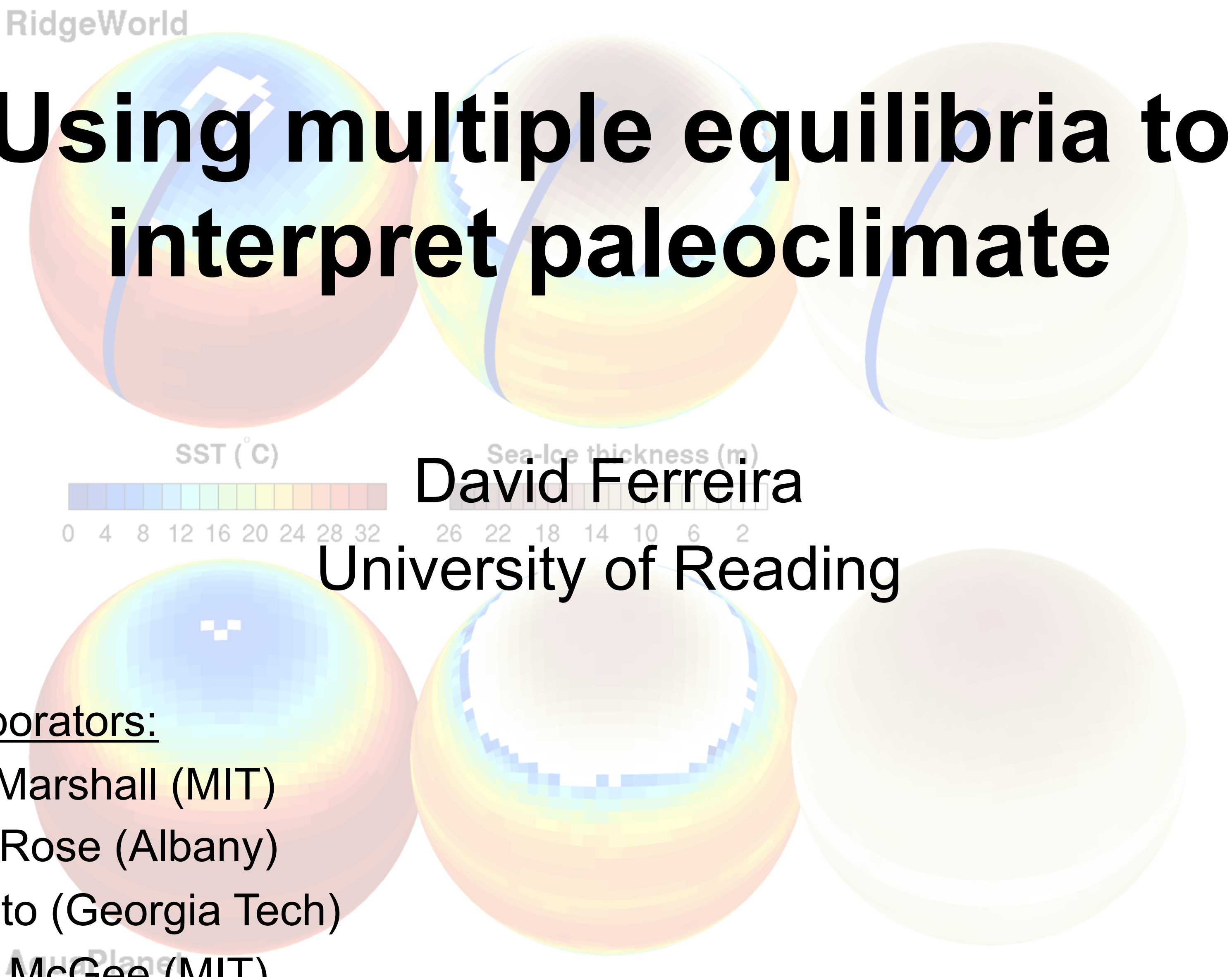
Using multiple equilibria to interpret paleoclimate



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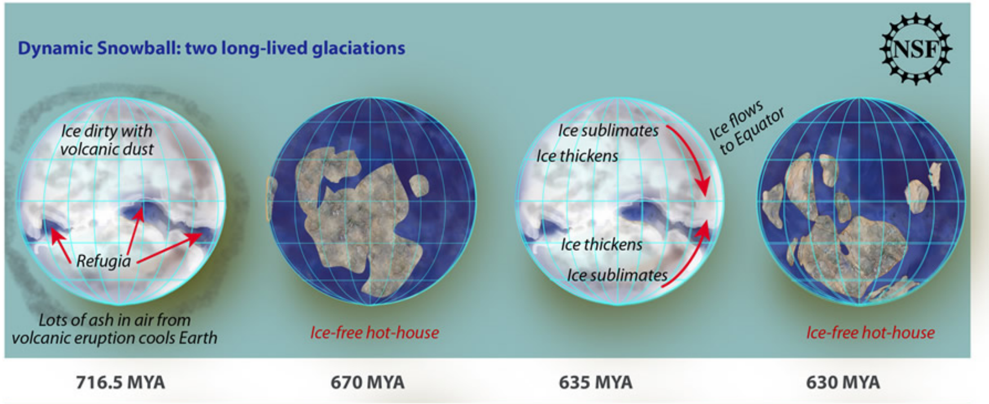
David McGee (MIT)

Outline

- Paleoclimate context
- Quick summary of multiple state dynamics
- Dynamics of transitions, link with DO events
- Glacial-interglacial states
- Stochastic resonance and GI cycles
- Bonus track

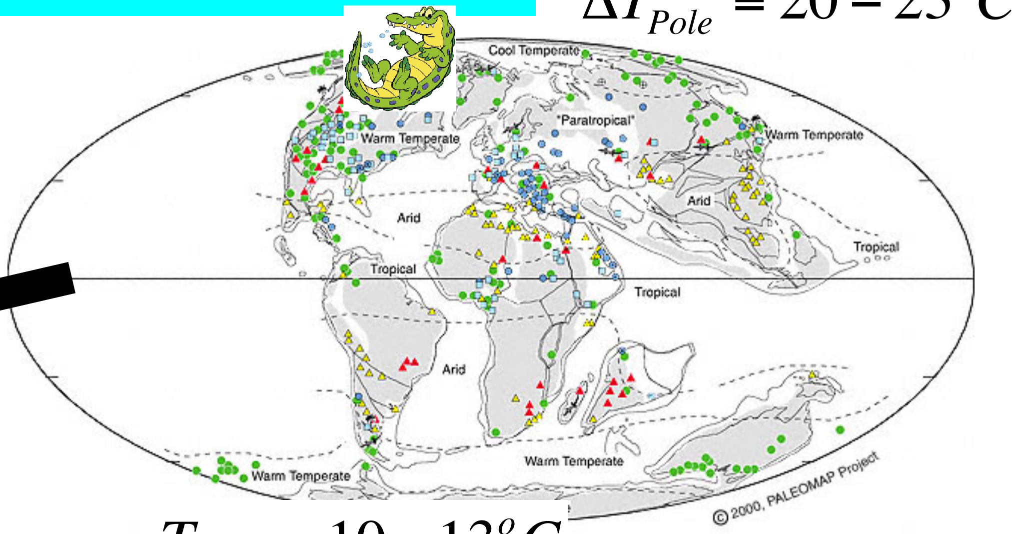
Geology and paleoproxies indicate Earth climate went through very different states



Neoproterozoic Snowball Earth

Ice-free Cretaceous

$$\Delta T_{Pole}^{Eq} = 20 - 23^{o} C$$

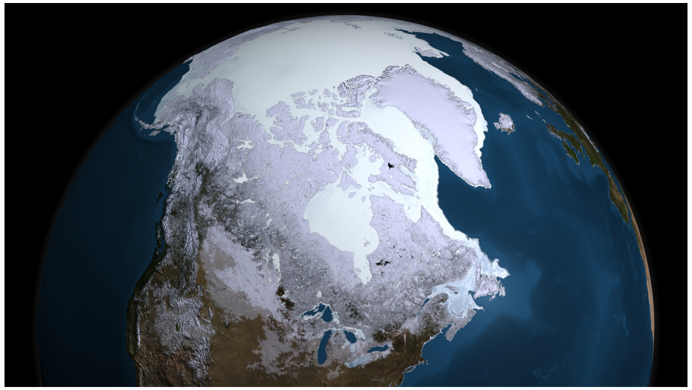


$$T_{Deep} = 10 - 13^{o} C$$

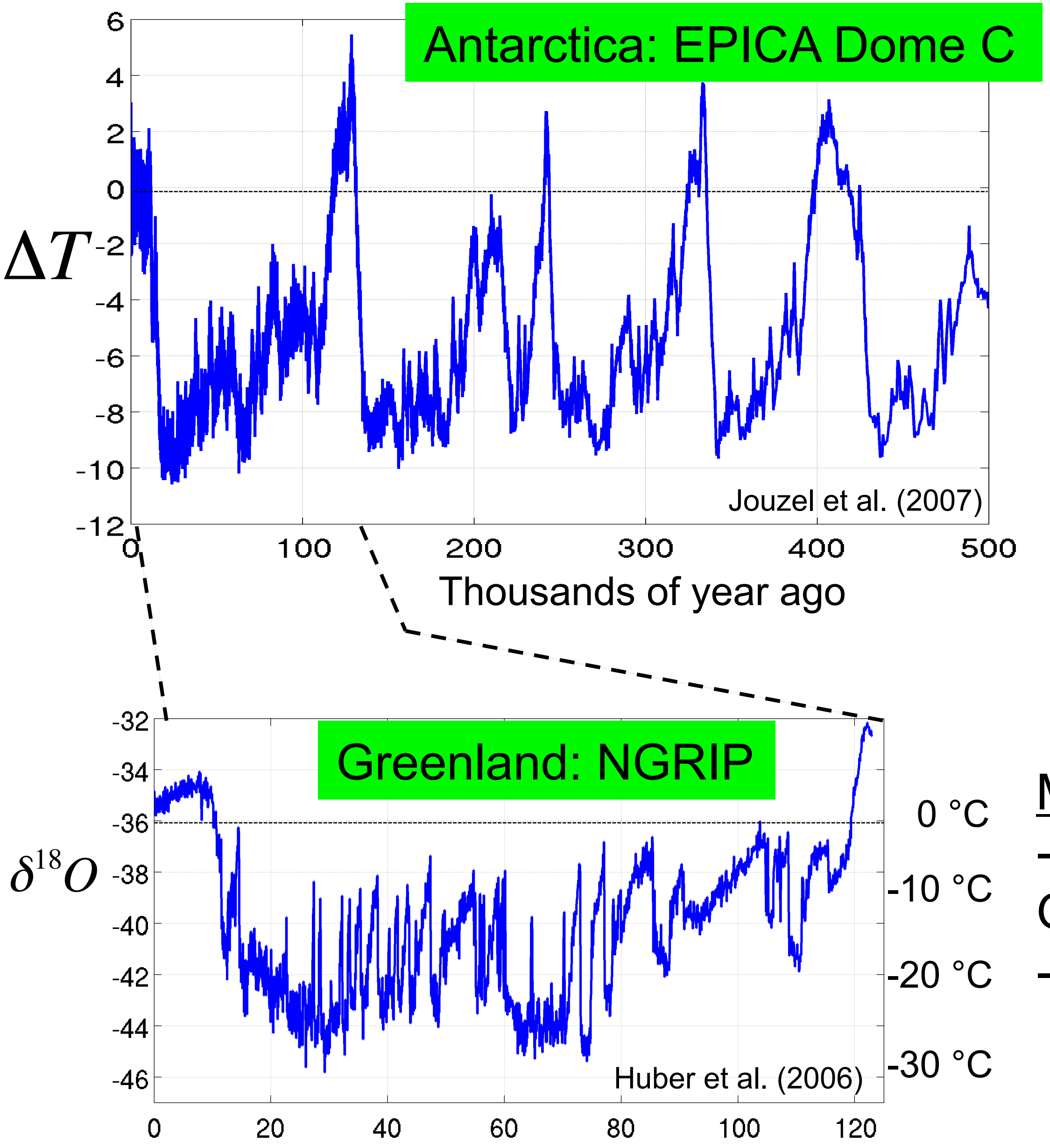
ous

“Moderate” present-day

$$\Delta T_{Pole}^{Eq} = 30 - 35^{o} C$$



Glacial-Interglacial cycles



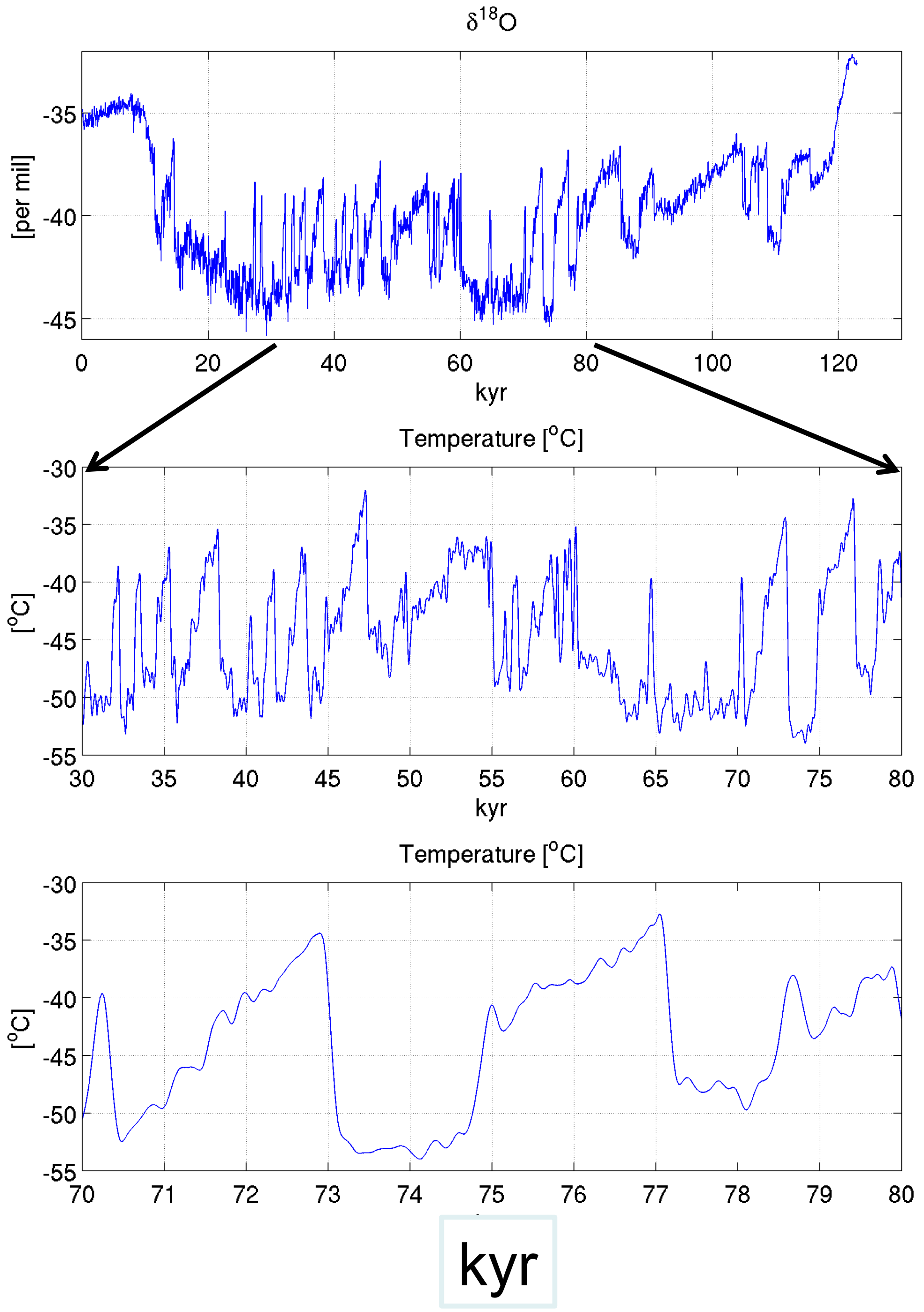
- Massive global climate shifts
  → large ice sheets over Canada/ US and Scandinavia (~120 m sea level drop)
  → a few deg. global cooling

- Missing link between forcing (Milankovitch cycles?) and climate response

<u>Millenial timescale fluctuations</u>

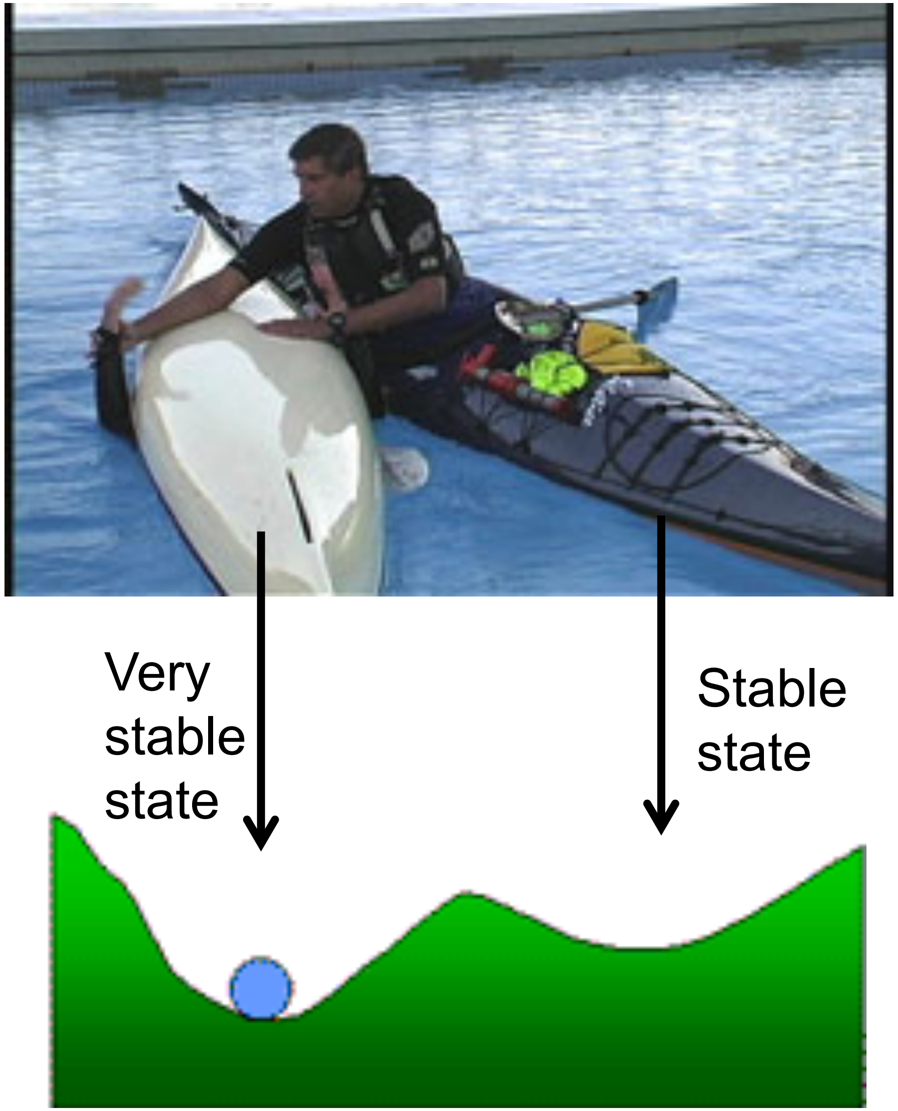
- @ Greenland: amplitude ~ Glacial-Interglacial
- Larger in North Atlantic

