On the Jormungand Global Climate State

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The Jormungand global climate state and implications for Neoproterozoic glaciations
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Geological and paleomagnetic evidence indicate that during at least two Neoproterozoic glacial periods (~630 Ma and ~715 Ma) continental ice sheets flowed into the ocean near the equator.

Glaciers at the equator: Evidence

- Occurrence of glacial debris near sea level in the tropics

Glaciers at the equator: Evidence

- Occurrence of glacial debris near sea level in the tropics

Dated volcanic ash within glacial deposits to 715.5 Ma


- Unusual deposits of iron-rich rock mixed in with glacial debris:
  -- ice cover deprives oceans of oxygen;
  -- dissolved iron expelled from seafloor hot springs accumulates in water;
  -- when ice melts, oceans exposed to atmospheric oxygen
  -- iron (virtually insoluble in presence of oxygen) precipitates out with debris once carried by glaciers

- Iridium (Ir) anomalies:
  -- Ir much more abundant in extra-terrestrial materials;
  -- Ir accumulates on and within the ice and snow, and precipitates out when ice melts;
  -- Ir anomalies used to estimate the duration of the Marinoan glacial episode (~630 Ma) at 12 My

Strong hysteresis vis-à-vis changes in greenhouse gas forcing

- Glacial formations nearly universally overlain with cap carbonates

Chemical breakdown of rocks converts CO$_2$ to bicarbonate, washed into oceans

Chemical reactions in ocean produce carbonate sediments, storing a great deal of carbon

Rapid accumulation of carbonate sediment on seafloor as Neoproterozoic glaciers retreat, later becoming rock


Strong hysteresis vis-à-vis changes in greenhouse gas forcing

- Marinoan cap carbonate sequences possess extremely negative $\Delta^{17}$O values

Neoproterozoic glaciation models

- Snowball Earth

  --J. Kirschvink, 1992¹. *The data are difficult to interpret in any fashion other than that of widespread, equatorial glaciation.*


Neoproterozoic glaciation models

- Snowball Earth

  “In many people’s minds, the hard Snowball is dead.”
  --Michael Arthur, PSU (geochemist)

  “We can get ice on land, it’s the oceans we can’t freeze over… The more sophisticated the model, the less likely you’d get a hard Snowball result.”
  --Mark Chandler, Goddard Institute for Space Studies

  “When the Snowball came up, the [geological] community was very open to it. Now, it’s my impression that 90% of the geological community is quite hostile to the idea.”
  --Philip Allen, Imperial College of London (geologist)

  “[Resistance to the hard Snowball] is really typical of scientific controversy. The problem is the experts reach a quick judgment and dig themselves into a position.”
  --Paul Hoffman, Harvard (retired, geologist)

Neoproterozoic glaciation models

- Snowball Earth -- biological ambiguities

  --evidence that photosynthetic eukaryotes thrived both before and immediately after the Snowball episodes
  (organism whose cells contain complex structures enclosed within membranes)

  --evidence that multiple lineages of sponges may have survived these glaciations
  (more complex marine animals)

Researchers have found a bacterium that is the first photosynthetic organism that doesn’t live off sunlight but from the dim light coming from hydrothermal vents deep within the ocean.

(http://www.asu.edu/feature/includes/summer05/readmore/photosyn.html)
Alternative Neoproterozoic glaciation models

- Slushball, Oasis, Soft-Snowball, Waterbelt

Ice expands over the ocean down to 25-40° latitude, and stabilizes

- Survival of marine animal and photosynthetic life

- Weak hysteresis in global climate models

Qualitatively similar to glaciations of the last few million years, only more extreme?

Alternative Neoproterozoic glaciation models

- Tropical “thin-ice” solution

Ocean is ice-covered, ice ~1 m thick in the tropics

- Penetration of photosynthetically active radiation

- Found in an energy balance climate model\(^1\); requires

  (a) Bare sea ice has high transmissivity & low albedo (0.4-0.5) relative to snow covered sea ice (~0.8)

  (b) Moisture in tropics is exported so that sea ice in tropics is bare.

- Stronger hysteresis in Pollard-Kasting model

- Debate whether the parameter regime in Pollard-Kasting is physically realistic

Not found in global climate model simulations of Neoproterozoic glaciations which use low bare sea ice albedo

Alternative Neoproterozoic glaciation models

- **Albedo**

  --Appropriate value of the albedo for exposed, non-melting ice formed by freezing seawater is 0.47 at temperatures above -23°C
  
  (at temps below -23°C, NaCl precipitates out which could increase the albedo to 0.71)

