Habitat Space on a Snowball Earth: Understanding Life On the Outer Edge of the Habitable Zone

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A. Using Earth History to Explore Other Worlds

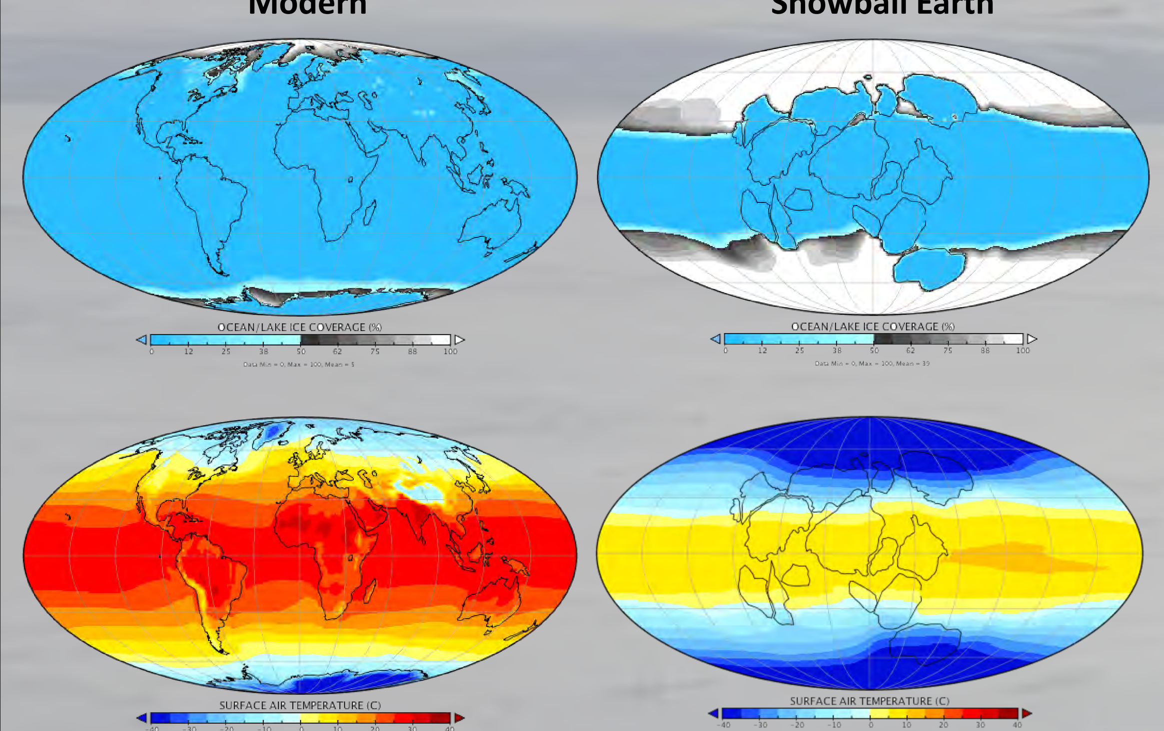
Habitable planets, by definition, have a surface environment capable of supporting liquid water, which is vital to life as we know it. Earth's history illustrates phases of habitability that we can use to understand the conditions under which life can arise and thrive, and to guide future NASA missions seeking habitable worlds.

As our case study, we examine here an extreme ice age referred to as "Snowball Earth." This event took place ca. 715 million years ago, when life appears to have been making significant evolutionary strides from simple single-celled microscopic organisms to complex multicellular organisms visible to the naked eye.