Dansgaard-Oeschger events
(DO events)



Greenland ice core record

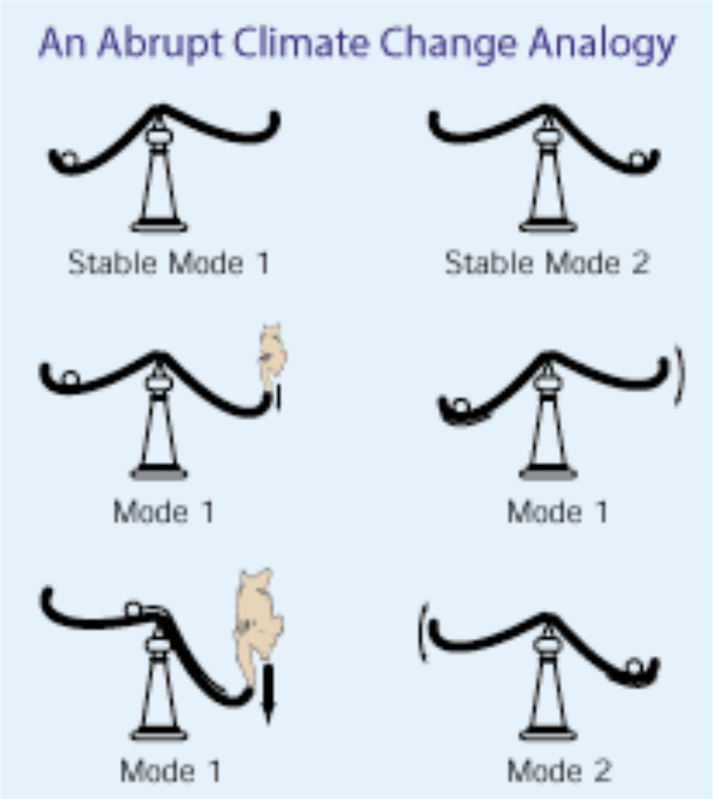
Multiple equilibrium states and abrupt changes



Very stable state

Stable state

A small forcing may trigger a large/abrupt change:



Can multiple equilibria play a role in Earth's climate history?

→ There have been many studies in this direction: Benzi et al. (1982) and Paillard (1998), Saltzman et al., Gildor and Tzipermann et al., etc.

Problem: multiple equilibria are commonly found in simple models, but not always/not easily found in complex coupled climate models.

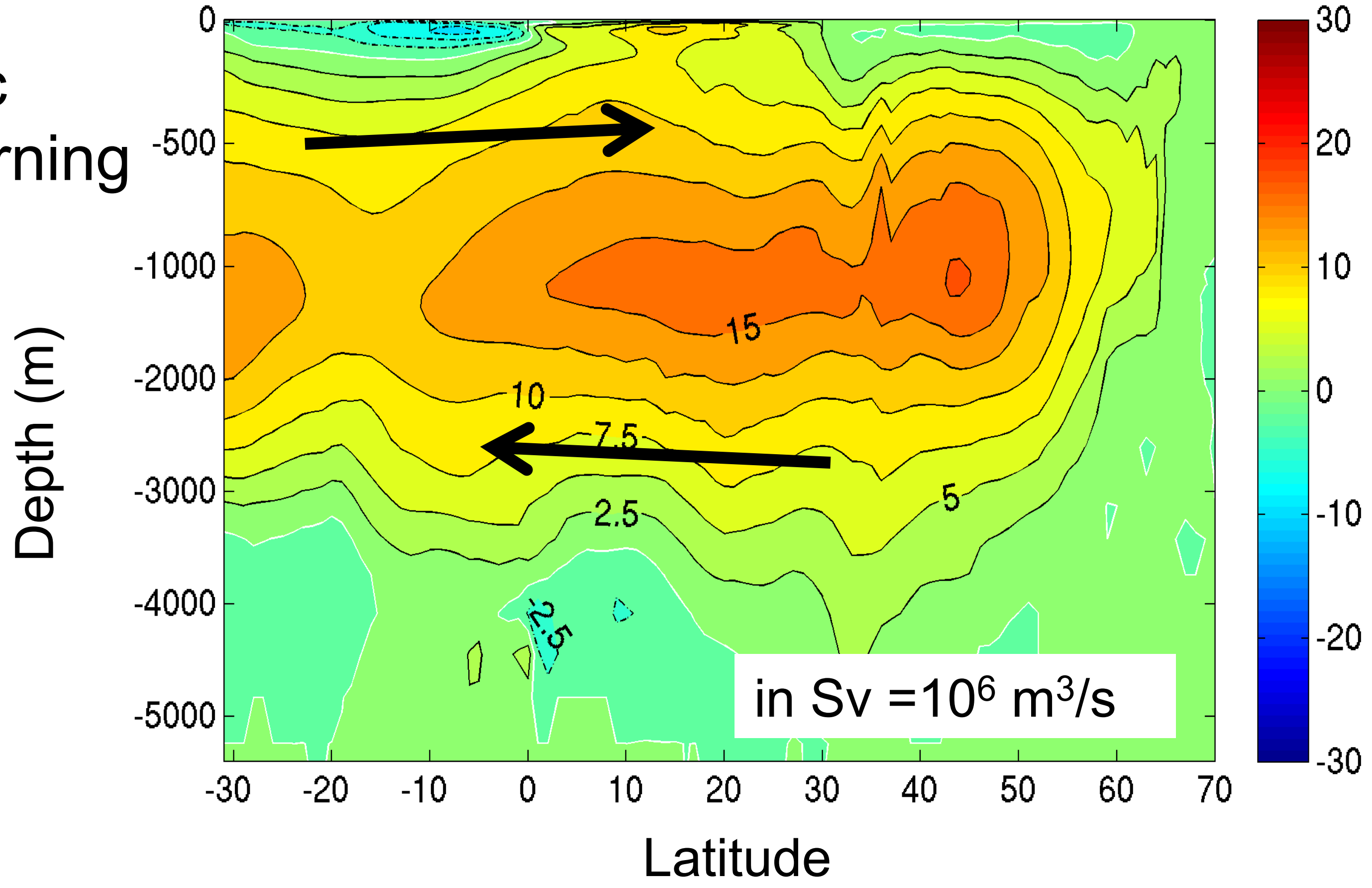
→ simple/low order models: (semi-)analytical models

→ GCMs: from intermediate complexity (e.g. zonally averaged models to state-of-the-art IPCC class models)

Multiple equilibrium states in low-order models

1 Multiple states of the Meridional Overturning Circulation

Atlantic Overturning



in Sv $=10^6$ m^3/s

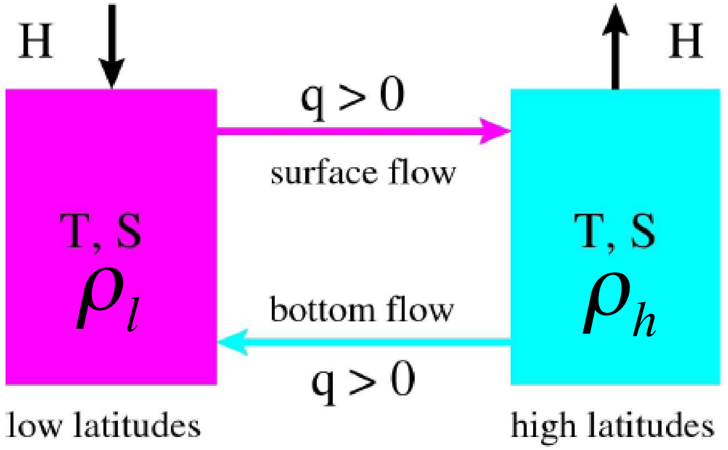
See Ferreira et al. (2018) for why there isn't a Pacific equivalent

OCCA Ocean state estimate (Forget, 2009)

Multiple equilibrium states in low-order models, II

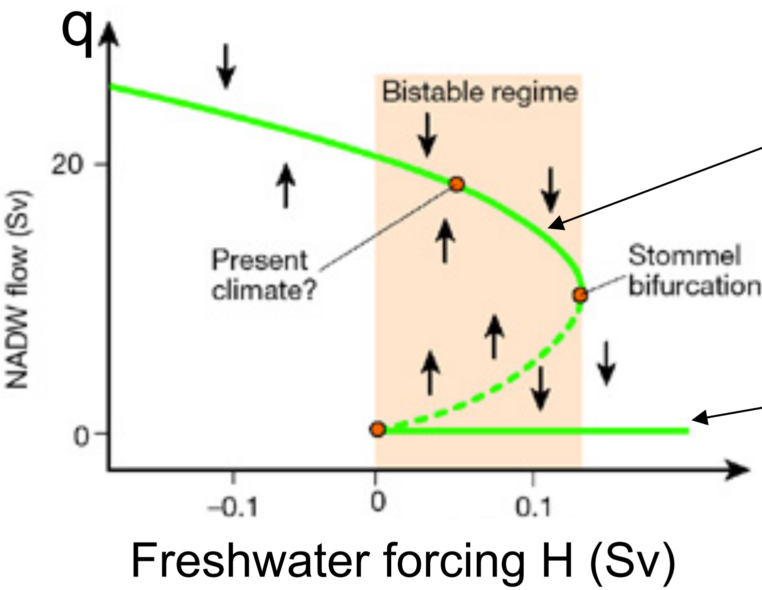
1 Multiple states of the Meridional Overturning Circulation

Stommel (1961)



Density-driven flow $q = k(\rho_h - \rho_l)$

$$\rightarrow |q|(1-q) - H = 0$$



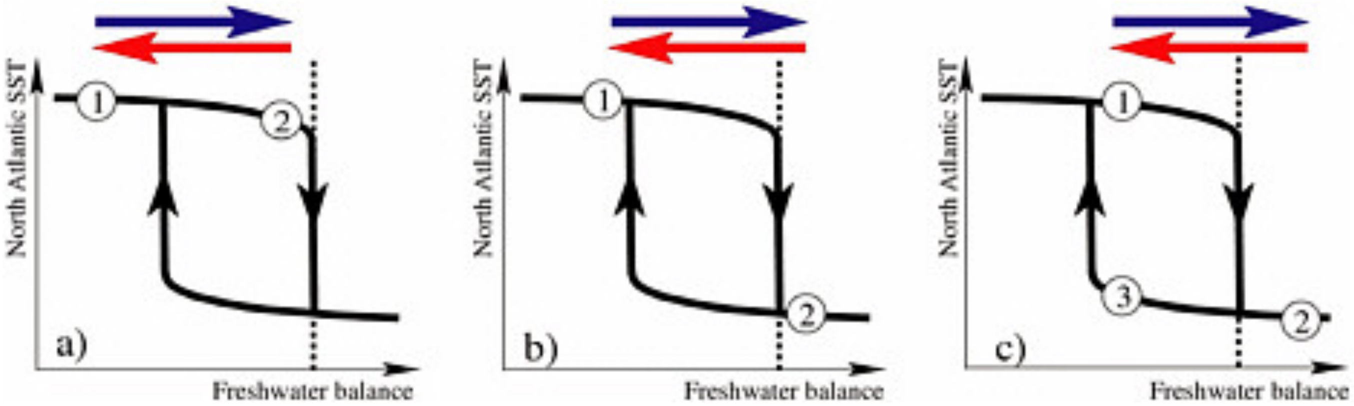
“On” branch: thermal mode

“Off” branch: haline mode

Rahmstorf (2002)

Multiple equilibrium states in low-order models

1 Multiple states of the Meridional Overturning Circulation

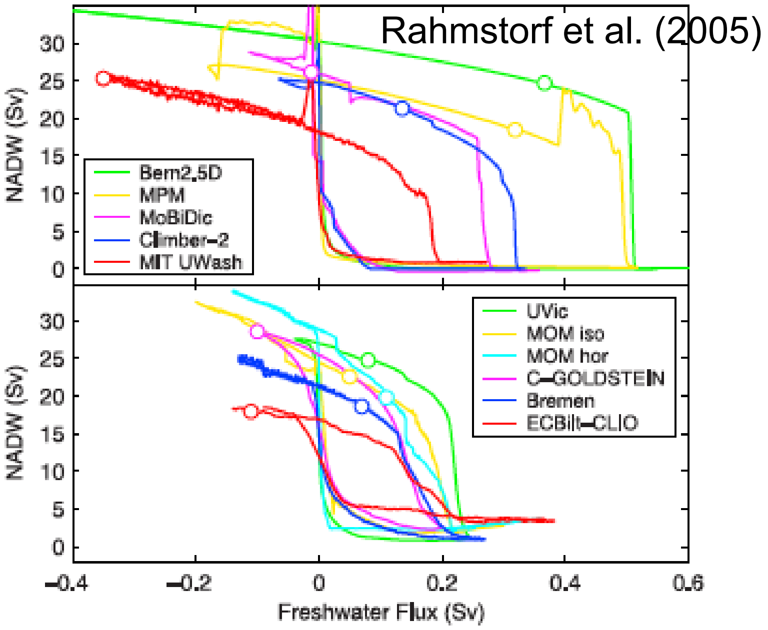


→ Widely used to interpret past abrupt changes (Broecker et al. 1985, Knutti et al, 2004)

→Easy to find in coupled GCMs of intermediate complexity (Water-hosing experiment,)

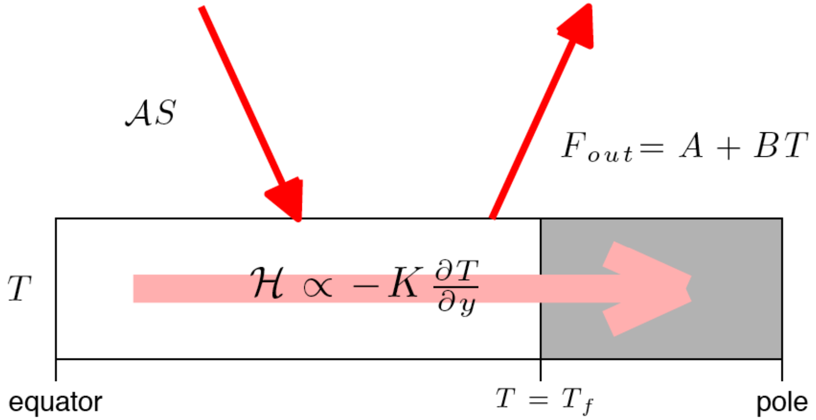
→Less obvious in IPCC-class GCMs (but, see Mecking et al. 2016)

→Freshwater forcing difficult to reconcile with estimates from paleoproxies (~ 0.1 Sv)


Rahmstorf et al. (2005)

Multiple equilibrium states in low-order models

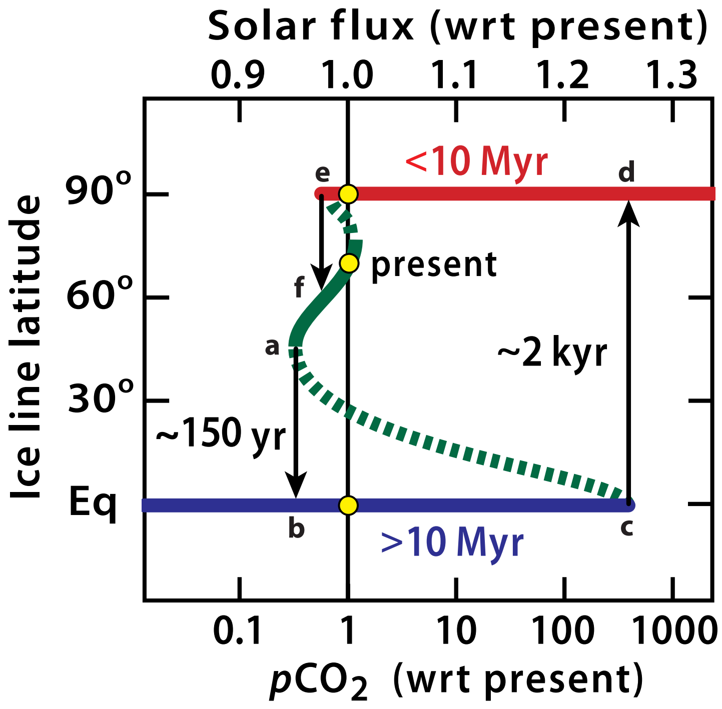
2 Sea ice-albedo feedback: Budyko-Sellers Energy Balanced Model (EBM)



Simple Energy Balance Model

Rose and Marshall (2009)

Hoffman et al. (2017)

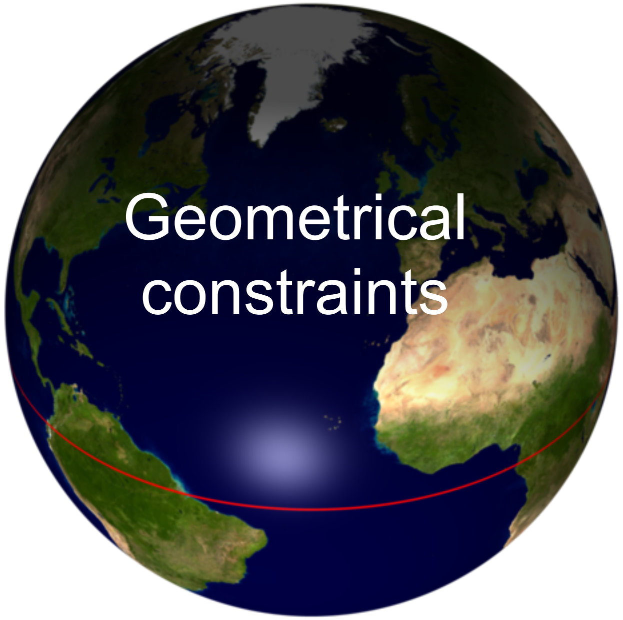


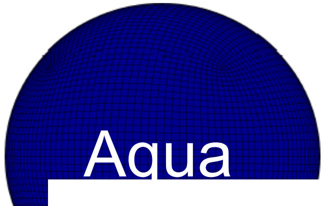
Few examples in GCMs:

