Studying Earth (and other planets) as an aqua-planet

Lecture I

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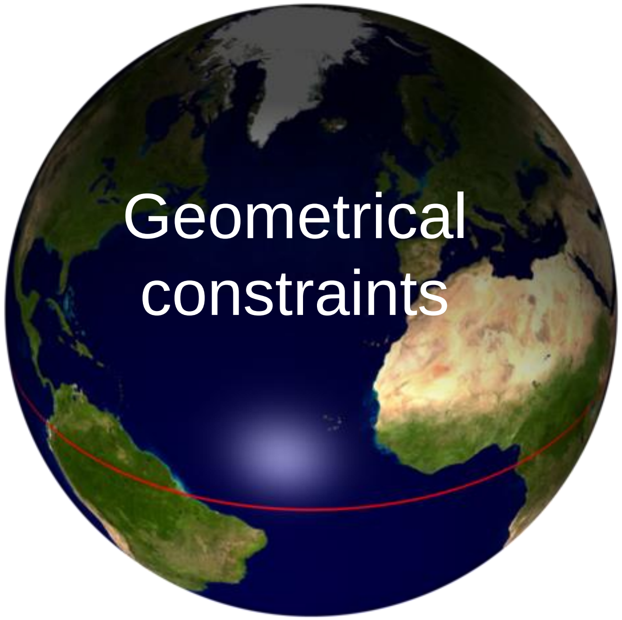
Outline

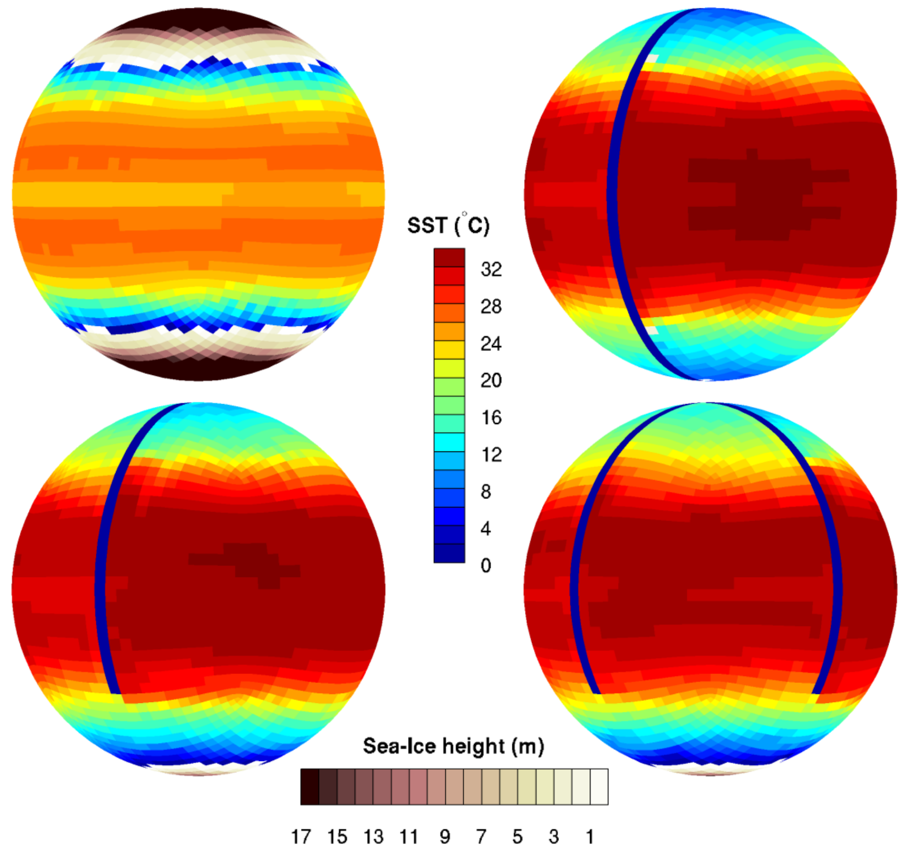
Focus here mainly on ocean

- Why using Aquaplanet set-ups?
- Modelling framework: MITgcm
- Some basics: SST distribution, MOC, etc.
- Topic 1: The structure of the OHT transport
- Topic 2: Localization of deep water formation
- Topic 3: Multiple equilibrium state of climate
- (Topic 4: Exoplanet applications)

Modeling approach

MIT GCM: Ocean-Atmosphere-Sea ice:

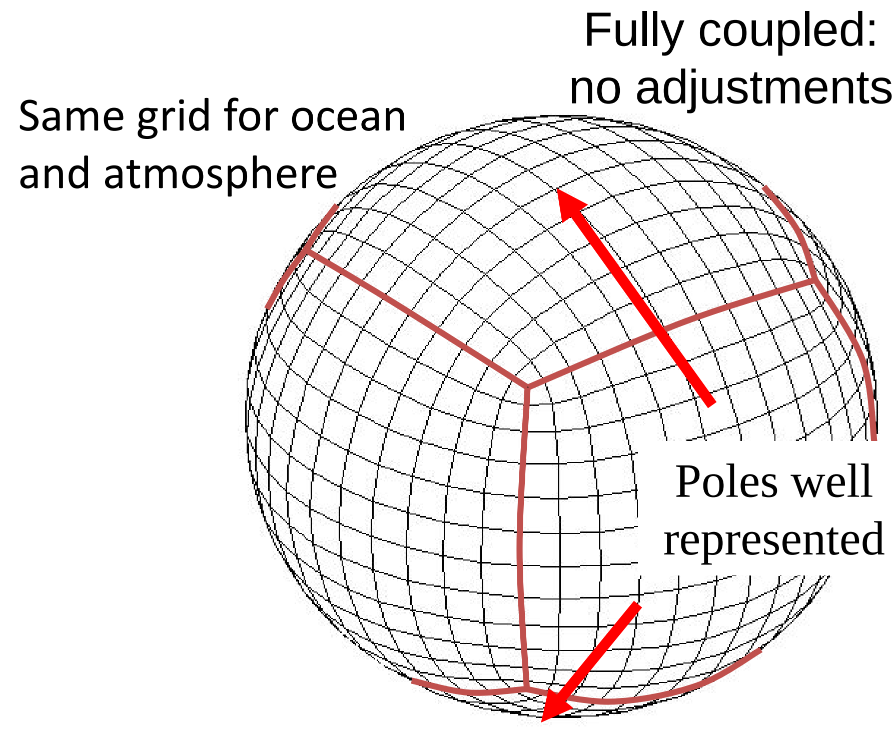


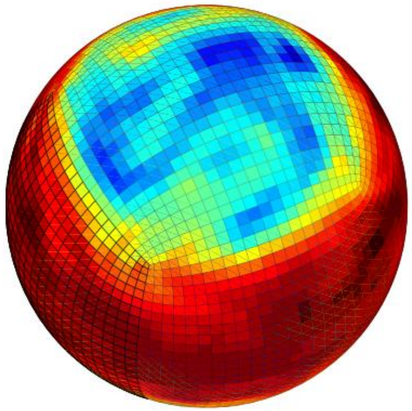


How much can we explain wit dynamics and simple geometries ?

2 MIT GCM: Coupled Ocean-Atmosphere-Sea ice:

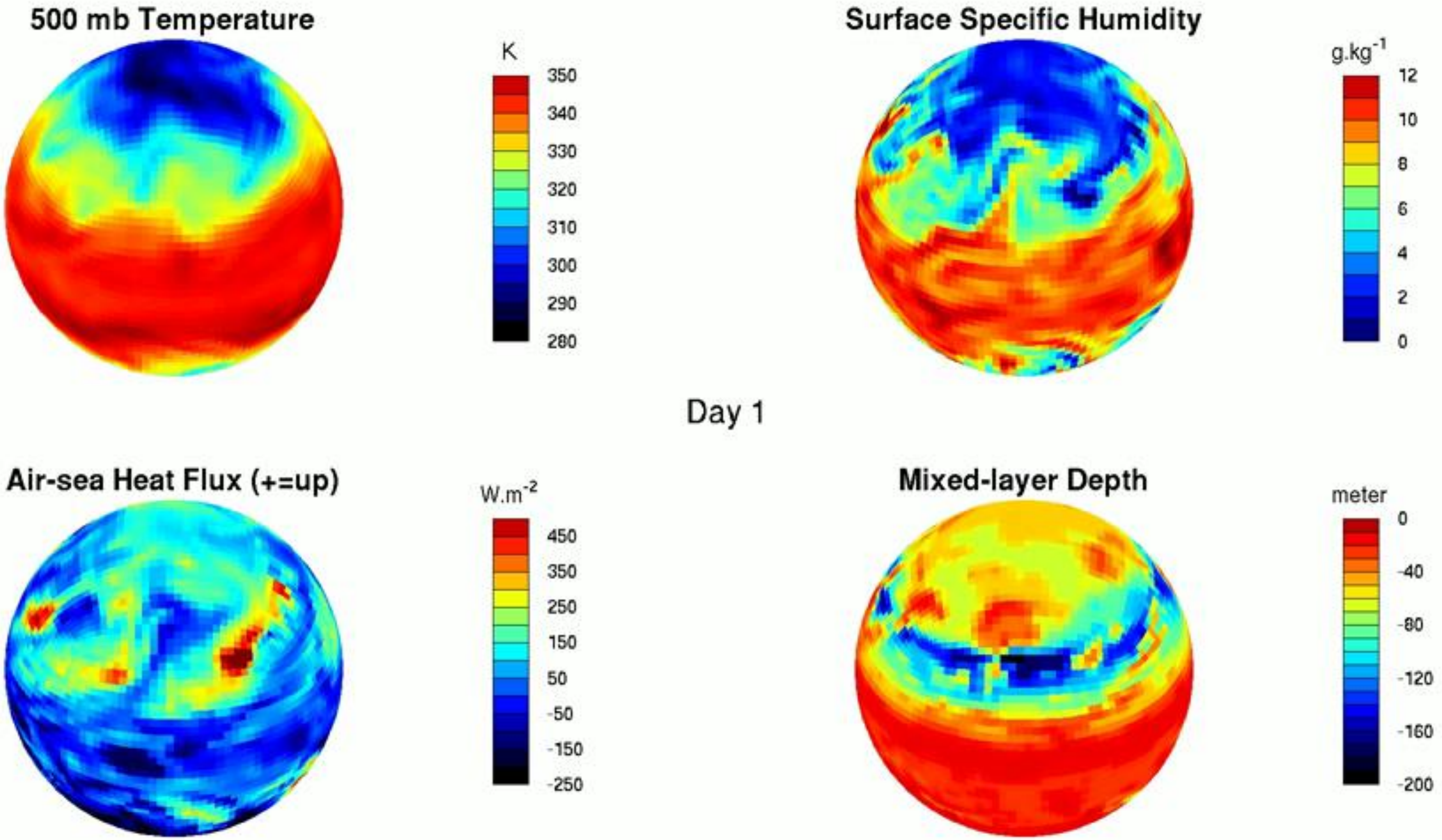
- Primitive equation models,
- Cube-sphere grid: ~3.75°,
- Synoptic scale eddies in the atmosphere,
- Gent and McWilliams eddy parameterization in the ocean,
- Simplified atmospheric physics (SPEEDY, Molteni 2003),
- Conservation to numerical precision (Campin et al. 2008)



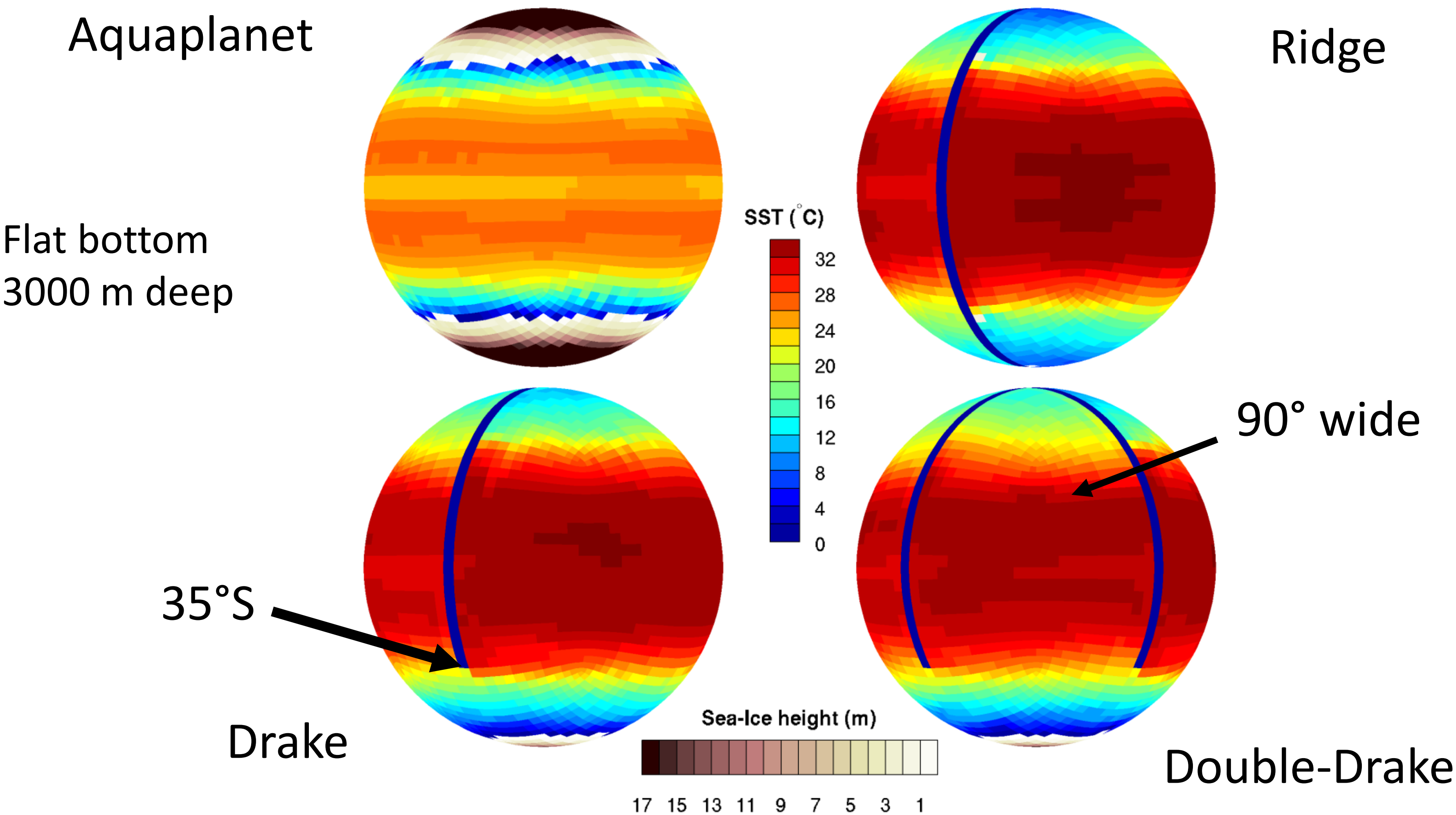


Temperature snap-shot at 500 mb.

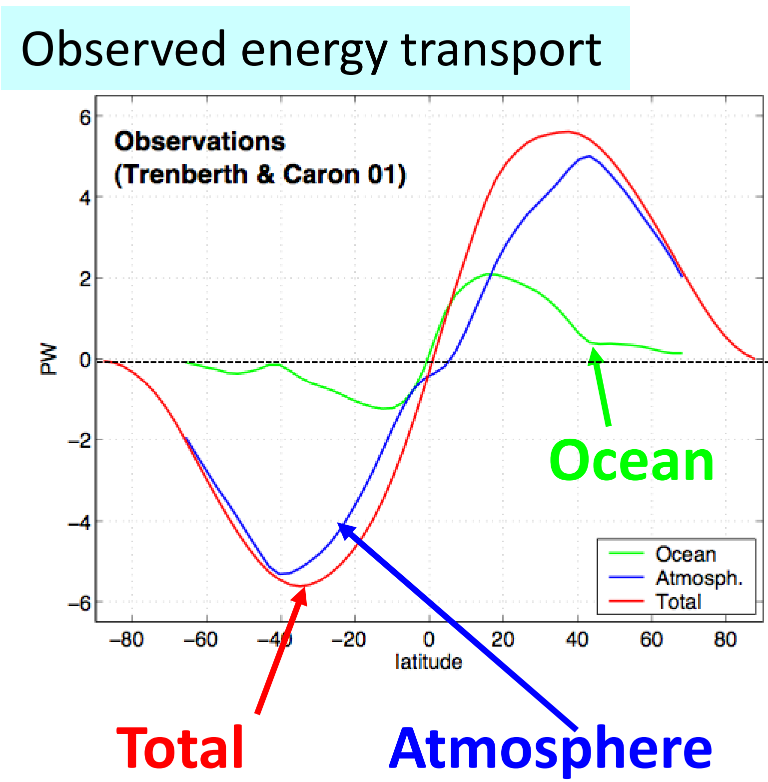
Aquaplanet circulation

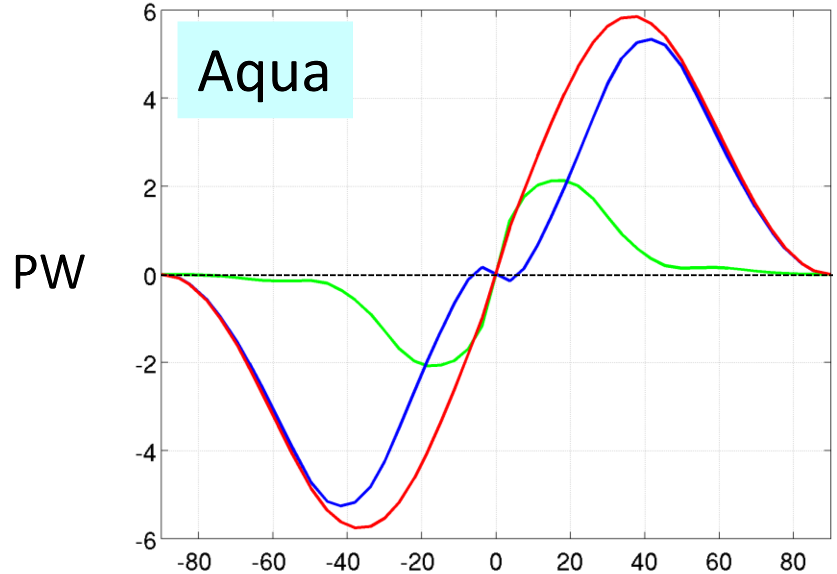


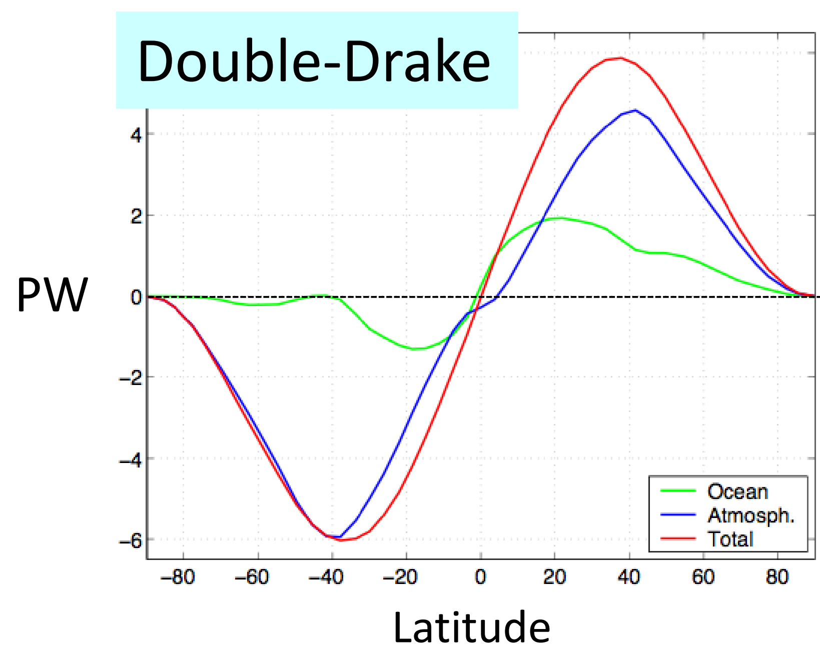
SST and sea-ice distributions

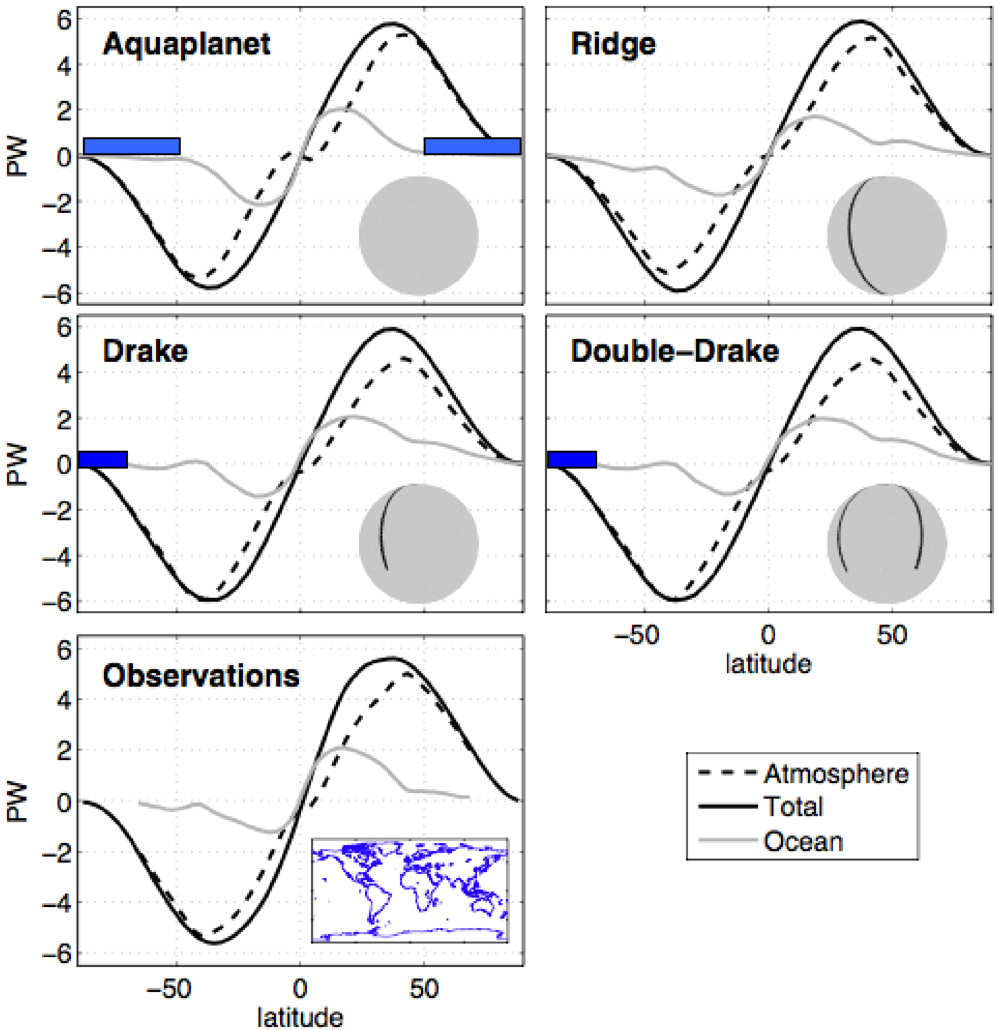


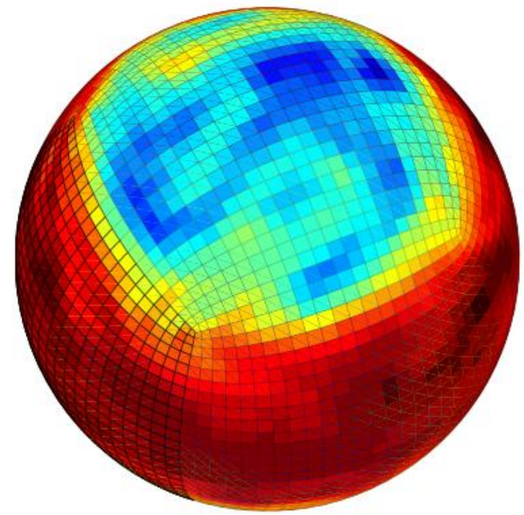
Does it make sense to use idealized configurations?



