(*This seminar examines some of the simpler mathematical models of climate change in the recent literature. Participants are encouraged to read a paper and report on it to the other participants, but passive participation is also welcomed.*)

On the Jormungand Global Climate State

Jim Walsh, Visiting Professor
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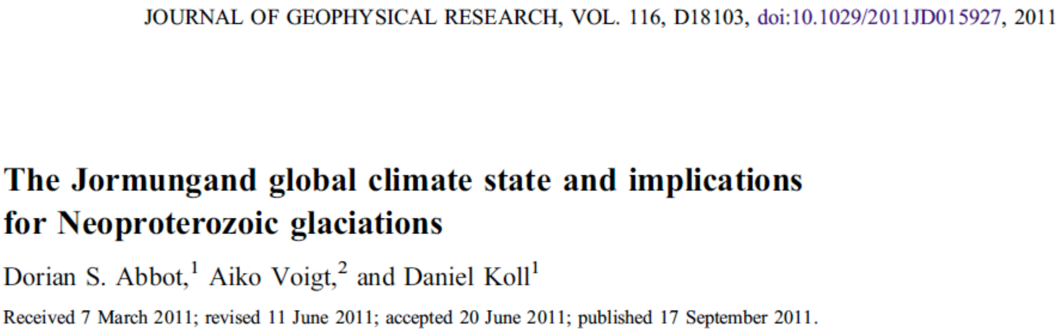
Professor, Oberlin College

October 26, 2011

University of Minnesota
Driven to Discover℠



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The Jormungand global climate state and implications for Neoproterozoic glaciations

Dorian S. Abbot,[1] Aiko Voigt,[2] and Daniel Koll[1]

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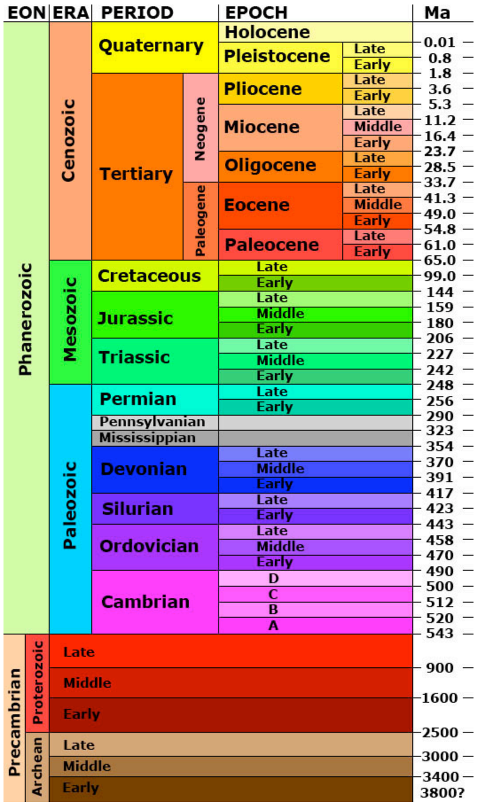

EON	ERA	PERIOD		EPOCH		Ma
Phanerozoic	Cenozoic	Quaternary		Holocene		0.01
				Pleistocene	Late	0.8
					Early	1.8
		Tertiary	Neogene	Pliocene	Late	3.6
					Early	5.3
				Miocene	Late	11.2
					Middle	16.4
					Early	23.7
				Oligocene	Late	28.5
					Early	33.7
			Paleogene	Eocene	Late	41.3
					Middle	49.0
					Early	54.8
				Paleocene	Late	61.0
					Early	65.0
	Mesozoic	Cretaceous		Late		99.0
				Early		144
		Jurassic		Late		159
				Middle		180
				Early		206
		Triassic		Late		227
				Middle		242
				Early		248
	Paleozoic	Permian		Late		256
				Early		290
		Pennsylvanian				323
		Mississippian				354
		Devonian		Late		370
				Middle		391
				Early		417
		Silurian		Late		423
				Early		443
		Ordovician		Late		458
				Middle		470
				Early		490
		Cambrian		D		500
				C		512
				B		520
				A		543
Precambrian	Proterozoic	Late				900
		Middle				1600
		Early				2500
	Archean	Late				3000
		Middle				3400
		Early				3800?

