Refugium for surface life on Snowball Earth in a nearly-enclosed sea?

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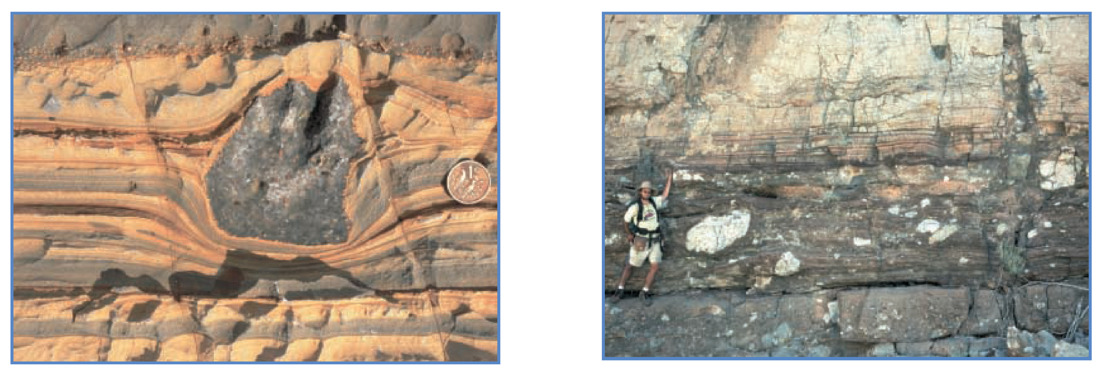
abstract

Photosynthetic eukaryotic algae are thought to have survived during so-called Snowball Earth events. Where such organisms persisted is not immediately clear. With net accumulation of ice at polar regions and net sublimation at the tropical regions thick ice called sea glaciers flowed from the poles toward the equator, covering the global ocean, and prohibiting the transmission of light.

In regions of net sublimation, sea glaciers may have been unable to fully penetrate long narrow embayments, or inland seas. Our previous work showed that refugia could exist at the landward ends of some idealized seas with uniform width.

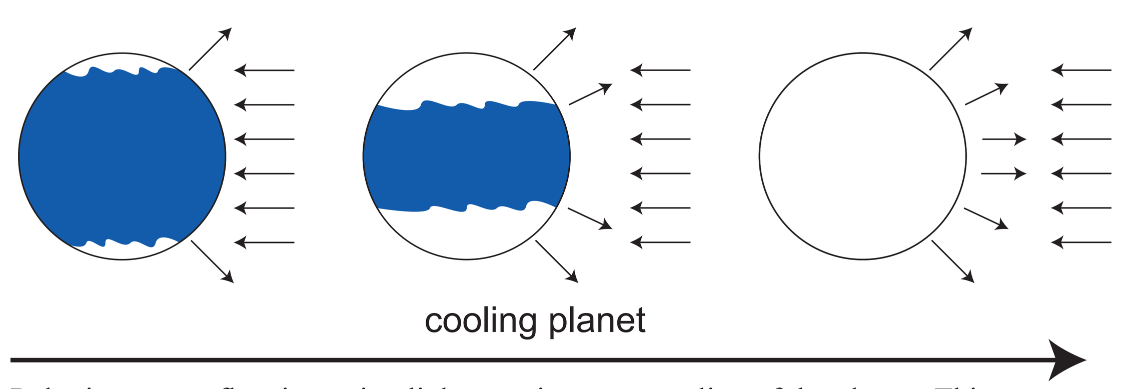
Here, we solve for penetration lengths of sea glaciers entering narrow channels with more realistic geometries by solving ice flow equations using a finite element model. Channel geometries containing narrow straits near the entrance (e.g. the Red Sea) restrict the ability of the sea glacier to penetrate the channel. This allows narrow channels to provide refugia under a wider variety of conditions.