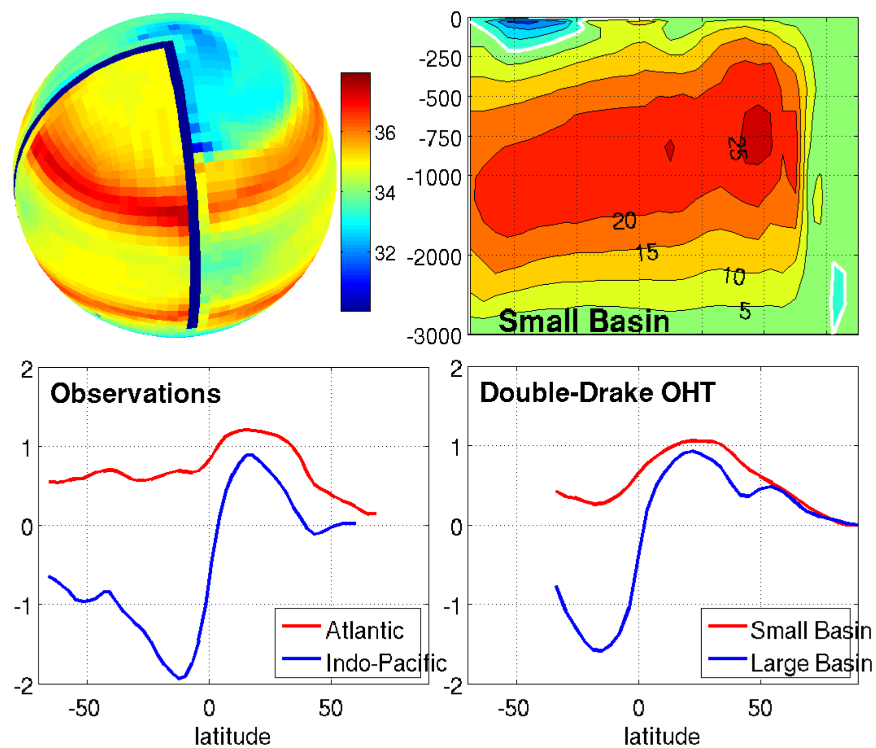








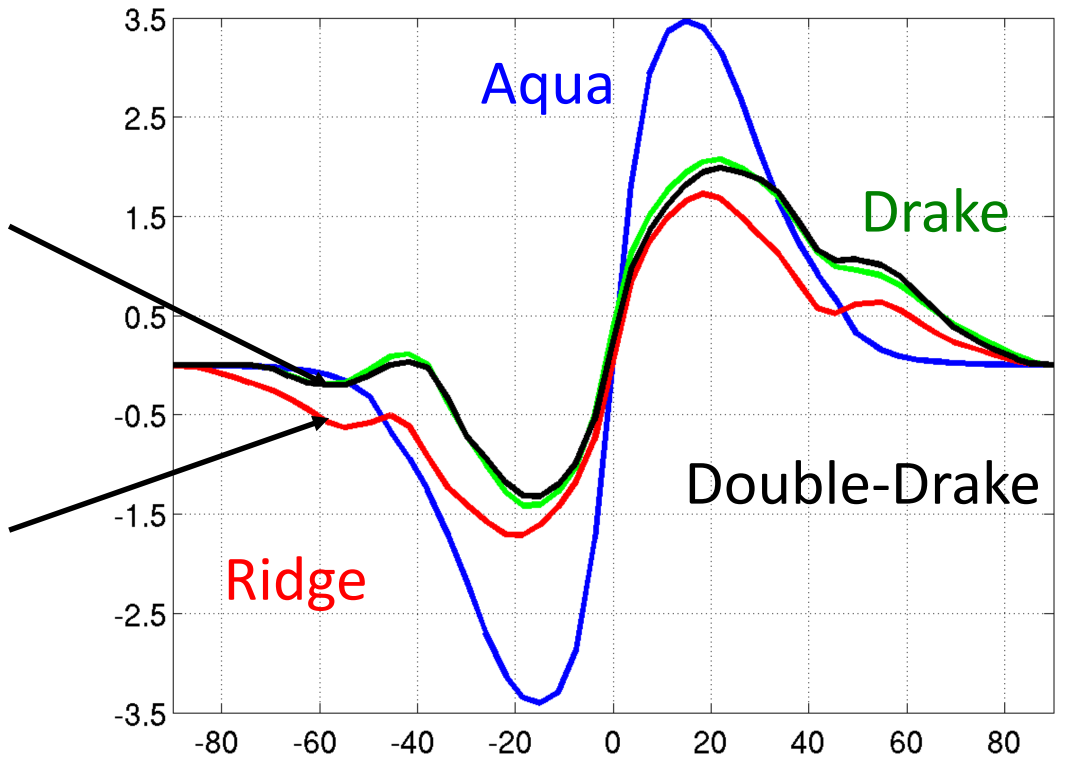
Effects of having two basins→



Ocean Heat Transport

ACC
0.2 PW

No ACC
0.6 PW

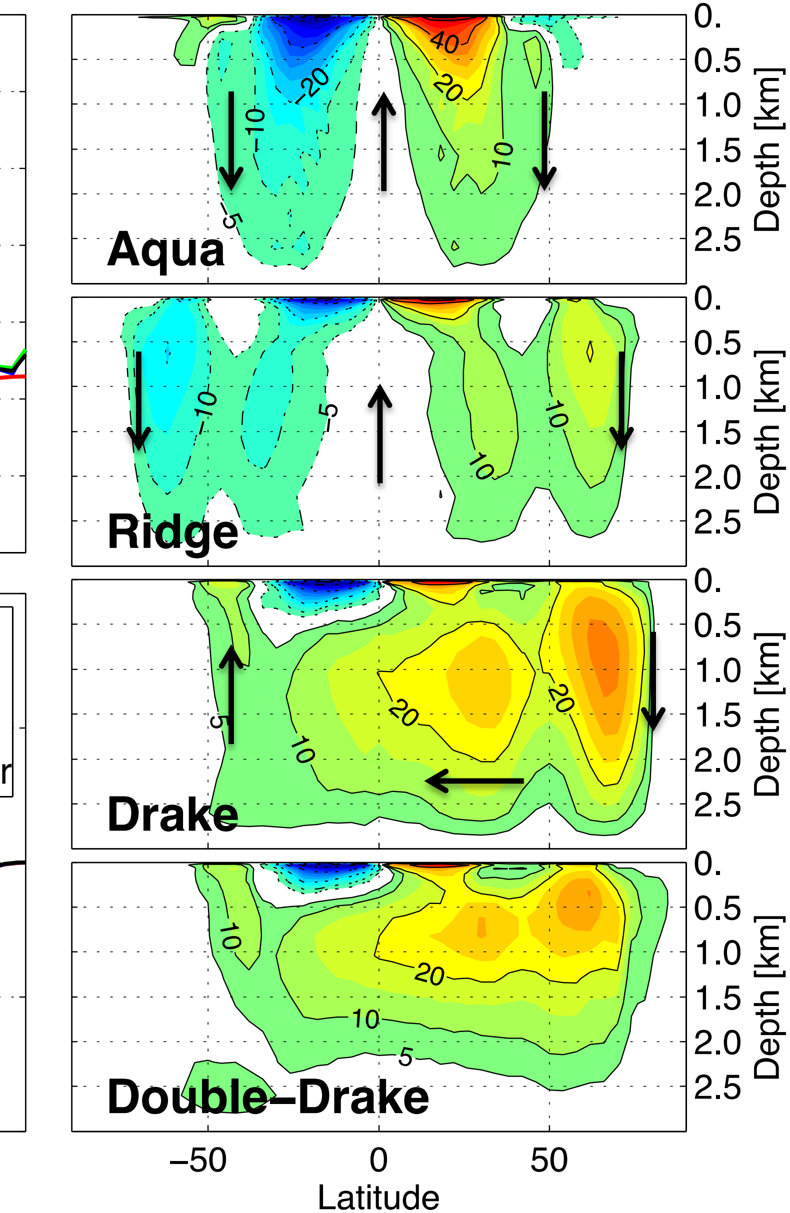


No meridional barrier
=
Small OHT at
high-latitudes

Drake & Double-Drake:
OHT shifted northward

Exhibit Earth-like
characteristics at large scale

Idealized coupled simulations



Overturning circulation

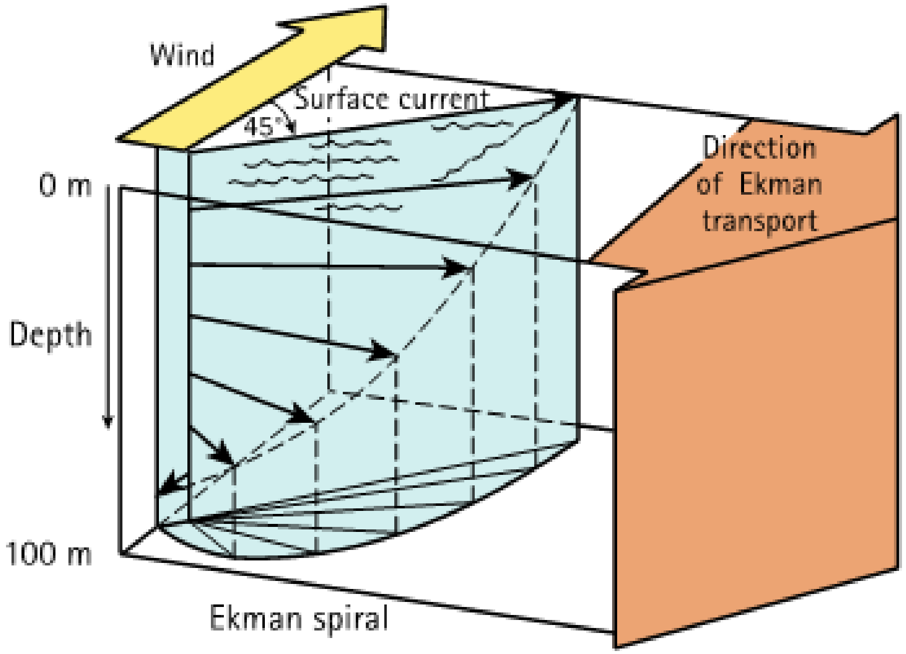
- Dominated by wind-driven equatorial cells
- Ekman dynamics

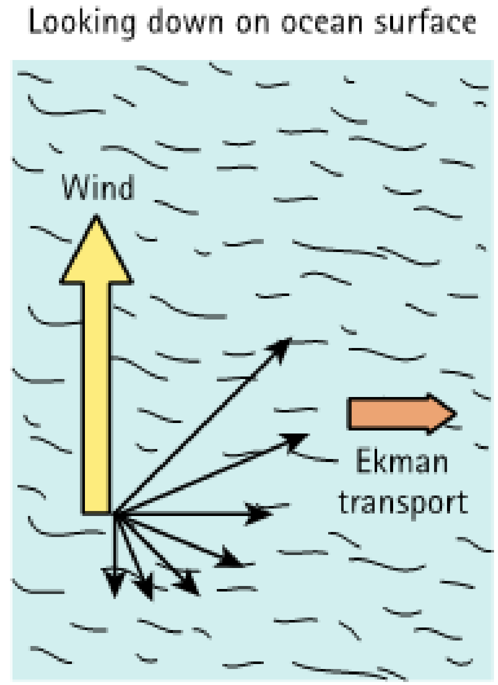
- Meridional boundaries allows "horizontal" gyres
- Deep convection at high latitudes

- Opening of "Drake Passage": inter-hemispheric overturning
- Links Southern Ocean to the Northern hemisphere deep convection

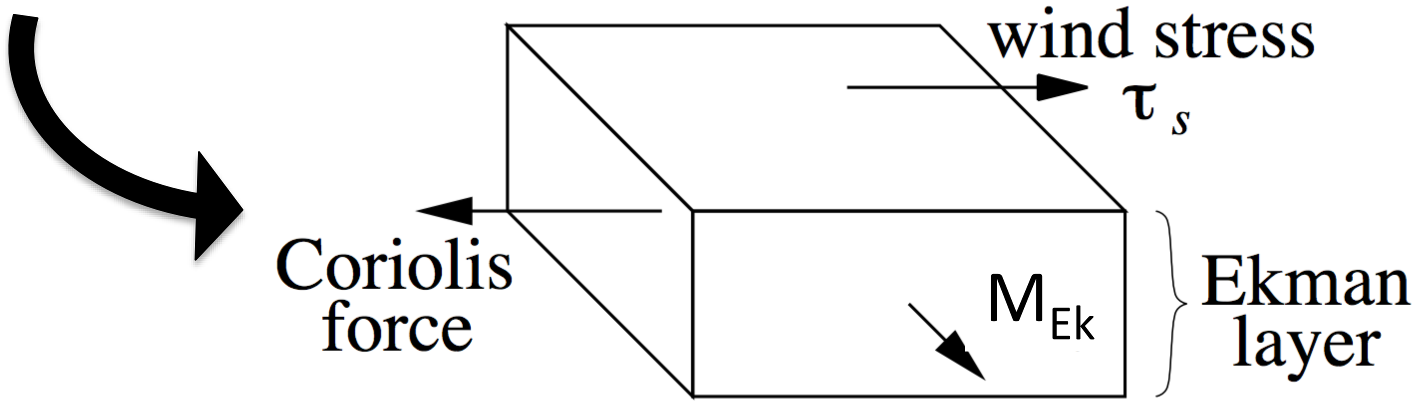
- Two basins → little impact on global scale
- Localization of deep convection in one basin

Ekman currents



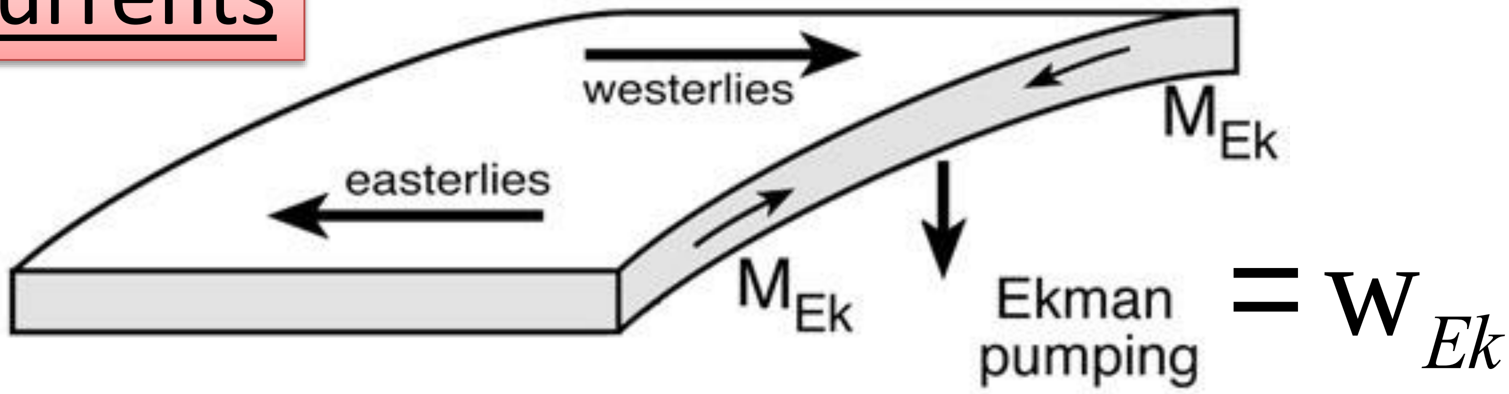


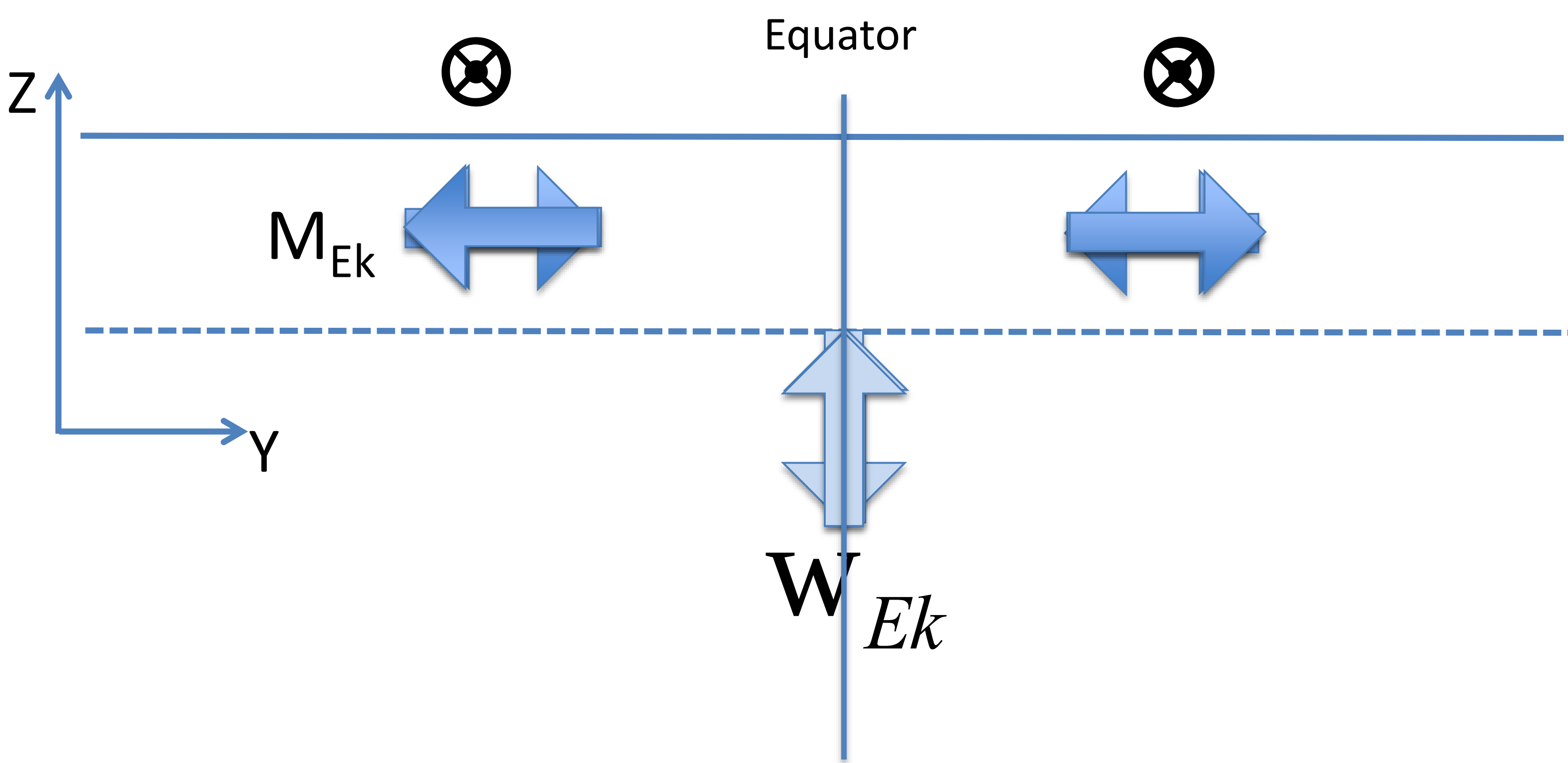
$$M_{Ek} = \frac{t_S}{r_O f}$$



Northern hemisphere!

