Noble Lectures: Toronto, April 2010

Snowball Earth and Snowball Earths
Part I: Meet the Proterozoic

Raymond T. Pierrehumbert

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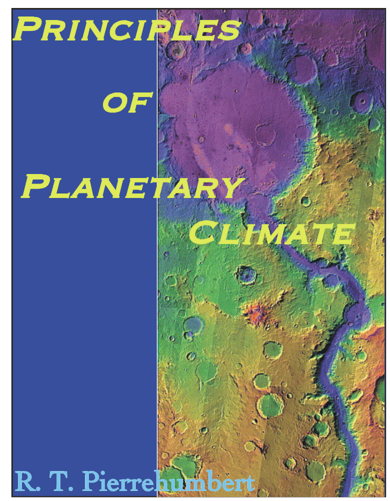
Neoproterozoic Climate review article

Ann. Rev. Earth Plan. Sci. (preprint July 2010)

(and ...)



JUNE, 2010

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The Snowball State

- Consider a planet that is all or mostly ocean
- If the planet freezes over completely, the high albedo can keep it frozen.
- This is the Snowball state. It takes a great deal of warming to break out.
- There is a multitude of geological evidence that this happened on Earth twice around 650 million years ago (the Neoproterozoic), and once around 2.5 billion years ago (the beginning of the Paleoproterozoic)
- Evidence for glaciers near equator is unequivocal. Evidence for totally frozen ocean is more indirect
- This is a habitability crisis for planets in general.

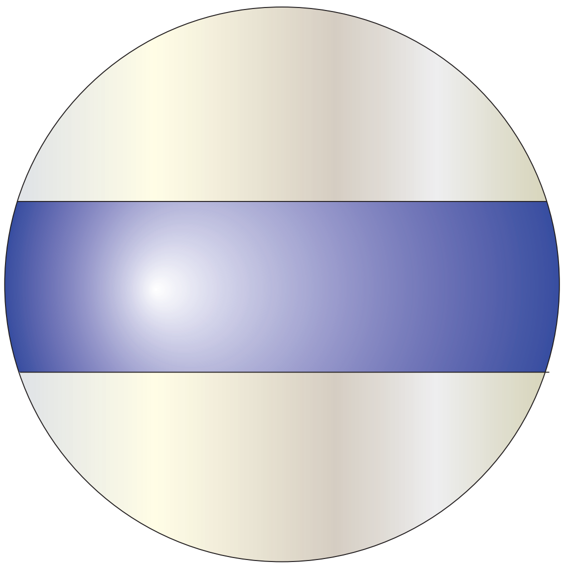
My collaborators on Snowball work

- Chris Poulsen
- Jason Goodman
- Yannick Donnadieu, Guillaume Le Hir, Yves Godderis
- Jonathan Mitchell, Xavier Levine, Rodrigo Caballero
- Dorian Abbot, Aiko Voight
- Paul Hoffman and Dan Schrag

The main questions

- Under what circumstances does a planet enter a global glaciation?
- Under what circumstances can you get out?
- What is the climate like while you're there?
- What is the climate like after you get out?

Additional questions: Tropical waterbelt worlds?



- Stable states with low-latitude ice margins?
- Are waterbelt states cold enough to have land ice sheets?

Geological evidence for a hard snowball

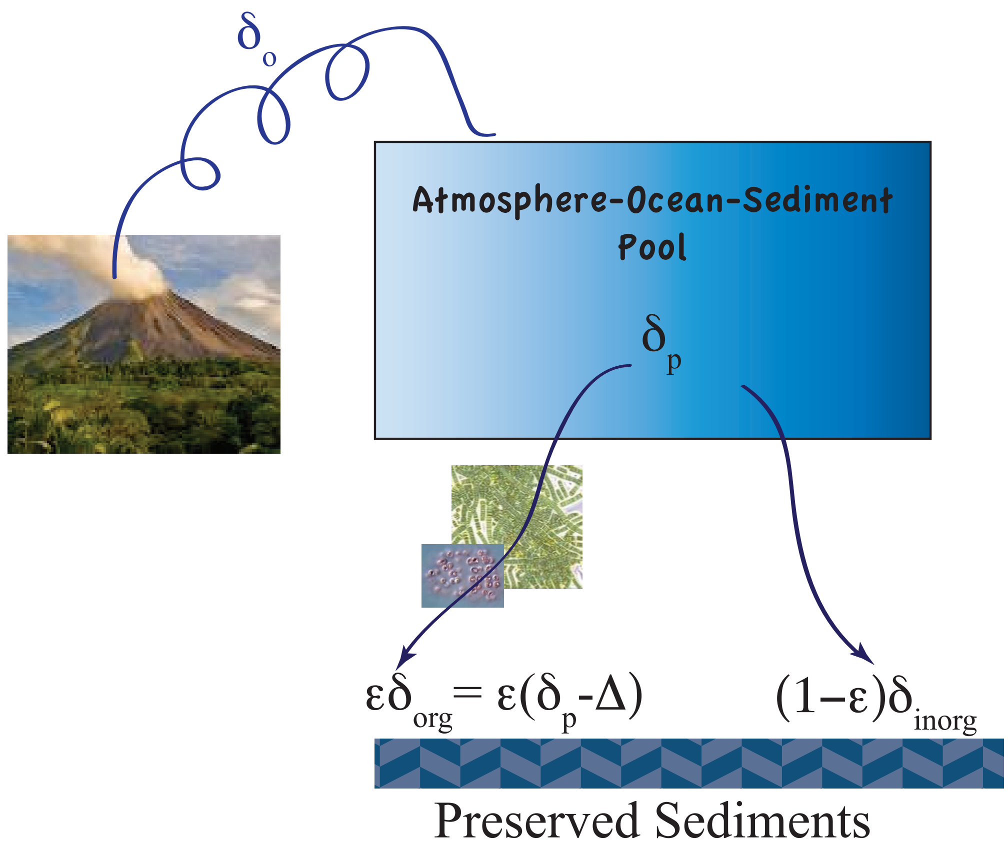
- Glacial deposits (diamictites, dropstones) at low latitudes
- Cap carbonates
- Reappearance of Banded Iron Formations (global ocean anoxia marker)
- Isotopic evidence of very high CO_2 after deglaciation
- Iridium anomaly (long accumulation on global ice cover)

Dramatis Personae

- Carbon cycle (CO_2, CH_4, organic carbon burial)
- Oxygen and Sulfur (SO_4^{--} and O_2; pyrite, H_2S)
- Glaciation

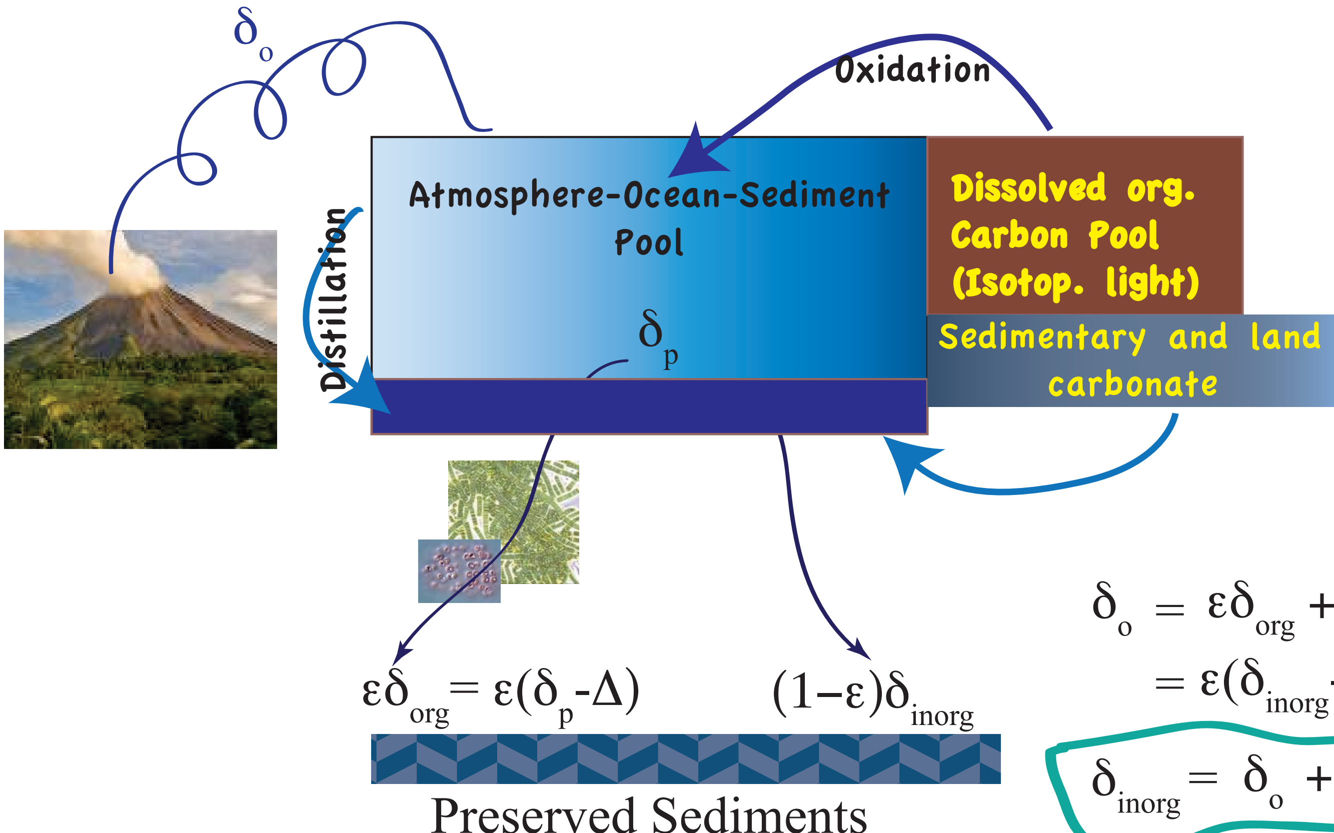
$\delta^{13}C$ Primer

- Stable isotopes ^{12}C and ^{13}C
- ^{12}C is dominant
- Photosynthetic/chemosynthetic life prefers ^{12}C (light carbon)
- Organic matter $\delta^{13}C$ shifted negative relative to pool it is made from



$$\delta_o = \varepsilon\delta_{org} + (1-\varepsilon)\delta_{inorg}$$
$$= \varepsilon(\delta_{inorg} - \Delta) + (1-\varepsilon)\delta_{inorg}$$
$$\delta_{inorg} = \delta_o + \varepsilon\Delta$$

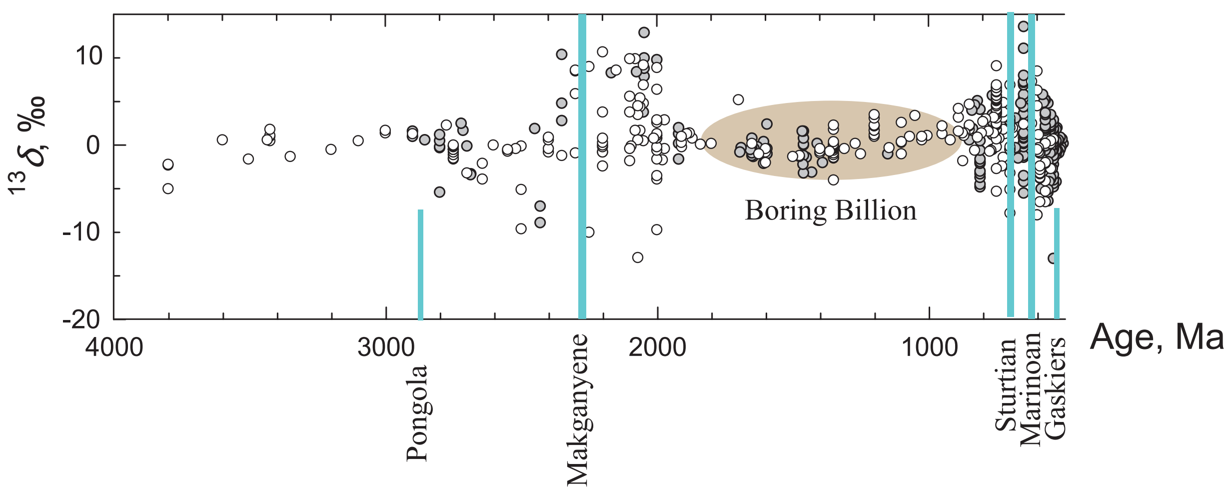
$$\delta_o \approx -6‰, \Delta \approx 25‰$$



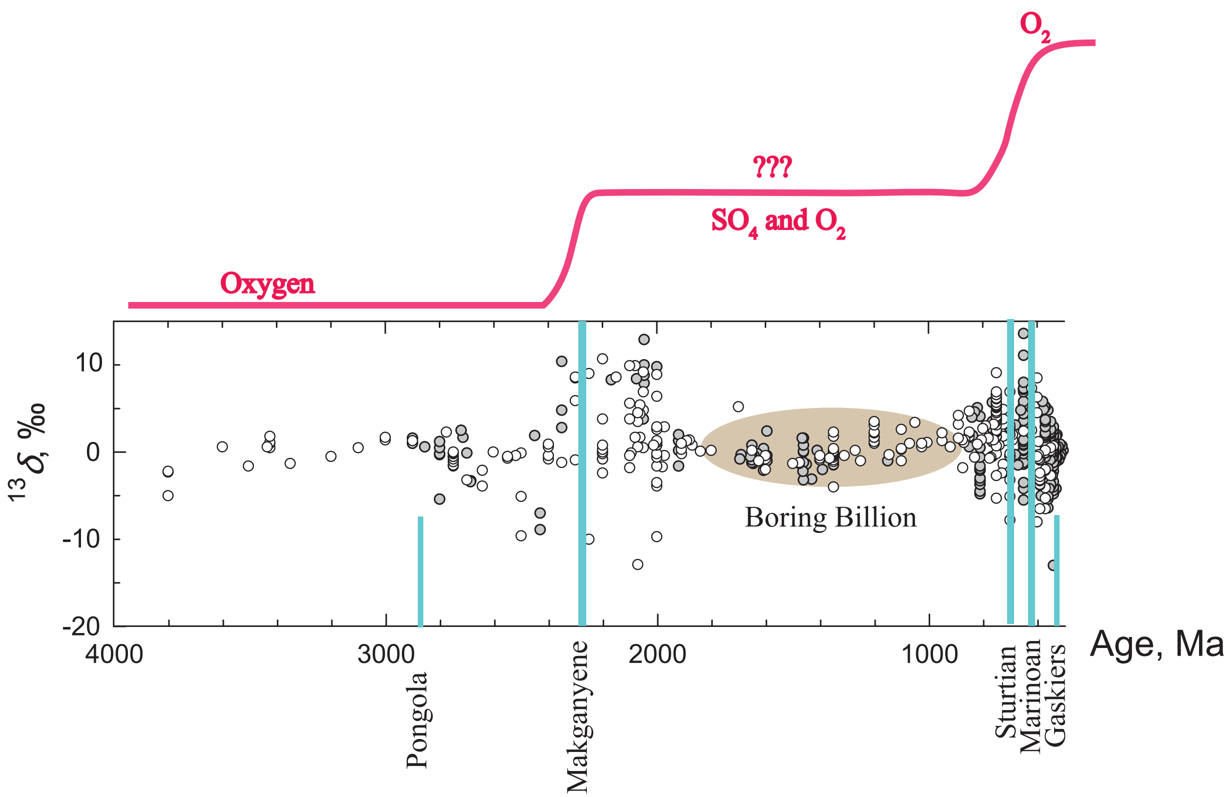
$$\delta_o = \varepsilon\delta_{org} + (1-\varepsilon)\delta_{inorg}$$
$$= \varepsilon(\delta_{inorg} - \Delta) + (1-\varepsilon)\delta_{inorg}$$
$$\delta_{inorg} = \delta_o + \varepsilon\Delta$$