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

Hoffman, P.F. & Schrag, D.P., 2000. Snowball Earth. *Scientific American* **282**, 68-75

Glaciers at the equator: Evidence

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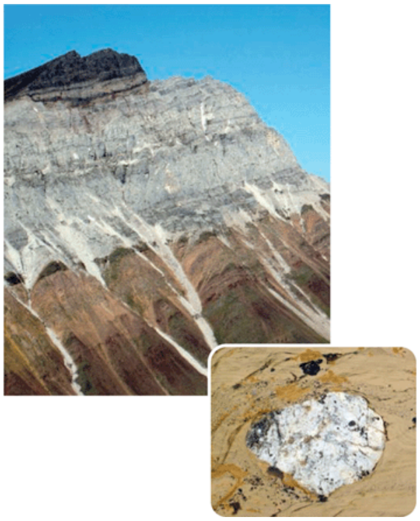


Dated volcanic ash within glacial deposits to 715.5 Ma

Kerr, R., 2010. Snowball Earth Has Melted Back To a Profound Wintry Mix. *Science* **327**, p. 1186

Macdonald, F. et al, 2010. Calibrating the Cryogenian. *Science* **327**, 1241-1243

Glaciers at the equator: Evidence

- 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;

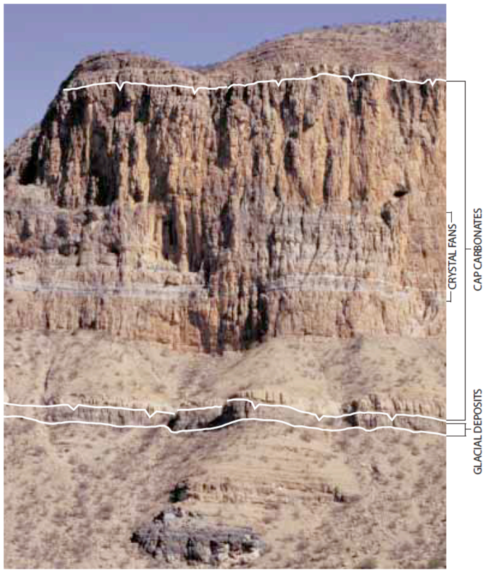
  --Ir accumulates on and within the ice and snow, and precipitates out when ice melts;

  --Ir anomalies used to estimate the duration of the Marinoan glacial episode (~630 Ma) at 12 My[1]

[1] Bodiselitsch, B. et al, Estimating duration and intensity of Neoproterozoic snowball glaciations from Ir anomalies, *Science* **308**, 239-242.

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

Hoffman, P.F. & Schrag, D.P., 2000. Snowball Earth. Scientific American 282, 68-75

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

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

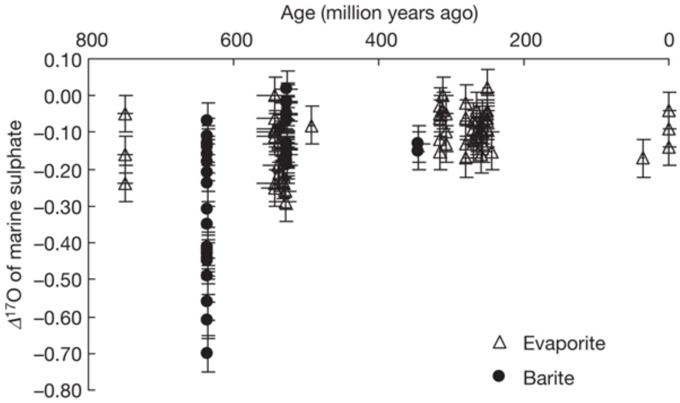


Figure 1 | The Δ^{17}O of evaporite and barite sulphate over the past 750 million years.