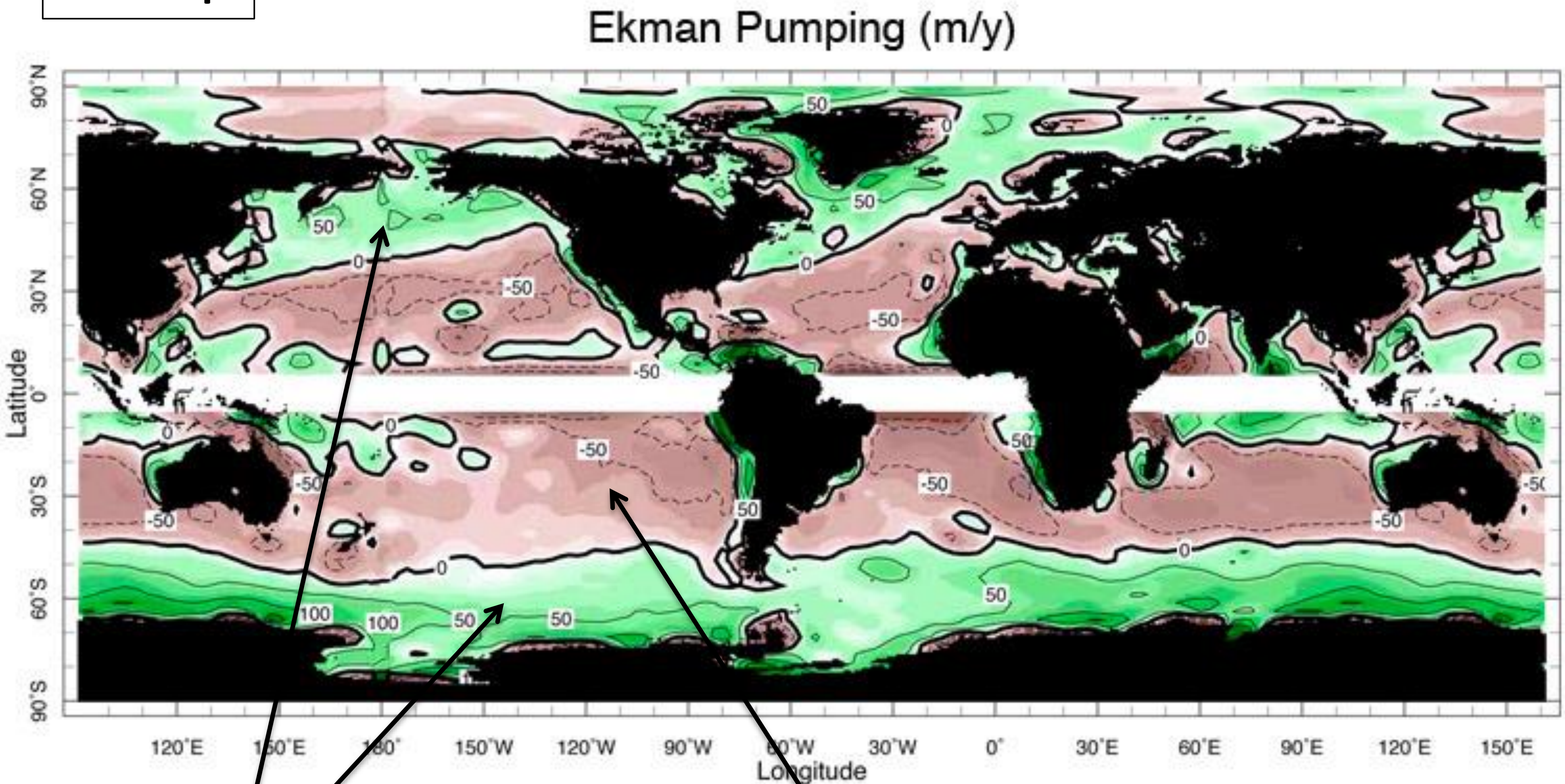
Ekman currents





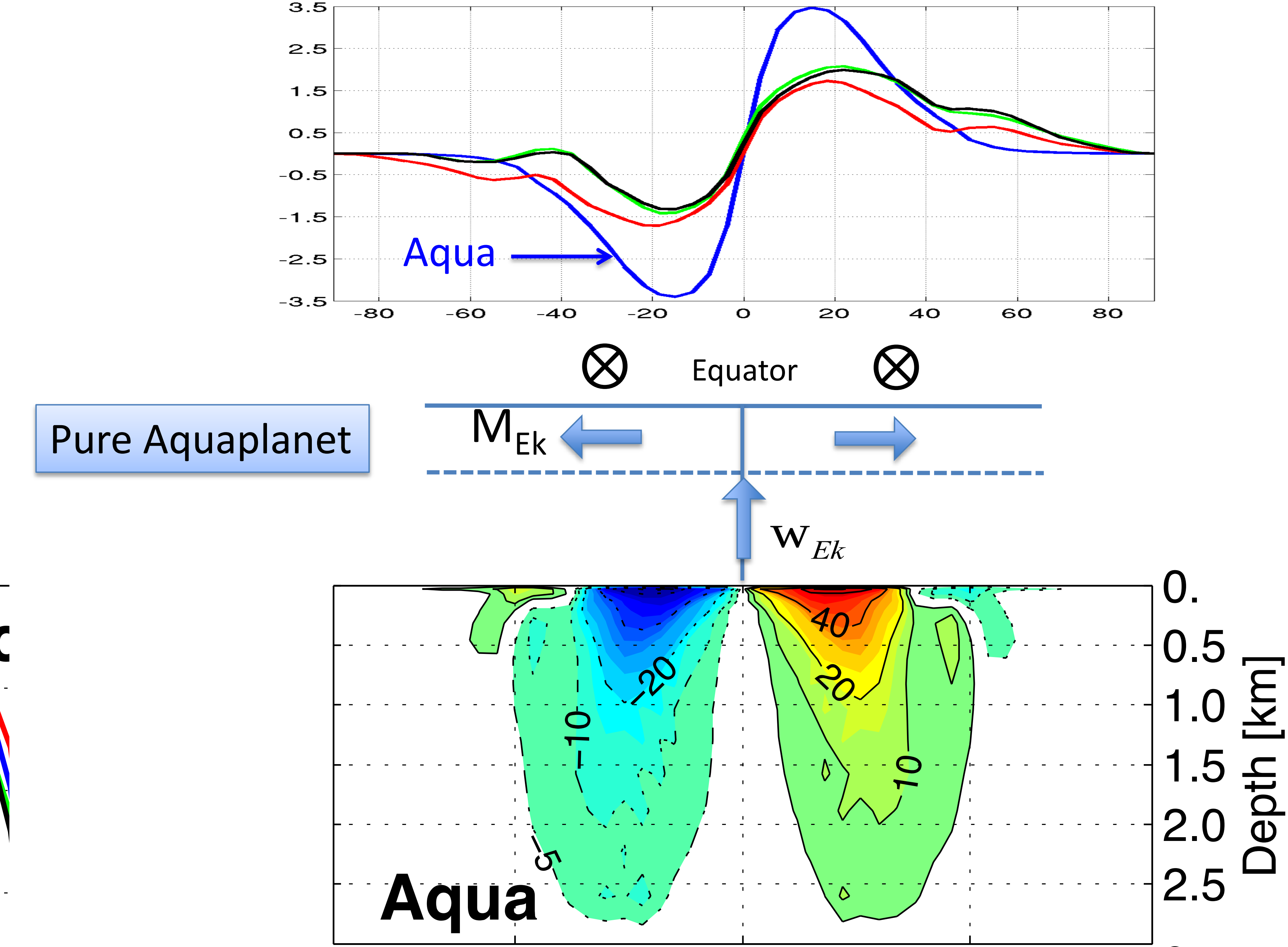
Observed Ekman pumping

+ = up



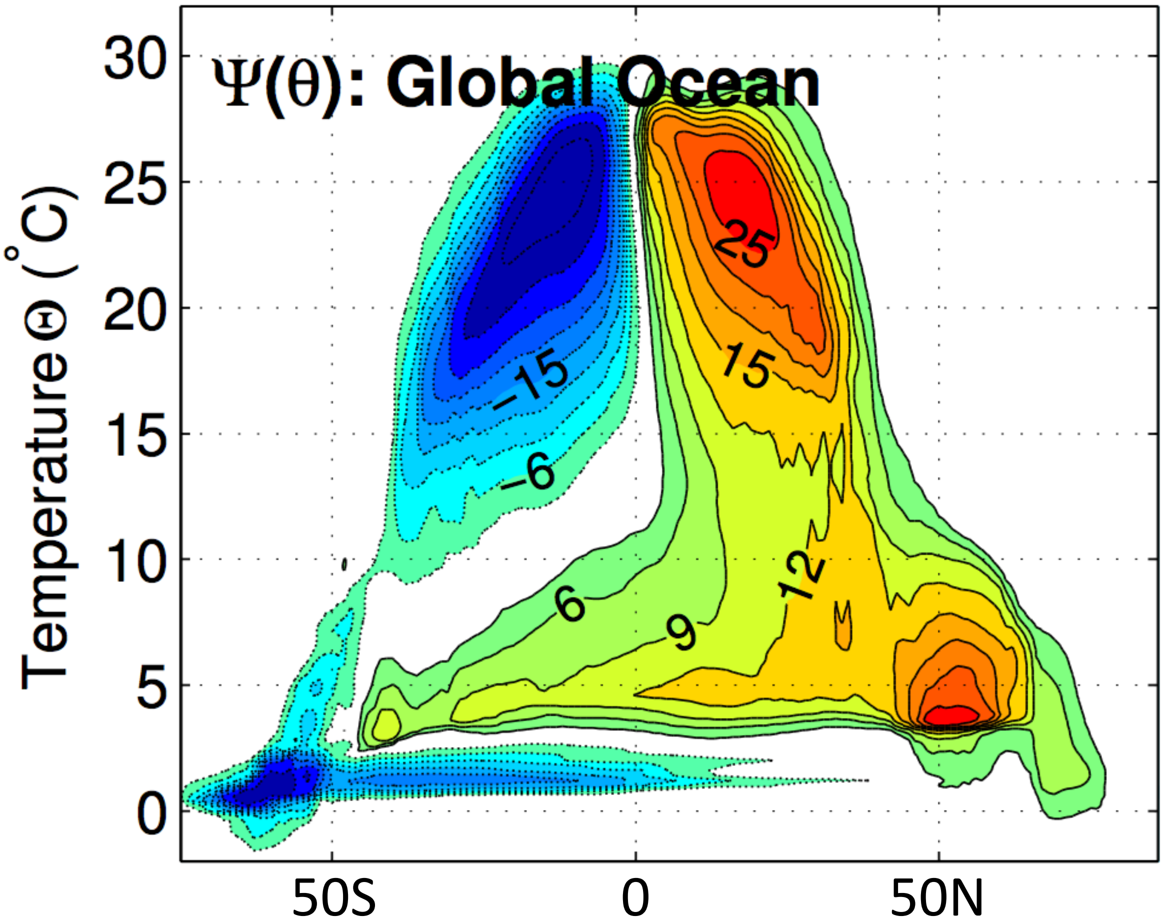
Upwelling

Downwelling



Aqua
Equator
Pure Aquaplanet
M_{Ek}
w_{Ek}
40
20
10
-20
-10
-5
Aqua
Depth [km]

<u>Overturning in temperature-layers</u>



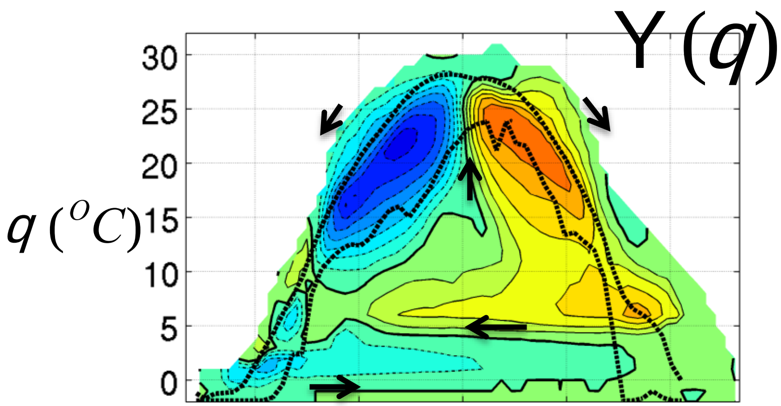
• Includes effects of standing and transient eddies

• relates to the net meridional heat transport

$$OHT \approx \rho_O C_P \Delta T \times \Psi$$

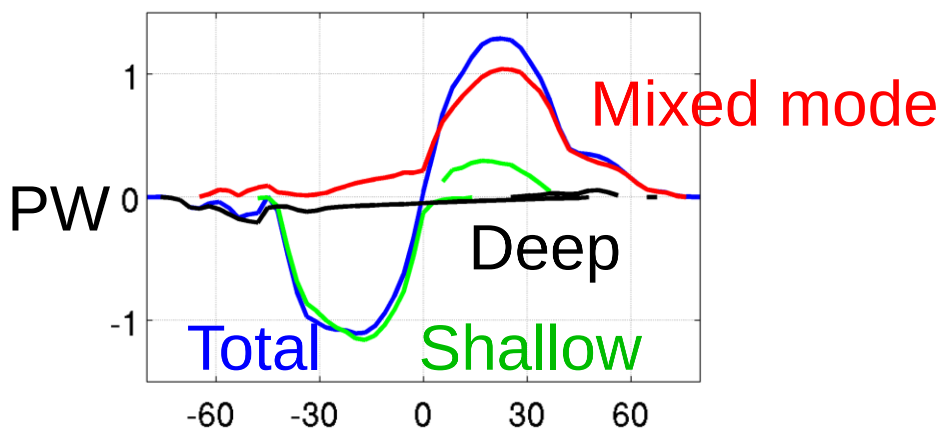
• a very useful tool to explore the dynamics of the OHT (e.g. Czaja and Marshall 2006, Ferrari and Ferreira 2011) and other topics (Doos and Webb ; Doos and Nilson, 2011; Held and Schneider, 1999 etc)

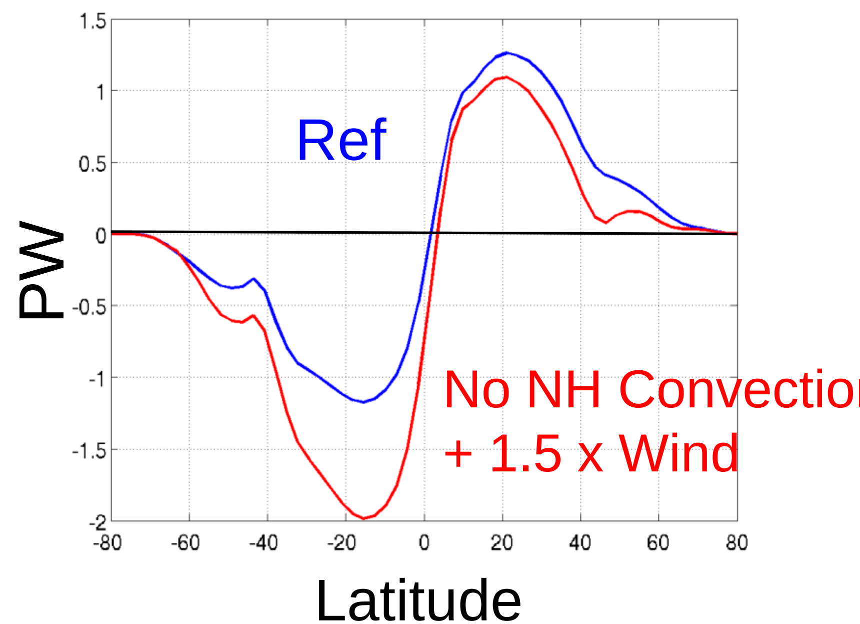
Dynamics of the OHT



$$OHT \approx \rho_O C_P \Psi(\theta) \times \Delta\theta$$

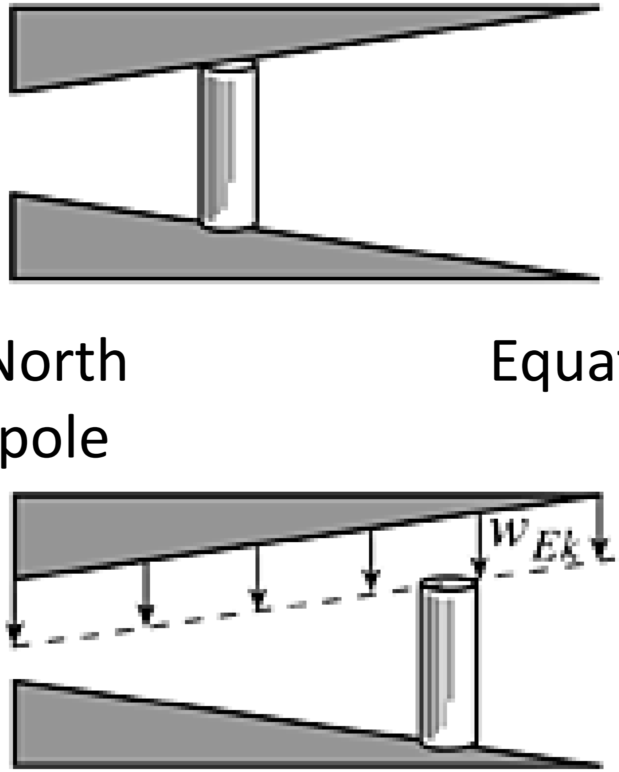
- Most of the OHT is achieved in shallow wind-driven overturning cells,
- Cross-Equatorial OHT associated with the deep Atlantic MOC and deep water formation
- OHT of the AABW cell is negligible,
- Diapycnal mixing has little effect of OHT





Ferrari and Ferreira (2011)

(b)



$t=t_0$

North pole

Equator

$t=t_1$

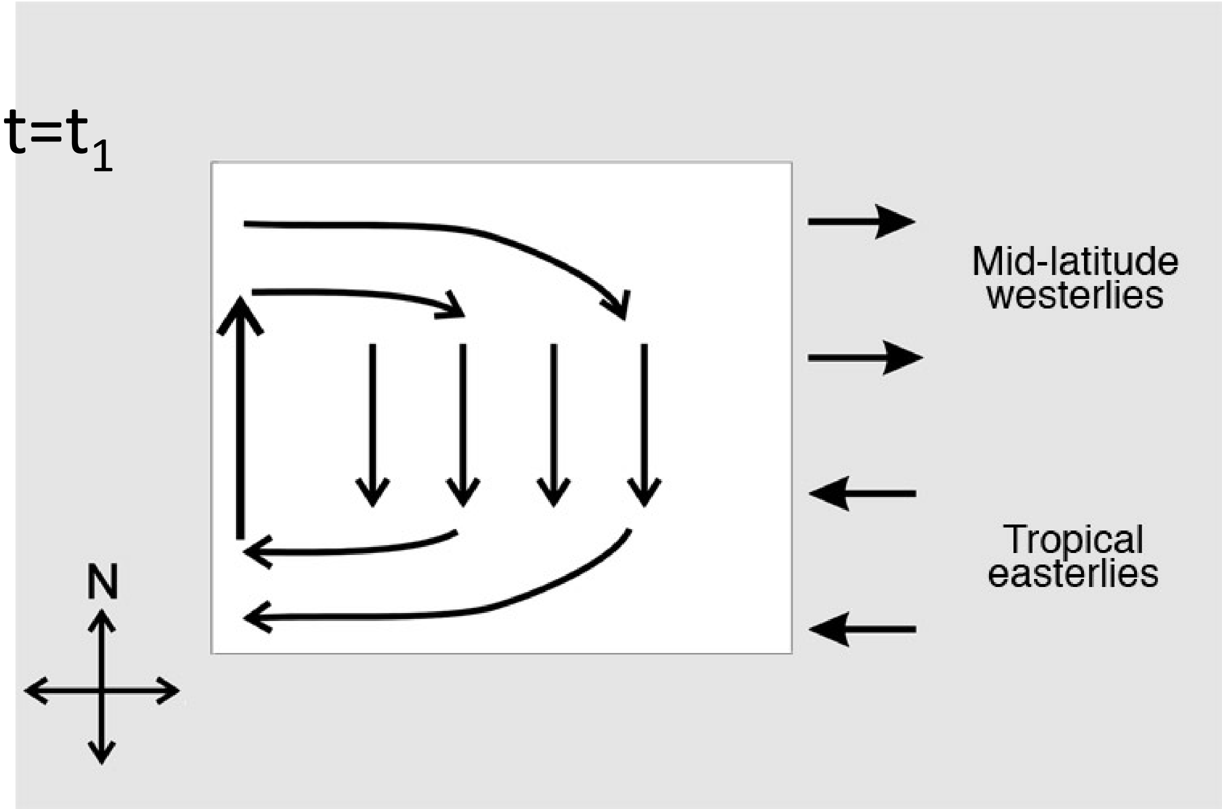
Sverdrup balance

$$bHv = f w_{Ek}$$

Beta-effect = df/dy

Coriolis parameter

- Requires a western boundary current and a continent



A few order of magnitudes

$$bHv = f w_{Ek}$$

$$f = 1´\ 10^{-4} s^{-1}$$

$$b = 1´\ 10^{-11} m^{-1} s^{-1} \quad \longrightarrow \quad \frac{f}{bH} = 2500$$

