A Jormungand Solution to the Snowball Paradox?

Dorian S. Abbot

THE UNIVERSITY OF CHICAGO

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

Friends:

Aiko Voigt

MAX-PLANCK-GESELLSCHAFT

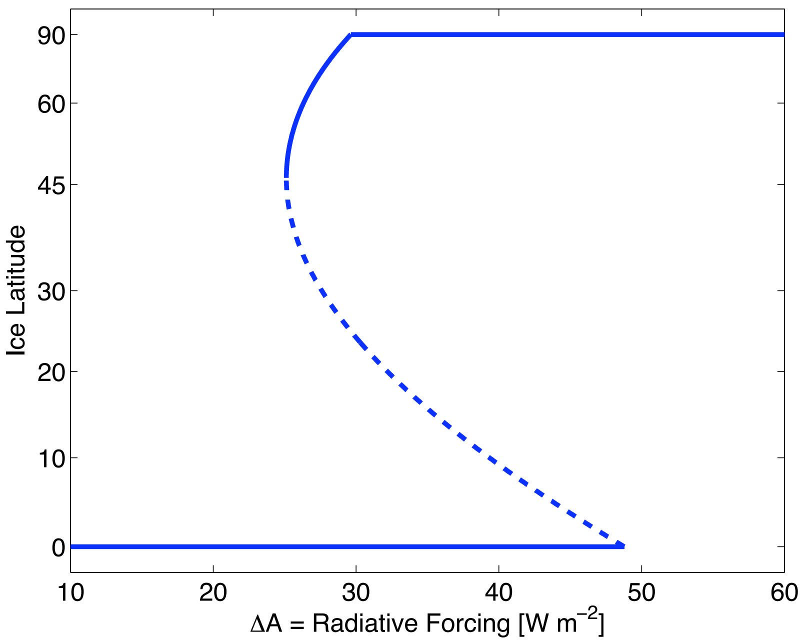
Daniel Koll

VE RI TAS
HARVARD

Raymond T. Pierrehumbert

THE UNIVERSITY OF CHICAGO

Outline

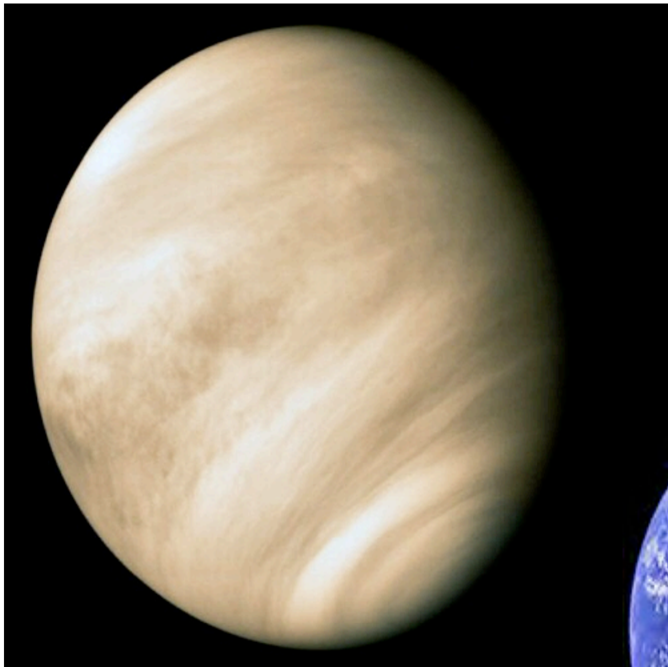


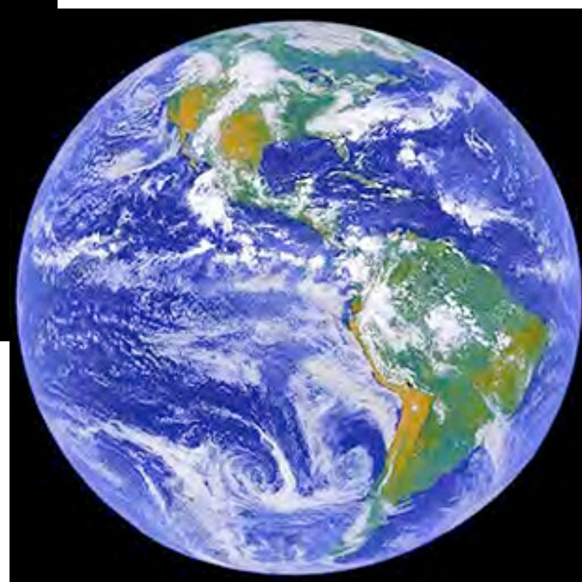
Basic global climate dynamics

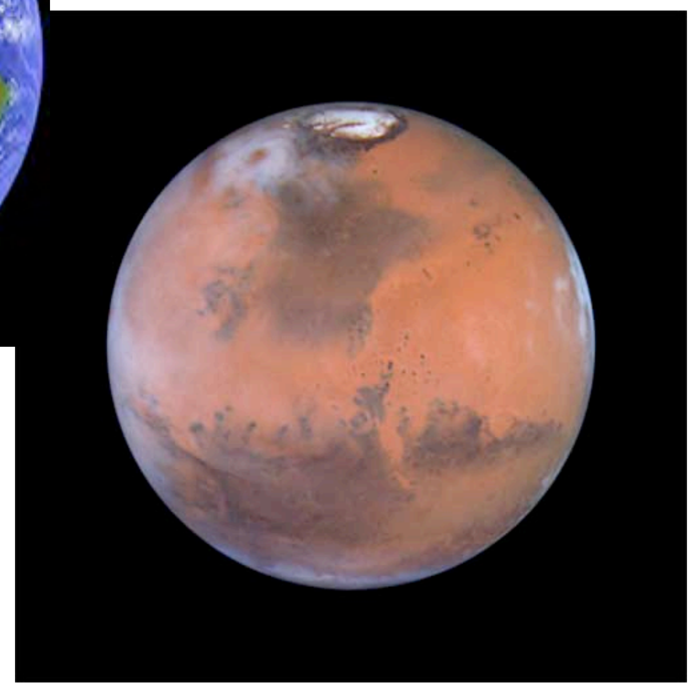
Snowball geology

The Jormungand global climate state

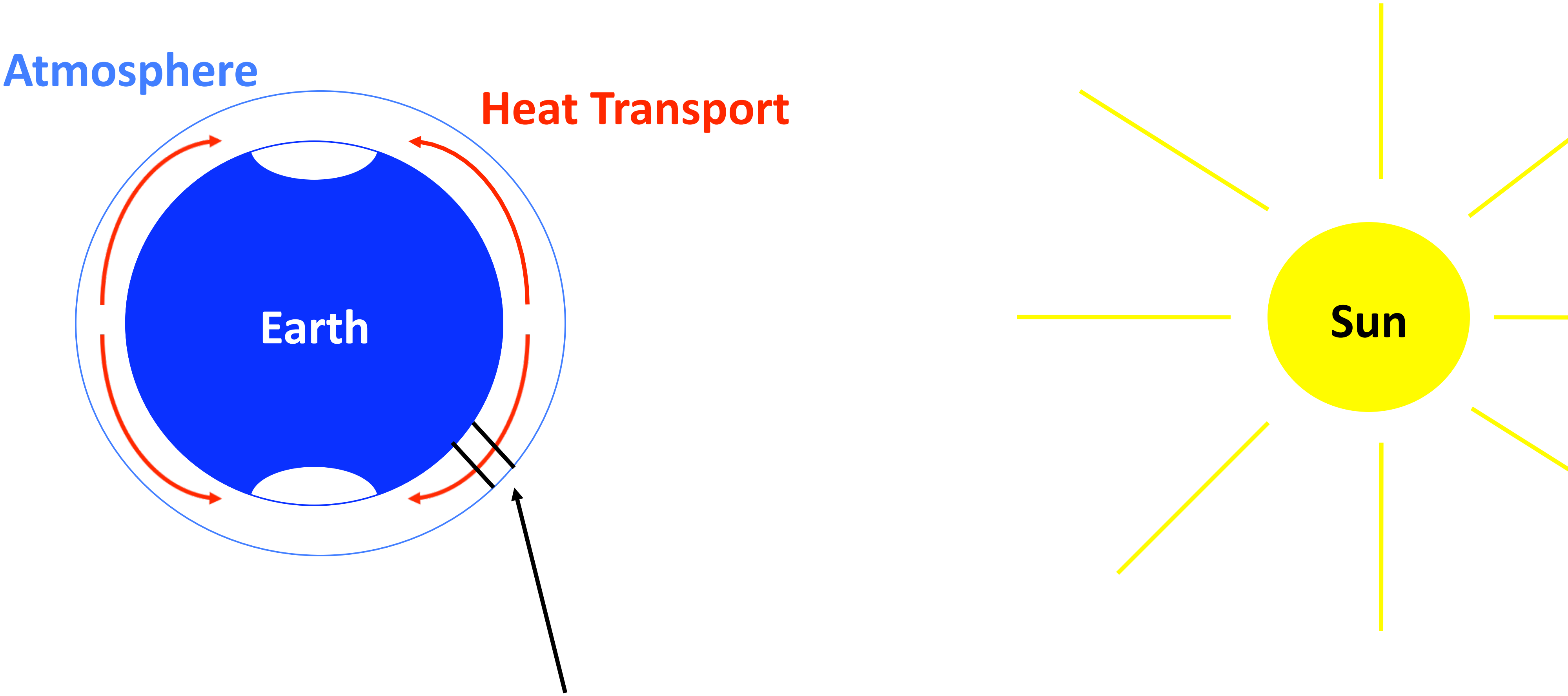
Basic Global Climate Dynamics







The Budyko-Sellers model is an idealized climate model based on zonal and annual mean heat balance.



absorbed solar rad. = emitted infrared rad. + divergence of heat trans.

[Budyko, 1969; Sellers, 1969]

The Budyko-Sellers equations

Heat Balance:

$$\frac{Q}{4}S(x)(1-\alpha(T(x))) = F_{olr}(x) + \nabla \cdot \vec{F}$$

albedo; outgoing infrared; solar constant; sin latitude; divergence heat trans.

Shape Solar Rad.: $S(x) = 1 + s_2 P_2(x)$

Ice-Albedo Feedback:

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

Simplified Equation:

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

linearize infrared rad.; non-local param. of heat trans.

Solving the Budyko-Sellers model

Global Heat Balance: $$\frac{Q}{4}(1-\alpha_p(x_s)) = A + B\overline{T}$$

ice line

Global-Mean Albedo:

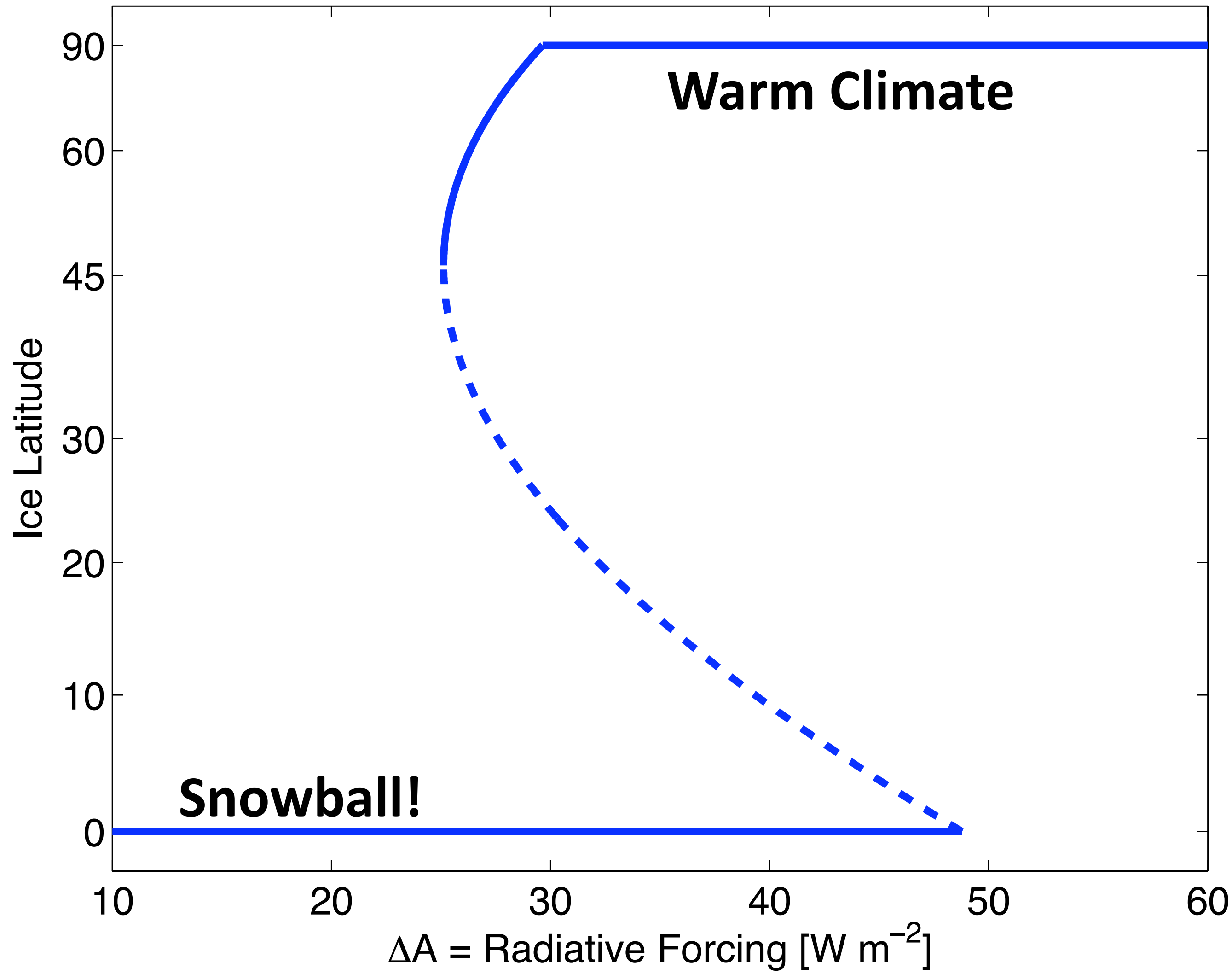
$$\alpha_p(x_s) = \int_0^1 \alpha(x)S(x)dx = \alpha_1 \int_0^{x_s} S(x)dx + \alpha_2 \int_{x_s}^1 S(x)dx$$

Heat Bal. at Ice Line: $$\frac{Q}{4}S(x_s)(1-\alpha_s) = A + BT_s + C(T_s - \overline{T})$$

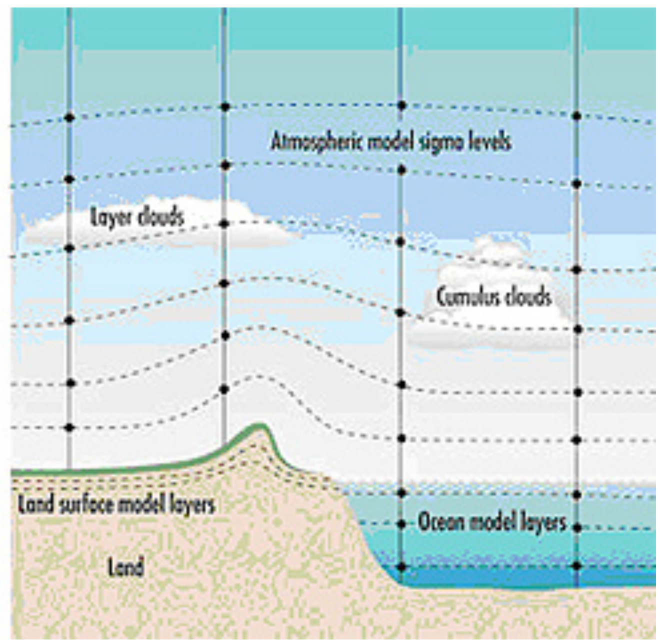
Solve for Mean Temp. and Combine:

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

The ice-albedo feedback leads to multiple equilibria in the Budyko-Sellers model.

