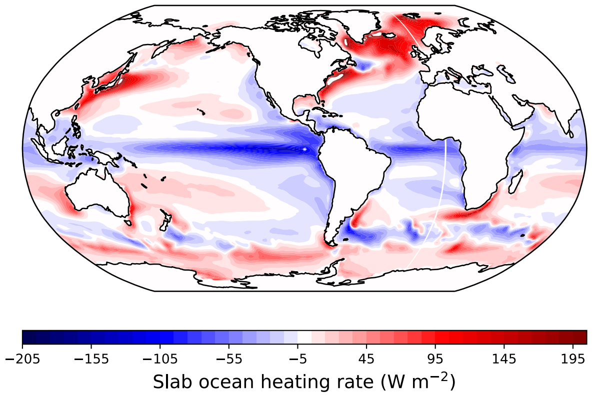
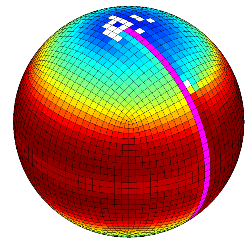
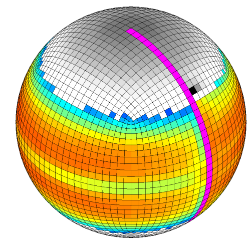
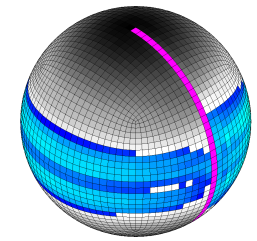
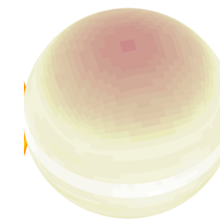
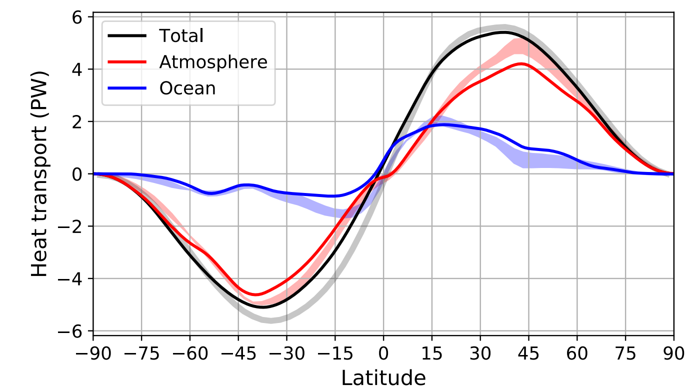












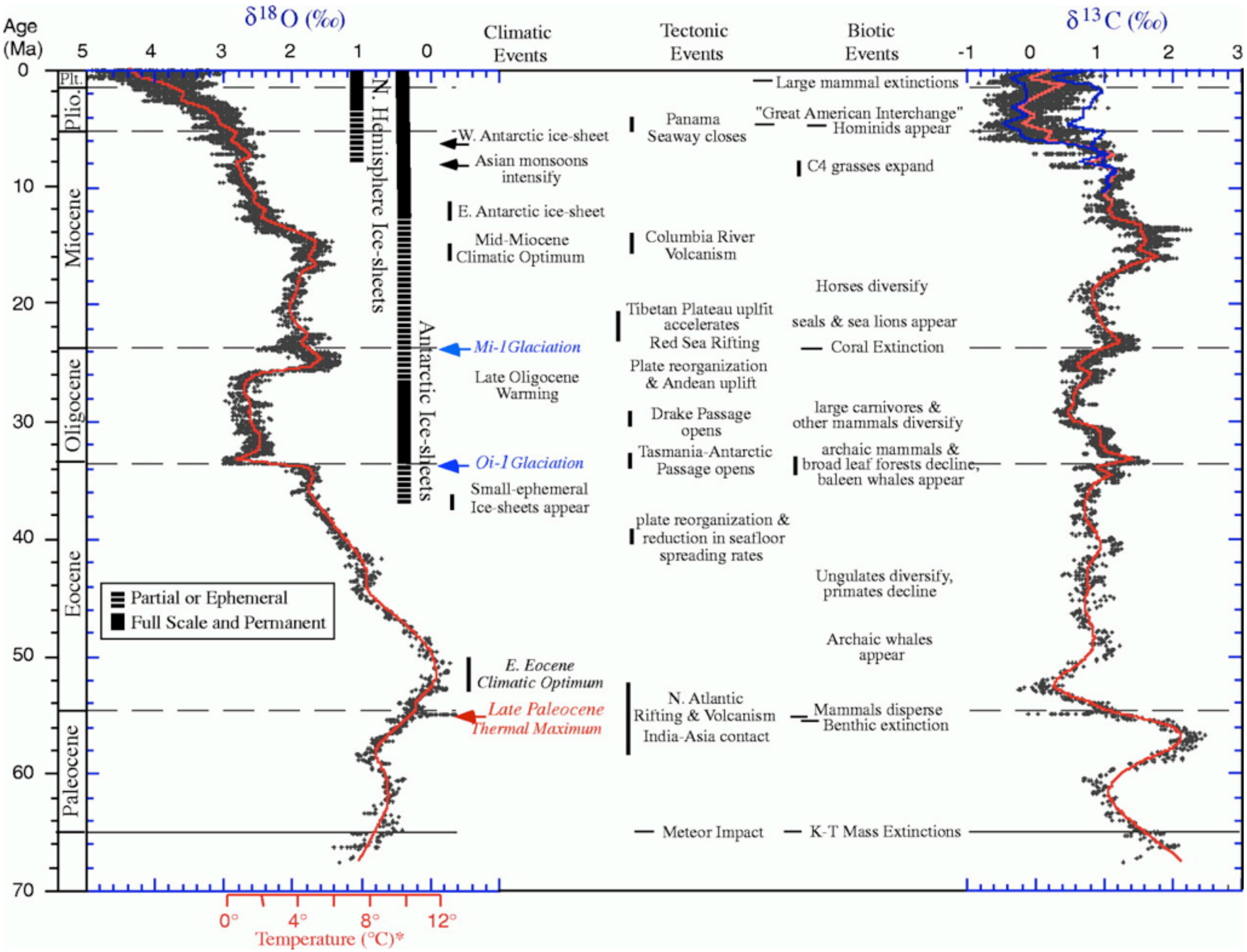
Multiple equilibria in the climate system:
understanding the role of oceans and sea ice

Brian E. J. Rose
University at Albany (New York, USA)

ICTP Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Multiple Equilibria in the Climate System

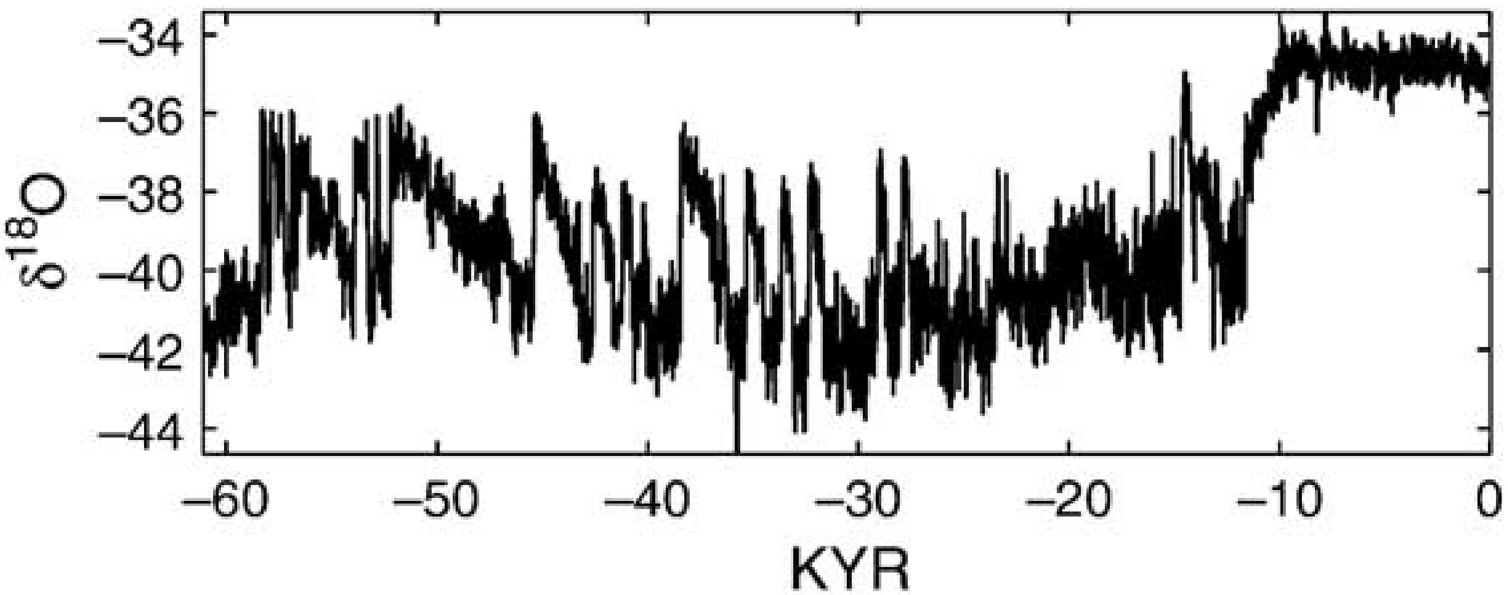
June 26, 2018

Contributions from: David Ferreira, John Marshall, Cecilia Bitz, David Battisti, Tim Cronin, Cameron Rencurrel



60 million years of Earth's climate history

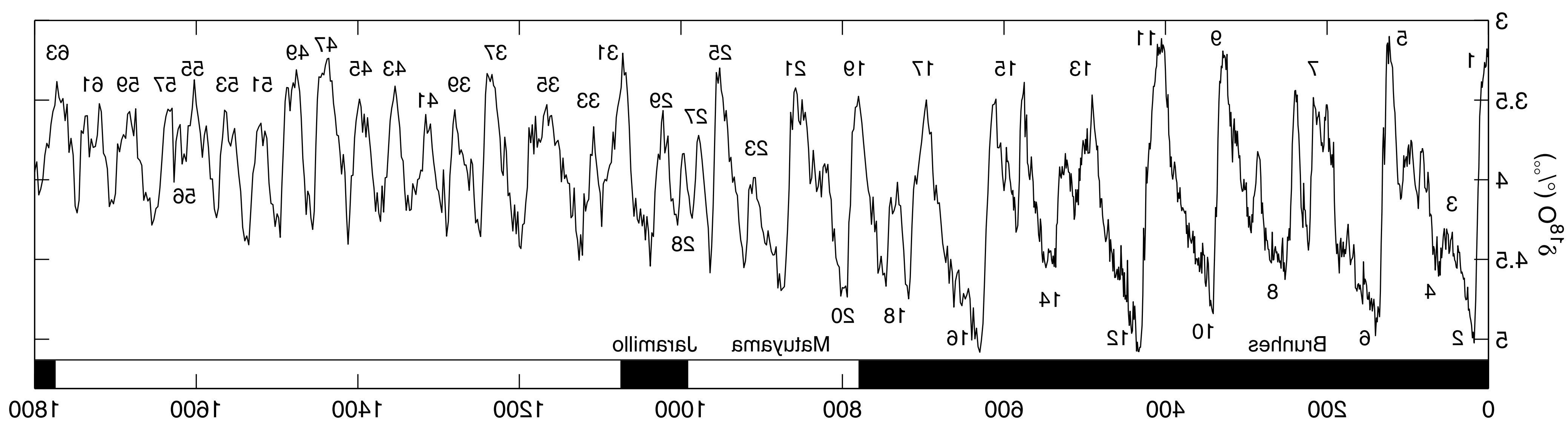
Zachos et al. (2001) *Science*



GISP2 ice core from Greenland (temperature)

Wunsch (2006)

Marine sediment records -- global ice volume



Lisiecki and Raymo, *Paleoceanog.* 2005

Glacial climates: “Sawtooth” at multiple timescales

Warming faster than cooling

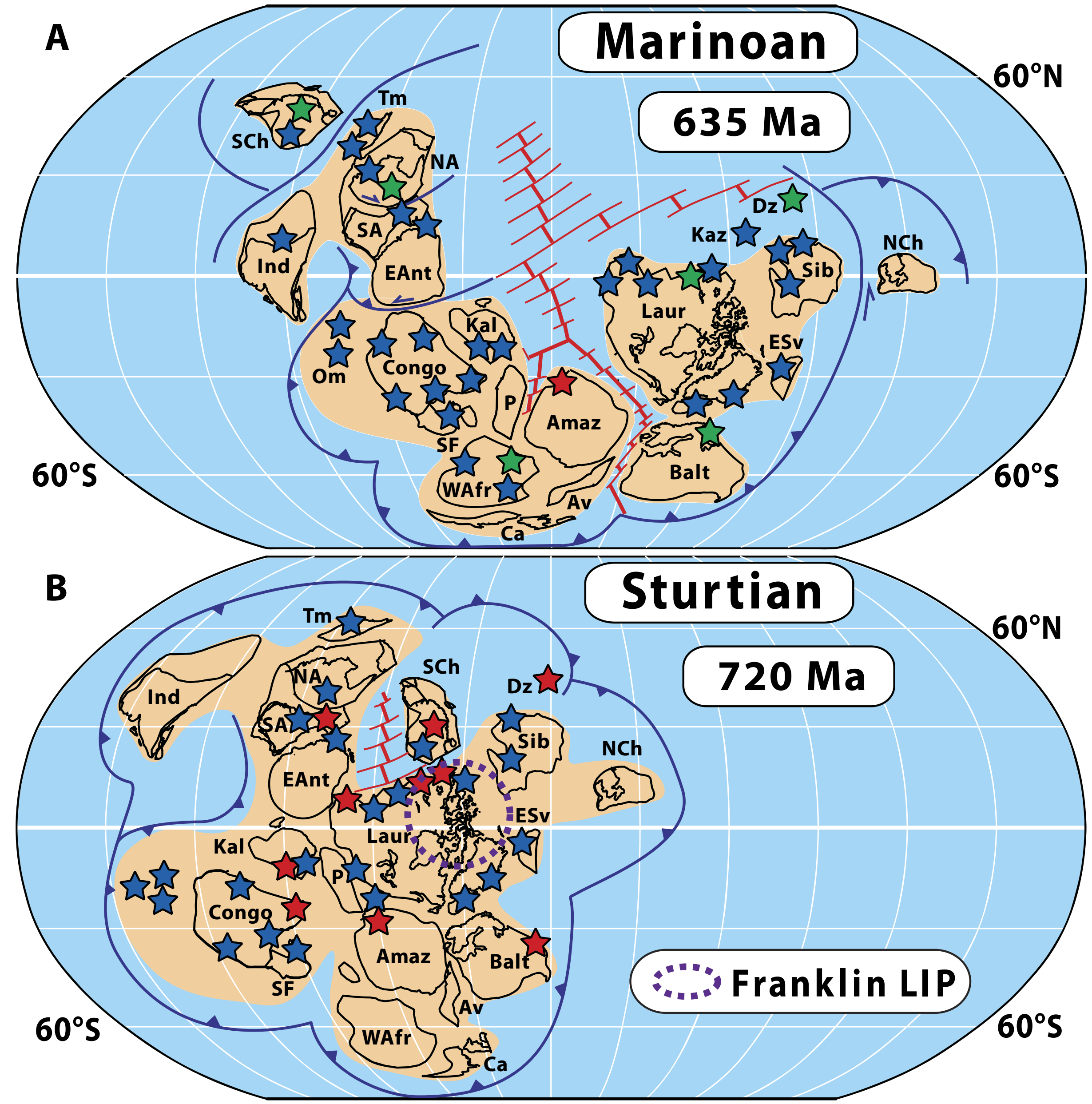


Fig. 5. Cryogenian paleogeography and the breakup of Rodinia. Global paleogeographic reconstructions in Mollweide projection for (**A**) Marinoan termination at 635 Ma and (**B**) Sturtian onset at 720 Ma (*34*). Red lines are oceanic spreading ridge-transform systems, and dark blue lines with barbs are inferred subduction zones. Stars are glacial-periglacial formations (Fig. 4), red stars are formations with

Hoffman et al., *Science Advances* 2017

Snowball Earth

Late Neoproterozoic,
circa 700 Ma

Is the climate unique?

- Big climate changes of the past:
  - large changes in **global mean temperature**, and **equator-to-pole gradient**
  - fraction of surface covered by **ice** has varied between **0%** and **100%**

- Two fundamental questions about our planet:
  - **What sets the equilibrium surface temperature?**
  - **Is the climate uniquely determined by its boundary conditions:** geography, CO_2 levels, etc? Or are multiple equilibria possible?
    - Does a large climate change necessarily imply a large change in external forcing?
    - Is climate modeling an initial value problem?

Outline

1. Ice-Albedo feedback and multiple equilibria in simple models (without the ocean!)

2. What's special about the ocean? Why do we need to model it? What's wrong with the simplest picture?

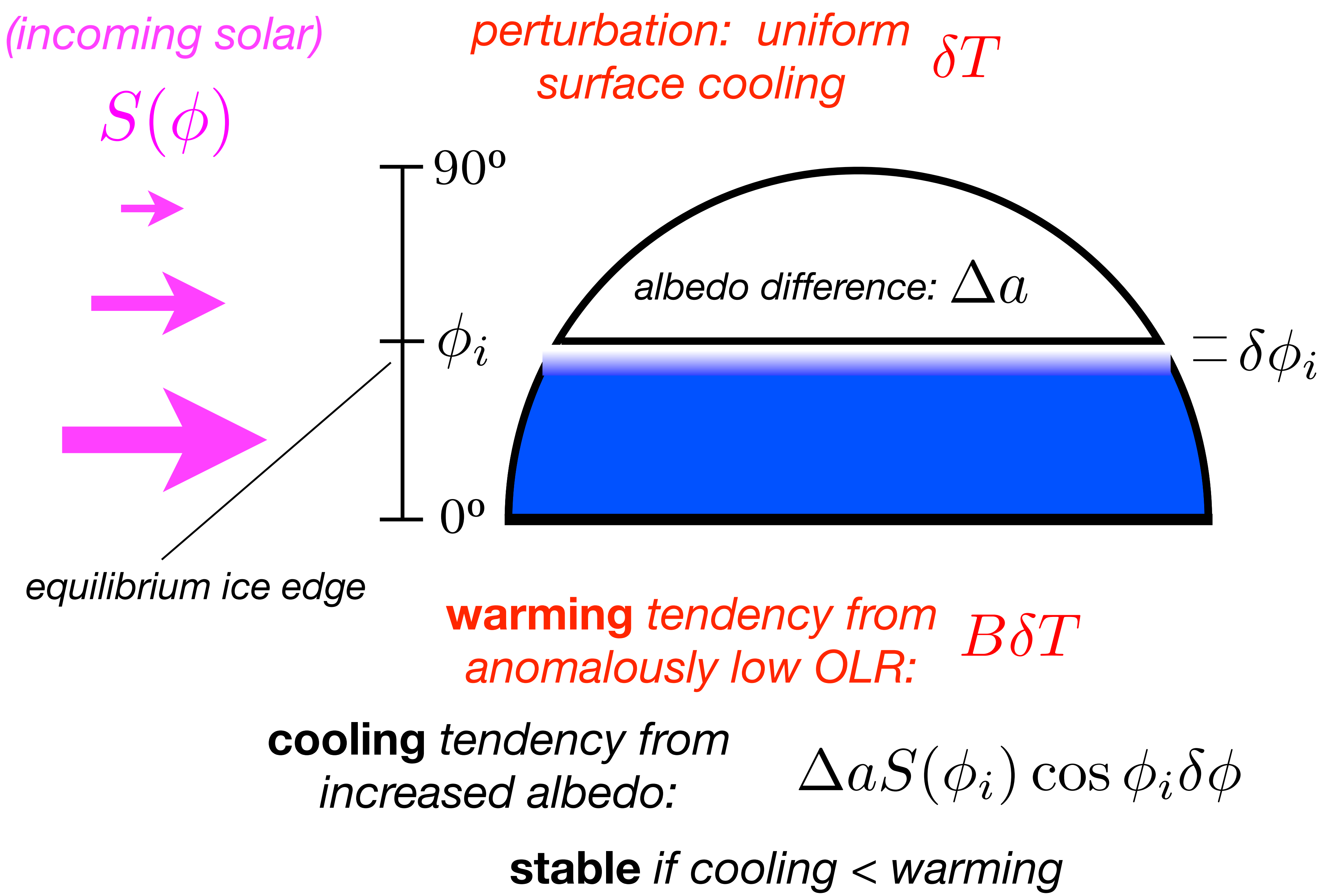
3. Multiple equilibria in a hierarchy of ice-ocean-atmosphere models

4. Climatic impact of ocean heat transport in ice-free worlds

To have multiple equilibria, need a non-linear system with competing positive and negative feedbacks

The Earth has these.

Classic example: ice-albedo feedback and the Snowball Earth instability

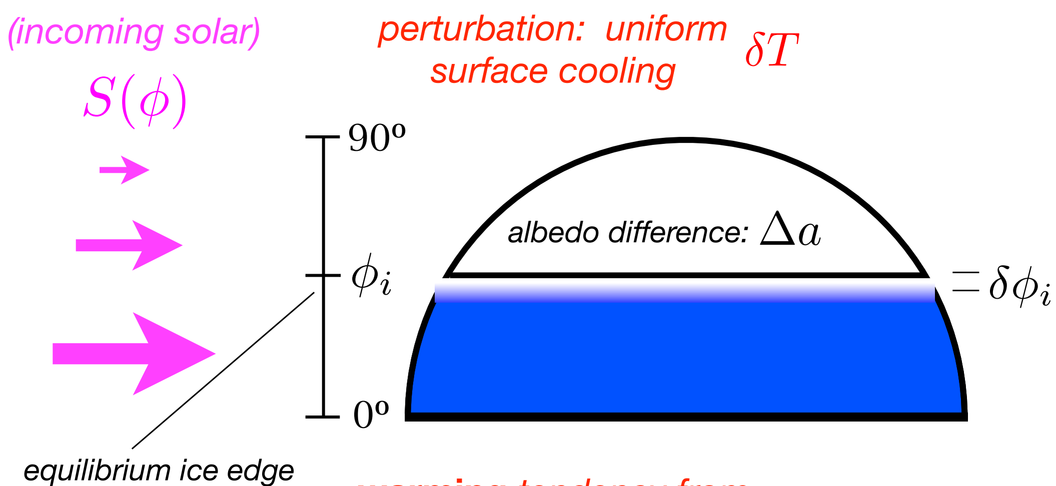


Large ice cap instability

A geometrical argument

Large ice cap instability

A geometrical argument



warming *tendency from anomalously low OLR:* $B\delta T$

cooling *tendency from increased albedo:* $\Delta a S(\phi_i) \cos\phi_i \delta\phi$

stable *if cooling < warming*

for small perturbations:

$$\delta T = -\frac{dT}{d\phi}\bigg|_{\phi_i} \delta\phi$$

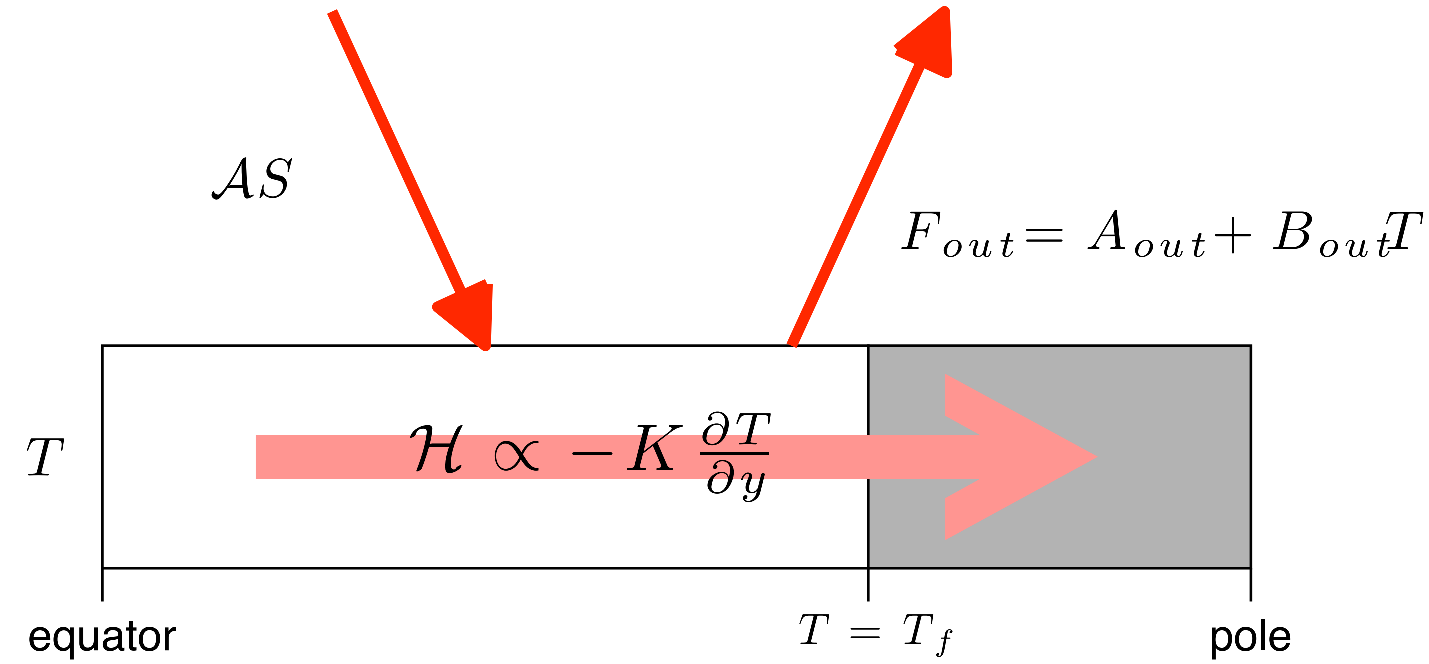
ice edge is ***stable*** *if*

$$\frac{\Delta a S(\phi_i)\cos\phi_i}{B} < -\frac{dT}{d\phi}\bigg|_{\phi_i}$$

Large at equator

Large in mid-lats, ~zero at equator

Ice edge must become unstable equatorward of some critical latitude



Simple Energy Balance Model

$$C\frac{\partial T}{\partial t} = (1-\alpha)S - [A + BT] + K\nabla^2 T$$

Seasonal heat storage

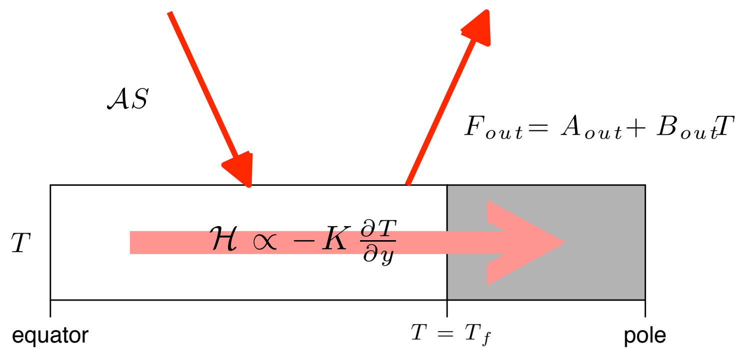
Absorbed solar radiation

Outgoing longwave radiation

Heat transport convergence

The classic Energy Balance Model

Local balance between incoming solar, outgoing longwave, and convergence of poleward heat transport.