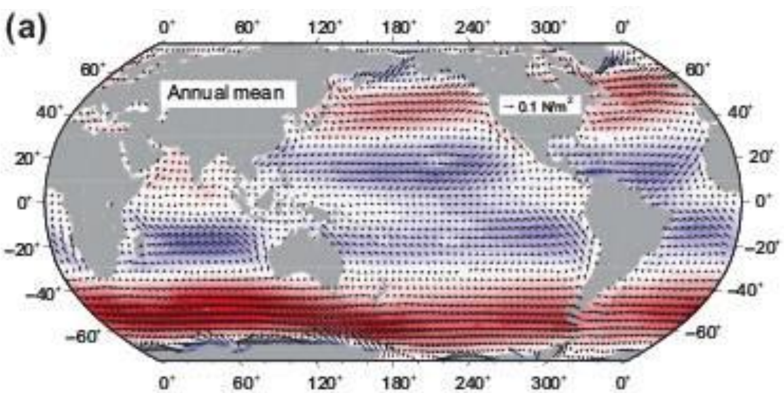
$$H = 4000 \text{ m}$$

$$w_{Ek} = 30 \text{ m/y} = 10^{-6} \text{ m/s}$$

$$\longrightarrow \quad v = 0.25 \text{ cm/s}$$

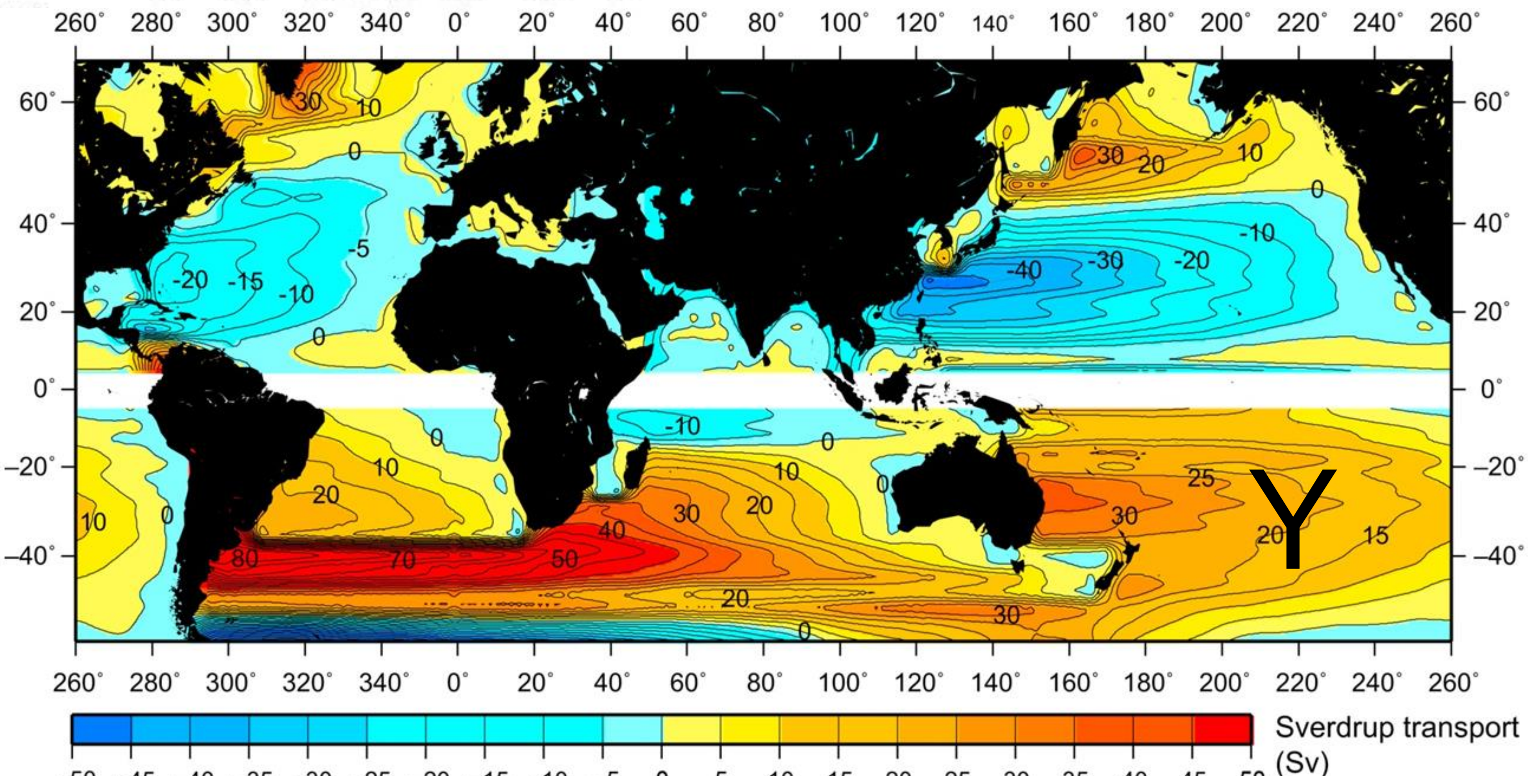
The wind-driven circulation

Surface stress τ_s



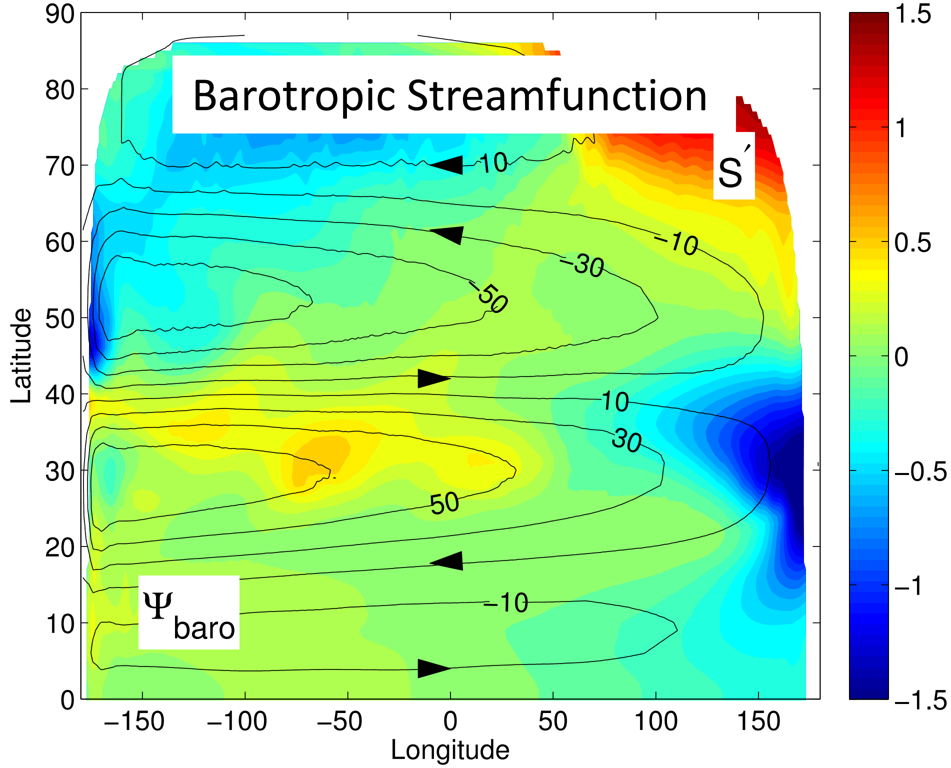
Sverdrup balance

$$bV = f\mathrm{w}_{Ek}$$

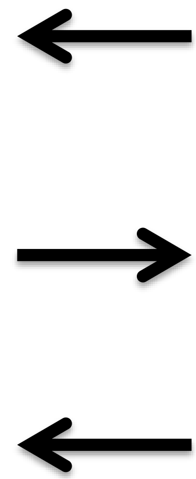


In Sv

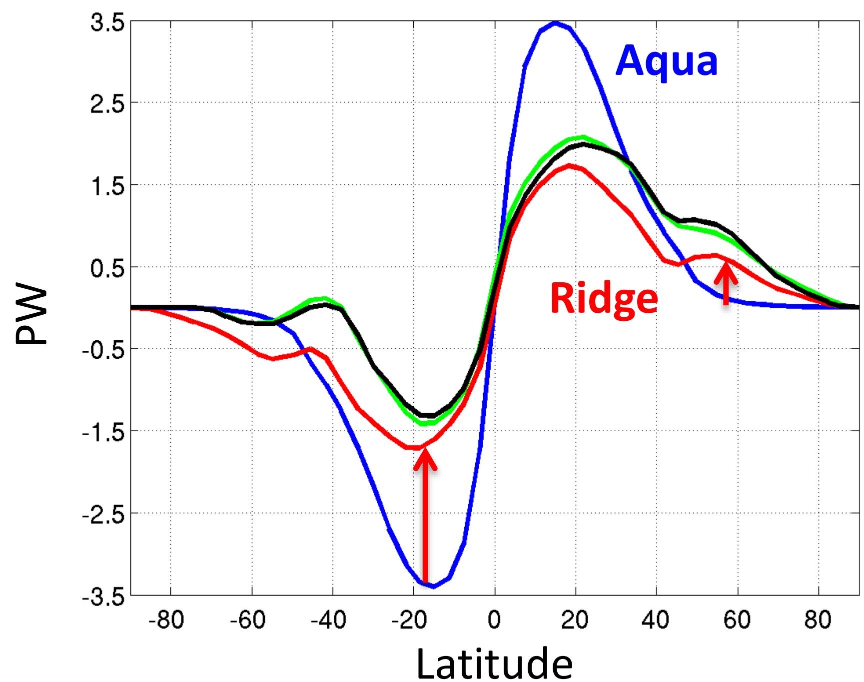
Ridge



Winds



Ocean Heat Transport

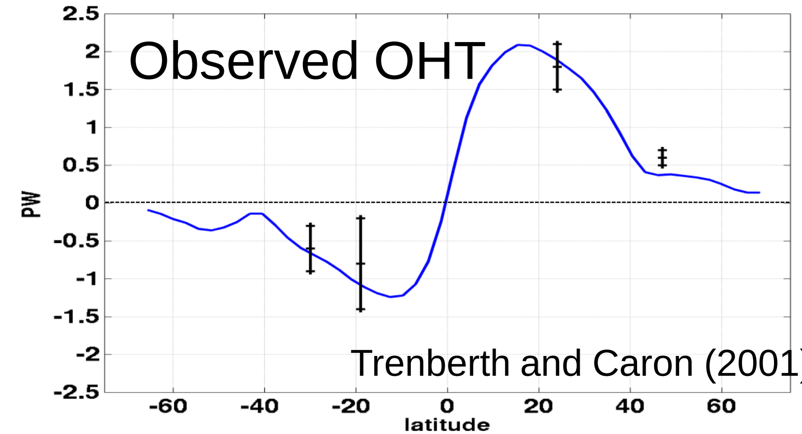


Meridional boundaries:

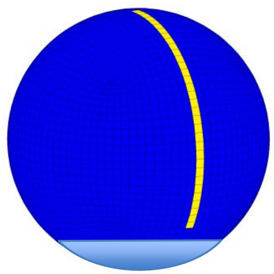
→ Gyre circulation: weakens the depth of wind-driven cells

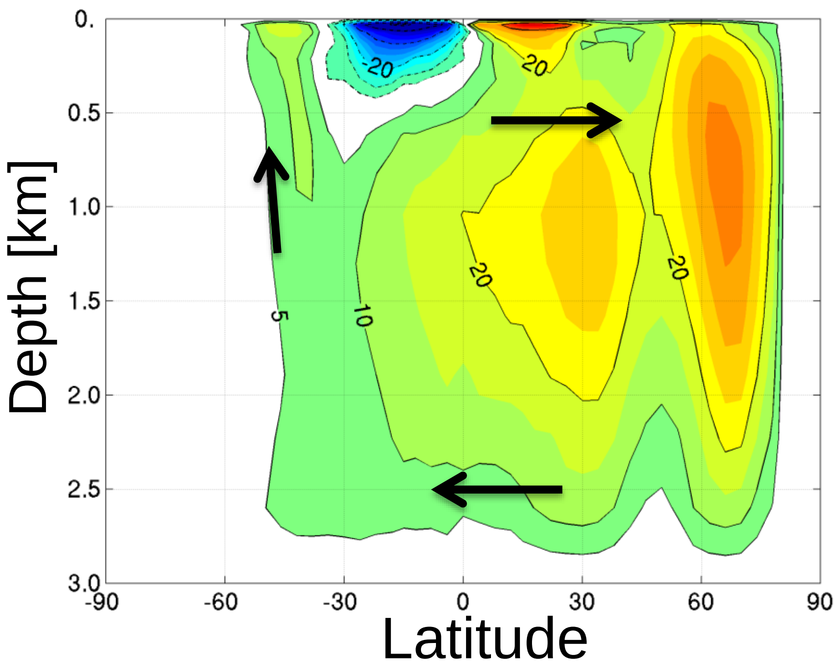
→ Strengthen northward OHT at high latitudes

Why does the Ocean Heat Transport have this shape ?

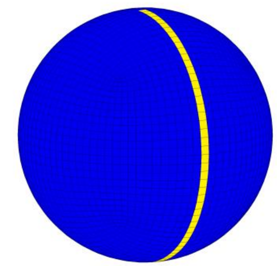


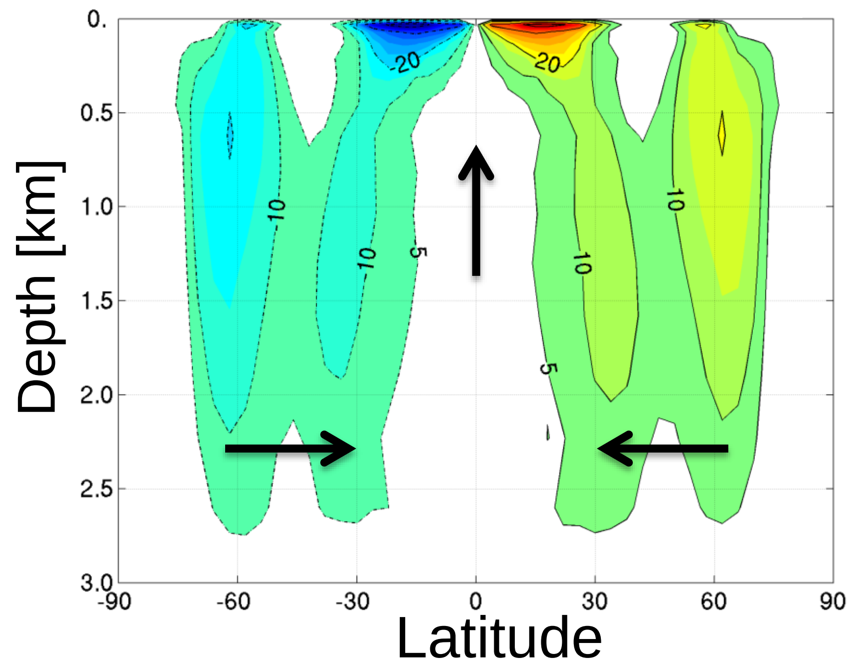
Drake

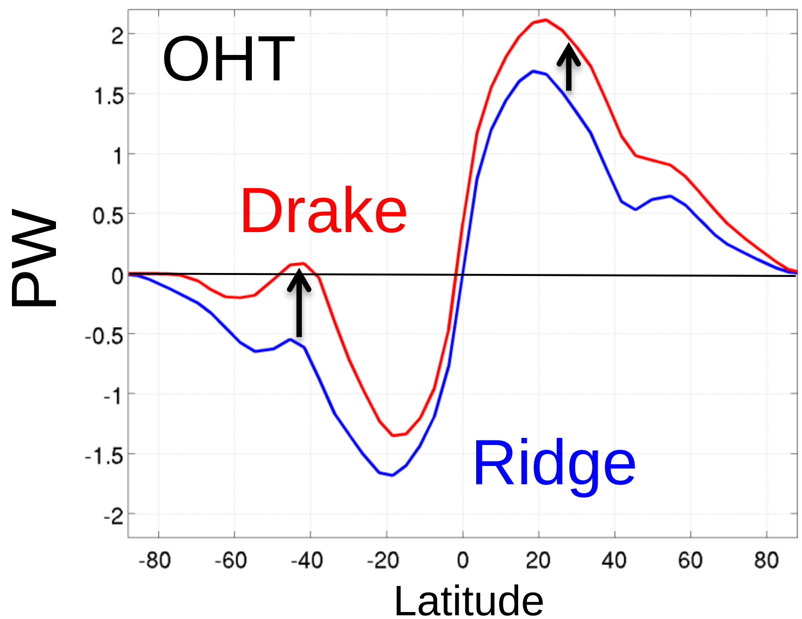


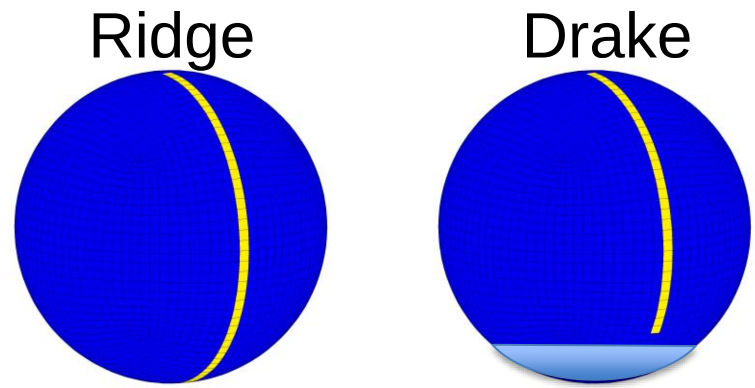


Ridge

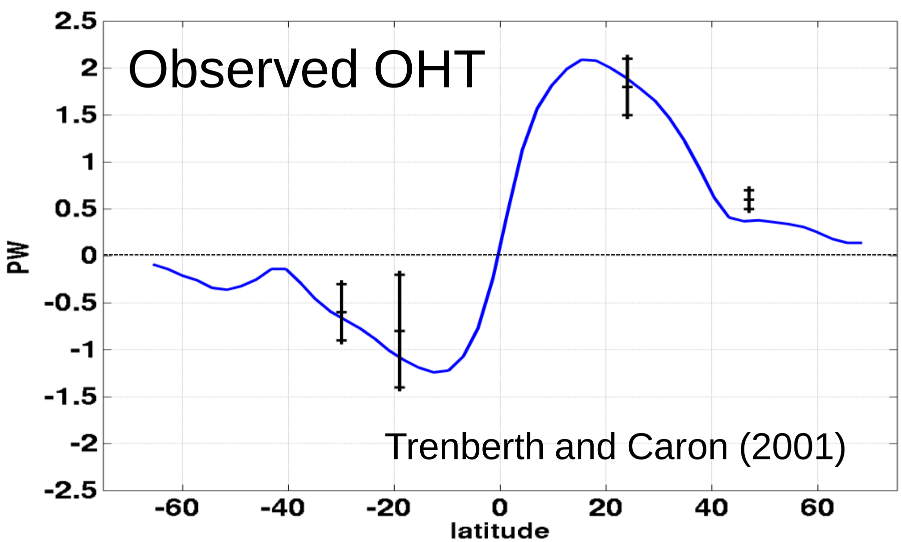




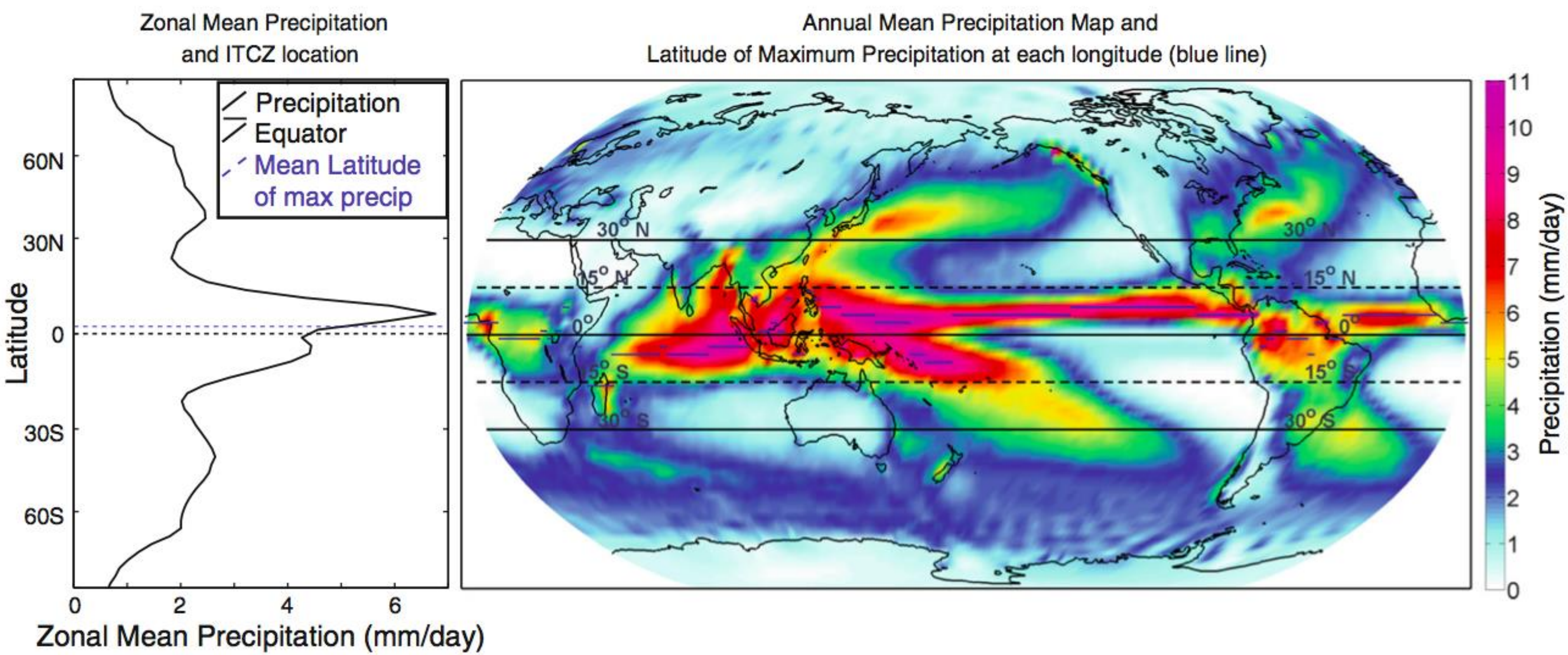




- Inter-hemispheric deep MOC = global shift of the OHT more “northward”
- But most of the OHT is due to shallow wind-driven overturning
  → peak at ~20N/S
- In real world too (Ferrari and Ferreira, 2011)
- The AMOC explains “only” 40-60% of Atlantic OHT