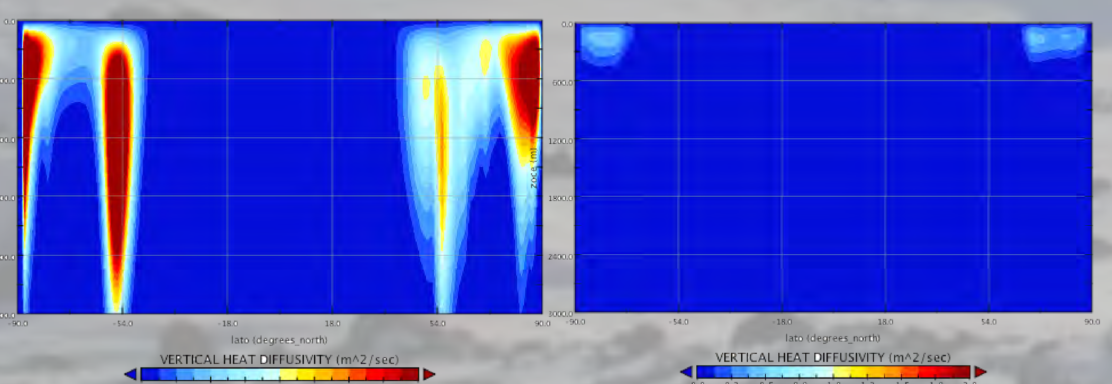
The geologic record suggests that the Snowball Earth world was quite cold and hostile, with widespread snow and ice on both land and ocean. Where was life finding space to survive? The expectation among paleobiologists has been that for marine life, ocean temperature would be a controlling factor.

B. The Environment

Influences on the Snowball Earth climate that were incorporated into our climate simulations include a dimmer Sun (6% less bright than today) and very low CO_2 (40 ppm).



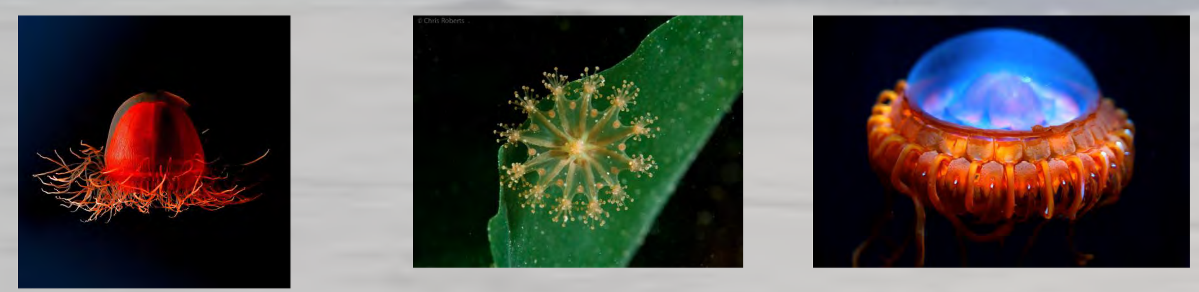
A comparison of Modern vs. Snowball Earth ocean ice cover area (top row) and the surface air temp-erature (bottom row) shows how extreme the climate was back then – the Snowball Earth had 34% more ice cover, and the difference in global average temperature was 26˚C (nearly 80˚F!).



Under such different conditions, we need to understand how changes in the ocean circulation might be affecting temperature and salinity patterns, as well as the distribution of nutrients – all important factors in allowing life to survive. In the plots above, we see how vertical mixing after 400 years (left) and 2000 years (right) has changed – suggesting that an equilibrium state in the model is not quickly achieved.

C. The Life Forms

The fossil record during the Snowball Earth is poor, so it is hard to know exactly what forms of life were present. To provide some insight into habitat needs at that time, we chose representatives of three kinds of organisms – **Cnidaria, Demospongiae,** and **Cyanobacteria** – that might be most closely related to early life .



Cnidaria are both filter-feeders and predators. All organic carbon consumed, through predation and filter-feeding, is expelled into the water column for benthic organisms, such as the Demospongiae, to consume.

Demospongiae are benthic, sessile filter-feeders. These organisms consume primarily particulate nutrition as well as Plankton. These organisms possess genes that allow them to resist adverse temperatures and survive food restrictions.

Cyanobacteria are small, planktonic organisms typically found on the surface of the ocean. They are filter-feeders that consume dissolved organic carbon in the environment. Cyanobacteria are consumed by larger metazoan filter-feeders such as Demospongiae and Cnidaria.

