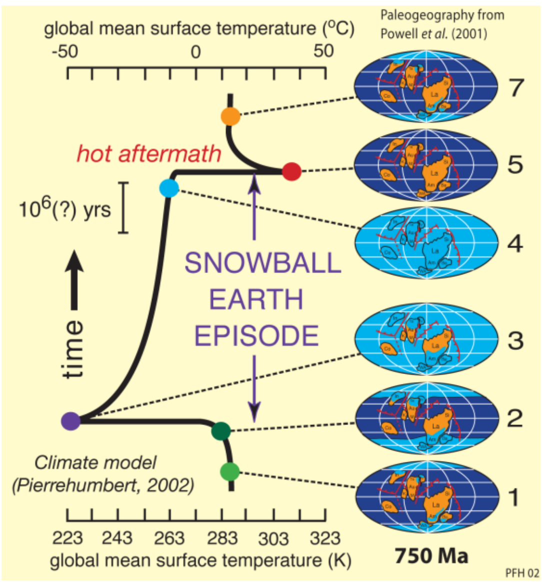


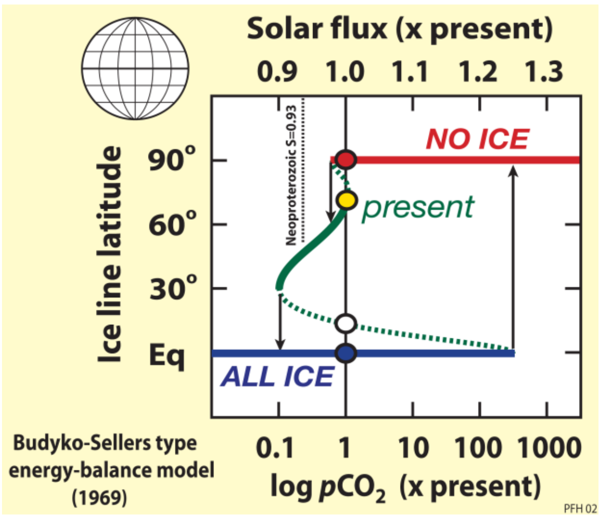


Figures illustrating selecting aspects of Milankovitch Cycles and elliptical solar orbit in milky way galaxy (http://journalofcosmology.com/ClimateChange116.html)

Deglaciation

The melting of the snowball earth periods are generally initiated by similar reasons although at different time scales. A total glaciation can't stop plate tectonic and the respective volcanic activity. The silicate weathering is minimized because of the ice sheet and the dry and cold atmospheric conditions inhibiting precipitation, but ongoing volcanic eruptions raise the CO_2 content. The concentration will build up fast in the beginning and slows down with further CO_2 emission (see figure). This is due to the non-linear (in time) formation of gaseous material (Hoffman *et al*. 2006).