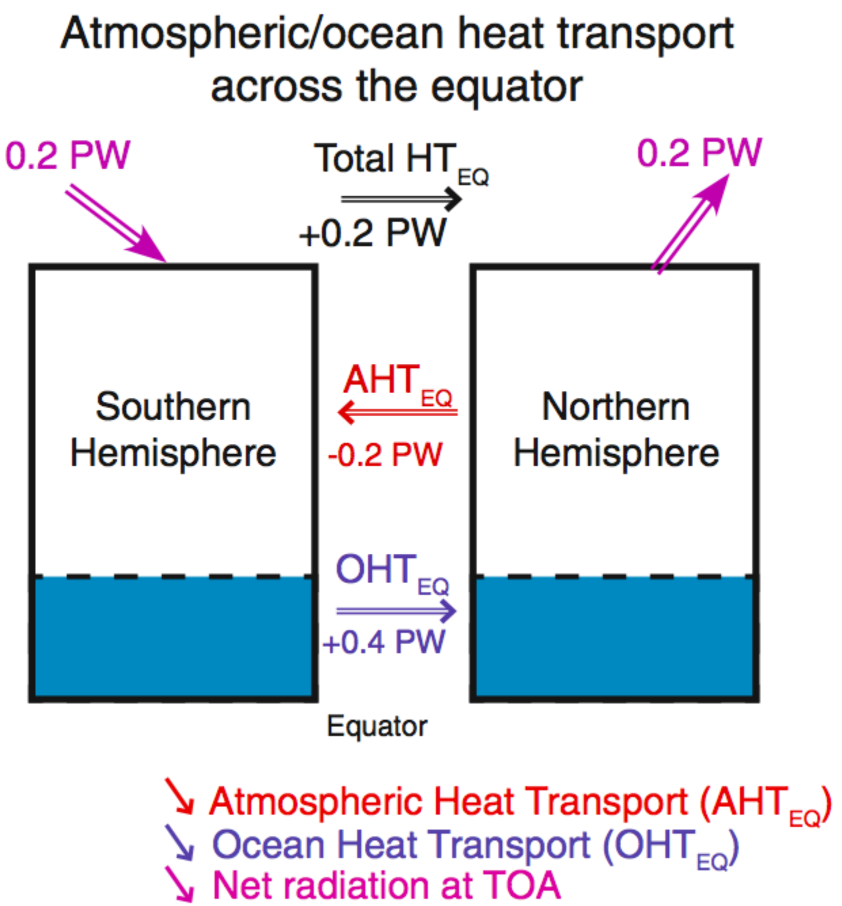


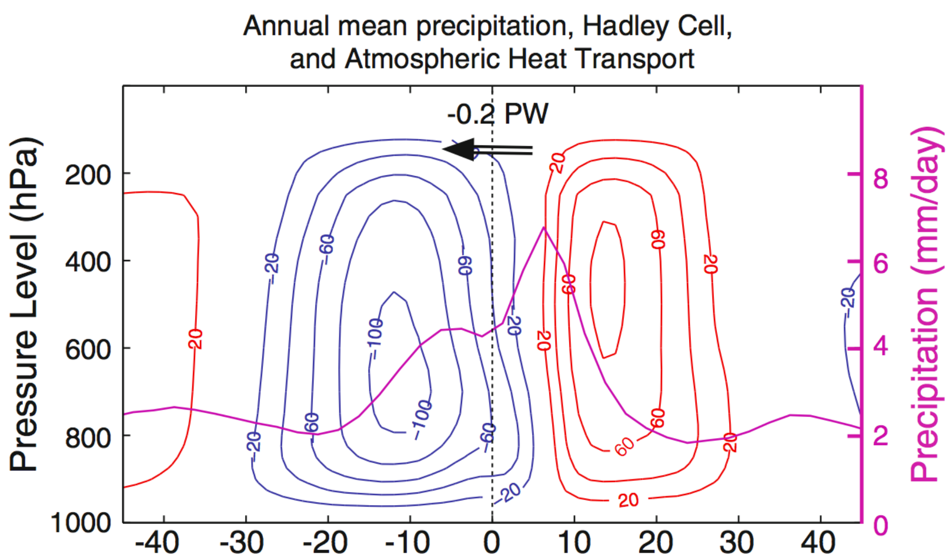
Why is the ITCZ in the Northern Hemisphere?



Donohoe et al. 2013

Why is the ITCZ in the Northern Hemisphere?

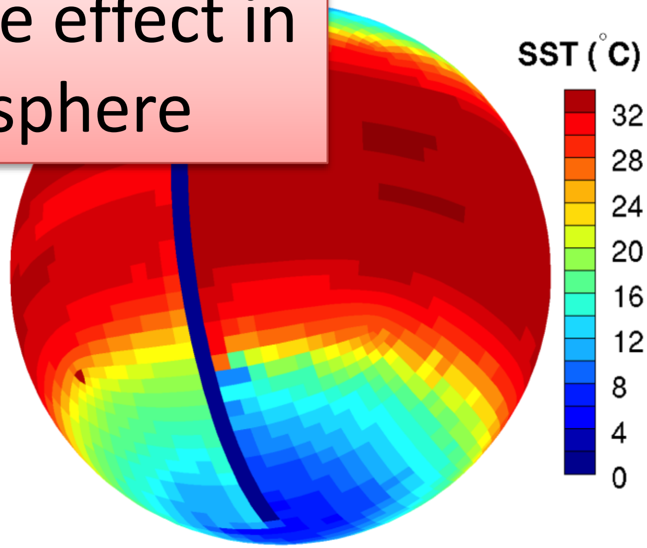


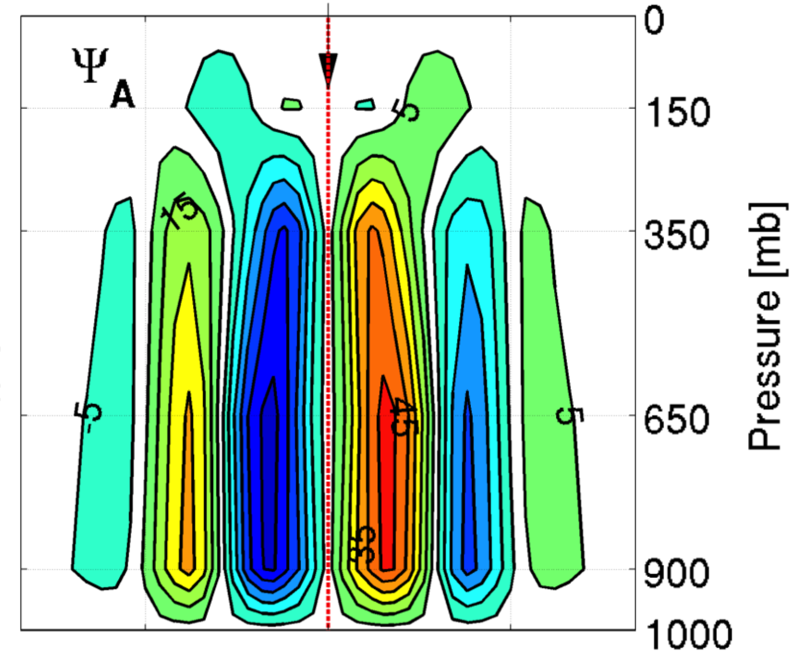


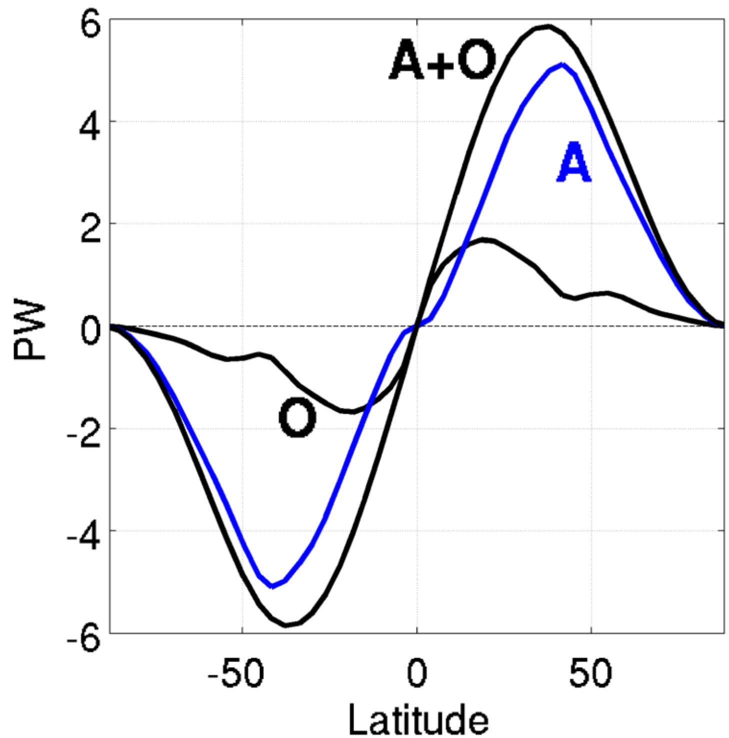
Marshall et al. 2013, Donohoe et al. 2013

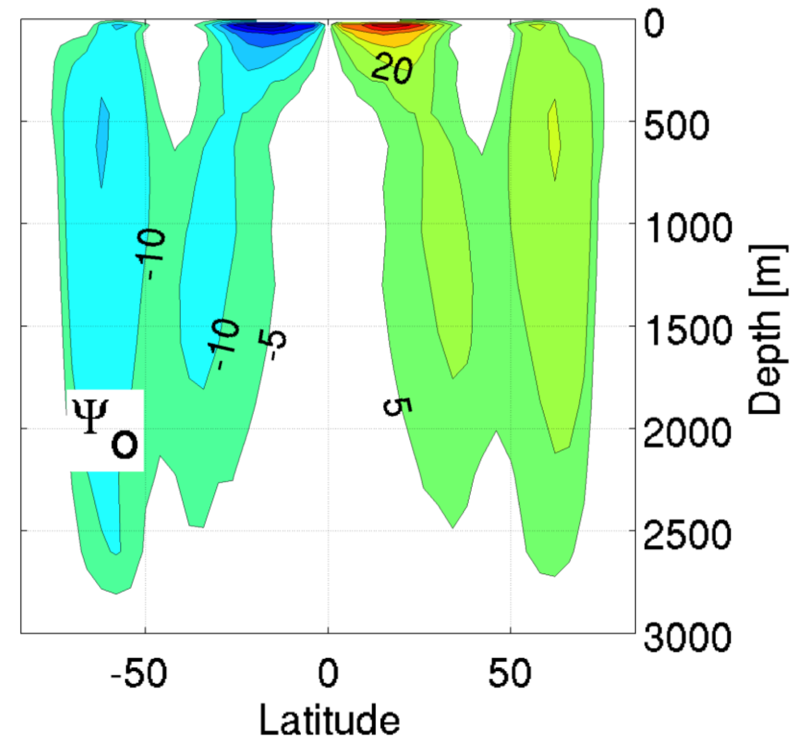
Drake Passage effect in the atmosphere

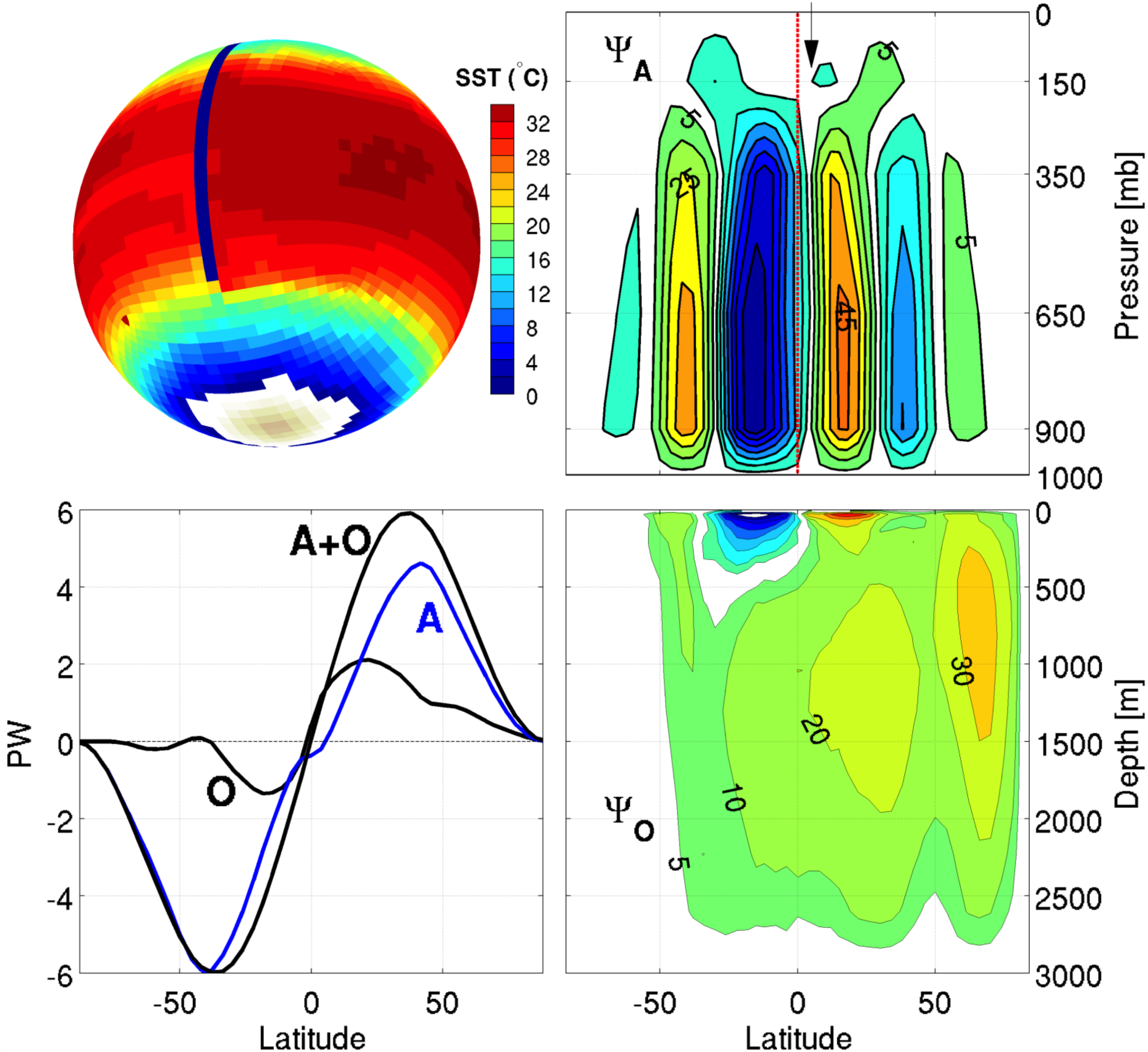
-Toggweiller and Bjornsson, 2000
-Toggweiller and Samuel, 1995
-Gnanadesikan 1999