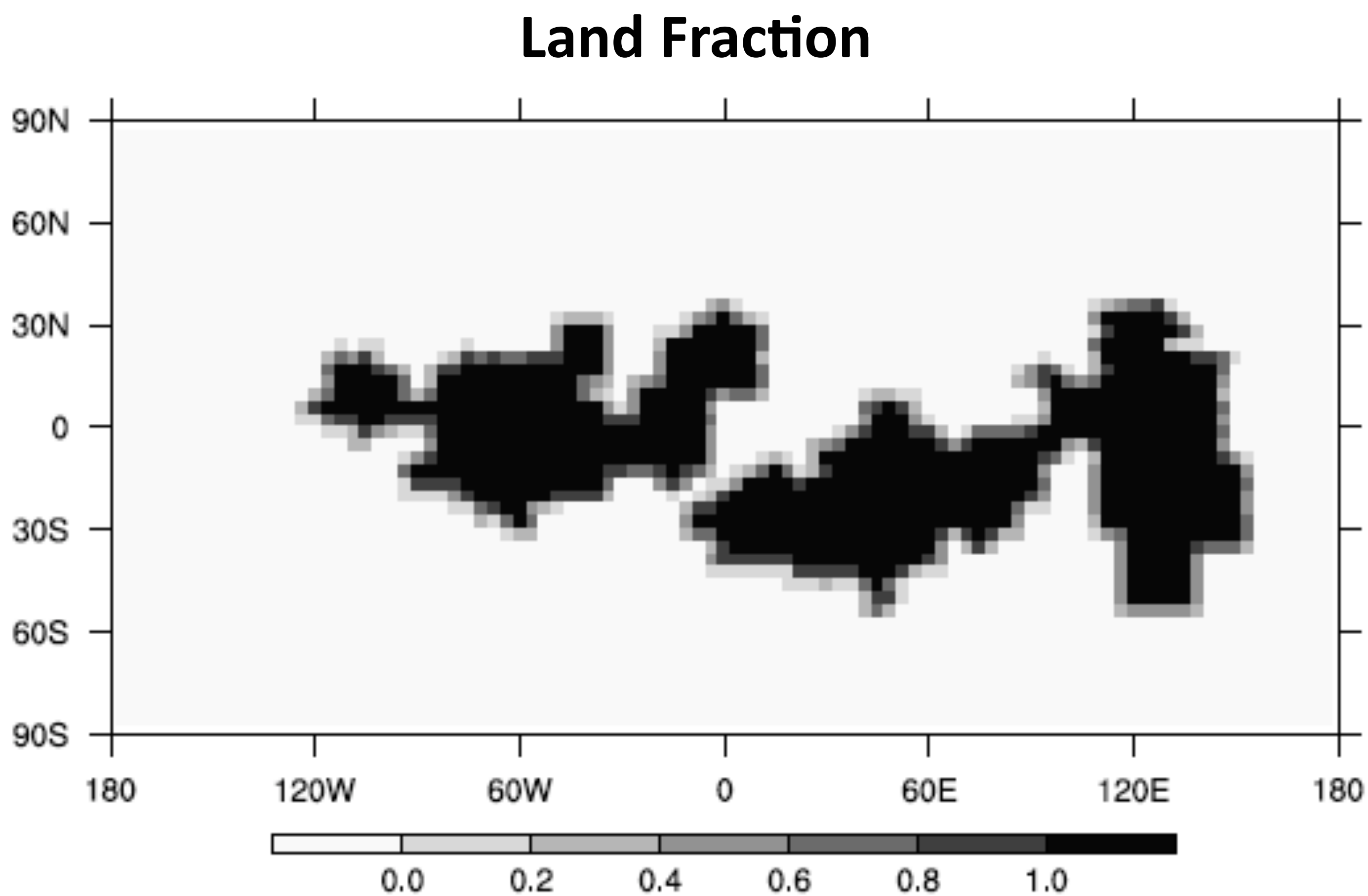


A global climate model solves numerically the equations of fluid flow and radiative transfer on a rapidly rot. sphere.

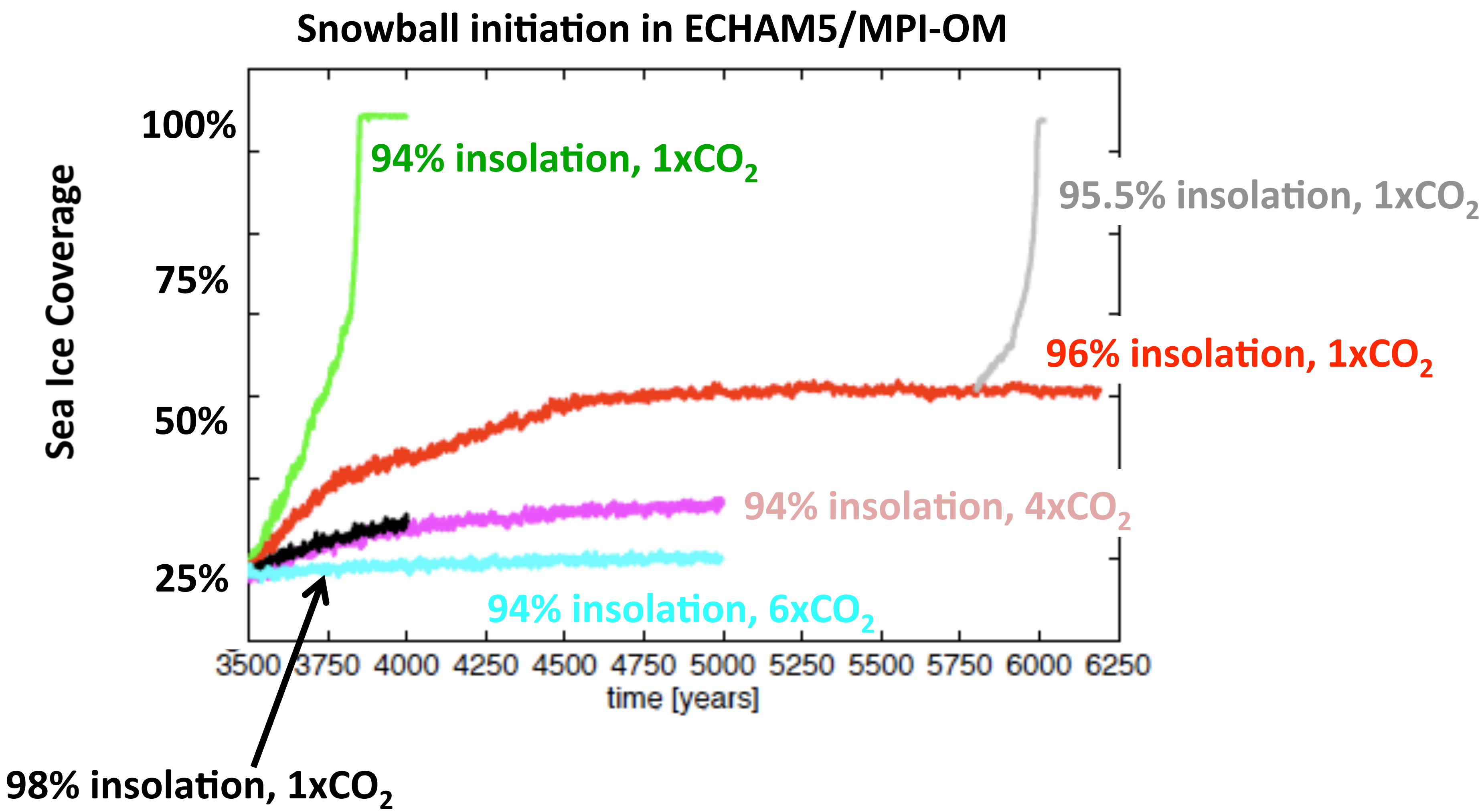


A global climate model typically has $O(10^6)$ degrees of freedom.

We use realistic ~600 Ma boundary conditions for the ECHAM5/MPI-OM runs.

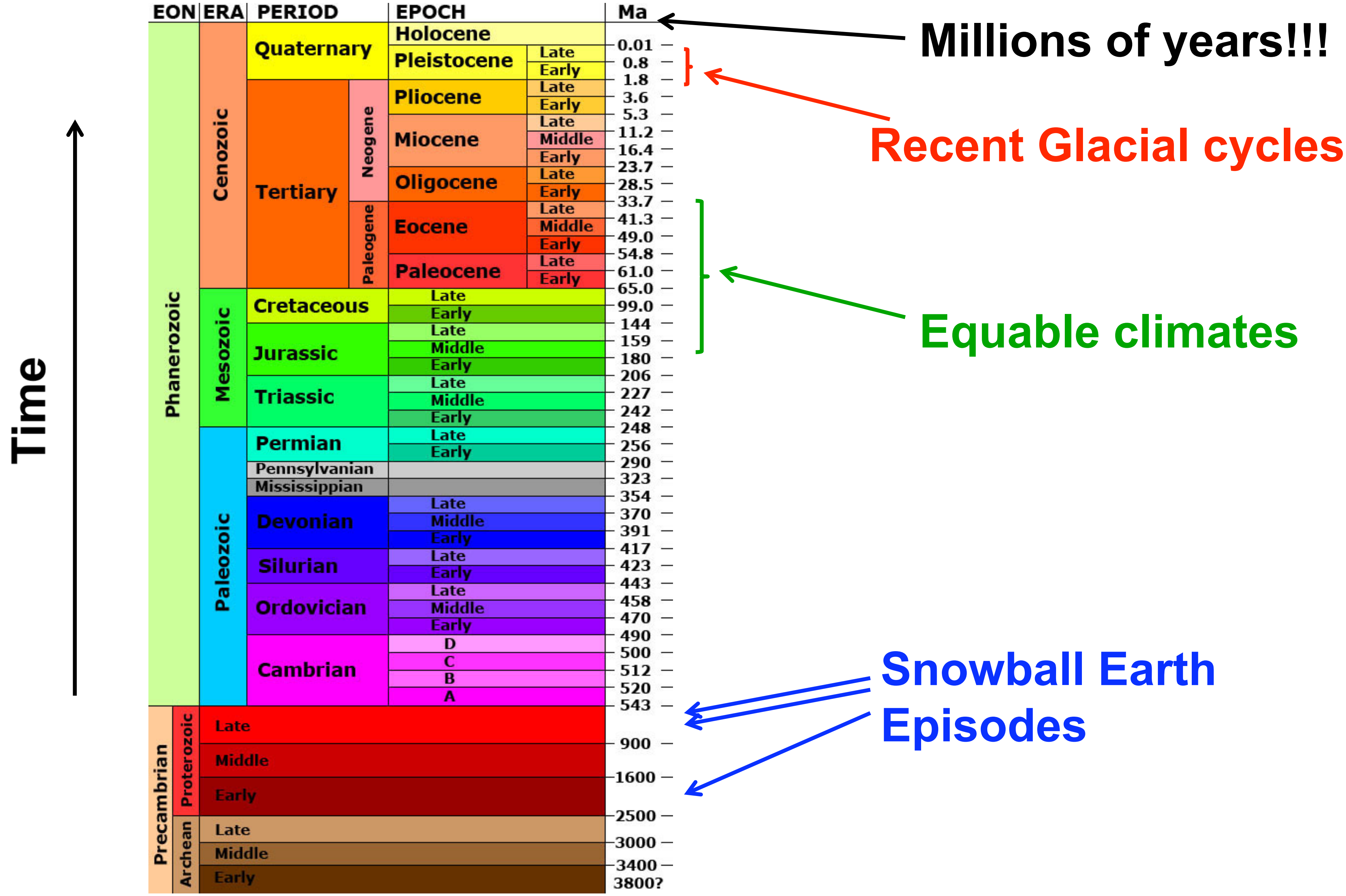


One of the world's most sophisticated global climate models reproduces the basic concepts from Budyko-Sellers.

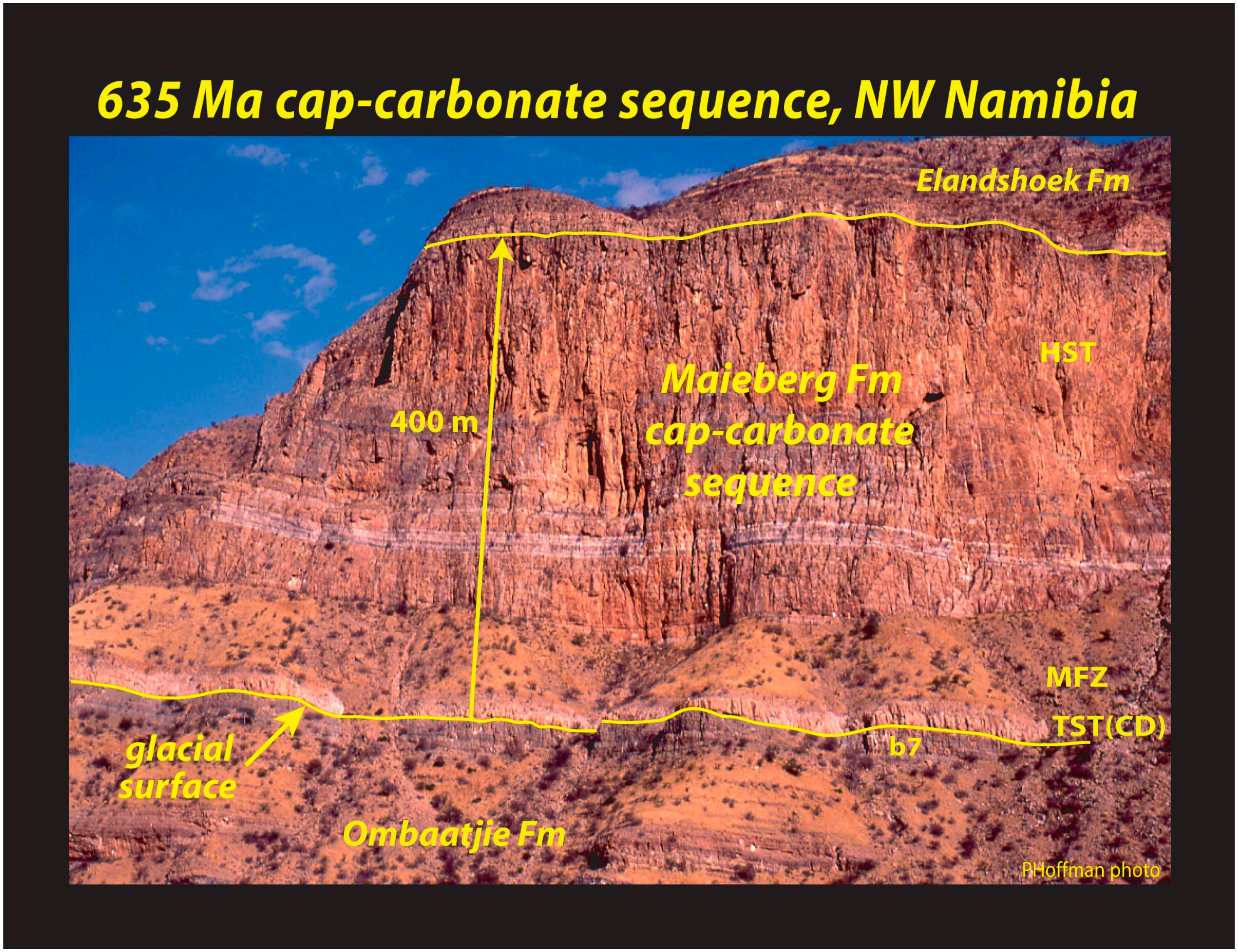


And now for something completely wacky… Some geologists think a Snowball may have actually happened!