$(\Delta^{17}\mathrm{O} = \delta'^{17}\mathrm{O} - 0.52 \times \delta'^{18}\mathrm{O})$

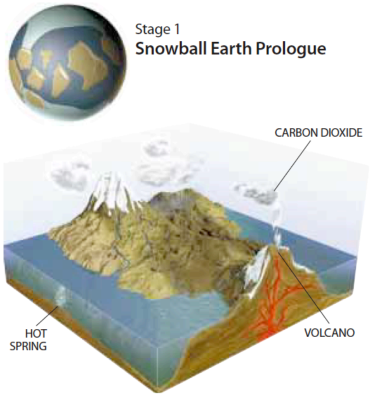
Boa, H. et al, 2008. Triple oxygen isotope evidence for elevated CO_2 levels after a Neoproterozoic glaciation. *Nature* **453**, 504-506

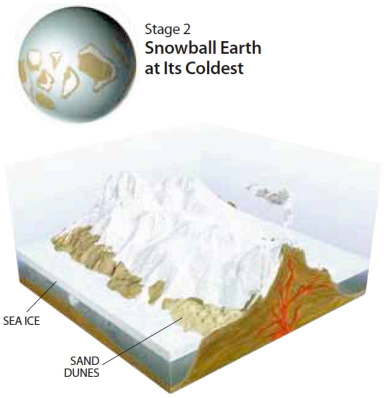
Neoproterozoic glaciation models

- Snowball Earth

  --J. Kirschivink, 1992[1]. *The data are difficult to interpret in any fashion other than that of widespread, equatorial glaciation.*

  --popularized/advocated for in “A Neoproterozoic Snowball earth,” Science 281, 1998, 1342-1346, by Hoffman, Kaufman, Halverson, & Schrag





[1] J. Kirschivink, Late Proterozoic low-latitude global glaciation: the Snowball Earth. In *The Proterozoic Biosphere: A Multidisciplinary Study*, J.W Schopf & C. Klein (eds.), Cambridge University Press, 1992.

Figures from: Hoffman, P.F. & Schrag, D.P., 2000. Snowball Earth. *Scientific American* **282**, 68-75

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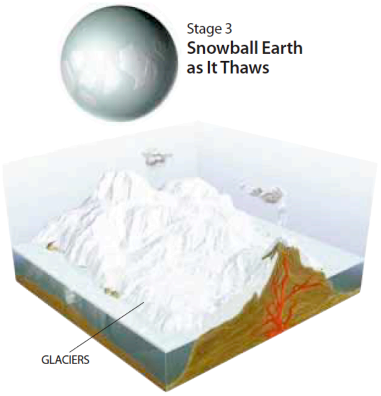

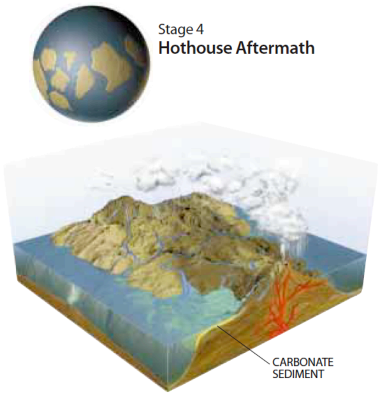

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Figures from: Hoffman, P.F. & Schrag, D.P., 2000. Snowball Earth. *Scientific American* **282**, 68-75

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

[1] Pollard, D. & Kasting, F., 2005. Snowball Earth: A thin-ice solution with flowing sea glaciers. *Journal of Geophysical Research* **110**, 1-16

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)[1]

--Appropriate value of the albedo for snow covered ice is 0.81[1]

Surface type	Albedo
Clean new H_2O snow	0.85
Bare sea ice	0.5
Clean H_2O glacier ice	0.6
Deep water	0.1
Sahara Desert sand	0.35
Martian sand	0.15
Basalt (any planet)	0.07
Granite	0.3
Limestone	0.36
Grassland	0.2
Deciduous forest	0.14
Conifer forest	0.09
Tundra	0.2

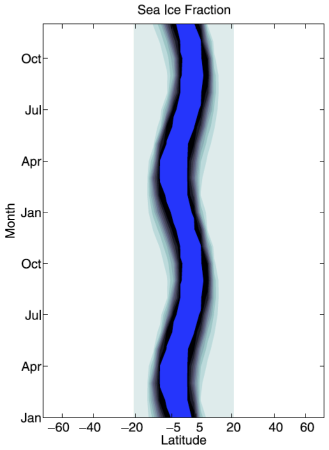
[1] Warren, S.G. et al, 2002. Snowball Earth: Ice thickness on the tropical ocean. *Journal of Geophysical Research* **107**, 3167.