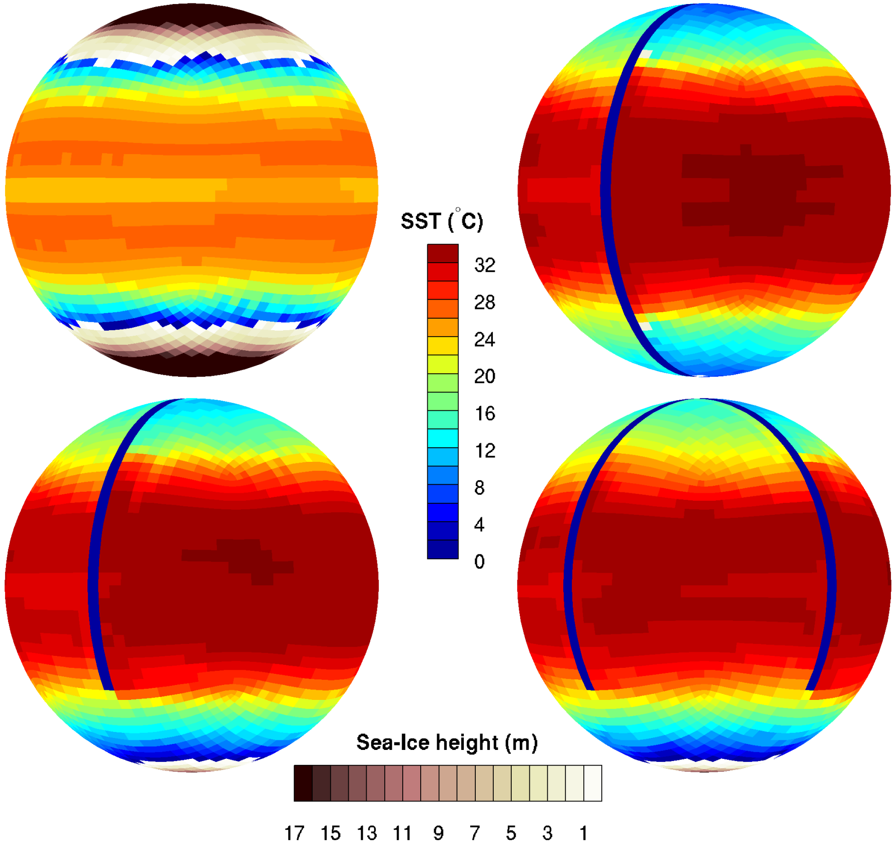
- Langen and Alexev (2004): atmosphere only GMC
- Marotzke and Bozet (2006): a warm state and a Snowball state

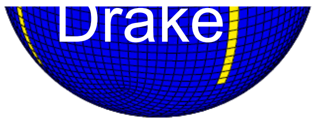
Modeling approach

MIT GCM: Ocean-Atmosphere-Sea ice:





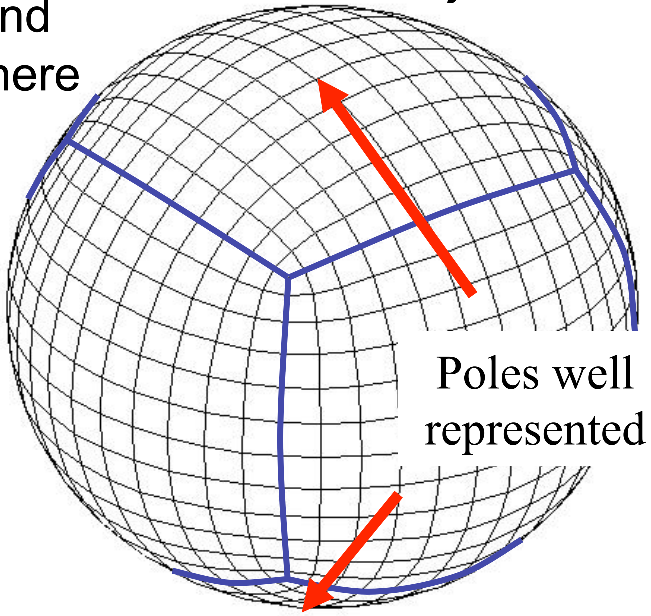




How much can we explain with dynamics and simple geometries ?

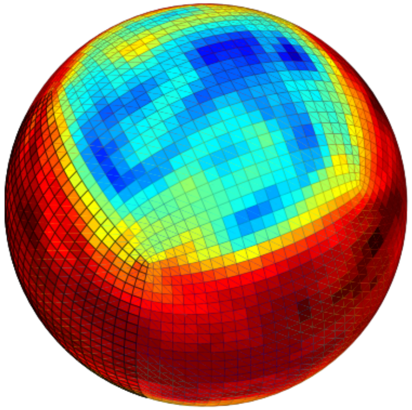
MIT GCM: Coupled Ocean-Atmosphere-Sea ice:

- Primitive equation models,
- Cube-sphere grid: ~3.75º,
- Synoptic scale eddies in the atmosphere,
- Gent and McWilliams eddy parameterization in the ocean,
- Simplified atmospheric physics (SPEEDY, Molteni 2003),
- Conservation to numerical precision (Campin et al. 2008)


Same grid for ocean and atmosphere

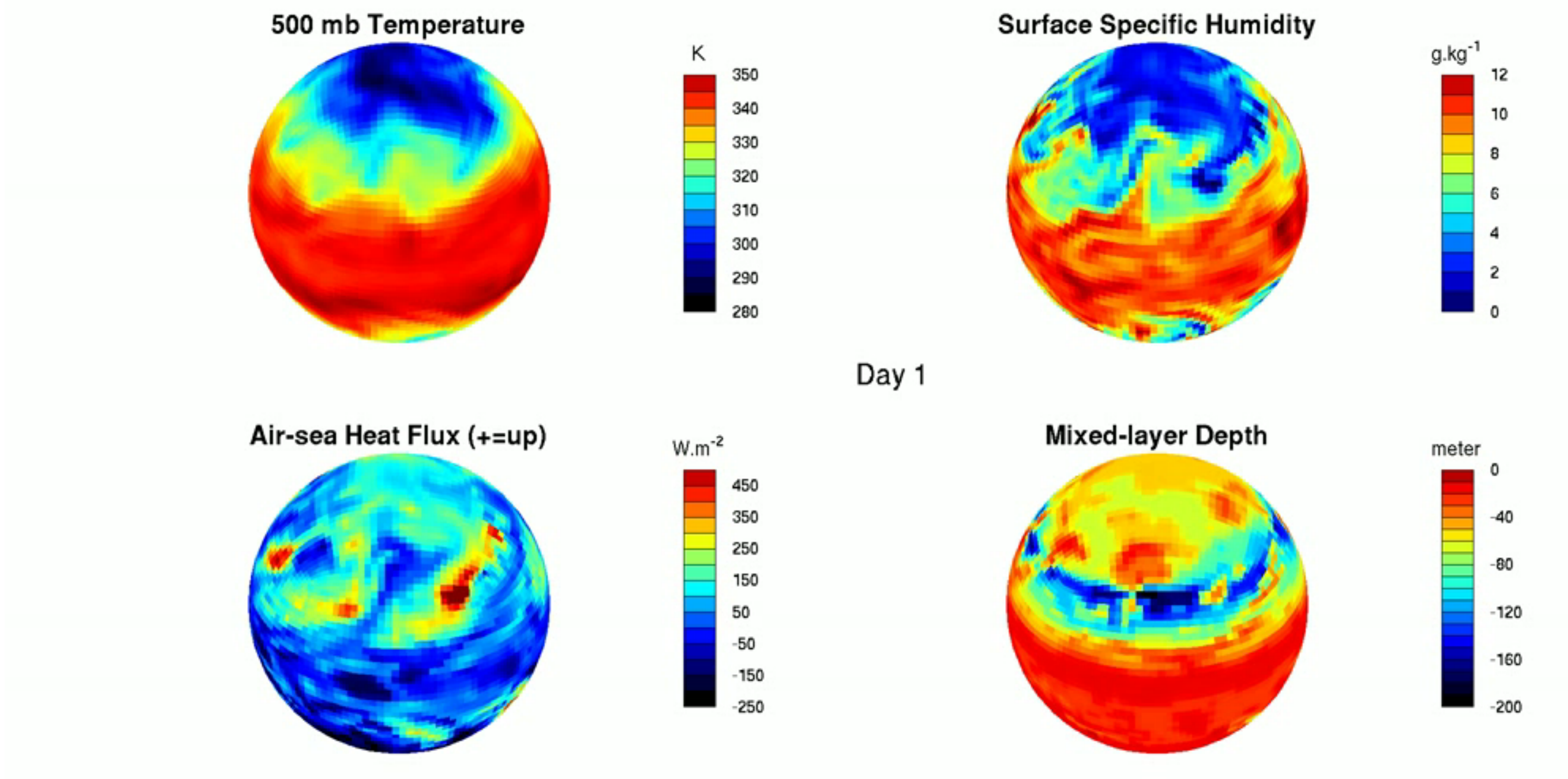
Fully coupled: no adjustments

Poles well represented


Temperature snap-shot at 500 mb.

Model complexity: Big step compare to EBM models

Idealized geometries but complex dynamics



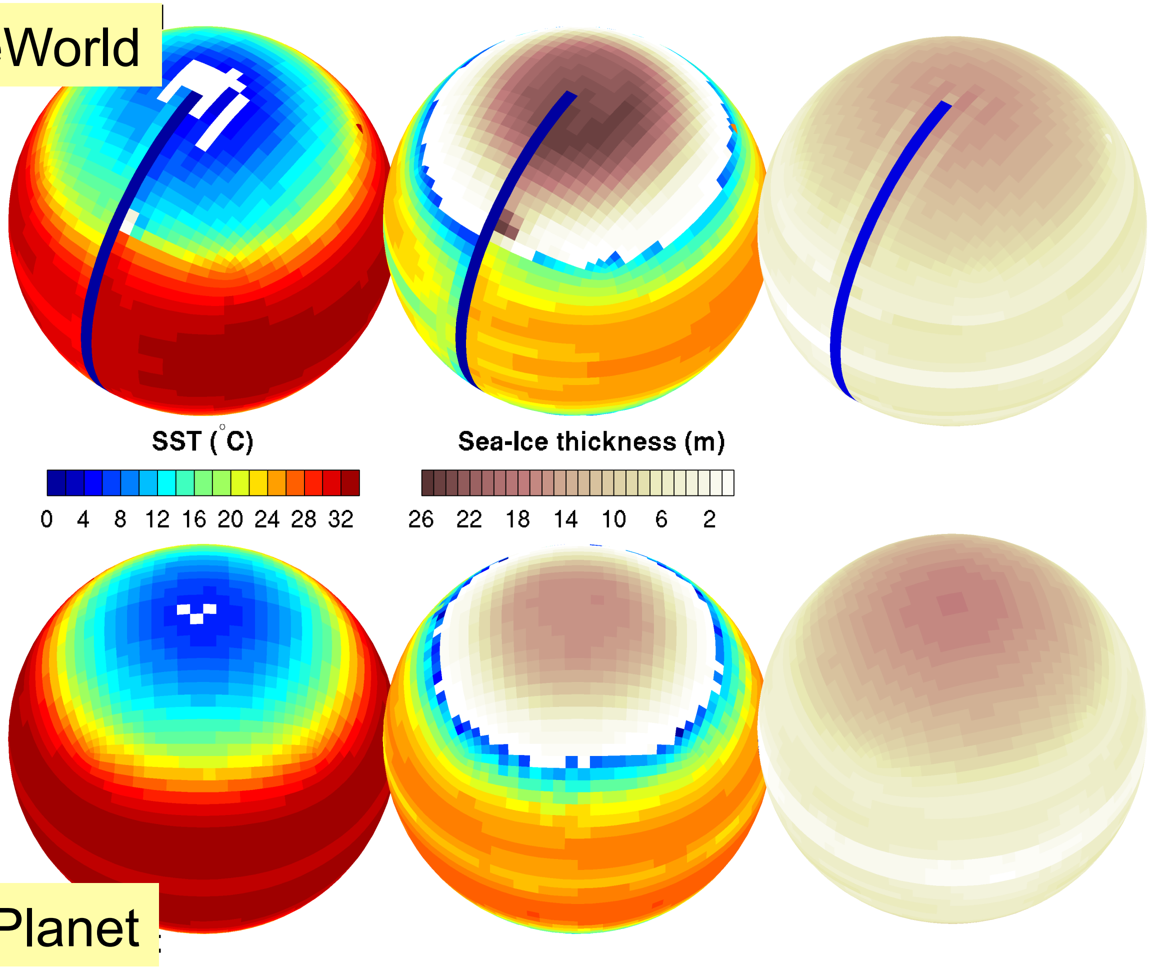
→ Not a low order model

Starting with highly idealized configurations

Warm state

Cold state

Snowball state



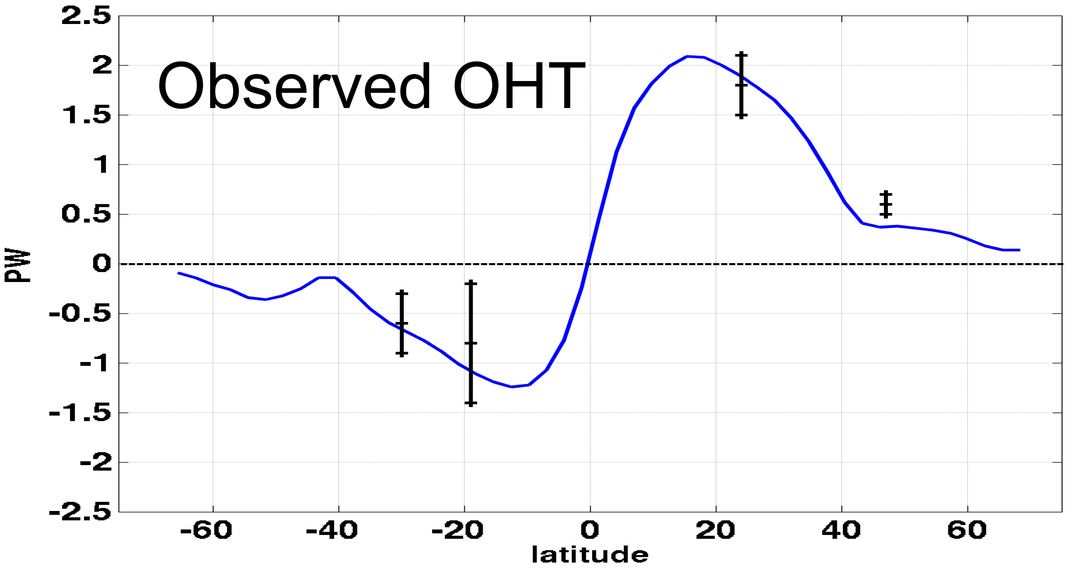
Stable states for thousands of year

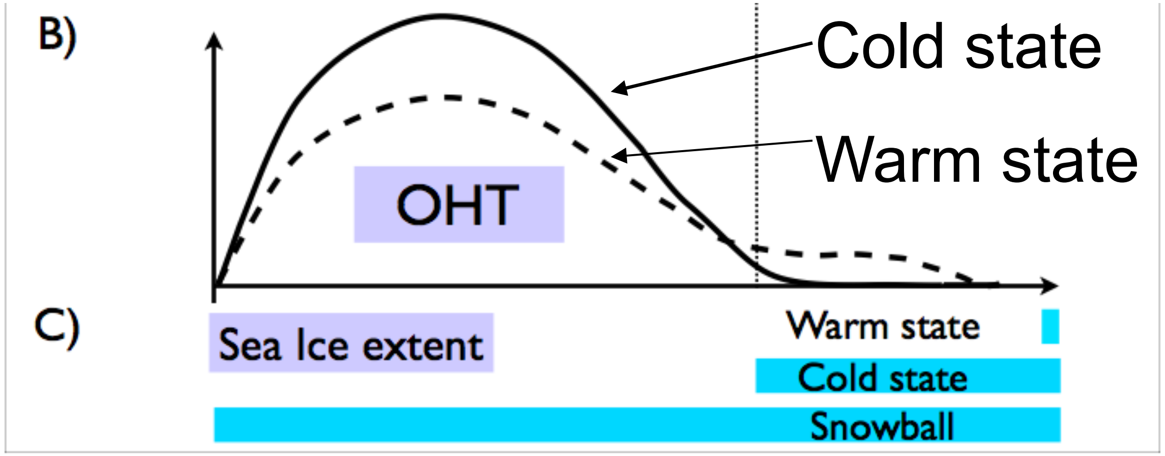
Ferreira et al. 2011

$\Delta T^{Eq}_{Pole} = 28^oC$ $\Delta T^{Eq}_{Pole} = 55^oC$

How are the multiple states maintained ?

It’s the shape of the OHT !





Cold State: OHT convergence arrests sea-ice expansion

Warm State:
OHT heats the poles remotely through enhanced mid-latitudes convection and green-house effect

Ferreira et al. (2011), Rose and Ferreira (2012)

Ocean-Atmosphere EBM

Key differences with the “classical” EBM (Rose and Marshall, 2009):

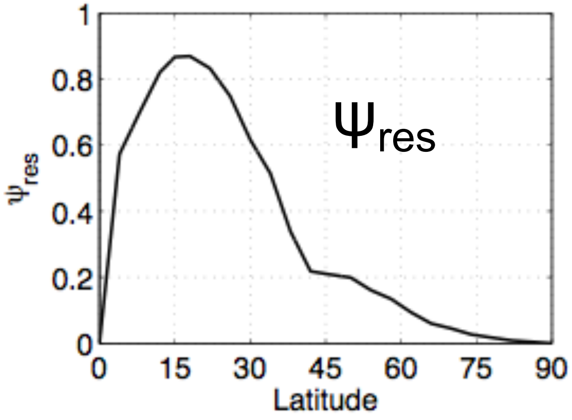
- A coupled ocean-atmosphere EBM,
- OHT has a meridional structure,
- sea ice insulates the ocean.