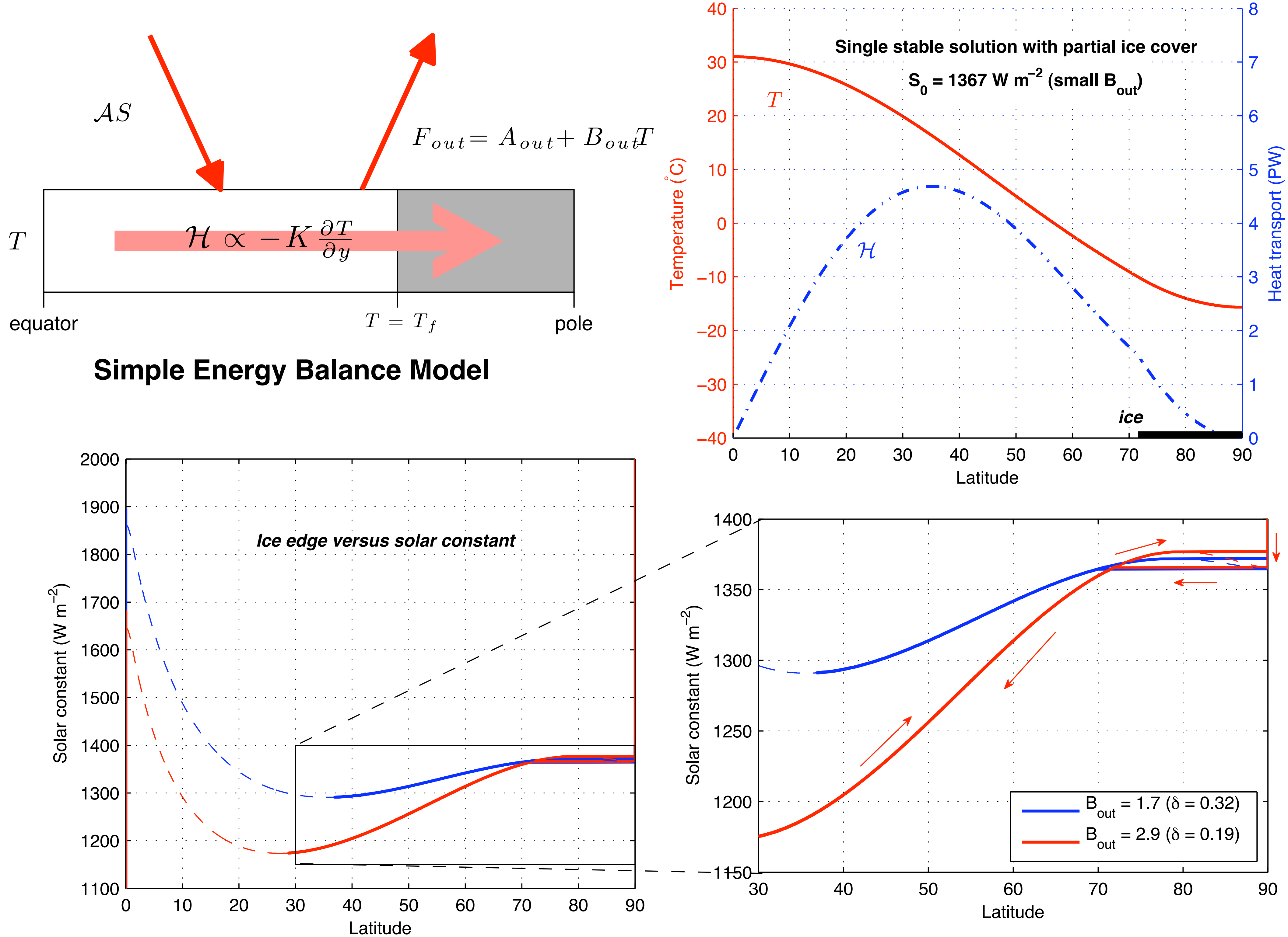
Simple Energy Balance Model

The ice line albedo parameterization

$$a[T(x,t)] = a_{\lrcorner} = \begin{cases} a_0, & T(x,t) > T_0 \\ a_1, & T(x,t) < T_0 \end{cases}$$

The model becomes nonlinear (but still analytically tractable)

Consider the **deep-water** limit *(deep mixed layer and/or short solar year)* → use steady-state **annual mean** model



The classic Energy Balance Model

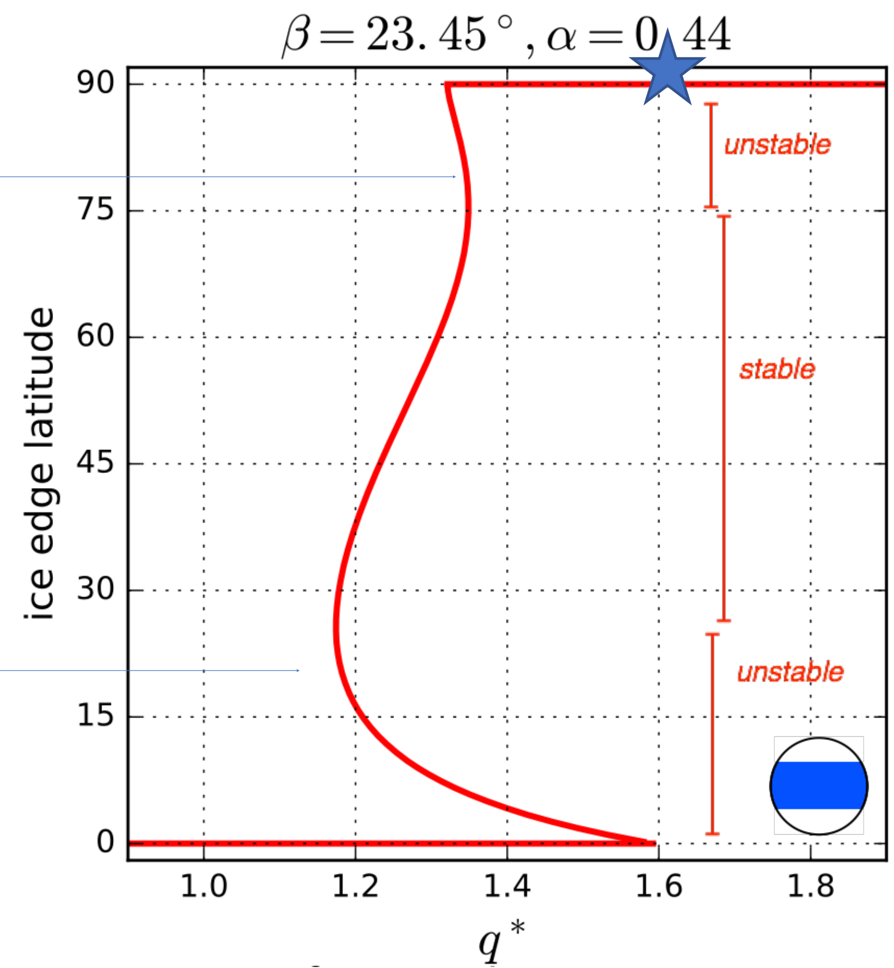
Nonlinear albedo feedback gives rise to multiple equilibria.

Stability of ice caps (1)

Graph of equilibrium ice edge position vs. radiative forcing (insolation) for one set of (quasi Earth-like) parameters
(e.g. North 1975)

Small Ice Cap Instability (SICI)

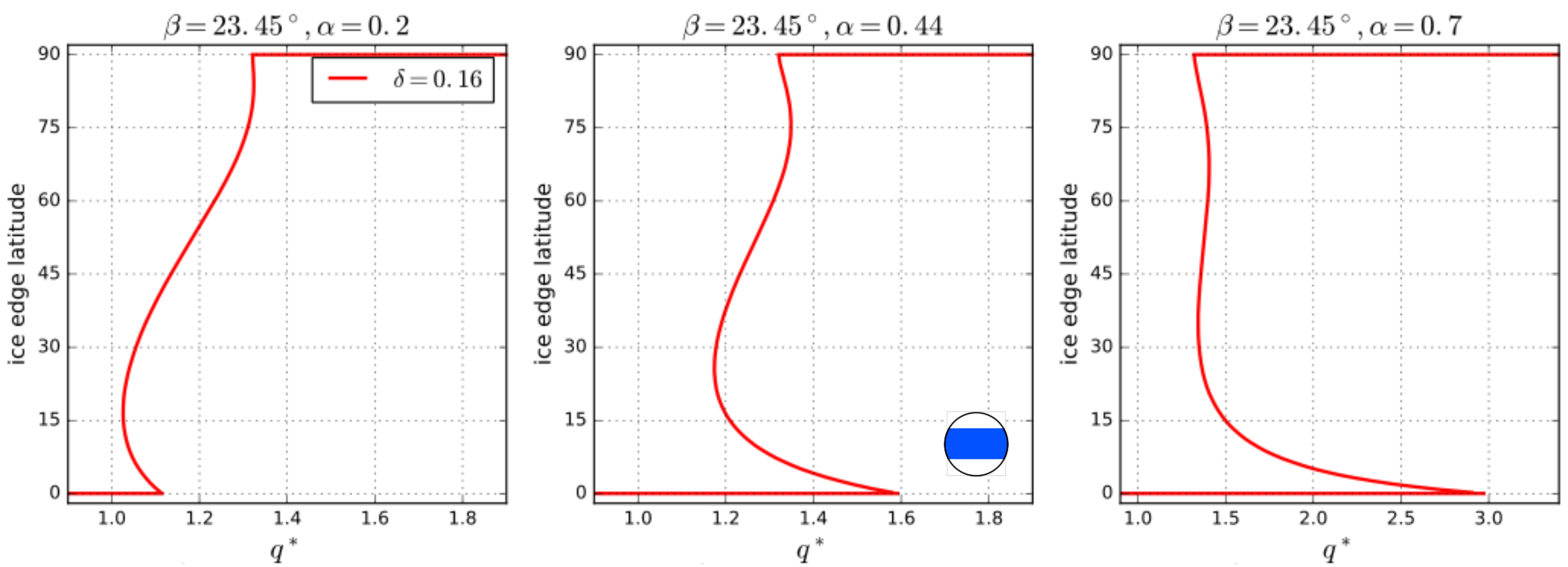
Large Ice Cap Instability (LICI)



Hysteresis loop with gradual decrease and increase in global radiative forcing

Stability of ice caps (2)

Weak albedo feedback



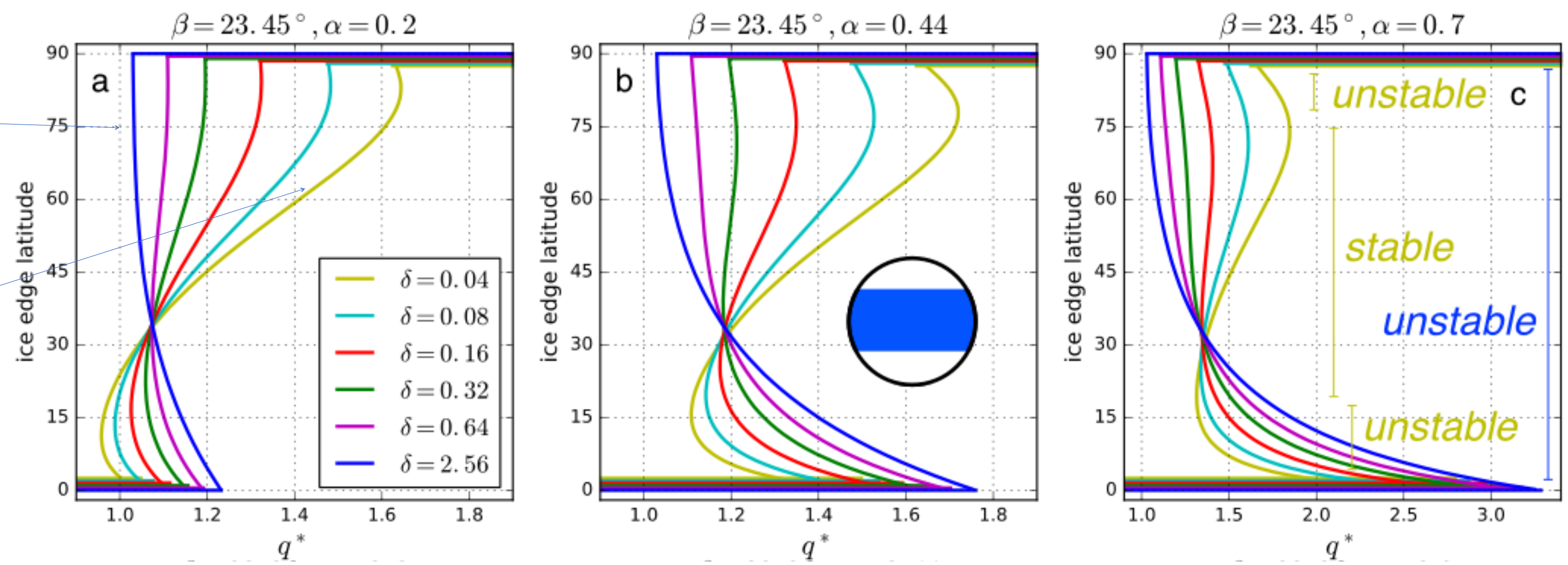
Strong albedo feedback

Rose, Cronin and Bitz (2017), *The Astrophysical Journal* 846

Stability of ice caps (3)

Efficient transport

Weak transport



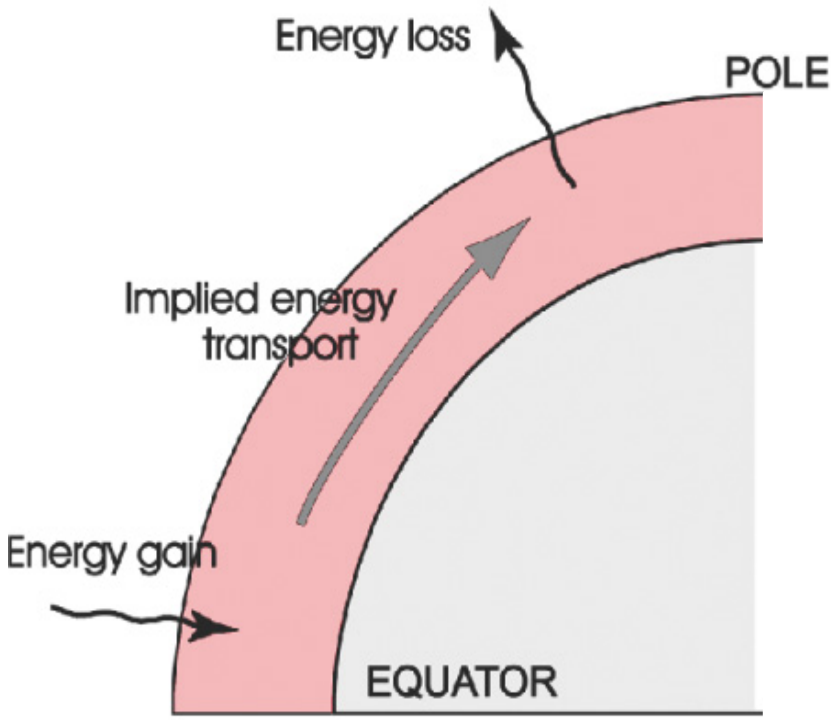
Weak albedo feedback

Strong albedo feedback

Rose, Cronin and Bitz (2017), *The Astrophysical Journal* 846

Energy Balance Models

Energy Budget

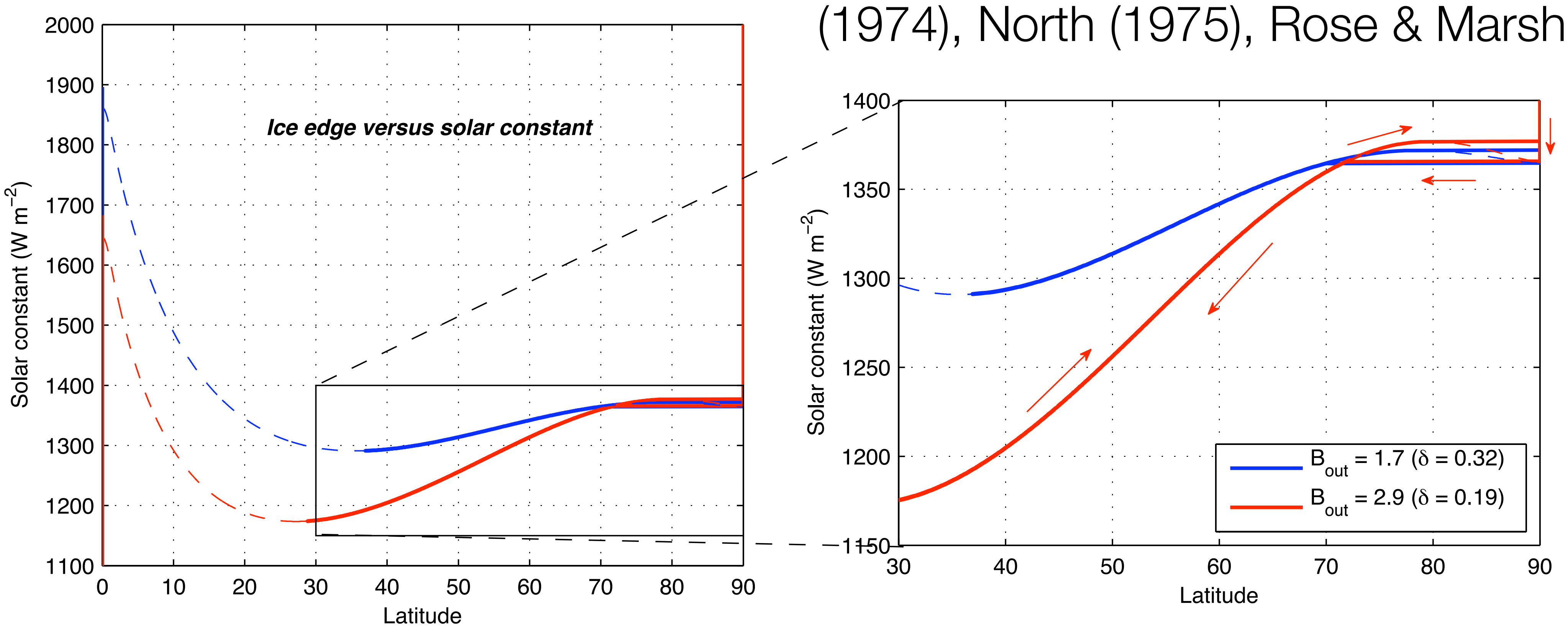


Typical solutions

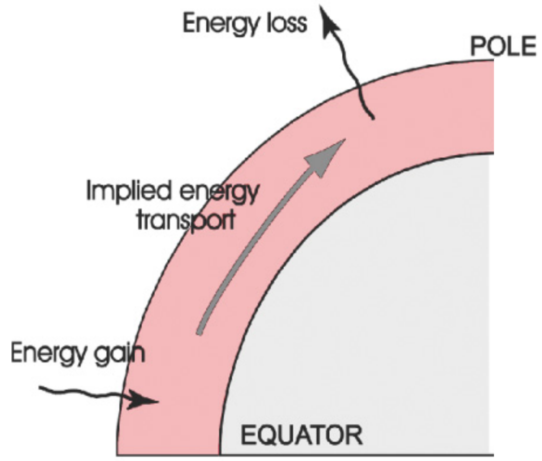
- Albedo feedback --> multiple equilibria (both stable and unstable)
- No stable ice edges equatorward of a certain subtropical latitude
- Never more than one stable solution with finite ice cover

Budyko (1969), Sellers (1969), Held & Suarez (1974), North (1975), Rose & Marshall (2009)

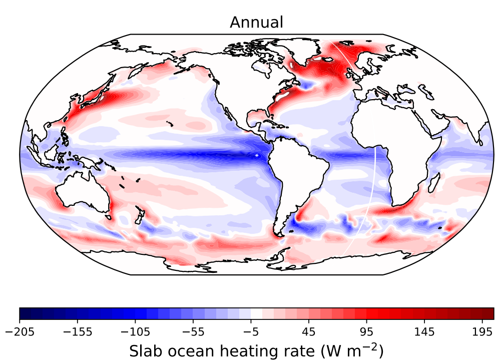
Ice edge versus solar constant

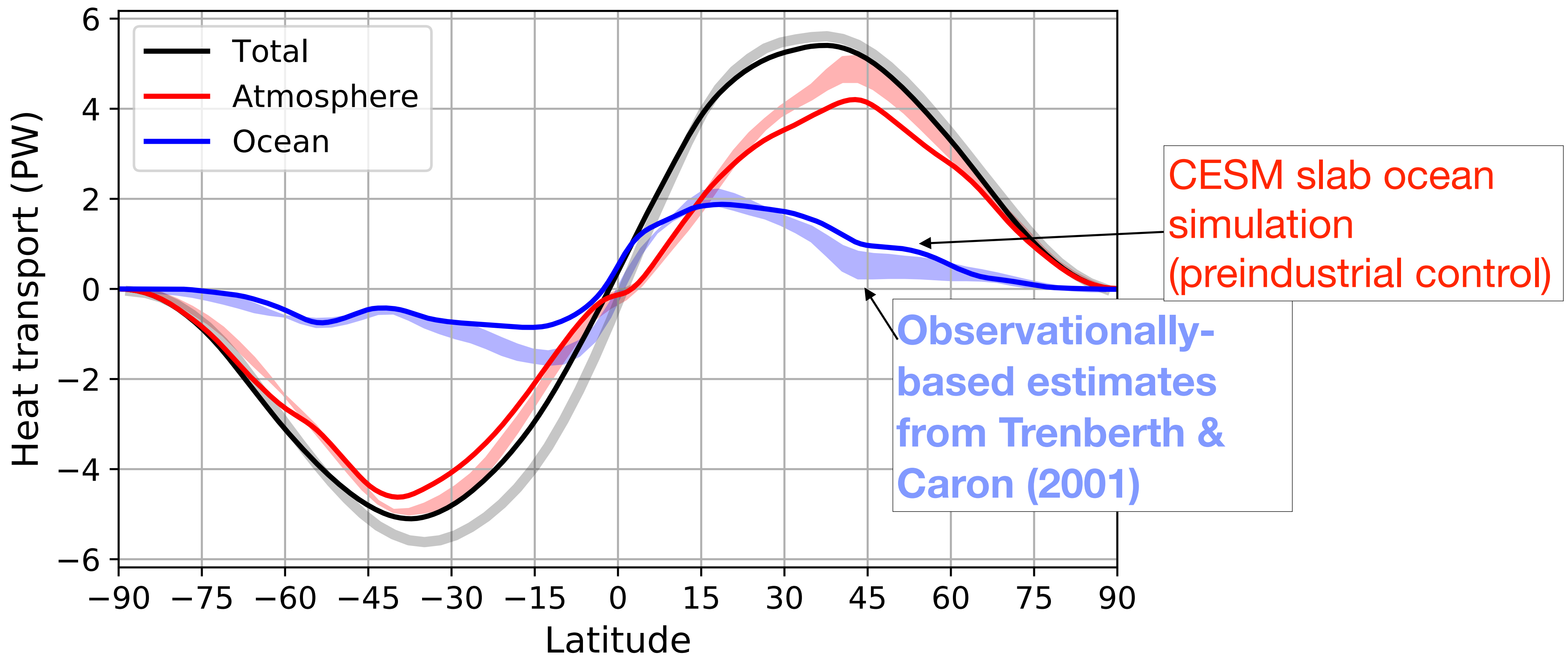


Energy Budget



Totally missing from the EBM…. The oceans!

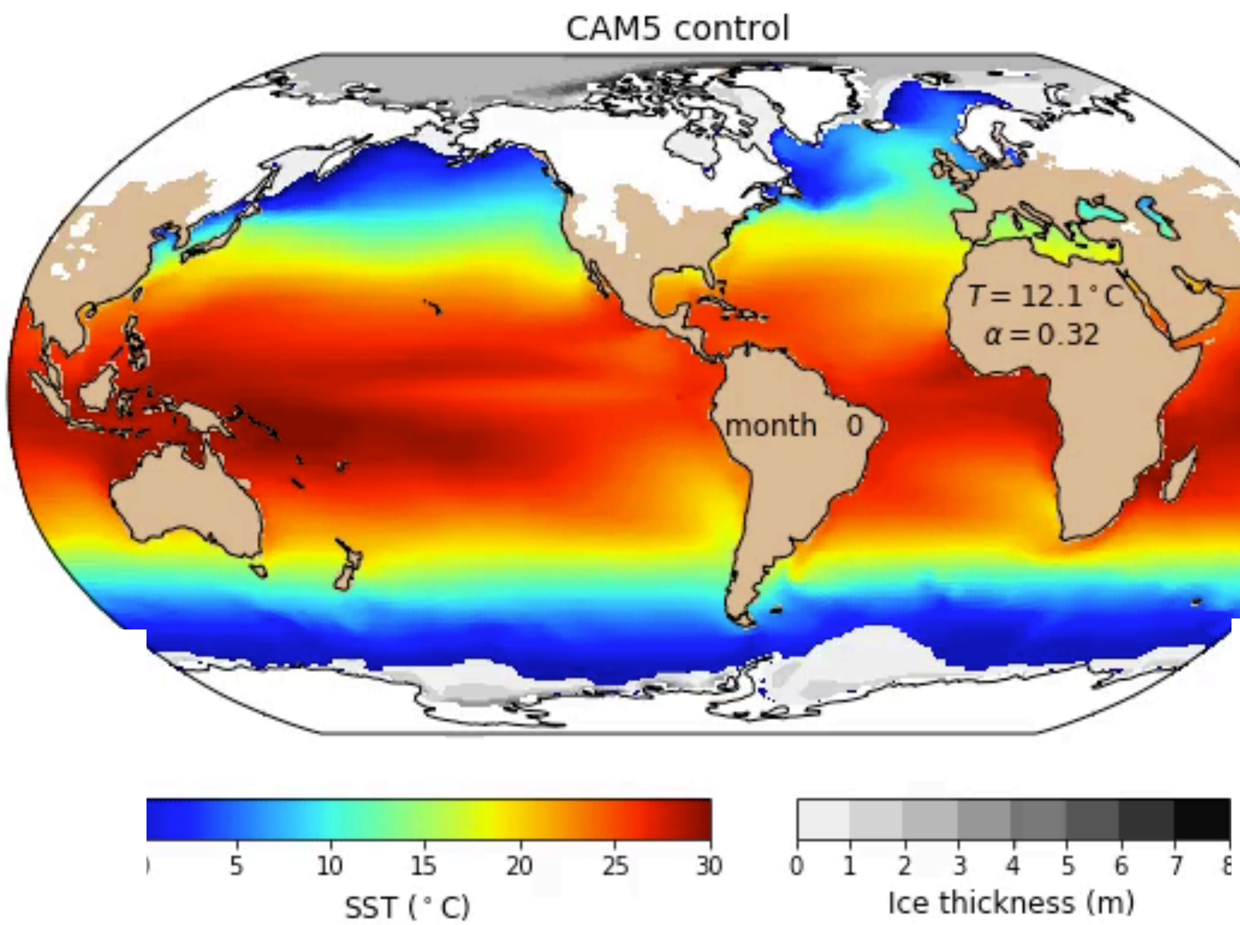


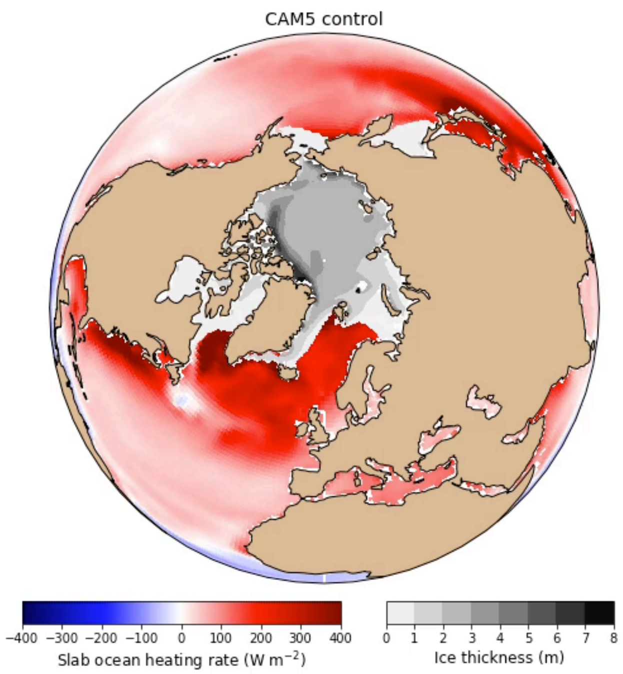


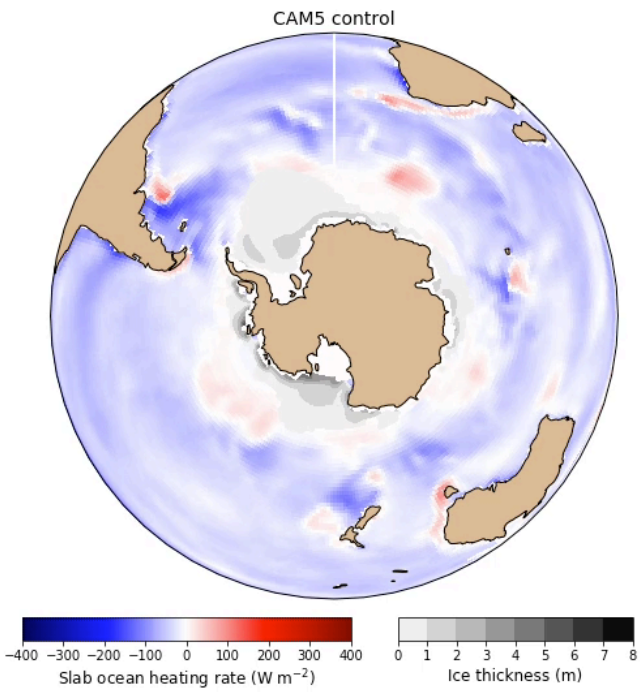
How does the energy redistribution by ocean currents affect the mean climate at Earth's surface?

Do ocean dynamics actually matter?