When were the Snowballs?

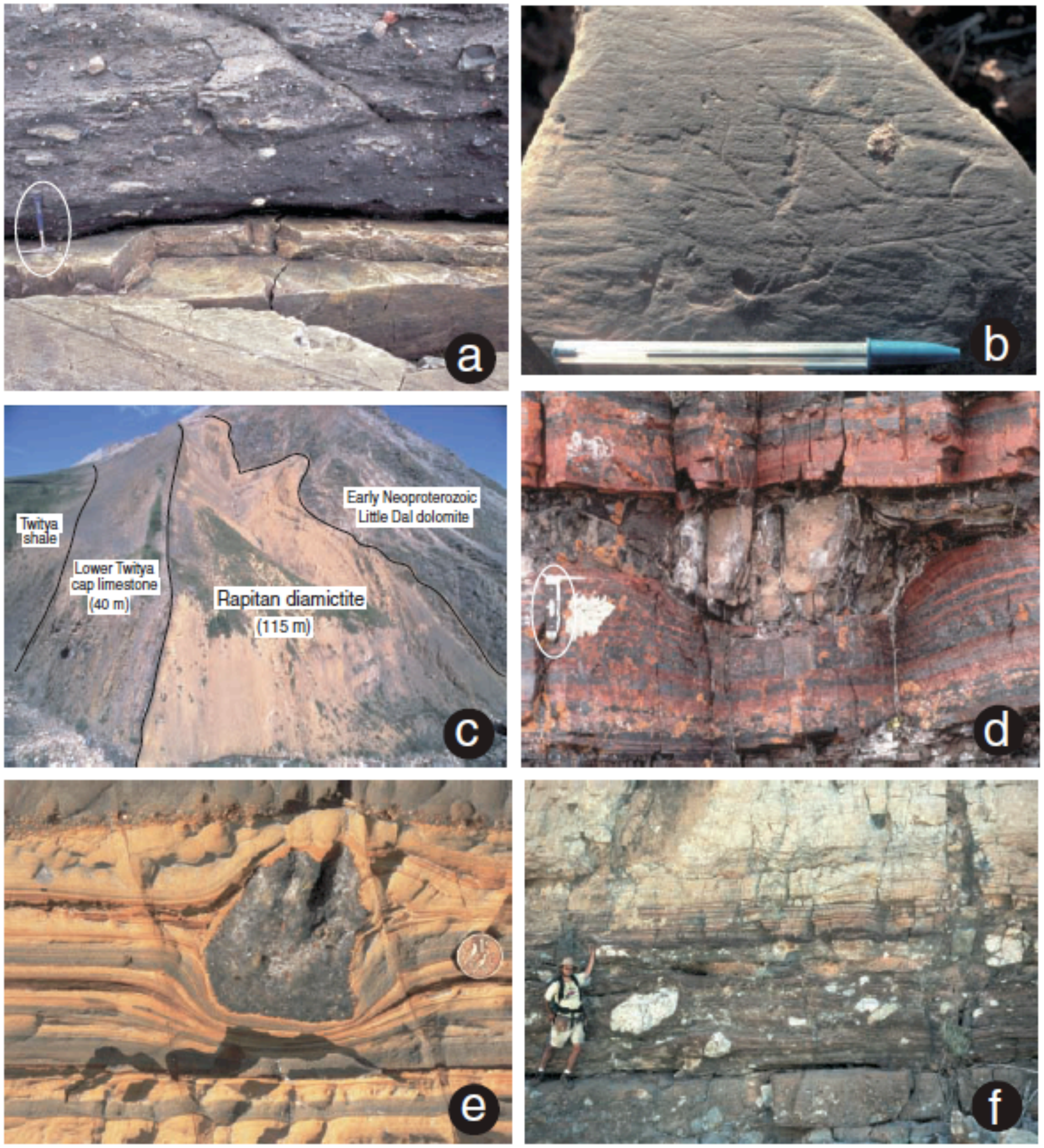


Glacial rocks are overlain with rocks that suggest an extremely hot and moist climate.

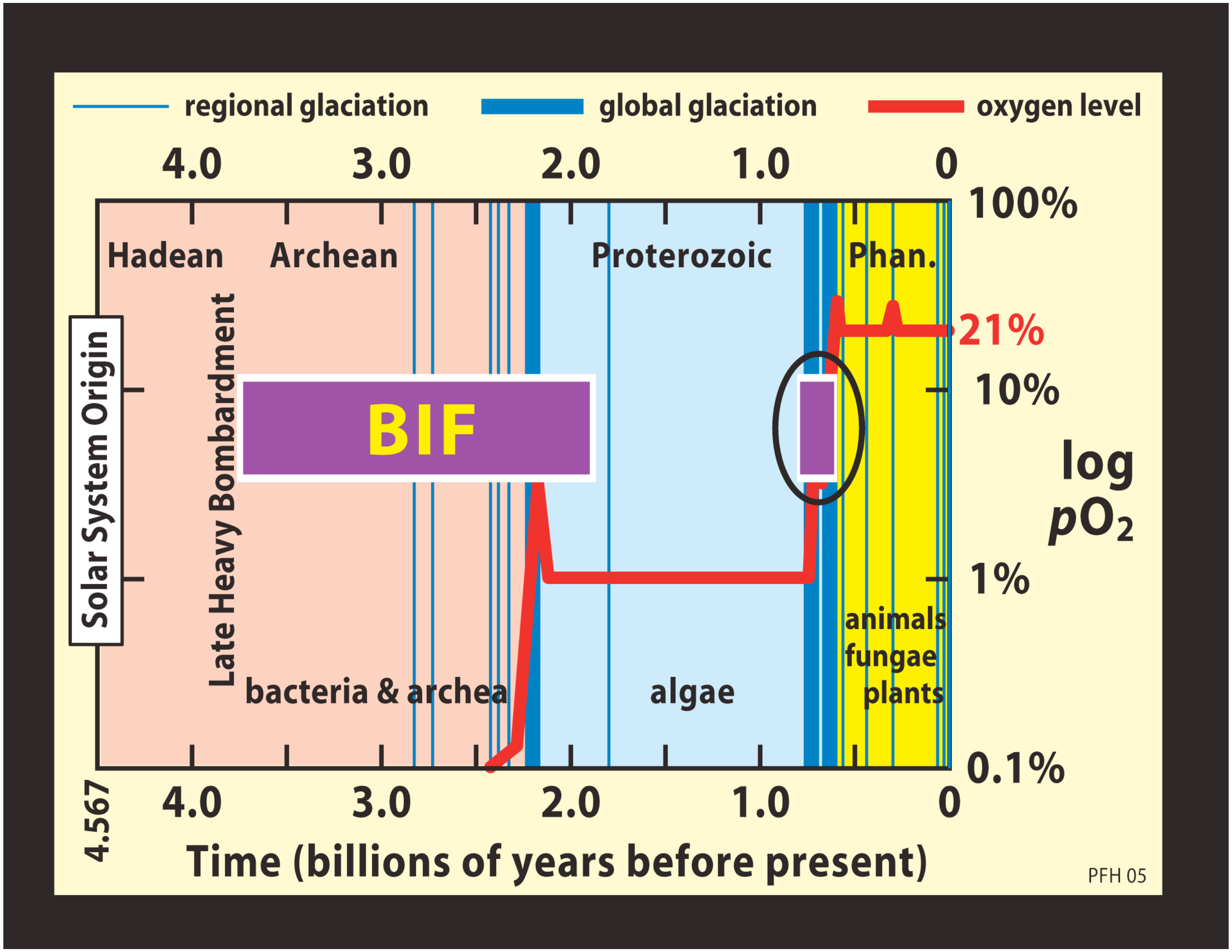


[thanks to P Hoffman for next four slides]

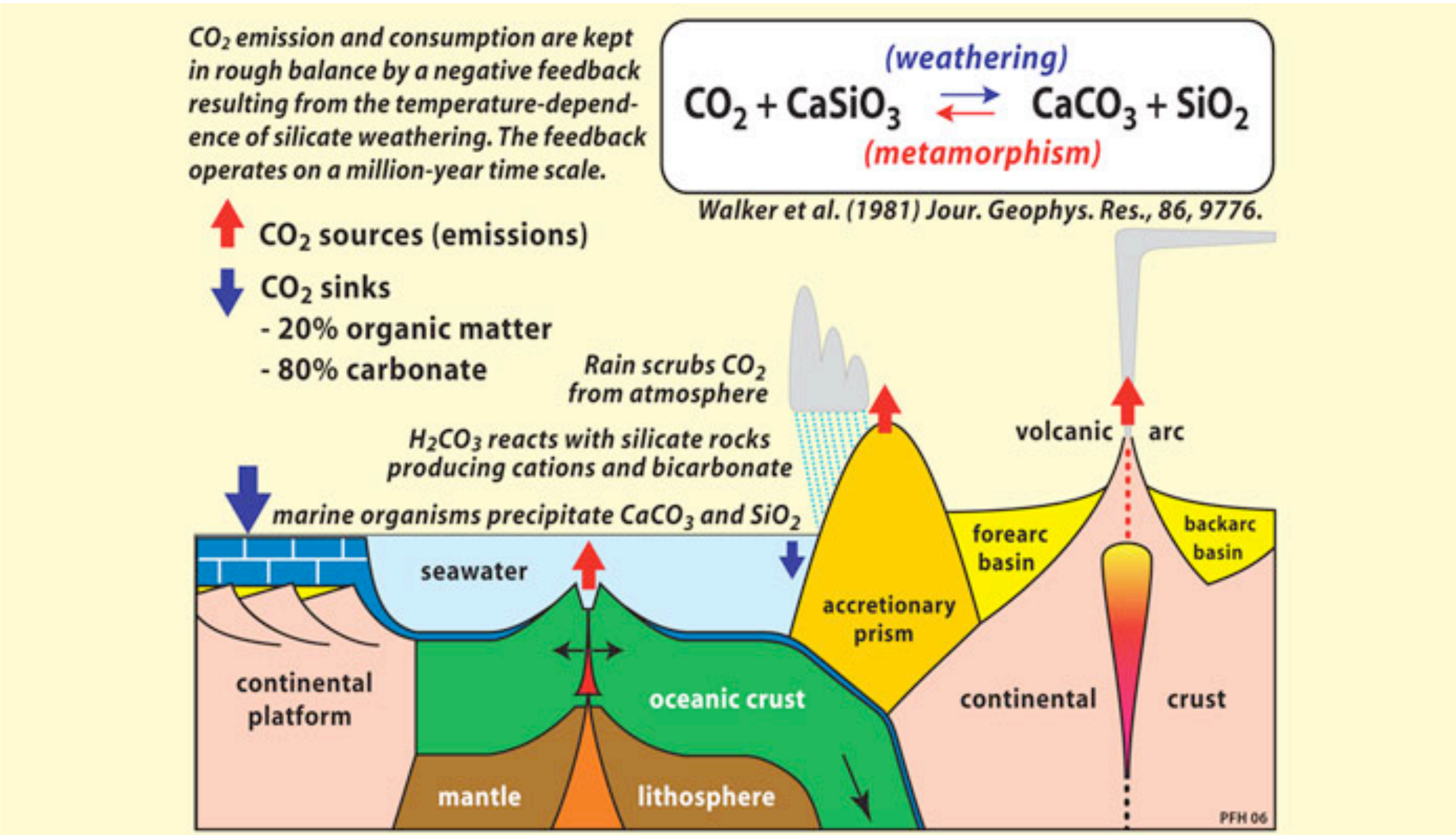
Rocks show evidence of glaciers at sea level at the equator about 600 million years ago.



The occurrence of banded iron formations may suggest the entire ocean was covered in ice.



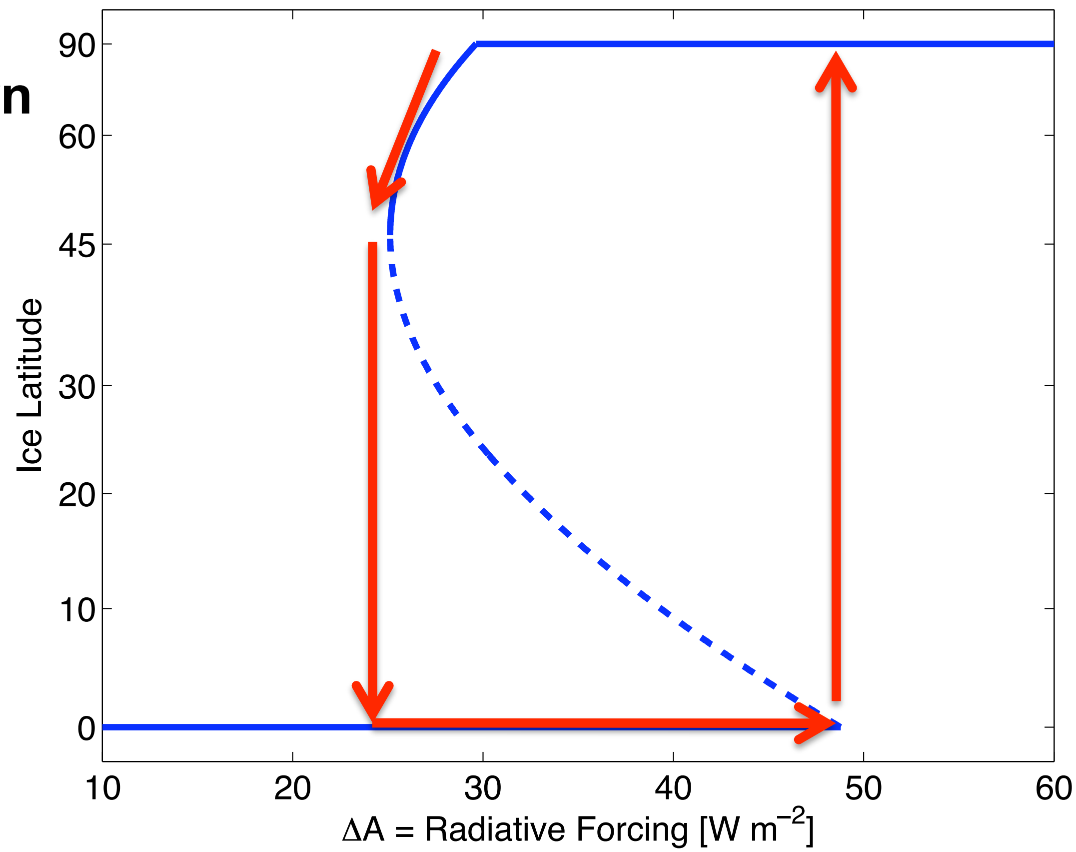
Silicate weathering reduces when the temperature is low, which increases CO_2 to form a negative feedback.