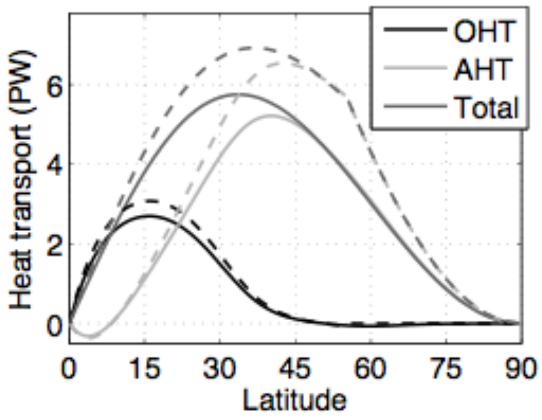
$$C_a \frac{\partial T_a}{\partial t} = D_y\left(C_a K_a \frac{\partial T}{\partial y}\right) + F_{up} - F_{out}$$

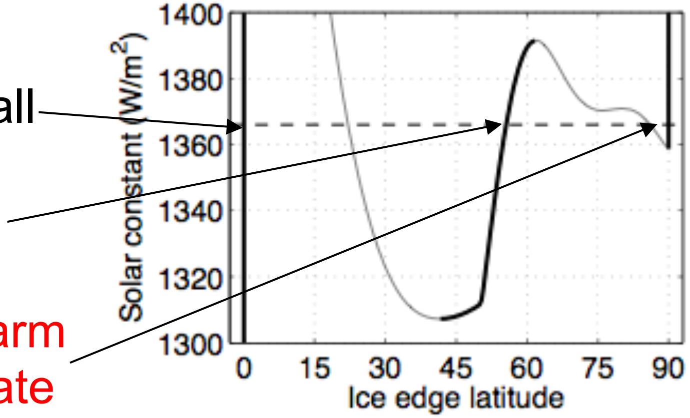
$$C_o \frac{\partial T_o}{\partial t} = D_y\left(H_o\right) - F_{up} + \Lambda \times S$$

OHT not diffusive but linked to (effective) MOC:

$$H_o \infty \psi_{res}\left(\frac{T_s - T_{deep}}{\Delta z}\right)$$







Snowball

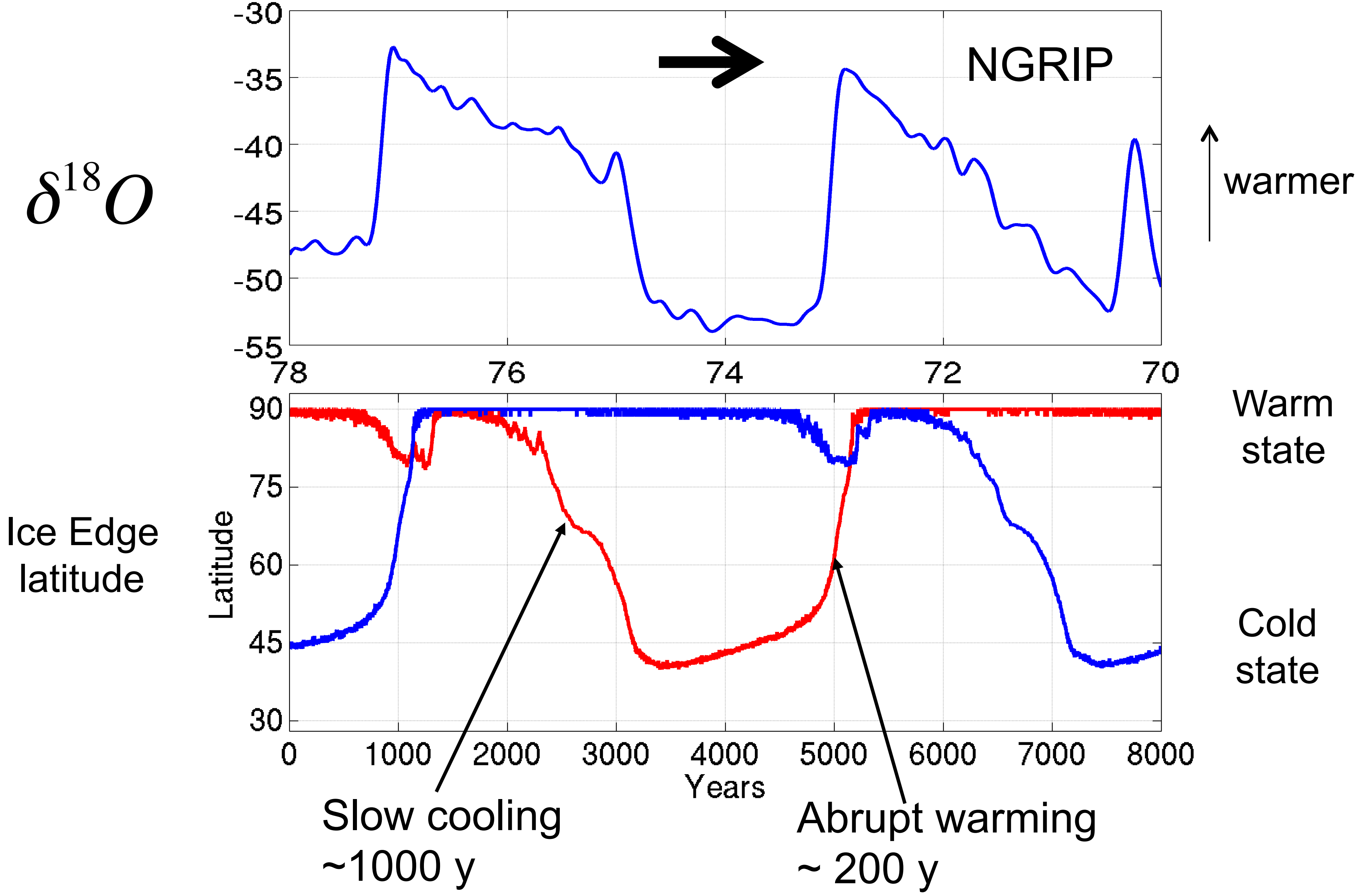
Cold state

Warm state

Transition between states

RidgeWorld

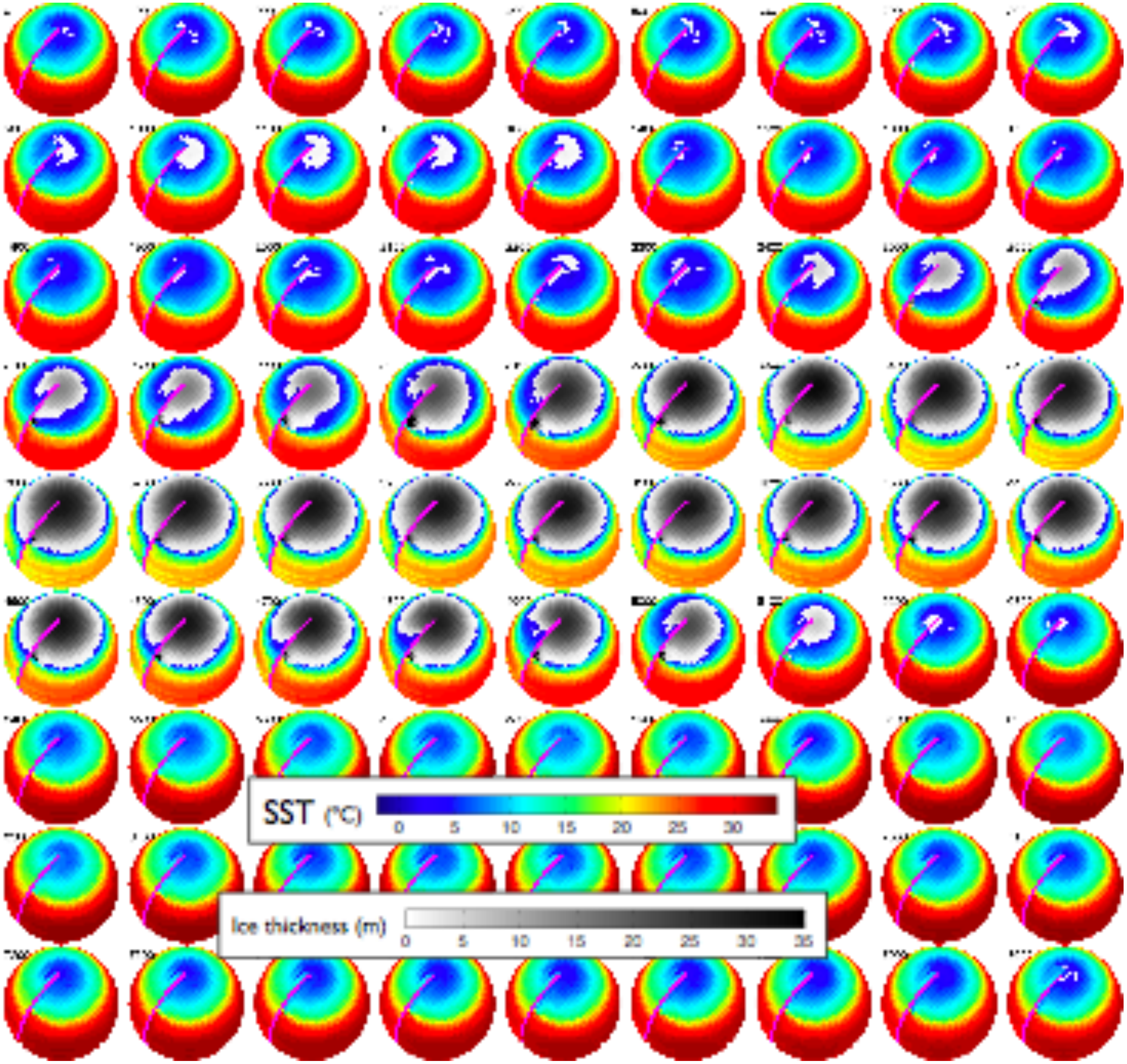
Rose et al. 2012



Slow cooling ~1000 y

Abrupt warming ~ 200 y

SST and Sea ice



Rose et al. 2012

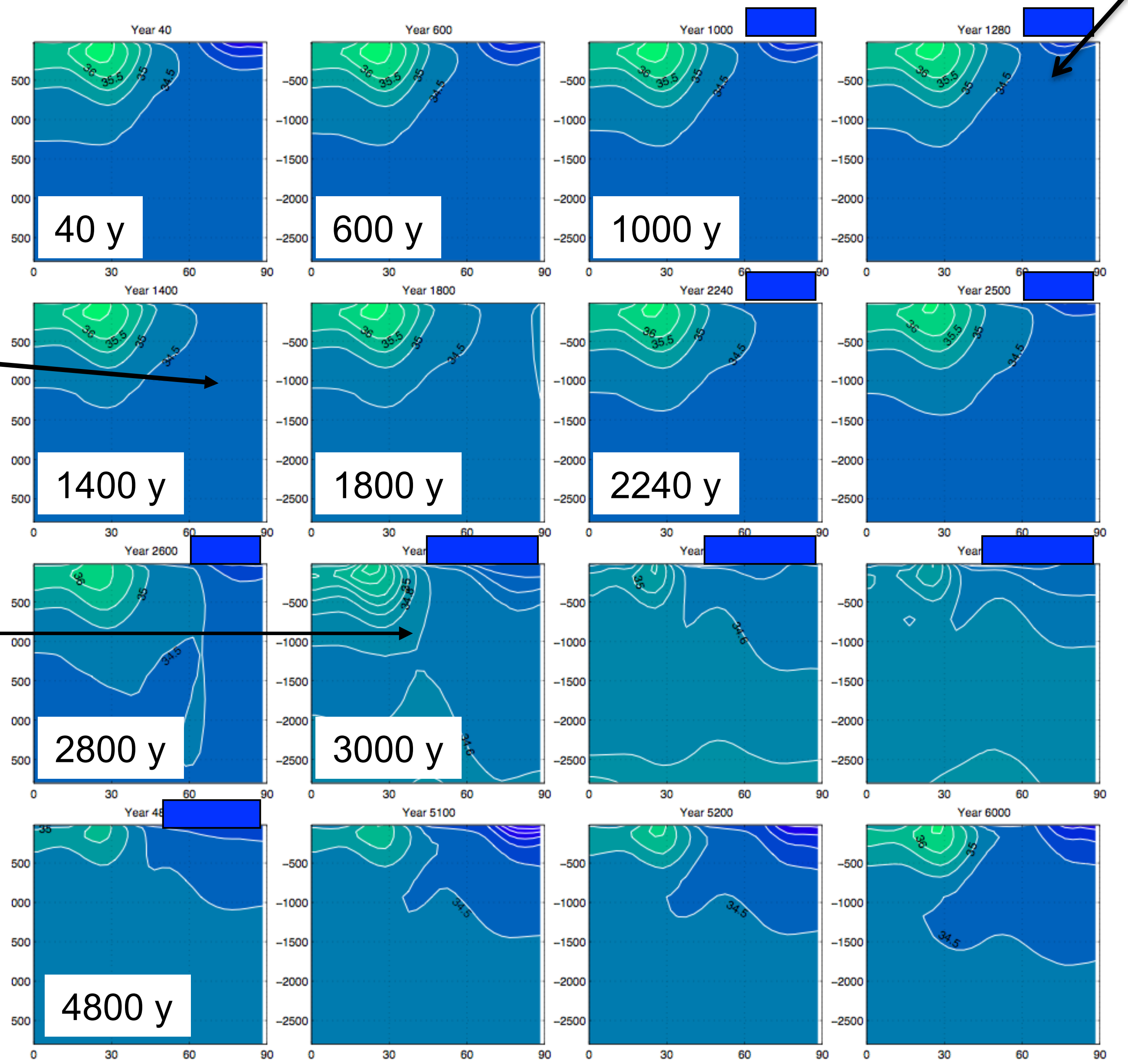
Evolution of Salt

Start from
Warm State

deep
convection

Peak of
glaciation

Ice grows
Brine rejection



40 y

600 y

1000 y

1400 y

1800 y

2240 y

2800 y

3000 y

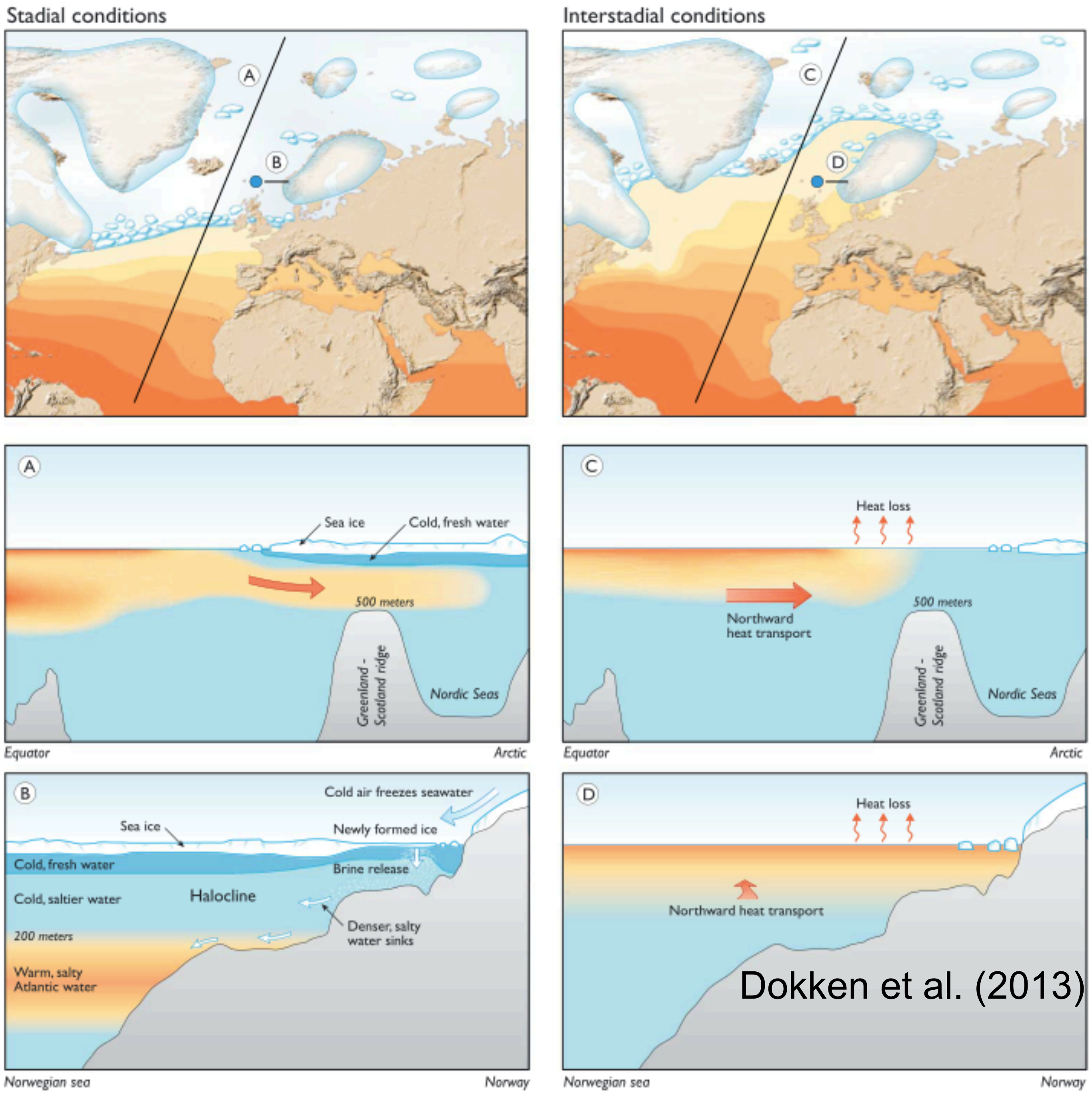
4800 y

Rose et al. 2012

Scenario from paleoproxies

→ Suggest an ocean/sea ice instability

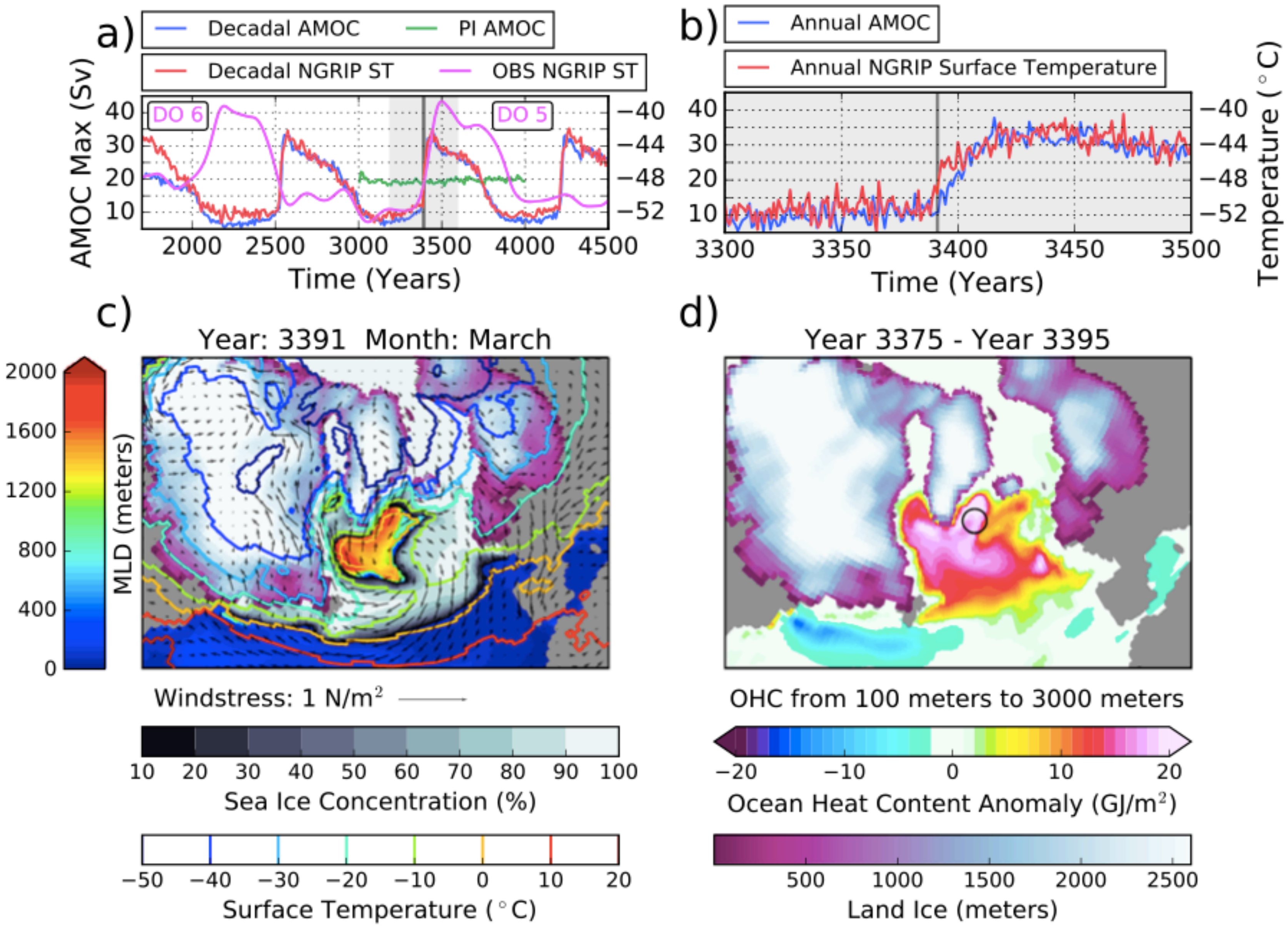
→ Does rely on AMOC on/off behavior



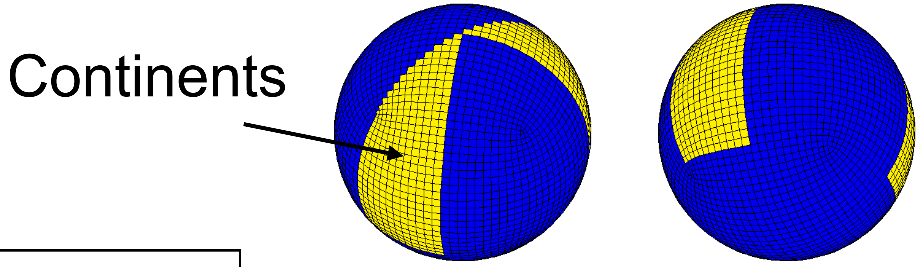
Dokken et al. (2013)

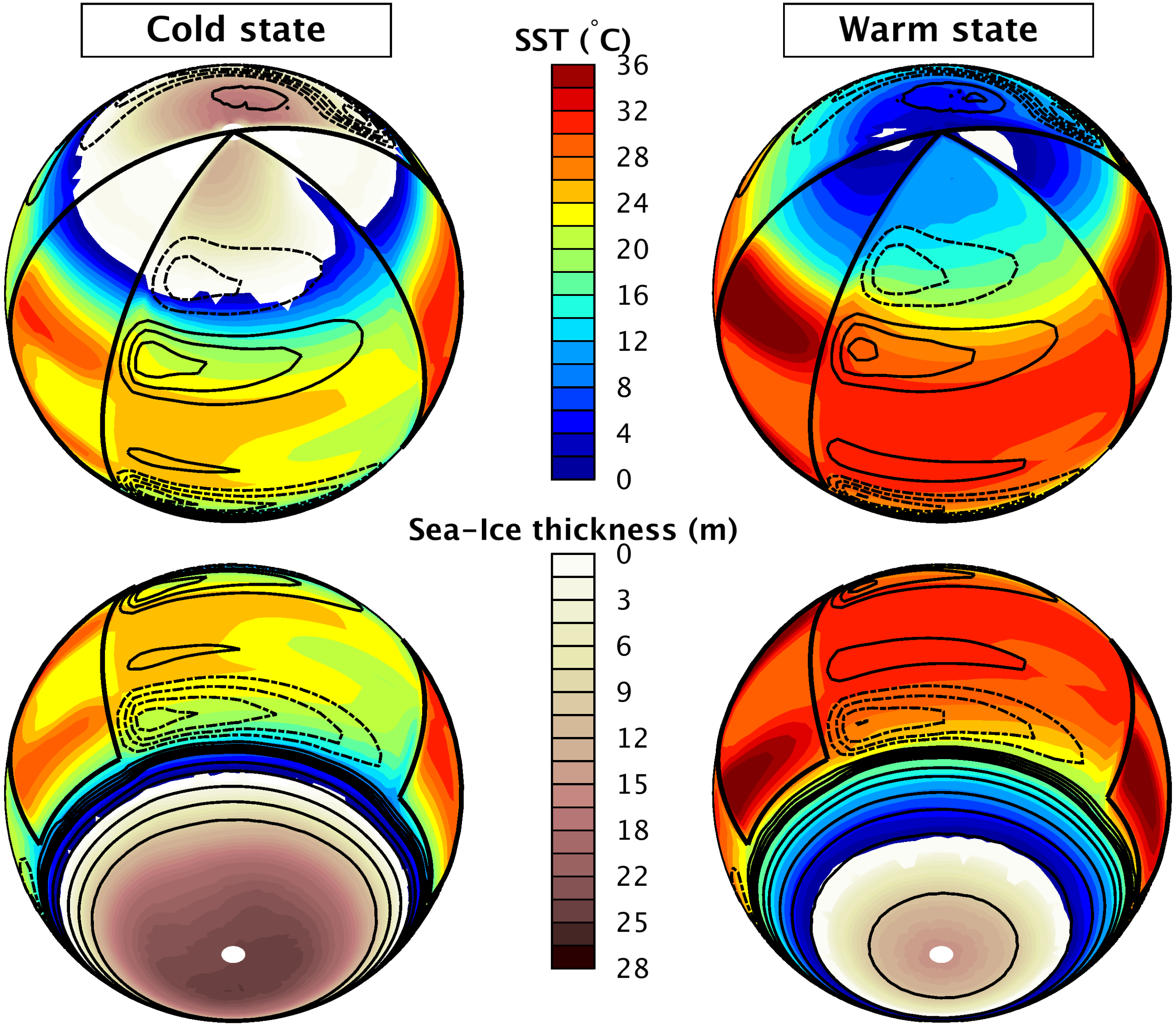
Self-sustained oscillations of ocean/sea ice system

Vettoreti and Peltier (2016)



Boomerang





- ΔSST = 8.2 °C
- ΔSAT = 13.5 °C

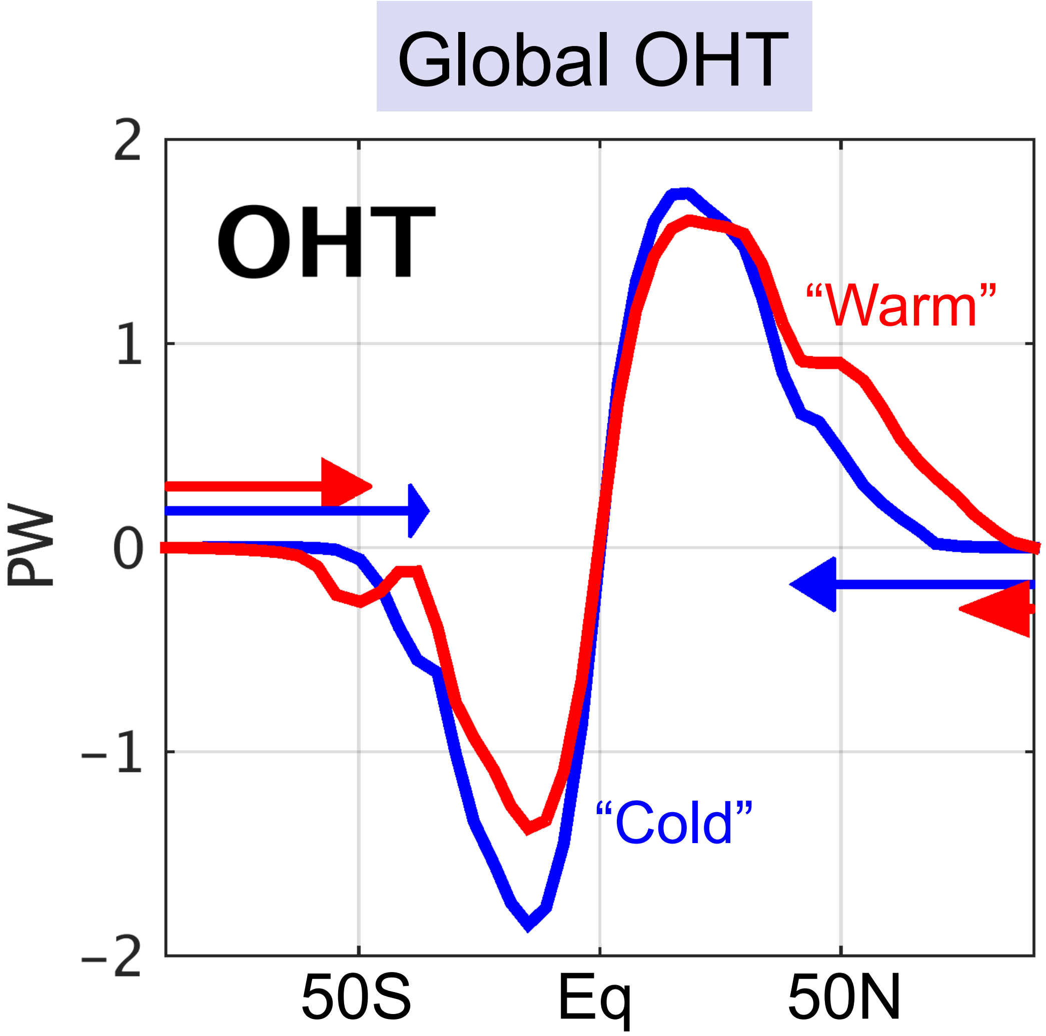
- SH sea ice: +14° in Winter

- NH sea ice cap grows to ~45°N

- Atm. pCO_2 : -108 ppm

(from 265 to 157 ppm).

OHT/sea ice edge relationship in “Boomerang”



→Ice edges rest poleward of the large mid-latitudes OHT convergences

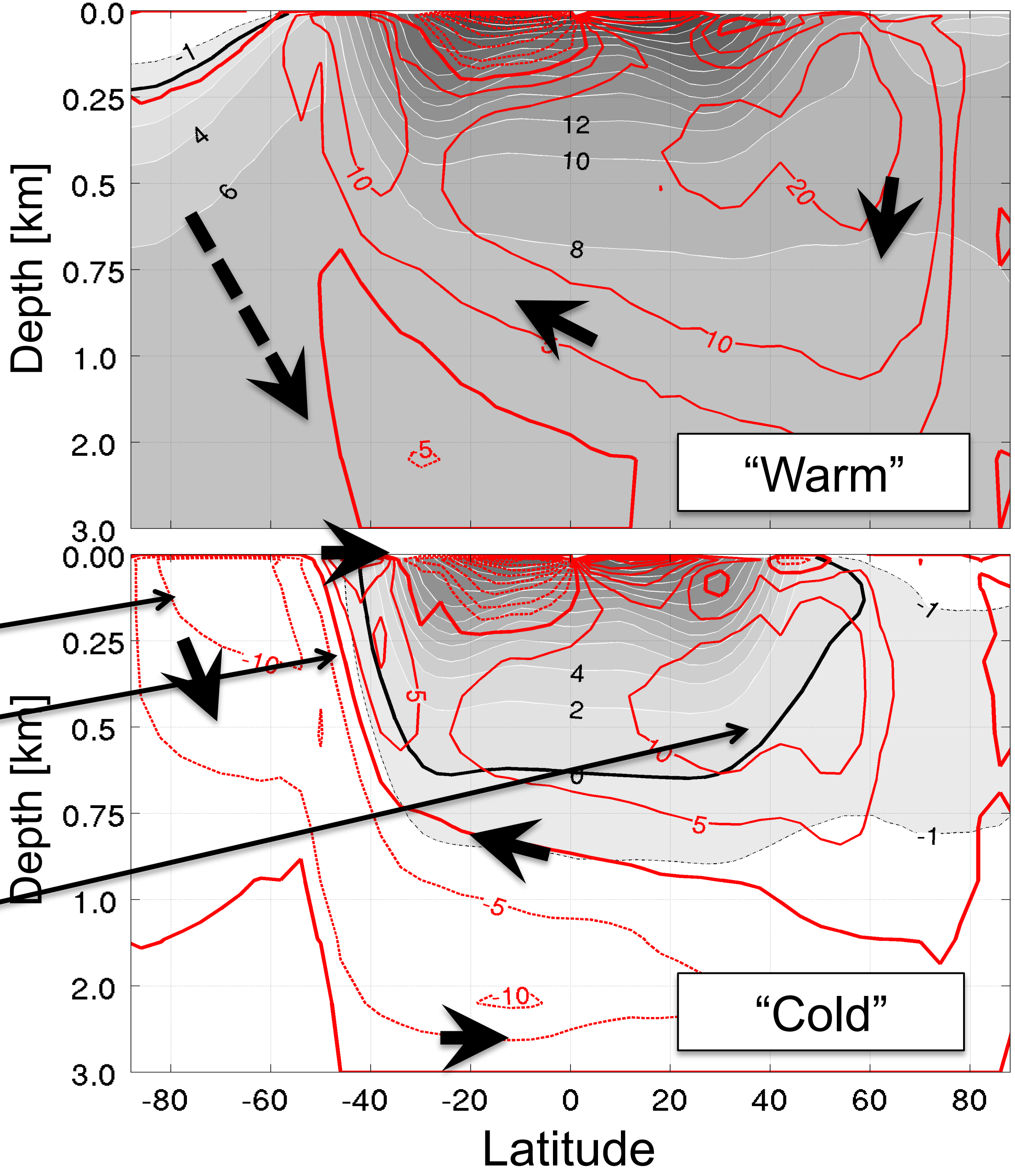
→ Multiple states emerge from Northern Hemisphere

Global MOC and Temperature

Ventilation of deep ocean shifts to the southern ocean:

"Cold" state bottom waters:

- colder: -1.5°C, ~freezing point
- saltier (+0.5 psu)
- See Adkins et al. (2002)

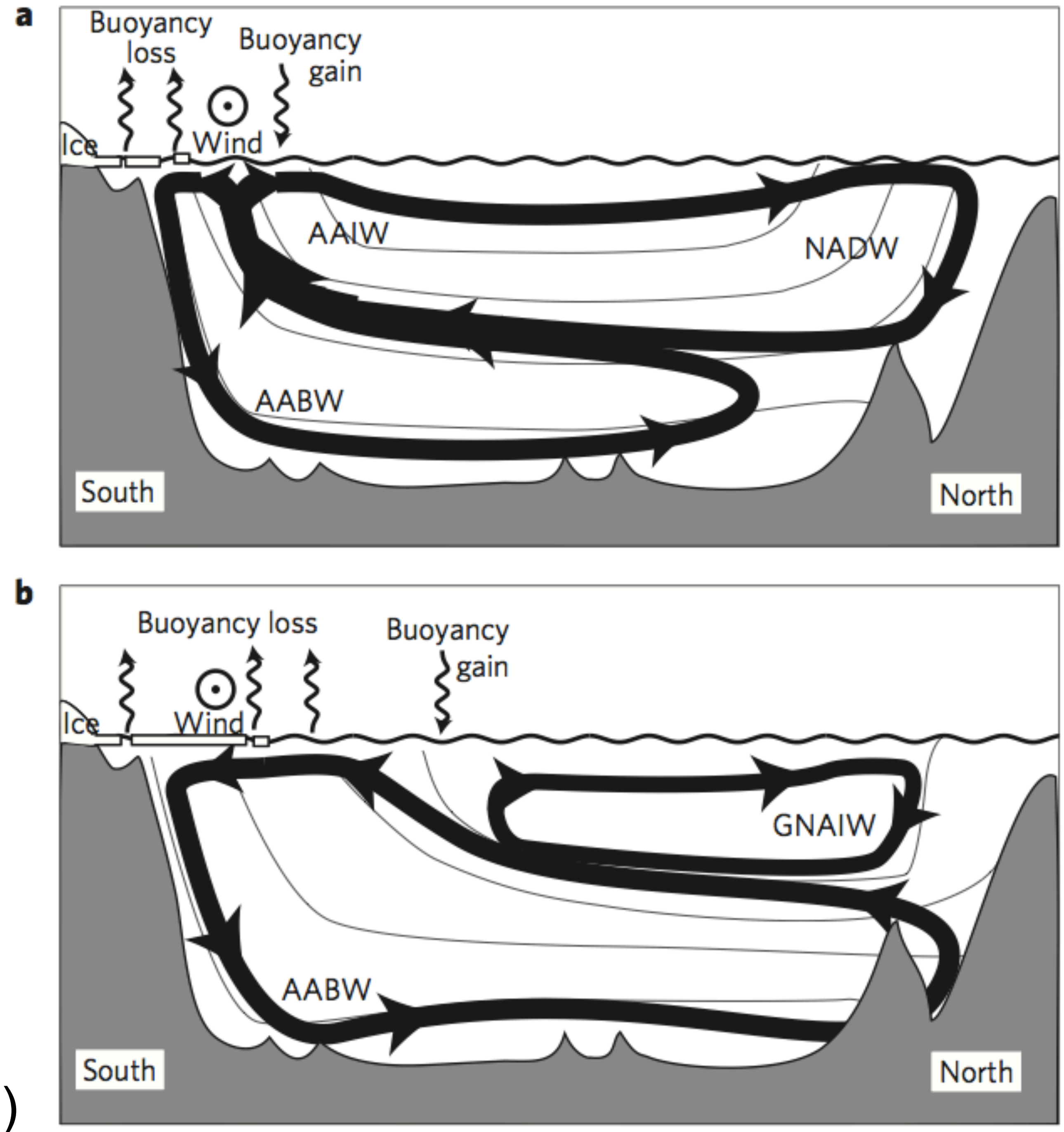


- Brine rejection drives AABW-like cell
- Net SO upwelling rate unchanged
- NH cell shoals and weakens

(see Watson et al. 2015, Ferrari et al. 2014)