Ocean heating, SST, sea ice and snow in state-of-the-art climate model simulation

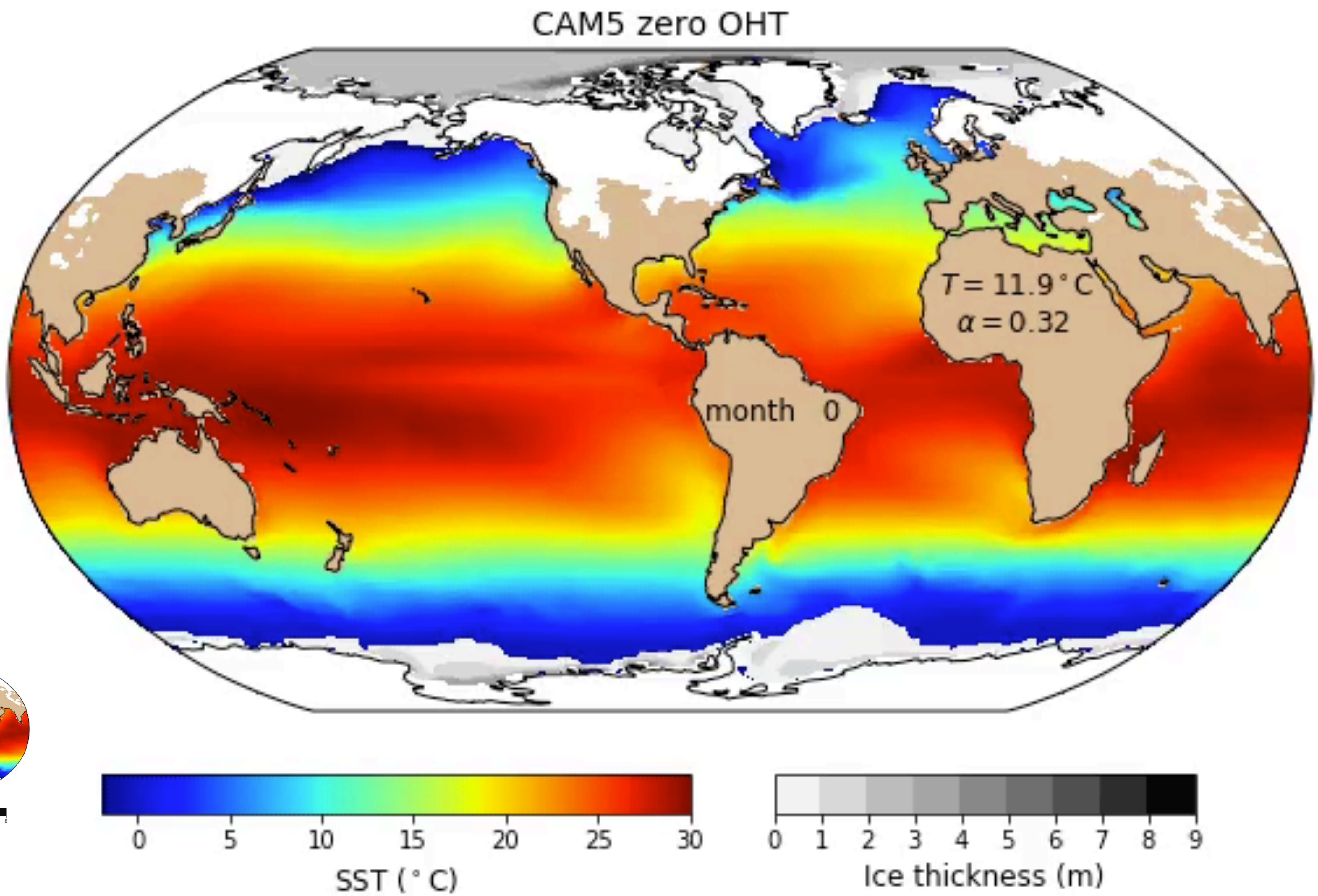


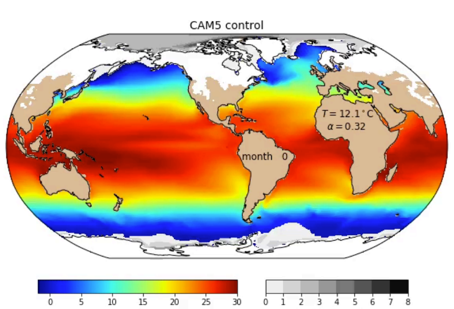




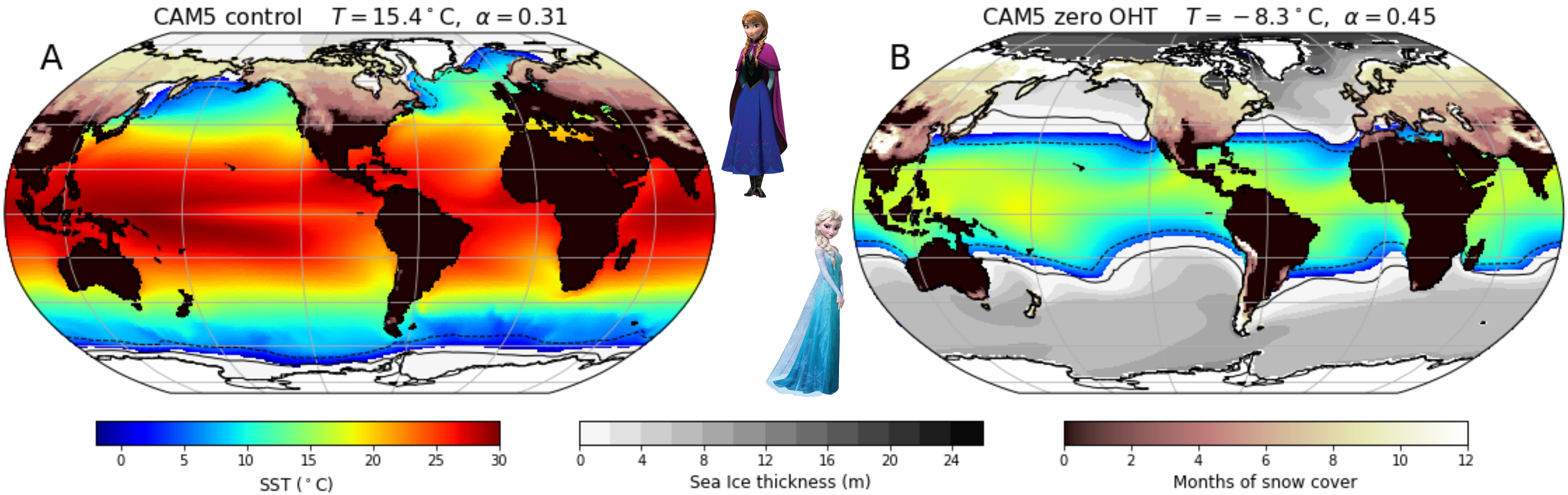
Now set the “q-flux” to zero!

treat the ocean as a 50 m deep swamp!





With and without ocean heat transport — two very different worlds!

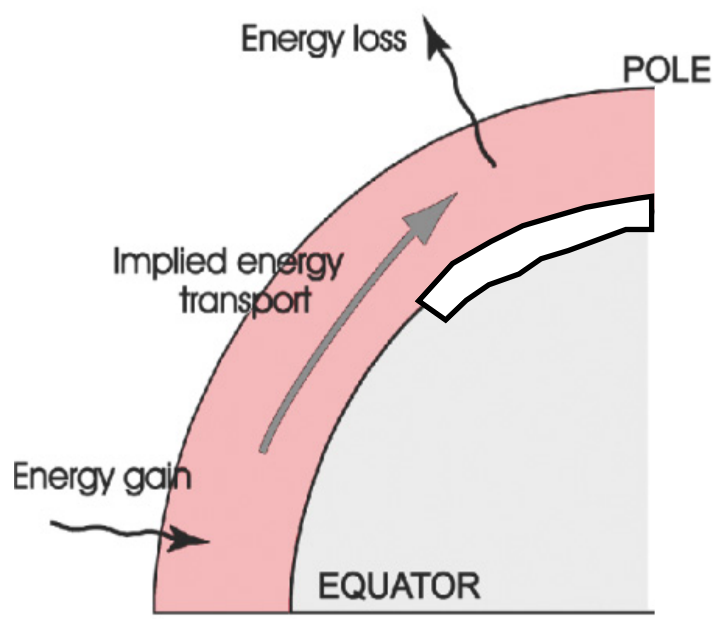


Without ocean heat transport:

- **global cooling** of 24ºC!
- More than half the planet covered by ice and snow
- Perennial snow cover on many high-latitude land surfaces would lead to glaciation and further cooling

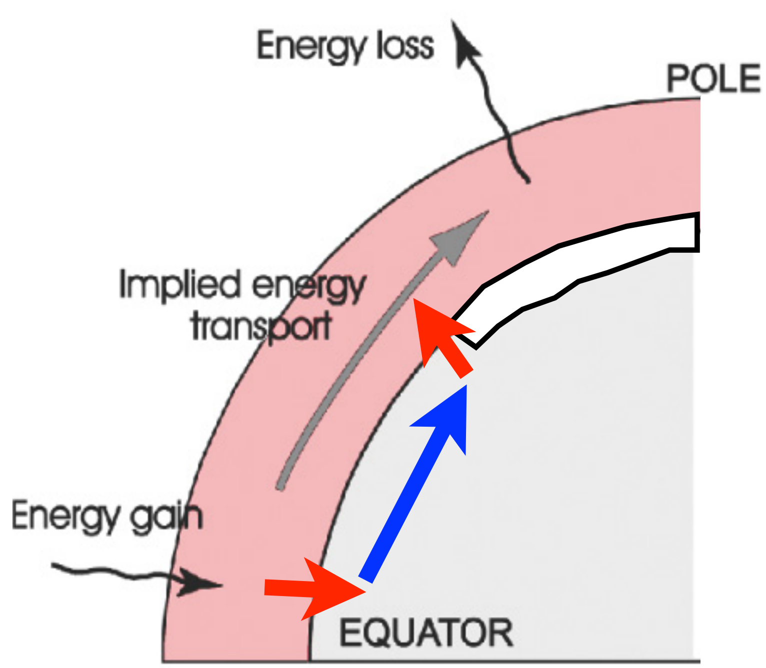
Oceans matter mostly through interactions with sea ice!

Atmospheric Heat Transport **destabilizes** the climate because heat is shared between the ice-free and ice-covered latitudes



atmospheric heat transport is continuous across the ice edge

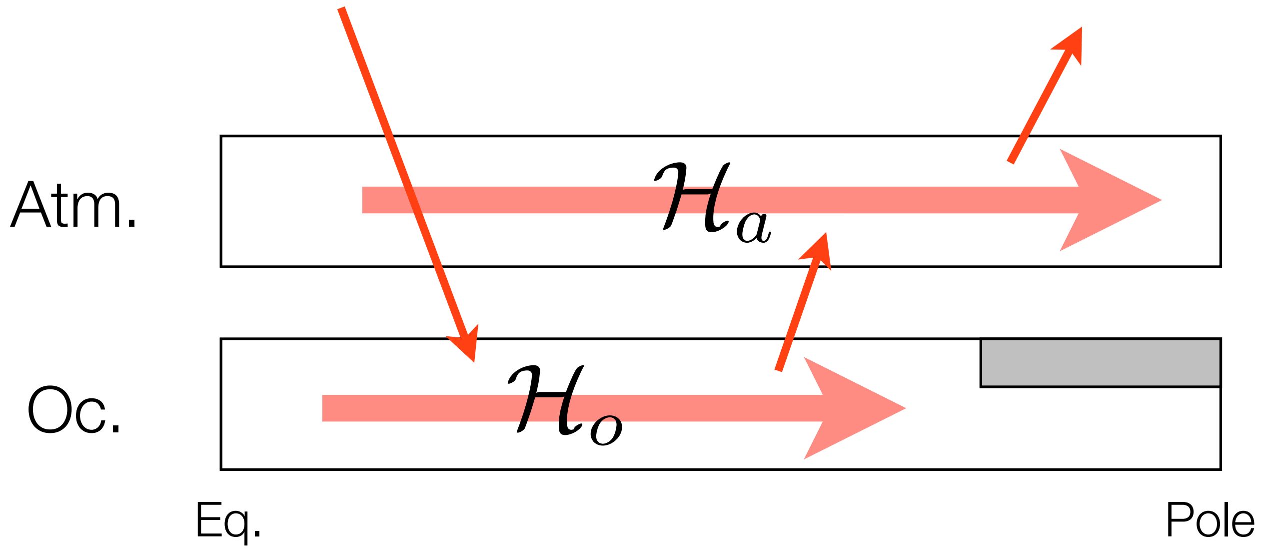
But Ocean Heat Transport tends to **stabilize** the sea ice edge



Sea ice is an insulator… ocean cannot carry heat under the ice (at equilibrium)

Meridional structure of OHT is critical

Putting the ocean in an EBM

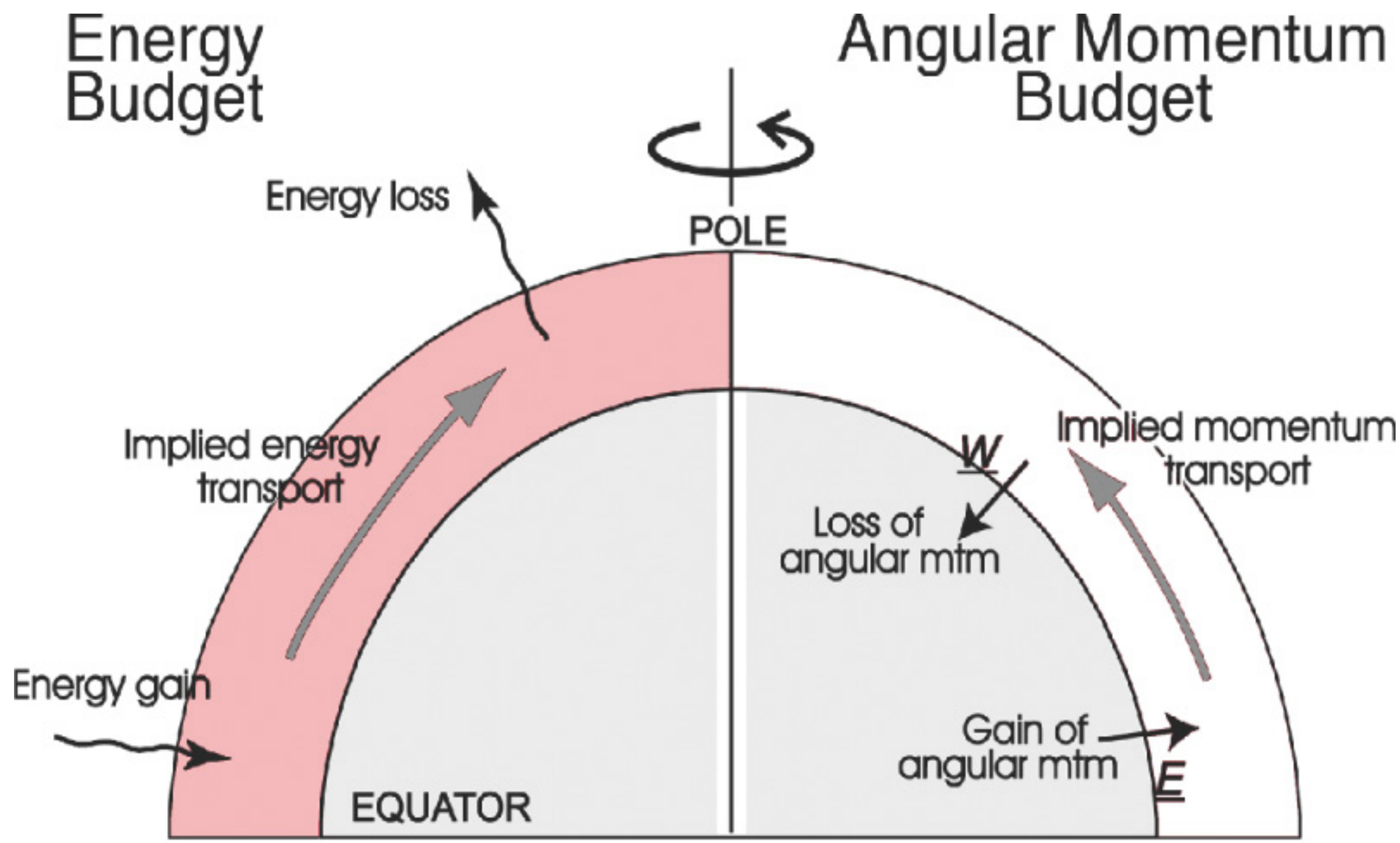


For wind-driven gyres

$$\mathcal{H}_o \approx -K_o\Big(curl(\tau)\Big)\frac{\partial T}{dy}$$

Rose & Marshall (2009) *JAS*

Energy-Momentum Balance Model



Extension of classic EBM to include: Rose & Marshall (2009) *JAS*

1. Mixing of potential vorticity subject to an angular momentum constraint (White, 1977; Marshall, 1981)
2. Representation of heat transport by wind-driven ocean circulation

Key is the 'surface wind equation'

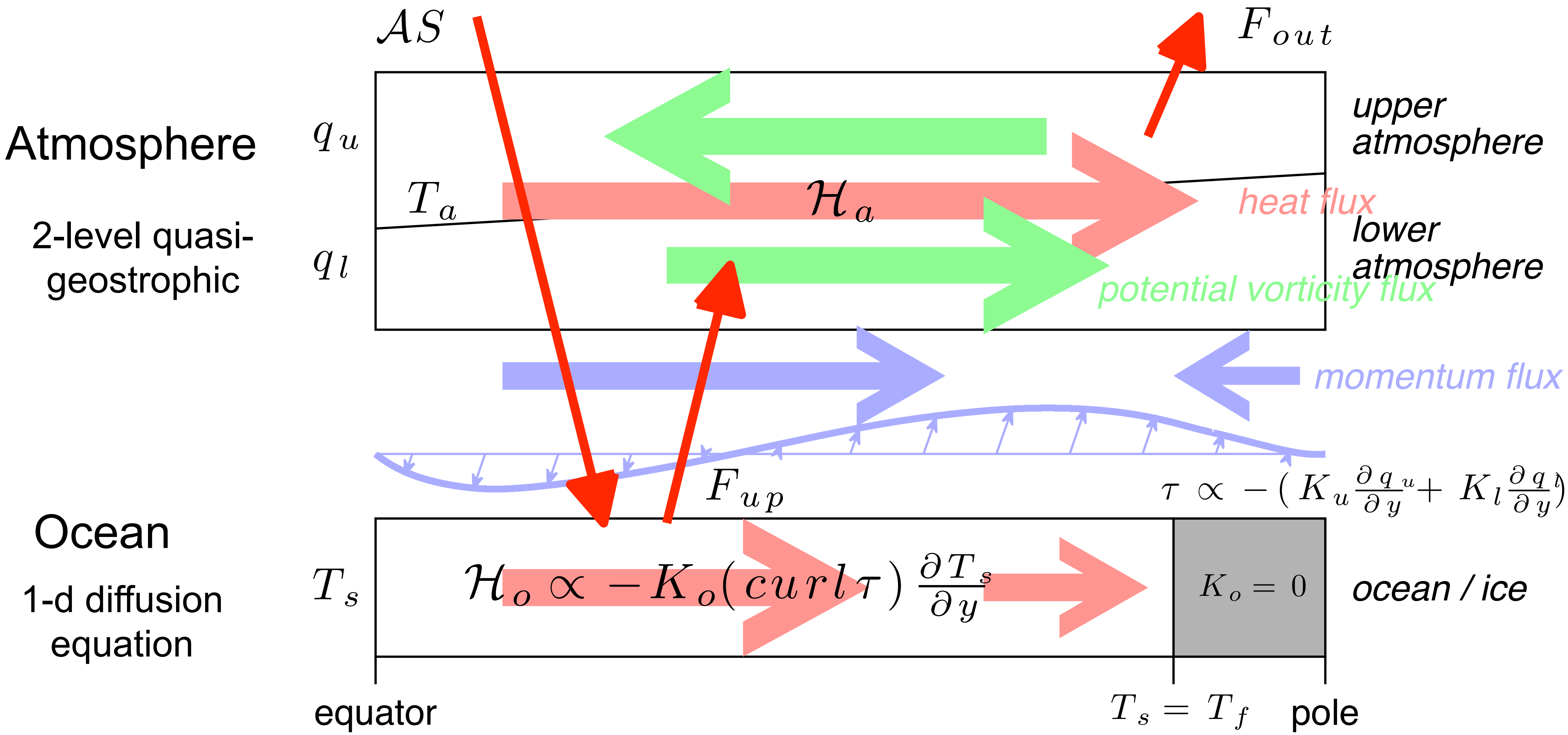
Wind stress and momentum flux

$$\tau(y) \approx -\frac{\partial}{\partial y}\int \overline{uv}dz$$

$$\approx \int \overline{vq}dz$$ quasi-geostrophic PV

Assume $$\overline{vq} \approx -K\frac{\partial q}{\partial y}$$ Green (1970)

get diffusive model for PV



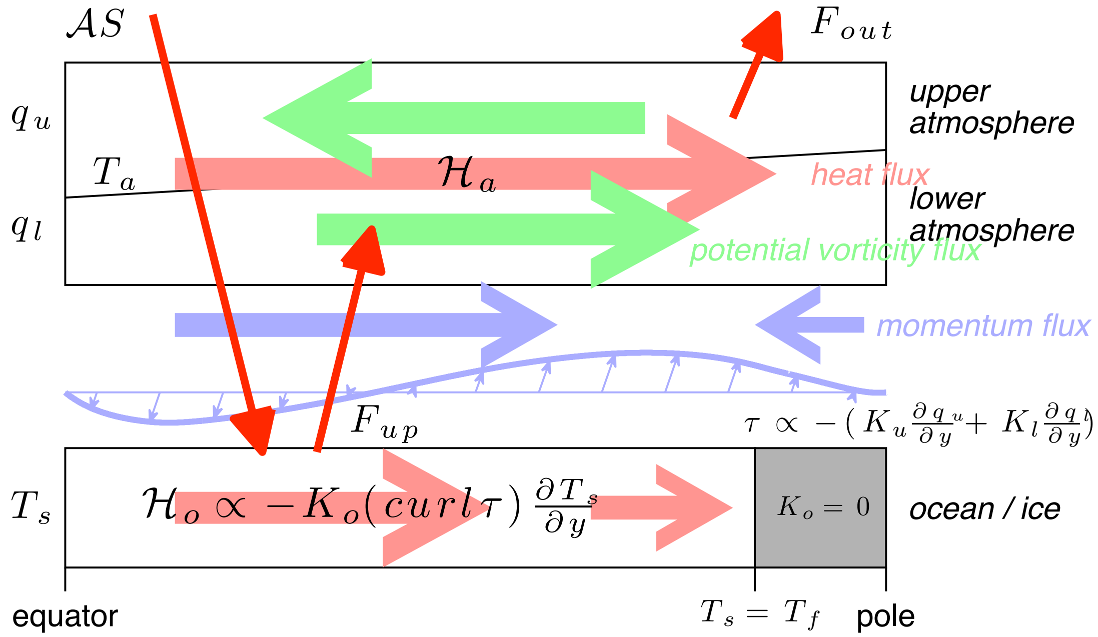
Energy – Momentum Balance Model

(interactive wind–driven gyres, insulating sea ice)

Rose & Marshall (2009) *JAS*

The Energy-Momentum Balance Model

Atmospheric heat and momentum transport represented by 2-level diffusion of QGPV.
Ocean heat transport by wind-driven gyres.



Energy – Momentum Balance Model

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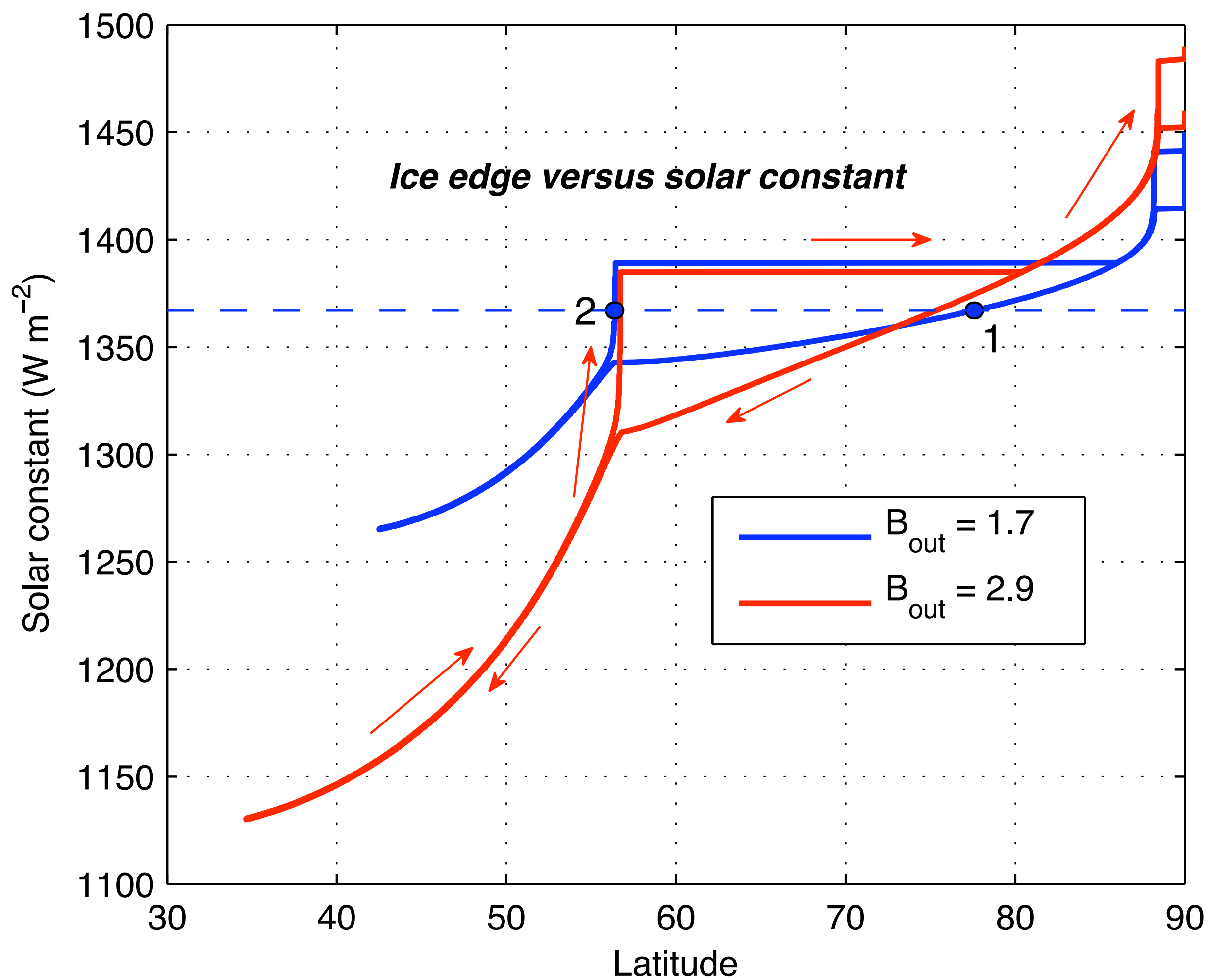
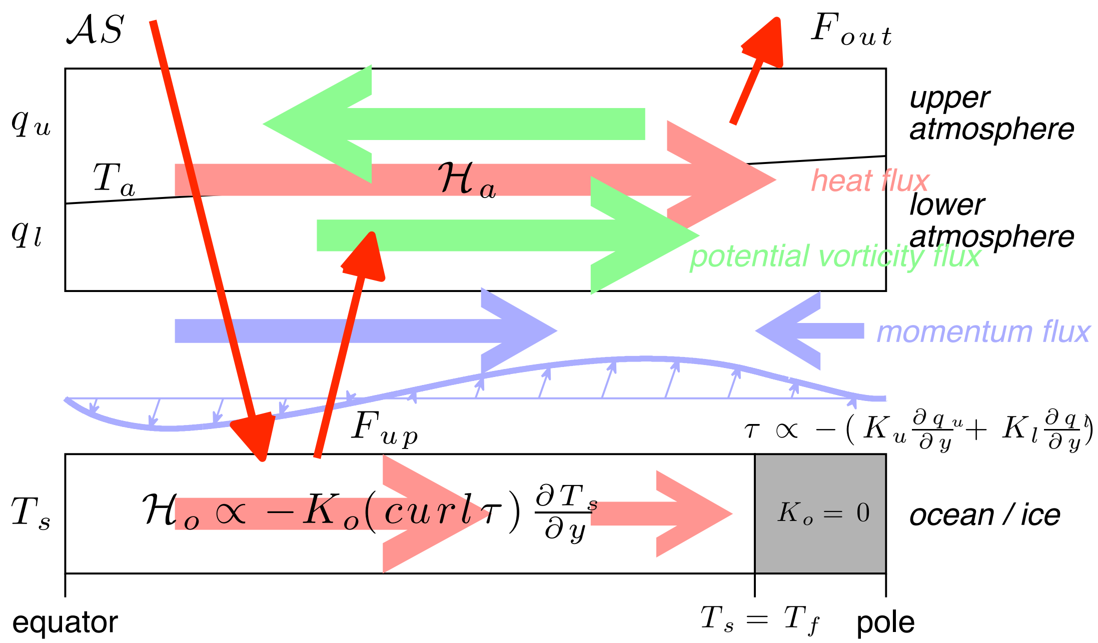