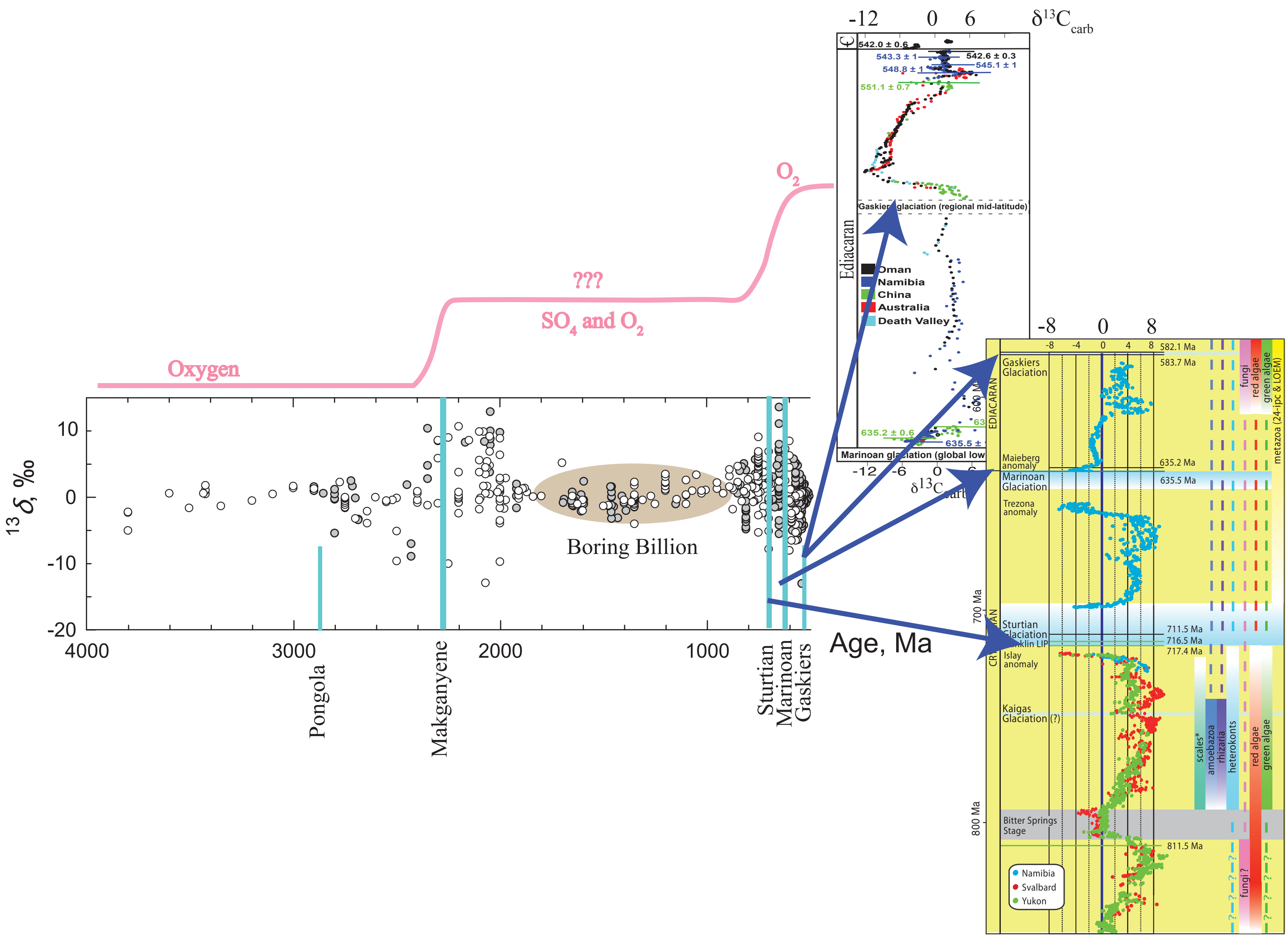
$$\delta_o \approx -6‰, \Delta \approx 25‰$$

$\delta^{13}C_{carb}$

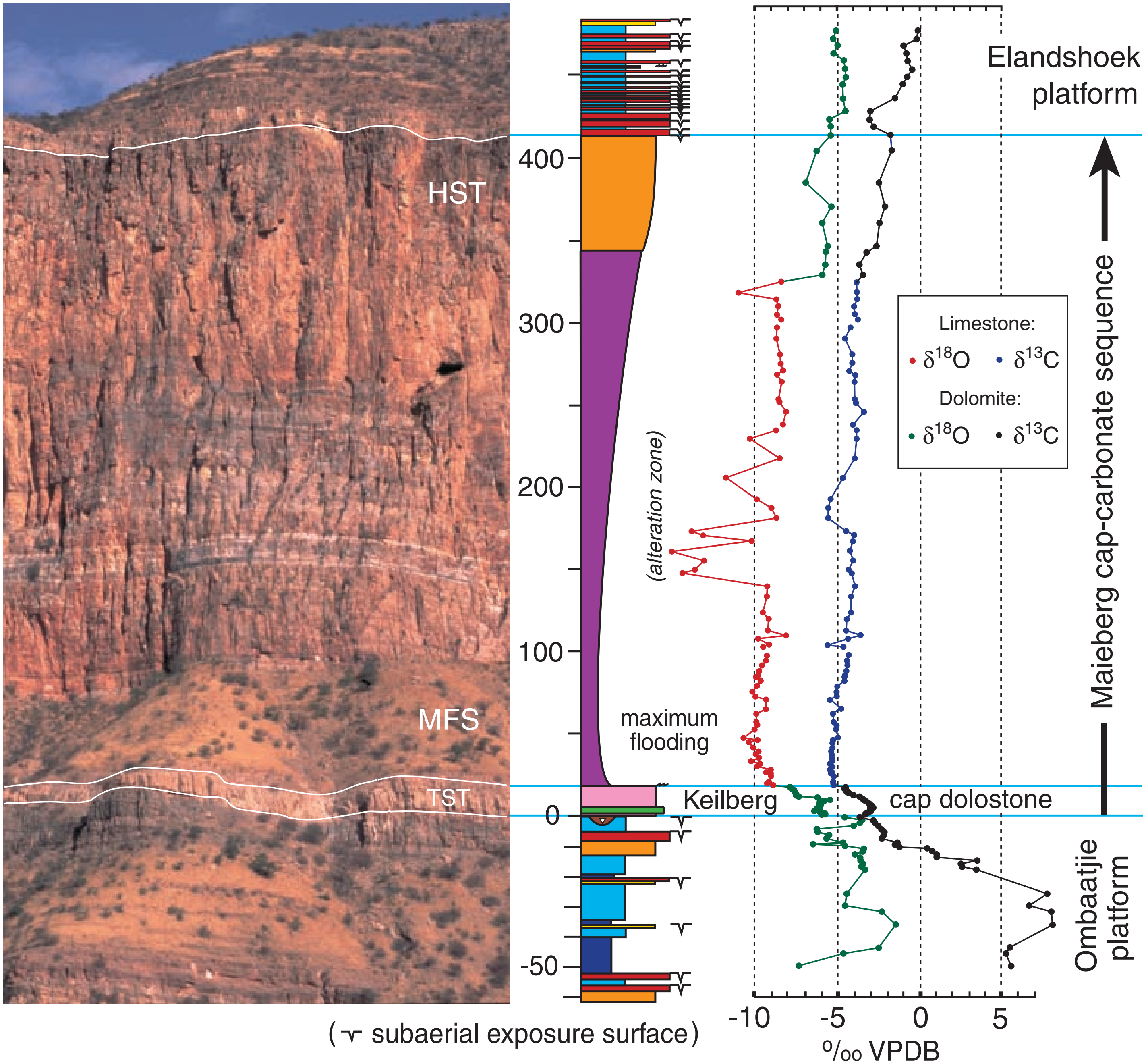


$\delta^{13}C_{carb}$




Oxygen
SO4 and O2
???
O2
Boring Billion
13δ, ‰
Age, Ma
Pongola
Makganyene
Sturtian
Marinoan
Gaskiers
δ13Ccarb
Ediacaran
Oman
Namibia
China
Australia
Death Valley
Gaskiers glaciation (regional mid-latitude)
Marinoan glaciation (global low
Gaskiers Glaciation
Maieberg anomaly
Marinoan Glaciation
Trezona anomaly
Sturtian Glaciation
Islay anomaly
Kaigas Glaciation (?)
Bitter Springs Stage
Namibia
Svalbard
Yukon
δ13C (‰ VPDB)
eukaryotic crown groups
fungi
red algae
green algae
metazoa (24-ipc & LOEM)
scales*
amoebazoa
rhizaria
heterokonts

Cap Carbonates



HST
MFS
TST
400
300
200
100
0
-50
(alteration zone)
maximum
flooding
Keilberg
cap dolostone
Elandshoek
platform
Maieberg cap-carbonate sequence
Ombaatjie
platform
Limestone:
δ18O
δ13C
Dolomite:
δ18O
δ13C
-10
-5
0
5
‰ VPDB
(subaerial exposure surface)

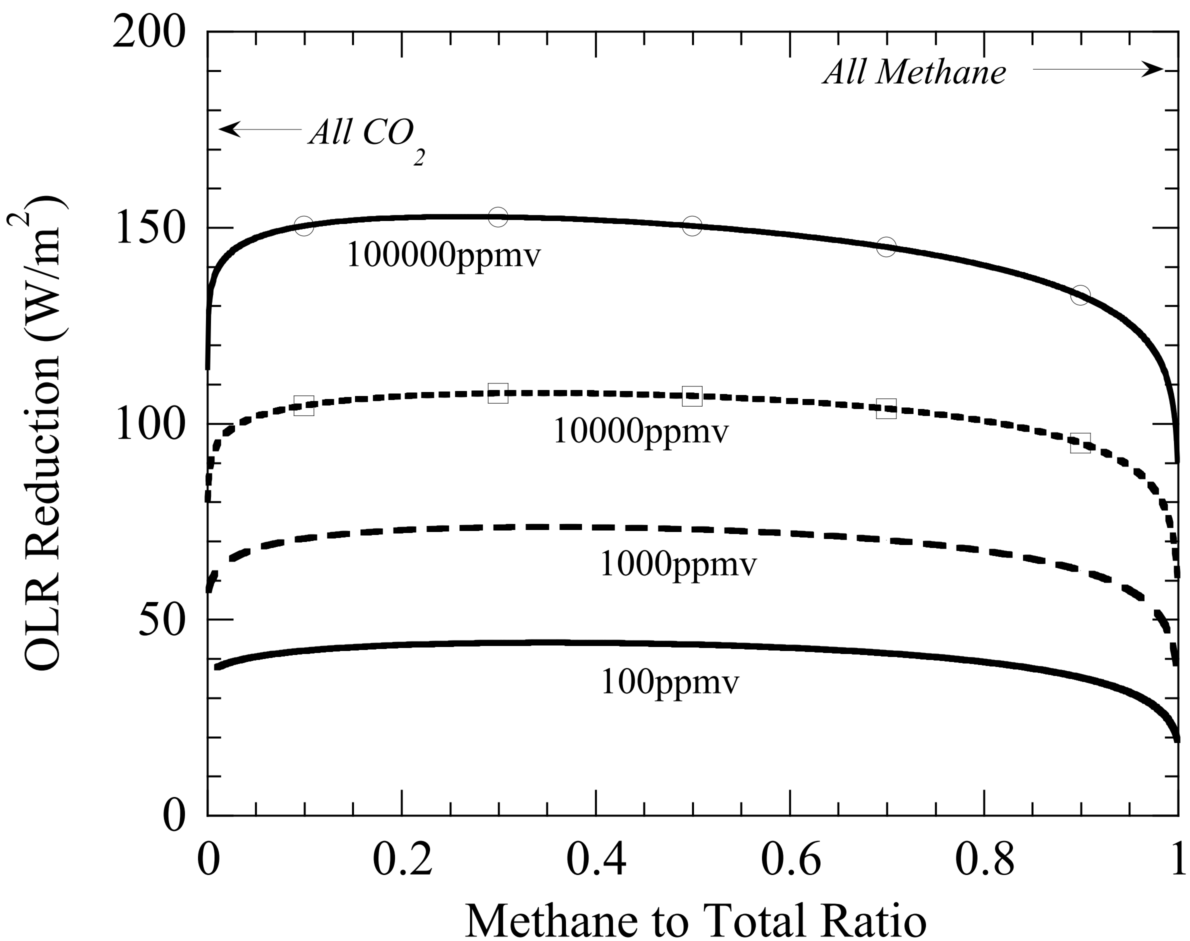
The cap carbonate story

- Features indicate rapid deposition (e.g. giant wave ripples, aragonite fans)
- Interpreted as postglacial, formed when carbonate from land dissolves under hot acid rain in th postglacial hothouse, and washes into ocean.
- Appears to require buildup to very high CO_2 followd by rapid deglaciation – bifurcation between wildly different states.
- i.e. strongly suggestive of a Hard Snowball state.