Snowball Earth



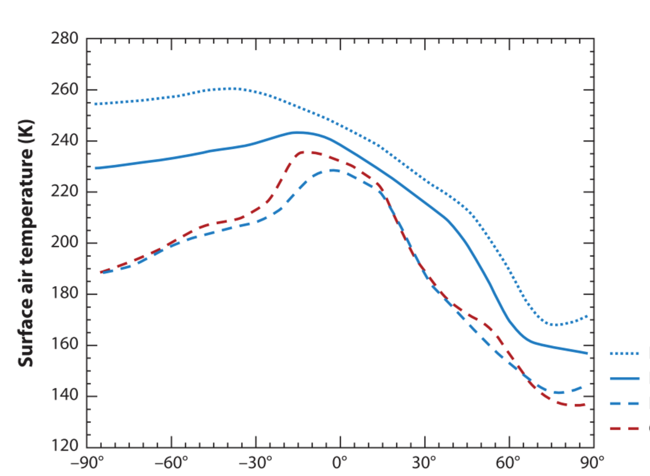
Hoffman and Schrag 2002

getting into this mess - ice albedo runaway



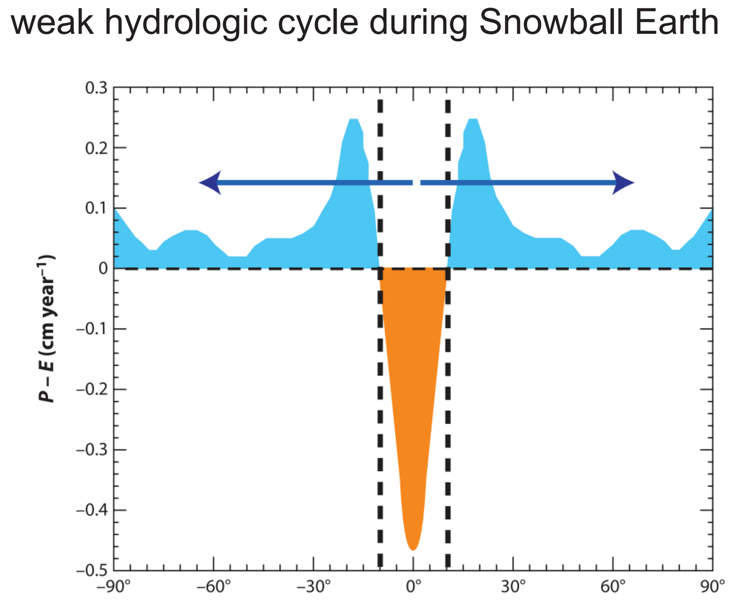
Polar ice caps reflect incoming light, causing a net cooling of the planet. This cooling in turn causes the ice caps to expand into lower latitudes where even more light can be reflected. This situation results in a positive feedback runaway until the entire planet is ice covered.