Rose & Marshall (2009) *JAS*

The Energy-Momentum Balance Model

Multiple equilibria: a stable large ice cap, not found in the simplest EBM



Energy – Momentum Balance Model

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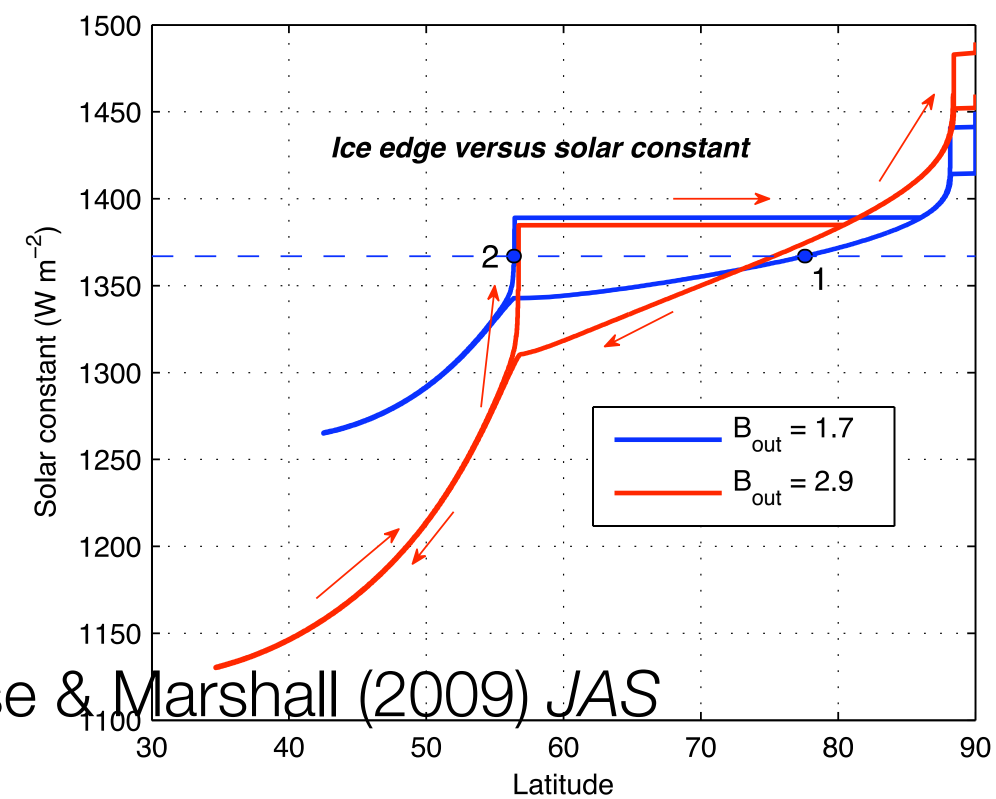
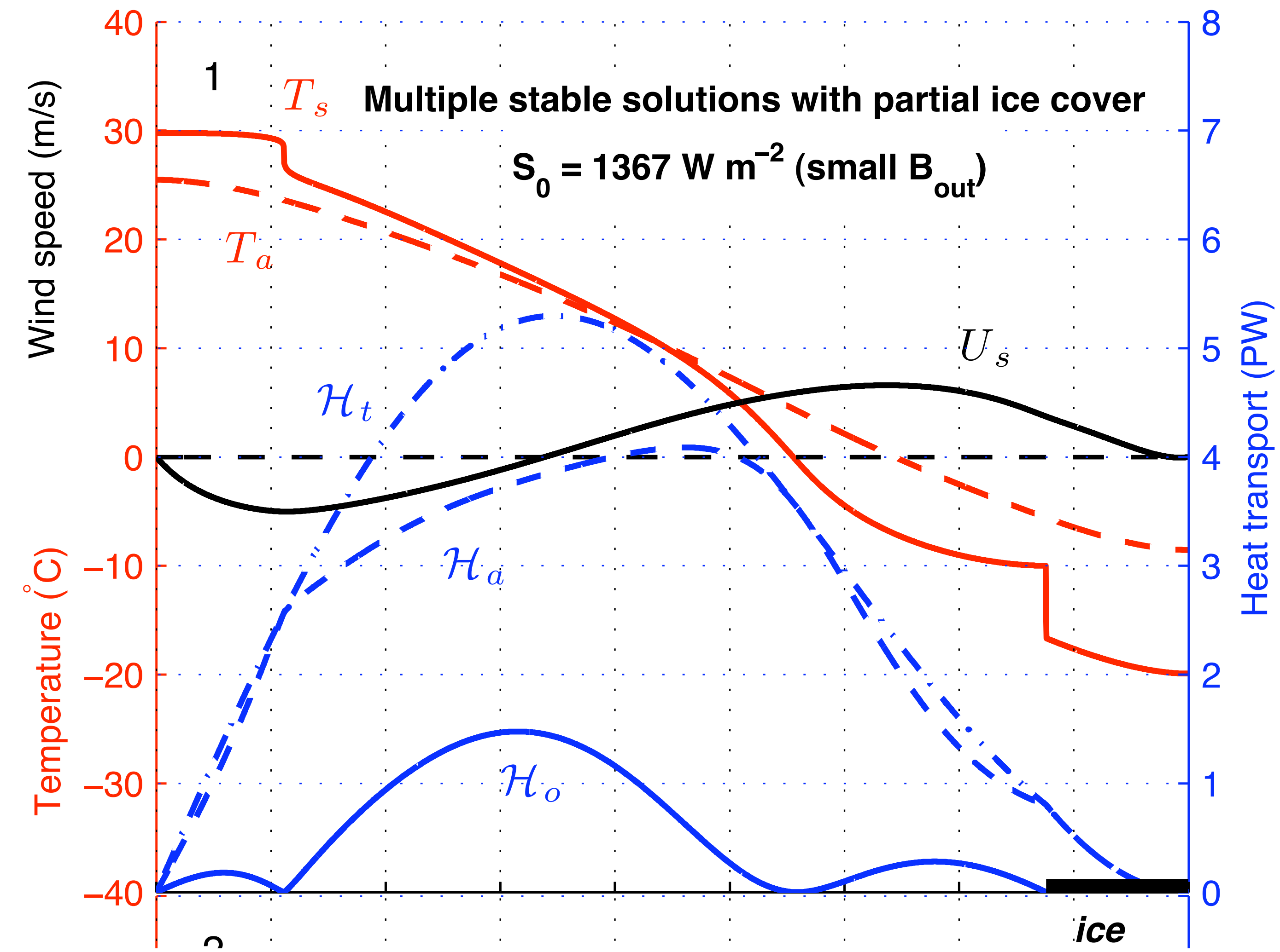


Rose & Marshall (2009) *JAS*



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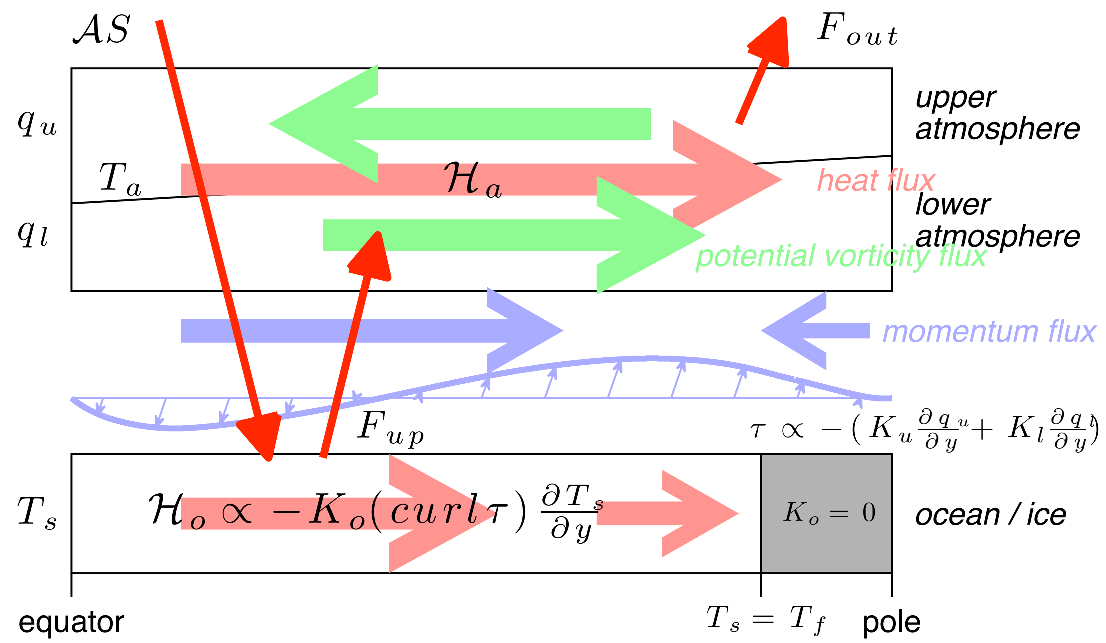

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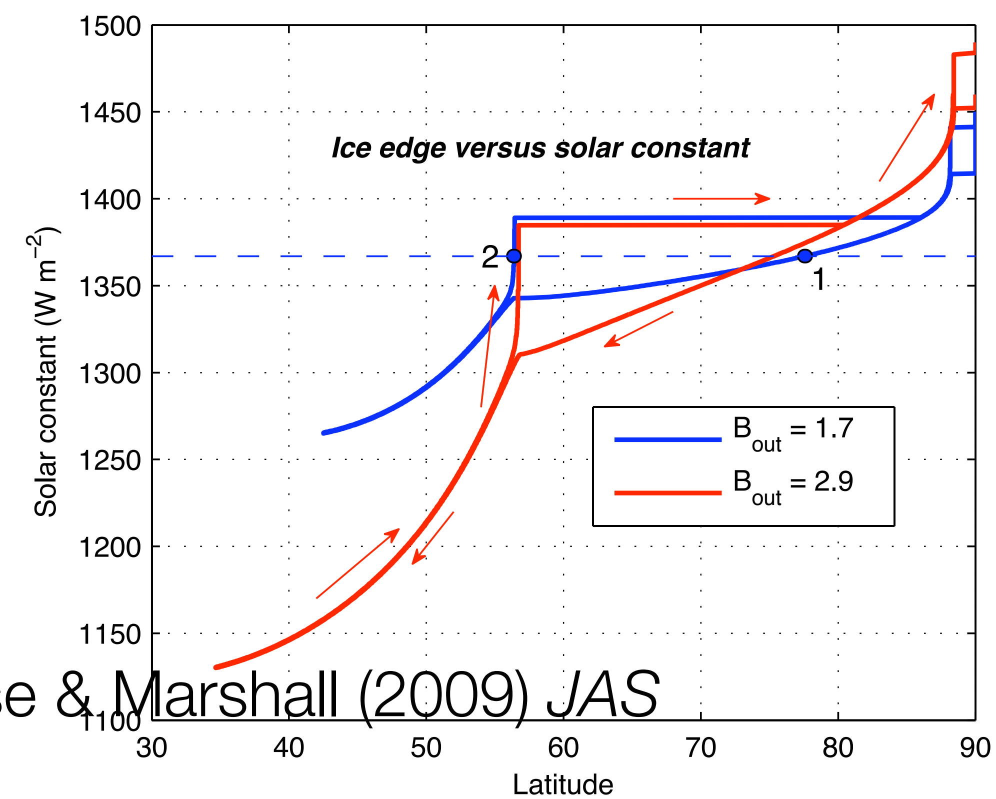
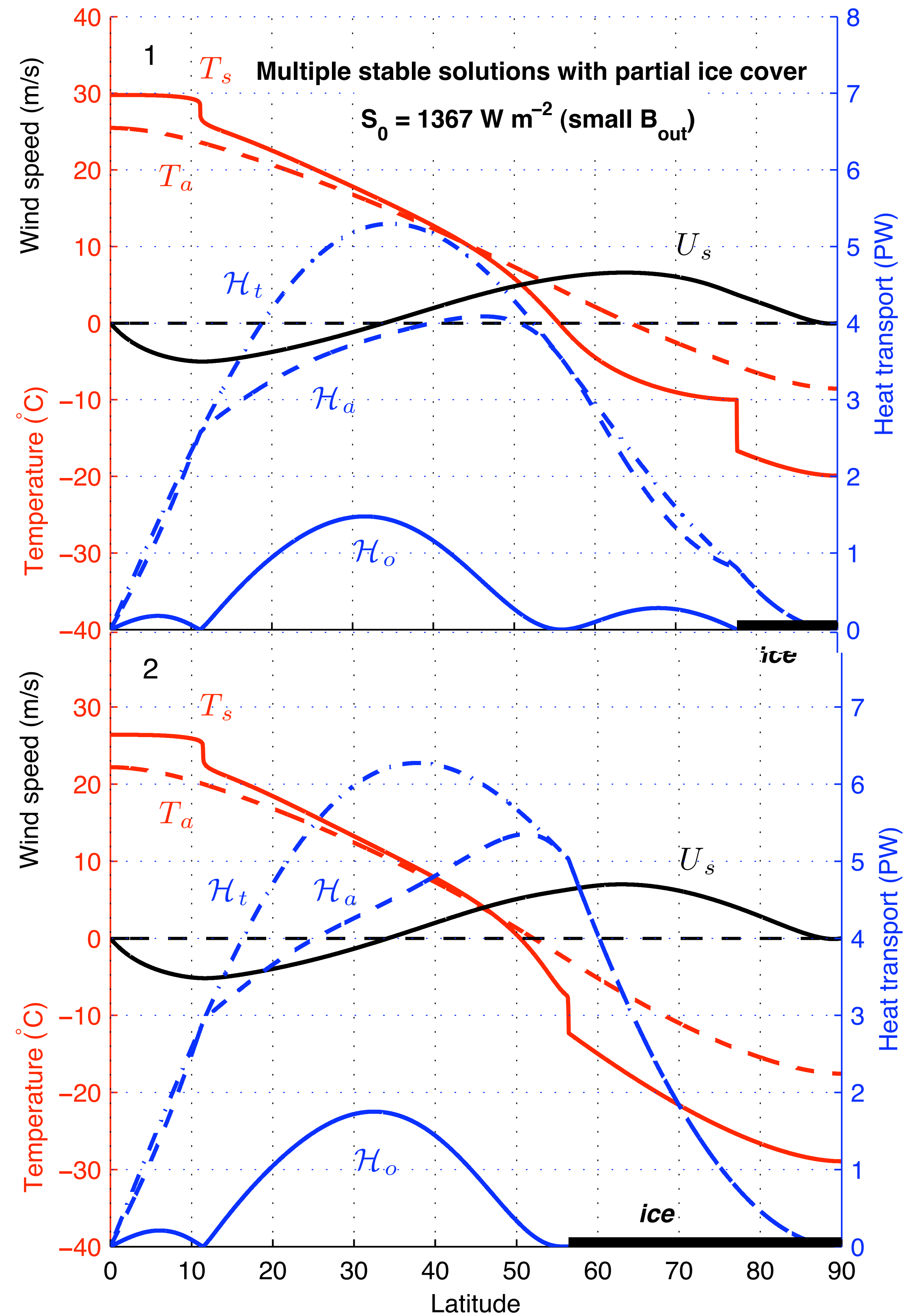


Rose & Marshall (2009) *JAS*



The Energy-Momentum Balance Model

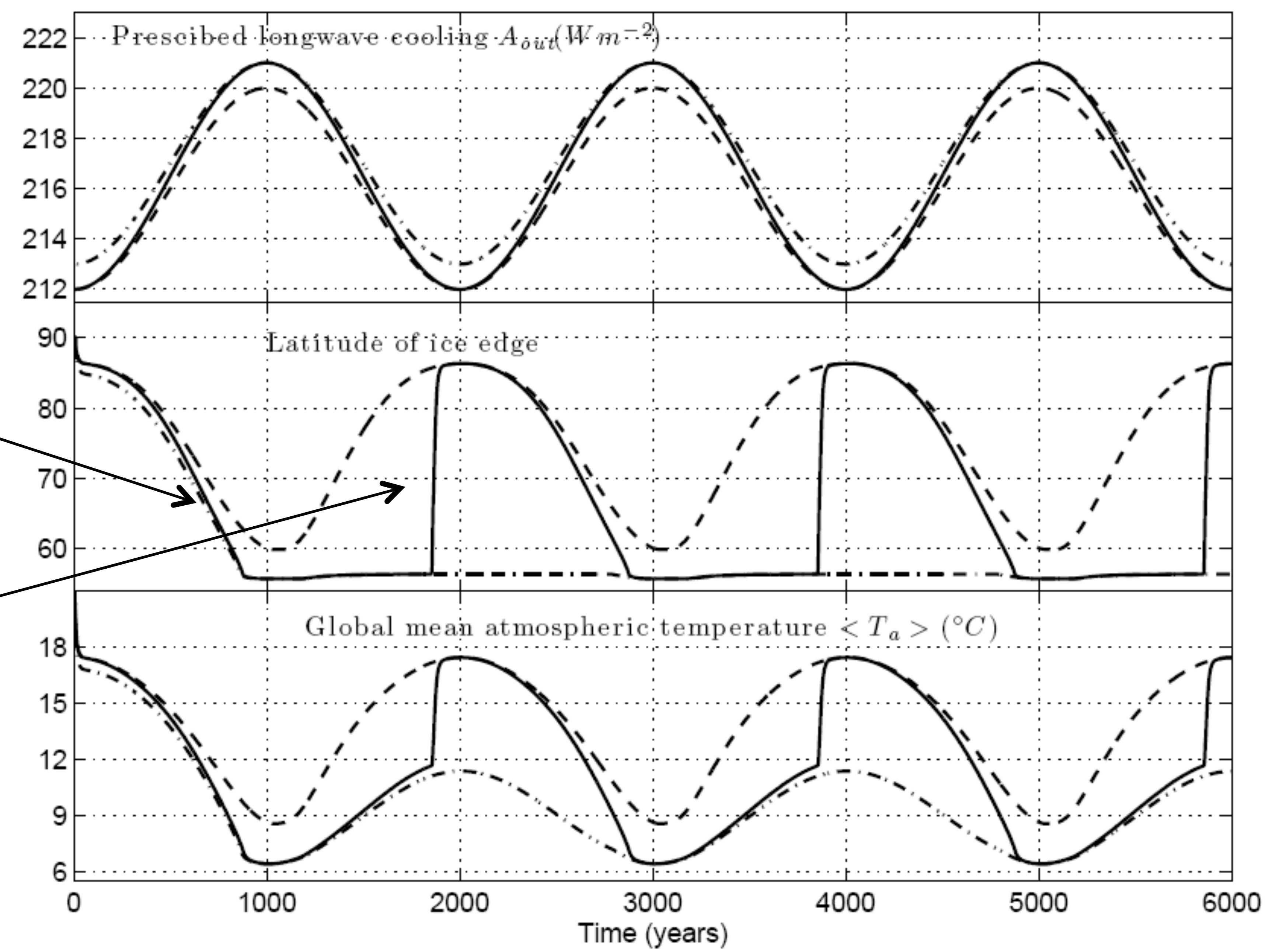
Multiple equilibria: a stable large ice cap, not found in the simplest EBM

Possible climatic implications

External forcing that raises/lowers energy budget has potential to generate asymmetrical warming/cooling

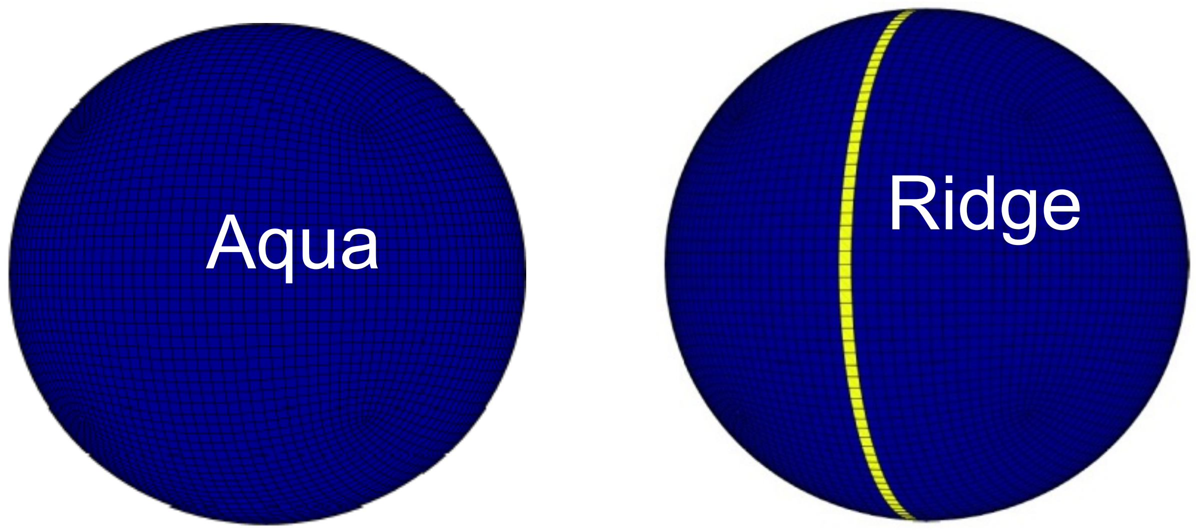
Freeze over subpolar gyre

Abrupt warming



Rose & Marshall (2009) *JAS*

What about more complex models?



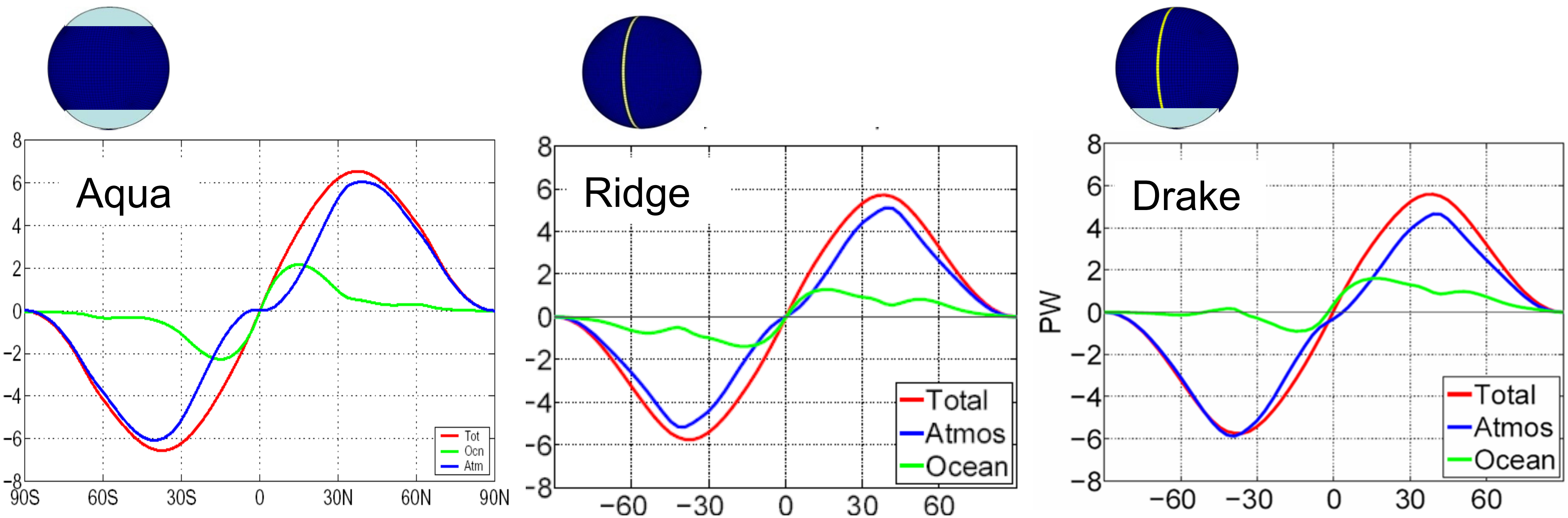
A series of calculations with a coupled **atmosphere-ocean-sea ice GCM** with highly **idealized continental boundaries** explores the elemental role of the oceans in climate

e.g. Enderton & Marshall (2009) *JAS*

Coupled MITgcm, primitive equations on the "cubed sphere": 5-level atmosphere, 15-level ocean, interactive clouds and thermodynamic sea ice

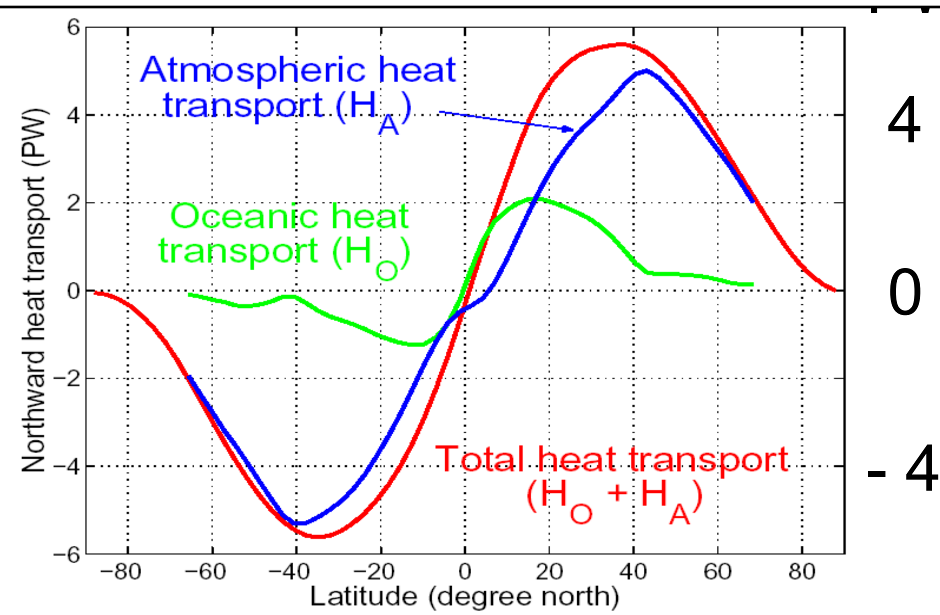
A deterministic view:

continents ---> OHT ---> sea ice extent ---> climate



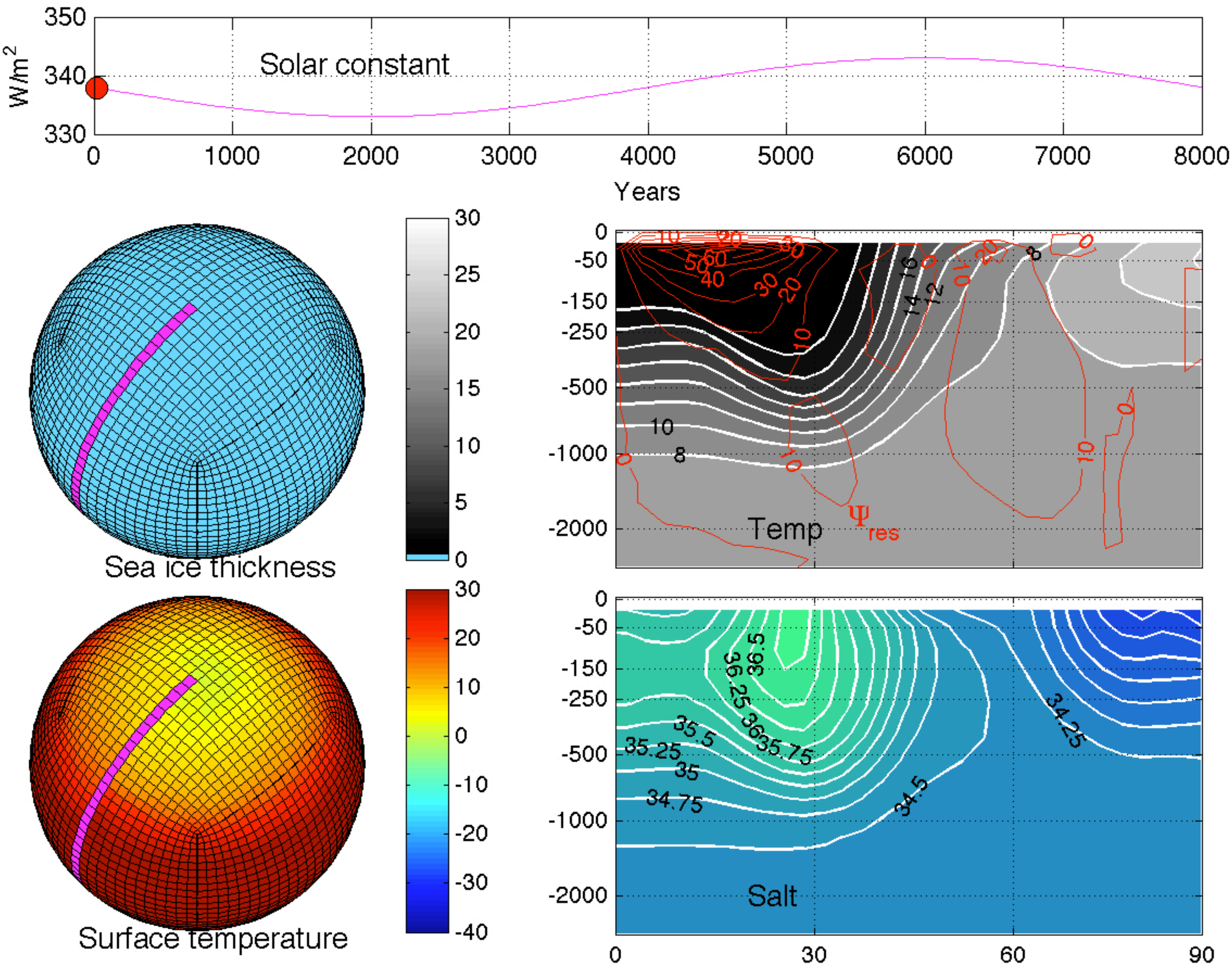
Enderton & Marshall (2009) JAS

Are these solutions unique? NO!