The climate model and silicate weathering feedback can be put together to explain geological observations.

CO_2 draw down

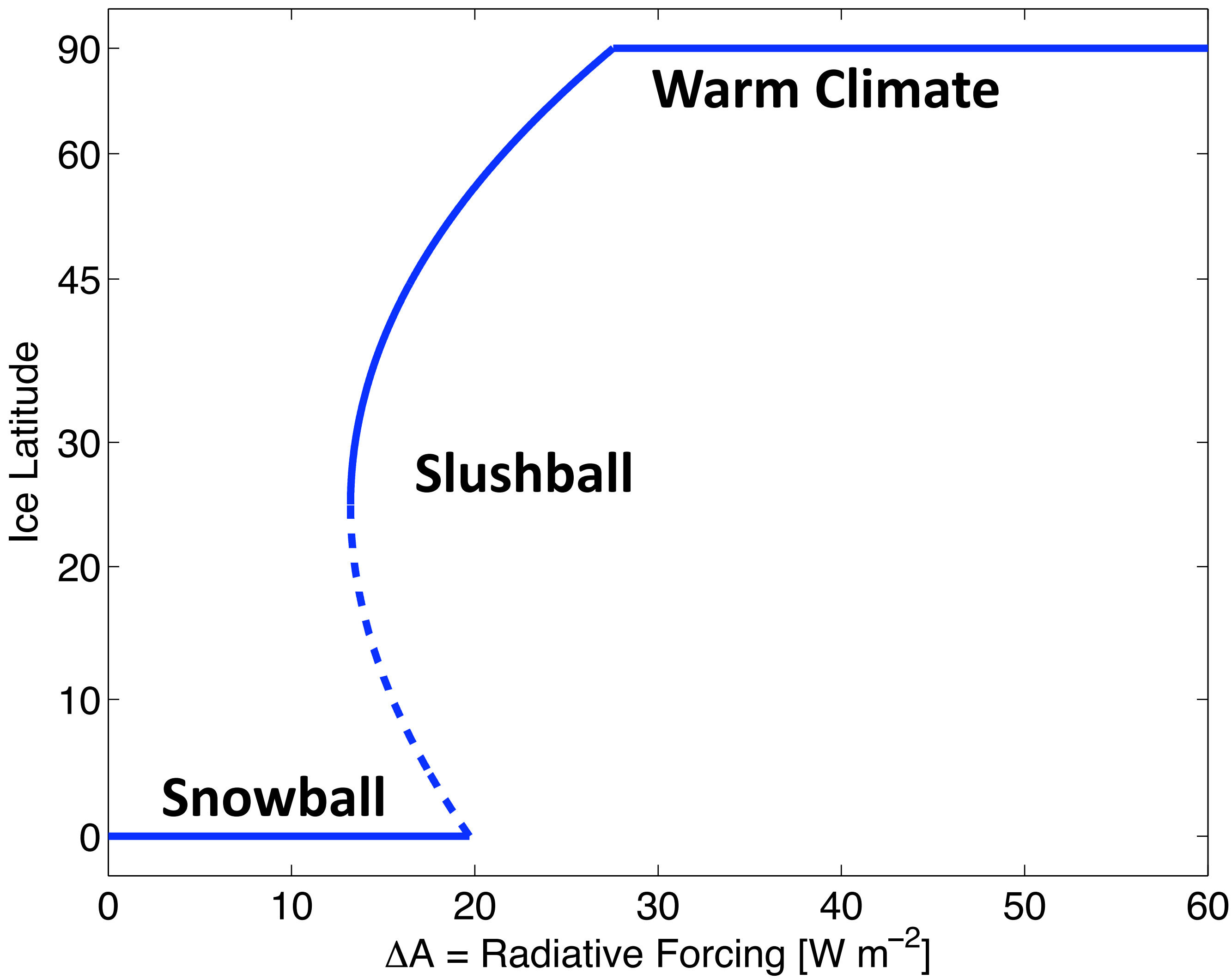
Runaway ice-albedo feedback



Tropical ice melts and reverse ice-albedo feedback occurs

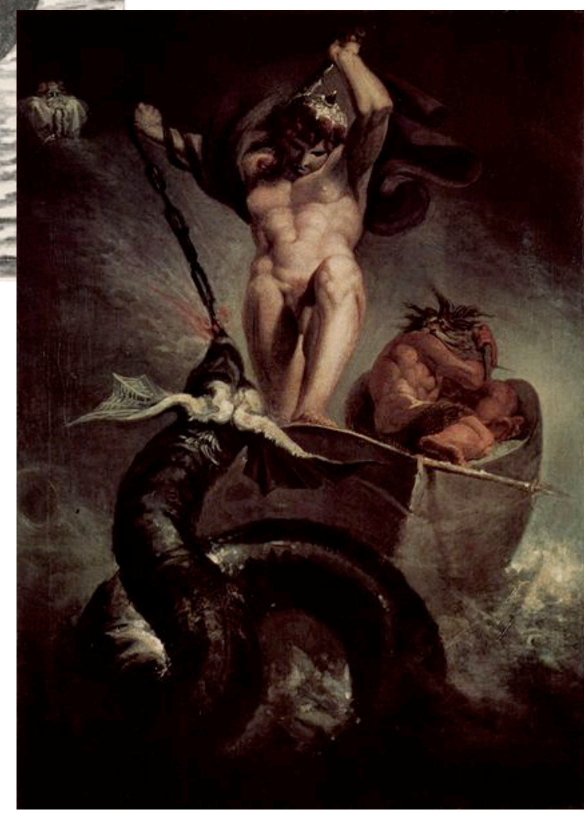
Very low weathering allows CO_2 to build up to ~10% of atmosphere over 1-10 million years

Concern about the survival of life has led some to propose a "Slushball Earth" model for Snowball events.

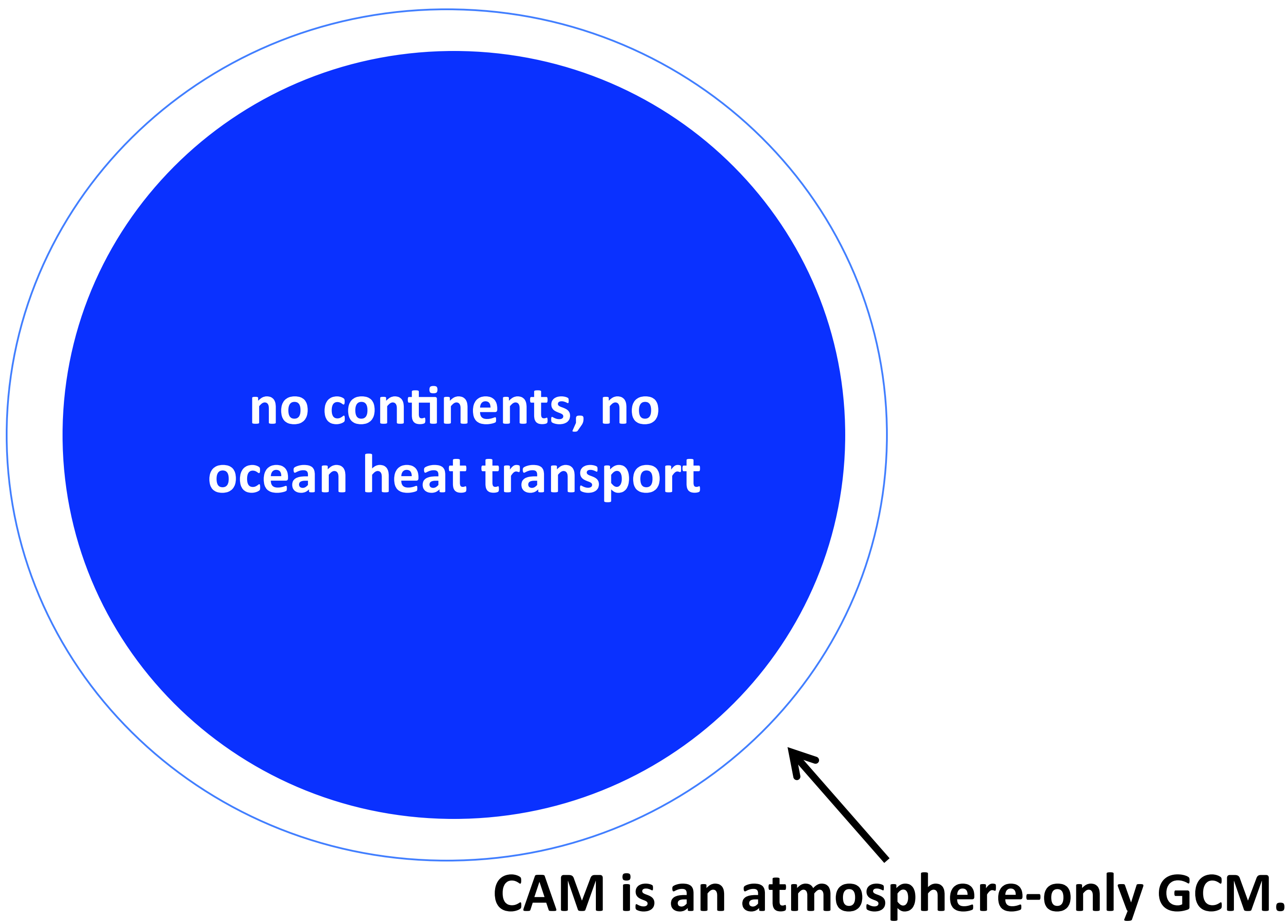


A Slushball would require very low ice-ocean albedo contrast and would be precariously close to Snowball bifurcation.