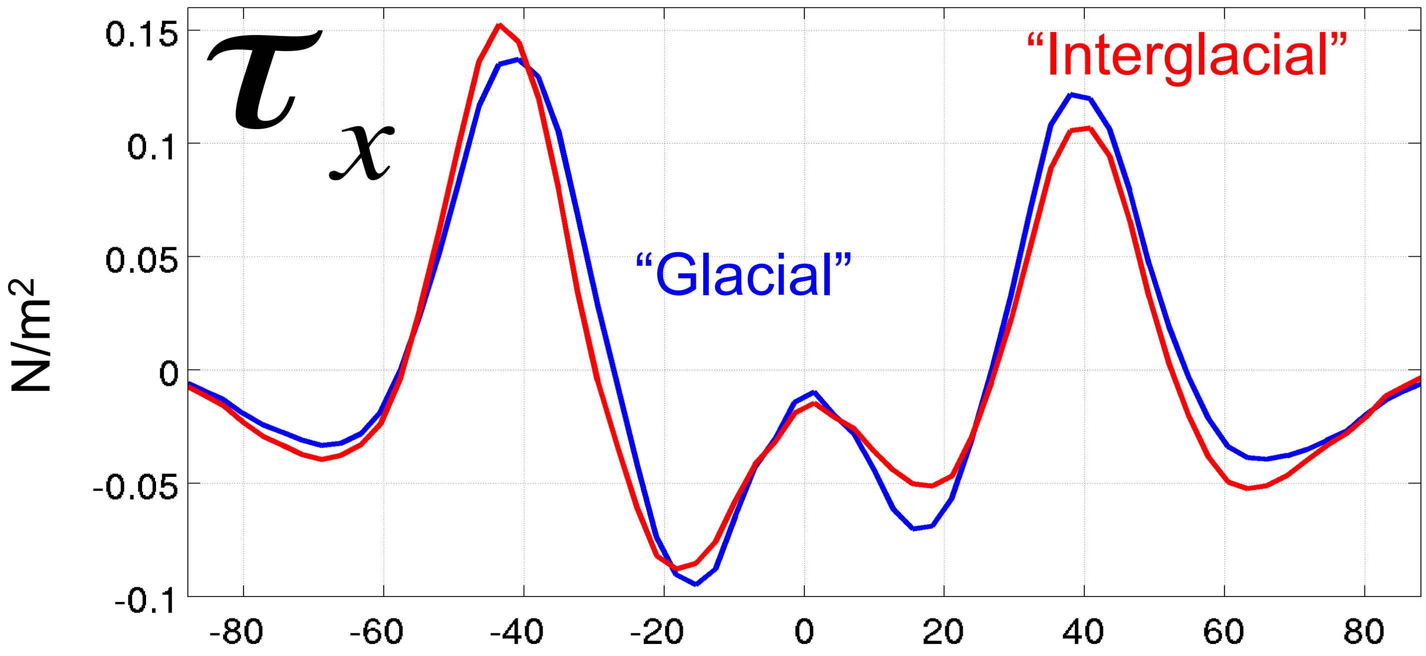
In steady state,
Water coming to the surface:

- Moves south for a buoyancy loss
- Moves to the North for a buoyancy gain



Watson et al. (2015)

Surface Winds



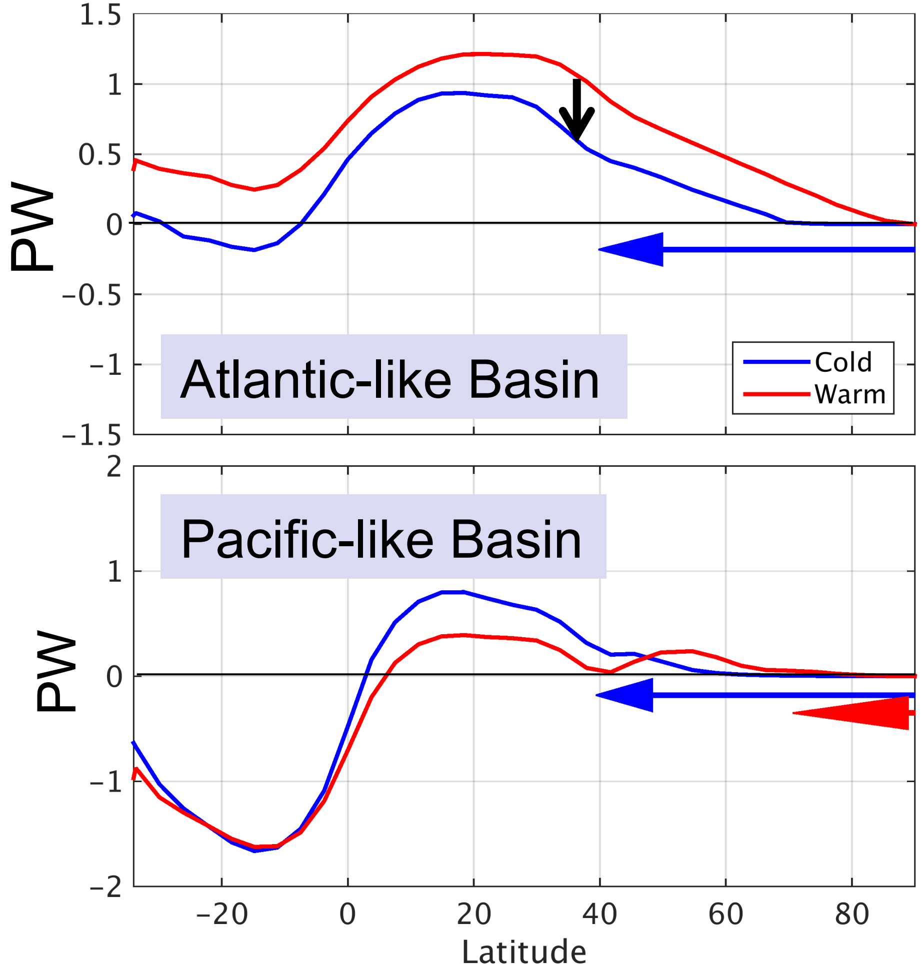
In glacial climate:

- Trade winds strengthen (as do the Hadley circulation)
- SH westerly winds shift equatorward ~1.5 deg
- and weaken ~10%

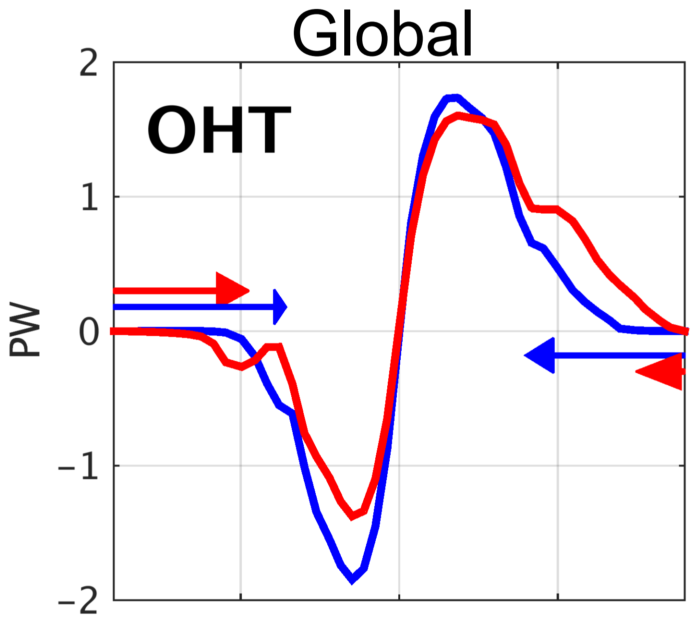
→ Driven by equatorward expansion of sea ice

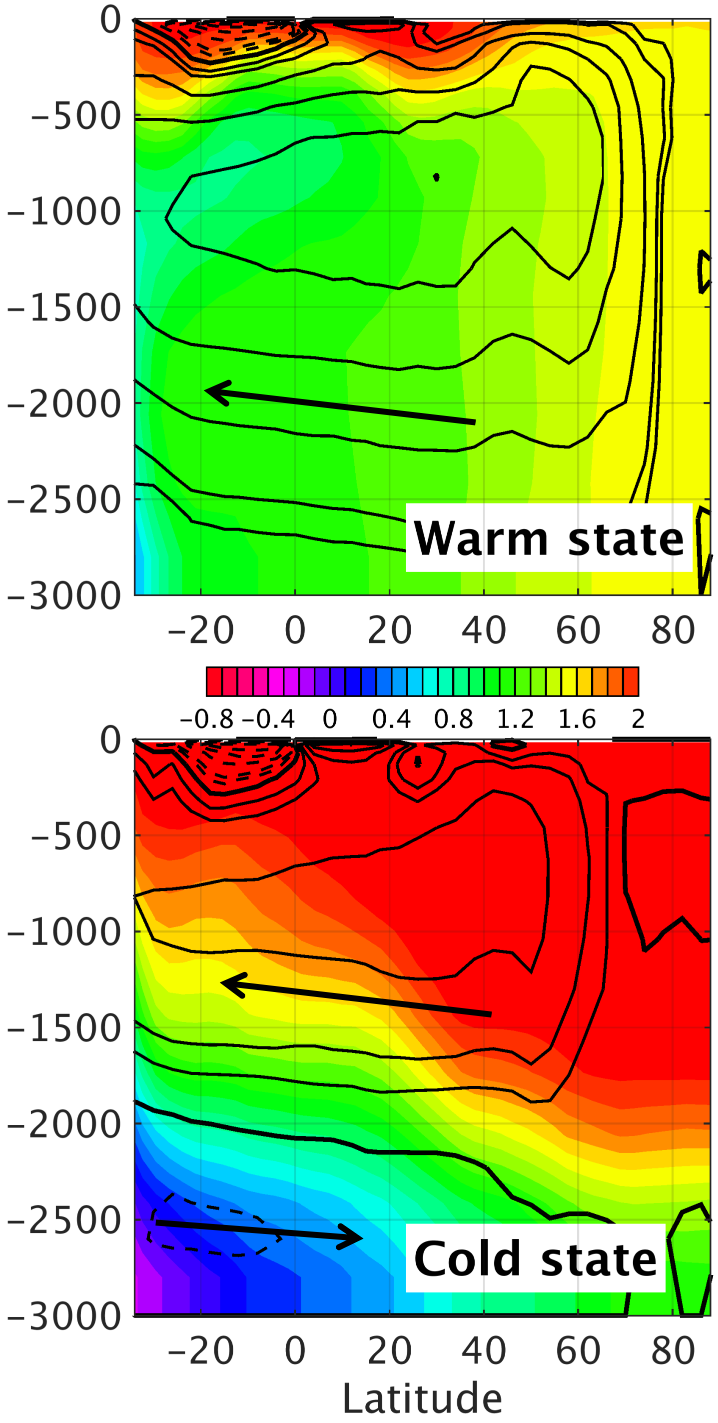
Paleoproxie: no consensus (Shulmeister et al. 2004, Kohfeld et al. 2016)
PMIP simulation: no consensus (Sime et al. 2016)

Ocean Heat transports

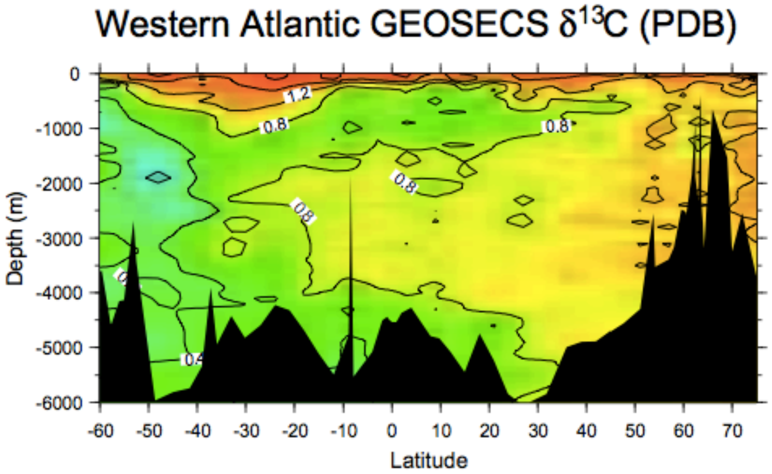


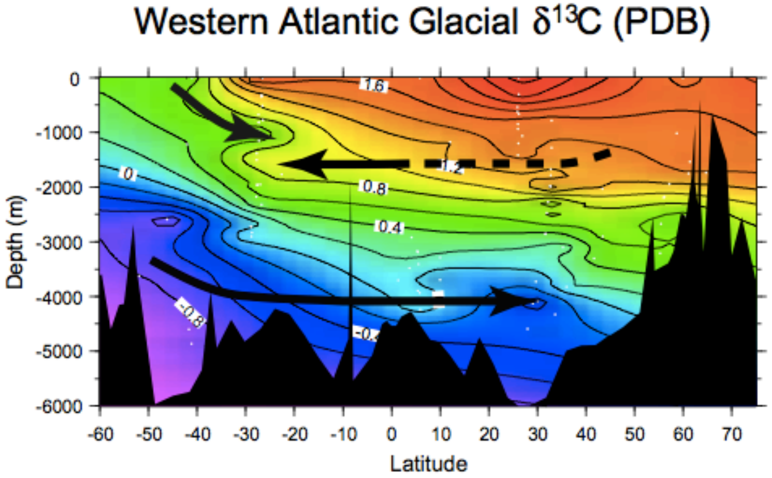
“AMOC” decreases
→ Decreased OHT in Small basins
→ Over compensated by increase in Large basin





$\delta^{13}C$





Curry and Oppo 2005

In “Cold” state:

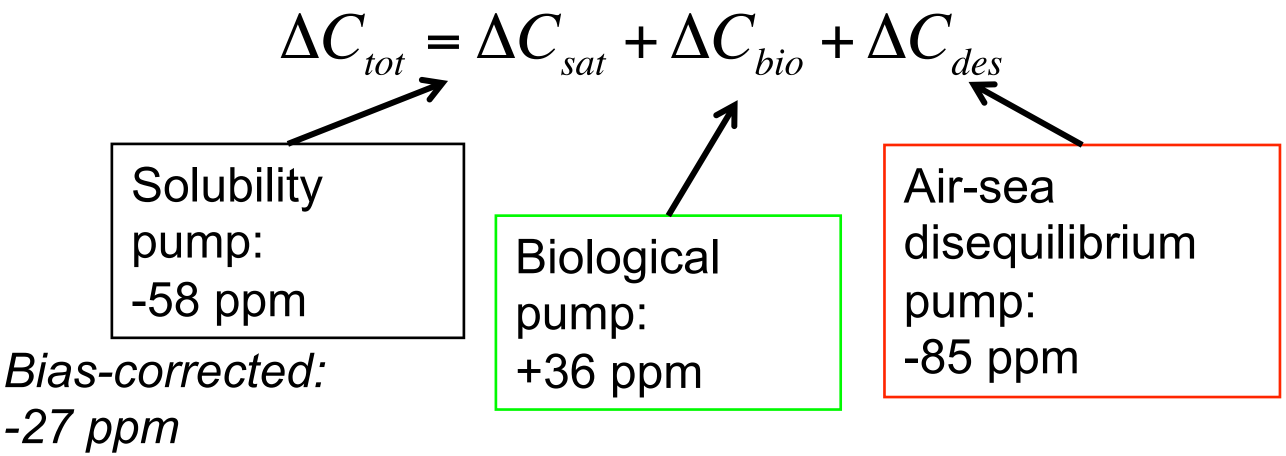
- Shallower, weaker “NADW”,
- Deep convection shifted by 15° southward
- Nutrient-rich AABW-like water
- Depleted upper ocean,

See also Lynch-Stieglitz etal. 2007

How is carbon stored in the “Glacial” ocean?

- ocean carbon-cycle model coupled to atmospheric CO_2,
- inventories of carbon, alkalinity, and phosphate are identical in the 2 solutions.
- the atmospheric CO_2 *is not radiatively active*.

<u>Change (“Warm” → “Cold”) in 3 carbon reservoirs:</u>



$$\Delta C_{tot} = \Delta C_{sat} + \Delta C_{bio} + \Delta C_{des}$$

Solubility pump: -58 ppm

Bias-corrected: -27 ppm

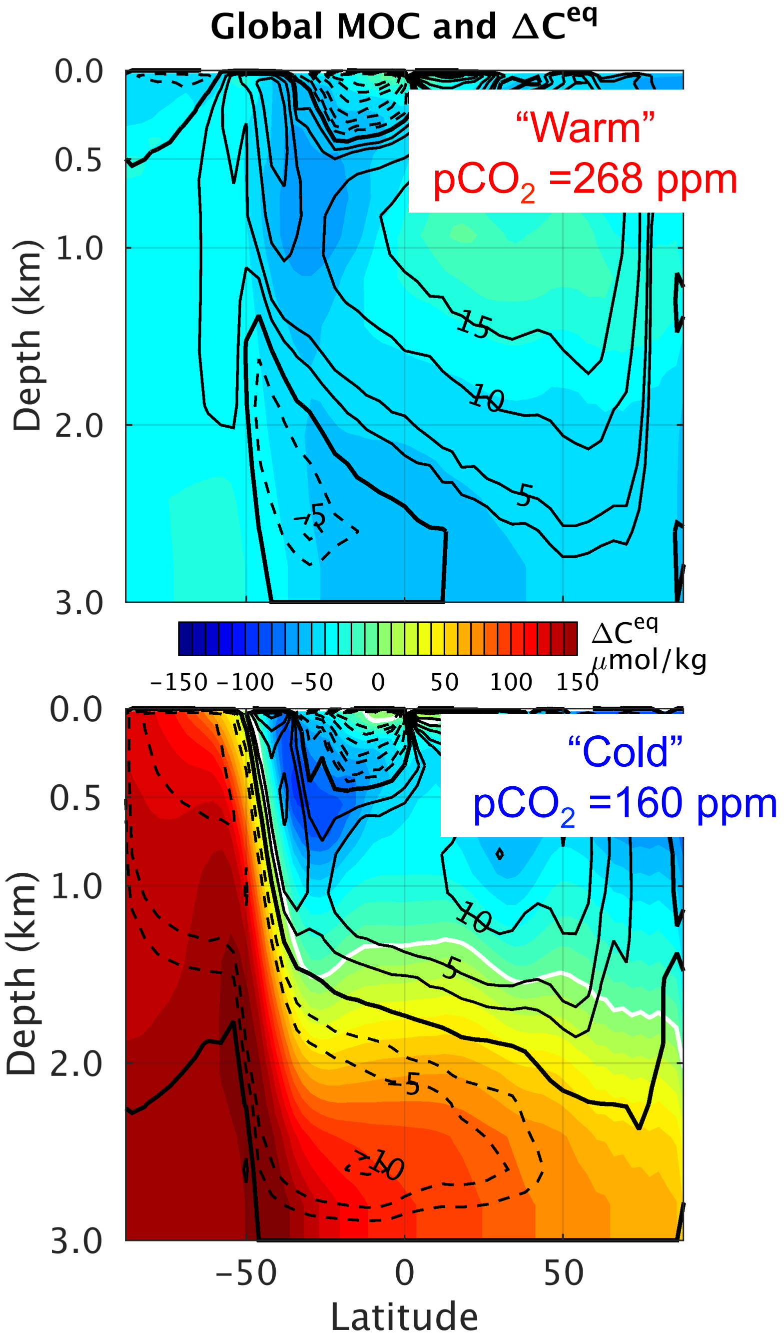
Biological pump: +36 ppm

Air-sea disequilibrium pump: -85 ppm

- Solubility pump: Temperature dominated (but include salt)
- Net Biological pump: organic + carbonate ($CaCO_3$ + Alkalinity)

How is carbon stored in the "Glacial" ocean?