Carbon Cycle and Climate: DOC pool, CO_2 and oxygen

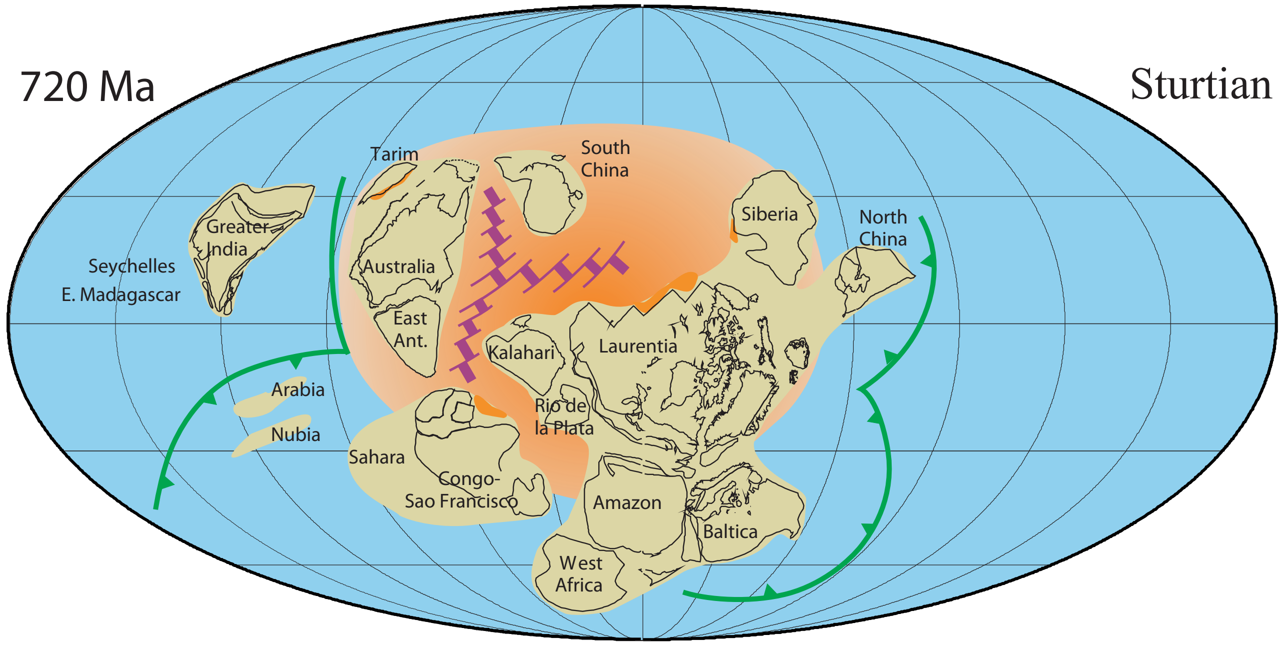
- Oxygenic photosynthesis and organic carbon burial (perhaps in DOC pool) convert a greenhouse gas (CO_2) into a non-greenhouse gas O_2.
- Oxygen may accumulate in the form of SO_4^{--} or oxidized iron instead of free O_2.
- Sulfate reducing bacteria can use SO_4^{--} to oxidize DOC pool
- DOC provides a pool of light carbon.
- Oxidation of DOC into CO_2 produces warming and negative isotopic excursion

Carbon Cycle and Climate: CO_2 vs CH_4



Carbon Cycle and Climate: CO_2 vs CH_4

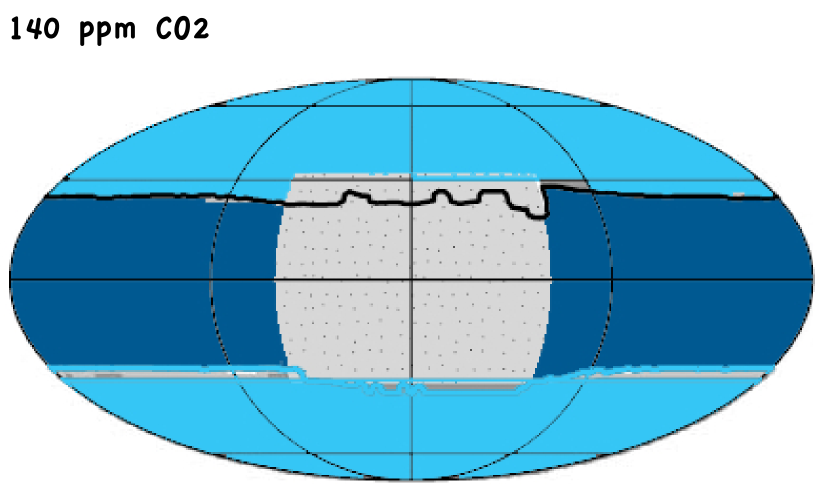
- Hence a methane-dominated greenhouse doesn't cause cooling when methane oxidizes to CO_2 in the air
- However CO_2 is more soluble (via carbonate equilibrium) than methane, so this allows some reduction of greenhouse effect
- Note that methane is isotopically light, so if methane carbon winds up in carbonate sediment, it drives a negative ^{13}C excursion


720 Ma
Sturtian
Tarim
South China
Siberia
North China
Greater India
Seychelles
E. Madagascar
Australia
East Ant.
Kalahari
Laurentia
Arabia
Nubia
Rio de la Plata
Sahara
Congo-Sao Francisco
Amazon
Baltica
West Africa

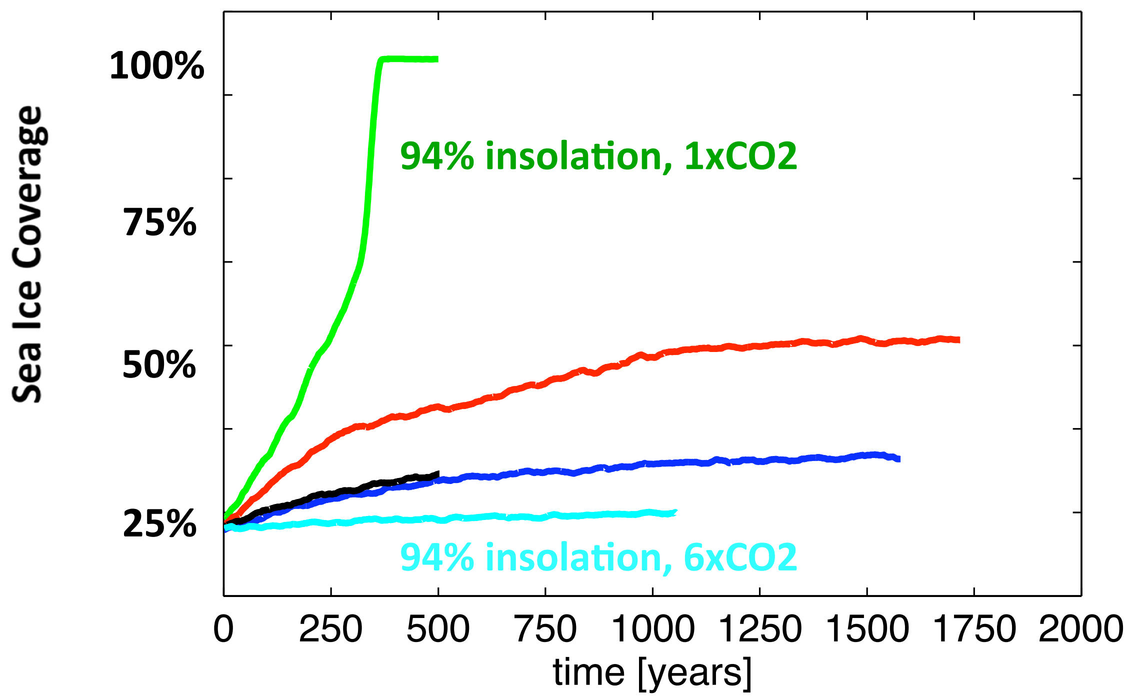

630 Ma
Marinoan
South China
Tarim
Kalahari
Greater India
Australia
Siberia
Seychelles
E. Madagascar
East Ant.
Rio de la Plata
Laurentia
North China
Congo-Sao Francisco
Arabia
Sahara
Nubia
West Africa
Amazonia
Baltica

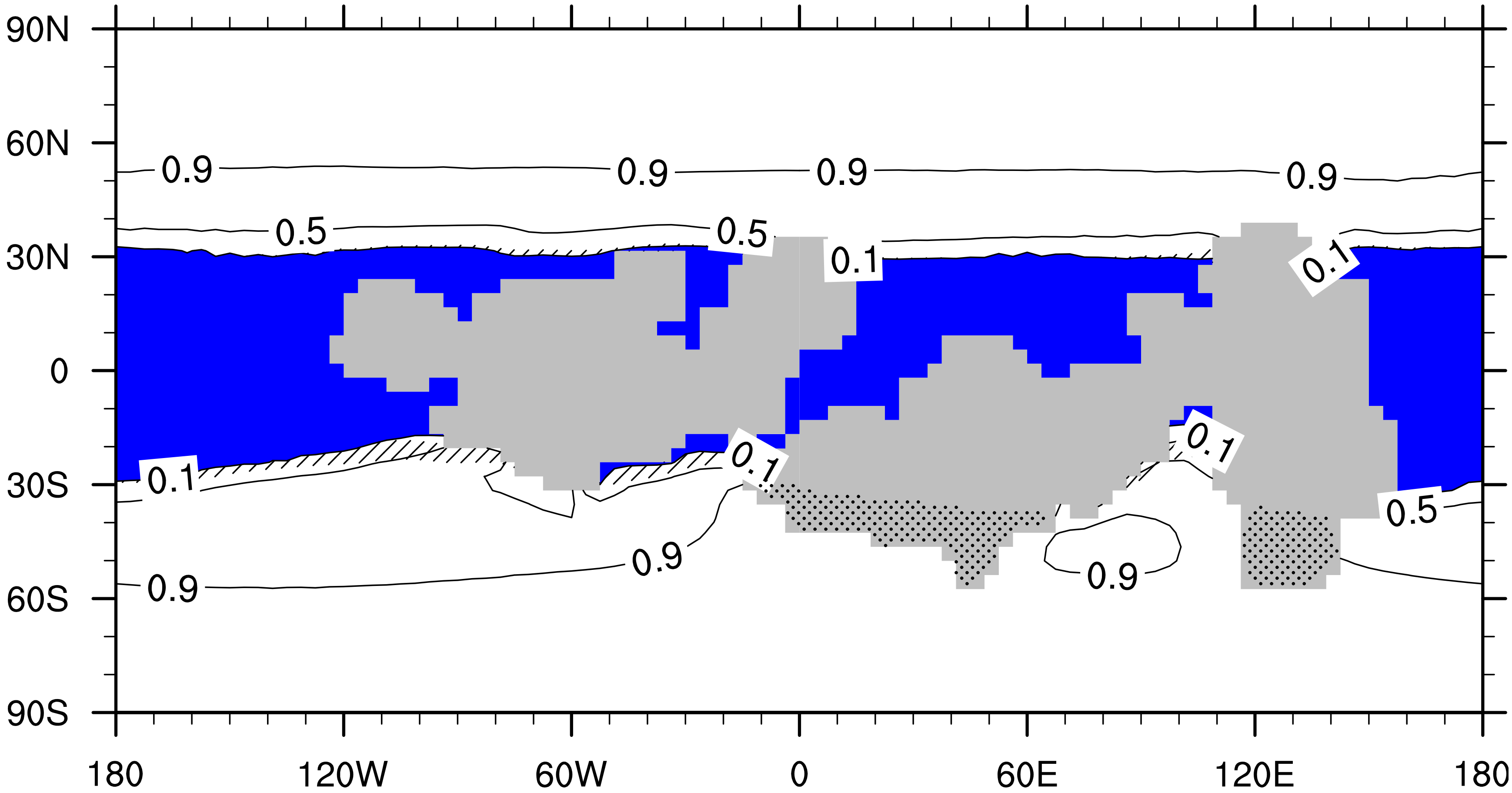
Jumping into the deep end: Ocean dynamics and initiation

Poulsen and Pierrehumbert *GRL* 2001, ...,
Poulsen and Jacob *Paleocean.* 2004



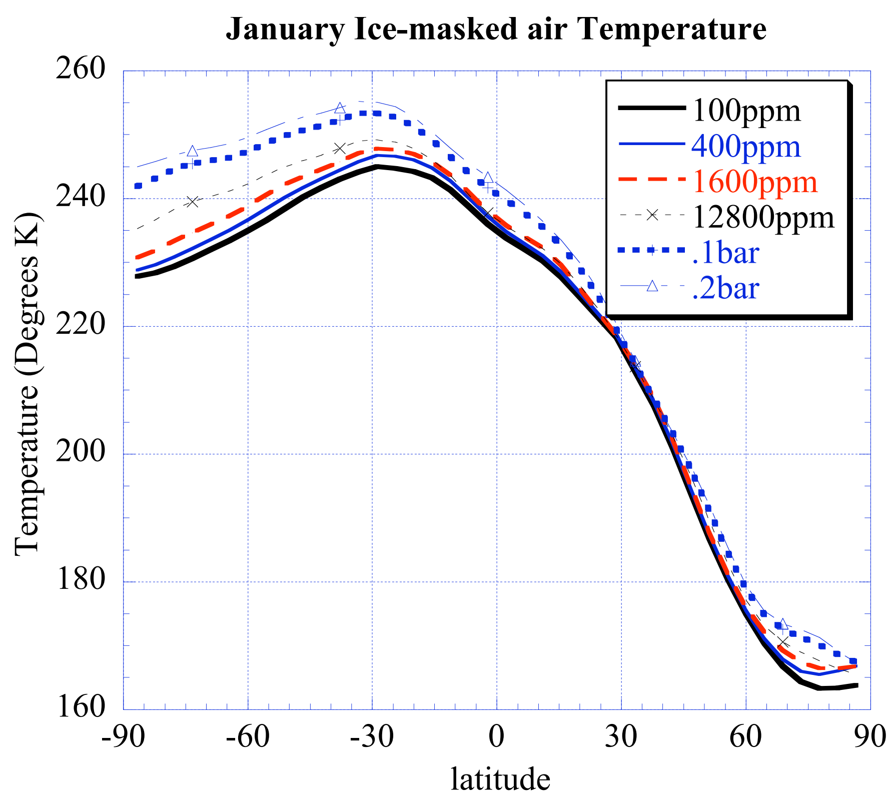
The MPI coupled global climate model initiates a Snowball at reasonable Neoproterozoic conditions.




90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0.9
0.9
0.9
0.9
0.5
0.5
0.1
0.1
0.1
0.1
0.1
0.5
0.9
0.9
0.9

Jumping into the deep end: Deglaciation

Pierrehumbert, *Nature* 2004, *J. Geophys Res* 2005.



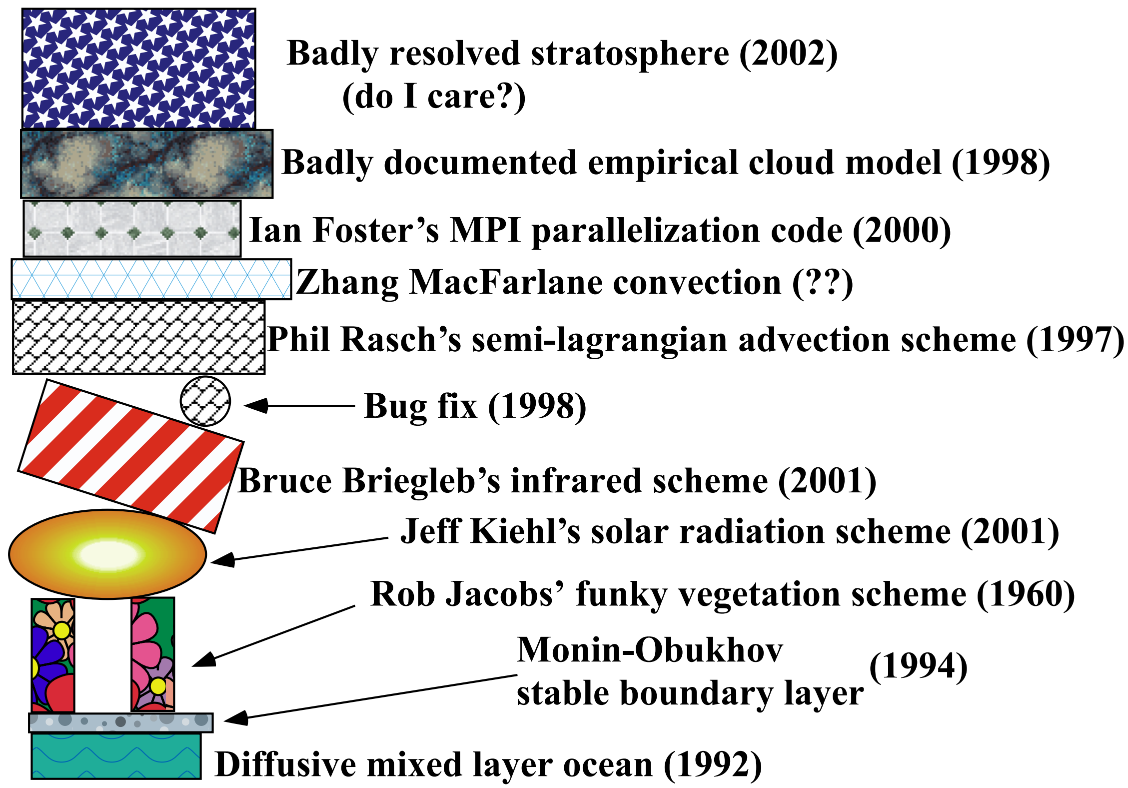
January Ice-masked air Temperature
Temperature (Degrees K)
260
240
220
200
180
160
-90
-60
-30
0
30
60
90
latitude
100ppm
400ppm
1600ppm
12800ppm
.1bar
.2bar

Advantages of using a GCM

- Includes physics you might not have thought was important, or known about
- Collective behavior between parts you didn't think would interact
- Very hard to systematically represent synoptic eddy transports in EBM's

(But there are also some disadvantages ...)