the climate of a snowball



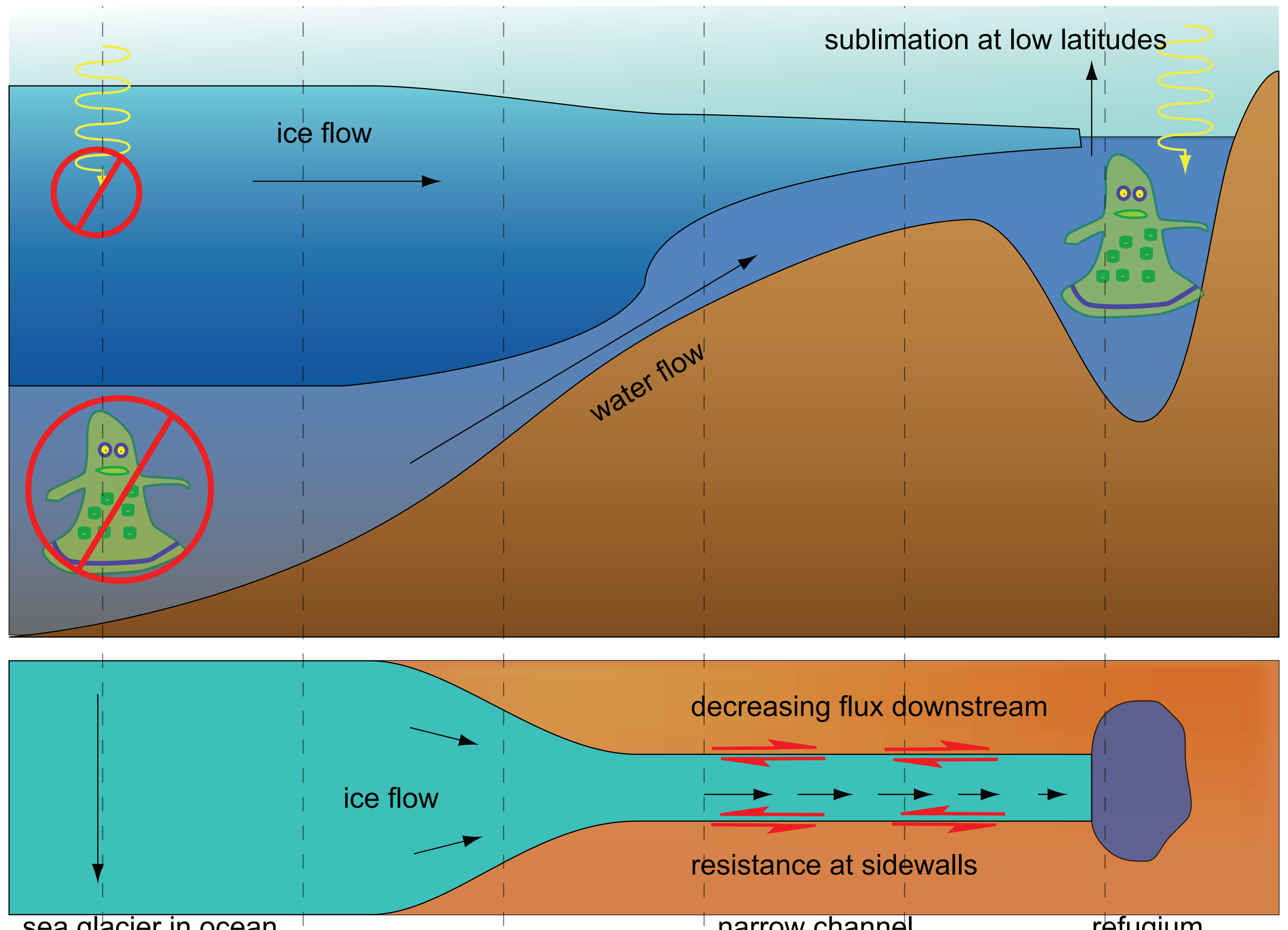
Pierrehumbert 2011

weak hydrologic cycle during Snowball Earth Events



Pierrehumbert 2011

where could refugia persist?

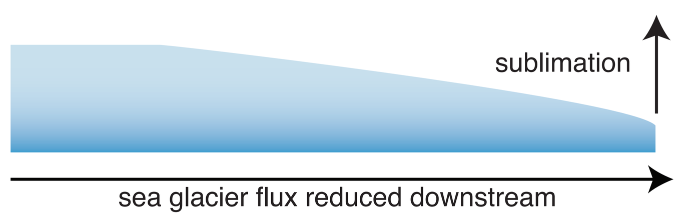


keys to success

1. Stop the flow of the sea glacier through the channel
2. Keep sea ice thin above refugia
3. Maintain water flow under the sea glacier

why would a sea glacier end?

It is possible equatorial sea glaciers flowed into narrow channels, perhaps similar to the modern day Red Sea. The sidewalls of these narrow channels would have resisted incoming ice from the sea glacier by providing lateral shear along channel boundaries. As ice flows down the channel from the sea glacier, ice is simultaneously sublimated from the surface because of net equatorial sublimation. Can the incoming sea glacier be sublimated fast enough to reach zero thickness before it reaches the end of the channel?