Disequilibrium pump



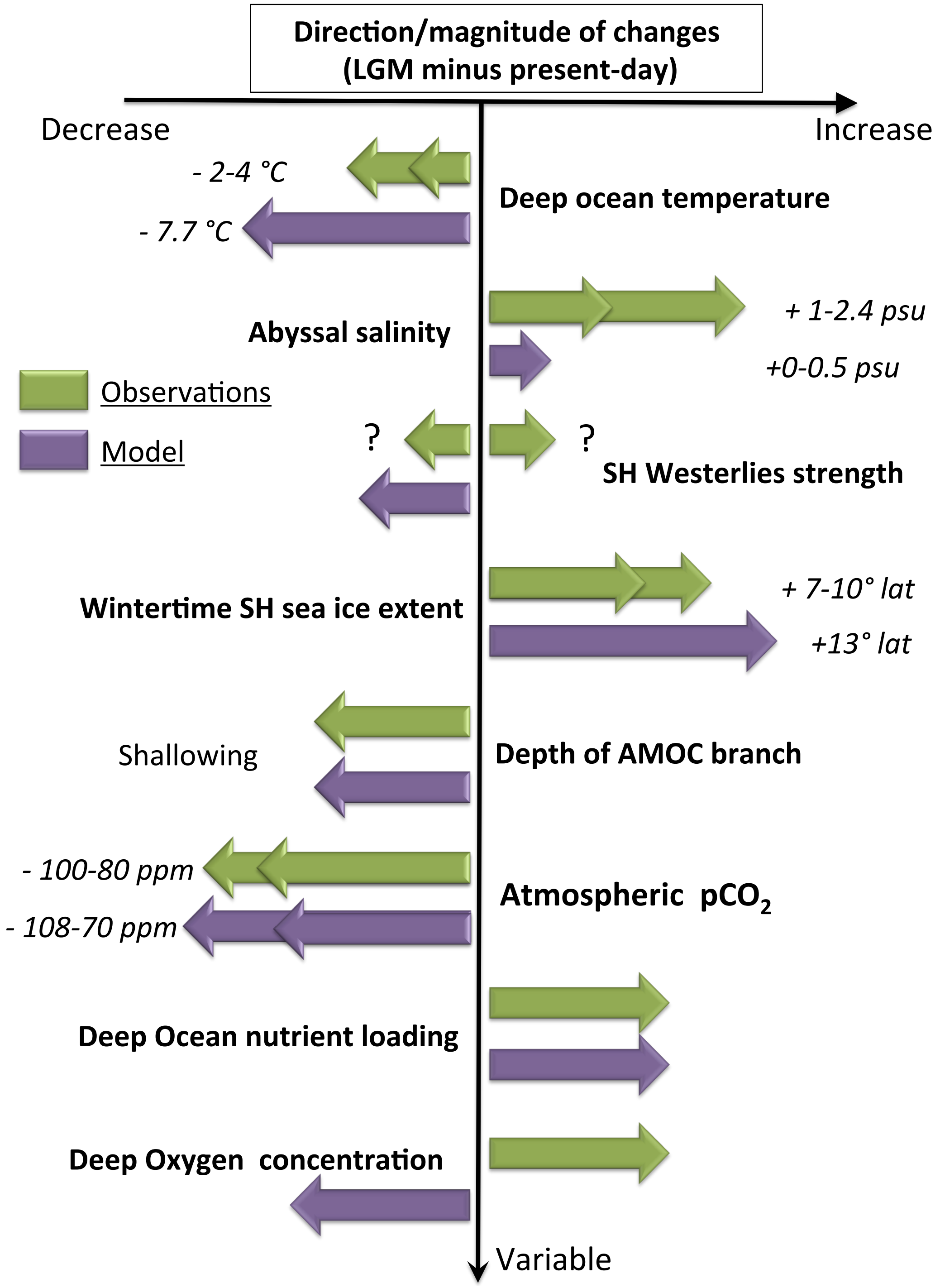
→ Increased sea-ice cover reduces the ventilation of upwelled deep waters: DIC accumulates in the deep ocean (Stephens and Keeling, 2000).

<u>Caveats:</u>

- Solubility is overestimated
- Biological pump decreases everywhere in Cold state; Oxygen content also increase in deep ocean (Jaccard and Galbraith 2011, Kohfel et al. 2005)

→ lack of iron cycle? More complex ecosystem

Summary of the changes: Simulation versus Paleoproxy



Direction/magnitude of changes
(LGM minus present-day)

Decrease

Increase

🟩 Observations

🟪 Model

- 2-4 °C

- 7.7 °C

Deep ocean temperature

+ 1-2.4 psu

+0-0.5 psu

Abyssal salinity

?

?

SH Westerlies strength

+ 7-10° lat

+13° lat

Wintertime SH sea ice extent

Shallowing

Depth of AMOC branch

- 100-80 ppm

- 108-70 ppm

Atmospheric pCO_2

Deep Ocean nutrient loading

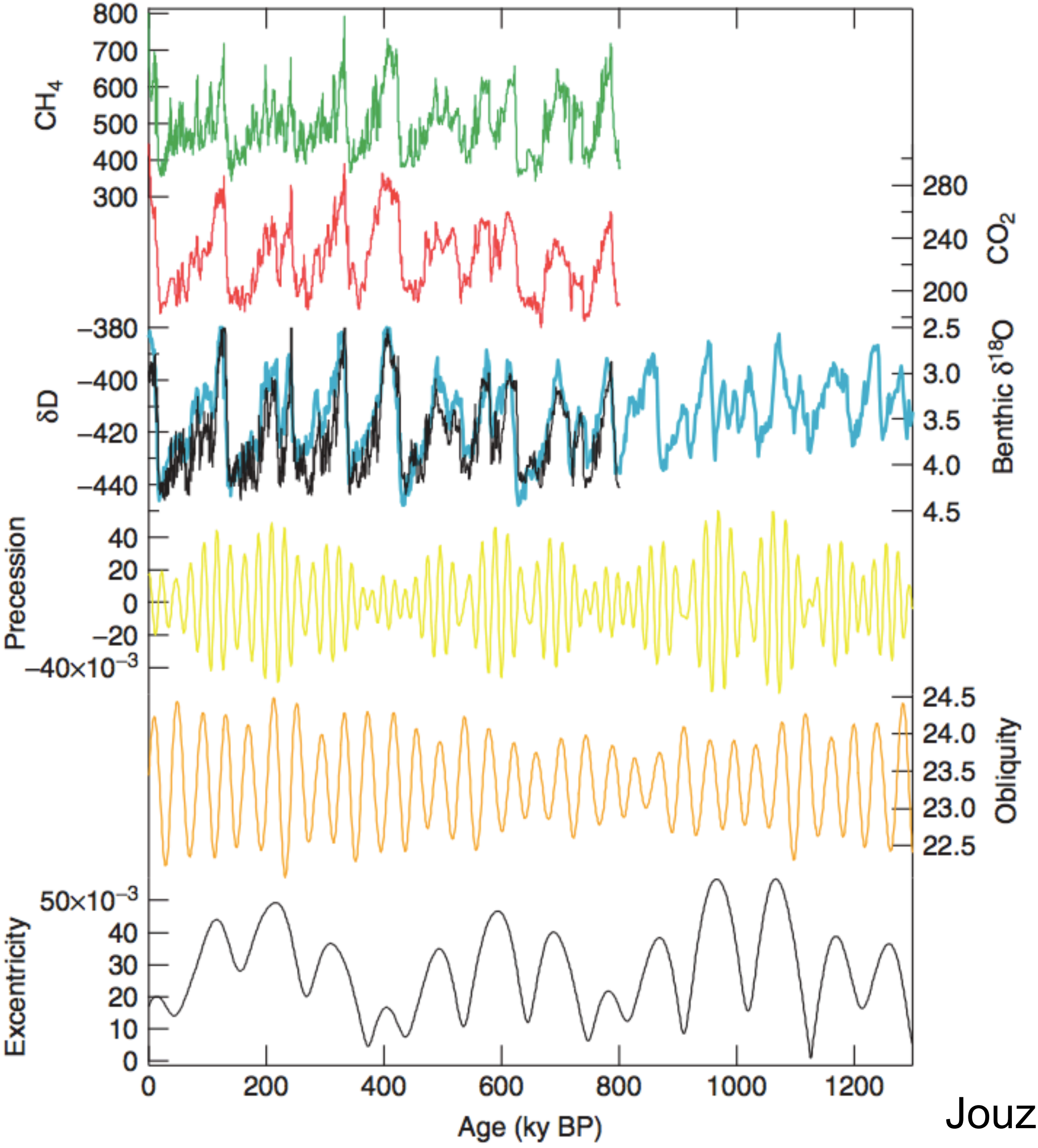
Deep Oxygen concentration

Variable

NH large sea expansion : consistent with paleoproxies (de Vernal et al. 00)

Curry and Oppo 05, Lynch-Stieglitz et al. 07, but Gebbie 14

Stochastic resonance



- Periodicity of orbital parameters found in paleoproxy record (Hays et al. 1976)

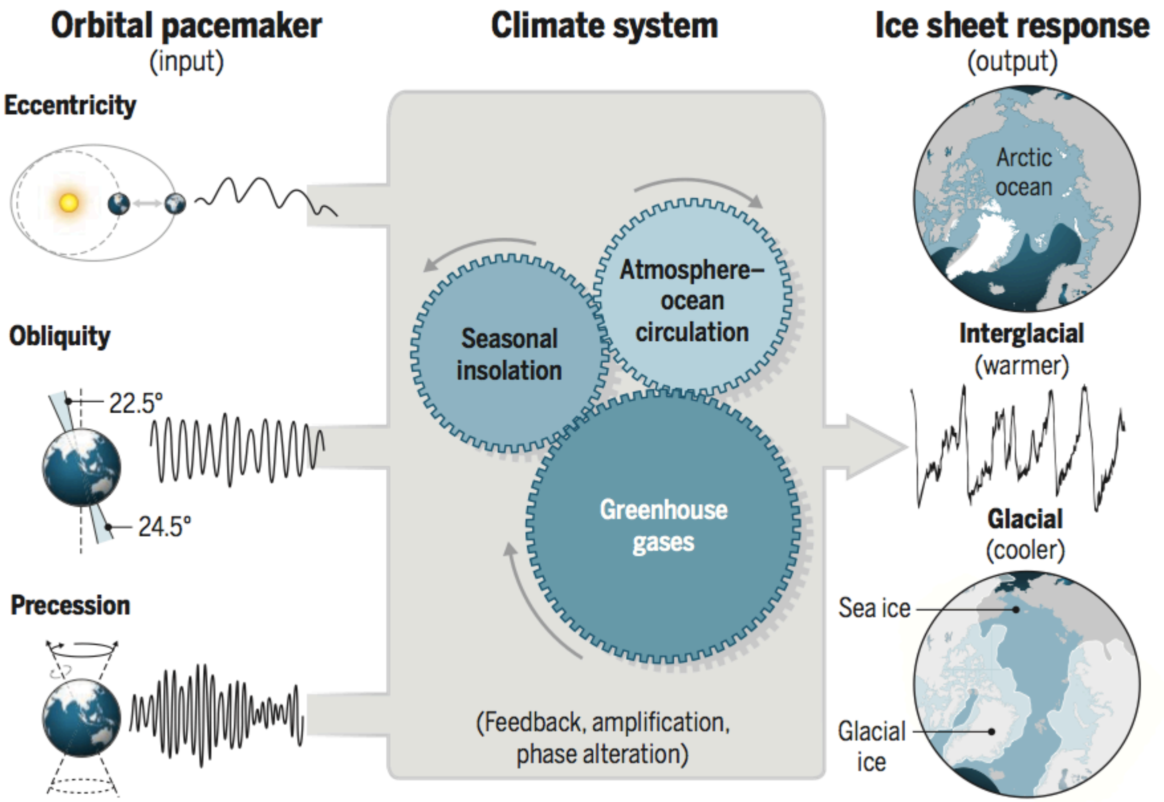
~20 kyr

~40 kyr

~100 kyr

Jouzel and Masson-Delmotte, 2010

Problem remains: we don't know the link between input and output

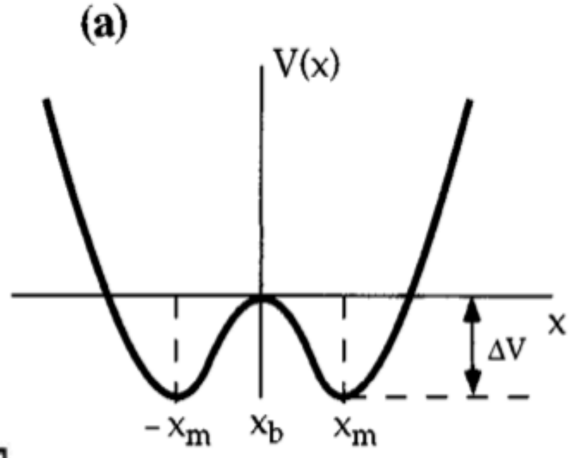


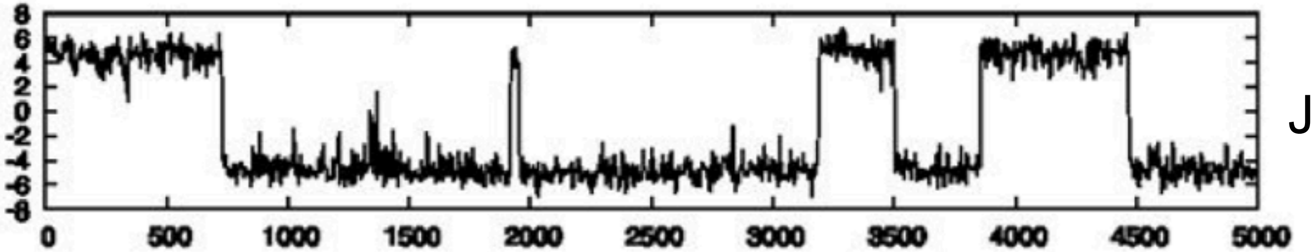
Hodell (2016)

Two families of mechanisms:

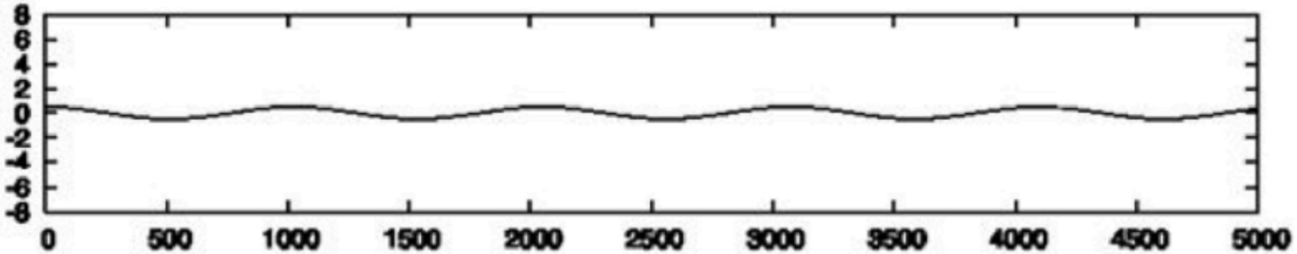
- "linear" view: forcing is amplified by strong feedbacks (CO_2, ice-sheet, sea ice)
- "non-linear" view: free oscillations of the climate system, paced or phased-locked by the Milankovitch forcing (Saltzman et al., Tziperman et al., etc.) or multiple states

The basics of stochastic resonance

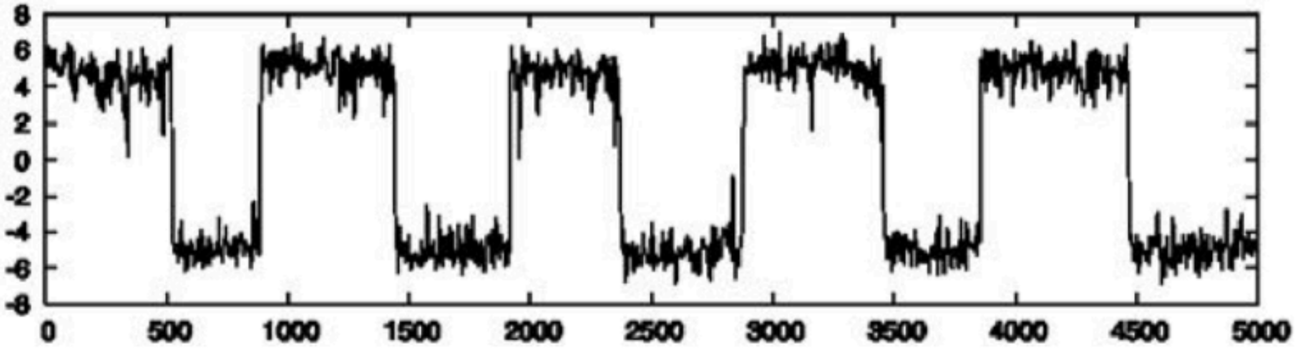




Just forced with noise



Small forcing that does n
trigger transition



Forced with noise +
small forcing

Benzi et al. (1982), Nicolis (1982)