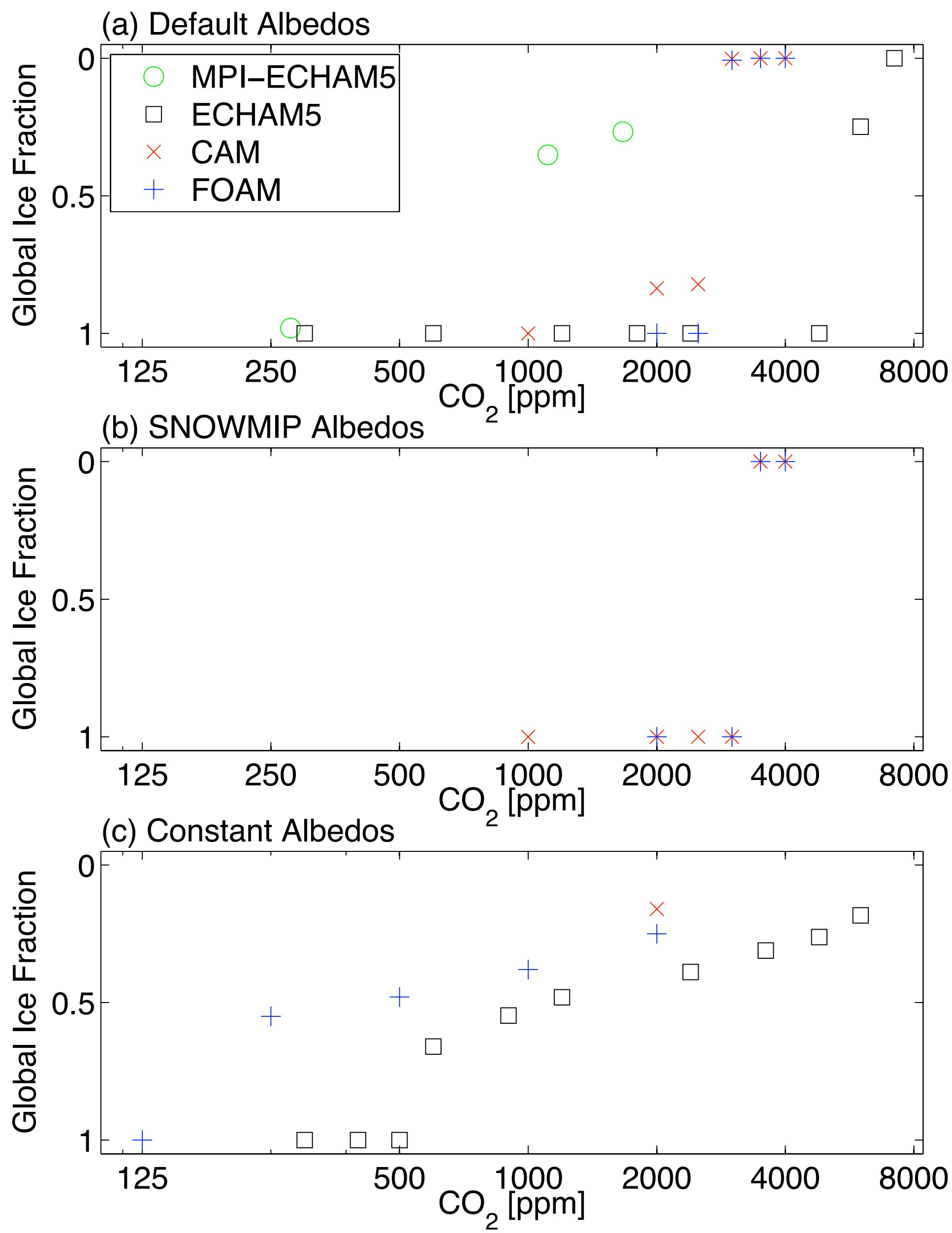
The Jormungand Global Climate State



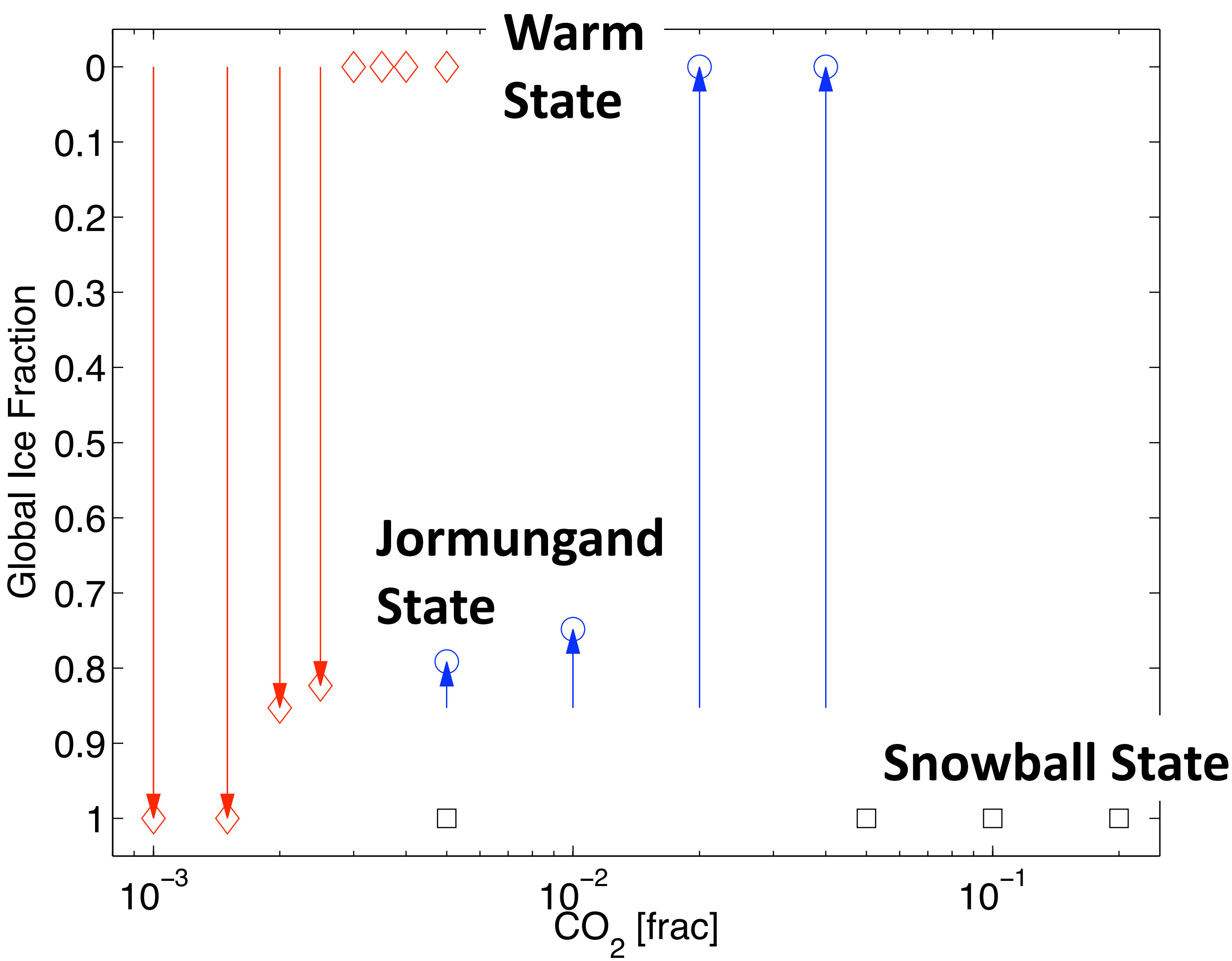
SNOWMIP simulations: slab ocean "aquaplanet" with no OHT, 0° eccentricity, and 94% insolation.



SNOWMIP will allow us to compare global climate models' simulation of Snowball initiation in the most basic set-up.



The CAM climate model produces an ***exciting new*** climate state with an ice line at low latitudes and ***strong hysteresis***!



Initial Conditions

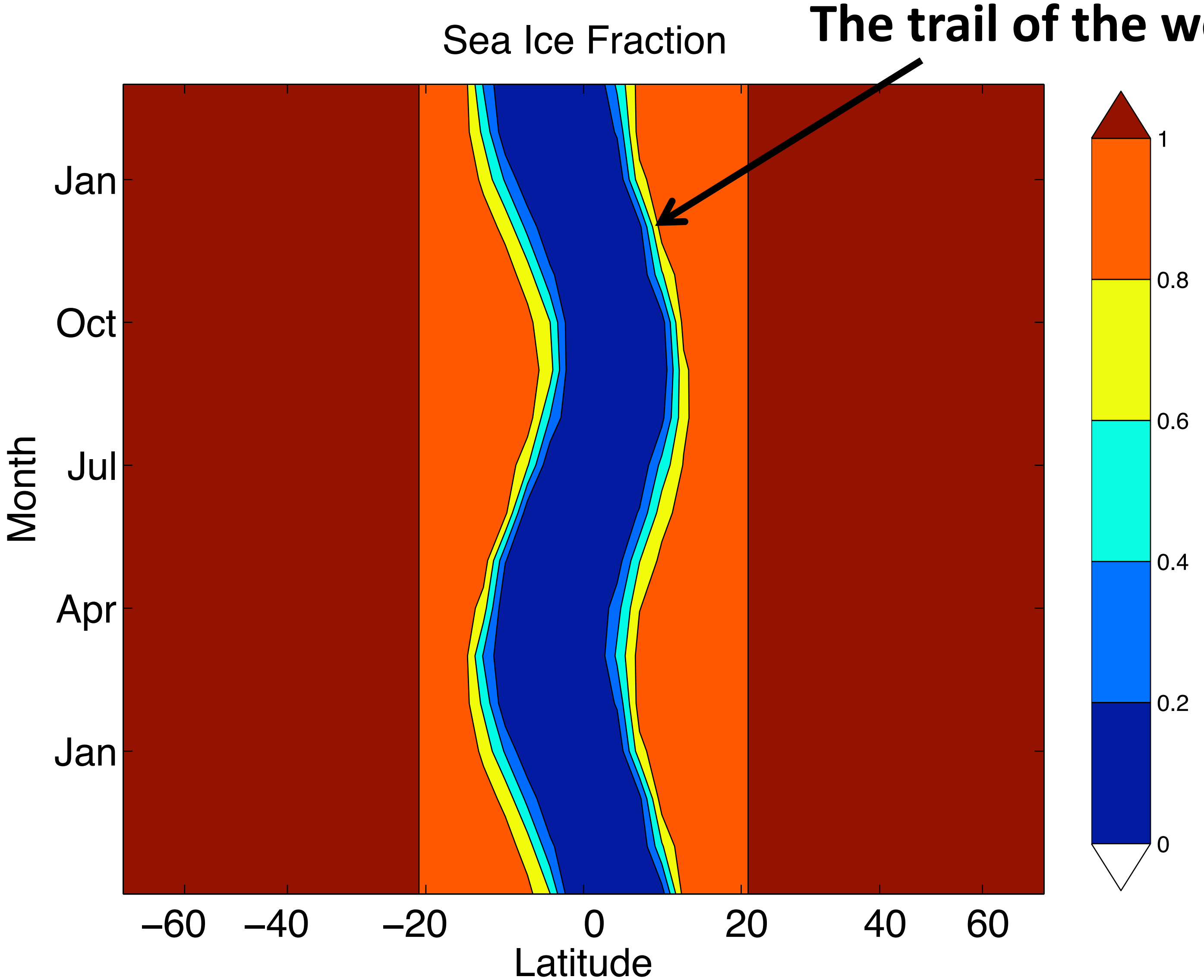
warm

Jormungand

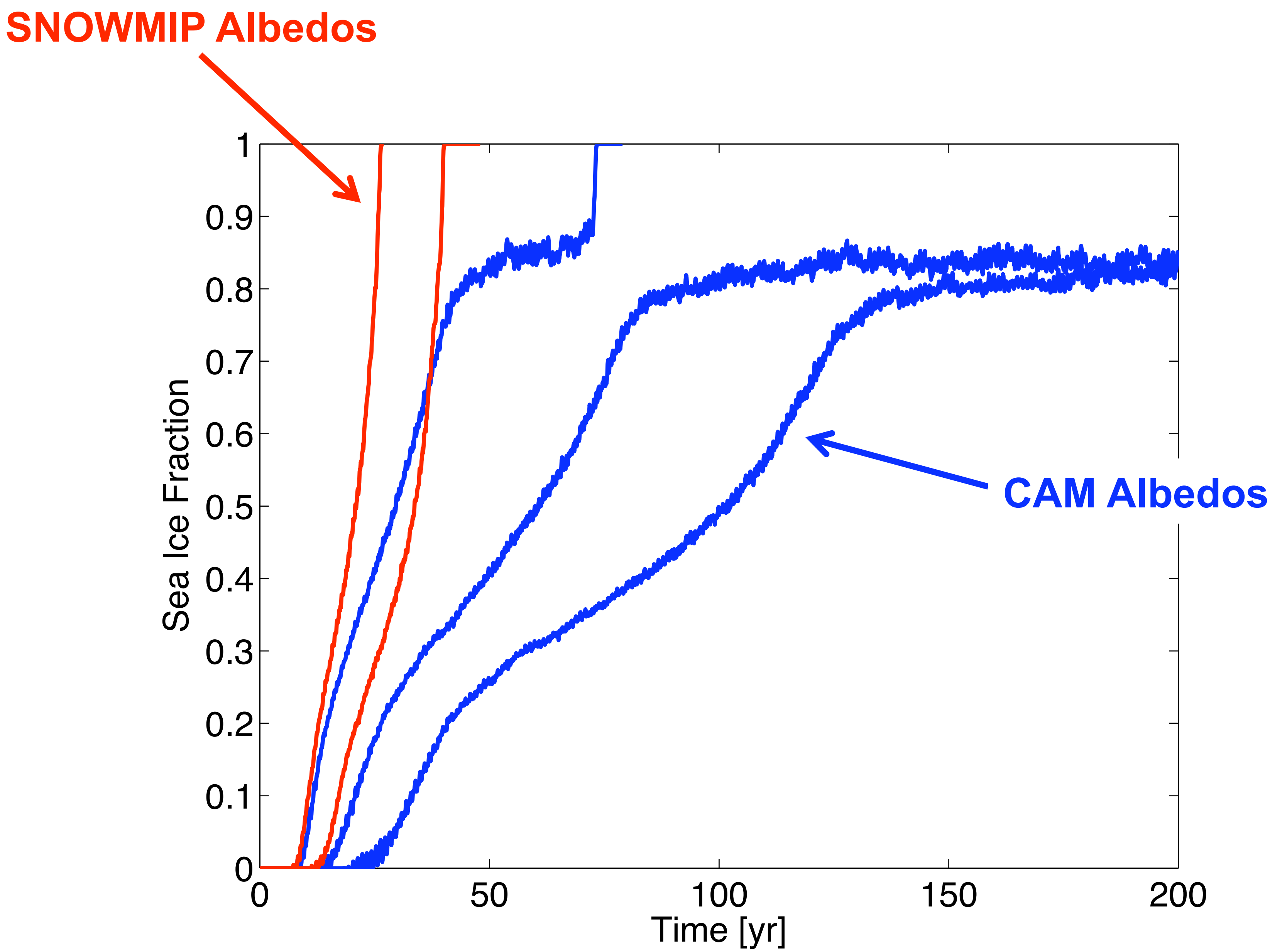
Snowball

We call this new global climate state a "Jormungand State."

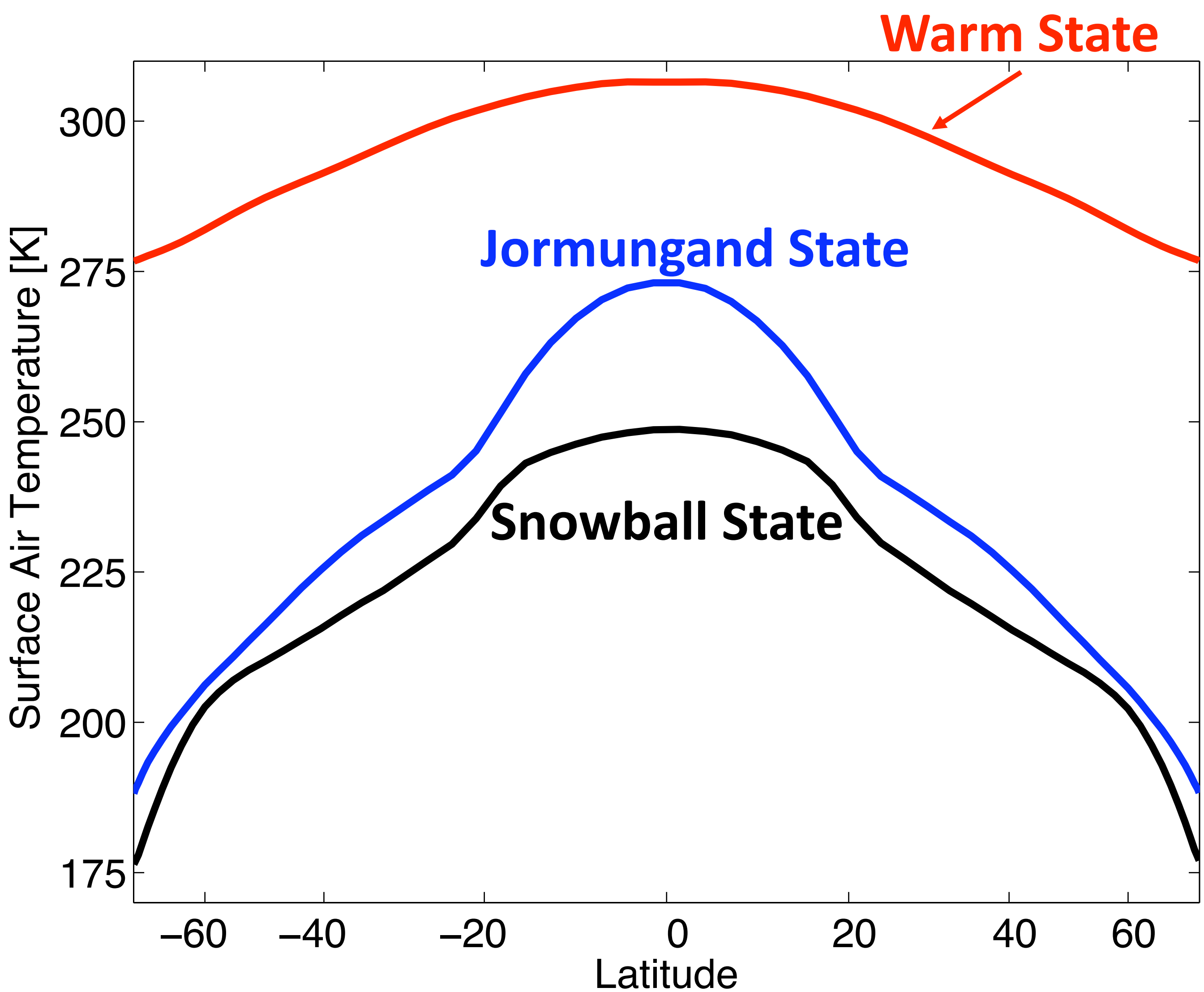
The trail of the world serpent.