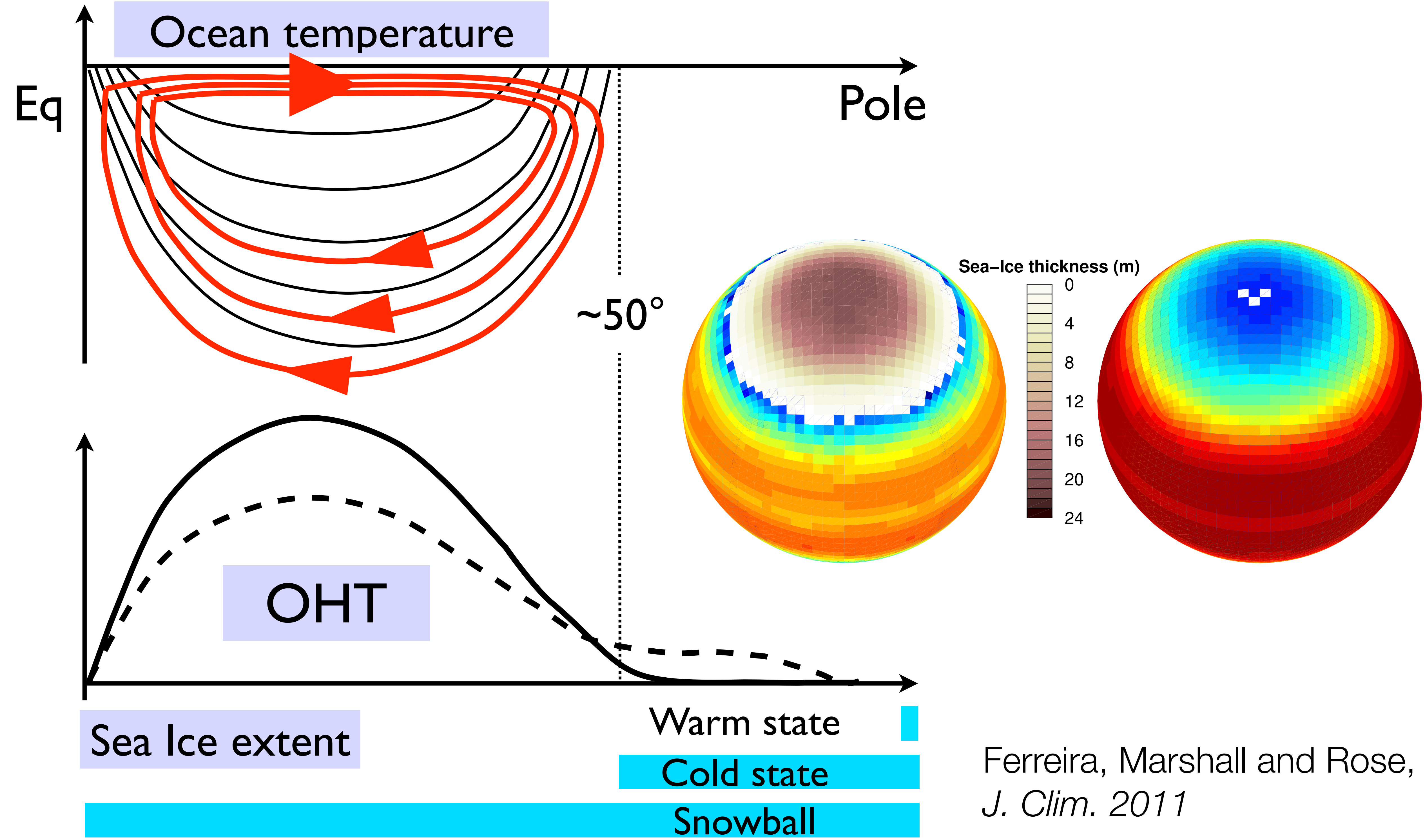


Model setup

- Coupled MITgcm at C24 resolution (cubed sphere, 24x24 points per cube face) with simplified geometry (*Aqua*, *Ridge*)
- **Atmosphere:**
  - 5 levels, primitive equations
  - Simplified moist physics based on SPEEDY (Molteni 2003)
  - No topography
- **Ocean:**
  - 15 levels, uniform 3 km depth
  - GM-Redi eddy parameterizations, vertical convective adjustment
- **Sea ice:**
  - Thermodynamic energy-conserving 3 layer model based on Winton (2000)
  - horizontal diffusion of ice thickness (a proxy for ice dynamics)
- Machine-accuracy global conservation of heat, water and salt during long simulations
- **External forcing:**
  - Insolation with full seasonal cycle
  - That’s it! (e.g. no flux adjustments)



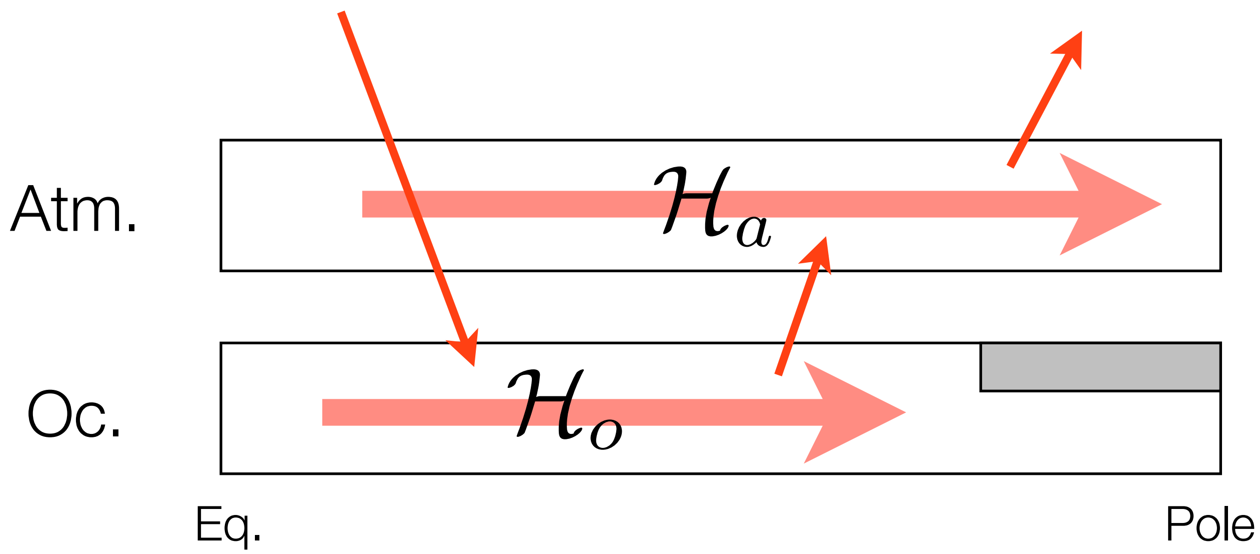
Solar constant
W/m^2
Years
Sea ice thickness
Surface temperature
Temp
Ψres
Salt



Ferreira, Marshall and Rose, *J. Clim. 2011*

Multiple ocean / sea ice states: a cartoon

Wind-driven subtropical cell deposits heat at poleward edge of subtropical thermocline, limits ice expansion



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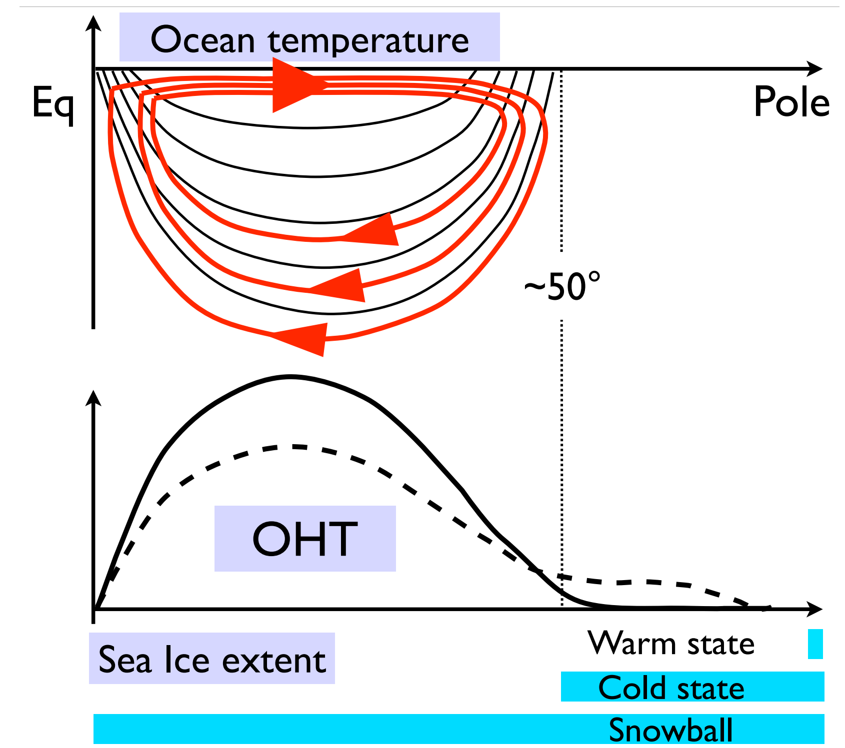

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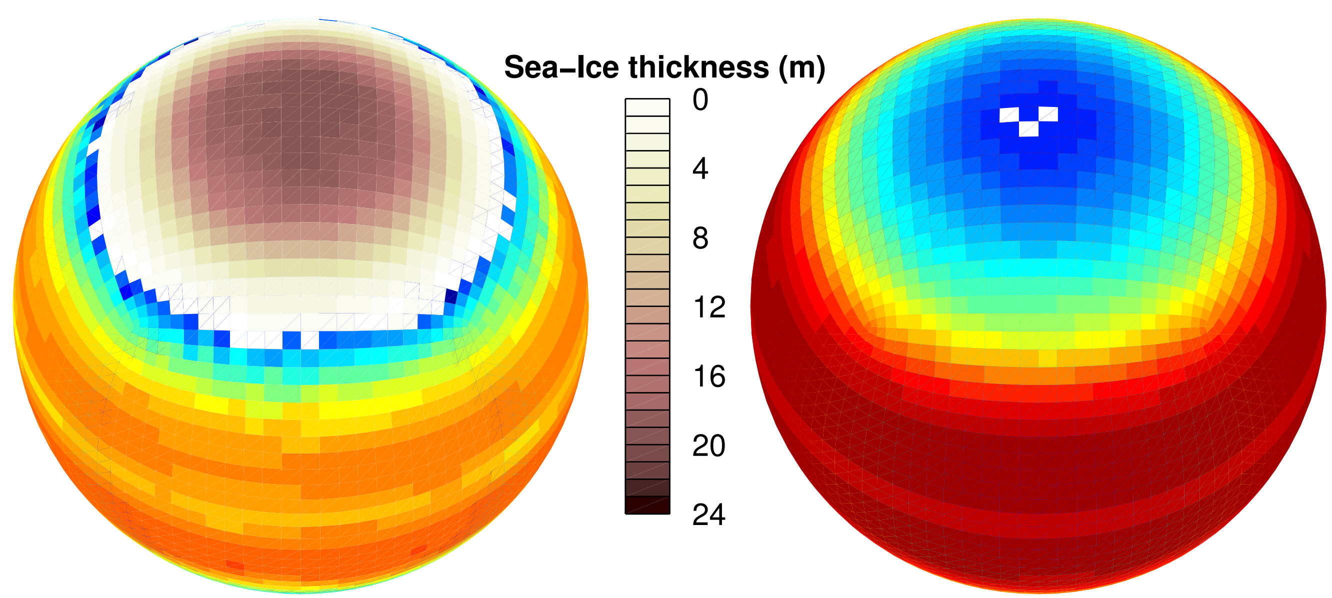
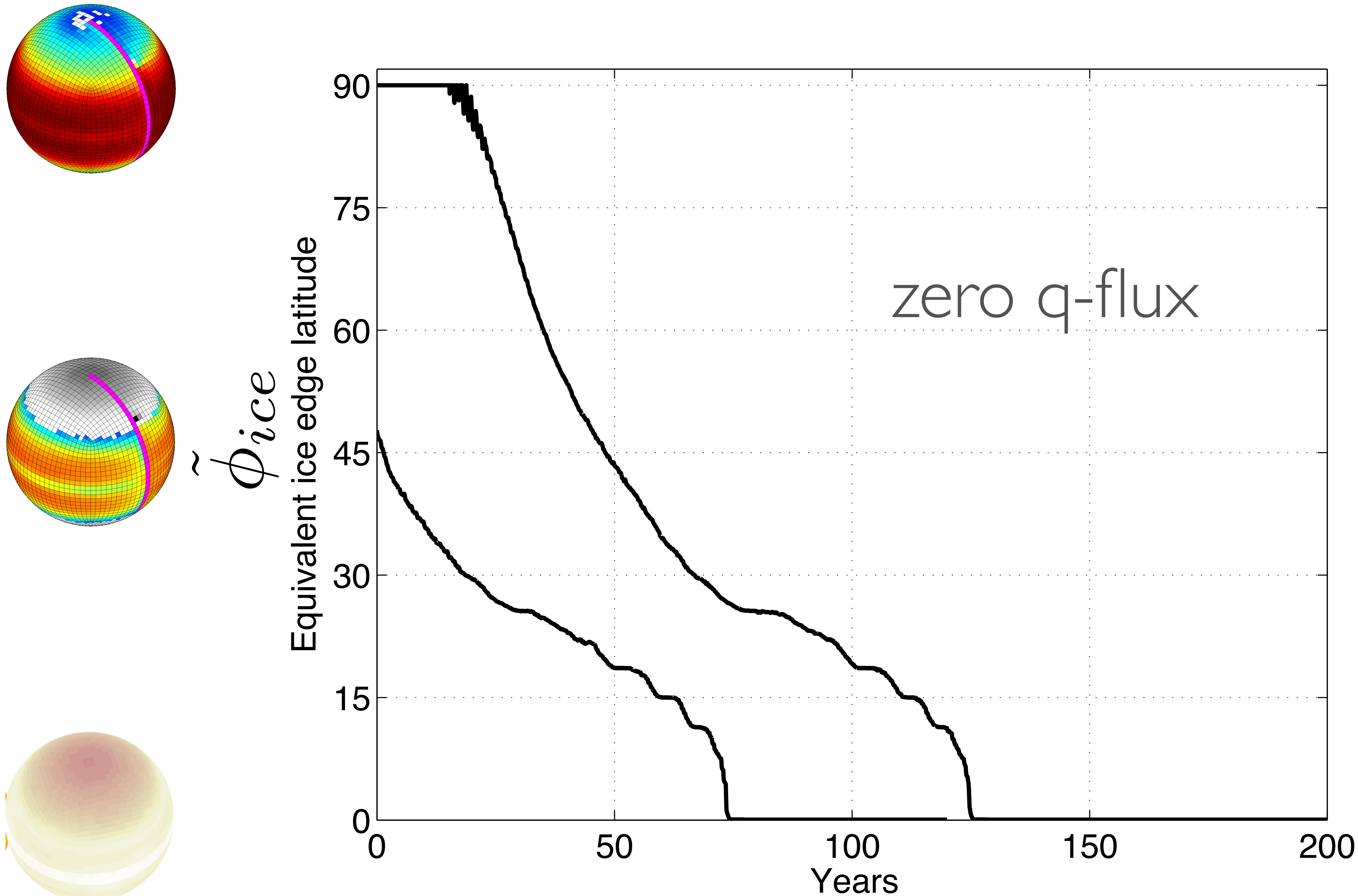


Capturing the Warm and Cold states in the EBM

Modify the AO-EBM to account for the heat transport by ocean's overturning circulation

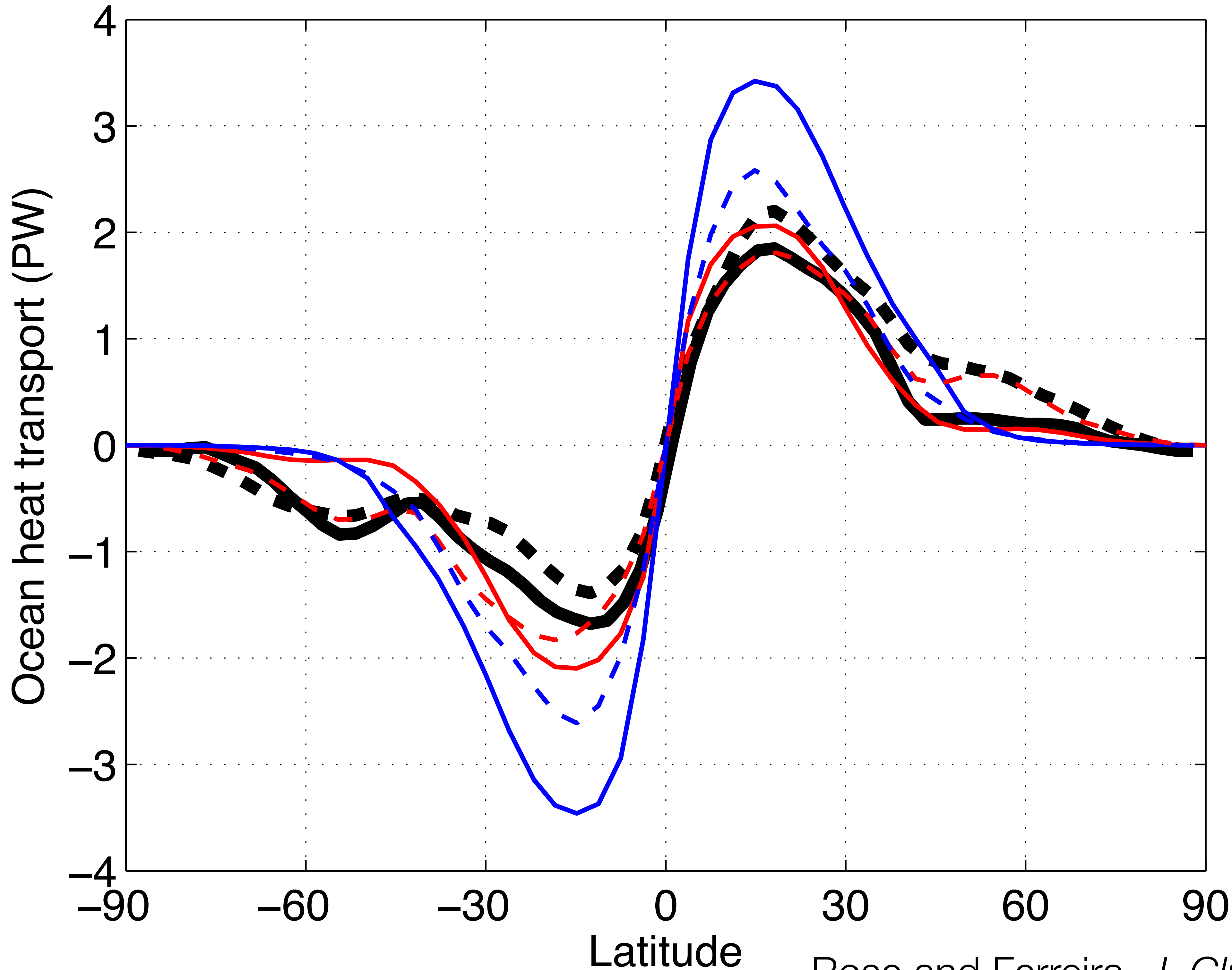
Let's decouple OHT from the climate system and vary it systematically.

- Replace the full ocean model with a slab mixed layer.
- Prescribe OHT as a heat source / sink term (q-flux).
- Is the climatic role of OHT very different in cold versus warm climates?



This is what happens when the oceans carry no heat at.

End up in a Snowball regardless of initial conditions



Rose and Ferreira, *J. Clim.* 2013

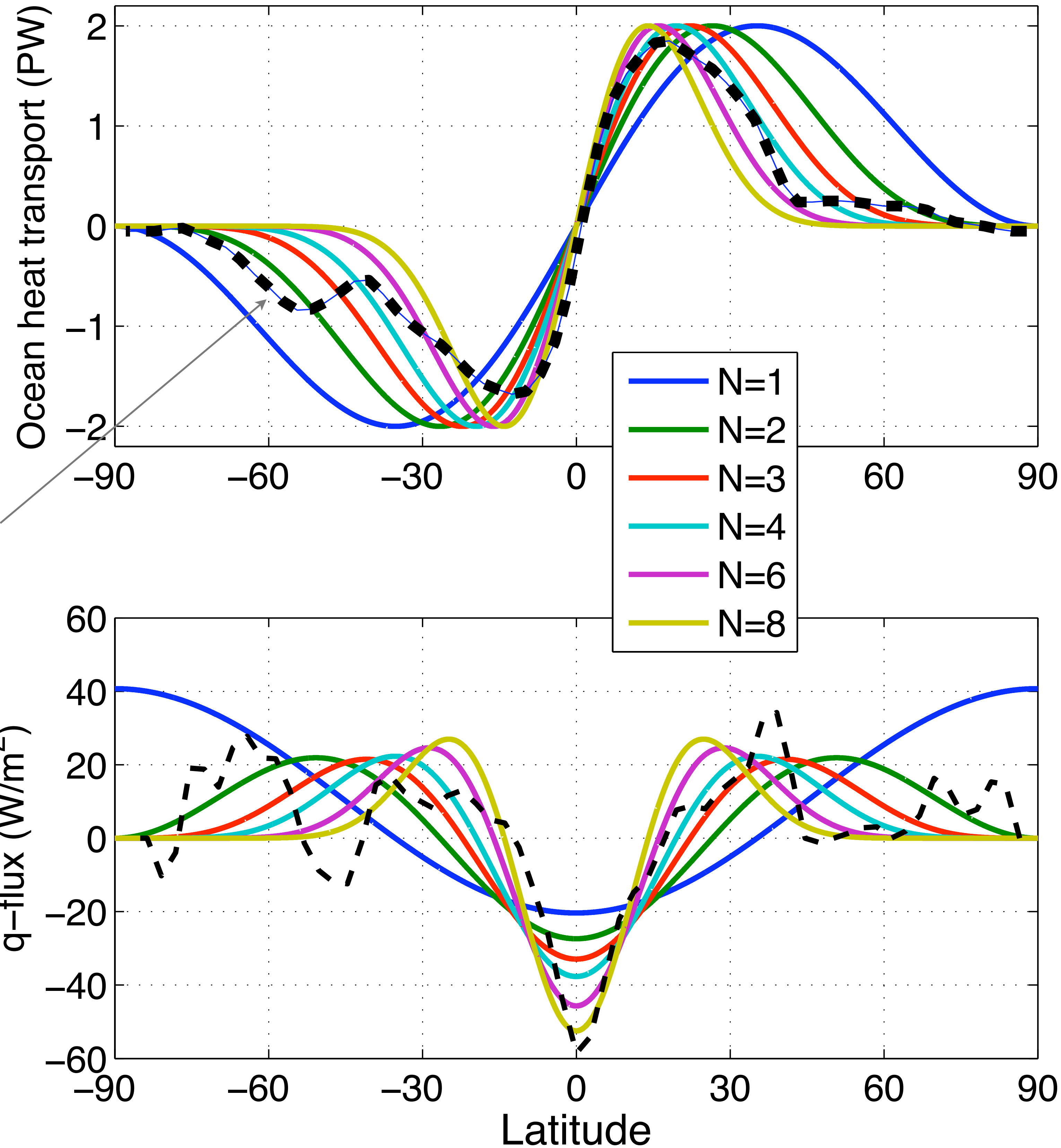
Ocean heat transport in models and observations

Estimates from Trenberth and Caron (2001) and Aquaplanet / Ridge GCM

Rose and Ferreira, *J. Clim.* 2013
Rencurrel and Rose, *J. Clim.* 2018

$$\mathcal{H}_o \sim \sin(\phi)\cos(\phi)^{2N}$$

Trenberth and Caron (2001) estimate



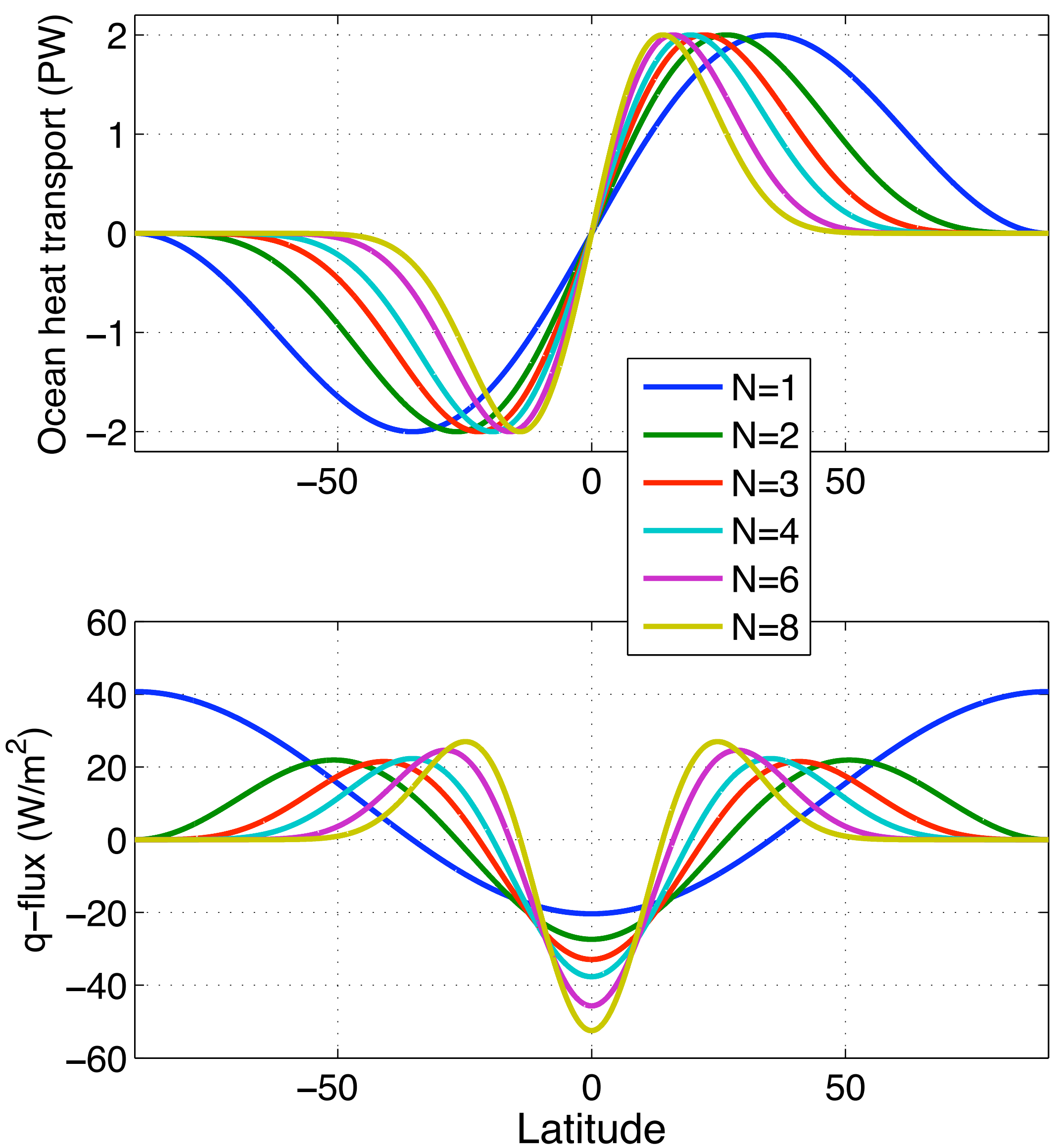
$$-\nabla \cdot \mathcal{H}_o$$

(heating rate)

An idealized analytical form for ocean heat transport

Can vary amplitude and meridional scale systematically

Map out the climatic impact of OHT



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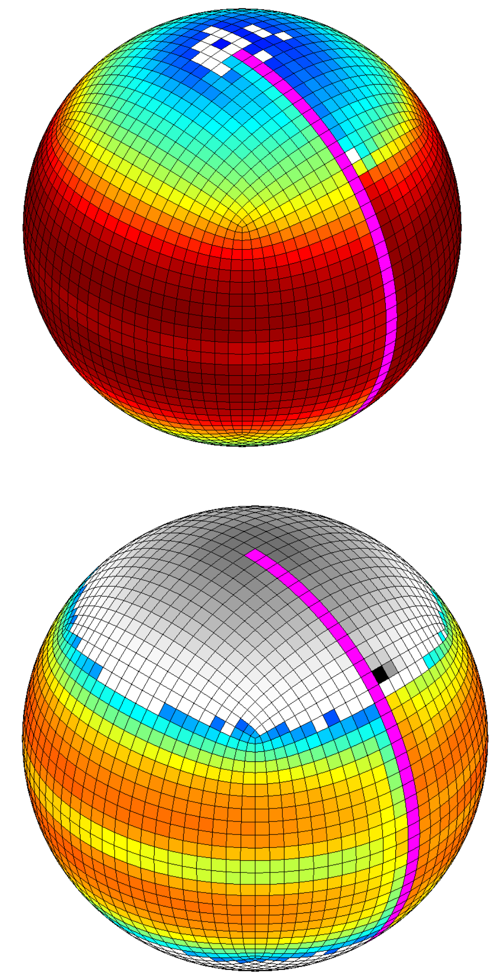
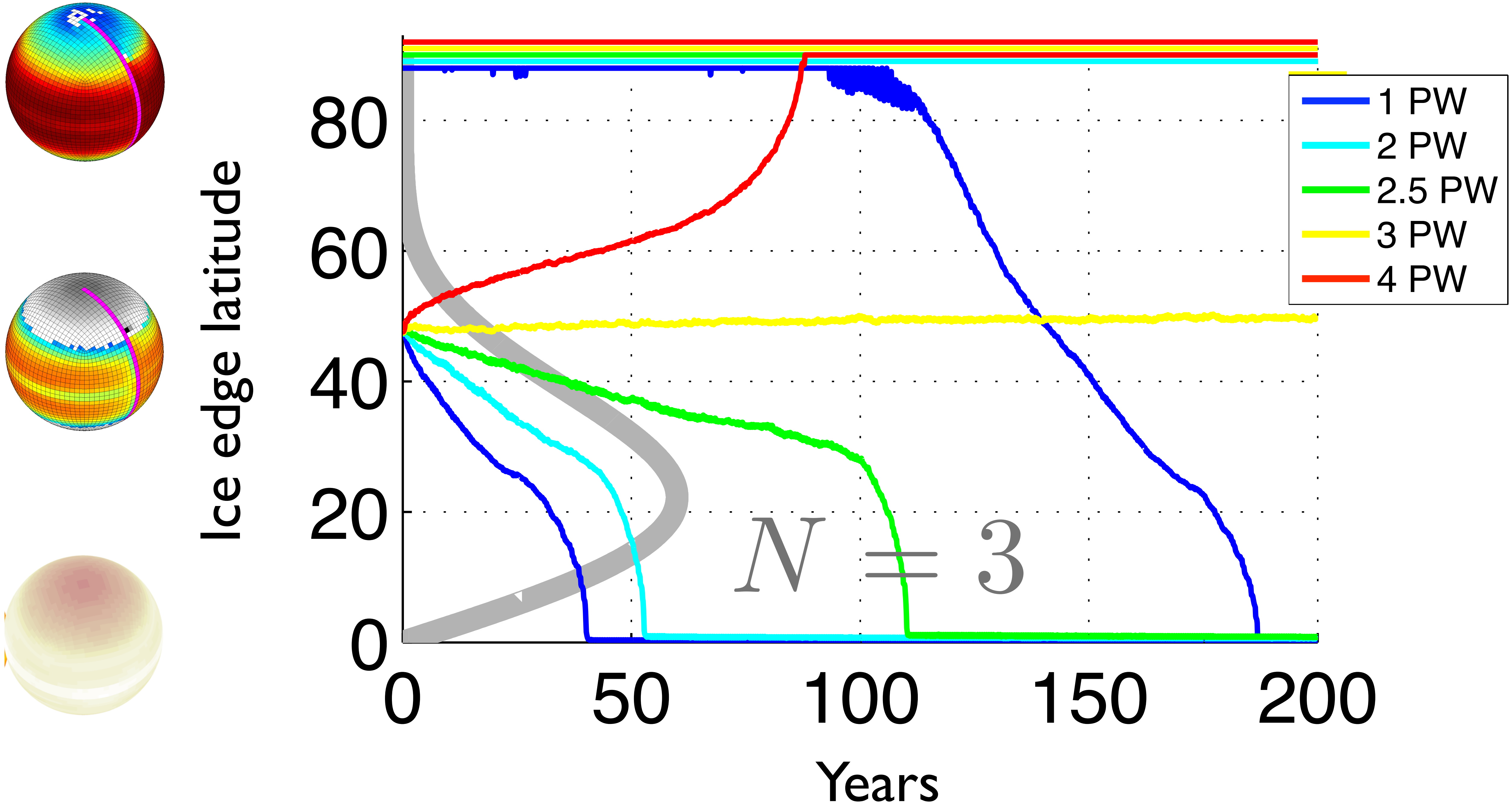


= ?