  --Appropriate value of the albedo for snow covered ice is 0.81

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean new H₂O snow</td>
<td>0.85</td>
</tr>
<tr>
<td>Bare sea ice</td>
<td>0.5</td>
</tr>
<tr>
<td>Clean H₂O glacier ice</td>
<td>0.6</td>
</tr>
<tr>
<td>Deep water</td>
<td>0.1</td>
</tr>
<tr>
<td>Sahara Desert sand</td>
<td>0.35</td>
</tr>
<tr>
<td>Martian sand</td>
<td>0.15</td>
</tr>
<tr>
<td>Basalt (any planet)</td>
<td>0.07</td>
</tr>
<tr>
<td>Granite</td>
<td>0.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.36</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.2</td>
</tr>
<tr>
<td>Deciduous forest</td>
<td>0.14</td>
</tr>
<tr>
<td>Conifer forest</td>
<td>0.09</td>
</tr>
<tr>
<td>Tundra</td>
<td>0.2</td>
</tr>
</tbody>
</table>


Alternative Neoproterozoic glaciation models

- **Jormungand climate state**

  Ocean is very nearly globally ice-covered, down to 5-15° latitude, with a thin strip of open ocean near the equator

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Abbot et al, p. 4

Henry Fuseli (1788)
Alternative Neoproterozoic glaciation models

- **Jormungand climate state**

Ocean is very nearly globally ice-covered, down to 5-15° latitude, with a thin strip of open ocean near the equator

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**Jormungand climate state:** Simulations with global climate models

- NCAR’s Community Atmosphere Model (CAM) v3.1

  Horizontal resolution 2.8° x 2.8°, with 26 vertical levels

  Use **idealized configuration**, including aquaplanet mode with ocean mixed layer of depth 50m, a thermodynamic sea-ice scheme, no ocean heat transport, solar constant 94% of its modern value, zero eccentricity, obliquity 23.5°, 24 hr day

  **Bare sea ice albedo ~0.45, snow covered sea ice albedo ~0.79 at temps below -1°C**

  At 0°C, bare sea ice albedo ~0.38 and snow covered sea ice albedo ~0.66 to account for formation of melt ponds on ice surface
**Jormungand climate state:** Simulations with global climate models

- NCAR’s Community Atmosphere Model (CAM) v3.1

![Graph](image1)

*Red diamonds:* ice-free initial state  
*Blue circles:* Jormungand initial state  
*Green squares:* Snowball initial state

(Abbot et al, p. 3)

**Jormungand climate state:** Simulations with global climate models

- NCAR’s Community Atmosphere Model (CAM) v3.1

![Graph](image2)

**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.

**Figure 4.** Annual and zonal mean precipitation minus evaporation for the ice-free state (red dashed) and the Jormungand state (blue) with $pCO_2 = 5000$ ppm.

(Abbot et al, p. 4)
**Jormungand climate state:** Atmospheric dynamics

![Diagram of Jormungand climate state]

(Abbot et al, p. 6)

**Jormungand climate state:** Simulations with global climate models

- Max Planck Institute’s atmospheric model v5.3.02p
  
  Horizontal resolution 3.75° x 3.75°, with 19 vertical levels

  Does not produce Jormungand state when run in idealized configuration: does not keep track of snow that falls on sea ice

  Modify: sea ice has CAM’s bare sea ice albedo equatorward of 20° latitude and CAM’s snow albedo poleward of 20° latitude

(Abbot et al, p. 7)
Jormungand climate state: Simple energy balance climate models

Budyko-Sellers Model: At equilibrium

\[ \frac{Q}{4} S(x)(1 - \alpha(T(x))) = A + BT(x) + C(T(x) - \bar{T}) \]

\( Q \) solar constant  
\( x \in [0, 1] \) sine of latitude (0-equator, 1-north pole)  
\( S(x) \) meridional distribution of insolation, \( \int_0^1 S(x)dx = 1 \)  
\( T \) surface temperature  
\( \bar{T} \) average surface temperature  
\( \alpha \) albedo  
\( A + BT \) linearization of OLWR  
\( C(T - \bar{T}) \) meridional heat transport  

\[ \alpha(T(x)) = \begin{cases} 
\alpha_1, & T > T_s \\
\alpha_s, & T = T_s \\
\alpha_2, & T < T_s 
\end{cases} \]

\( T_s \) temperature at the ice line  
\( \alpha_s = \frac{\alpha_1 + \alpha_2}{2} \)

\[ \frac{\partial \alpha_s}{\partial x_s} = 0 \]

\( \alpha \)

Budyko-Sellers Model

(1) \[ \frac{Q}{4} S(x)(1 - \alpha(T(x))) = A + BT(x) + C(T(x) - \bar{T}) \]

Global mean energy balance: integrate from \( x=0 \) to \( x=1 \)

(2) \[ \frac{Q}{4}(1 - \alpha_p(x_s)) = A + B\bar{T} \quad x_s = \text{sine of the ice latitude} \]

\[ \alpha_p(x_s) = \int_0^1 \alpha(x)S(x)dx = \alpha_1 \int_0^{x_s} S(x)dx + \alpha_2 \int_{x_s}^1 S(x)dx \]

Plug \( x_s \) into (1):

(3) \[ \frac{Q}{4}S(x_s)(1 - \alpha_s) = A + BT_s + C(T_s - \bar{T}) \]