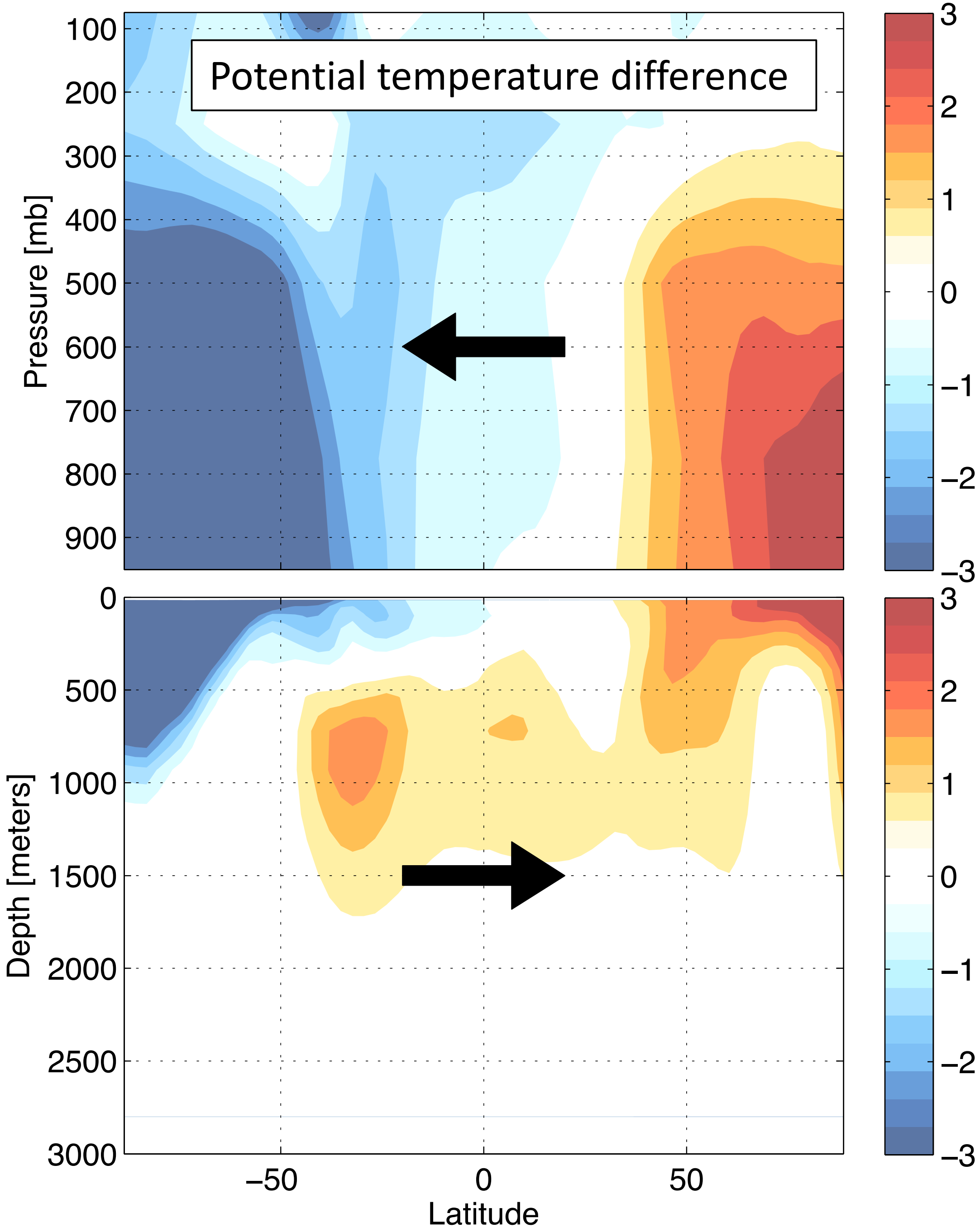




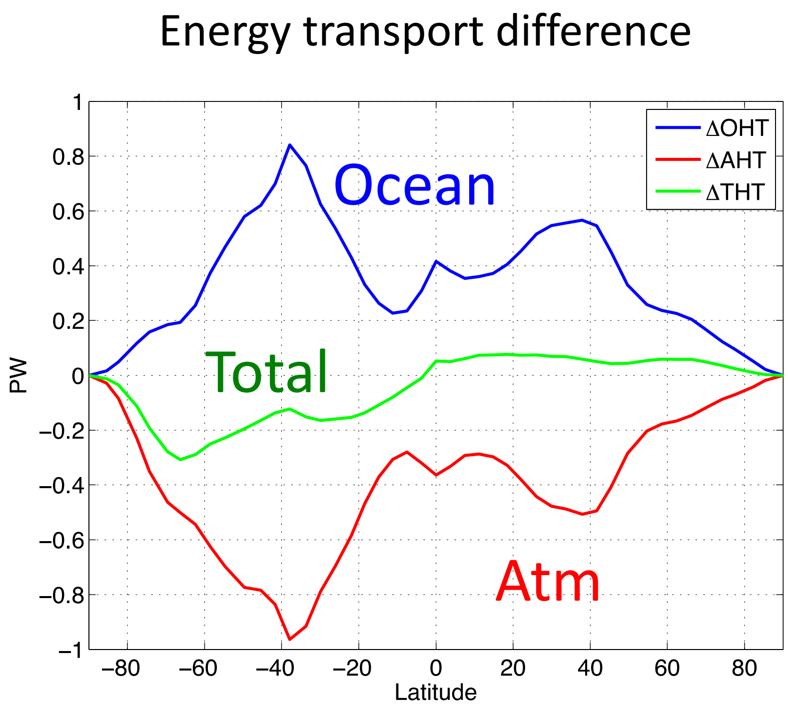




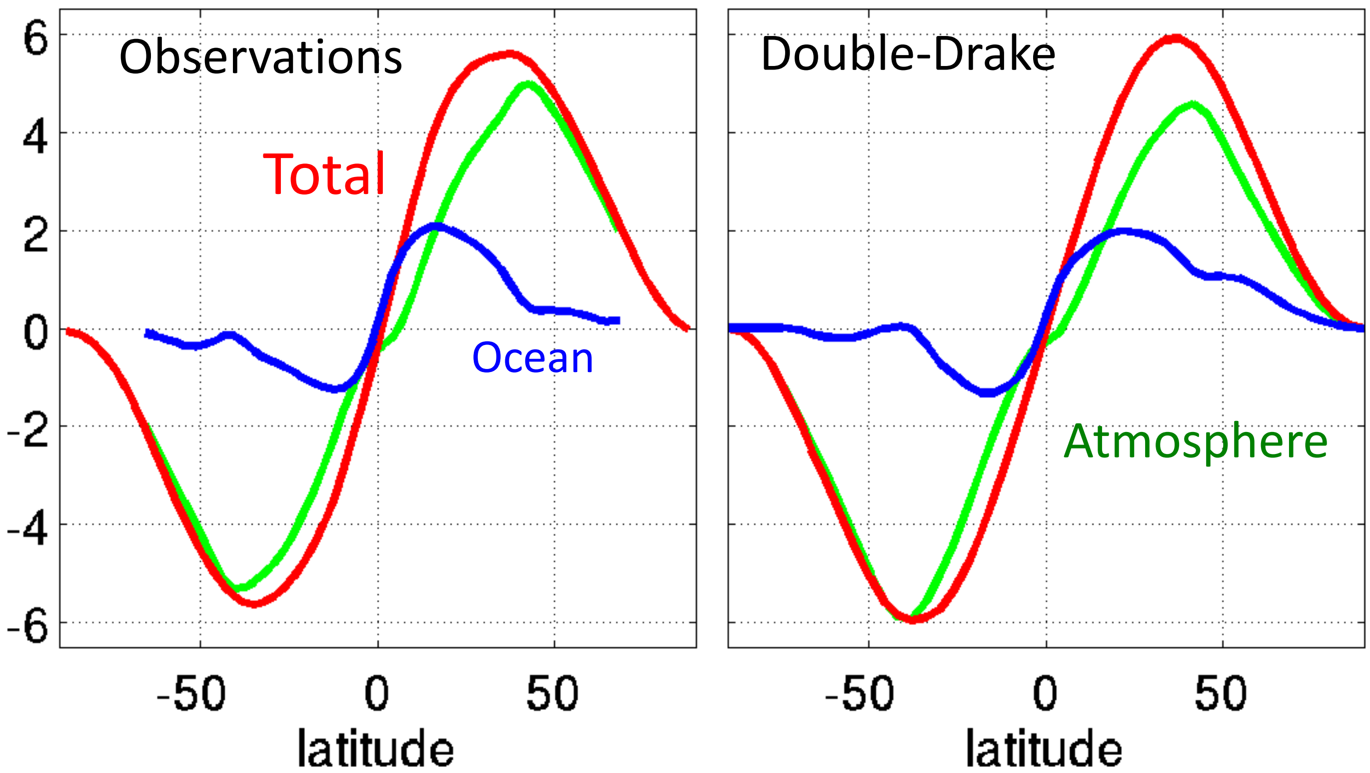
SST (°C)
32
28
24
20
16
12
8
4
0
Ψ A
5
25
45
5
5
Pressure [mb]
0
150
350
650
900
1000
A+O
A
O
PW
6
4
2
0
-2
-4
-6
-50
0
50
Latitude
Ψ O
5
10
20
30
Depth [m]
0
500
1000
1500
2000
2500
3000
-50
0
50
Latitude



Drake minus Ridge



Conclusion: Double-Drake = Real World + O(1)



Two ingredients:

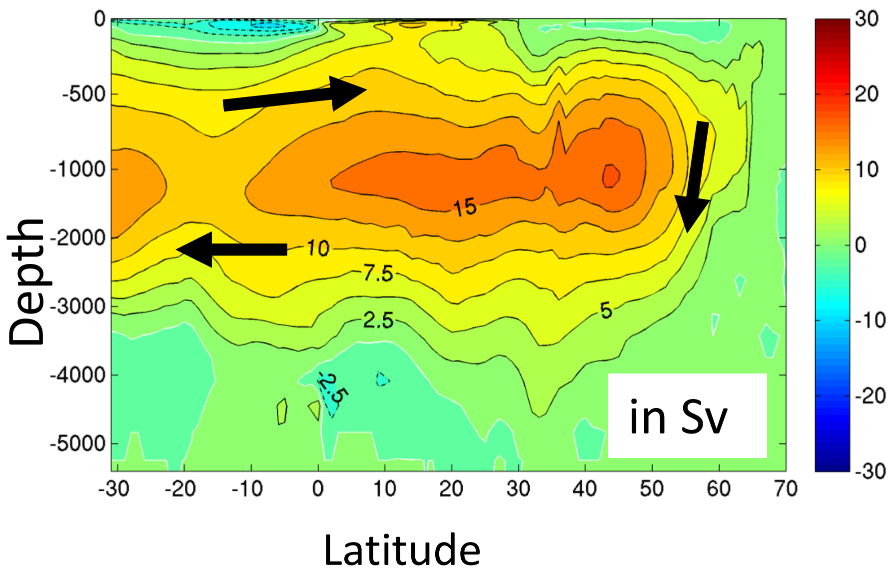
1) a meridional asymmetry: an ACC in the SH

2) a zonal asymmetry: a small and a large basin

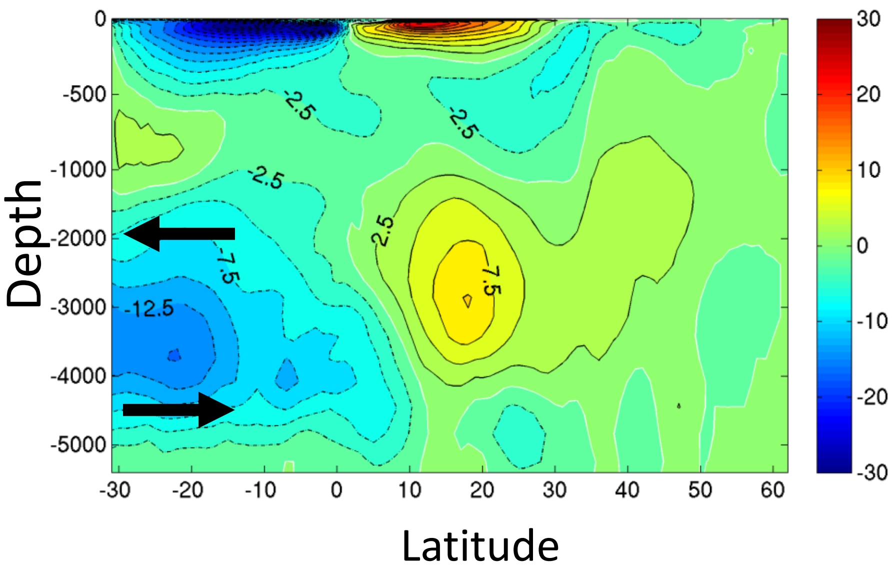
Atlantic/Pacific asymmetry

Present-day Meridional Overturning Circulation

<u>Atlantic:</u> warmer, saltier, dense water formation, well ventilated

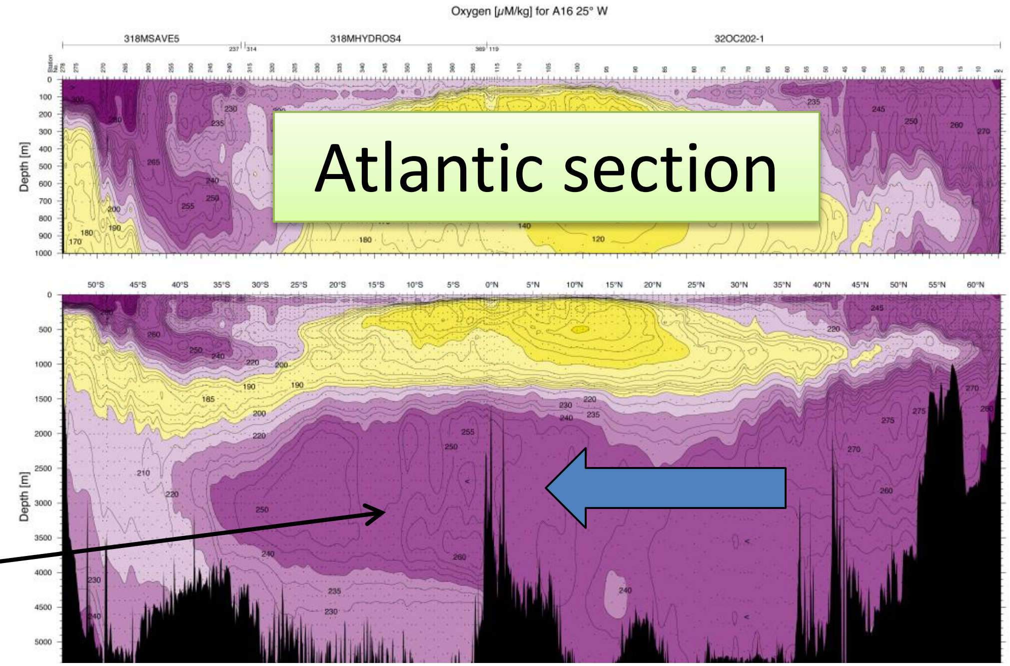


<u>Pacific:</u> colder, fresher, wind-driven shallow circulation



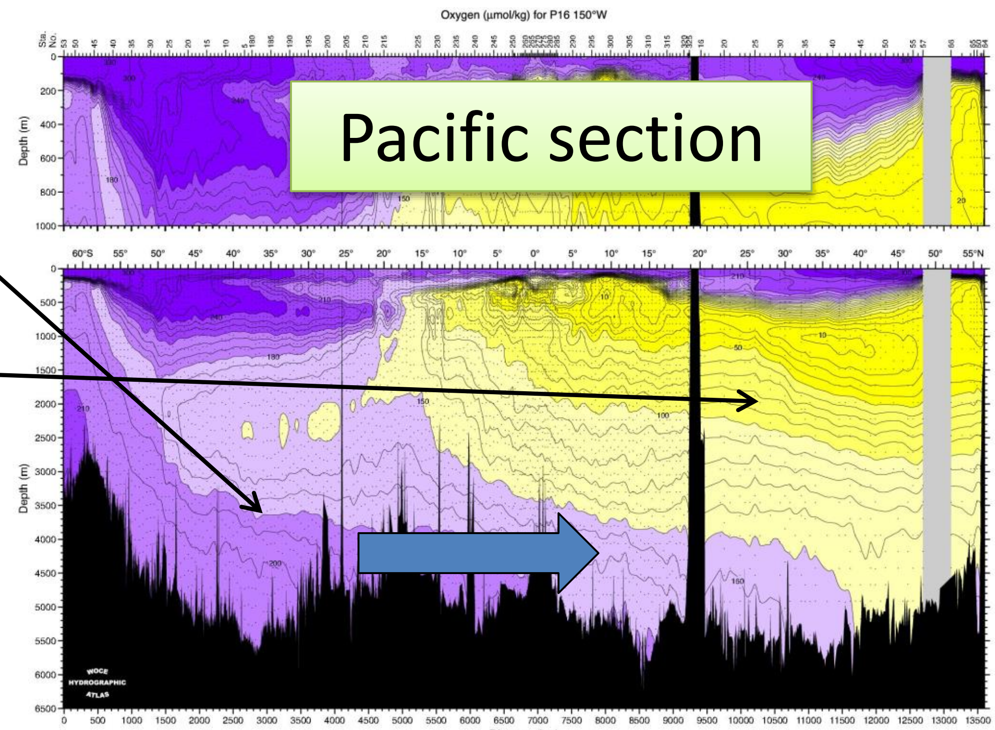
OCCA Ocean state estimate (Forget, 2009)

Oxygen distribution



High O_2

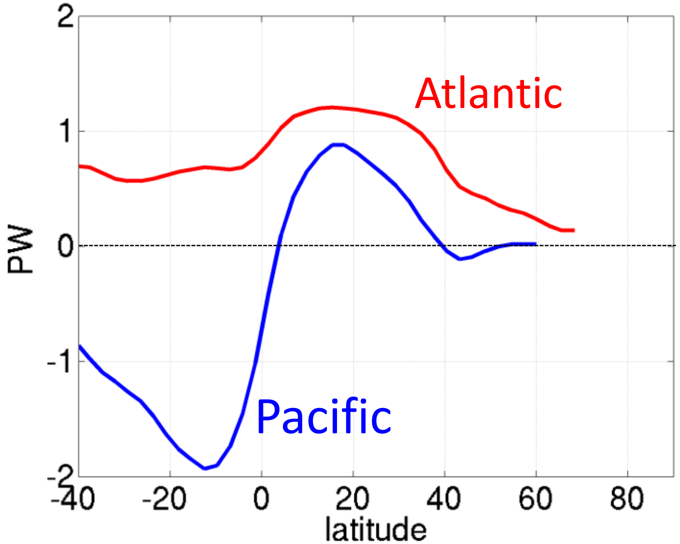
Low O_2



WOCE sections

Observations

Heat transport

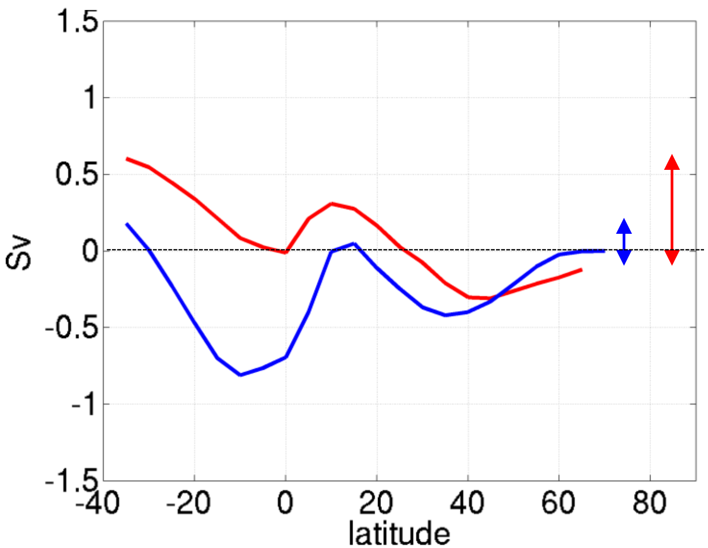


Atlantic: northward everywhere

Pacific : anti-symmetric

Trenberth and Carron (2001)

Freshwater transport



$$\Delta F_{Alt} > 0$$

$$DF_{IP} \approx 0$$

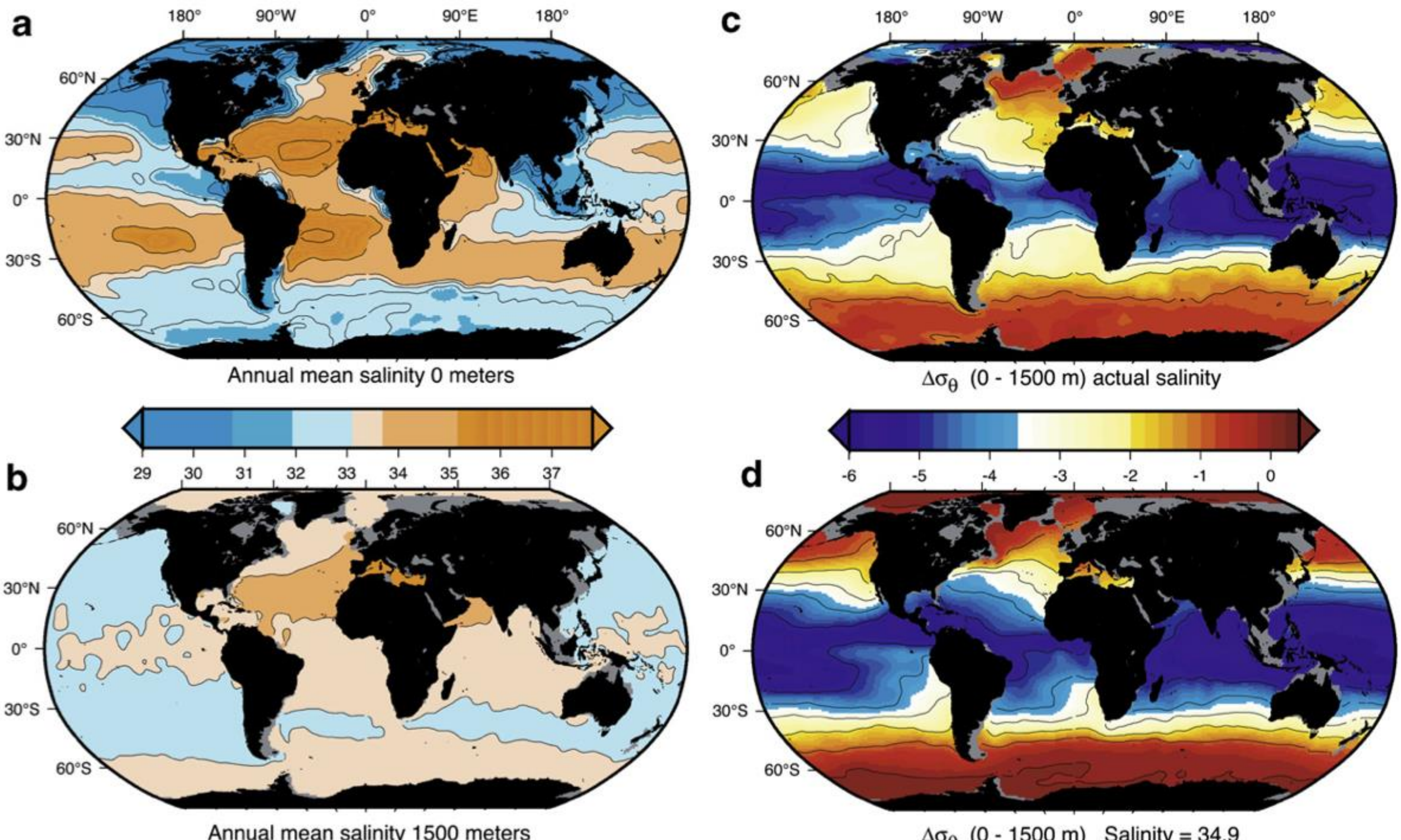
Wijffels et al. (92)

$$(E - P)_{Atl} > (E - P)_{IP}$$

→ Export of freshwater from Atlantic to Pacific

Sea surface Salinity

MOC in Atlantic ←→ high salinity in Atlantic



Talley (2008)

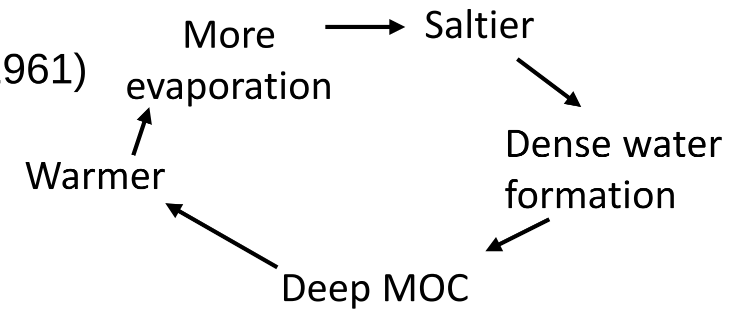
Why does deep water formation occur in the North Atlantic only?