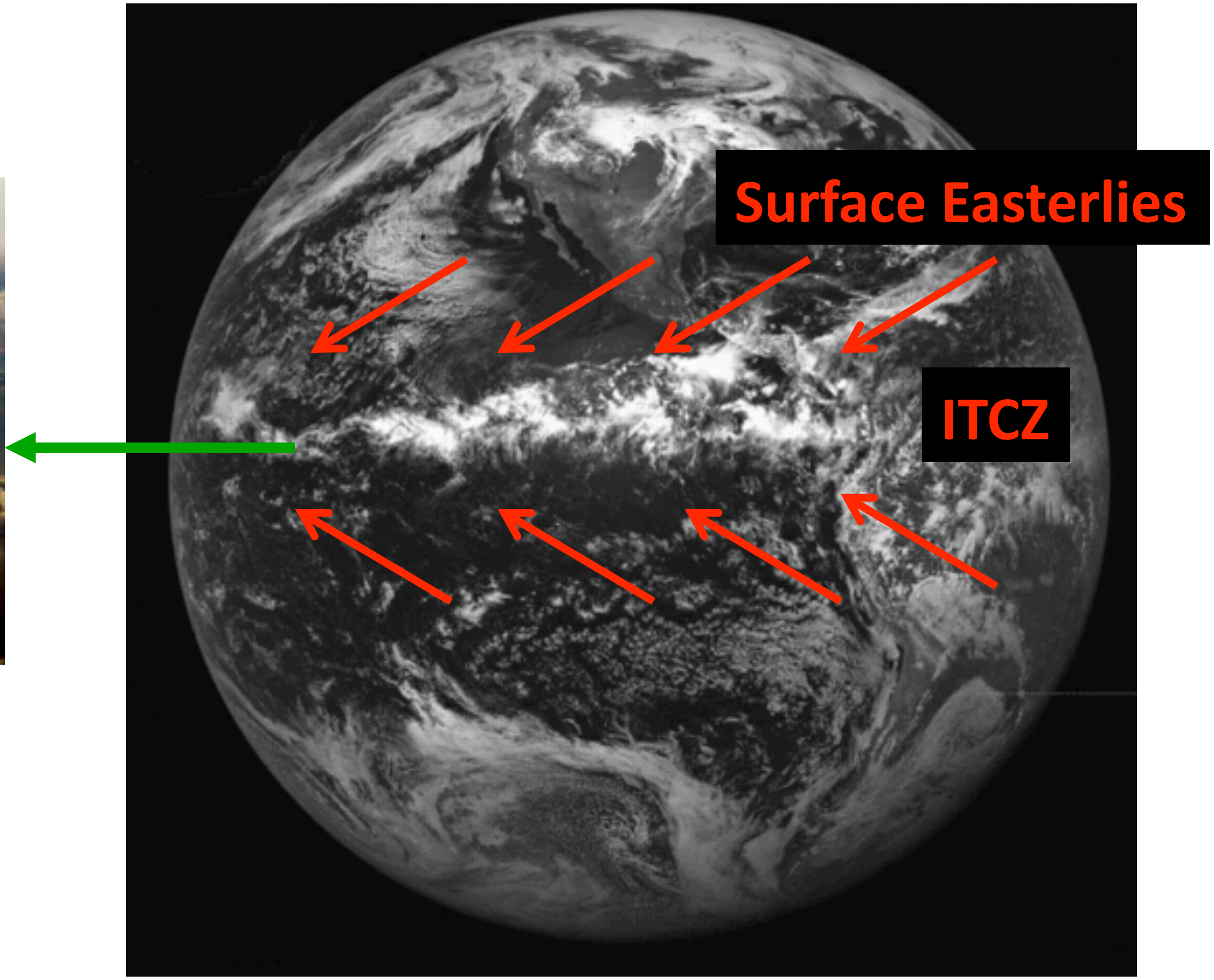
The Jormungand states have equilibrated.



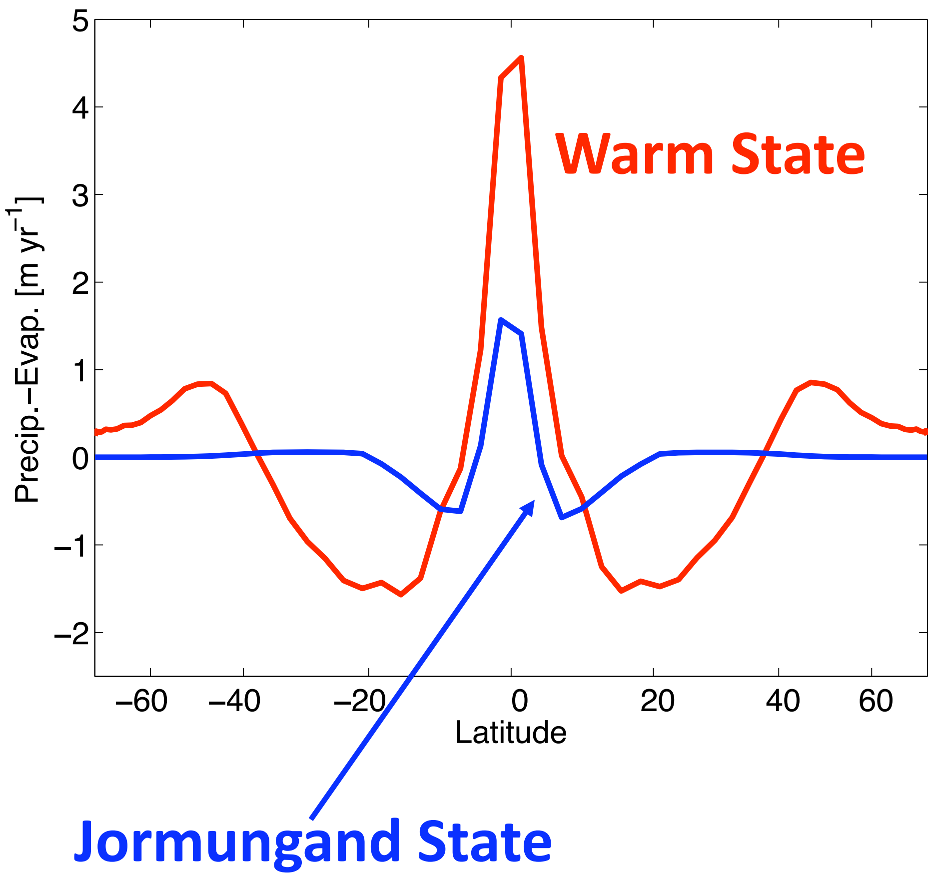
Global climate exhibits tristability in CAM.

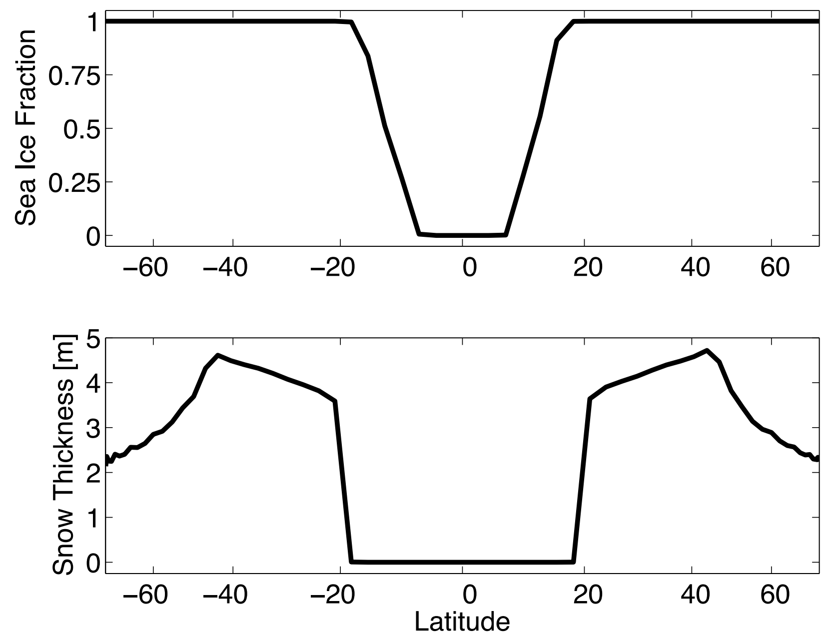


Tropical precipitation is concentrated in the intertropical convergence zone in the modern climate.

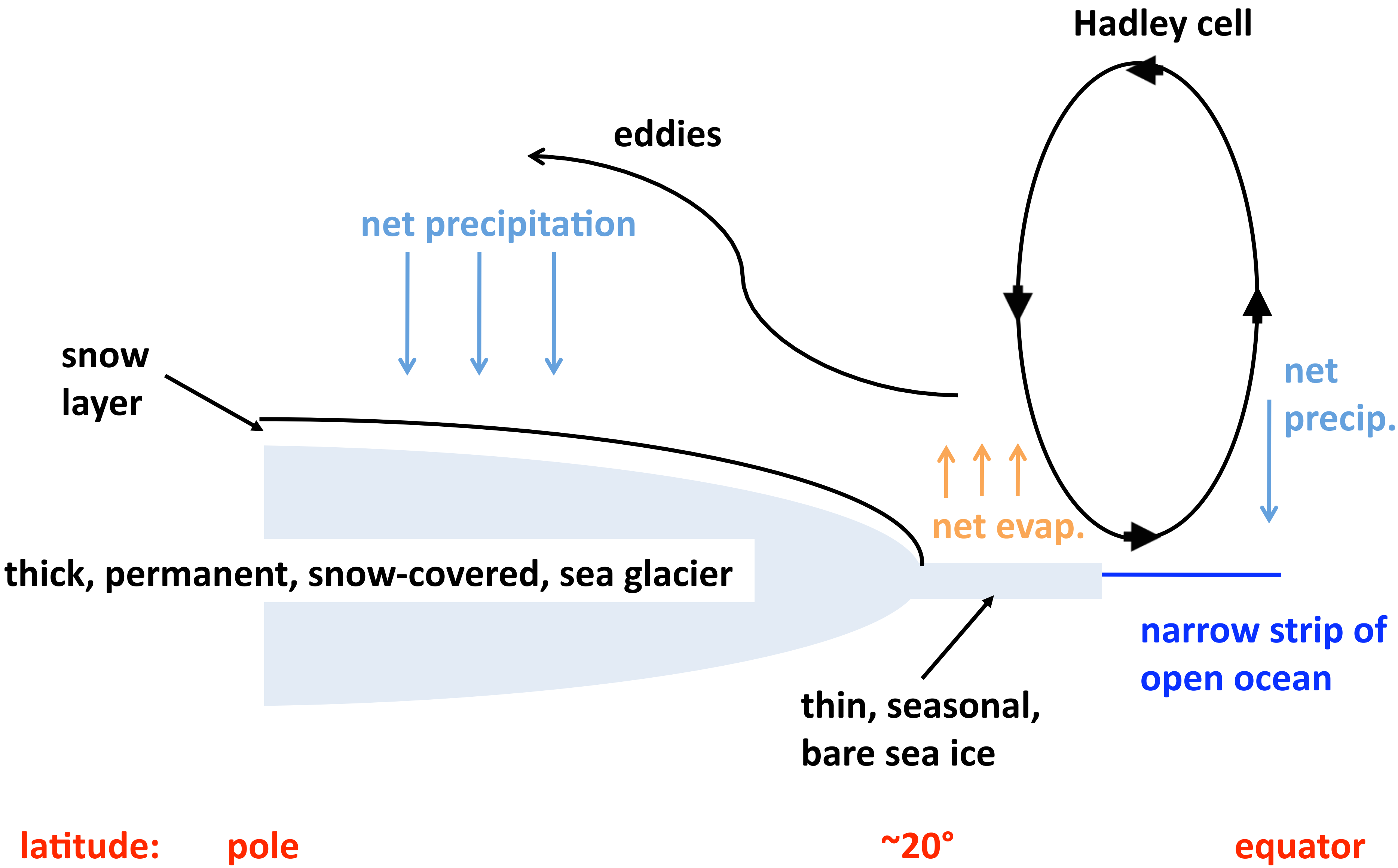


The global hydrological cycle exposes low-albedo sea ice at low latitudes, which maintains the Jormungand state.





A strong ice/snow albedo contrast and internal atmospheric dynamics sustain the Jormungand state.



To study the Jormungand state in the Budyko-Sellers model we must add a snow albedo.

New Albedo:

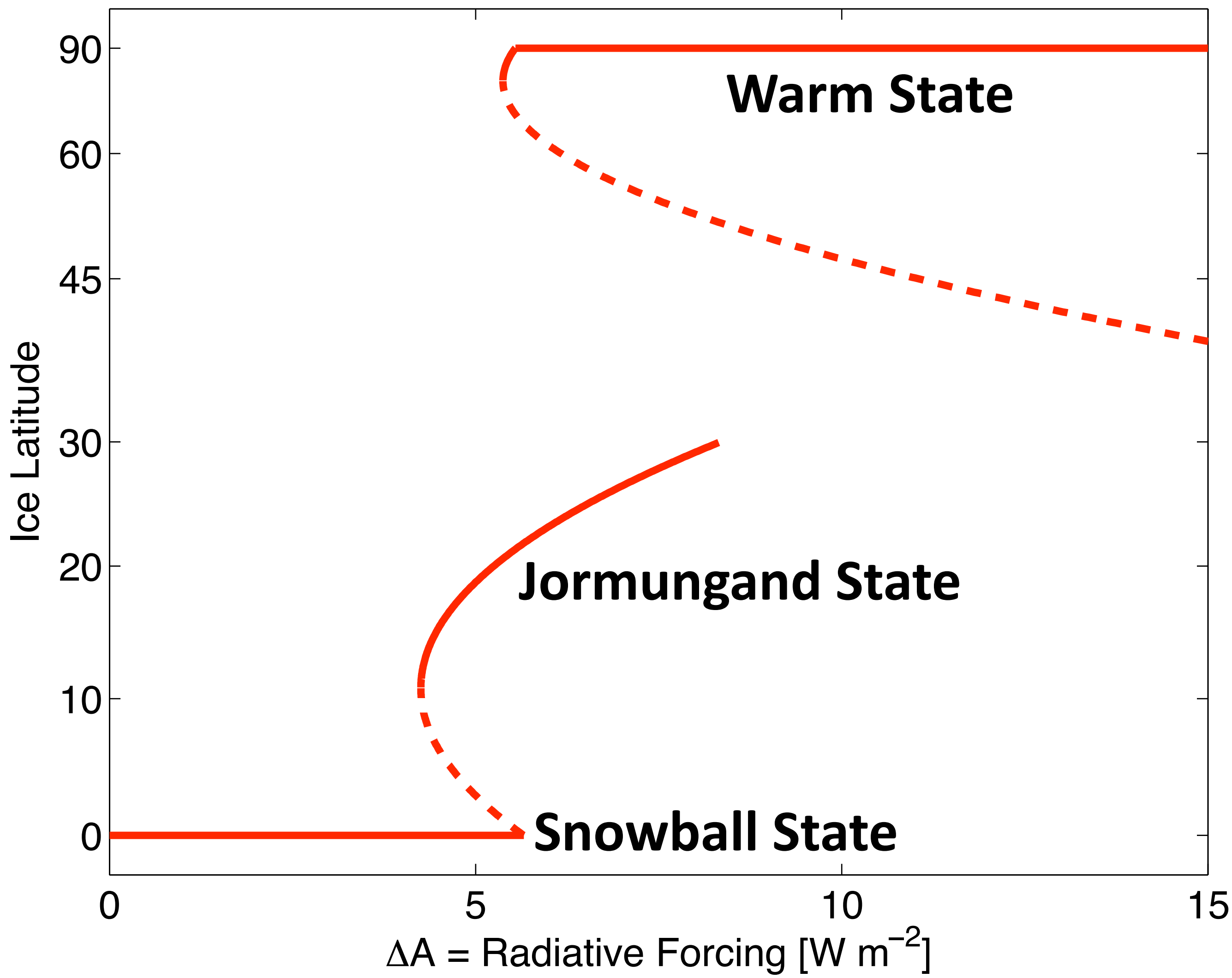
$$\alpha(T(x)) = \begin{cases} \alpha_1 & T > T_s \\ \alpha_s & T = T_s \\ \alpha_2 & T < T_s, x < x_s \\ \alpha_3 & T < T_s, x \geq x_s \end{cases}$$

snow accumulation latitude (← x_s)