Stratigraphic analysis of an Atmospheric GCM



Snowball Earth and Snowball Earths
Part II: Simulations, theory,mathematics

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The Snowball provides a rich lode of idealized climate dynamics problems

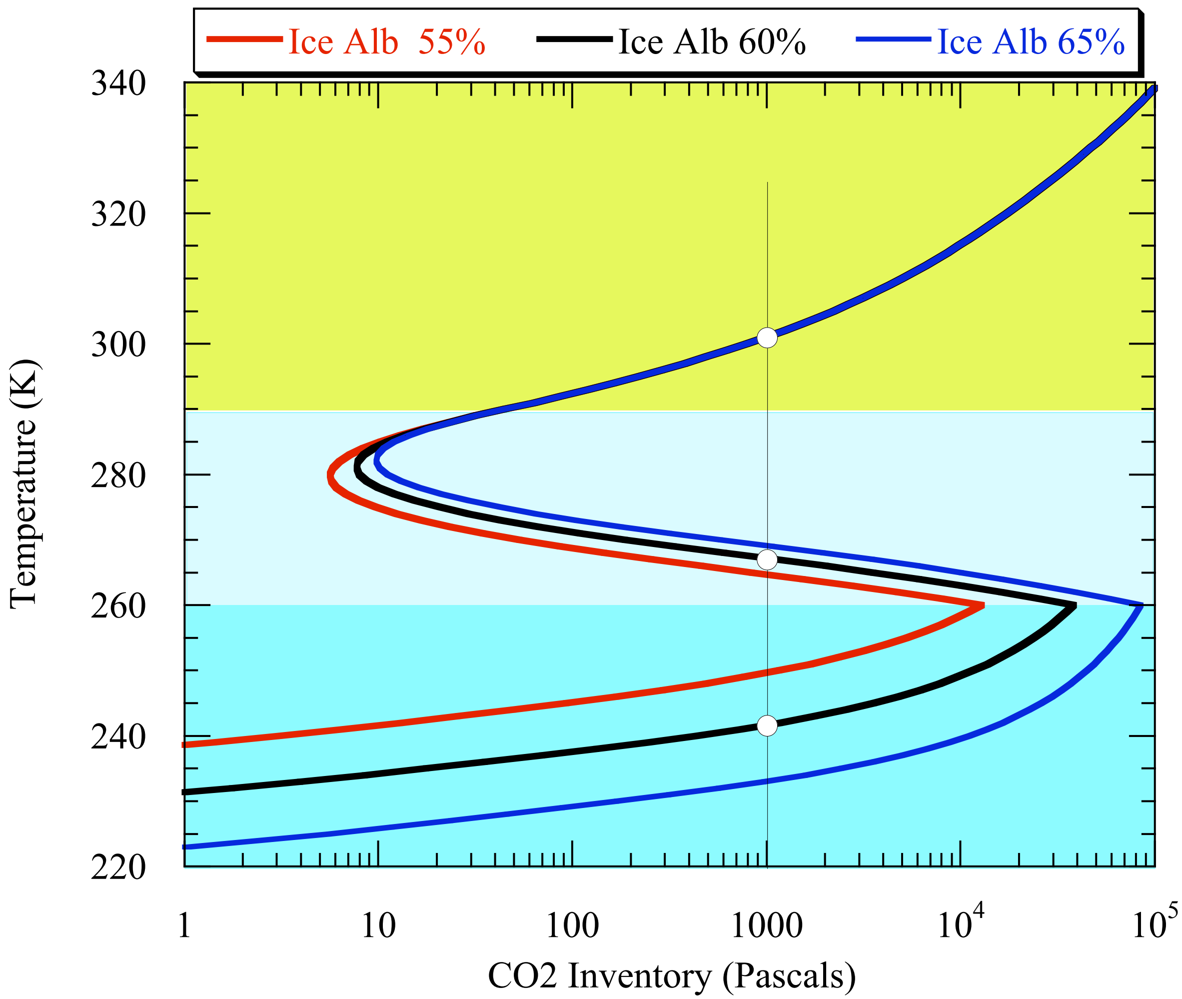
- Snowball state:
  - Dry dynamics, no water vapor feedback
  - Clouds are radiatively active, but quasi-passive tracers
  - No ocean dynamics or thermal inertia
- We'll start with Earthlike configurations, then generalize to exoplanets with exotic orbits and spin states

Our theoretical toolkit for understanding what's going on Snowball simulations

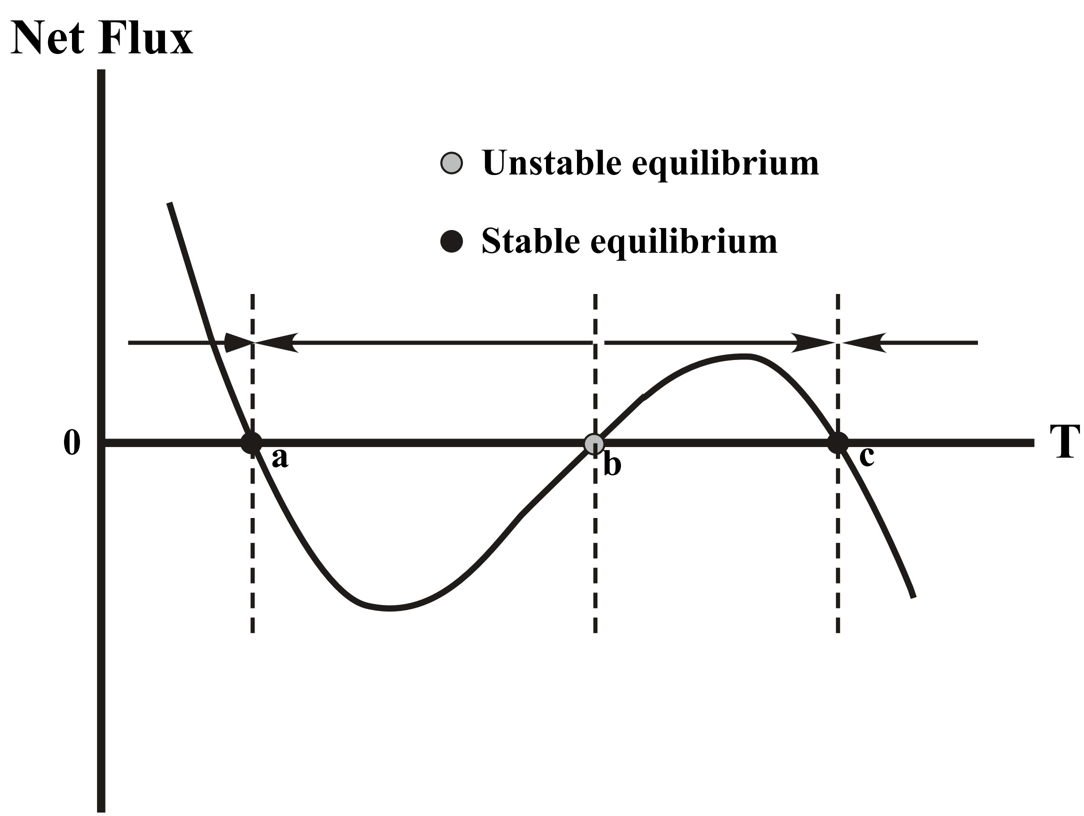
- Energy balance models (various flavors)
- Radiative-convective column models
- Surface energy balance models
- Thermal diffusion in ice with nonlinear upper flux B.C.
- Hadley cell theory (various flavors)
- WTG models
- Synoptic eddy transport theory ???
- 1D "shallow ice" models (Sea Glaciers)
- Precipitation-Temperature relation models
- Carbon cycle box models (Geochemical weathering)

Zero D Steady Snowball Model

$$\frac{1}{4}(1-\alpha(T))L_{\circledast} = OLR(T, CO_2)$$


Ice Alb 55%
Ice Alb 60%
Ice Alb 65%
340
320
300
280
260
240
220
Temperature (K)
1
10
100
1000
10^4
10^5
CO2 Inventory (Pascals)

Attractor basins

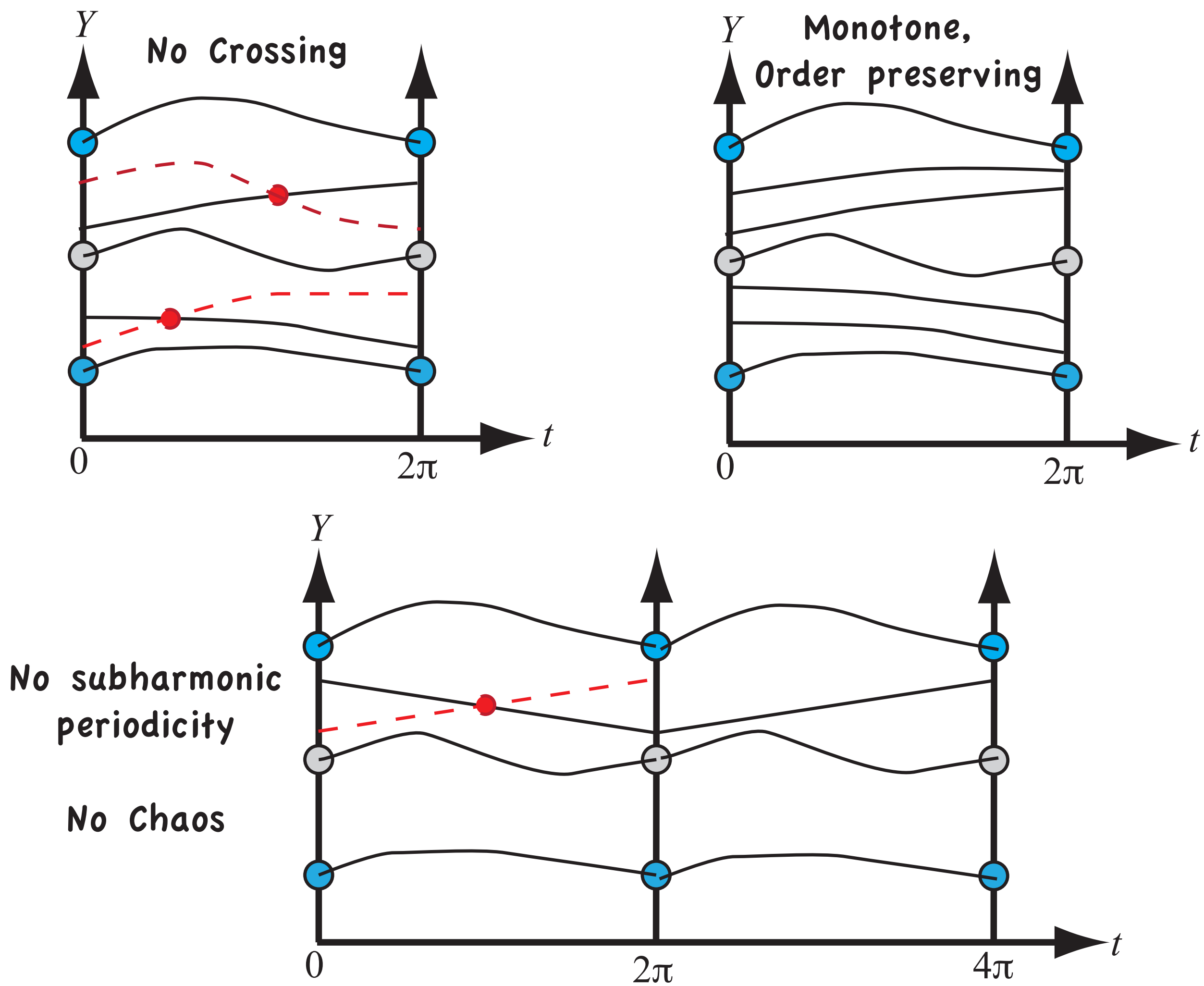


Zero-D nonlinear with seasonal forcing

$$\frac{dY}{dt} = F(Y,t)$$

$$F(Y,t+2\pi) = F(Y,t)$$

$F < 0$ for large Y, $F > 0$ for $Y \to 0$


Y
No Crossing
t
0
2π
Y
Monotone,
Order preserving
t
0
2π
Y
No subharmonic
periodicity
No Chaos
t
0
2π
4π

1-D nonlinear PDE with seasonal forcing

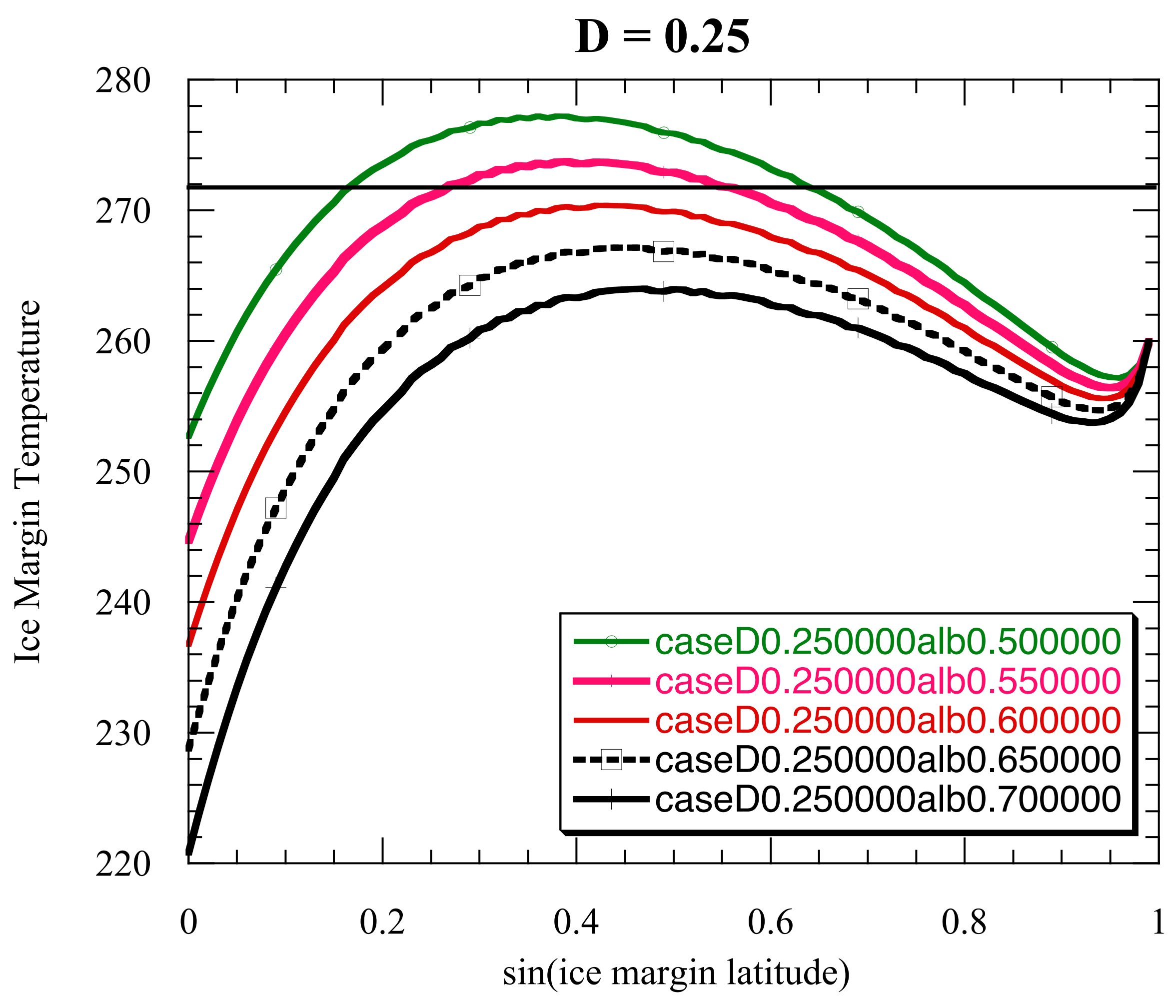
$$\partial_t E(T) = \partial_y (1 - y^2) D \partial_y T + (1 - \alpha(h_i)) S(y,t) - OLR(T)$$