- Salinity is key: produce densest waters

  (e.g. Seidov and Haupt 2003, Talley, 2008, de Boer et al. 2008)

- Two limits
  - Salinity contrast driven by ocean:

    → the "self-sustained Atlantic MOC" (Stommel, 1961)

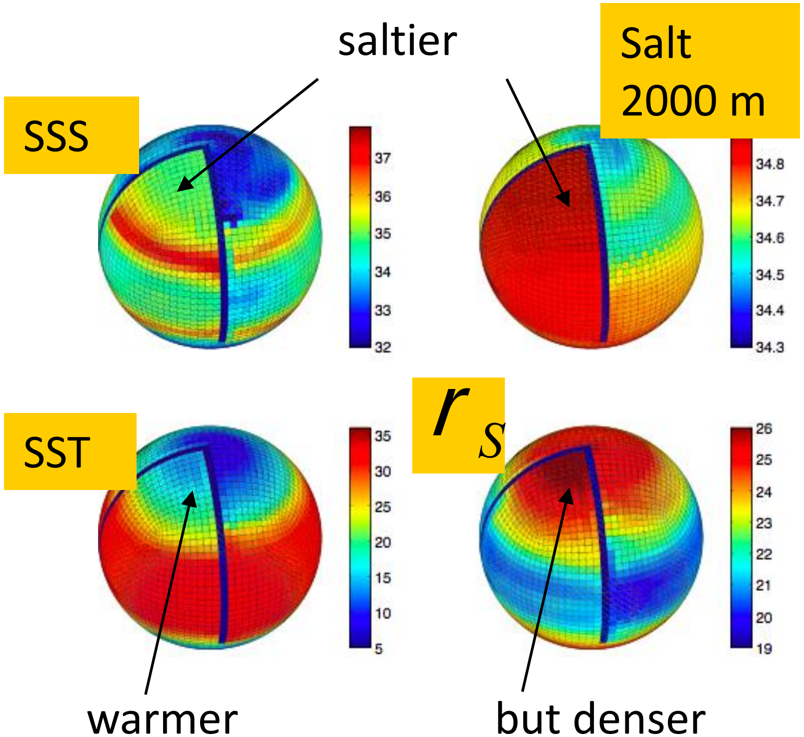


  - Salinity contrast driven by the atmosphere

Geographical factors invoked in the literature:

- The "long America"/"short Africa"
- The effect of the Mediterranean
- The northward extension of the Atlantic
- The difference in surface wind features
- Topographically-forced stationary waves

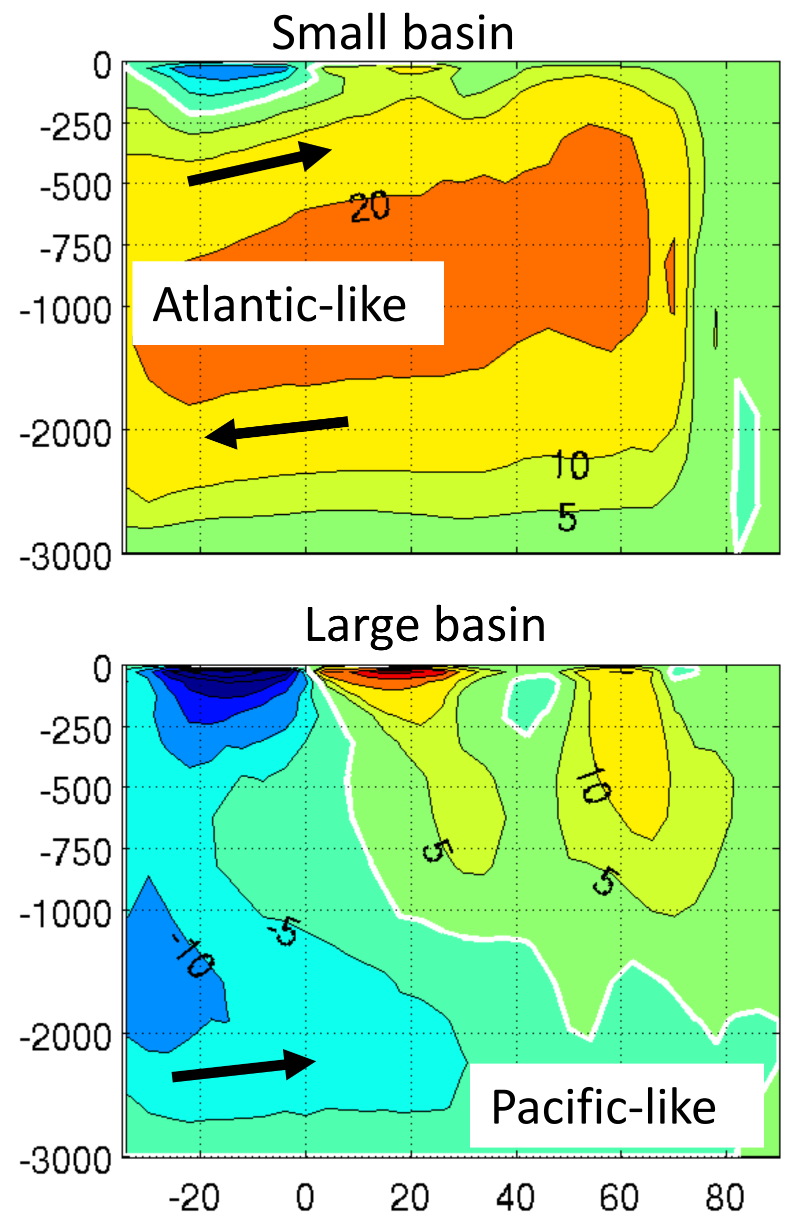
Double-Drake



Deep Convection → in Small basin

→ reproduces the observed OHT basin asymmetry

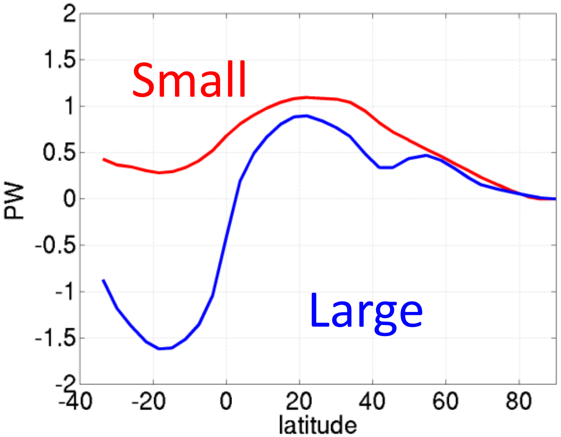
Overturning Circulation

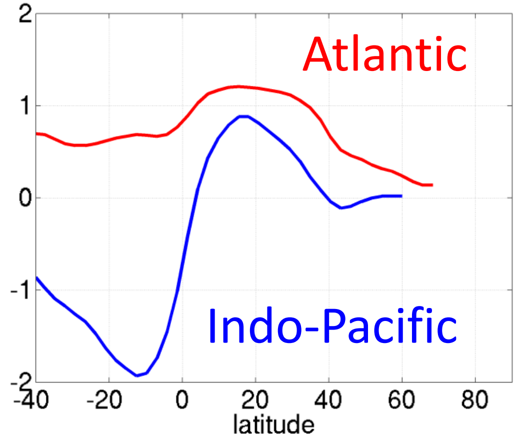


Ferreira et al. (2011)

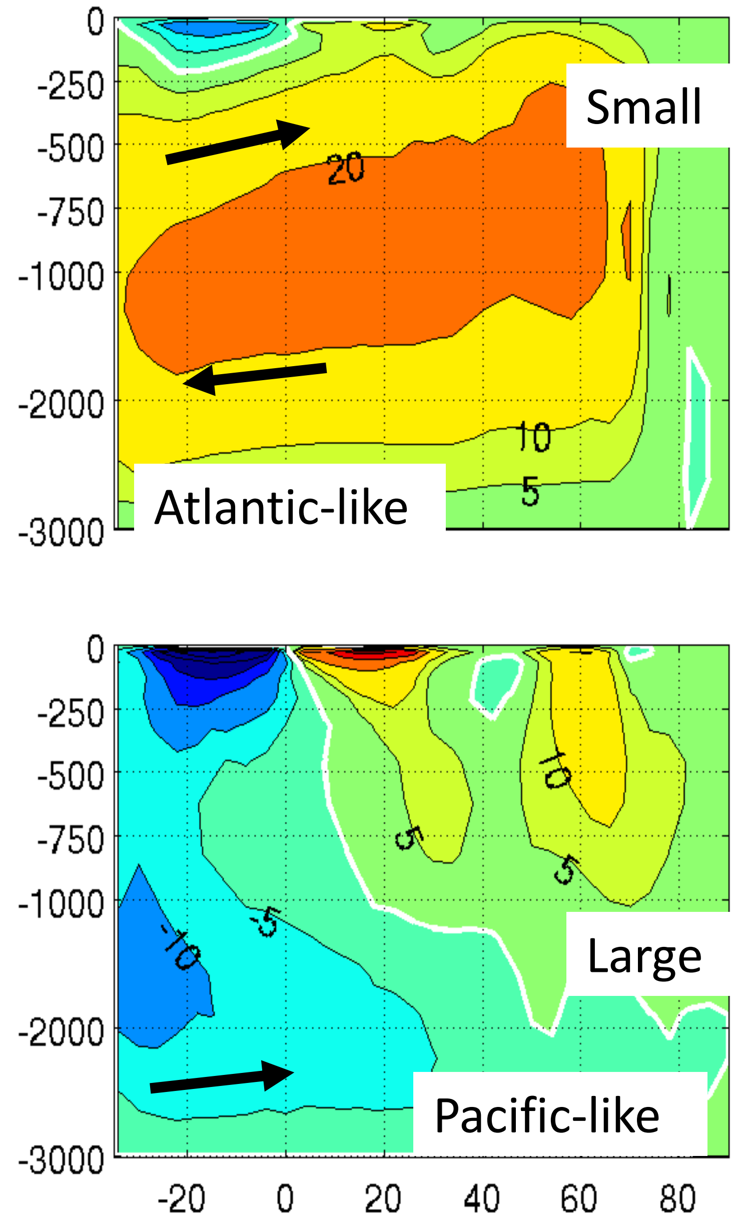
Double-Drake

Ocean Heat Transport



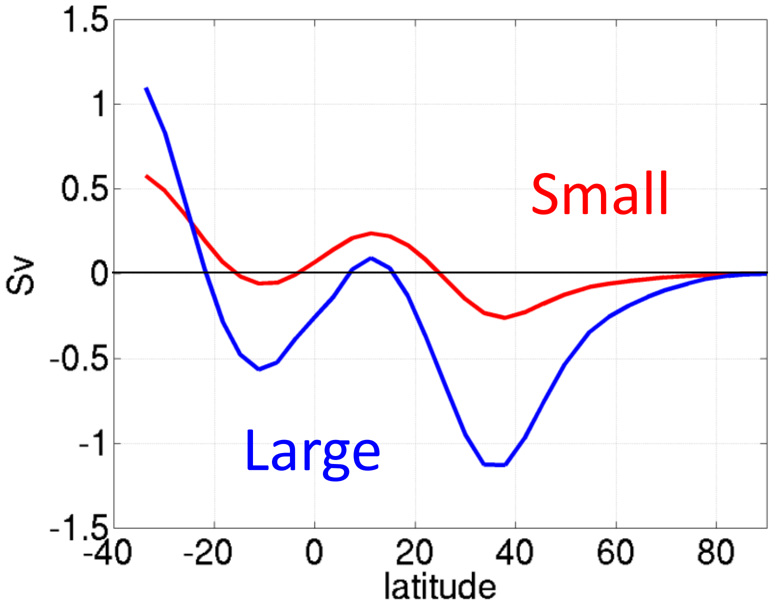


Overturning Circulation



Double-Drake reproduces the observed basin asymmetry

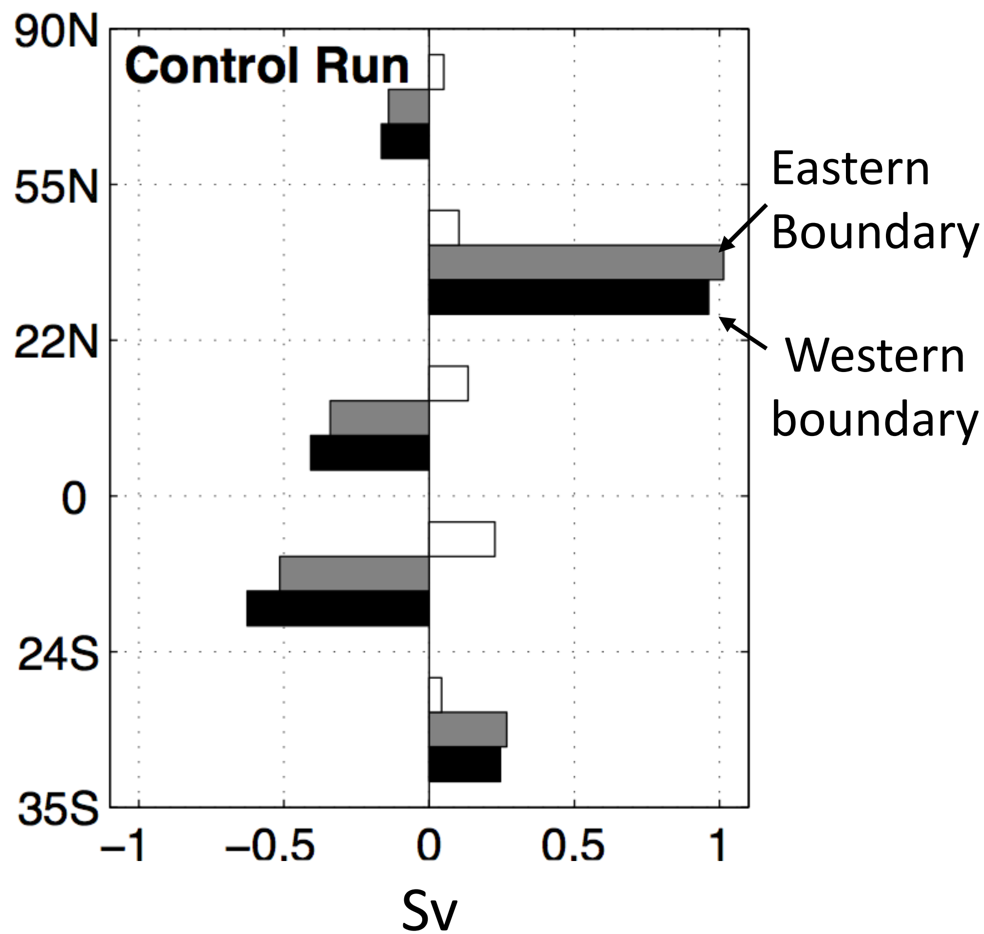
Ocean freshwater transport



Equivalent to the observed E-P asymmetry

A difference in precipitation or in evaporation?

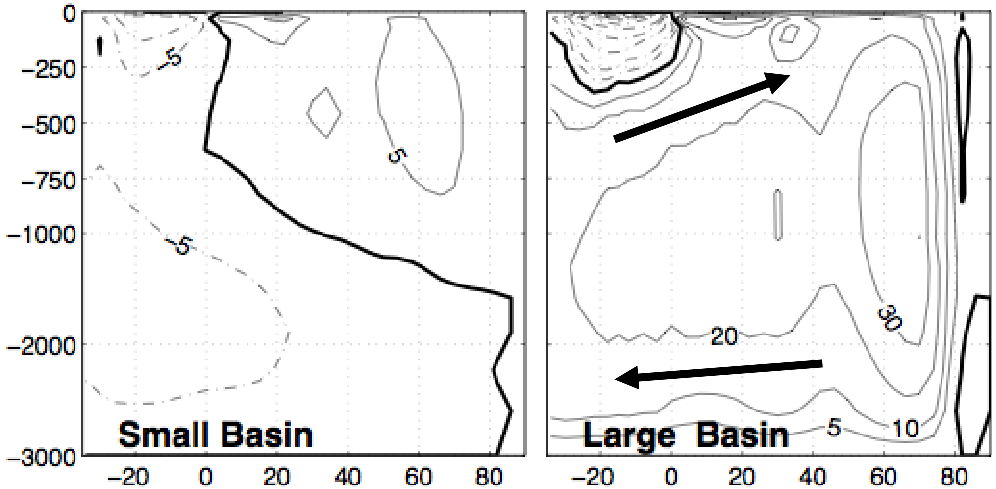
Atmospheric Zonal moisture flux:
Flux out > flux in @ all latitudes



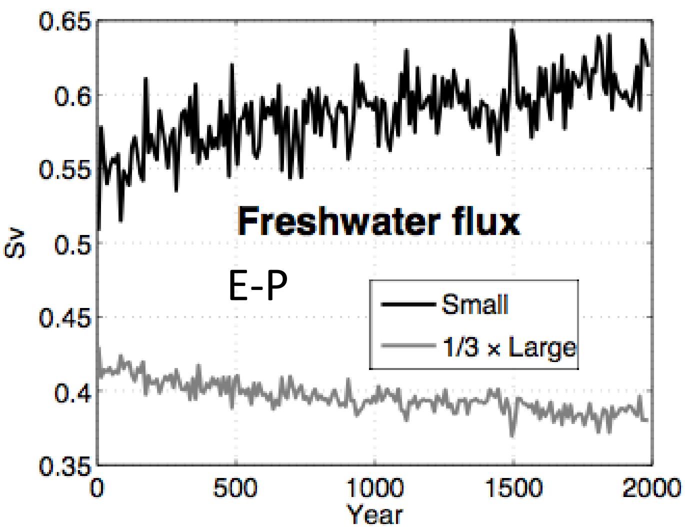
Switch experiment

Re-start run with Temp/Salt of Small basin as Initial Conditions in Large basin and vice-versa

After 10 years

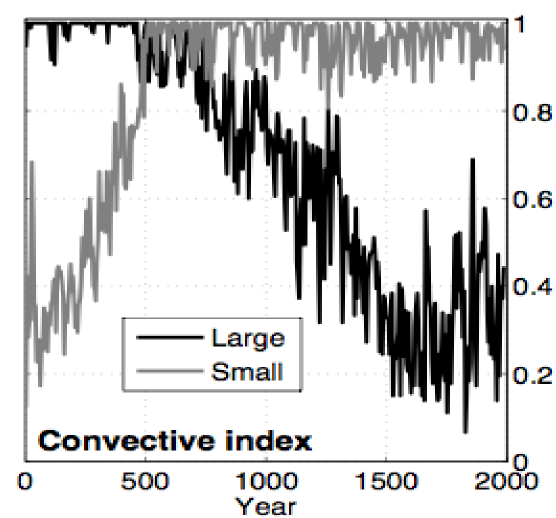


Large basin is now warmer, saltier, has dense water formation, a deep MOC, and a higher rate of evaporation …



… but still looses freshwater water to the atmosphere at a smaller rate than the Small basin

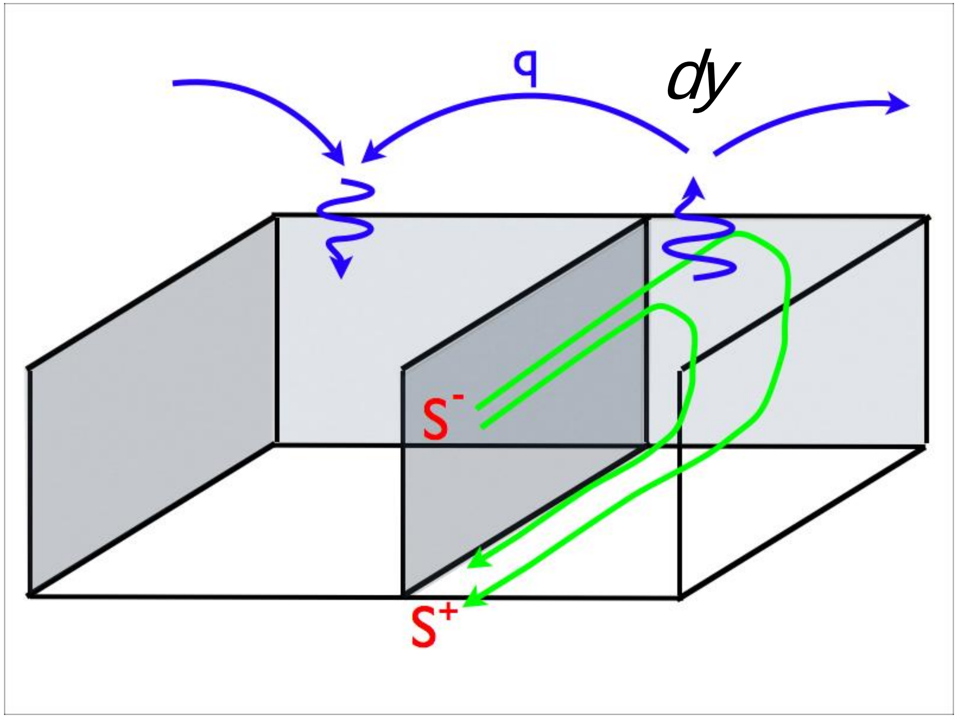
→ Unstable state



- E-P contrast between the two basin

$$(E - P)_{SMALL} > (E - P)_{LARGE}$$

- Not because of higher rate of evaporation
- <u>but a deficit of precipitation</u>



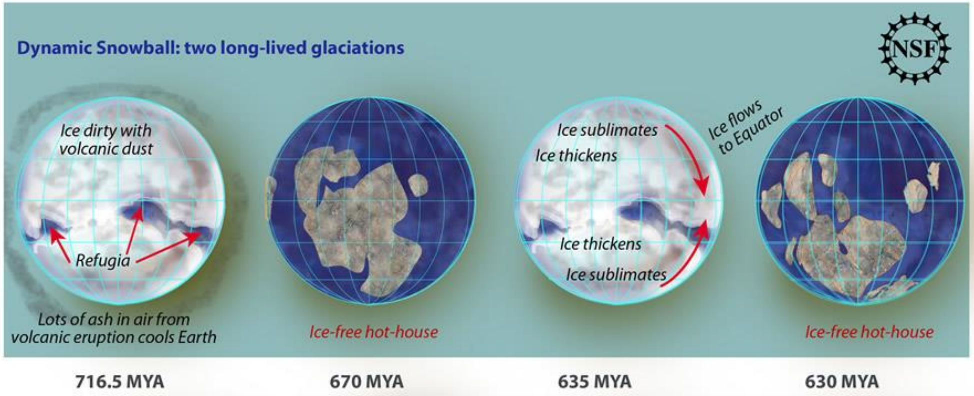
→ In Double-Drake: width of the basins

- Water evaporated over the Small basin is rained out into the Large basin

→ Other Models: Mountain range (Sinha et al. 2012, Schmittner et al. 2012)