New Global-Mean Albedo:

$$\alpha_p(x_s, x_i) = \begin{cases} \alpha_1 \int_0^{x_i} S(x)dx + \alpha_2 \int_{x_s}^{x_i} S(x)dx + \alpha_3 \int_{x_i}^{1} S(x)dx & x_s < x_i \\ \alpha_1 \int_0^{x_s} S(x)dx + \alpha_3 \int_{x_s}^{1} S(x)dx & x_s \geq x_i \end{cases}$$

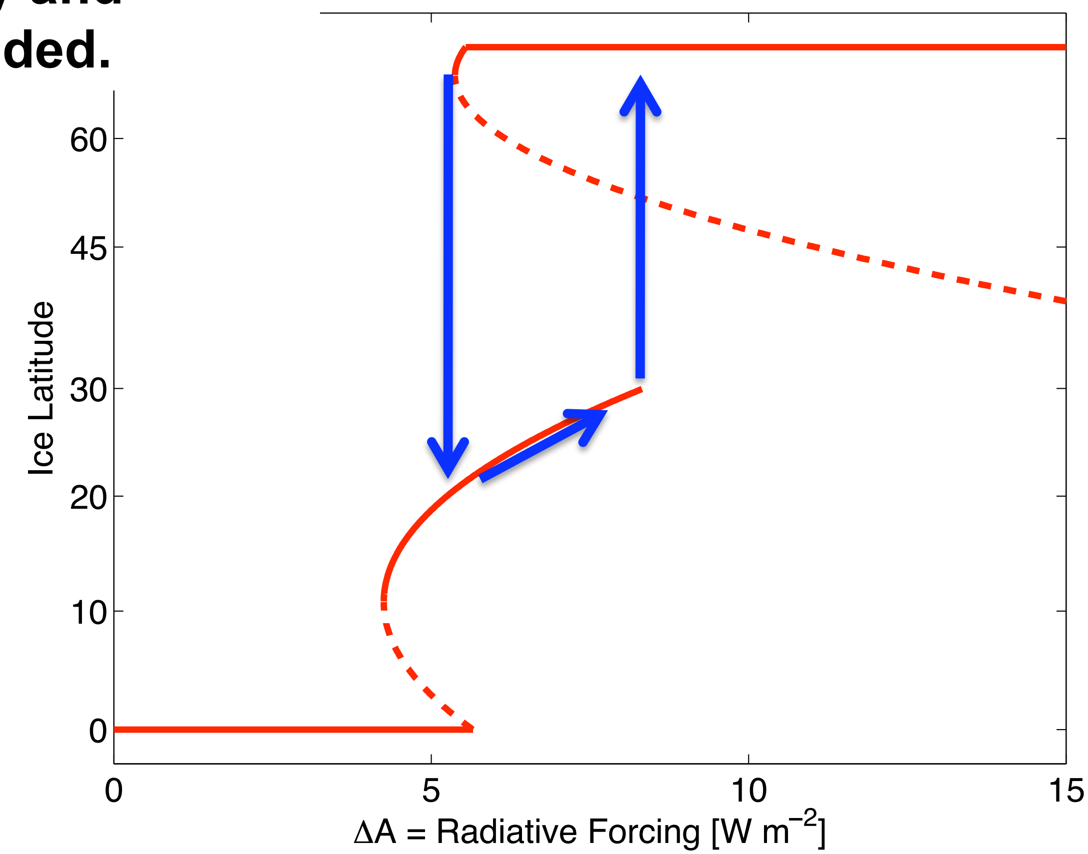
The modified Budyko-Sellers reproduces the picture from CAM, lending credibility to the fancy model.



The Jormungand lifecycle can explain Neoproterozoic glaciations

Enter Jormungand through CO_2 drawdown. Weathering slows drastically and Snowball is avoided.

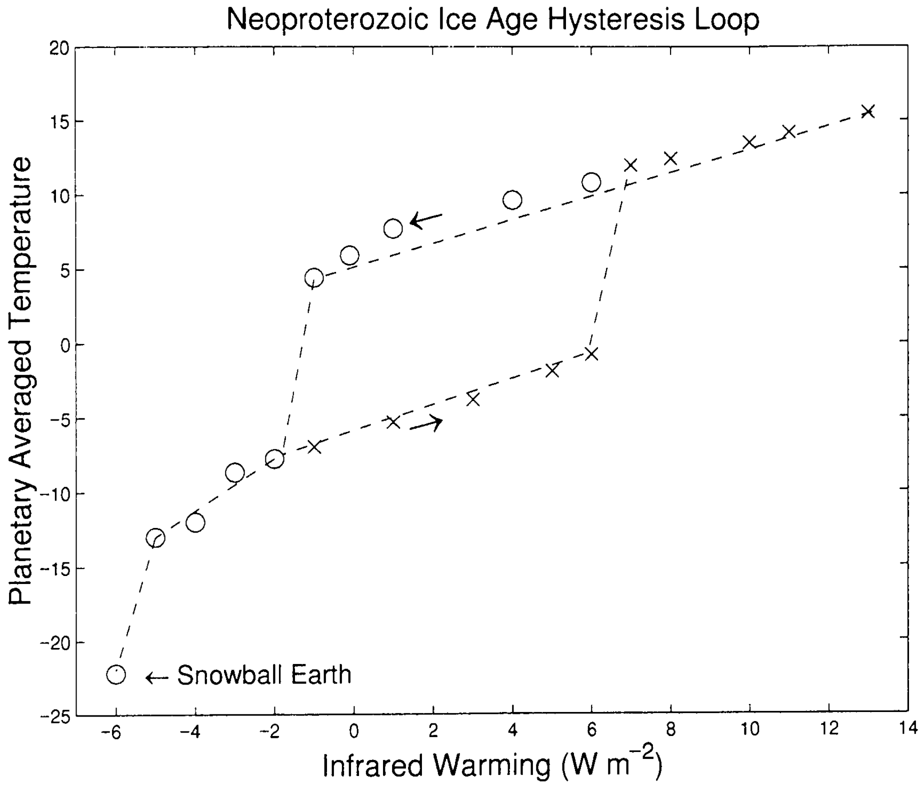
Cap carbonates are deposited after sudden jump into hot climate.

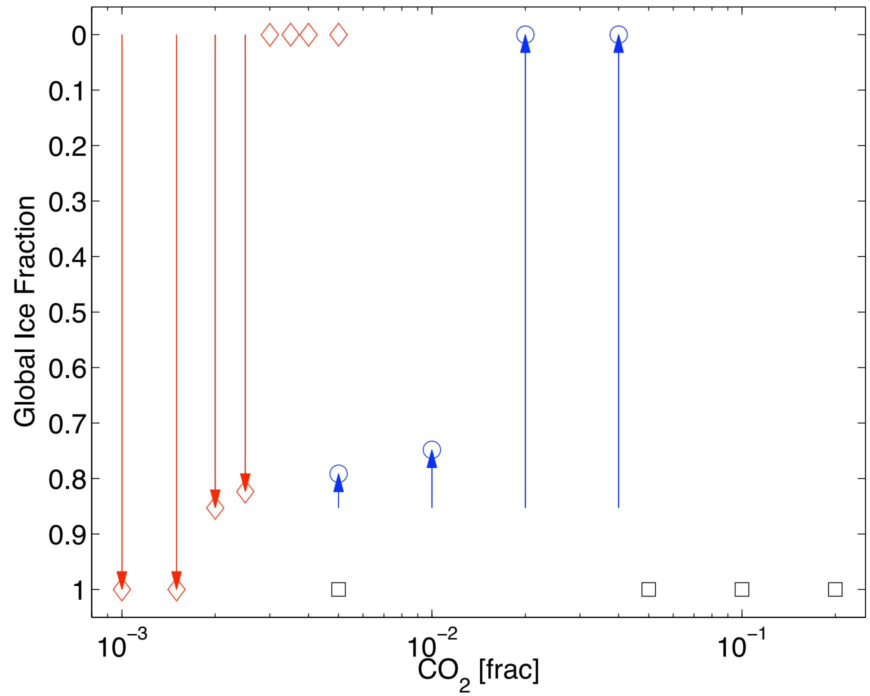


Accumulate CO2 slowly because ocean equilibrates and sea floor weathering is active.

Jormungand state is result of a new bifurcation and has much stronger hysteresis than the Slushball.

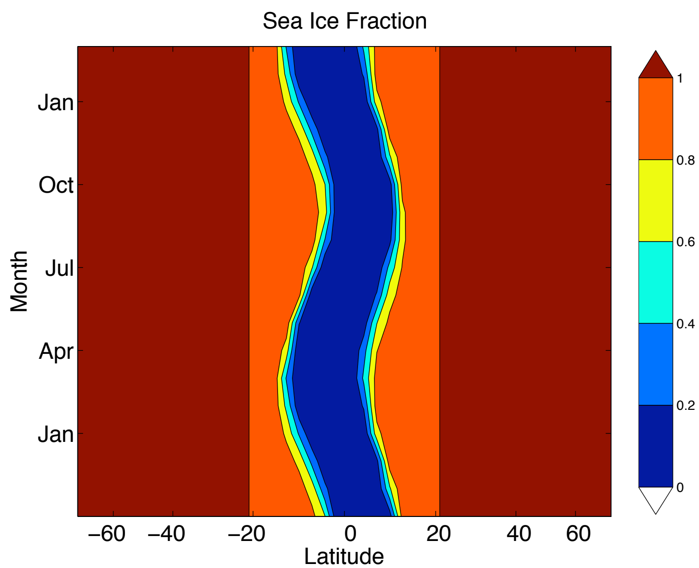
Slushball has a small hysteresis loop caused by growth of land ice.





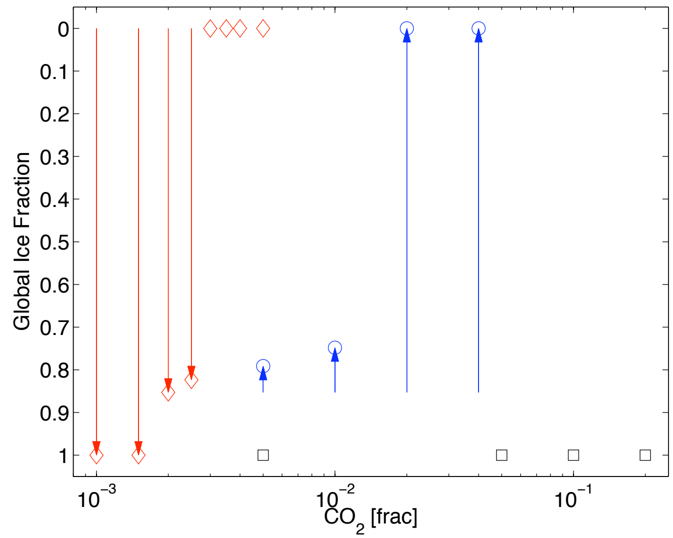
Jormungand state has a large hysteresis loop caused by hydrological cycle and ice/ snow albedo contrast. It would ALSO have land ice hysteresis loop if model had dynamic glaciers.

The narrow band of open ocean in the Jormungand state easily allows the survival of life.



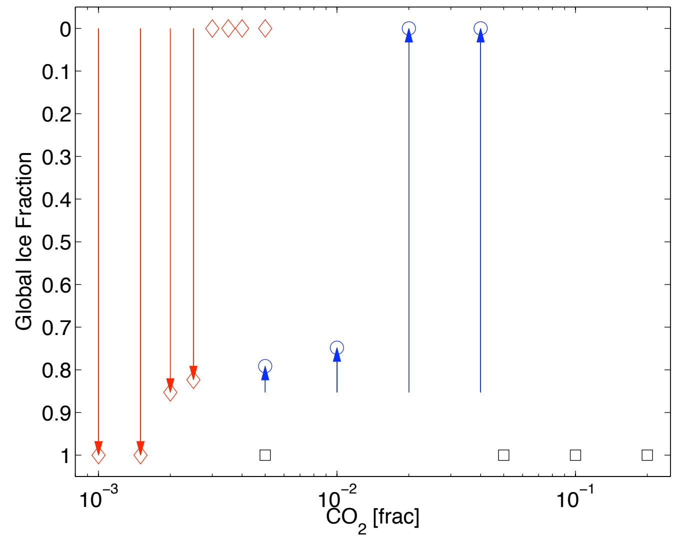
	Snowball	Slushball	Jormungand
survival of life	?	✔	✔

Large climate jump on Jormungand exit and significant hysteresis would make cap carbonates.



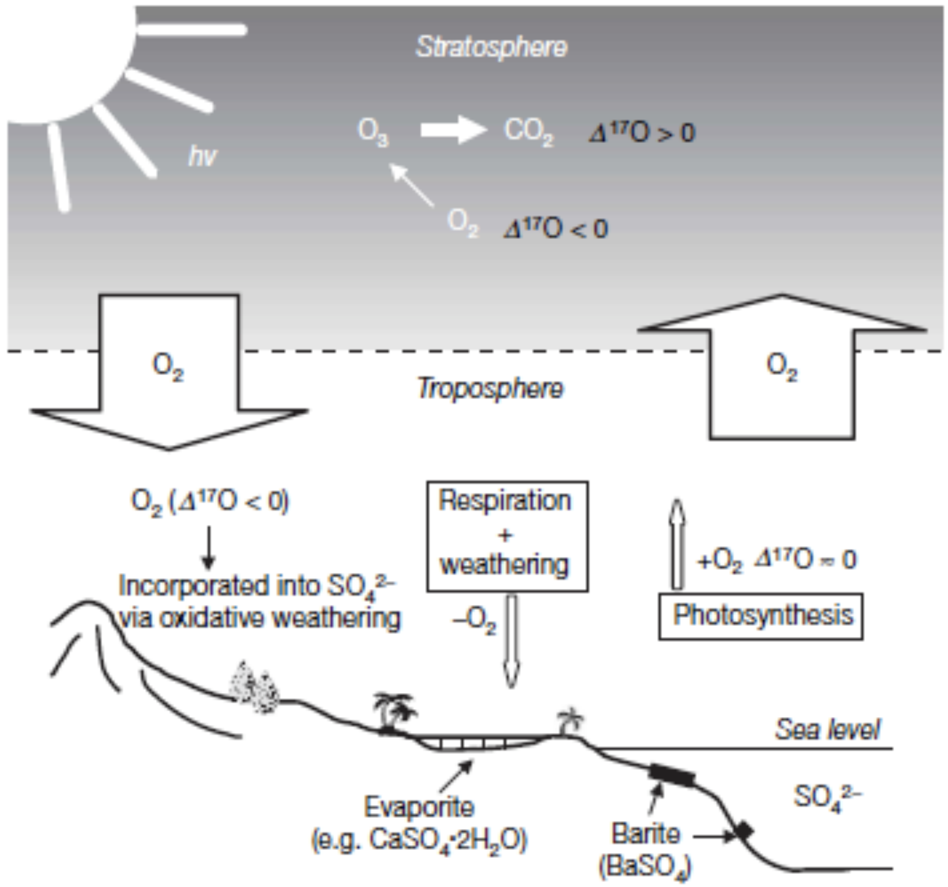
	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔

Jormungand hysteresis leads to long lifetime, particularly if CO_2 equilibrates with ocean.