Table from: Pierrehumbert, R., 2010. *Principles of Planetary Climate*, Cambridge University Press, p. 154

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



Abbot et al, p. 4

Henry Fuseli (1788)

Alternative Neoproterozoic glaciation models

- Jormungand climate state

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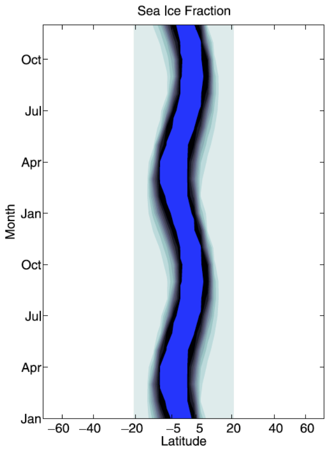

The *Kraken* and Captain Jack Sparrow

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

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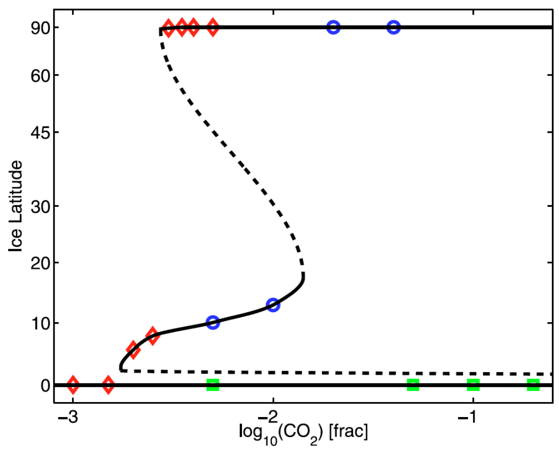

(Abbot et al, p. 3)

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

Jormungand climate state: Simulations with global climate models

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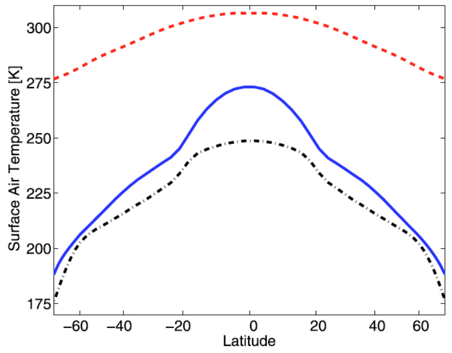


Figure 3. Annual and zonal mean surface air temperature for the ice-free state (red dashed), Jormungand state (blue), and Snowball state (black dash-dotted) with pCO_2 = 5000 ppm.

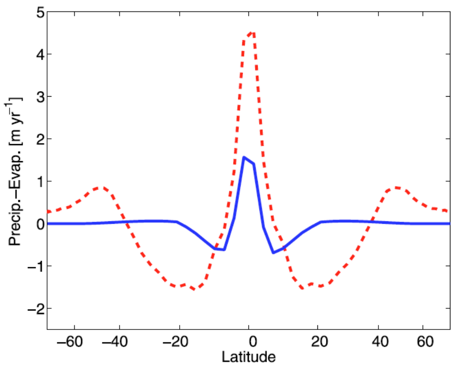
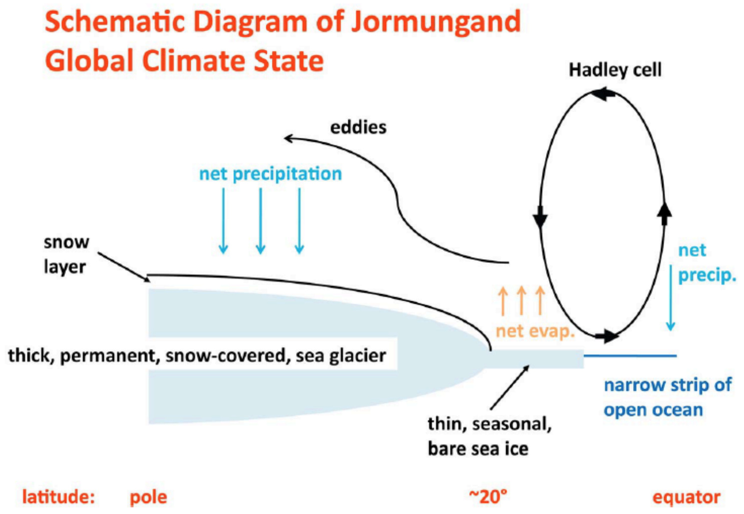


Figure 4. Annual and zonal mean precipitation minus evaporation for the ice-free state (red dashed) and the Jormungand state (blue) with pCO_2 = 5000 ppm.