- What is the equilibrium relationship between OHT and sea ice?
- Can we change the number and type of different possible equilibria by varying OHT?



$$\mathcal{H}_o \sim \sin(\phi)\cos(\phi)^{2N}$$

Ice edge evolution in the slab ocean model

Adjustment of the sea ice from Warm and Cold initial conditions for different amplitudes of OHT

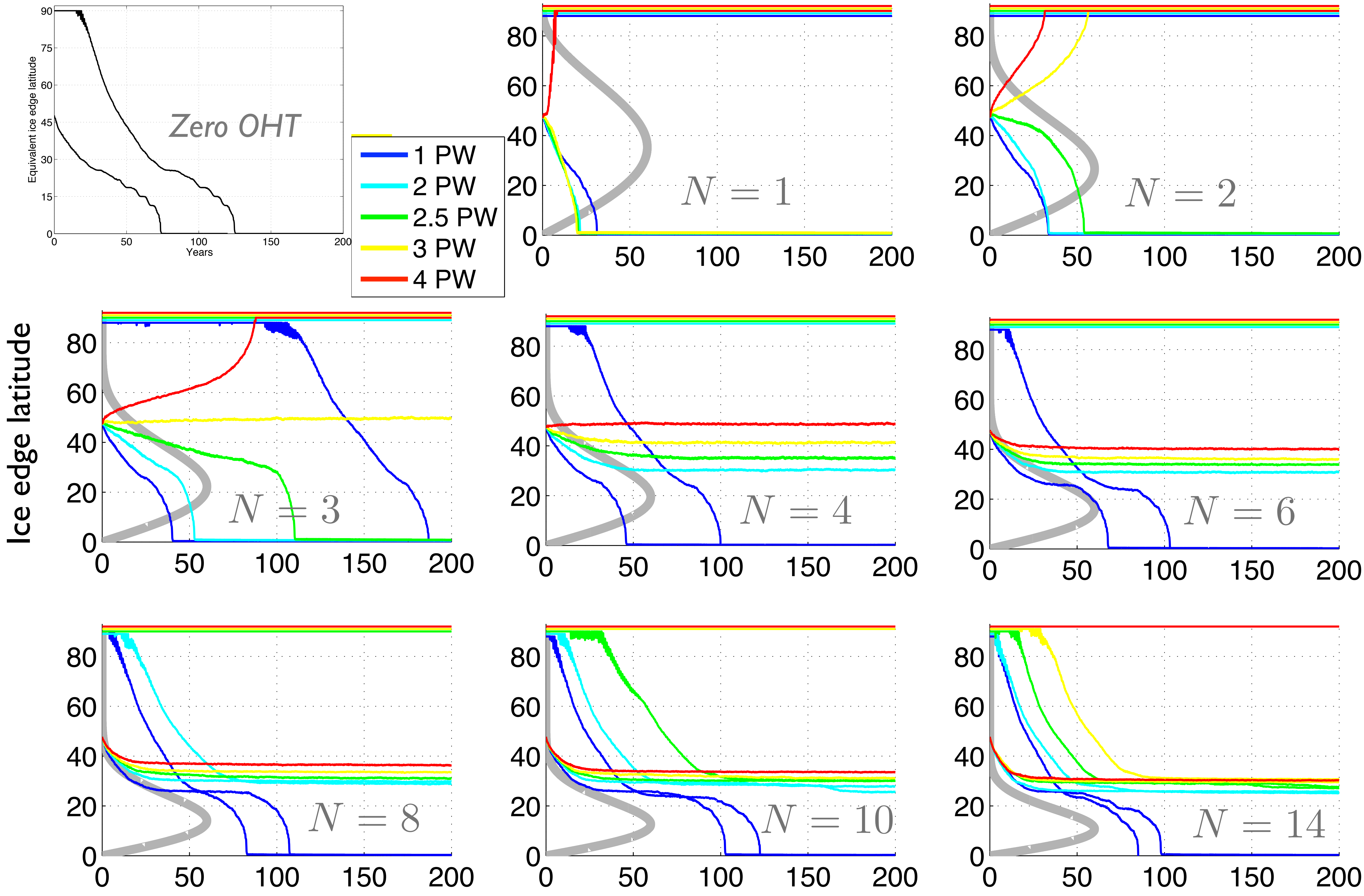
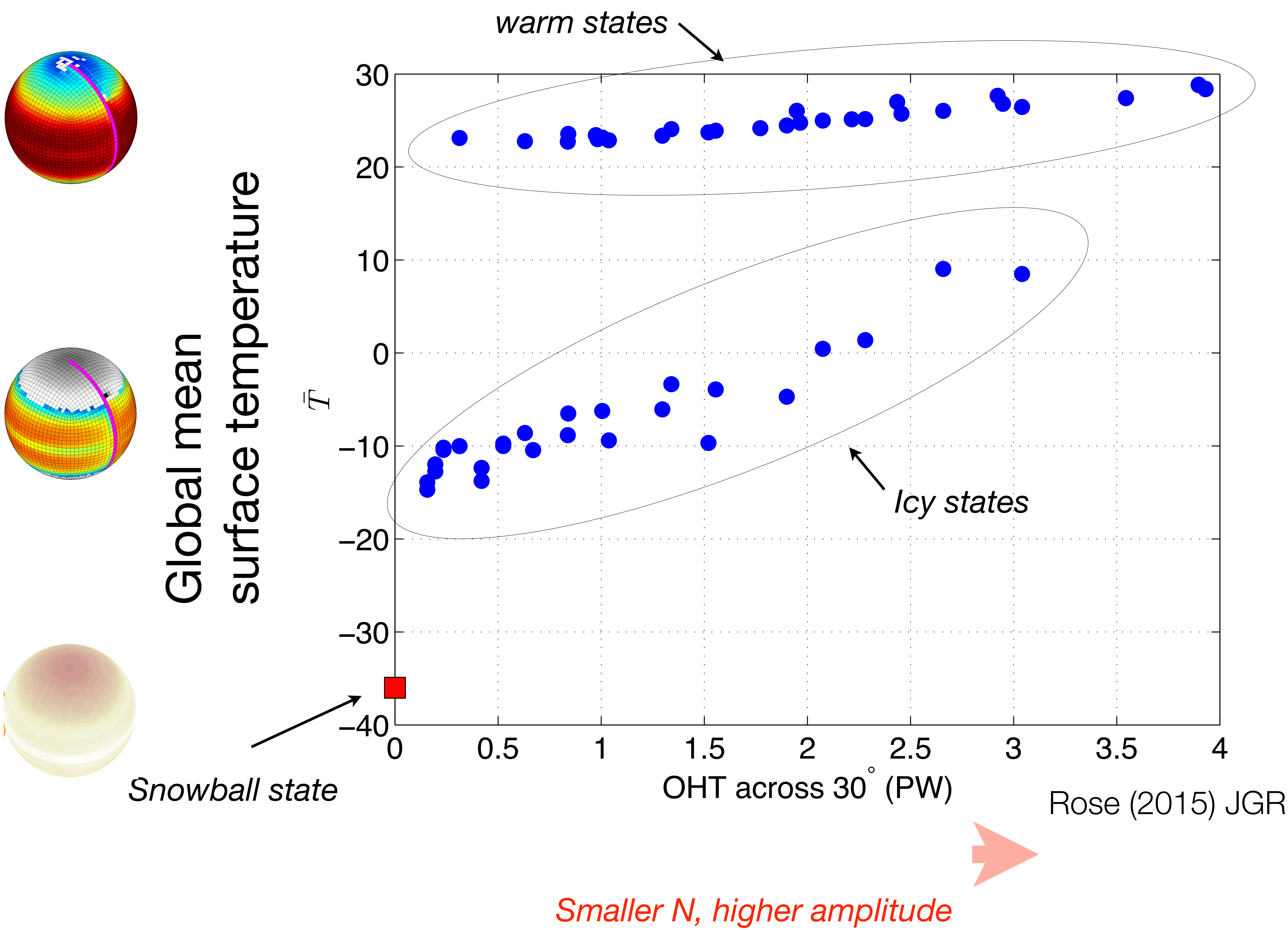
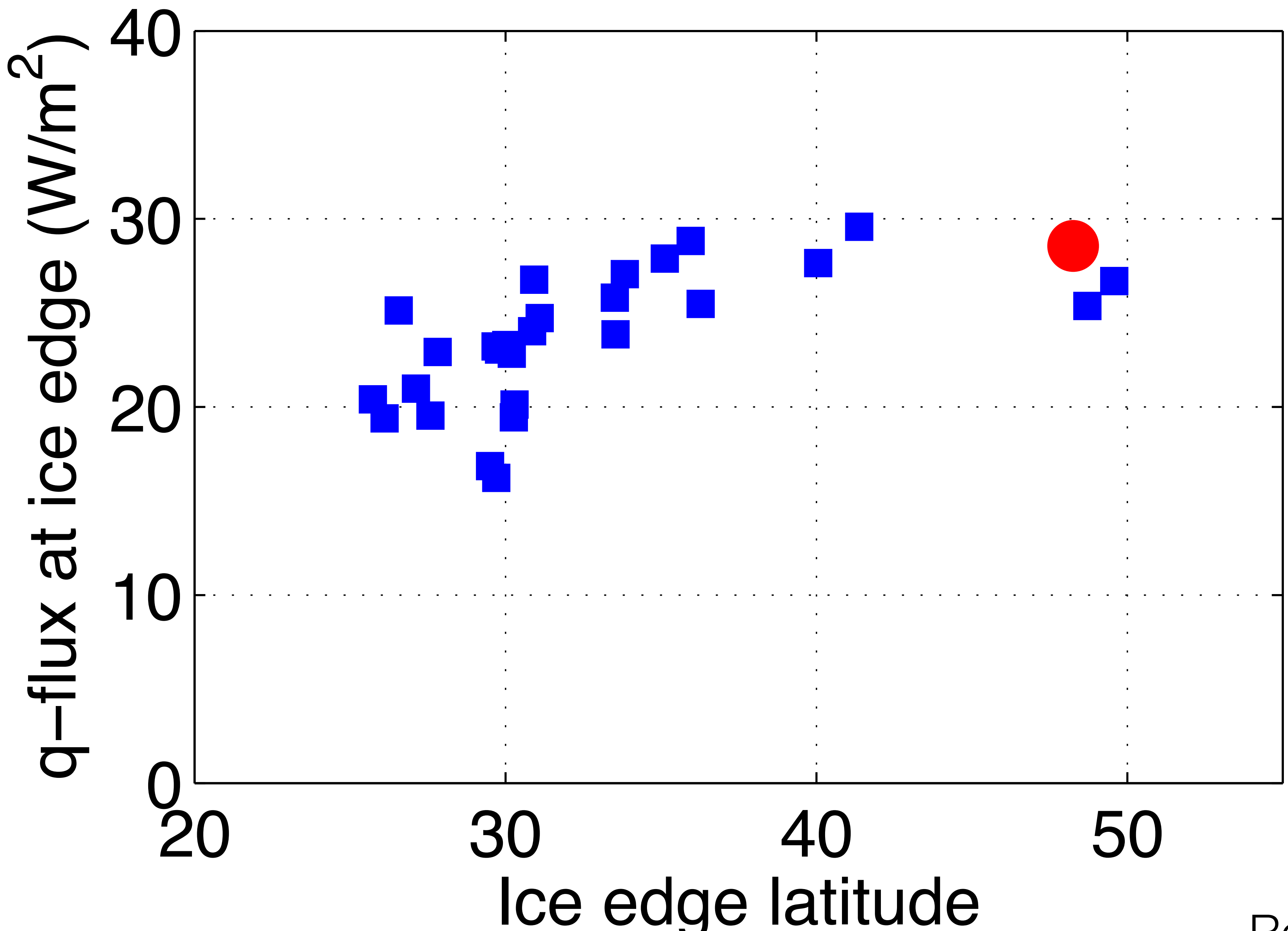
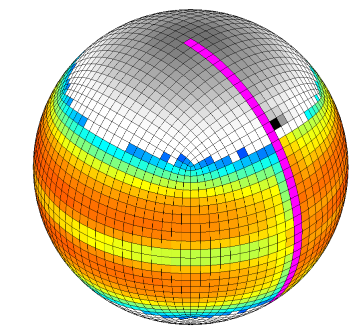


Figure 9. Ice edge latitude in slab ocean simulations. Meridional structure of prescribed OHT is sketch in thick grey curves. Colors indicate peak amplitude of prescribed OHT. Runs are initialized in two different initial conditions: no ice and ice near 45°.

Rose (2015) JGR


warm states
Icy states
Snowball state
Global mean surface temperature
$\bar{T}$
30
20
10
0
−10
−20
−30
−40
0
0.5
1
1.5
2
2.5
3
3.5
4
OHT across 30° (PW)
Rose (2015) JGR
Smaller N, higher amplitude



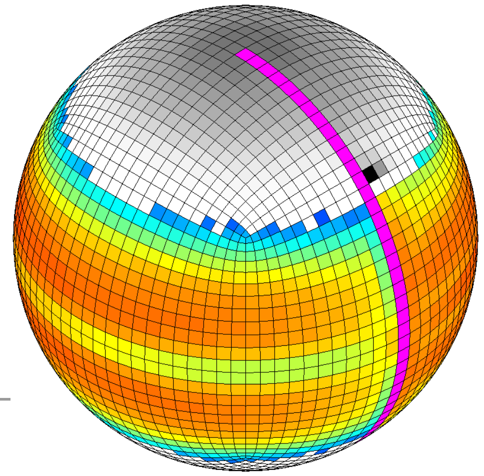


Rose (2015) JGR

OHT convergence at the ice edge

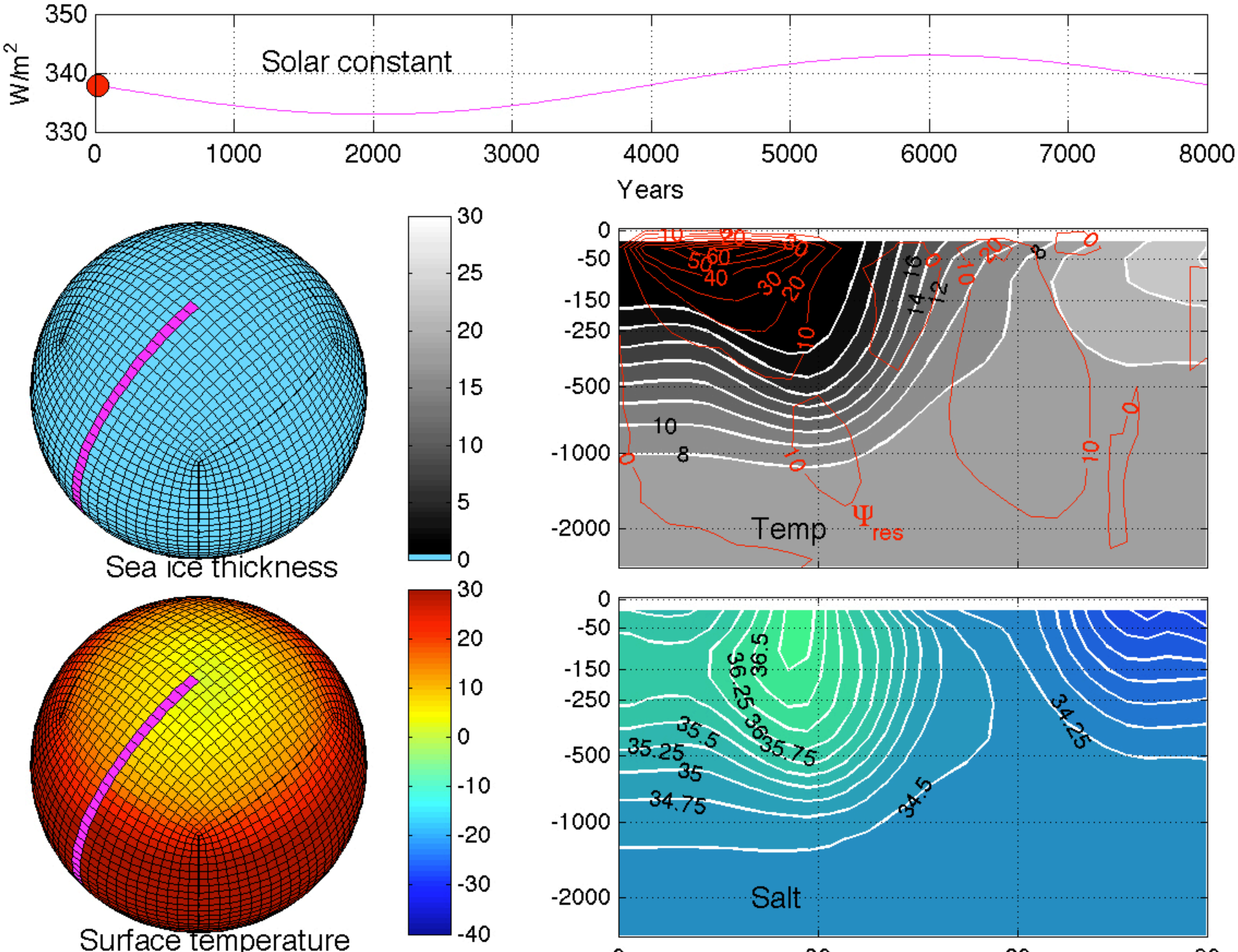
30 W/m² (annual mean) is an upper bound.

In the icy regime:



- Idealized GCM (and simple EBM) has a continuum of cold icy climates, in which the sea ice edge is slaved to the OHT convergence.
- Sea ice edge must be poleward of any location receiving > 30 W/m^2 OHT convergence.
- This limit is set by the insulating effect of the ice.
- In this model, no small ice caps are possible (poleward of about 50º). Detailed shape of high-latitude OHT convergence is probably important here!
- Very cold, stable tropical ice edges are possible, so long as OHT is sufficiently intense and narrow.

Let's go back to the fully coupled system with a dynamic ocean



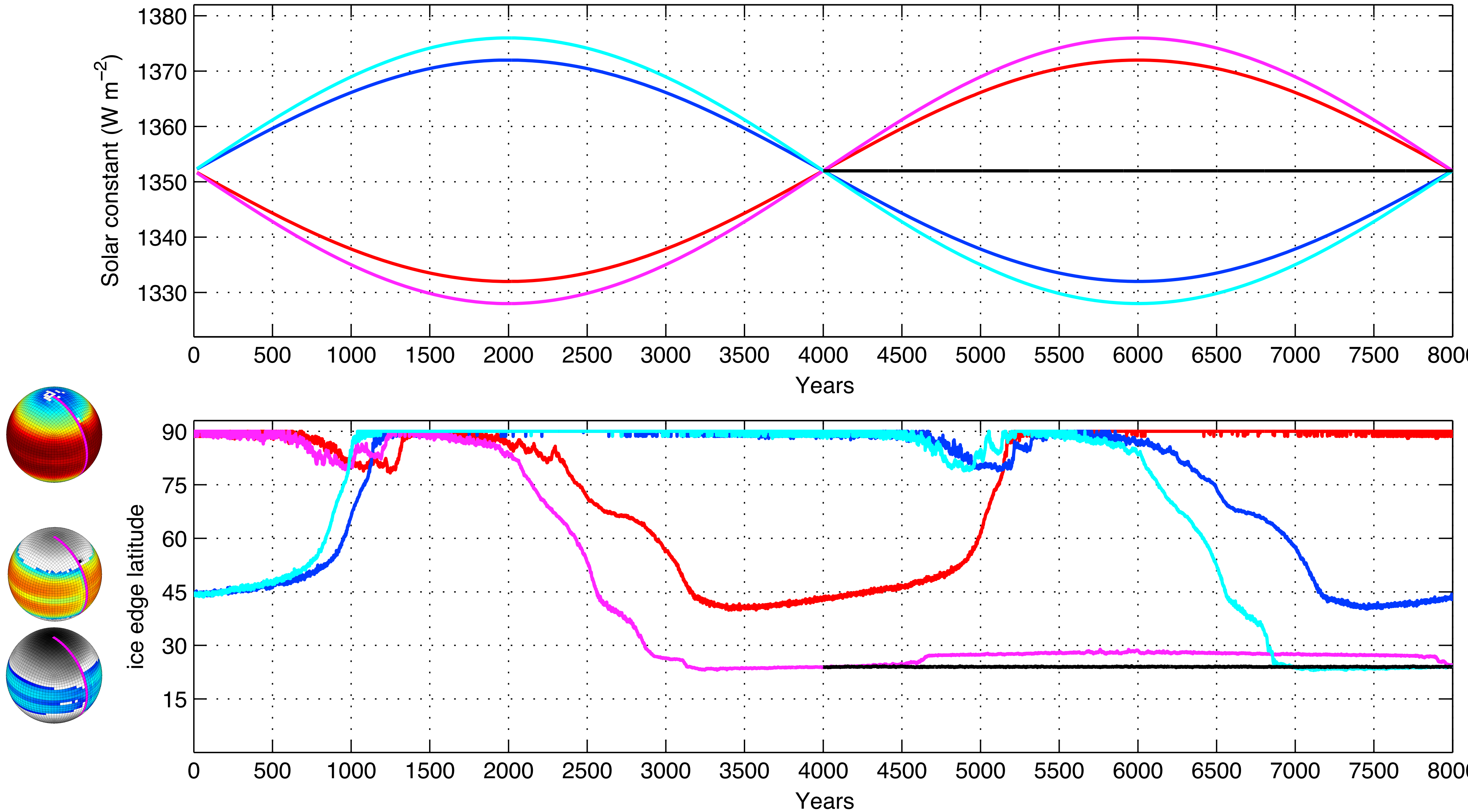
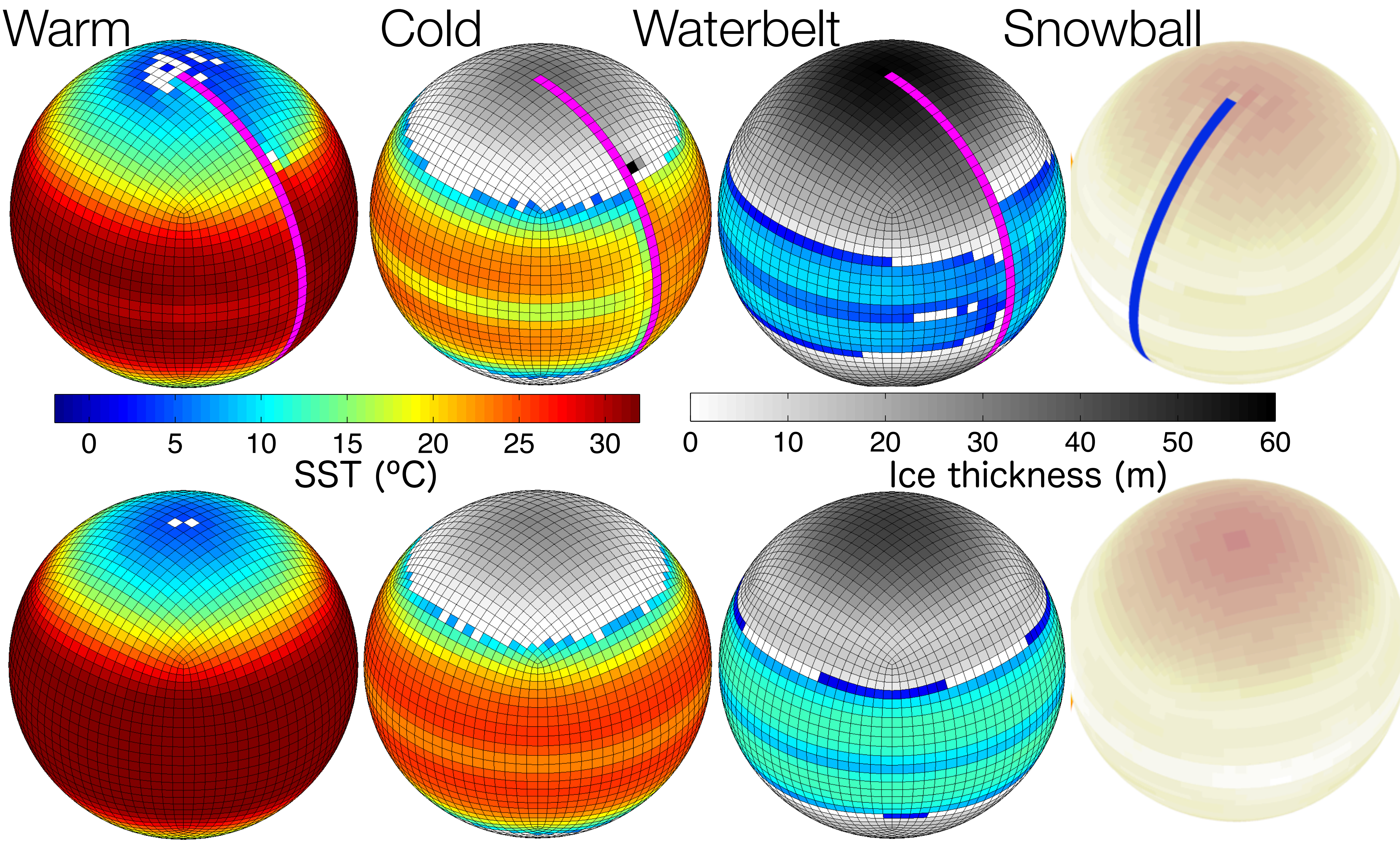


Figure 6. Evolution of the sea ice edge in long integrations of the coupled *Ridge* GCM with time-varying solar constant. The red and blue curves were described in detail by *Rose et al.* [2013]. This figure shows that a slight increase in the amplitude of the forcing leads to qualitatively different behavior: the model enters the Waterbelt state with subtropical sea ice. The Waterbelt state with ice edge at 24° latitude is a stable equilibrium of *Ridge* (black curve) at the reference solar constant of 1352 W m^{-2} (as used by *Ferreira et al.* [2011] and *Rose et al.* [2013]), along with the Warm, Cold, and Snowball states pictured in Figure 1. Once in the Waterbelt state, the ice edge adjusts only minimally to a 35 W m^{-2} increase in solar constant (magenta curve).