Solve (2) for \( \bar{T} \), plug into (3)

\[ A(x_s) = \frac{B}{B+C} \left( \frac{Q}{4} \left( S(x_s)(1 - \alpha_s) + \frac{C}{B}(1 - \alpha_p(x_s)) \right) - (B + C)T_s \right) \]

Change in radiative forcing \( \Delta A = A_0 - A \), \( A_0 \) present value

Budyko-Sellers Model: Linear stability analysis \( \Delta A = A_0 - A \)

\[ A(x_s) = \frac{B}{B+C} \left( \frac{Q}{4} \left( S(x_s)(1 - \alpha_s) + \frac{C}{B}(1 - \alpha_p(x_s)) \right) - (B + C)T_s \right) \]

\[ A(x_s + \delta x_s) = \frac{B}{B+C} \left( \frac{Q}{4} \left( S(x_s + \delta x_s)(1 - \alpha_s) + \frac{C}{B}(1 - \alpha_p(x_s + \delta x_s)) \right) - (B + C)T_s \right) \]

Linear approximation: \( f(x + \delta x) \approx f(x) + f'(x)\delta x \)

\[ \frac{\delta x_s}{\delta(\Delta A)} = \frac{\frac{4}{Q}(B + C)}{C\frac{\partial S}{\partial x_s} - B\frac{\partial S}{\partial x_s}(1 - \alpha_s)} \]

\( Q = 1285 \text{ W m}^{-2}, \quad A_0 = 210 \text{ W m}^{-2}, \)
\( B = 1.5 \text{ W m}^{-2} \text{ K}^{-1}, \quad C = 2.5B, \quad \alpha_1 = 0.3, \)
\( \alpha_2 = 0.6, \quad T_s = -10^\circ \text{C}, \quad \delta_2 = -0.482 \)
Jormungand climate state: Simple energy balance climate models

Modified Budyko-Sellers Model: At equilibrium

\[
\frac{Q}{4} S(x)(1 - \alpha(T(x))) = A + B T(x) + C(T(x) - \bar{T})
\]

\[
\frac{\partial \alpha_s}{\partial x_s} = 0
\]

\[
\alpha_2 = \alpha_2(x) = \alpha_2^i + \left( \frac{\alpha_2^s - \alpha_2^i}{2} \right) \left( 1 + \tanh \left( \frac{x - x_i}{\Delta x_i} \right) \right)
\]
Modified Budyko-Sellers Model:

\[ \Delta A = A_0 - A \]

\[
A(x_s) = \frac{B}{B + C} \left( \frac{Q}{4} \left( S(x_s)(1 - \alpha_s(x_s)) + \frac{C}{B} (1 - \alpha_p(x_s)) \right) - (B + C)T_s \right)
\]

\[
\alpha_p(x_s) = \int_0^1 \alpha(x) S(x) \, dx = \alpha_1 \int_0^{x_s} S(x) \, dx + \int_{x_s}^1 \alpha_2(x) S(x) \, dx
\]

\[
\frac{\delta x_s}{\delta (\Delta A)} = \frac{4Q(B+C)}{BS \frac{\partial \alpha_s}{\partial x_s} + C \frac{\partial \alpha_p}{\partial x_s} - B \frac{\partial S}{\partial x_s} (1 - \alpha_s)}
\]

\( \alpha_1 = 0.35, \alpha_2^i = 0.45, \alpha_2 = 0.8, x_i = 0.35 \)

\( \Delta x_i = 0.04, T_s = 0^\circ C, C = 1.5B \)

CAM Simulation

Modified Budyko-Sellers Model

(Abbot et al, p. 3)
Jormungand climate state: Accessibility

![Figure 12](image)

Figure 12. As in Figure 11, with $\Delta F = 0.45$ (black) and with $\Delta F = 0.65$ (red). In the latter case the Jormungand state is not “accessible” if the radiative forcing ($\Delta A$) is increased and decreased through a hysteresis loop between the warm state and the Snowball state.

(Abbot et al, p. 10)

Jormungand climate state & Neoproterozoic glaciations: Recap

High CO$_2$ initially to balance reduce insolation

For some reason there is a reduction of one or more greenhouse gases, and ice latitude decreases

Reach first bifurcation, and ice latitude rushes toward the equator

At 20-30$^\circ$ atmospheric circulation ensures the sea ice is generally bare, lowering ice-albedo feedback, climate enters Jormungand state

Very cold, dry, ice sheets cover large areas of continents: silicate weathering greatly reduced, so climate never enters Snowball state

Strong hysteresis, CO$_2$ build up over millions of years, high enough eventually to melt ice, return violently to ice-free state, depositing cap carbonates

![Schematic Diagram of Jormungand Global Climate State](image)
**Jormungand climate state & Neoproterozoic glaciations**

Coupled global climate model simulations described in recently submitted work appears to further support the idea that the Jormungand state can exist with a dynamical ocean and realistic continents\(^1\)

The Jormungand state represents a potential model for Neoproterozoic glaciations, although further study of this issue is needed.

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