Steady-State becomes an ODE

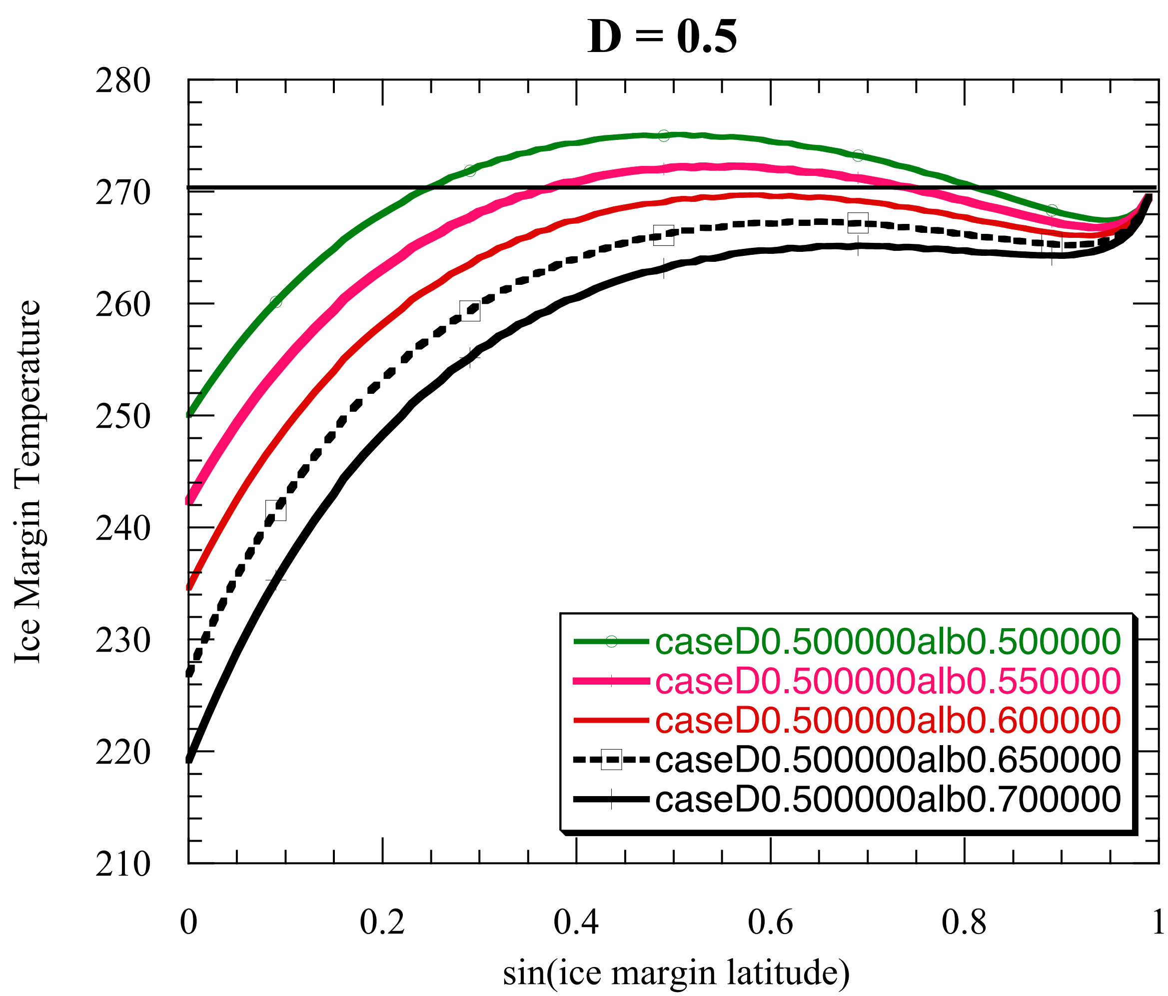
$$0 = \partial_y (1 - y^2) D \partial_y T + (1 - \alpha(h_i)) S(y, t) - OLR(T)$$