(Abbot et al, p. 4)

Jormungand climate state: Atmospheric dynamics



(Abbot et al, p. 6)

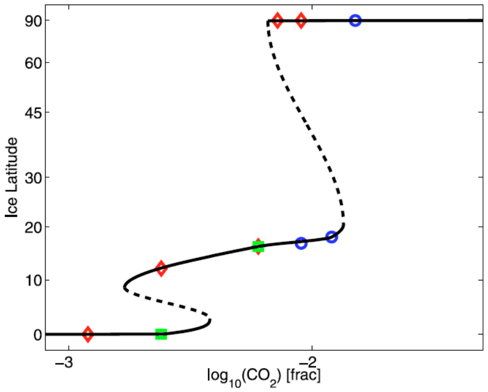
Jormungand climate state: Simulations with global climate models

- Max Planck Institute's atmospheric model v5.3.02p

  Horizontal resolution 3.75^{o} x 3.75^{o}, 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 equatorword of 20^{o} latitude and CAM's snow albedo poleward of 20^{o} latitude



(Abbot et al, p. 7)

Jormungand climate state: Simple energy balance climate models

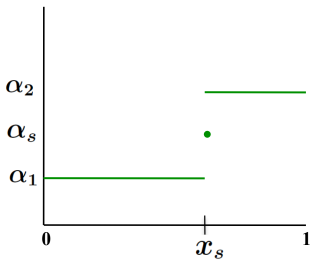
Budyko-Sellers Model: At equilibrium

$$\overbrace{\frac{Q}{4}S(x)(1-\alpha(T(x)))}^{\text{in}} = \overbrace{A + BT(x) + C(T(x) - \overline{T})}^{\text{out}}$$

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
$\overline{T}$	average surface temperature
α	albedo
$A + BT$	linearization of OLWR
$C(T - \overline{T})$	meridional heat transport
symmetry	

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

$$\frac{\partial \alpha_s}{\partial x_s} = 0$$



$T_s =$ temperature at the ice line

$= -10^{\circ}$C

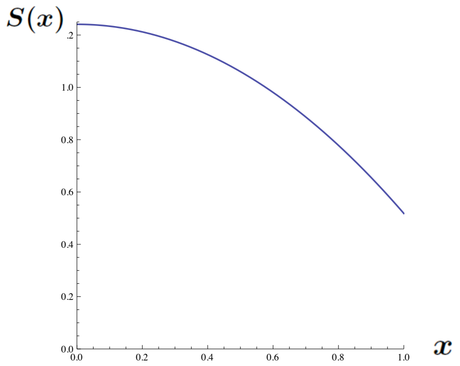
$$\alpha_s = \frac{\alpha_1 + \alpha_2}{2}$$

Budyko-Sellers Model

$$\frac{Q}{4}S(x)(1-\alpha(T(x))) = A + BT(x) + C(T(x) - \overline{T})$$

$S(x)$ is uniformly approximated within 2% by

$$S(x) = 1 - \frac{s_2}{2} + \frac{3}{2}s_2 x^2, \quad s_2 = -0.482$$



North, G., 1975. Analytic solution to a simple climate model with diffusive heat transport. *Journal of Atmospheric Sciences* **32**, 1301-1307.

Budyko-Sellers Model

(1) $$\frac{Q}{4}S(x)(1-\alpha(T(x))) = A + BT(x) + C(T(x) - \overline{T})$$

Global mean energy balance: integrate from *x*=0 to *x*=1

(2) $$\frac{Q}{4}(1-\alpha_p(x_s)) = A + B\overline{T}$$ $x_s =$ 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) $$\frac{Q}{4}S(x_s)(1-\alpha_s) = A + BT_s + C(T_s - \overline{T})$$

Solve (2) for $\overline{T}$, 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