The basics of stochastic resonance

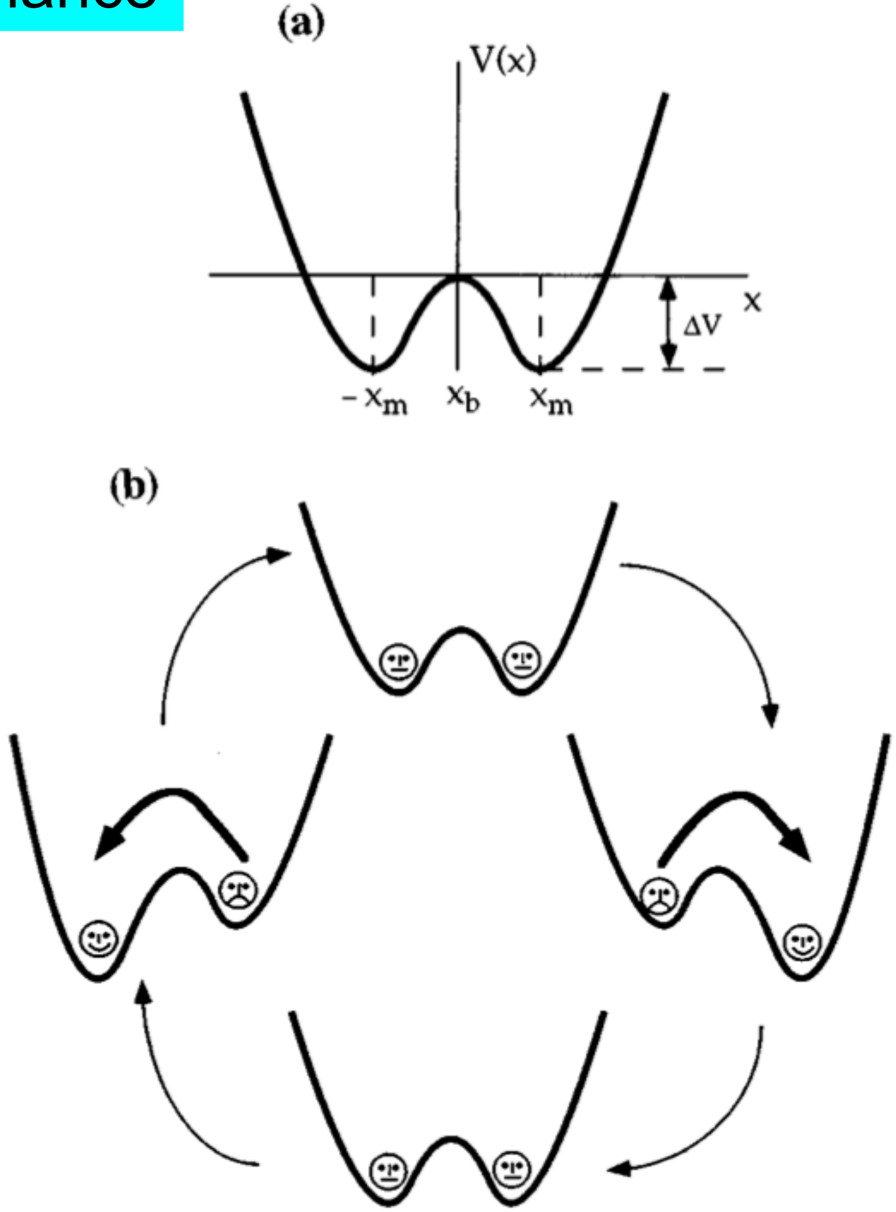
Kramers transition rate, i.e. expected time between transition in the presence of noise:

$$T_n \propto \exp\left(\frac{\Delta V}{\sigma^2}\right)$$

Noise variance

Add a forcing with period T_f:

→resonance (synchronization) for $T_n \sim T_f$

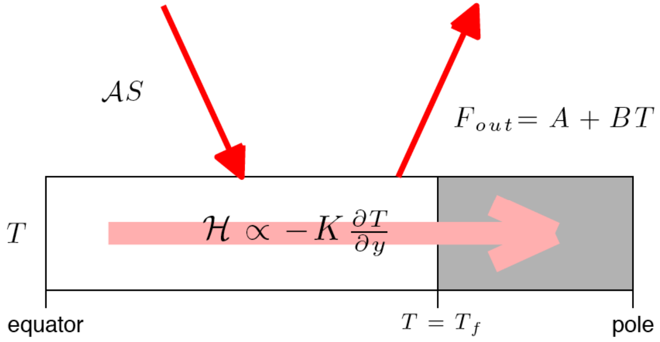


Gammaitoni et al. 1998

SR was born with glacial-Interglacial cycles in mind, but:

- ad-hoc/oversimplified models (0D)
- need multiple states

→ Time to revise



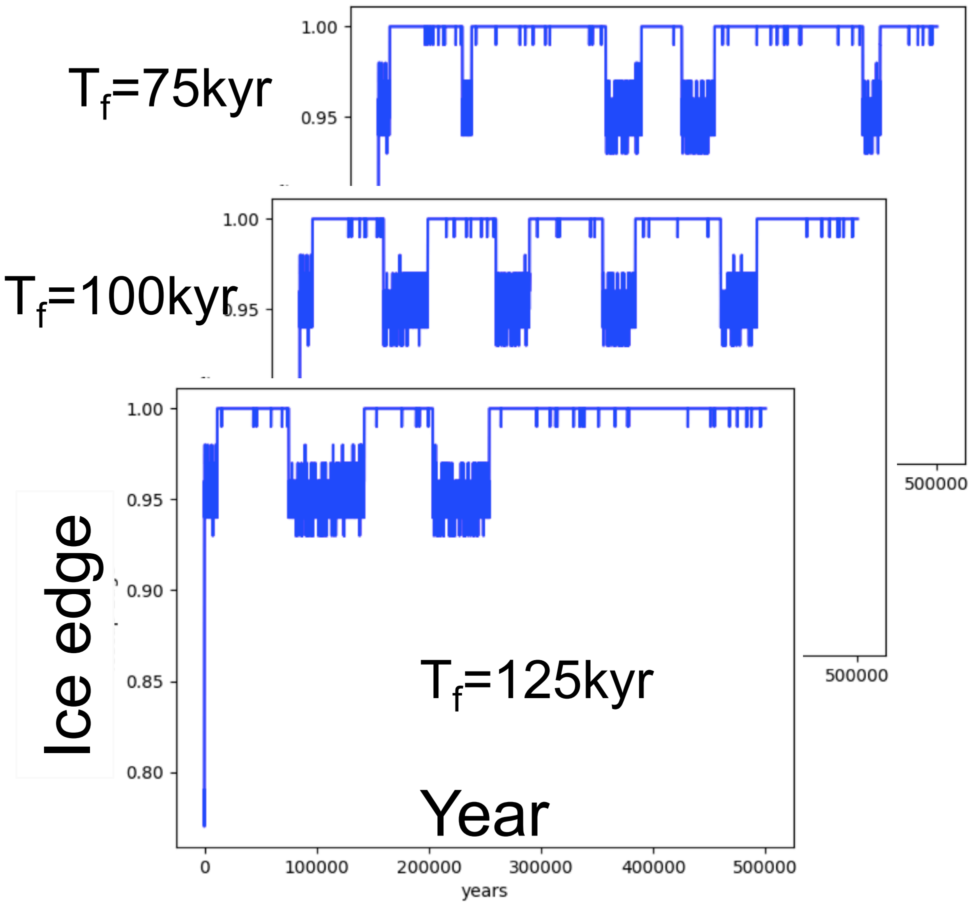
Simple Energy Balance Model

→ Use simple classic EBM = 1D

→ Tune noise so Kramers rate ~100 kyr

→ Forcing amplitude Q/2000 with Q=340 W/m^2

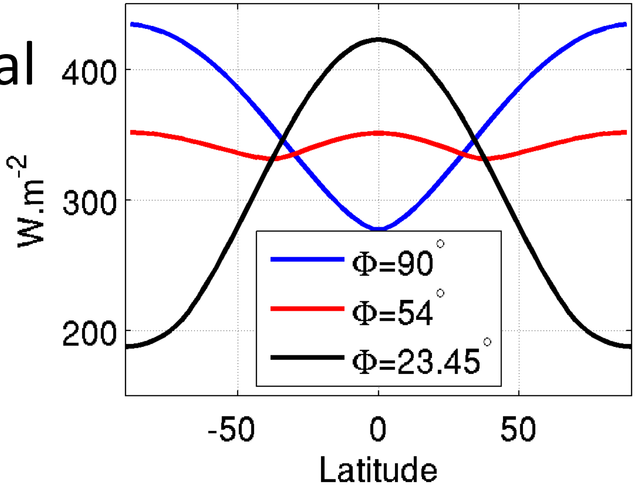
Ioannis Katharopoulos



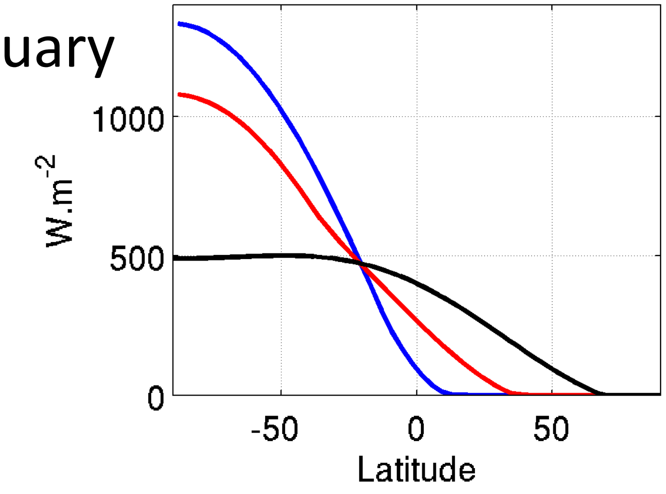
1 High-obliquity aquaplanet

Incoming solar radiation

Annual mean



January



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SCIENCE

Summer Solstice 2018: The Search for Life in the Galaxy

As you mark the longest day of the year, consider the debate among astronomers over whether Earth's tilt toward the sun helps make life on our world and others possible.

By Shannon Hall

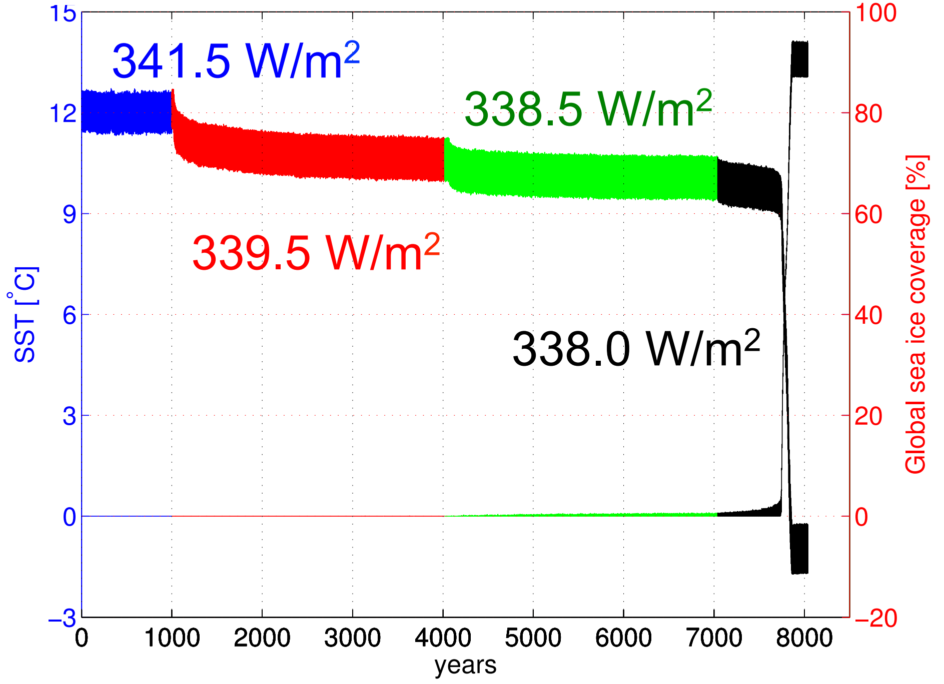
June 20, 2018

in NYT

Habitability

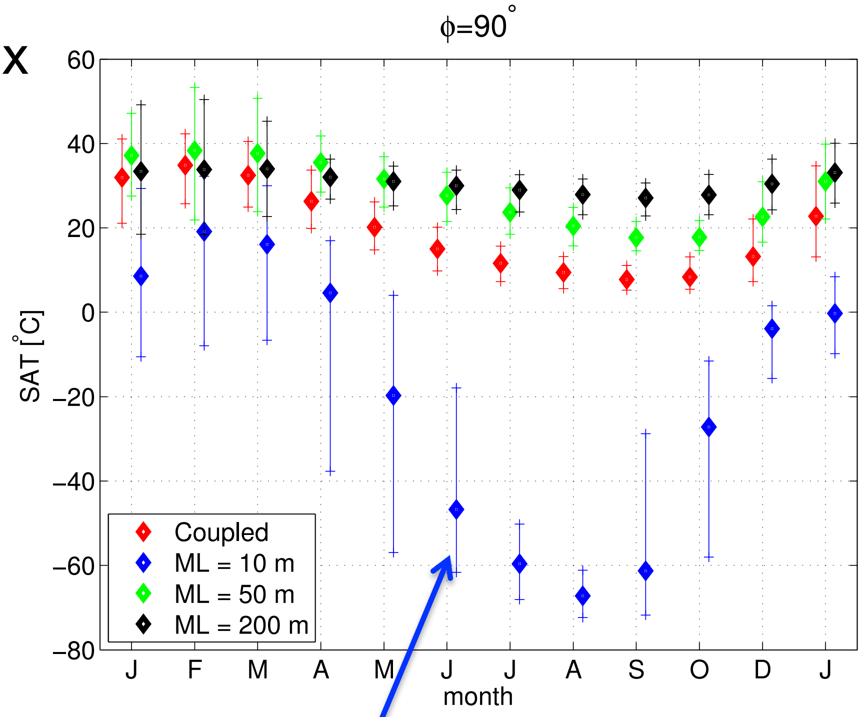
- “Deep” ocean stabilizes climate
- Too shallow ocean →global glaciation

Coupled runs @ Φ=90 deg



Surface Air Temperature

Median+min/max over 90-55°S

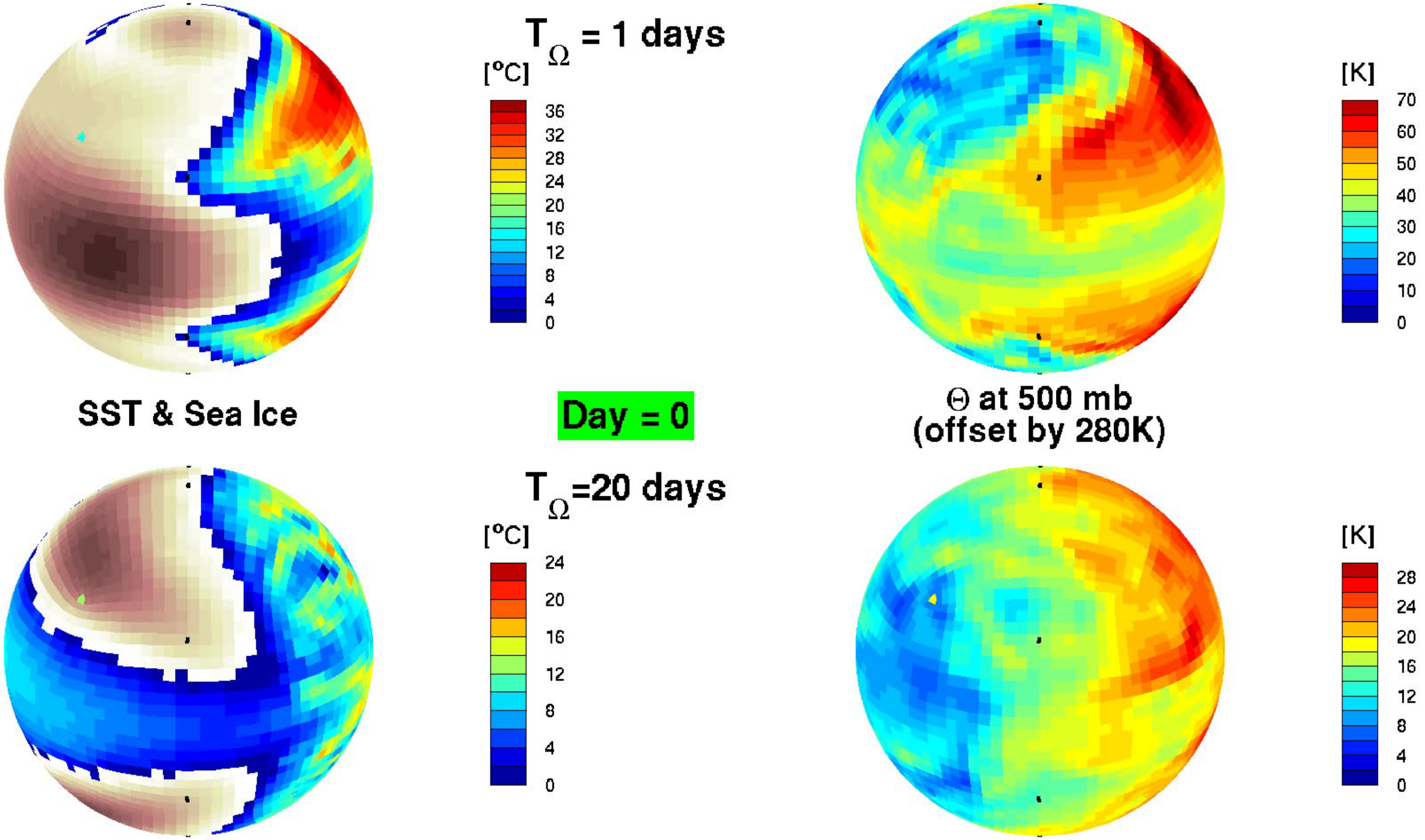


Snowball collapse

Climate system unstable to small sea ice covers

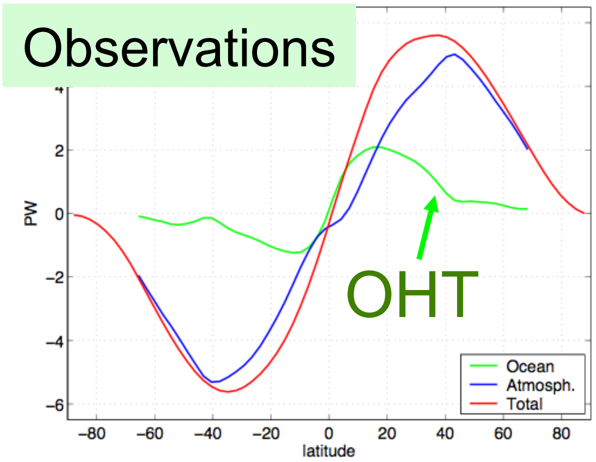
Ferreira et al. (2014)

2 Tidally-locked aquaplanet



Ferreira et al., in prep

Summary



- Multiple equilibrium states can exist in a complex fully dynamical 3d climate GCM

- Meridional structure of the OHT is key: a large mid-latitude convergence (as observed, wind-driven)

- Think less about AMOC bi-stability (fundamentally an ocean-only process)

- Think more ocean/sea ice multiple states/instability

- Need a more systematic search for this type of equilibria (as was done for the MOC bi-stability)