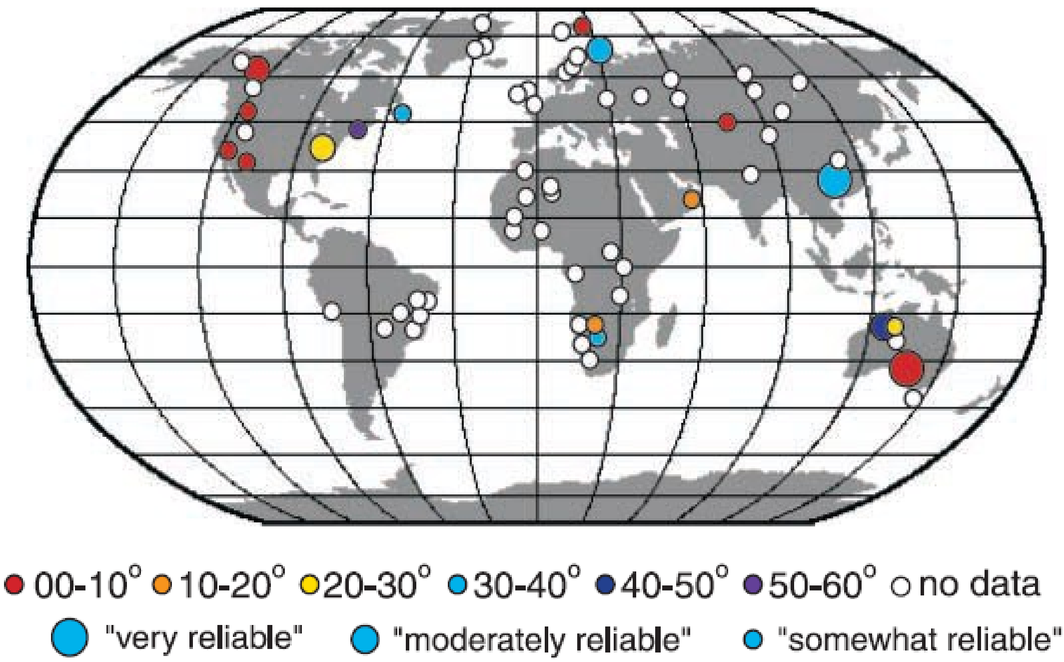


Glaciation effects (http://www.snowballearth.org/)

The calculated enrichment of CO_2 to conquer the extensive ice sheet is about 350 times higher than PAL, which would be about 13% of the today's atmosphere (Crowley *et al.* 2001). The atmospheric CO_2 concentration at present is <0.1%. After the melting point is reached, the meltdown of the entire ice shelf would assumedly be finished within 2000yrs triggering an extremely hot aftermath. The initially revealed areas of free sea water shift the albedo, expand the existent free water zones and catalyze the deglaciation. This ultra greenhouse transition is visible at geological layerings (Hoffman *et al*. 2006)**.**

Evidence

The first piece of evidence to suggest a snowball earth was found in the Elatina formation in the Flinders Range, Australia. The Flinders Range is a late Neoproterozoic glacial formation and the sample collected from there was an uncompacted, reddish and rhythmically laminated siltstone. The siltstone has a stable remnant magnetism which suggests it was deposited near the equator. Natural Remnant Magnetism (NRM) is the permanent magnetisation of a rock and due to the multiple reversals in the Elatina formation this suggests that the glacial period lasted for 10^5- 10^6 years (Hoffman et al. 2002). It has been found that all Late Neoproterozoic Glacial Deposits (LNGD) are widely distributed around the world as shown in the figure below.



The diagram above shows the distribution of LNGD around the world. The palaeolatitudes are estimated based on palaeomagnetic data. (Hoffman et al. 2002)

On top of the LNGD lie cap carbonates/ dolostones. These are on average 3-30m thick and occur on slopes across the world from Australia, Canada and Namibia and can be lithologically distinct. They correspond to post glacial sea level rise (Hoffman et al. 2002).

The Sturtian and Marinoan cab carbonates are lithologically distinct from one another but a consistent feature in all cap carbonates is the moderately depleted $\delta^{13}C$ compared to the stable isotope $\delta^{12}C$ (Hoffman et al. 2000). $\delta^{13}C$ concentration varies in time due to the productivity rate, organic carbon deposition and vegetation type (Hoffman et al. 2002). The low amount of $\delta^{13}C$ detected correlate with a snowball earth as life of earth and the carbon cycle would be reduced and weak. Cap carbonates are formed in warm climates therefore suggesting that they form after the deglaciation of snowball earth as the temperature began to rise, and the concentration of greenhouse gases in the atmosphere rose as did the sea level and increased precipitation.

Life?

The oldest fossils of higher life forms with a multicellular body have been found in Arctic Russia about 550 Ma. Terrestrial animals and vesicular plants didn't evolve for another 100 million years. That means that no spices higher than the sponge stage lived before the snowball earth events. But microorganism like bacteria both prokaryote and eukaryote leaved before the snowball earth and are still leaving today. The question is, how the survived a snowball earth event if they needed sunlight for photosynthesis. There must have been some remains of liquid water exposed to the sunlight. The photosynthesis dependent animals need a permanent liquid refugee to survive. But for example snow algae need only a small film of water on the surface of the glacier during the summer, when the temperature touches the melting point to survive. Hoffman, P. et al.