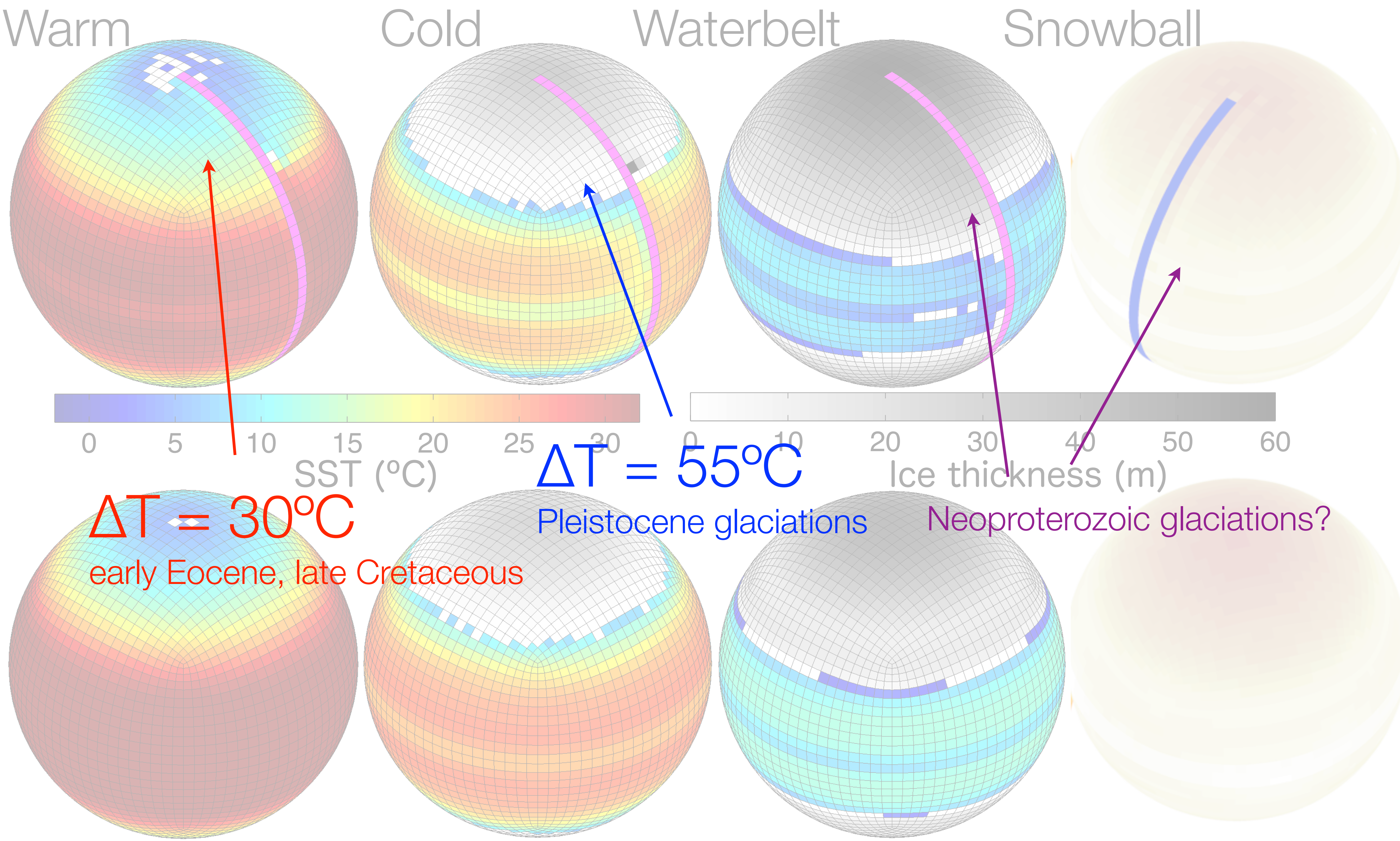
Hysteresis in the Ridgeworld

Transient simulations with slowly varying solar constant



Multiple equilibria in a coupled GCM

Same model, same forcing, four very different climates for each geographical configuration



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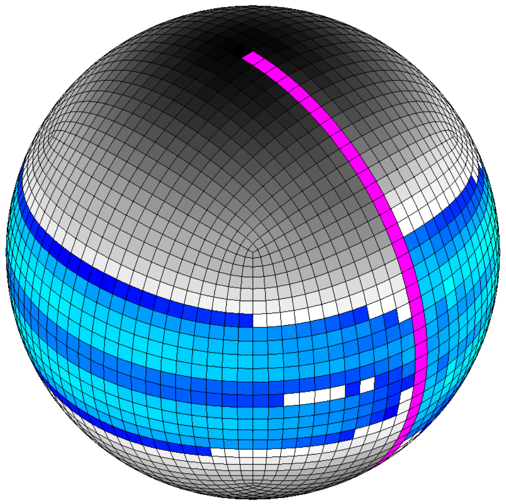


The coupled system equilibrates to a very cold climate

Sea ice edge is sitting in the **subtropics**

The ocean must be working very hard to stabilize this **very large ice cap**

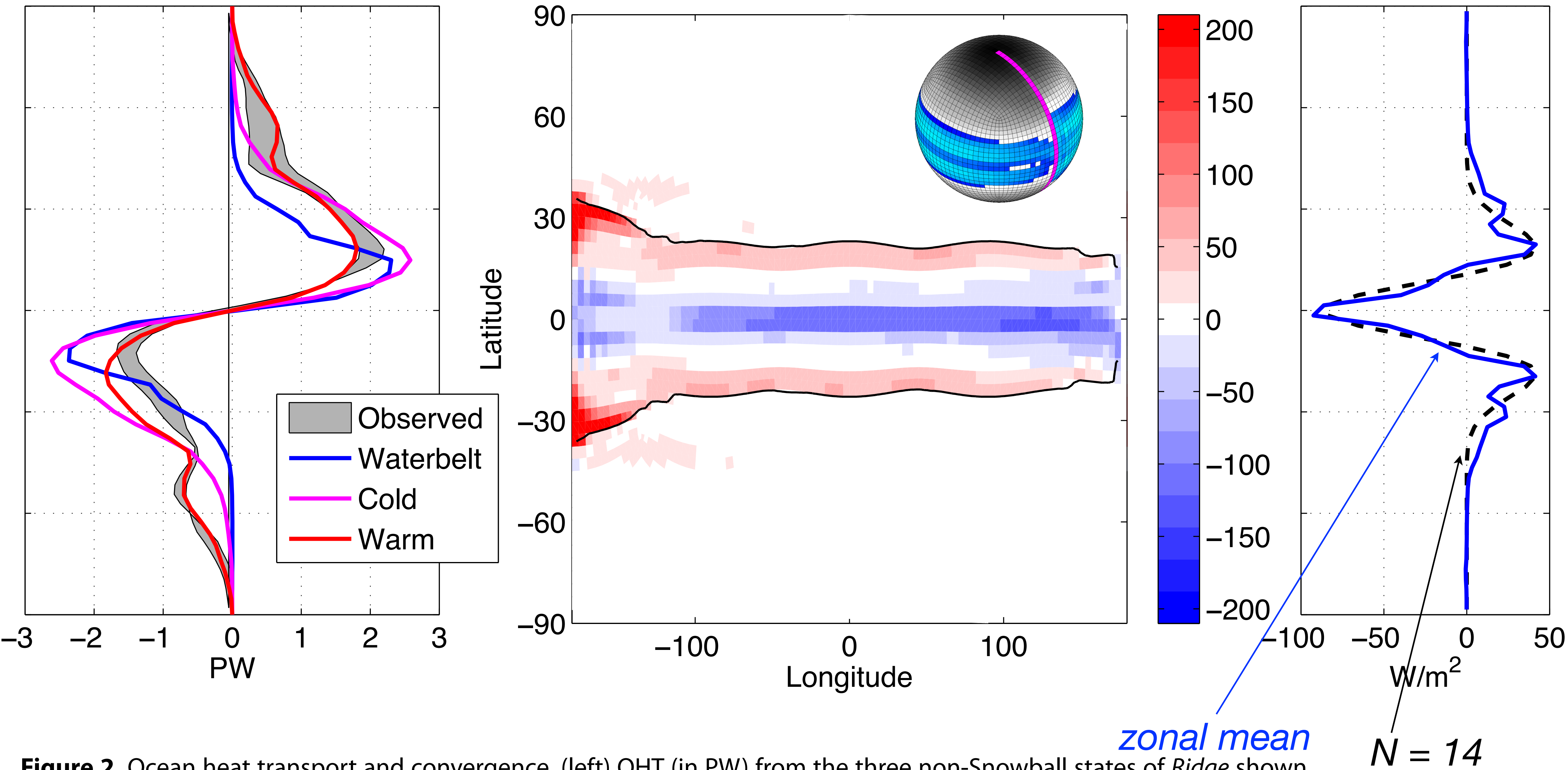
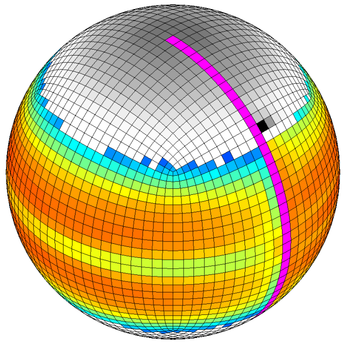


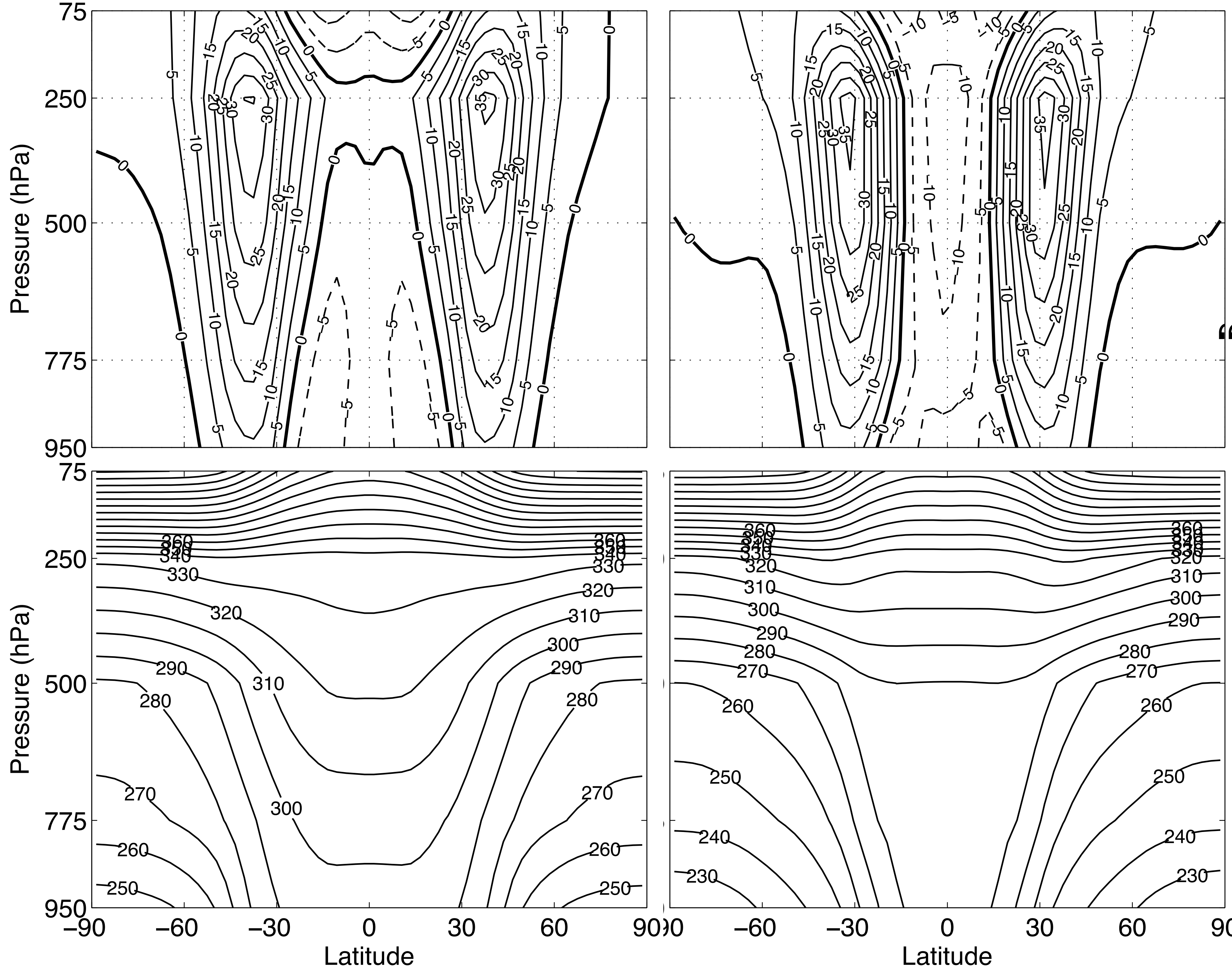
Figure 2. Ocean heat transport and convergence. (left) OHT (in PW) from the three non-Snowball states of *Ridge* shown in Figure 1. The grey shading spans two different observational estimates of present-day OHT [*Trenberth and Caron*, 2001]. (center) Spatial map of OHT convergence (W m^{-2}) in the Waterbelt *Ridge* simulation, with the ice edge indicated by the black contours. This shows the zonal asymmetries associated with the subtropical gyre circulation. (right) zonal average convergence in Waterbelt (blue line). The dashed black line is the convergence estimated from equation (1) with $N = 14$ and 2.5 PW amplitude.

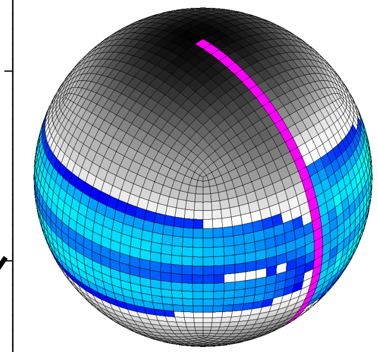
Ocean heat transport

Rose (2015), JGR



“Cold”





“Waterbelt”

Figure 5. Zonally averaged zonal wind (upper) and potential temperature (lower) for the Cold (left) and Waterbelt (right) states of *Ridge*. For the wind, solid and dashed curves indicate westerly and easterly flow respectively, with the zero contour highlighted. Contour intervals are 5 m s^{-1} for u and 10 K for θ. The five model levels are centered at the pressures indicated on the vertical axes (950, 775, 500, 250, and 75 hPa); contours are interpolated smoothly between these levels.

Atmospheric circulation

Equatorward shift of wind systems

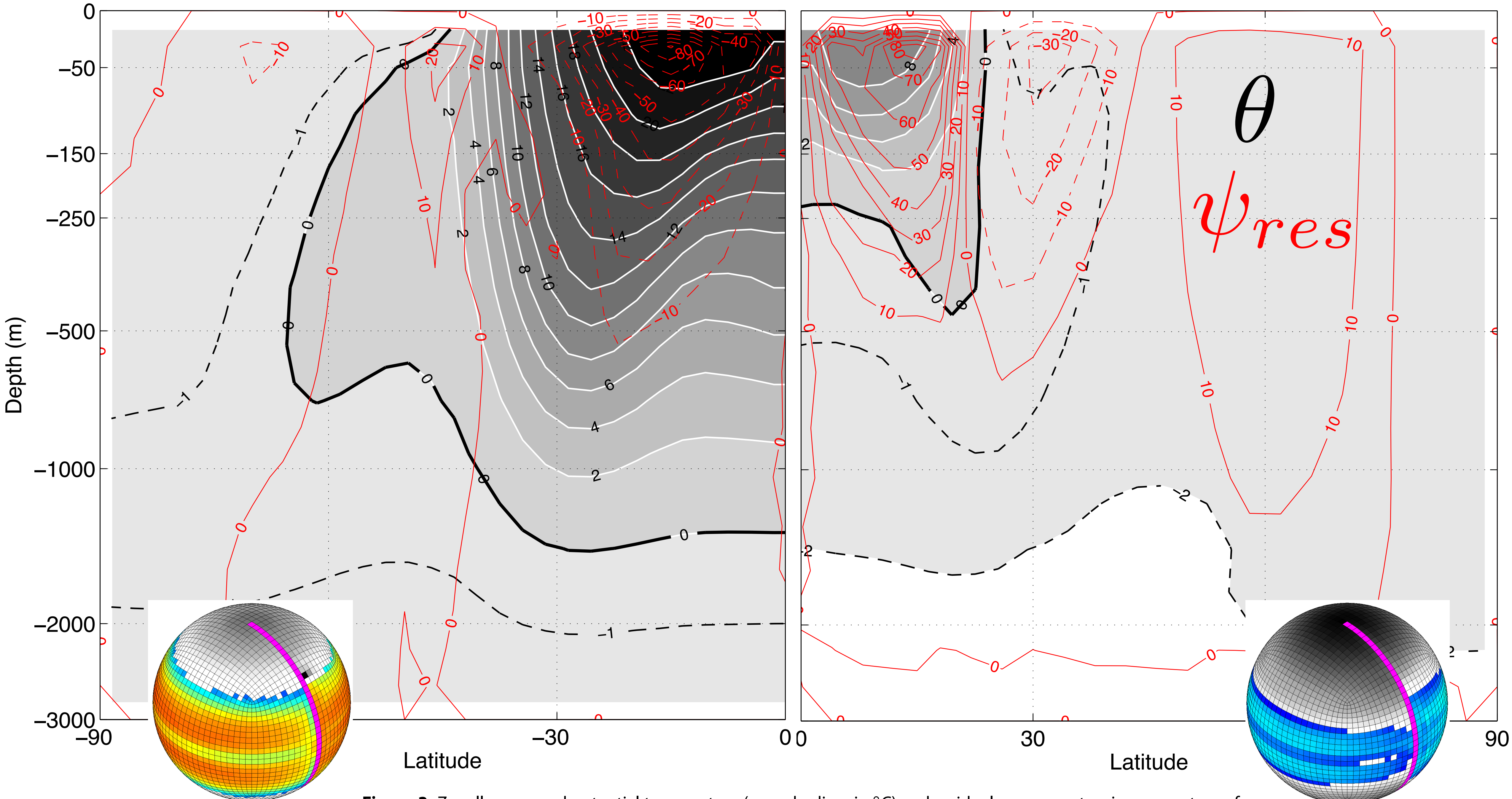


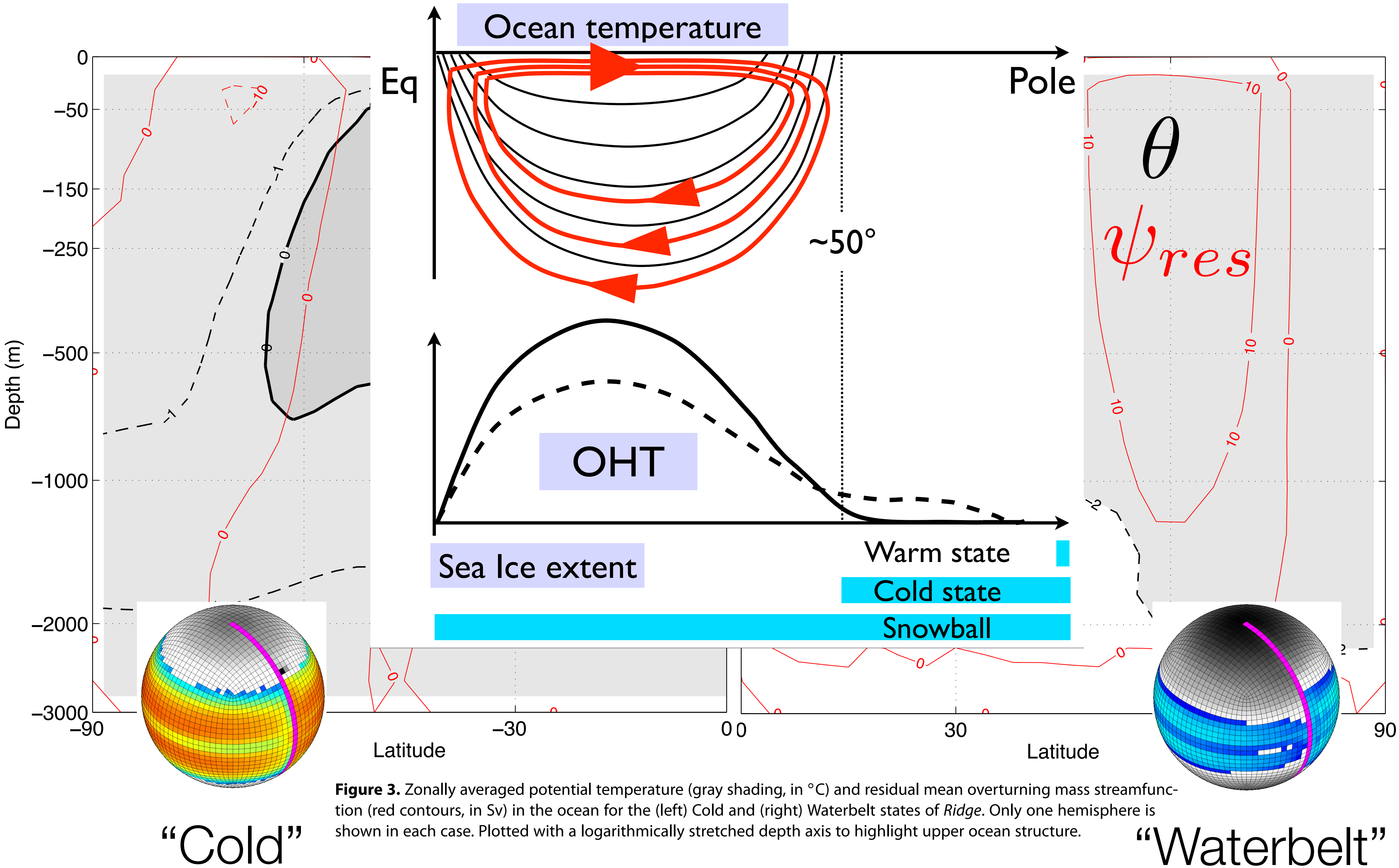
Figure 3. Zonally averaged potential temperature (gray shading, in °C) and residual mean overturning mass streamfunction (red contours, in Sv) in the ocean for the (left) Cold and (right) Waterbelt states of *Ridge*. Only one hemisphere is shown in each case. Plotted with a logarithmically stretched depth axis to highlight upper ocean structure.

"Cold"

"Waterbelt"

Ocean: thermal structure and overturning

Shallow thermocline, intense but narrow wind-driven overturning



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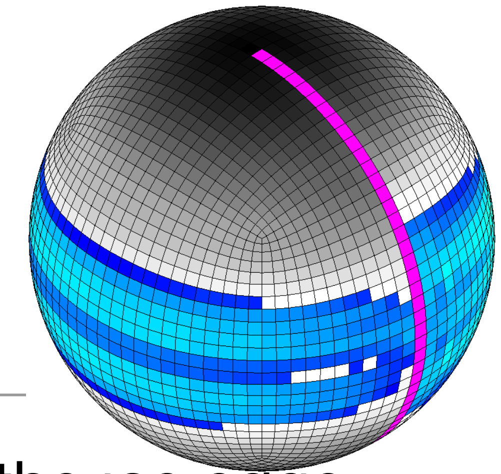
Ocean: thermal structure and overturning

Shallow thermocline, intense but narrow wind-driven overturning

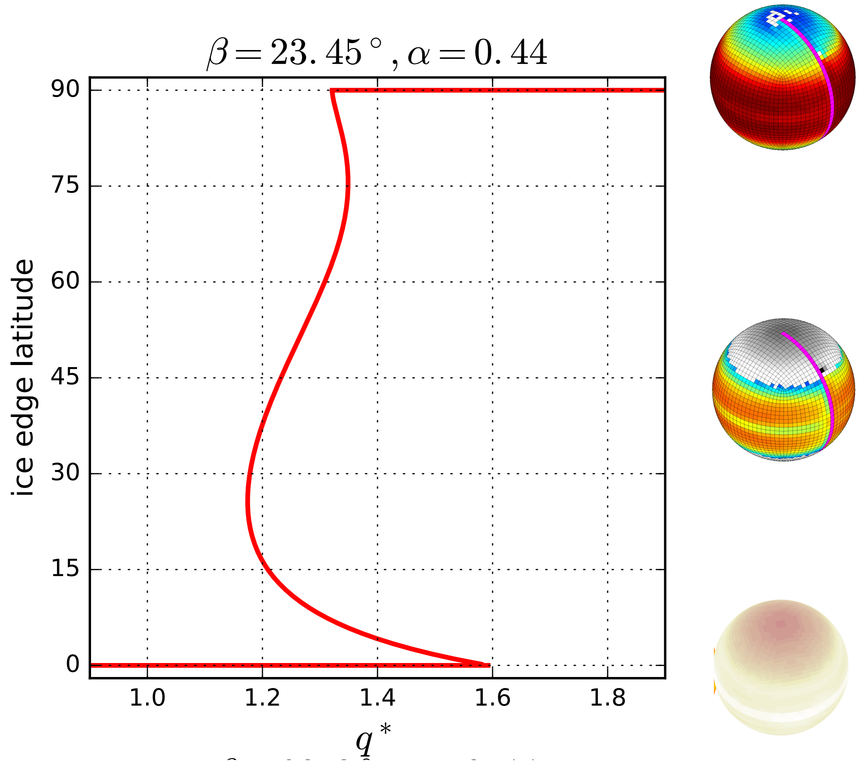
Surprises from the Waterbelt Climate:



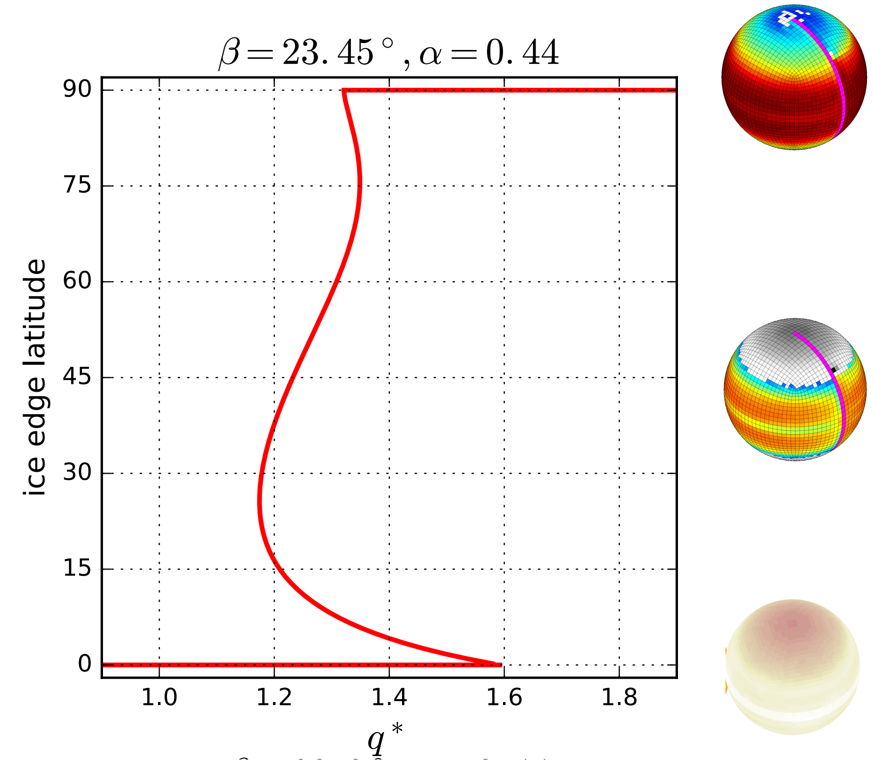
- Atmospheric storm tracks are influenced by the strong baroclinicity at the ice edge.
- As ice edge moves equatorward, storm tracks and jets shift along with it.
- New equilibrium is made possible by narrow, intense STCs in the ocean, carrying large amounts of tropical-source heat to the edge of the ice. *A robust feature of tropical ocean circulation, need to account for it in any theory of cold climates!*
- A fundamentally coupled mechanism: stable ice edge requires intense OHT convergence, which requires equatorward shift in wind systems, which requires equatorward shift in ice edge!
- *Relevance to Neoproterozoic Snowball Earth?* Ridgeworld model suggests this state is "easy" to get into and "hard" to get out of. Exists over a 46 W m^{-2} range of solar constant.
- Future work: distinguish between "hard snowball" and "waterbelt" scenarios for Snowball Earth based on the ocean circulation and its implications for the sedimentary record.

Back to basic ideas…

Bifurcation diagram for the simple EBM
(no ocean)



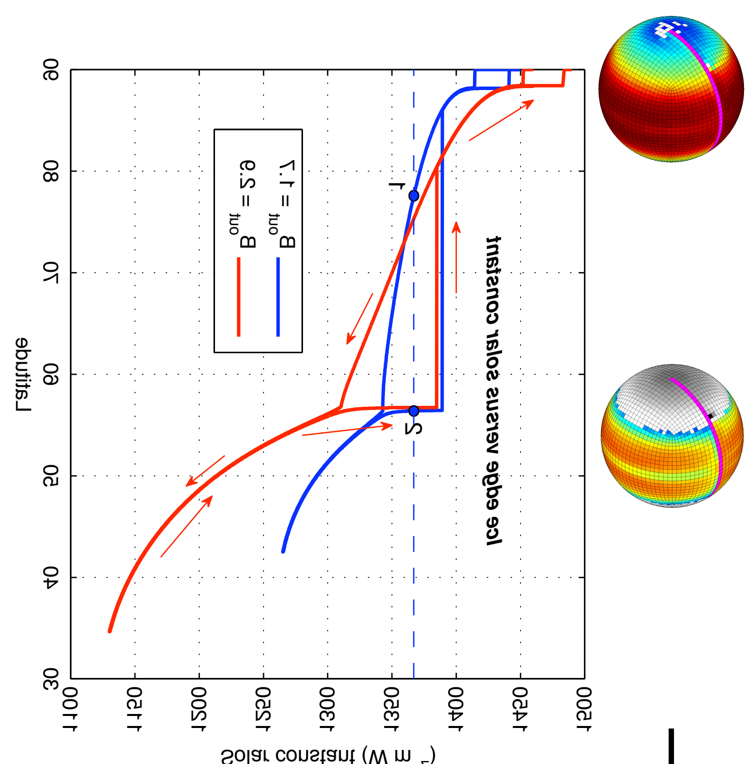
Back to basic ideas…

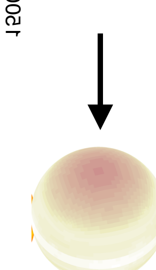


Bifurcation diagram for the simple EBM

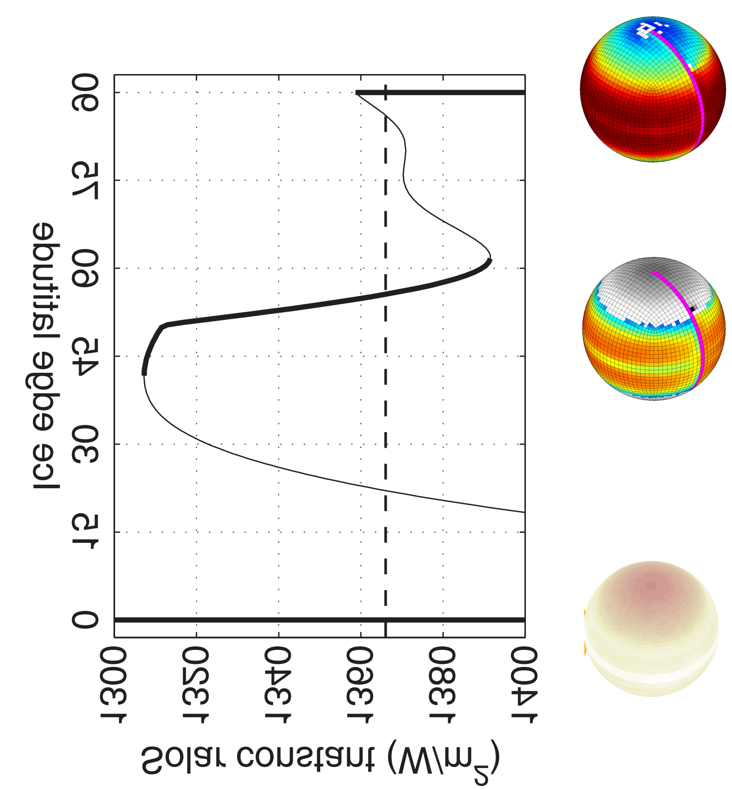
(no ocean)

Convergence of ocean heat transport into midlatitudes creates an additional fold in the diagram, with a “stability ledge” for mid-latitude ice edges