Plot ice margin T vs ice margin position

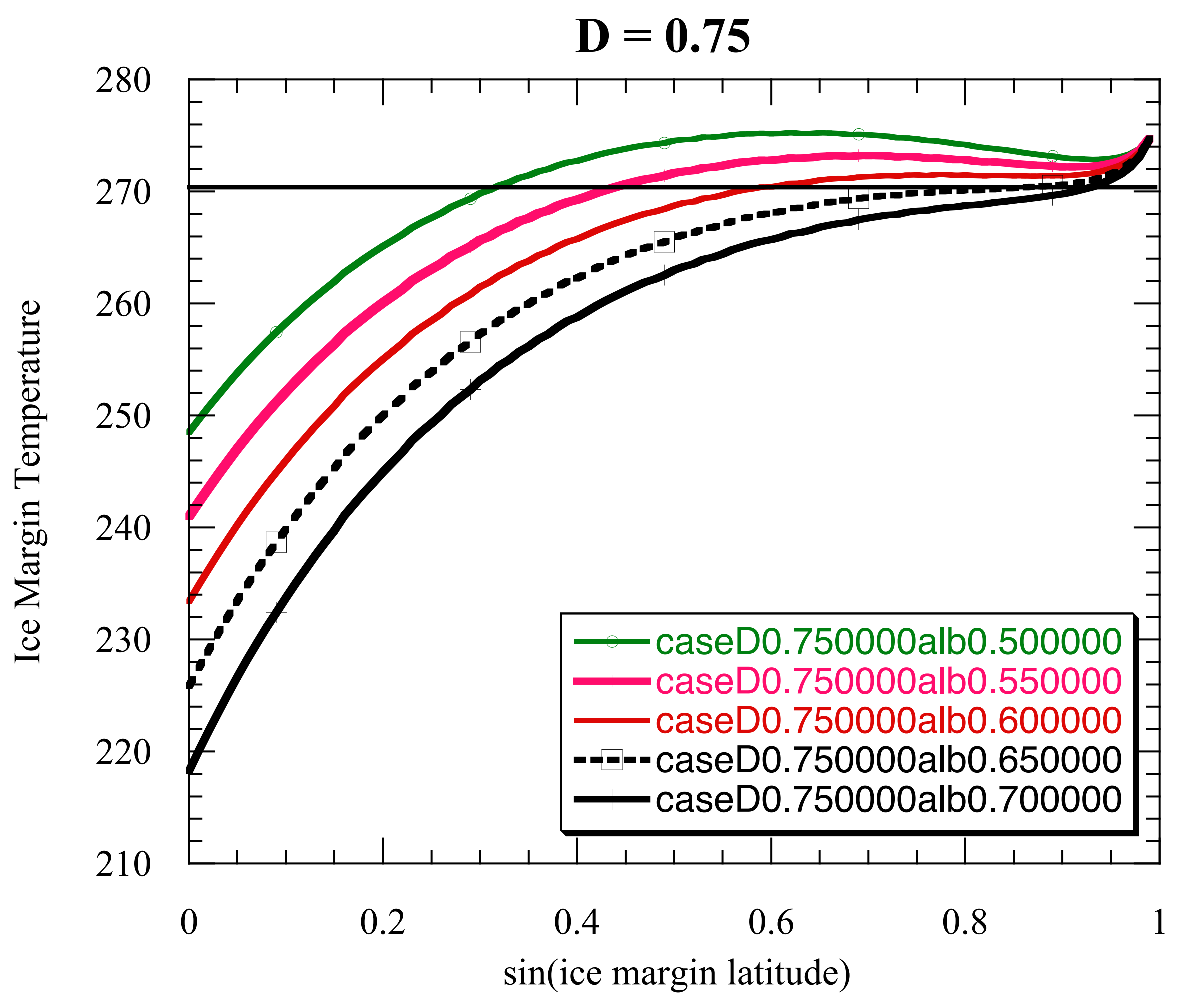
Steady State



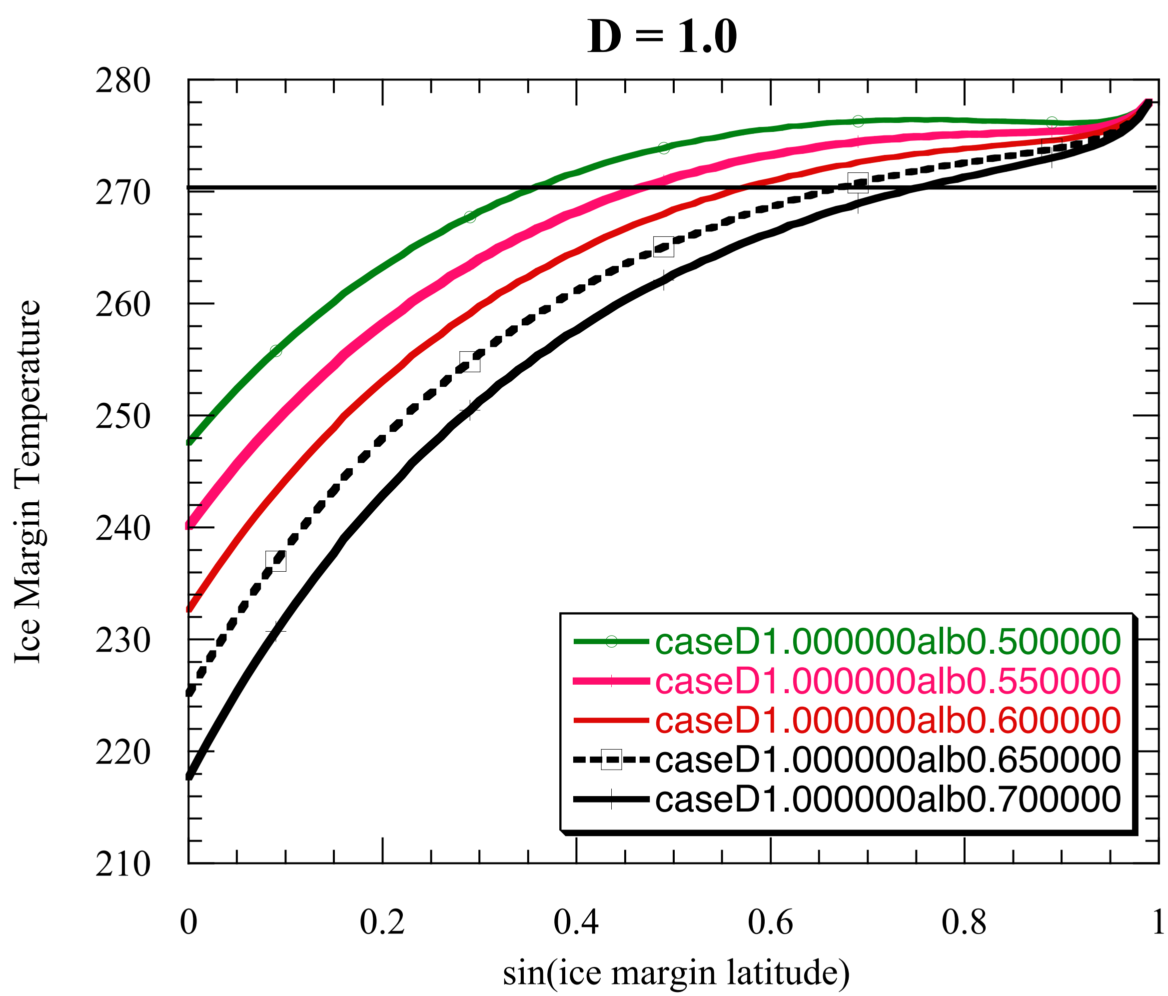
Steady State



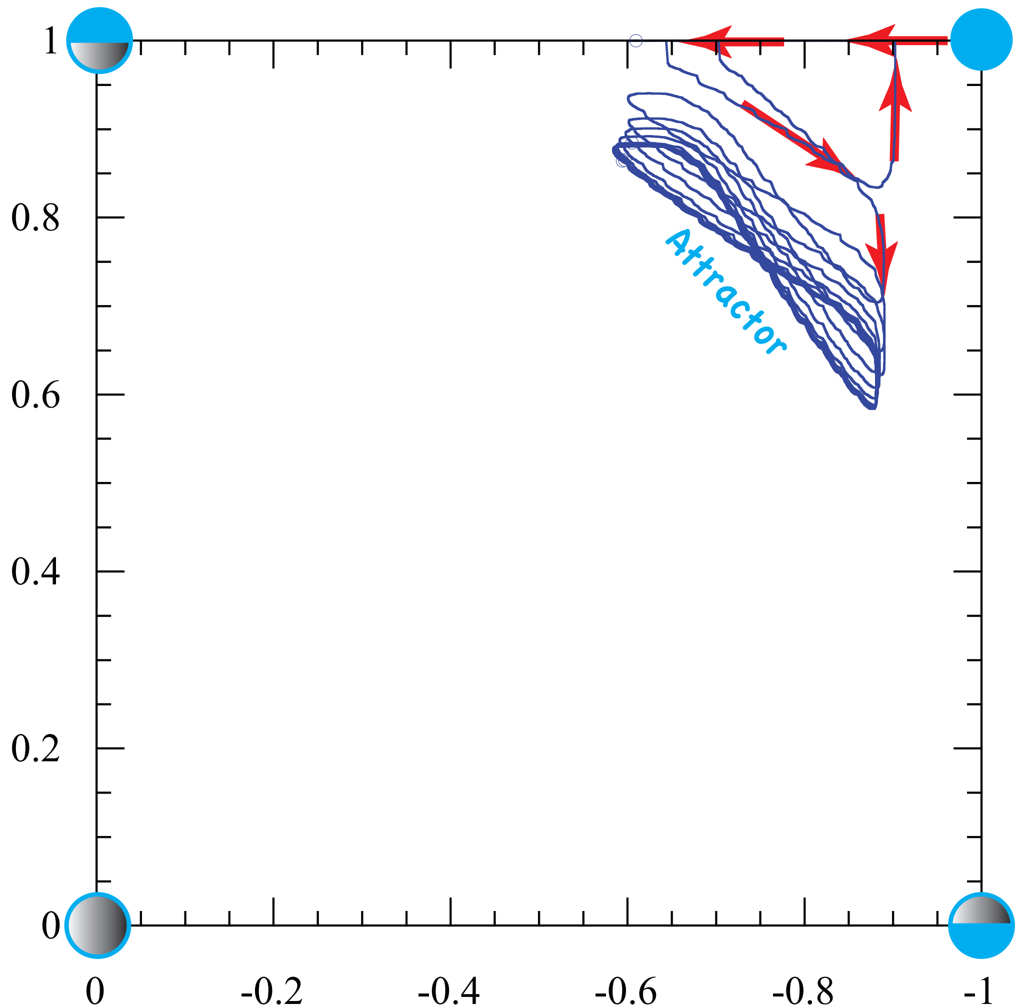
Steady State



Steady State

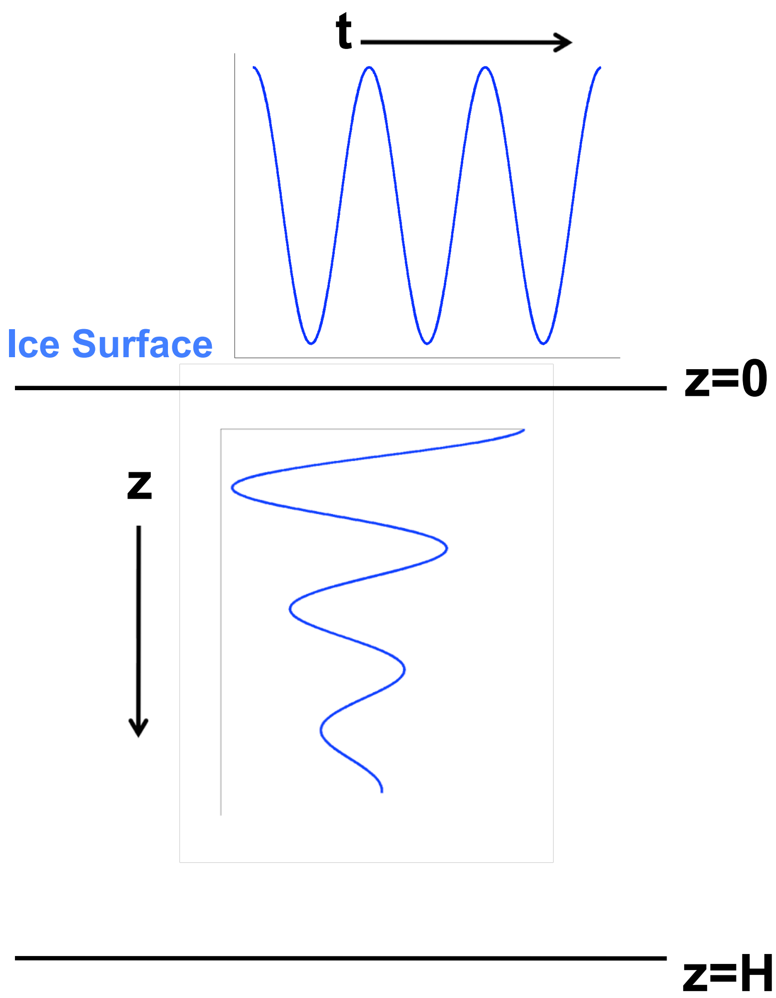


Attractor for 1D PDE Seasonal Snowball EBM

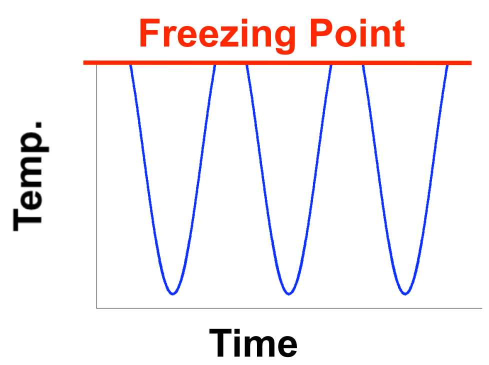


1
0.8
0.6
0.4
0.2
0
0
-0.2
-0.4
-0.6
-0.8
-1
Attractor

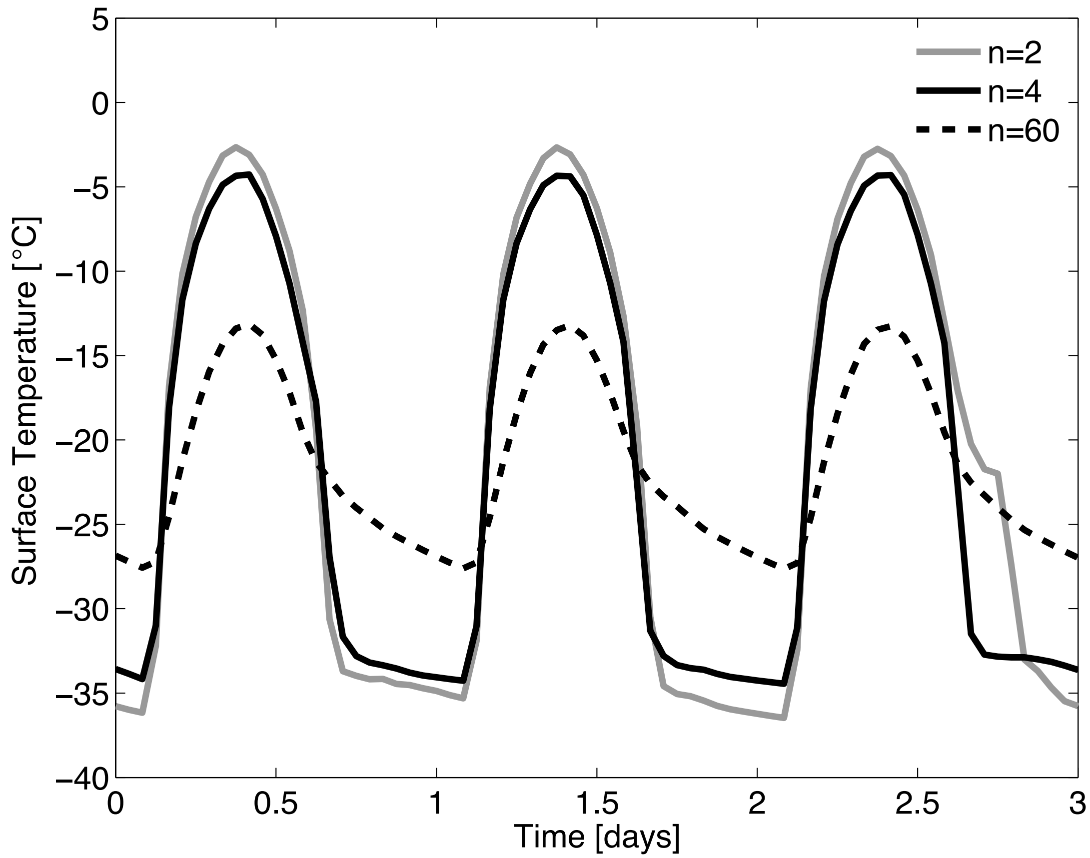
An exaggerated surface temperature diurnal cycle can lead to false deglaciations.



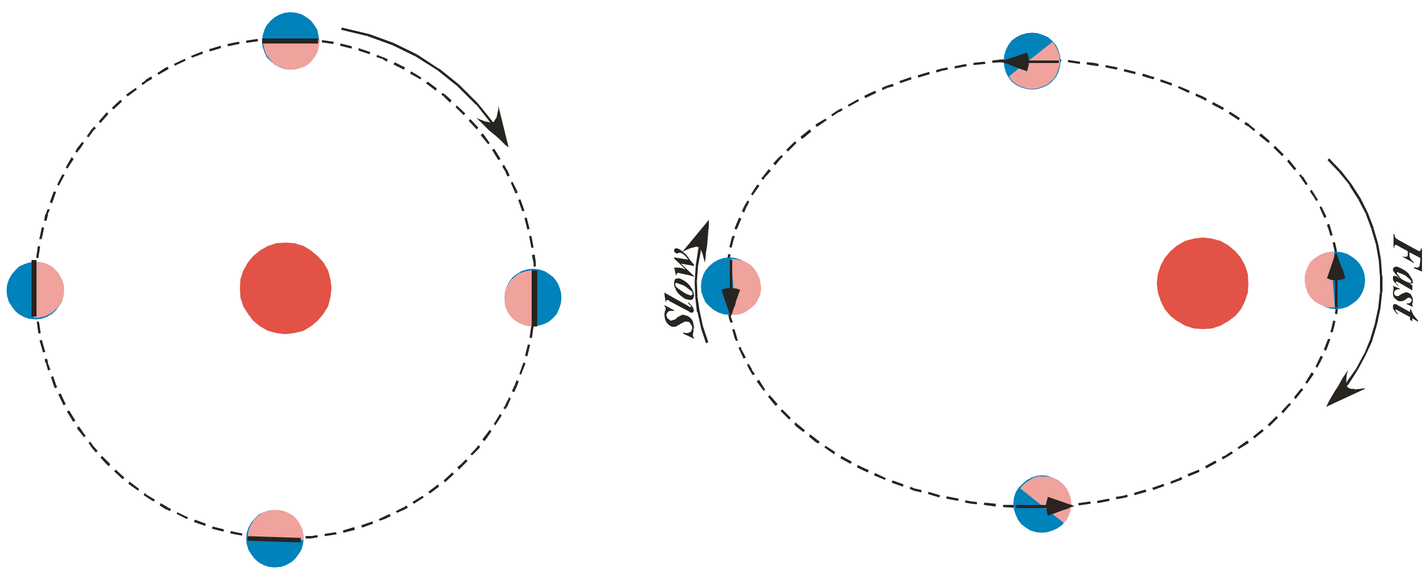
We care because melting occurs at noon



Drastic reduction in diurnal cycle occurs when you increase sea ice resolution below a single column atmosphere as well.



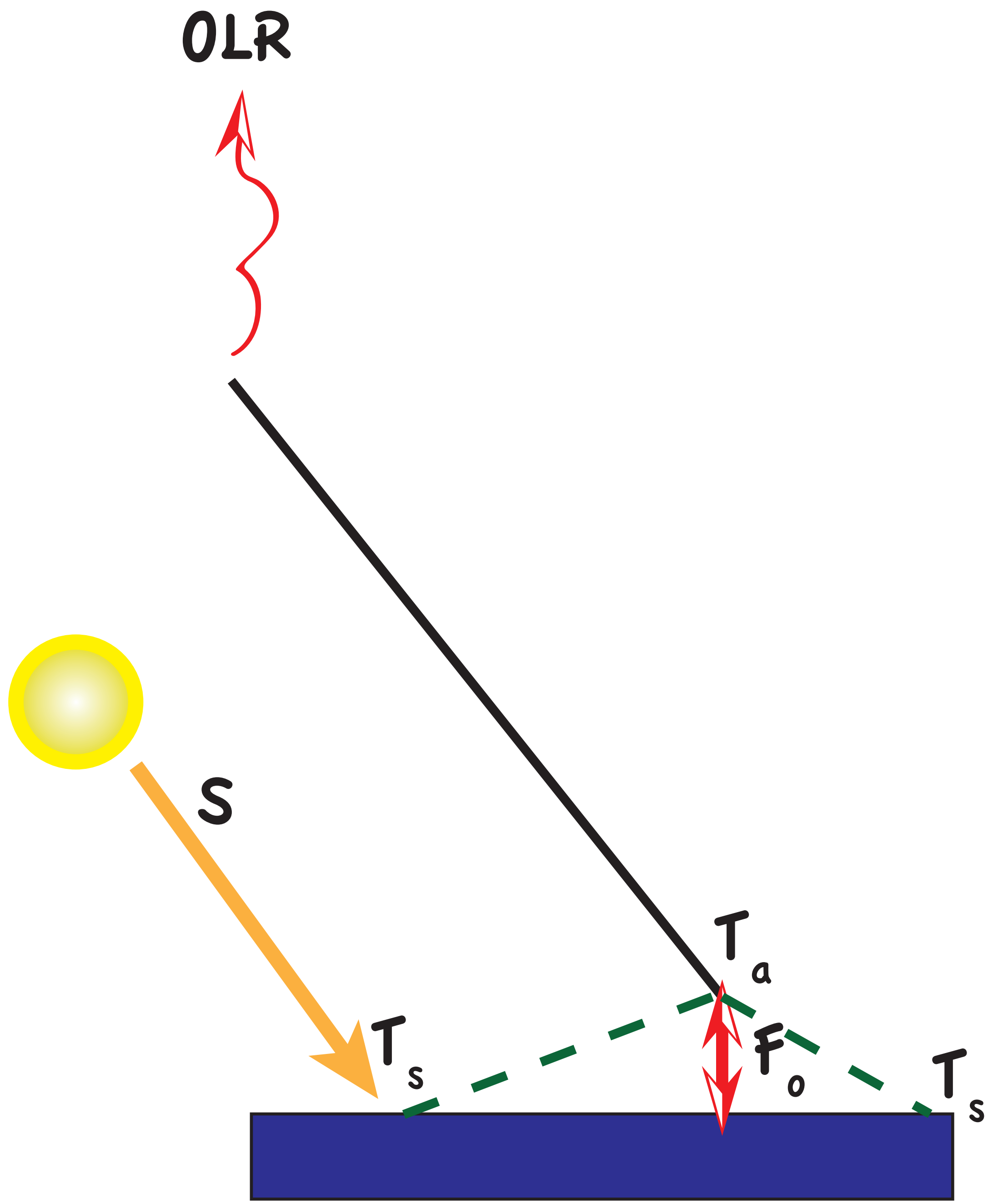
Review: Tide-locked and quasi-synchronous states



Review: The basic dynamical regime

- Orbital/diurnal periods of 20-100 Earth days
- Coriolis effects at short end comparable to Titan
- Low Coriolis force implies efficient atmospheric heat transport. Nearly isothermal free atmosphere.
- Can use WTG approximation globally
- Applies to 3:2 spin-orbit resonance case as well