---

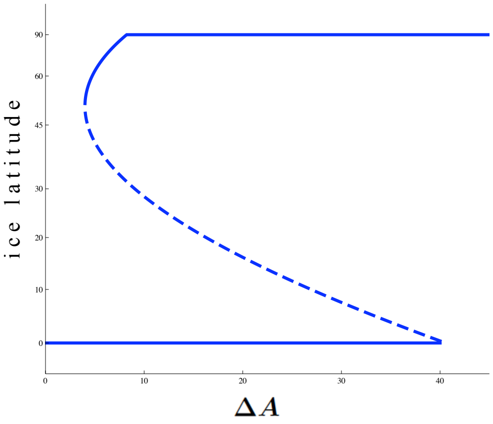
Budyko-Sellers Model: Linear stability analysis $\Delta A = A_0 - A$

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

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

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

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



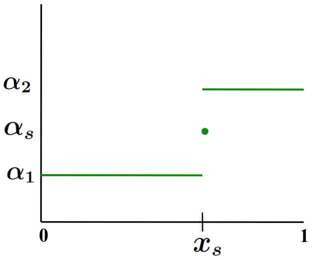
$Q = 1285$ W m^{-2}, $A_0 = 210$ W m^{-2},
$B = 1.5$ W m^{-2} K^{-1}, $C = 2.5B$, $\alpha_1 = 0.3$,
$\alpha_2 = 0.6$, $T_s = -10^o$C, $s_2 = -0.482$

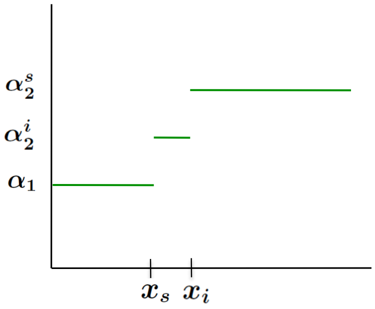
Jormungand climate state: Simple energy balance climate models

Modified Budyko-Sellers Model: At equilibrium

$$\overbrace{\frac{Q}{4}S(x)(1-\alpha(T(x)))}^{\text{in}} = \overbrace{A+BT(x)+C(T(x)-\overline{T})}^{\text{out}}$$

$$\frac{\partial \alpha_s}{\partial x_s} = 0$$





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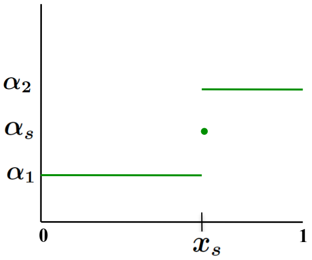
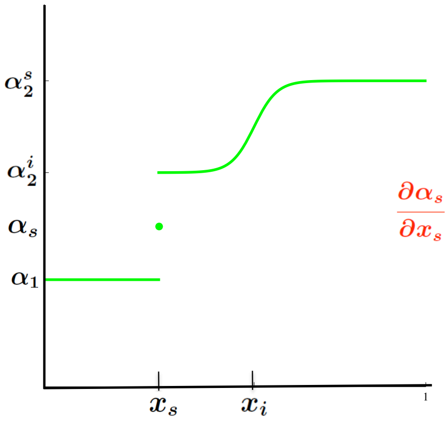




$$\frac{\partial \alpha_s}{\partial x_s} \neq 0$$

$$\alpha_2 = \alpha_2(x) = \alpha_2^i + \left(\frac{\alpha_2^s - \alpha_2^i}{2}\right)\left(1 + \tanh\left(\frac{x - x_i}{\Delta x_i}\right)\right)$$

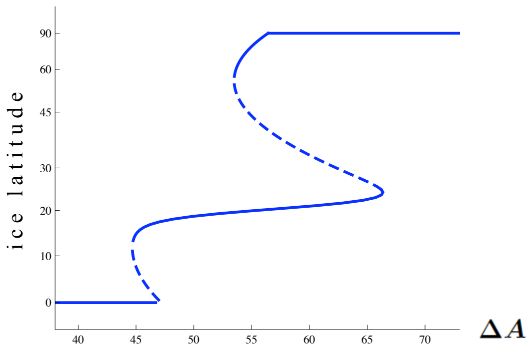
Modified Budyko-Sellers Model:

$$\Delta A = A_0 - A$$

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

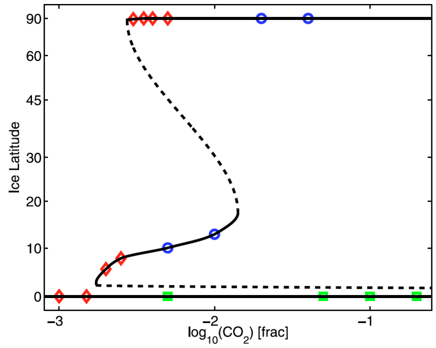
$$\alpha_p(x_s) = \int_0^1 \alpha(x)S(x)dx = \alpha_1\int_0^{x_s} S(x)dx + \int_{x_s}^1 \alpha_2(x)S(x)dx$$