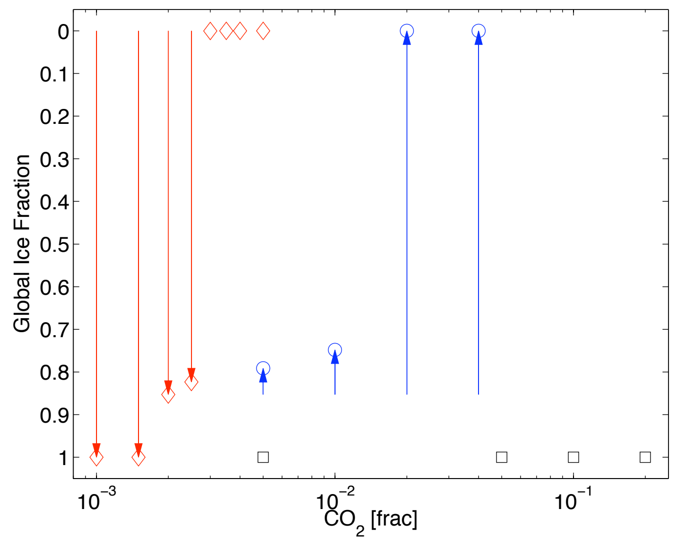
	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔

Observations suggest deglaciation occurred at pCO_2= 0.01-0.08 bar.



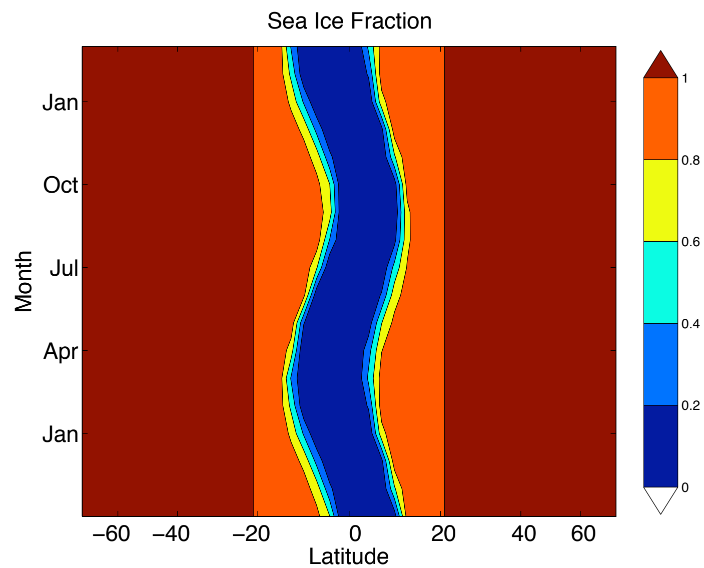
[Bao et al., 2009]

Jormungand hysteresis means CO2 must reach fraction O(0.01) to exit, consistent with Bao et al.



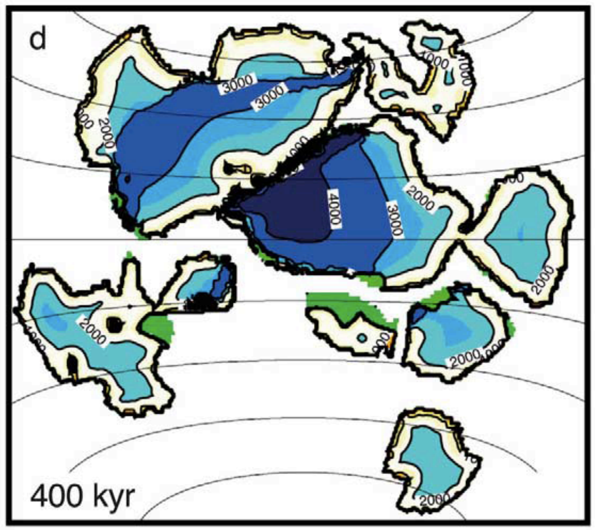
	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔
CO_2	?	✗	✔

Ocean strip is so narrow in Jormungand that ocean could become anoxic under ice, allowing BIFs.



	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔
CO_2	?	✗	✔
BIF	✔	?	?

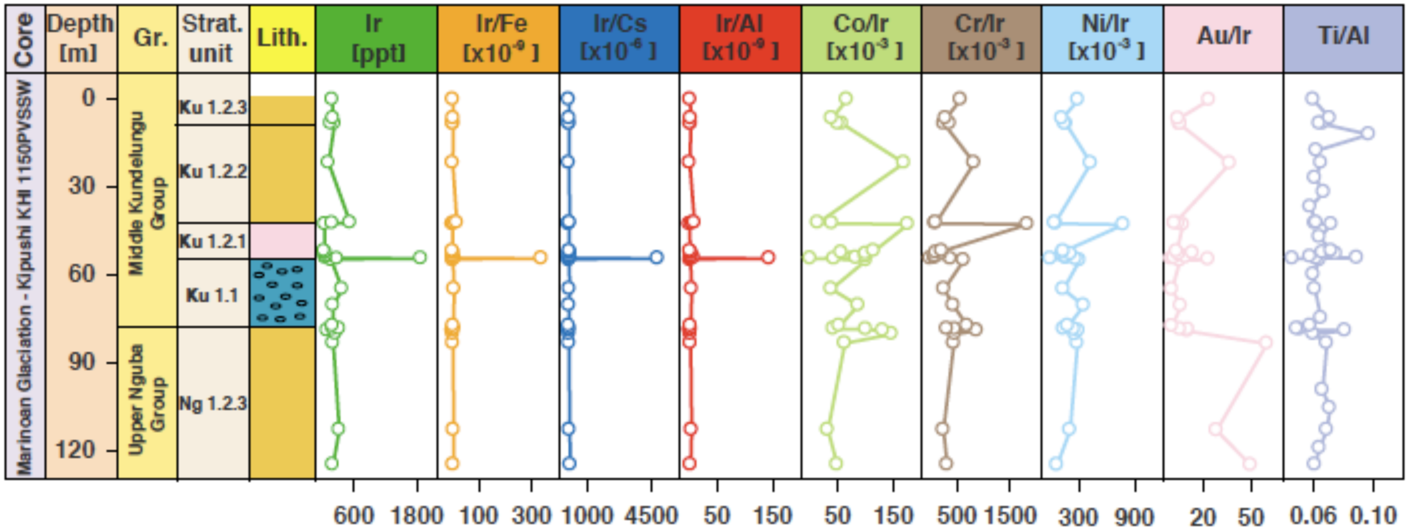
Dynamic land glaciers are manifestly possible in a Jormungand state.



[Donnadieu et al., 2003]

	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔
CO_2	?	✗	✔
BIF	✔	?	?
dynamic land ice	✔	✔	✔

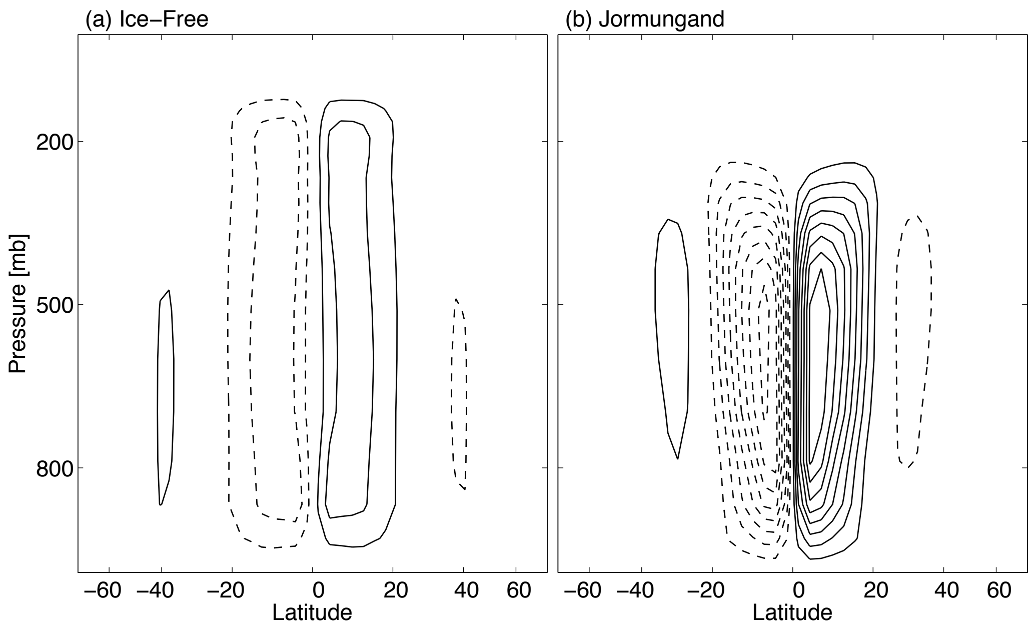
Iridium anomaly could result from slow-moving extratropical ice in Jormungand, esp. in bays.

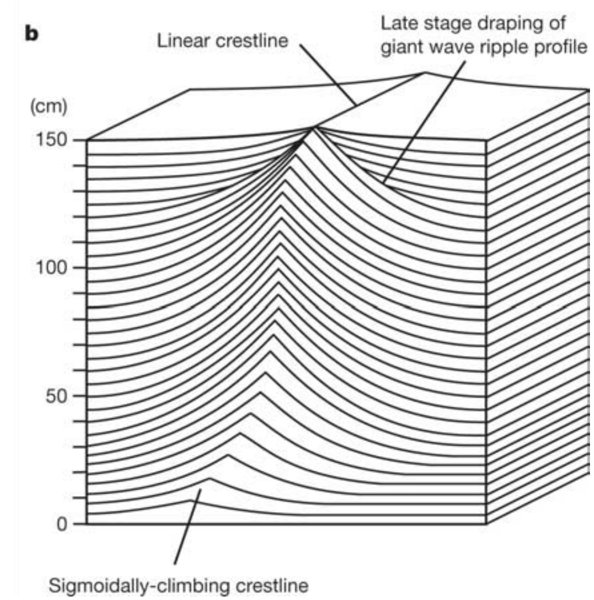


[Bodiselitsch et al, 2005]

	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔
CO_2	?	✗	✔
BIF	✔	?	?
dynamic land ice	✔	✔	✔
Iridium	✔	✗	✔

Extremely strong Hadley cell in Jormungand state could explain giant wave ripples.





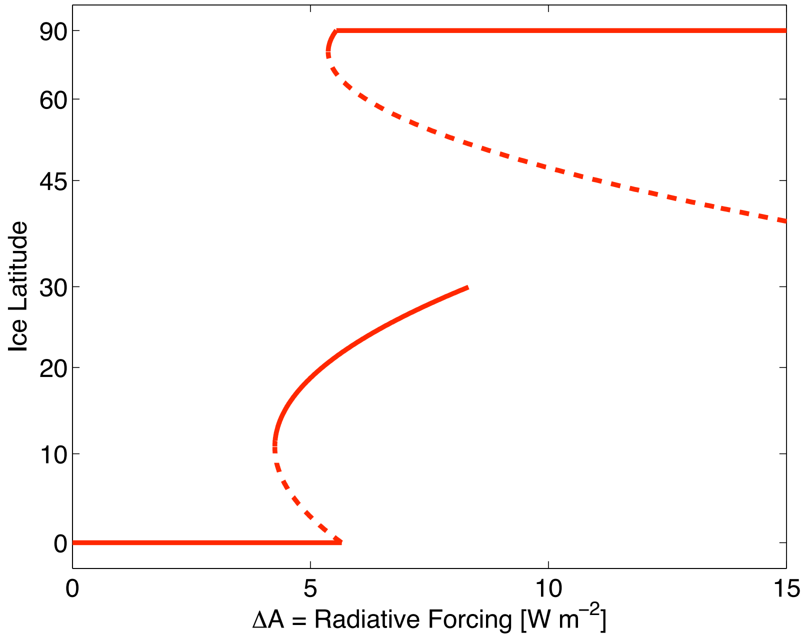
[Allen and Hoffman, 2005]

	Snowball	Slushball	Jormungand
survival of life	?	✔	✔
cap carbonate	✔	✗	✔
lifetime	✔	✗	✔
CO_2	?	✗	✔
BIF	✔	?	?
dynamic land ice	✔	✔	✔
Iridium	✔	✗	✔
wave ripples	?	?	✔

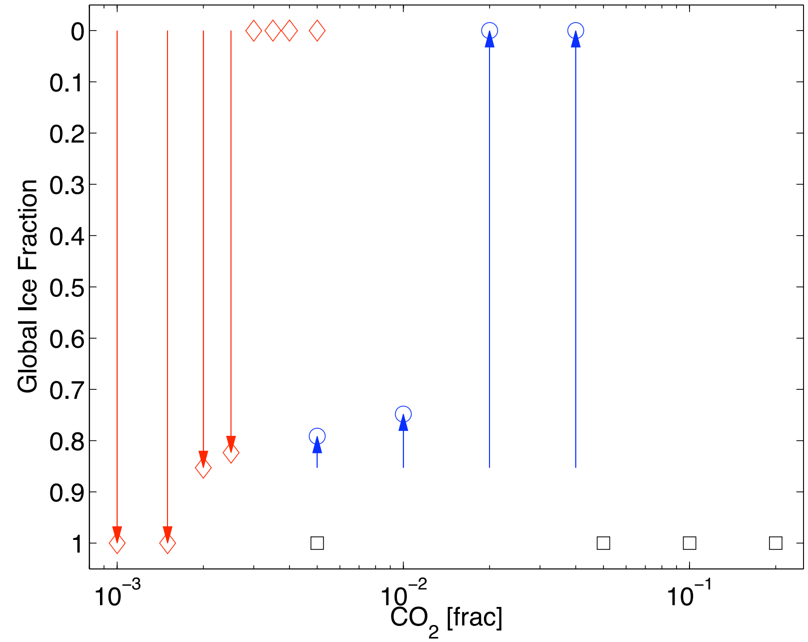
Summary and Conclusions

There has been a longstanding debate about whether a "Snowball" or "Slushball" model is more appropriate for Neoproterozoic glaciations. Both models have significant problems.

Jormungand in Budyko-Sellers



Jormungand in CAM



We propose a new global climate state, the Jormungand state, that could represent a solution to the "Snowball Paradox." We have shown that this state exists in simple and complex global climate models, as long as the contrast between sea ice and snow albedo is large enough.