For WTG Snowball, surface budget is what makes it interesting

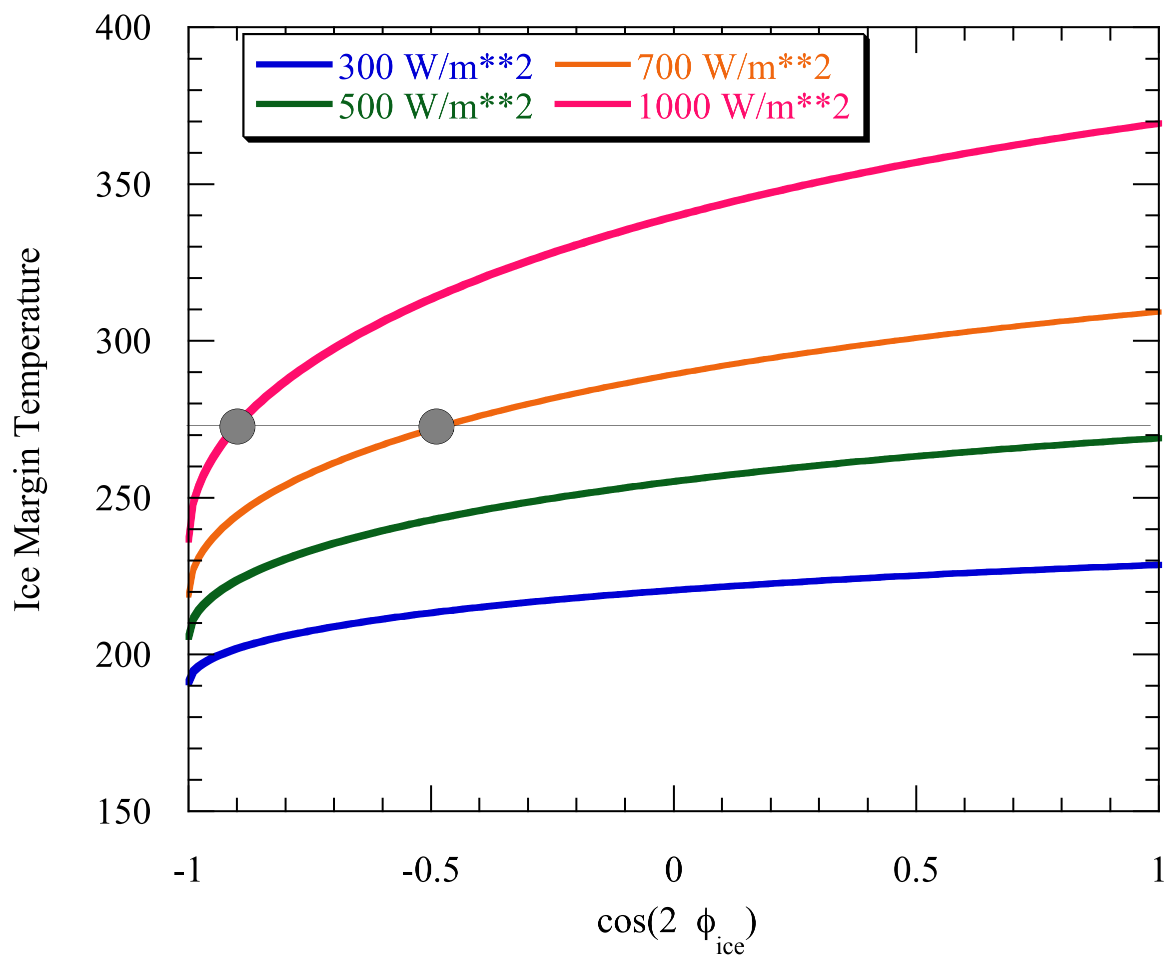


OLR
S
T_a
T_s
F_o
T_s

$$OLR(T_a) = L_{\circledast} f(\phi_i)$$

$$F_o(T_a) + a_s \cdot (T_s(\phi) - T_a) = L_{\circledast} \cos \phi$$

Equilibrium results for a tide-locked planet



Planet, Planet shining bright

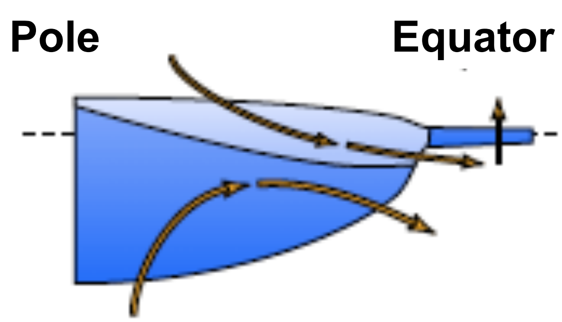
In the Kepler's wobbly sight

Are you like Venus dry and hot?

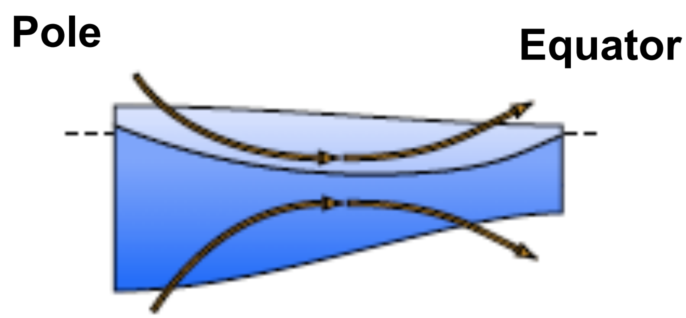
Or icy Snowball that is not?

The hydrological cycle drives ice flow.

Sea Ice Elevator
[Hoffman and Schrag, 1999]

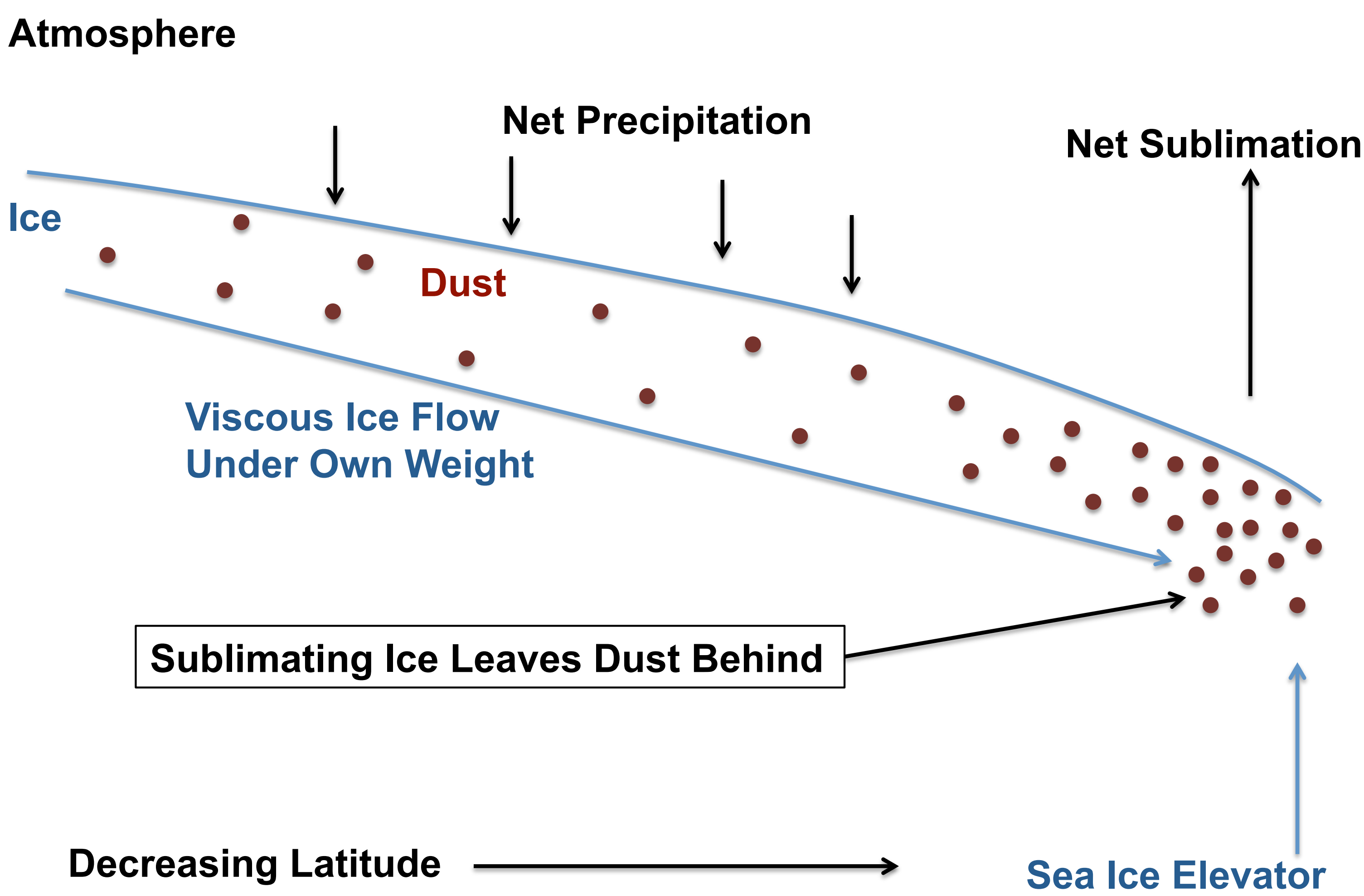


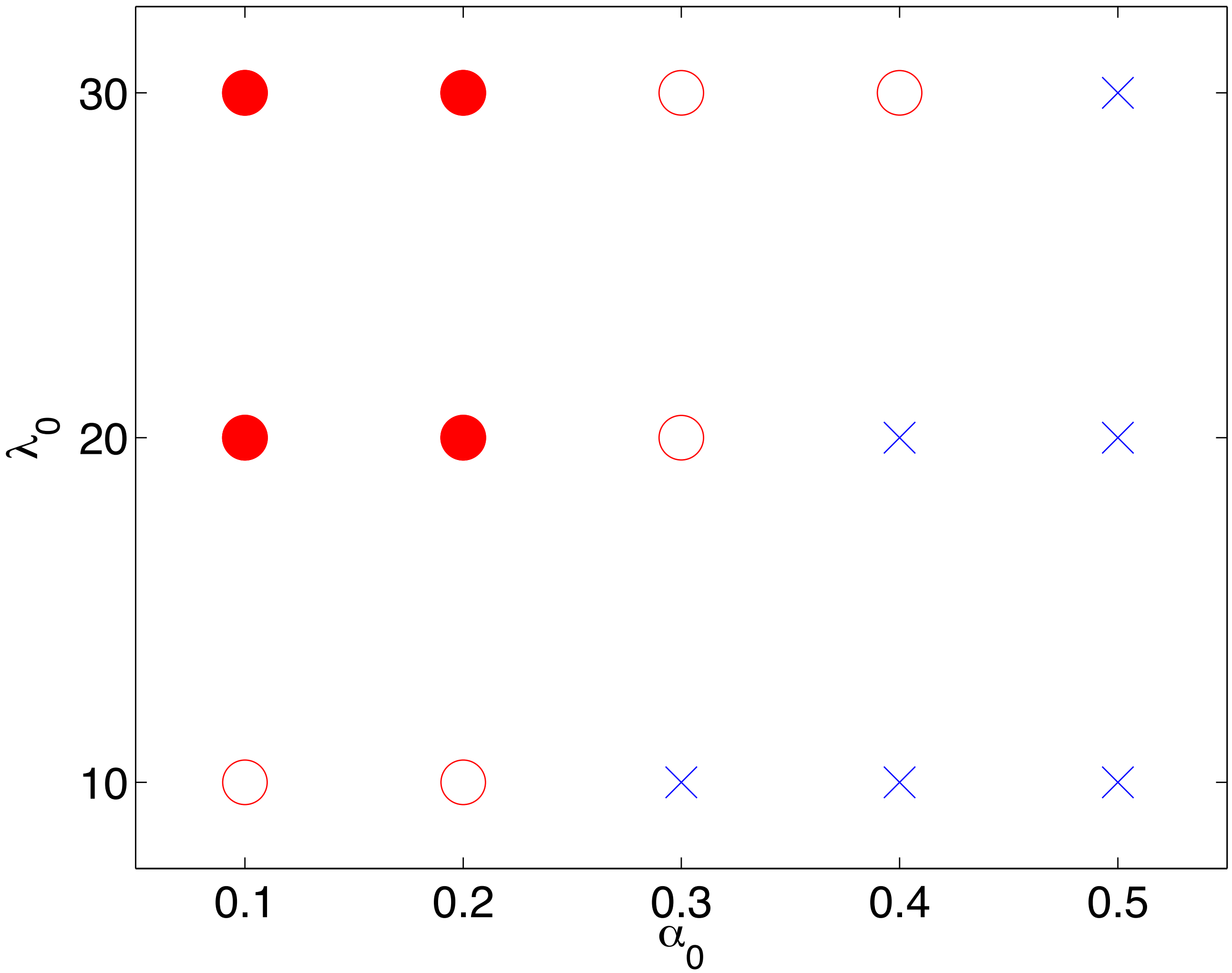
Ice flow from higher latitudes
[Goodman and Pierrehumbert, 2003]



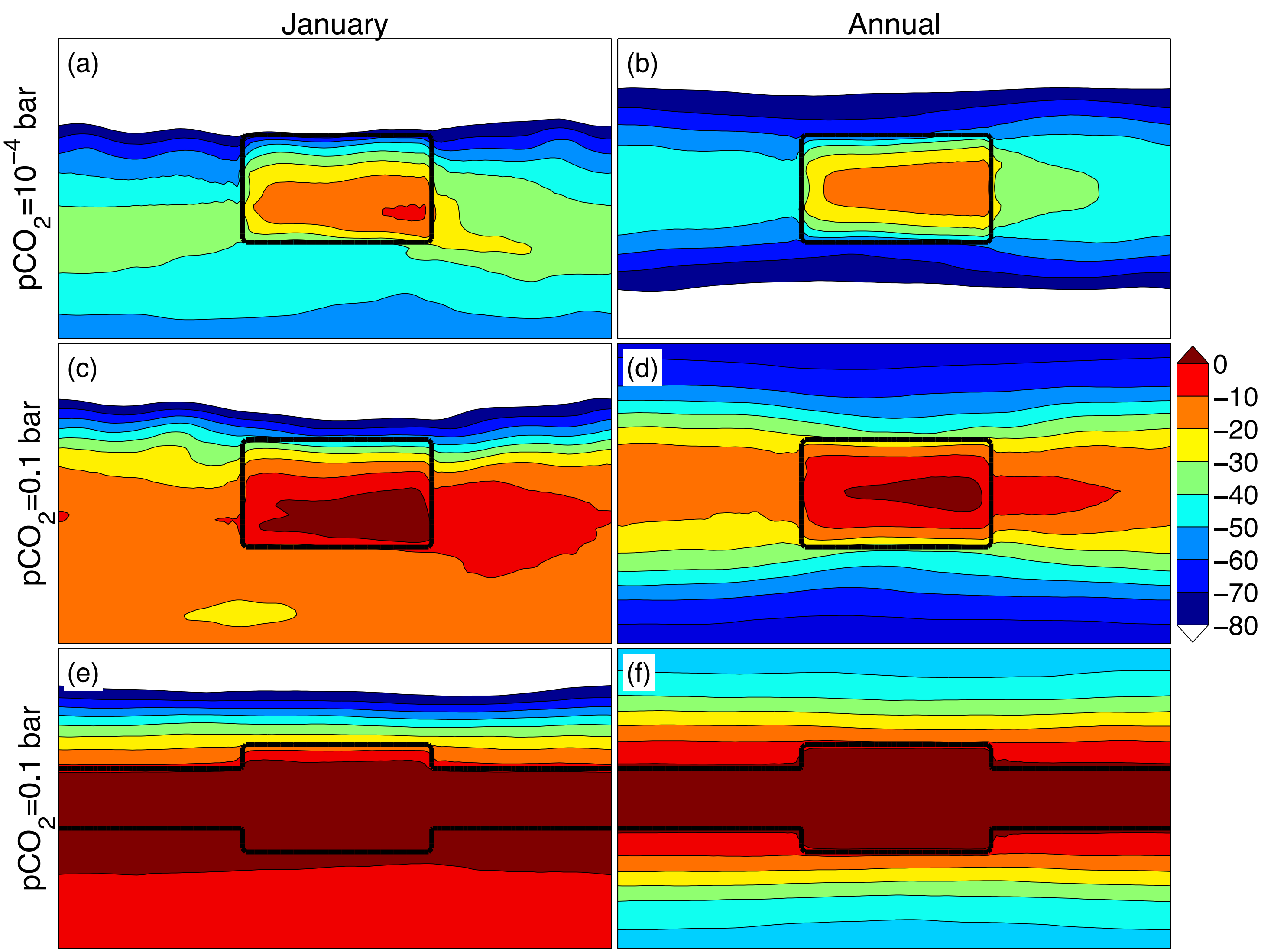
Figures from Goodman (2006)

Ice flow should trap dust in tropics.