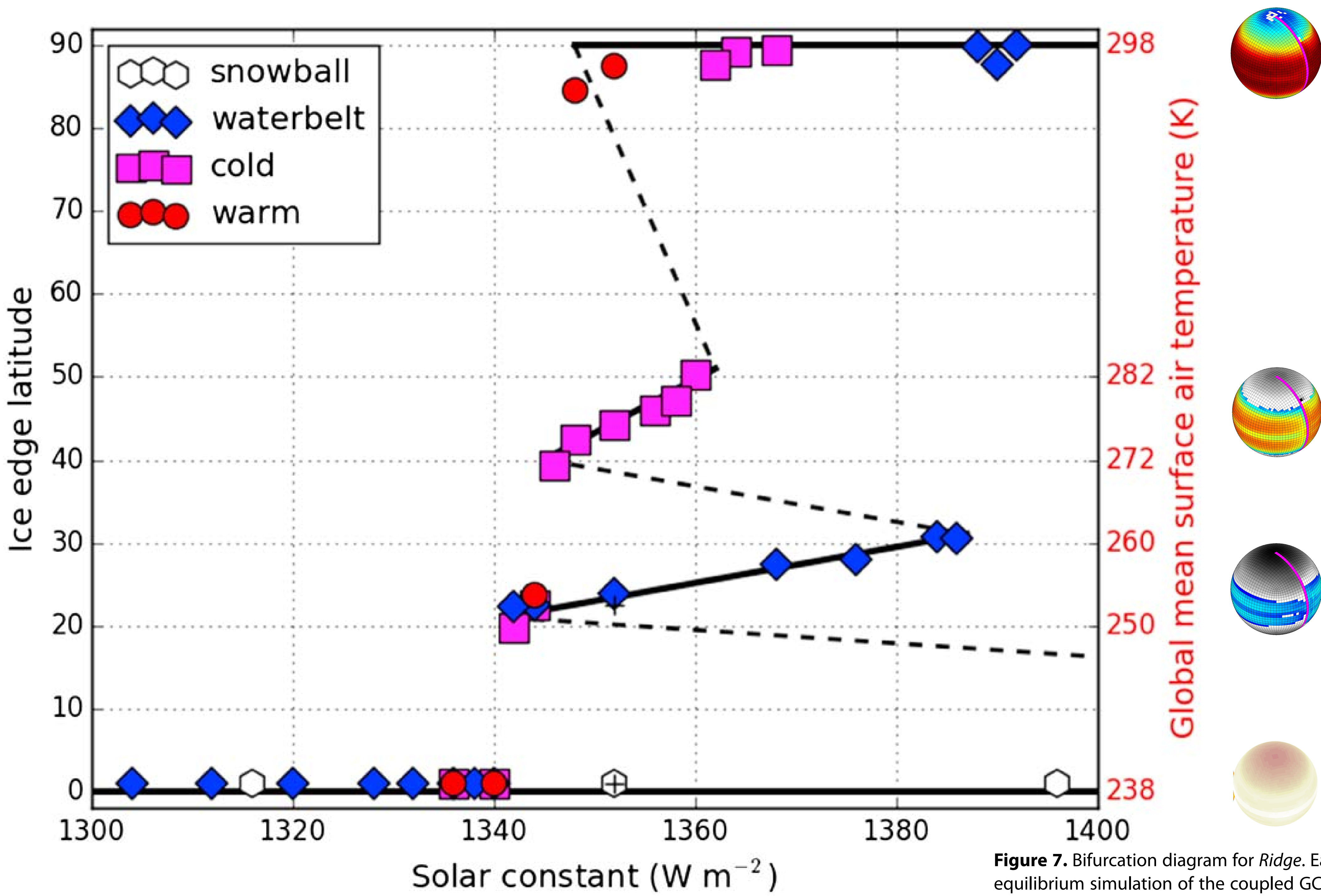


Rose and Marshall (2009) JAS



Ferreira, Marshall and Rose (2011) J. Climate

But the fully coupled system has an even more rich bifurcation structure…



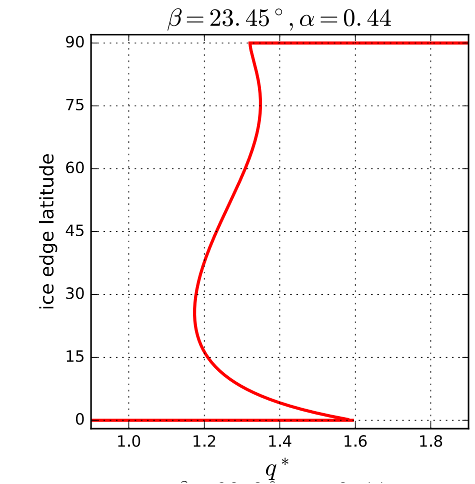
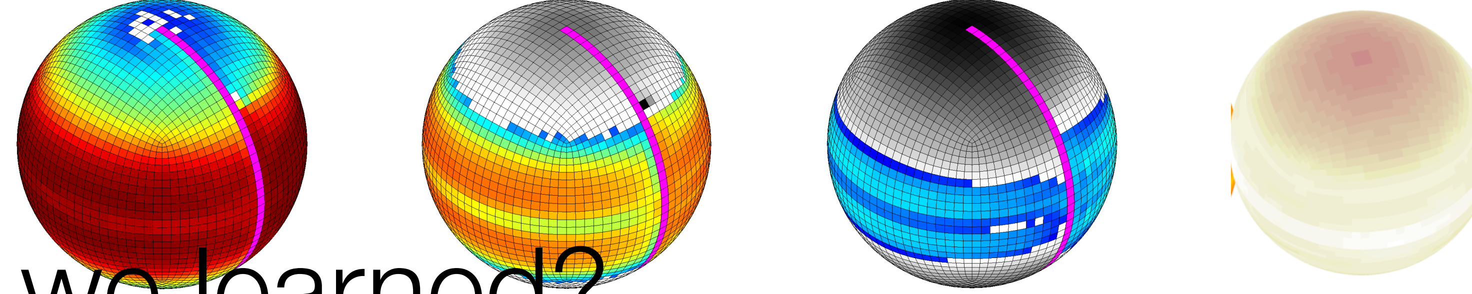


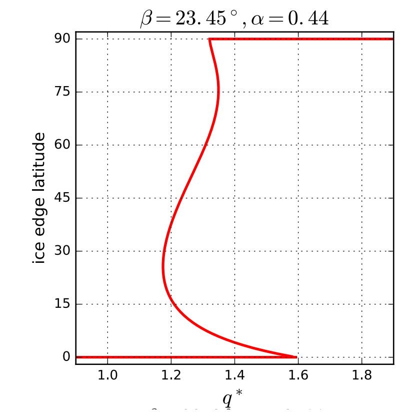
Figure 7. Bifurcation diagram for *Ridge*. Each marker represents a long equilibrium simulation of the coupled GCM with fixed parameters. The model is initialized in Warm, Cold, Waterbelt, or Snowball state as indicated by marker color. A range of solar constants is used to map out the stable branches for each model state. A stable Waterbelt is found for solar constant between 1341 and 1387 W m^{-2}, with ice lines ranging from 21° to 30° latitude. The red axis shows approximate global mean surface temperature; the Waterbelt states range between 250 and 260 K. These are well separated from the Cold states, which have ice lines between 40° and 50°, and temperatures between 272 and 282 K. Black lines give a schematic sketch of the continuous bifurcation diagram of ice edge versus solar constant, with solid (dashed) lines indicating stable (unstable) branches (the critical value for Snowball deglaciation was not searched for). The two crosses at 1352 W m^{-2} show a sensitivity test on the sea ice thickness diffusion coefficient: a 50% diffusivity increase leads to a stable ice expansion of 1° latitude, while a 100% increase results in a Snowball climate.

Bifurcation and multiple equilibria in the Ridgeworld



Summary... what have we learned?

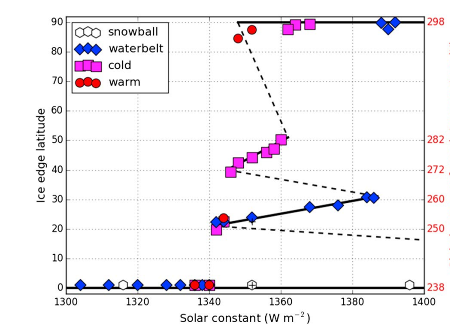
- **Multiple equilibria of ice, oceans and climate found across a hierarchy of models**



- **Stable ice edges occur poleward of wherever OHT convergence is strong. Meridional structure of OHT is key.**

- **Spatial structure of OHT is not fixed! In (long) transients at least, it is tightly coupled to changes in sea ice.**

- **A continuum of different climates is possible for given radiative forcing, depending on meridional structure of OHT.**



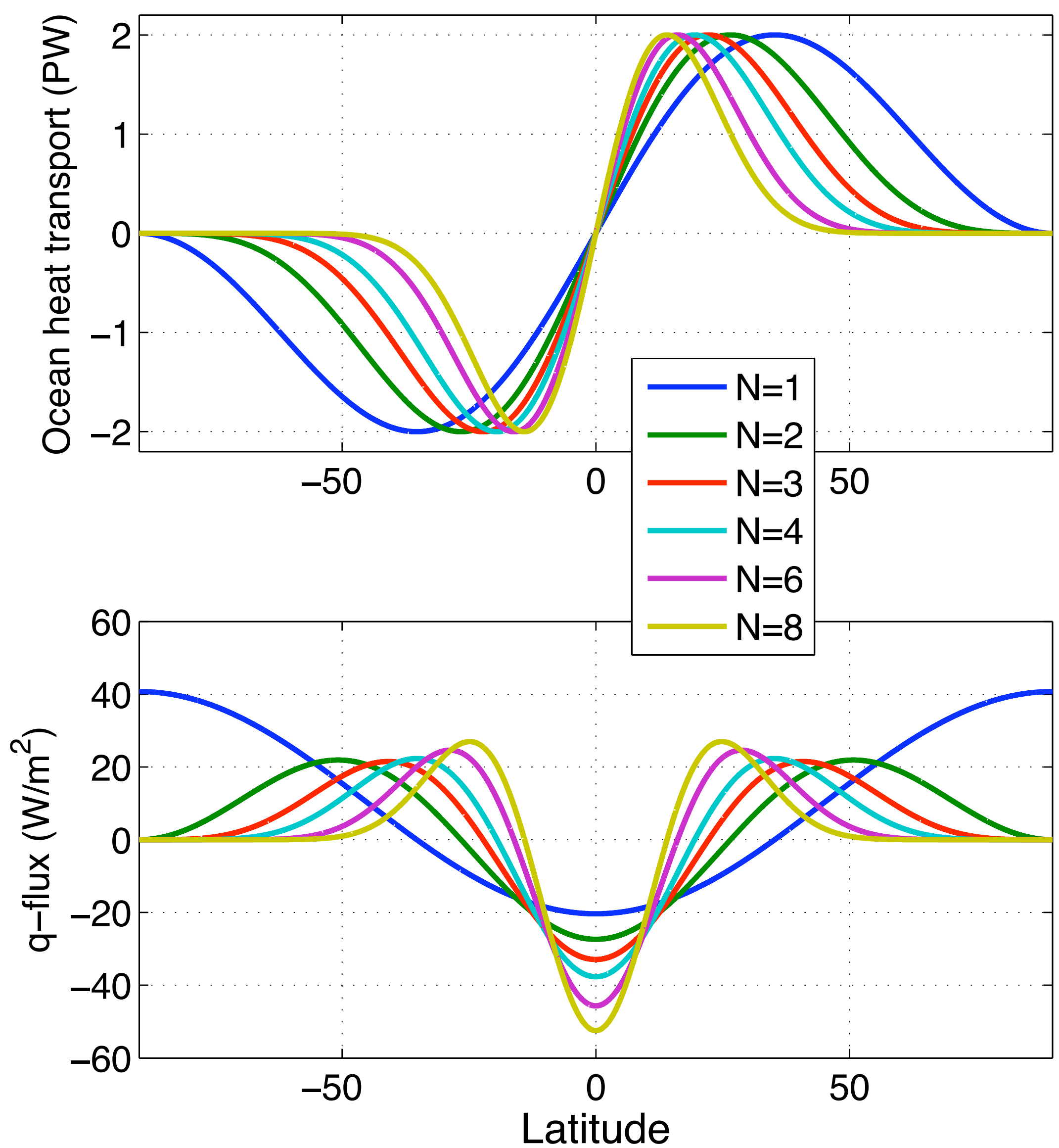
- **A fully coupled atmosphere-ocean-sea ice GCM has four stable states ranging from 100% to 0% ice cover. All four are found for present-day climate forcing and with two different basin geometries.**

- **The Waterbelt is stabilized by equatorward shift of winds and ocean circulation. Narrow, intense OHT by subtropical cells makes it possible. This wind shift is tied to the baroclinicity associated with the ice edge. Thus, the Waterbelt results from three-way coupled wind-ocean-ice feedback.**

- **Freezing over the tropical ocean is hard.** ***Implications for Snowball Earth***

Bonus:
Does ocean heat transport matter in ice-free worlds?

Map out the climatic impact of OHT



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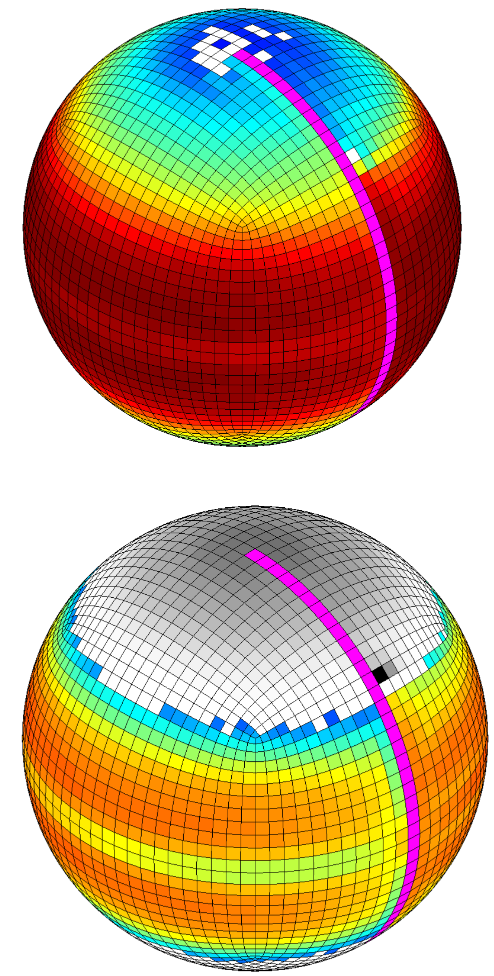

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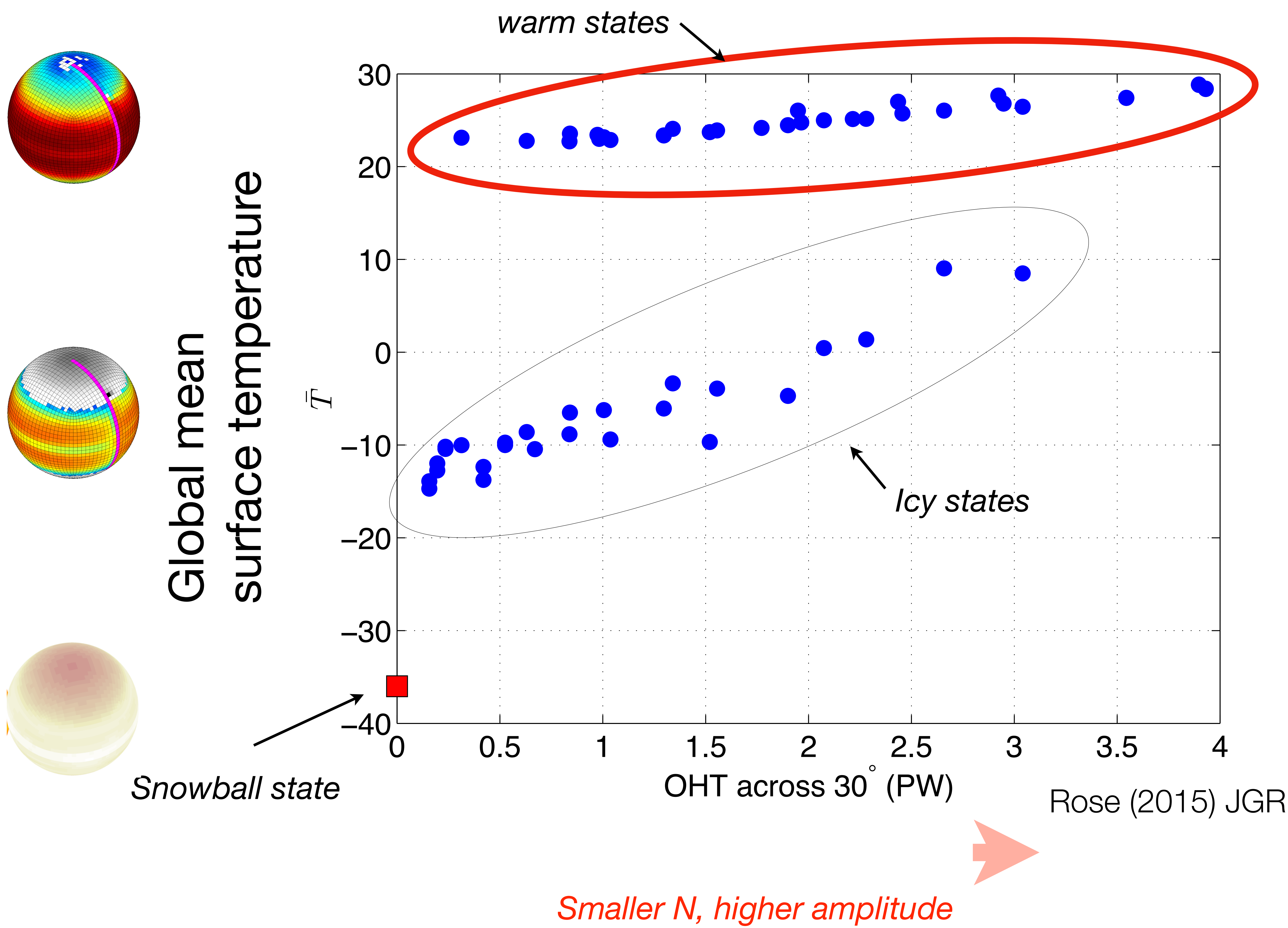
- What is the equilibrium relationship between OHT and sea ice?
- Can we change the number and type of different possible equilibria by varying OHT?



warm states
Global mean surface temperature
$\bar{T}$
30
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−30
−40
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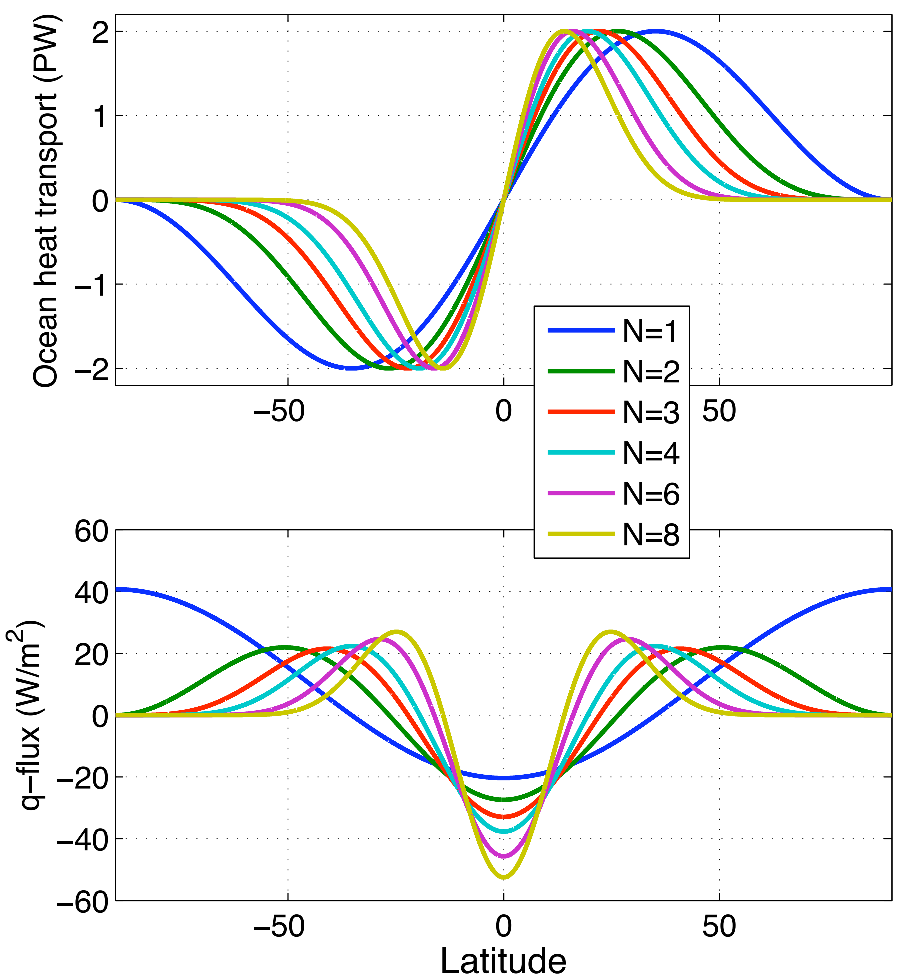
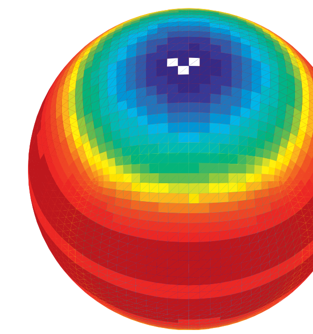
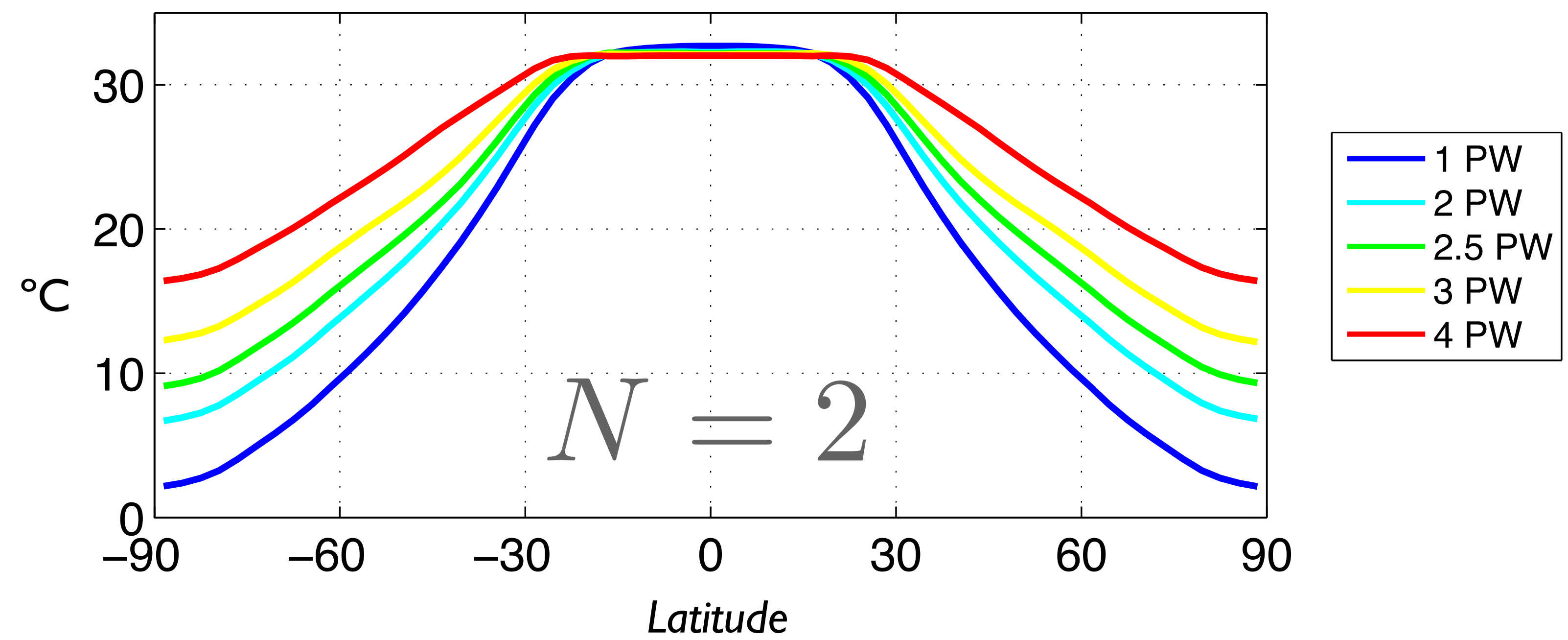
OHT across 30° (PW)
Icy states
Snowball state
Rose (2015) JGR
Smaller N, higher amplitude



In the ice-free regime:





- Increased OHT warms the poles, does not cool the tropics
- No change in **total** (A + O) poleward heat transport (atmosphere compensates)
- In absence of ice, the strongest coupling between OHT and climate is through the distribution of **surface evaporation, moist convection, and clouds**
- Consequent **radiative feedbacks** warm the planet!
  - Rose and Ferreira (2013), *J. Climate*
  - Rencurrel and Rose (2018), *J. Climate*

Work by Cameron Rencurrel:
Same q-flux experiments in a more comprehensive GCM

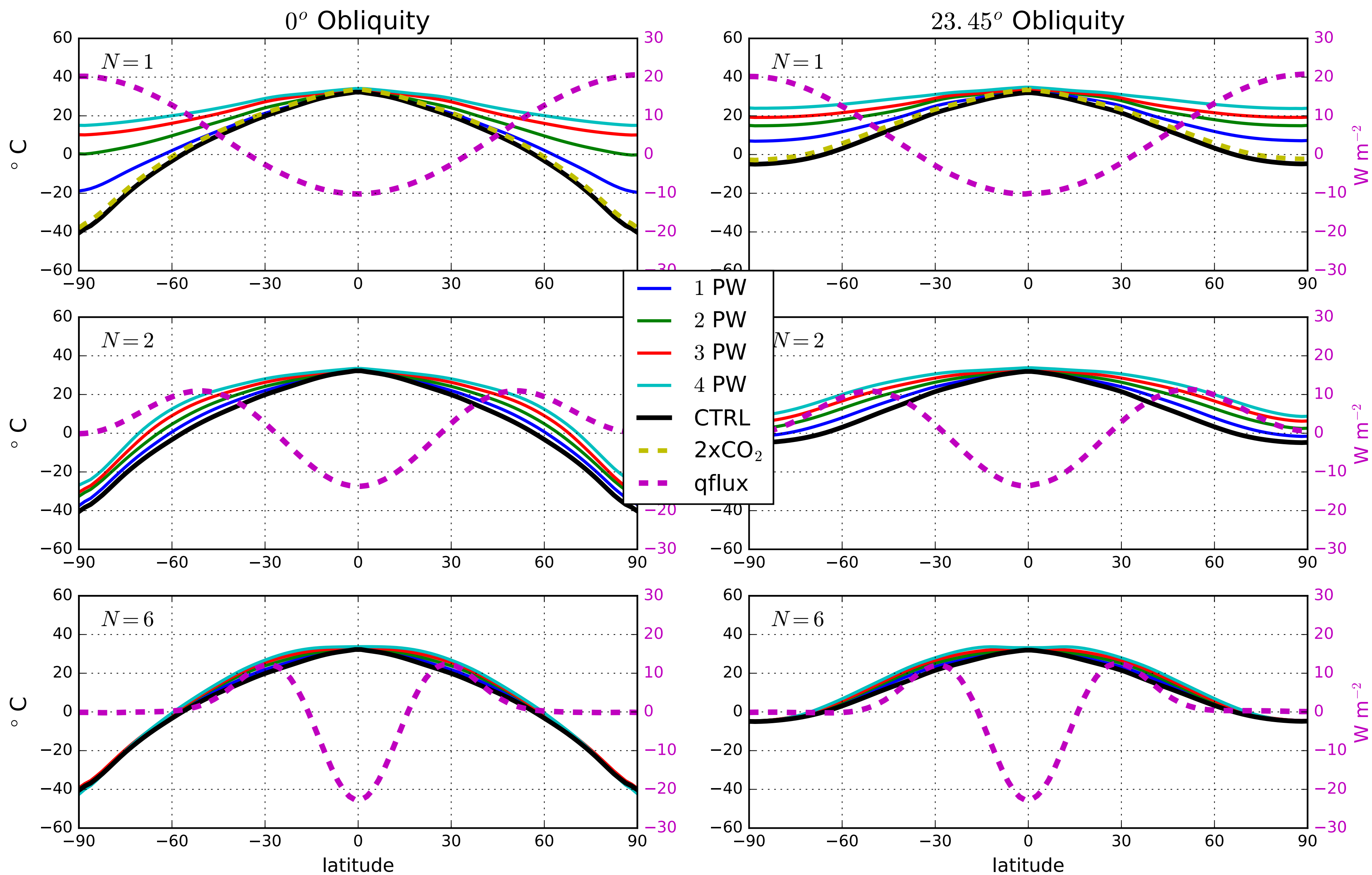


FIG. 2. Zonal, annual mean SST vs latitude as a function of amplitude for 0° (left) and 23.45° (right) obliquity. Each panel has a fixed meridional scale parameter N as indicated. The dashed magenta lines show the spatial pattern of the q-flux (plotted in W m^{-2} for a 1 PW peak transport). Dashed yellow lines (plotted in the $N = 1$ panels only) show the effects of doubling CO_2 from the zero-OHT control states.

Rencurrel and Rose (2018) *J. Climate*

References

- Rencurrel and Rose (2018), Exploring the climatic response to wide variations in ocean heat transport on an aquaplanet. J. Climate (in press), doi:10.1175/JCLI-D-17-0856.1
- Rose, BEJ, TW Cronin and CM Bitz (2017), Ice Caps and Ice Belts: The Effects of Obliquity on Ice−Albedo Feedback. Astrophys. J. 846, doi:10.3847/1538-4357/aa8306
- Rose, BEJ (2015), Stable “Waterbelt” climates controlled by tropical ocean heat transport: a non-linear coupled climate mechanism of relevance to Snowball Earth. J. Geophys. Res. 120, doi: 10.1002/2014JD022659
- Rose, BEJ, D Ferreira and J Marshall (2013), The role of oceans and sea ice in abrupt transitions between multiple climate states. J. Climate 26, 2862-2879.
- Rose, BEJ and D Ferreira (2013), Ocean heat transport and water vapor greenhouse in a warm equable climate: a new look at the low gradient paradox. J. Climate 26, 2117-2136.
- Ferreira, D, J Marshall and BEJ Rose (2011): Climate determinism revisited: multiple equilibria in a complex climate model. J. Climate. 24, 992-1012.
- Rose, BEJ and J Marshall (2009): Ocean heat transport, sea ice, and multiple climate states: insights from energy balance models. J. Atmos. Sci. 66, 2828-2843.