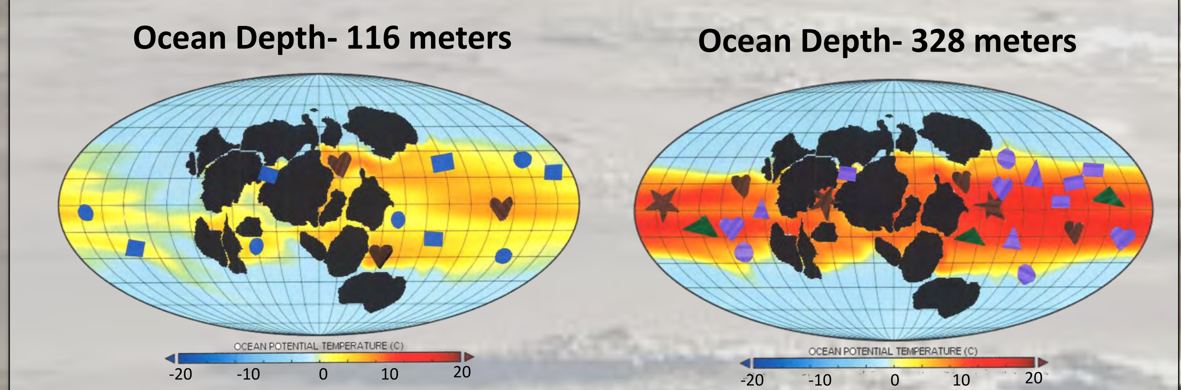
D. Defining Habitats

Using the habitat requirements (in terms of temperature and salinity) of our three modern organisms as a guide, we mapped their possible distribution in a Snowball Earth setting.

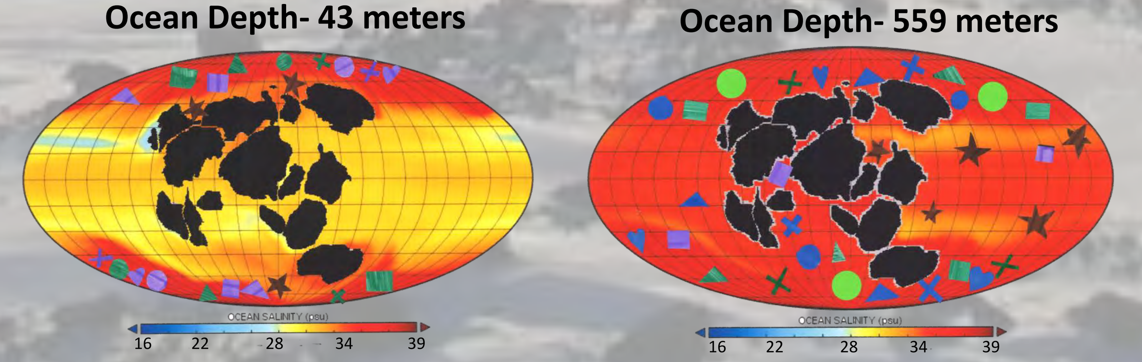
This task was done for individual layers of ocean down to depth of roughly 1500m, after which temperature and salinity values became fairly geographically constant.

Symbol Guide

	Demospongaie	Cnidaria	Cyanobacteria
●	Red Tree Sponge	Crossota Norvegica	
■	Bamel Sponge	Wyville's Crown Jellyfish	
▲	Flesh Sponge	Kaleidoscope Jellyfish	
X	Red Boring Sponge	Box Jellyfish	
♥		Red Sea Finger	Synechocystis
★			Anabaena



Ocean Temperature: Not surprisingly, the warm-est ocean temperatures occur in shallow tropical regions away from the sea ice front. At greater depths the water cools considerably. Based on temperature alone, we would have predicted that most of our organisms would be found in shallow water environments near the equator.



Salinity: Salinity concentrations increased with depth of water, especially in the tropics, owing to a persistent lens of fresh water at the surface. Since most of our organisms prefer higher salinities closer to the modern ocean value, these organisms would tend to be found at shallower depths only in the polar regions where vertical mixing is strong.

E. Conclusions

The Snowball Earth ocean environment differs considerably from the modern in terms of three key facets that can influence marine habitat space: temperature, salinity, and circulation patterns (especially vertical mixing) that might influence the distribution of nutrients. An unexpected result is the possibility that salinity, and not temperature, had a greater influence on the distribution of habitat space for early complex organisms.

Further investigations will include a focus on characterizing the final equilibrium state of the ocean; the additional consideration of nutrient availability on habitat space; and an expanded review of modern organism analogues of Snowball Earth life for a greater range of salinity and temperature tolerances.

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