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



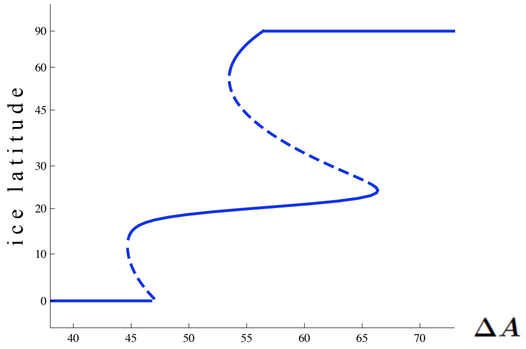
$\alpha_1 = 0.35, \alpha_2^i = 0.45, \alpha_2^s = 0.8, x_i = 0.35$
$\Delta x_i = 0.04, T_s = 0^{\text{o}}\text{C}, C = 1.5B$

CAM Simulation



(Abbot et al, p. 3)

Modified Budyko-Sellers Model



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$\Delta x_i = 0.04, T_s = 0^{\text{o}}\text{C}, C = 1.5B$

Jormungand climate state: Accessibility

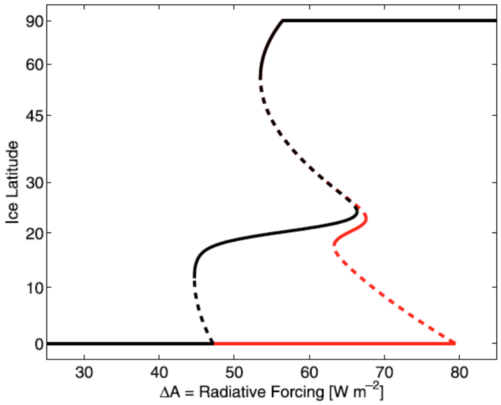


Figure 12. As in Figure 11, with $\alpha_2^i = 0.45$ (black) and with $\alpha_2^i = 0.65$ (red). In the latter case the Jormungand state is not "accessible" if the radiative forcing (ΔA) is increased and decreased through a hysteresis loop between the warm state and the Snowball state.

(Abbot et al, p. 10)

Jormungand climate state & Neoproterozoic glaciations: Recap

High CO$_2$ initially to balance reduce insolation

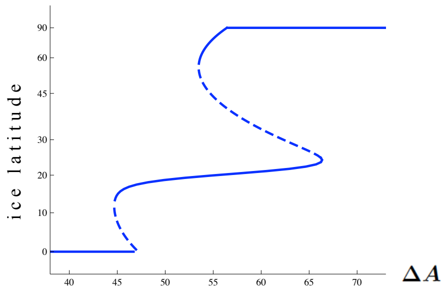
For some reason there is a reduction of one or more greenhouse gases, and ice latitude decreases

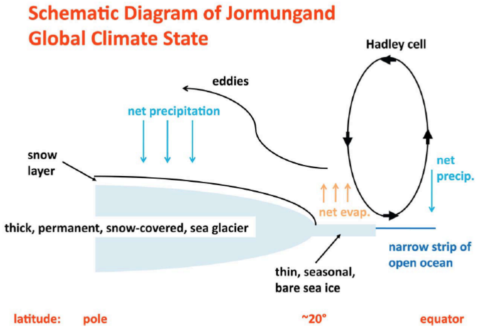
Reach first bifurcation, and ice latitude rushes toward the equator

At 20-30^o 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





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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[1] Yang, J. et al, The initiation of modern "soft Snowball" and "hard Snowball" climates in CCSM3. Part I: The influence of solar luminosity, CO2 concentration and the sea ice/snow albedo parametrization; Part II: Climate dynamic feedbacks, submitted.