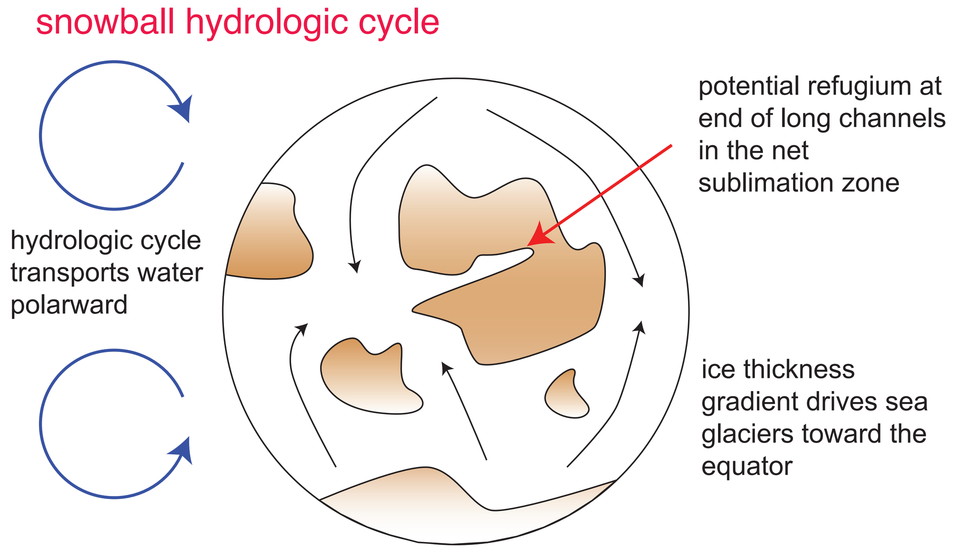
photosynthetic life

Photosynthetic eukaryotic algae were present before and after Snowball Earth events. For these organisms to have persisted they must have been able to survive in refugia. Refugia must have liquid water where light could have been transmitted in order to allow for photosynthesis. It is possible that a thin cover of floating sea ice over an inland sea would allow for sufficient transmission of light to allow for the inland sea to act as a refguim, provided the sea remains free of sea-glacier-derived ice.

why is water flow important?

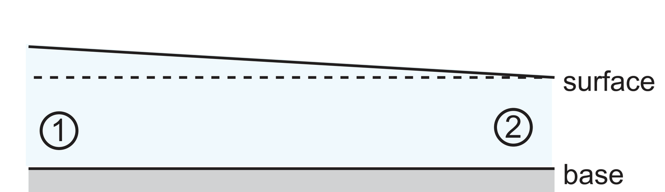
The connection of liquid water between the ocean and refugia is required for this scenario. If inland seas did not remain connected to the ocean, even extremely small rates of net sublimation would dry up the seas during the ~10 Ma Snowball Earth events, destroying the refugia. Alternatively, if inland seas were in regions of extremely small net accumulation, ice would thicken until it would not permit for the penetration of light through the ice. An ocean connection allows for water to be replenished in the sea so that it may maintain its ability to provide a refugium for photosynthetic organisms during Snowball Earth events.

snowball hydrologic cycle



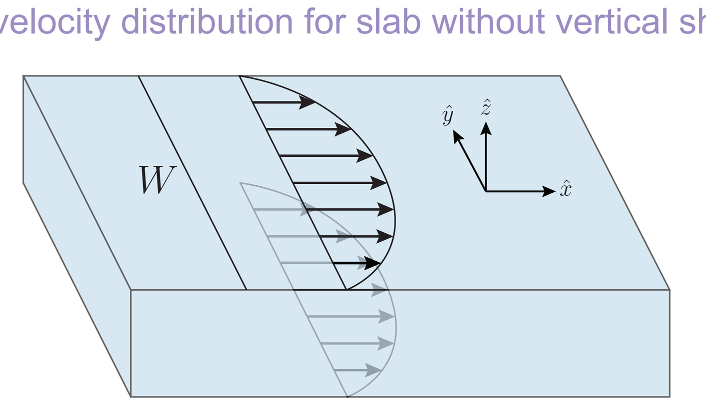
glacier flow

gravitational driving stress



extra pressure at ① compared to ② yields a stress gradient, ice deforms (flows) in response

velocity distribution for slab without vertical shear



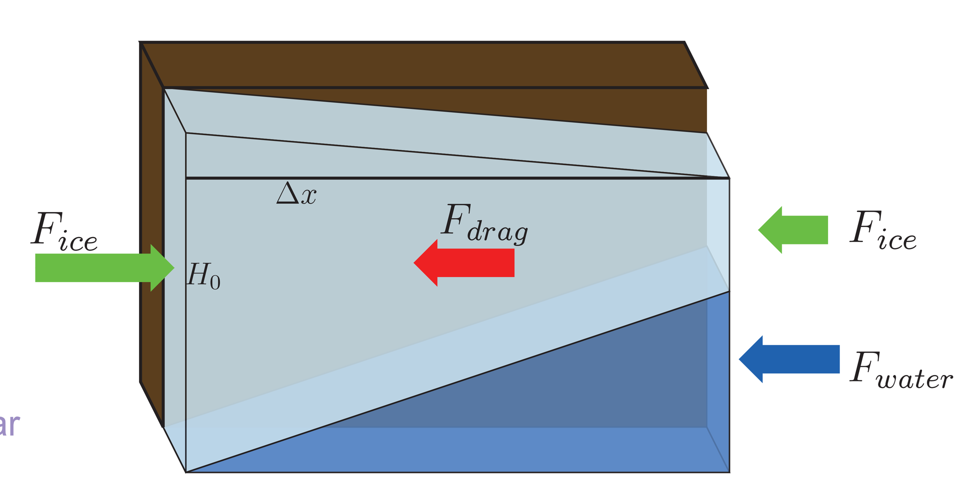
$$u(y) = \frac{WAk^n}{2(n+1)}\left(1-\left|\frac{2y}{W}\right|^{n+1}\right)$$