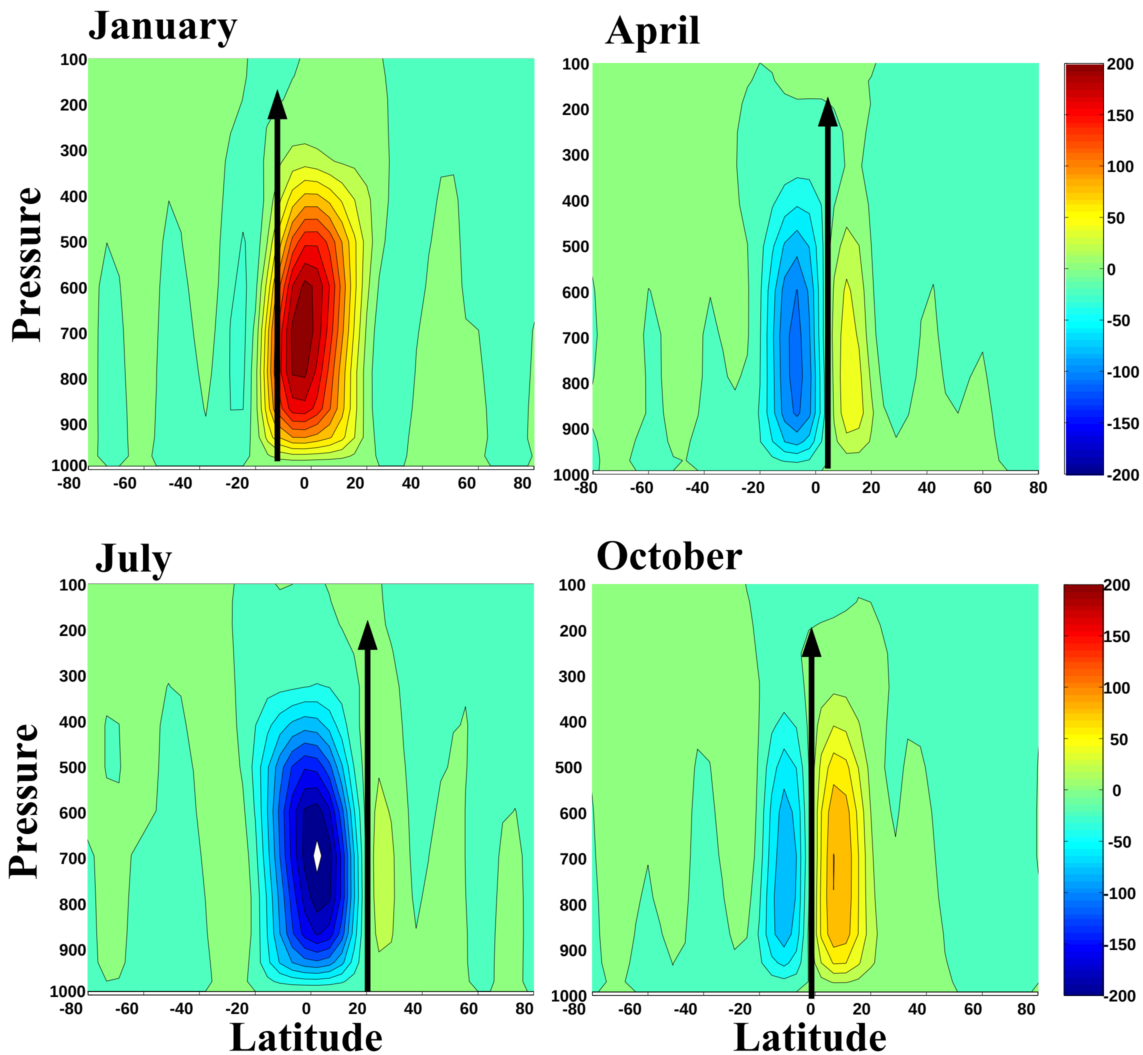


30
20
10
λ_0
0.1
0.2
0.3
0.4
0.5
α_0



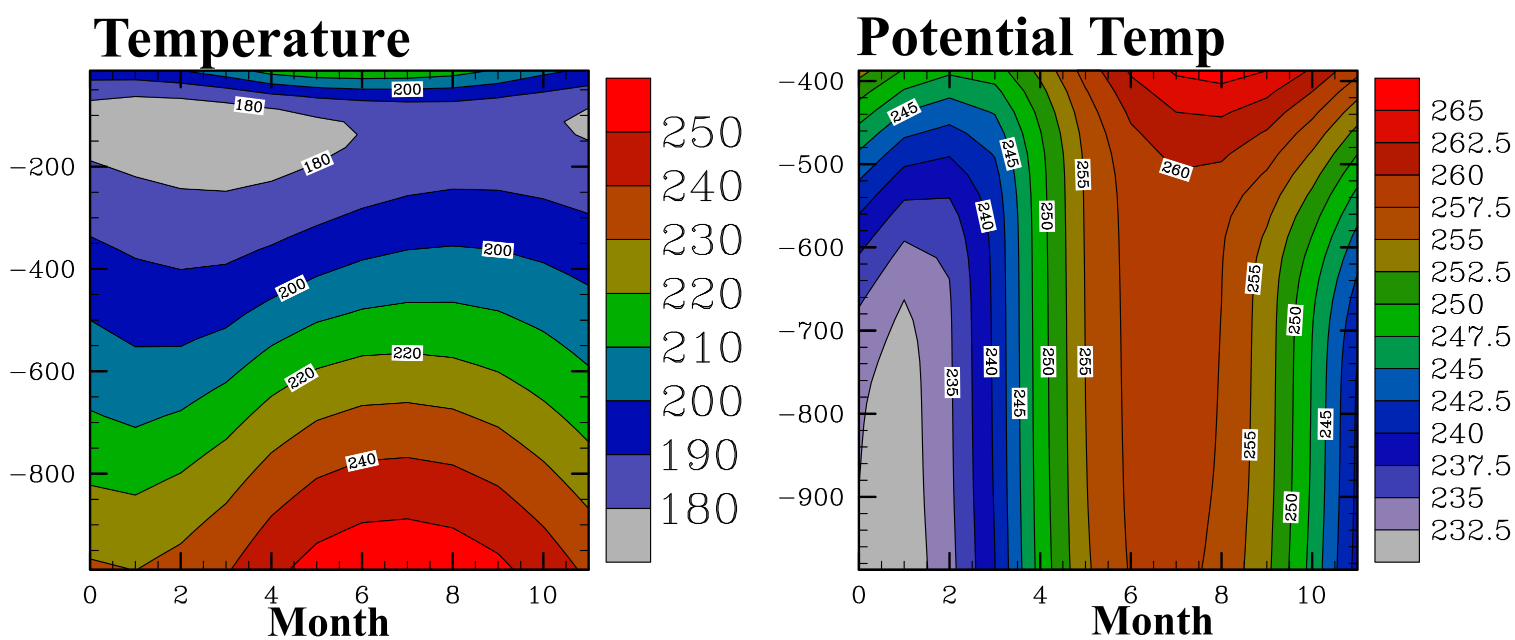
January
Annual
(a)
(b)
(c)
(d)
(e)
(f)
$pCO_2=10^{-4}$ bar
$pCO_2=0.1$ bar
$pCO_2=0.1$ bar
0
−10
−20
−30
−40
−50
−60
−70
−80

Snowball Hadley Cell

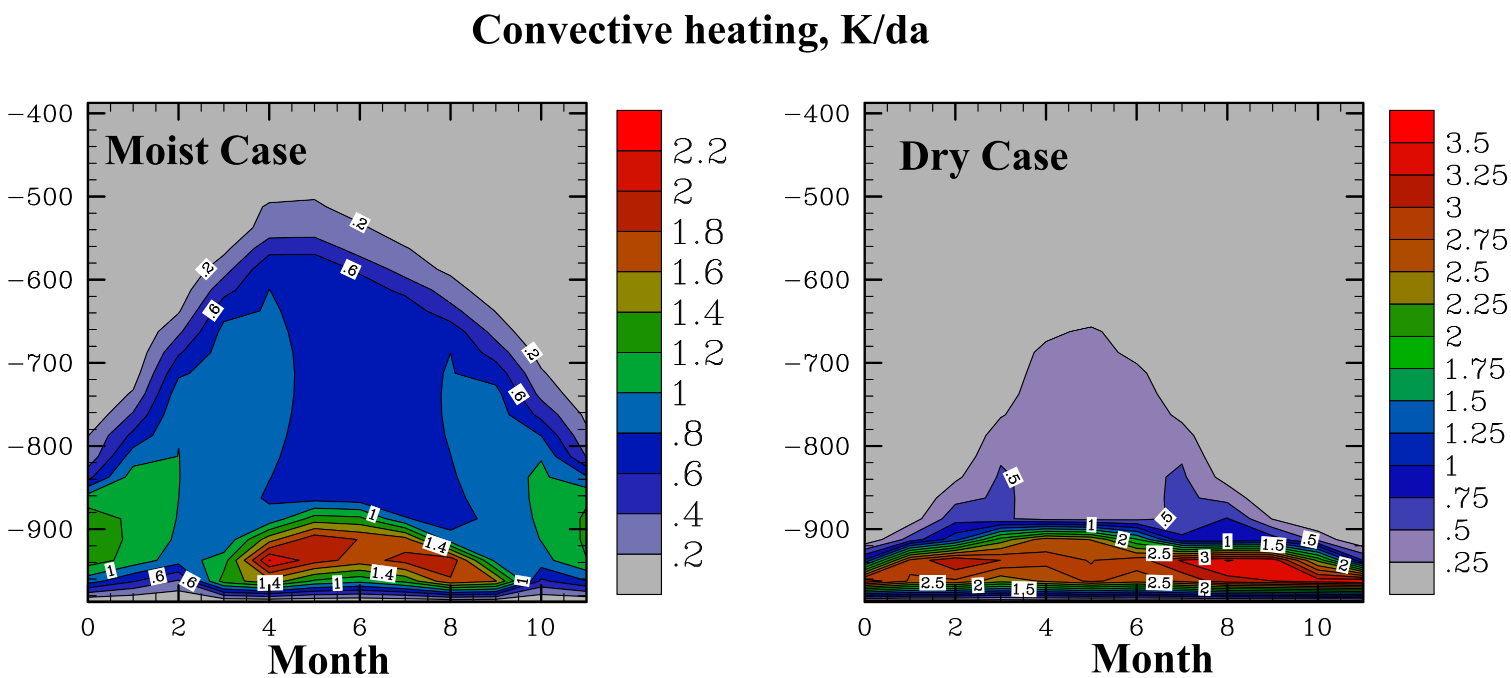


January
April
July
October
Pressure
Pressure
Latitude
Latitude
100
200
300
400
500
600
700
800
900
1000
-80
-60
-40
-20
0
20
40
60
80
200
150
100
50
0
-50
-100
-150
-200

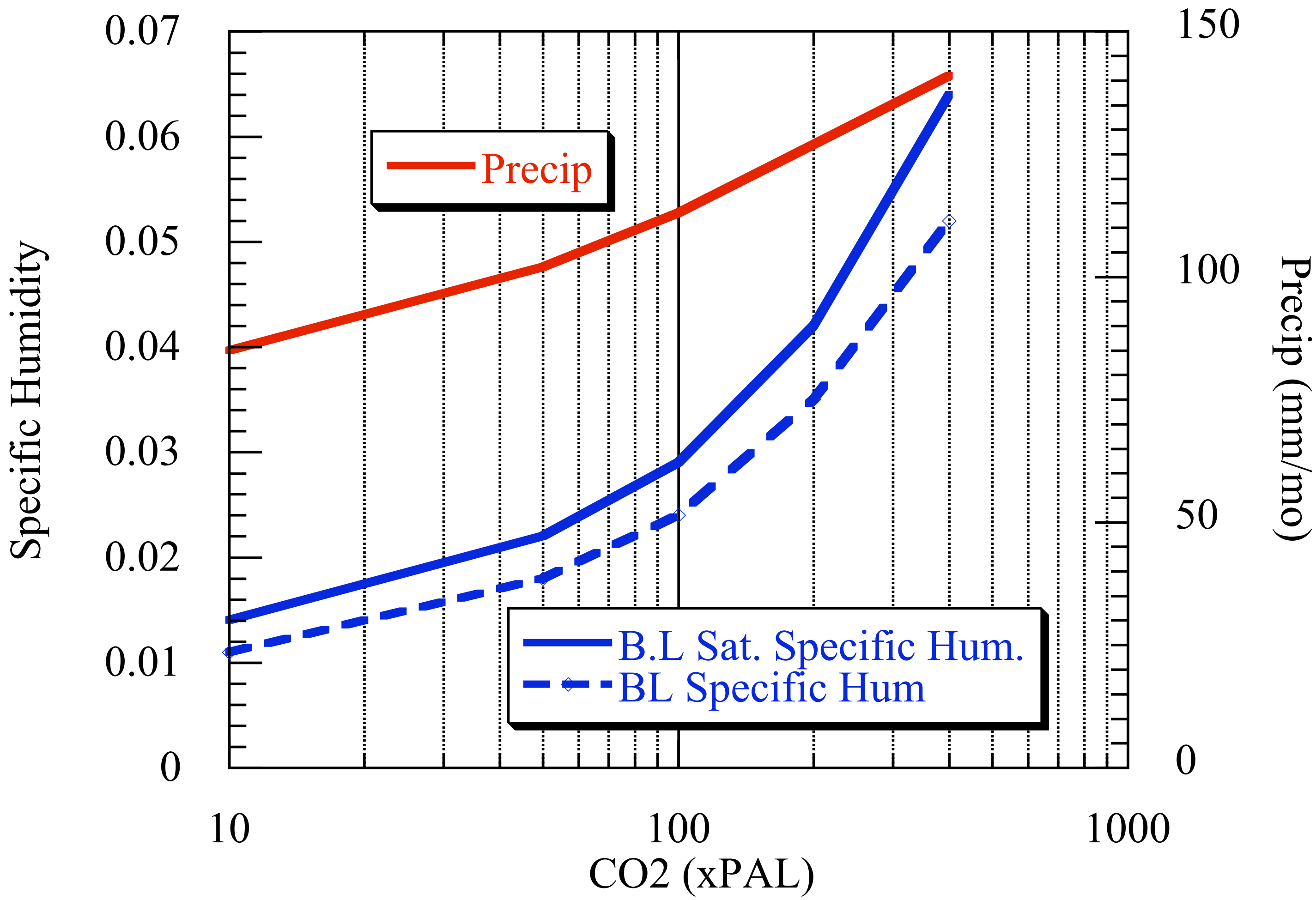
RC: Weak Winter lapse rate doesn't need dynamics



Convection is shallow and weak



Precipitation and temperature in the postglacial hothouse



Conclusions and prospects

- Critical question: Why Snowball glaciations at beginning and end of Proterozoic, but not any glaciation for a billion years in between? Similarly for ^{13}C fluctuations
- Is the Shuram anomaly real? Is it caused by the same things as the Shuram and Marinoan anomalies? If so, why no glaciation?
- With ocean heat transport, stable low-latitude sea ice margins are quite robust, though you can freeze over at low enough CO_2
- Very unlikely that there are waterbelt states cold enough to allow land glaciation, but need to do calculation with coupled ice sheets.
- Hard to reconcile waterbelt (nee slushball) states with geochemical signatures. Waterbelt (incomplete Snowball) state is implausible.
- It would be promising to explore EBM's based on MSE diffusion

- Albedo! Albedo! Albedo!
- Fate of surface transient melt water

- Dust moraine provides viable means for deglaciating Snowball
- Need to interactively couple sea-glacier and dust cycle to EBM. 3D sea glaciers
- Small-particle ice clouds could also help deglaciation, but cold convective cloud problem is untouched

- WTG model of the tide-locked waterworld reproduces the ”swimming pool” state
- Extension to optically thick CO_2 atmospheres (easy)
- Extension to quasisynchronous eccentric orbit and 3:2 spin-orbit cases

Conclusions and prospects

In order to use a GCM safely and productively, it is essential to have a very good theoretical toolkit