At the present day, so called brine channels exist in the arctic sea ice and carry a lot of microorganisms with it. Probably that was also one refugee during the snowball earth period. On the grounding line between the grounded glacier and the flowing part of the glacier, cracks are opening and get filled with seawater including brine. Life forms like different kinds of algae (mostly diatoms), protozoa and foraminifera can survive under these conditions. The brine can also be a O_2 storage, because the photosynthetic O_2cant escape the brine channels. This could also be the reason for the massive O_2 increase after the last snowball earth event and it could be the reason for the massive increase the diversity and development of higher life species.

Another possible refugee is a volcanic active island like for example Iceland and Hawaii today. On these islands the organisms are isolated from other populations. The isolation is stimulating the evolution by mutation. (Schrag &Hoffmann: 2001) But hot springs last only 1000s of years, so the organisms must survived the transport form one hot spring to an other with the wind. The volcanic fields itself can be active for millions of years, but located very sparsely on the earth, that's why the genetic isolation of the organisms is that high. (Schrag & Hoffmann 1999) The Cambrian explosion of the live forms 575-525 million years ago is related with the end of the last snowball earth event, the ultra greenhouse effect and the biochemical changes. (Schrag & Hoffmann: 2001)

According to snowball earth models, the ice was way too thick to let pass solar radiation for animals, which need photosynthesis to survive. But according to more resent climate models by Dave Pollard and Jim Kasting form the Pennsylvania State University; the ice near the equator was only about 2 m thick. Whereas the ice at a latitude of about 13° is one km thick.

The snow line was somewhere between the thick ice and the very thin ice near the equator, that means that the ice near the equator is clearer and absorbs more light. Even crack are common so that more light and enter the sea. This is similar to todays sea ice on the poles. It is not certified if the earth was completely covered by ice. There might have always been some ice free areas with open water. This solution of the survival of the life during a snowball earth event is more reasonable then the thin ice solution.

According to Hoffmann and Schrag (2000) organisms, which don't necessarily need sunlight to survive, can survive in hot water springs. Life will continue although chemical gradients that are exploited metabolically, such as redox (reduction-oxidation) and pH (acid-base) gradients, might be weakened. According to William at. al. (2001) live on the ground of the seafloor was not possible because the chemosynthetic organisms needed free oxygen at that time to survive. Their stage of evolution was to low and primitive.

The cold conditions and climate are good for cold loving organisms also called psychrophilic. Today in the dry valleys in Antarctica those kinds of organisms are still living. The climatic conditions there are not very different to the conditions during the snowball earth.
Some prokaryotic species like cyanobacteria and eukaryotic algae are living in snow, porous rock and on the surface of dust on floating ice. The eukaryotic algae must survived the snowball earth event, because fossils that are older then the snowball earth event were found and some species are still leaving today.

Conclusion – Snowball Earth in Future?

There are a couple of reasons arguing for a modern snowball earth in the future. One of them is the sustained cooling during the last 50 Ma, with a maximum ice sheet coverage about 20,000 years ago. Further, simulations showed that an impact of an asteroid of about 10km in diameter would be sufficient to trigger a new worldwide glaciation under the contemporary conditions. In addition, the ongoing continental spreading may finally end up in a new supercontinent in the distant future.

On the other hand, as already mentioned, the solar luminosity at present times is about 6% higher than in the cryogenian period, comprising the Sturtian and Marinoan snowball earth, and will rise even further in the future. The current distribution of landmass is strengthening the improbability of a new snowball earth as well, since the albedo of the distributed continents is rather low, strong and hot sea currents from the mid to the highest altitudes are existing and silicate weathering is diminished. As the temperature of the earth´s interior continues to decrease exponentially with time, consequences of massive supervolcano eruptions might decrease. The sum and correlation of these arguments confirms that a new snowball earth glaciation in the nearer future is rather unlikely, especially when considering the anthropogenic global warming at the present time (Hoffman *et al*. 2006).

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