Nye 1965

laterally integrated

$$\bar{u} = \frac{WAk^n}{2(n+2)}$$

force balance on the incoming sea glacier



force balance yields resistive stress

$$F_{ice} + F_{water} = -2W\rho_{ice}g\left(1-\frac{\rho_{ice}}{\rho_{water}}\right)\frac{dH}{dx}H_0\Delta x$$

$$F_{drag} = 2k(x)H(x)\Delta x$$

$$\sum F = 0$$

$$k(x) = gW\rho_{ice}\left(1-\frac{\rho_{ice}}{\rho_{water}}\right)\frac{dH}{dx}$$

continuity of flow

$$\frac{\partial H}{\partial t} + \nabla\cdot(\bar{u}H) = \dot{b}$$

$$H\frac{\partial \bar{u}}{\partial x} + \bar{u}\frac{\partial H}{\partial x} = \dot{b}$$

control on penetration length

$$\frac{L}{W} = \frac{H_0}{D}$$

$$D = \left(\frac{2^n\dot{b}(n+2)}{A\Gamma^n}\right)^{\frac{1}{n+1}}$$

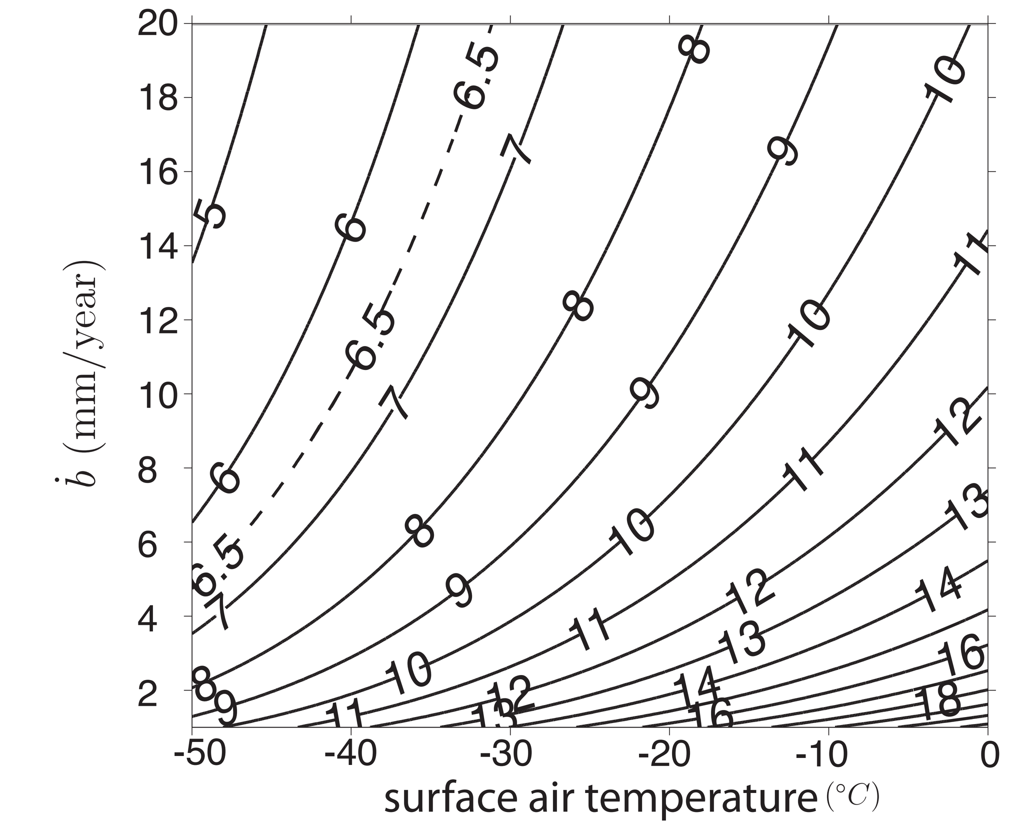
$$\Gamma \equiv \rho_i g\left(1-\frac{\rho_i}{\rho_w}\right)$$

temperature dependence of flow

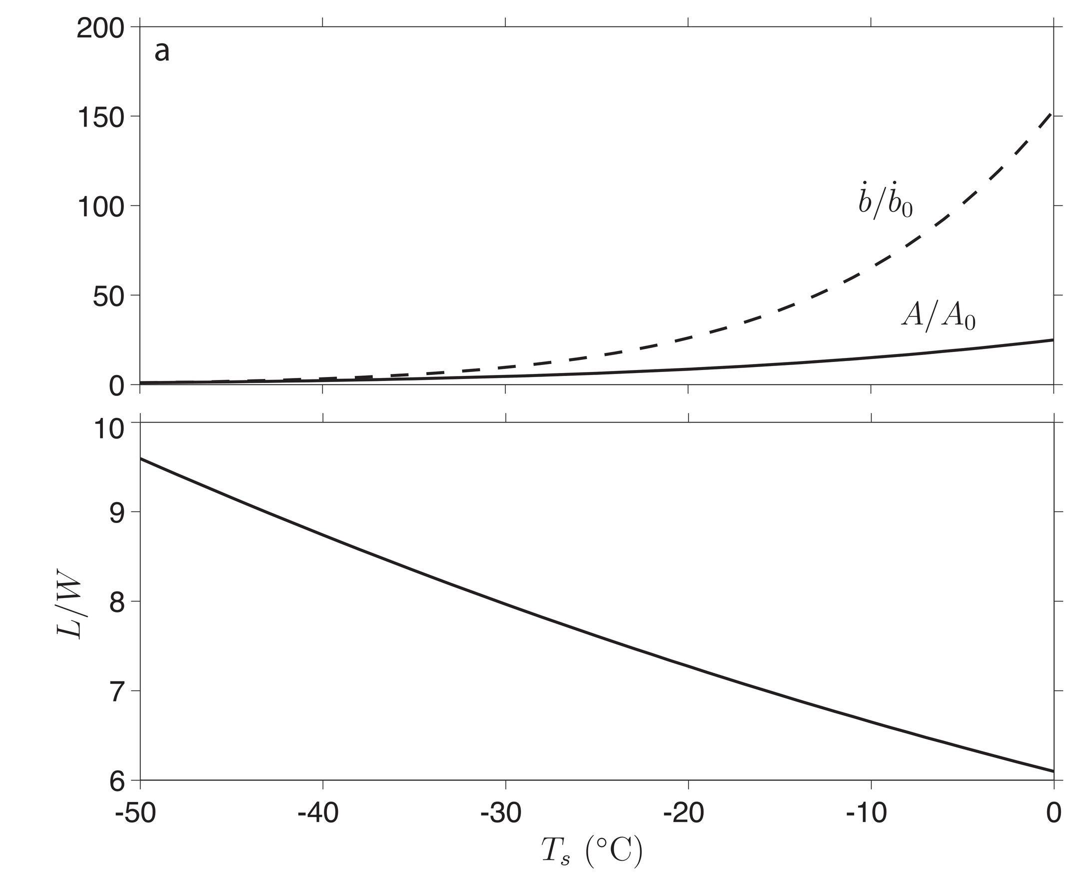
Ice becomes softer when it is warm. It is expected that warmer ice would flow more easily and be more likely to penetrated the full length of an inland sea.

penetration length of incoming sea glacier

length to width ratio for idealized channels



length to width ratio evolution with temperature



conclusions

The flow of sea glaciers penetrating into narrow channels can be calculated analytically for an idealized geometry. When a channel is unrestricted, with a wide opening to the ocean, sea glaciers can penetrated the full length of the channel, under some conditions. In a warming climate is found that L/W decreases with temperature due to increasing sublimation. It is likely the inland seas remained free of sea glacier ice during the entire Snowball Earth Events and possibly acted as refugia photosynthetic organisms during these events.

references

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