- Rocky mountains force precipitations in Pacific
- Low Isthmus of Panama

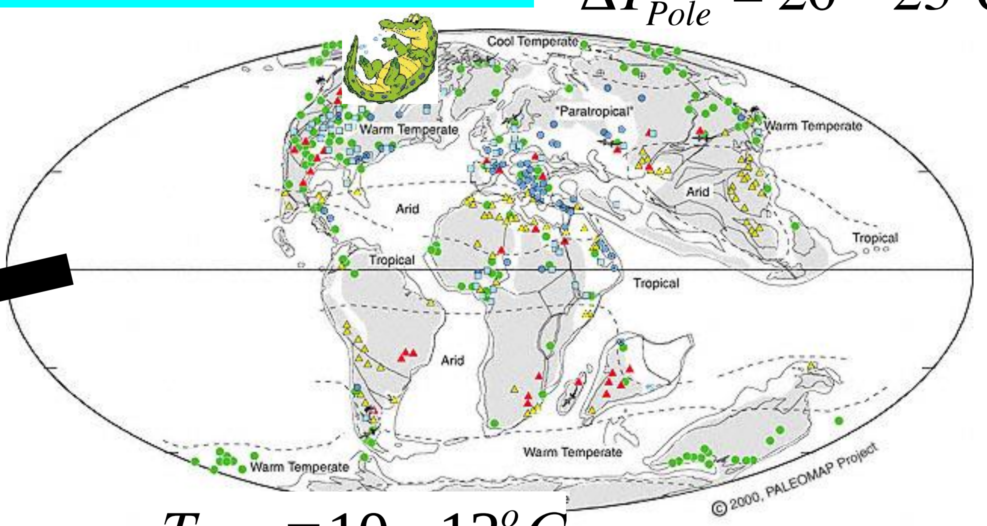
Geology and paleoproxies indicate Earth climate went through very different states



Neoproterozoic Snowball Earth

Ice-free Cretaceous

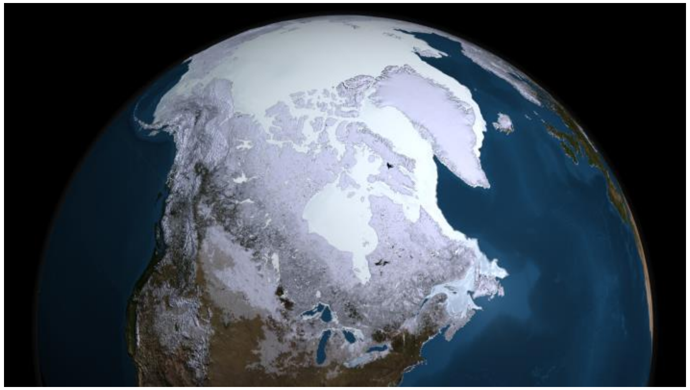
$$\Delta T_{Pole}^{Eq} = 20 - 23^{o}C$$



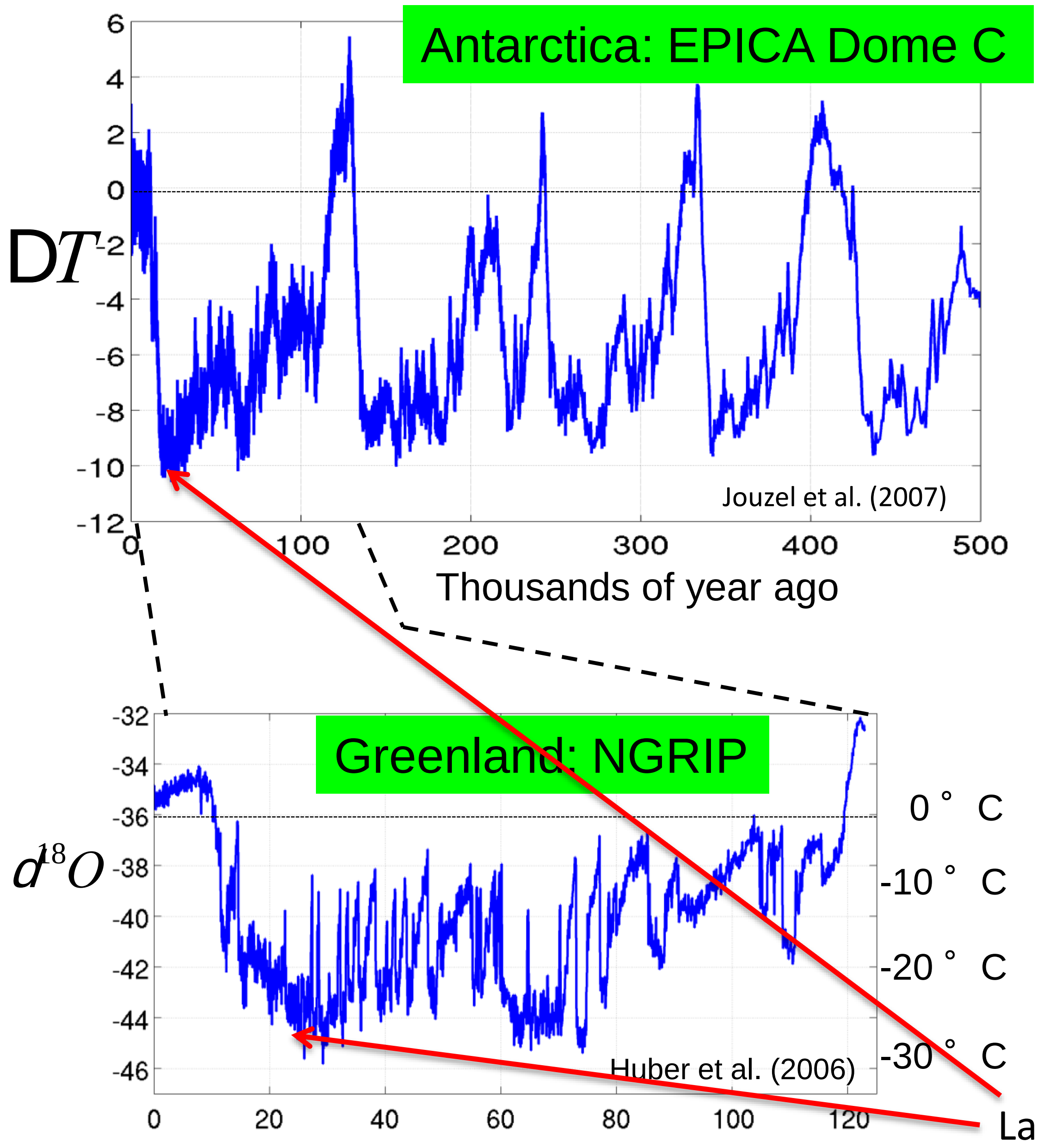
$$T_{Deep} = 10 - 13^{o}C$$ ous

“Moderate” present-day

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



Glacial-Interglacial cycles



- Massive global climate shifts,

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

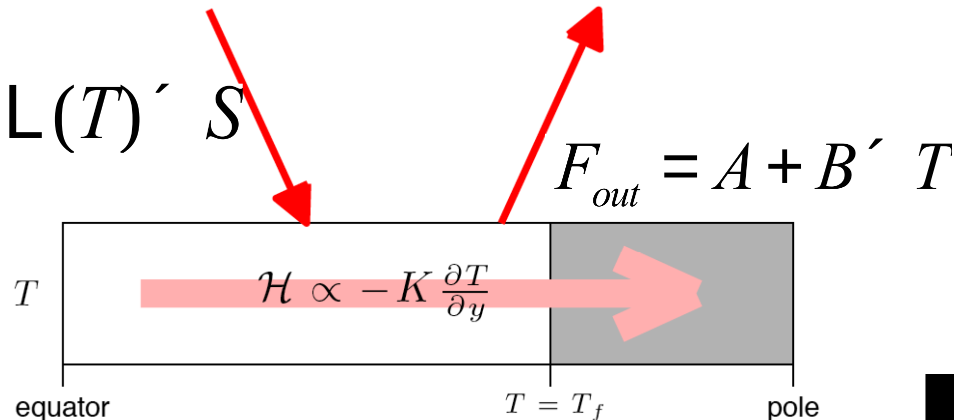
Can multiple equilibria play a role in Earth's climate history?

see Benzi et al. (1982) and Paillard (1998)

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

Multiple equilibrium states in low-order models, I

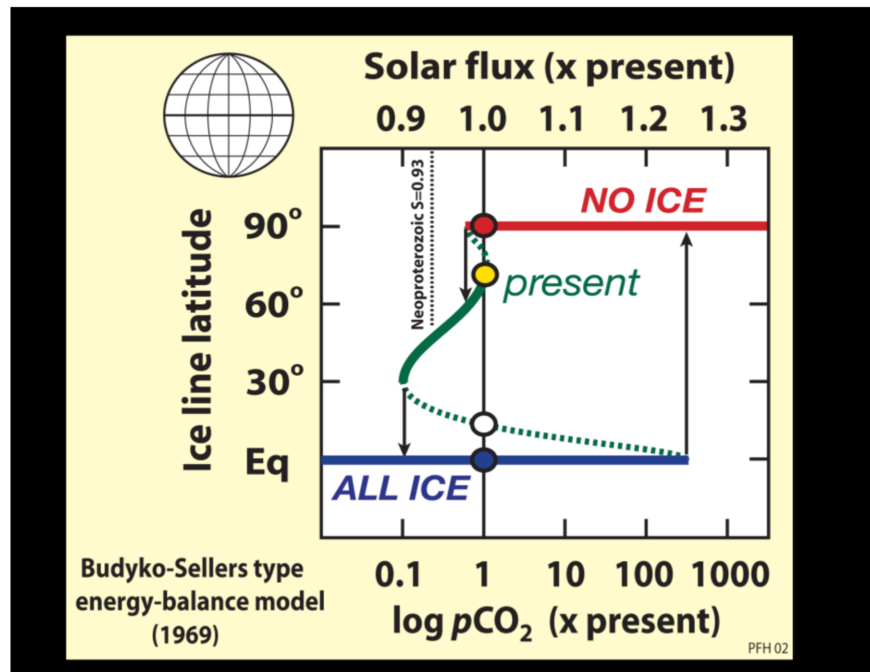
Sea ice-albedo feedback: Budyko-Sellers Energy Balanced Model (EBM)



Simple Energy Balance Model

$$C\frac{\partial T}{\partial t} = D_y\left(CK\frac{\partial T}{\partial y}\right) + \Lambda \times S - F_{out}$$

Heat transport	Absorbed SW	Outgoing LW

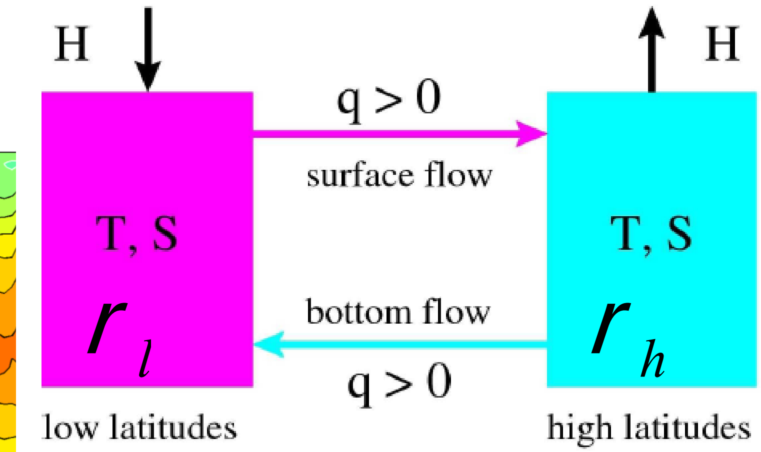


www.snowballearth.org

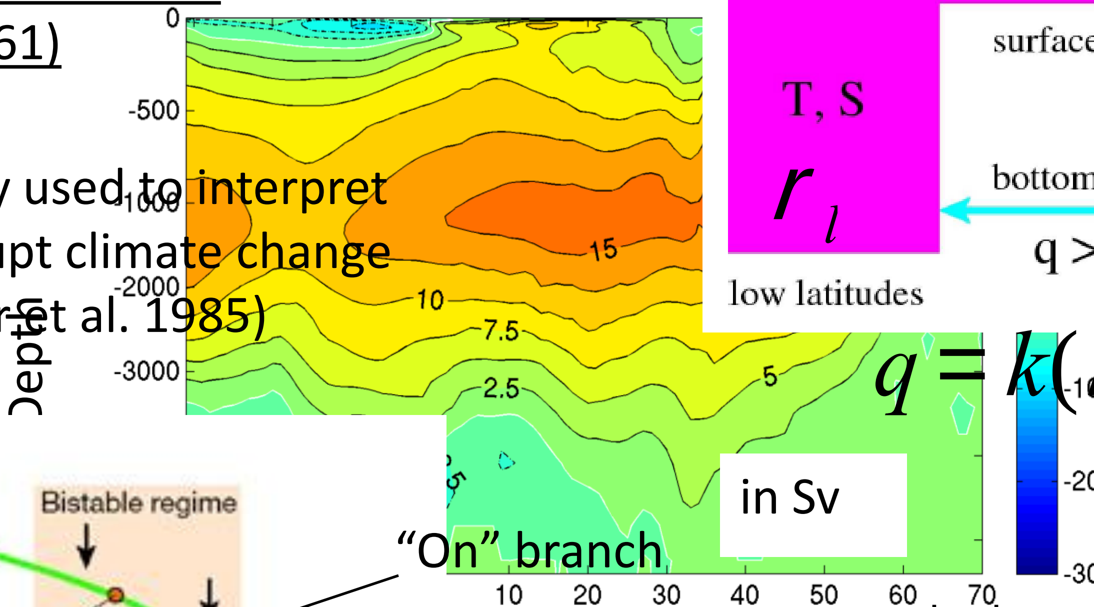
Multiple equilibrium states in low-order models, II

Multiple states of the Meridional Overturning Circulation
Stommel (1961)

→Widely used to interpret past abrupt climate change (Broecker et al. 1985)



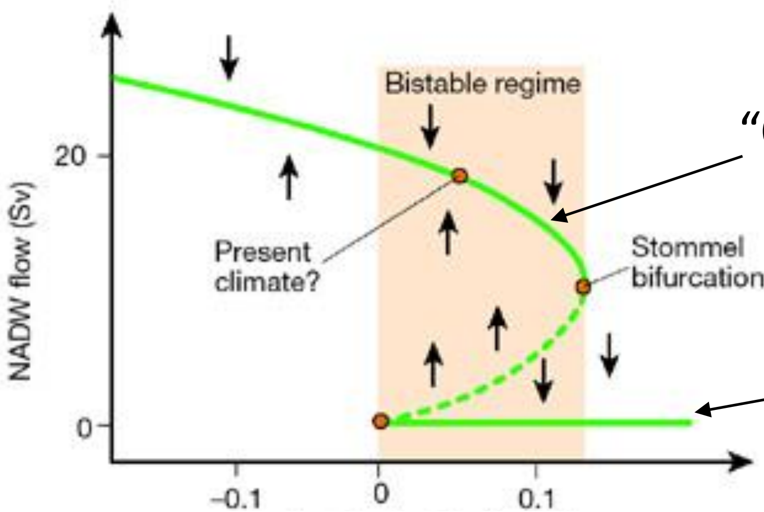
$$q = k(r_h - r_l)$$



in Sv

n state estimate (Forget, 2009)

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



“On” branch

“Off” branch

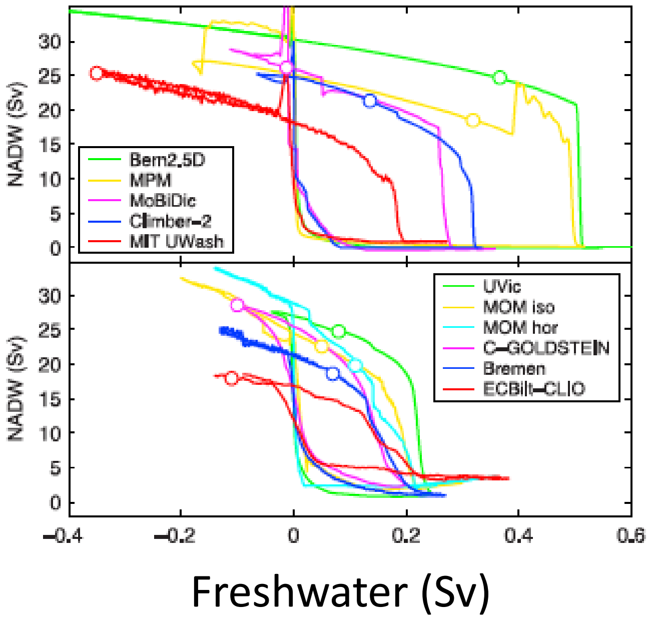
Freshwater forcing H (Sv)

Rahmstorf (2002)

Hard to find in coupled GCM

Stommel's multiple MOC states:

- Manabe and Stouffer (1988), but flux adjustments
- "Water-hosing" to reveal MOC multiple states:
  - found in EMICs (Rahmstorf et al. 2005), but flux adjusments, EBM, …
  - not in IPCC-class models (Stouffer et al. 2006)
  - One intermediate model (Hawkins et al. 2011)



Sea-ice albedo feedback:

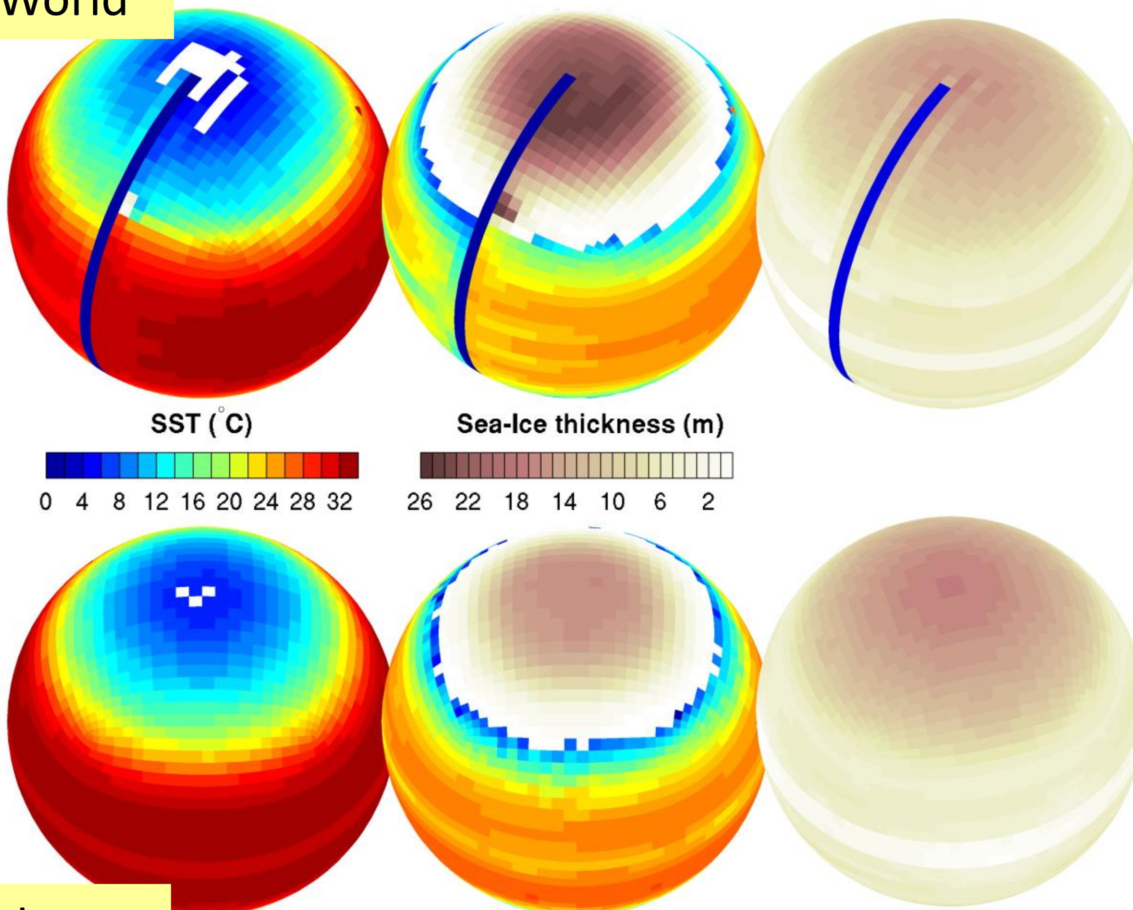
- Langen and Alexev (2004): atmosphere only GMC
- Marotzke and Bozet (2006): a warm state and a Snowball state

SST and Sea ice cover

Warm state | Cold state | Snowball state

RidgeWorld

Stable for thousands of year

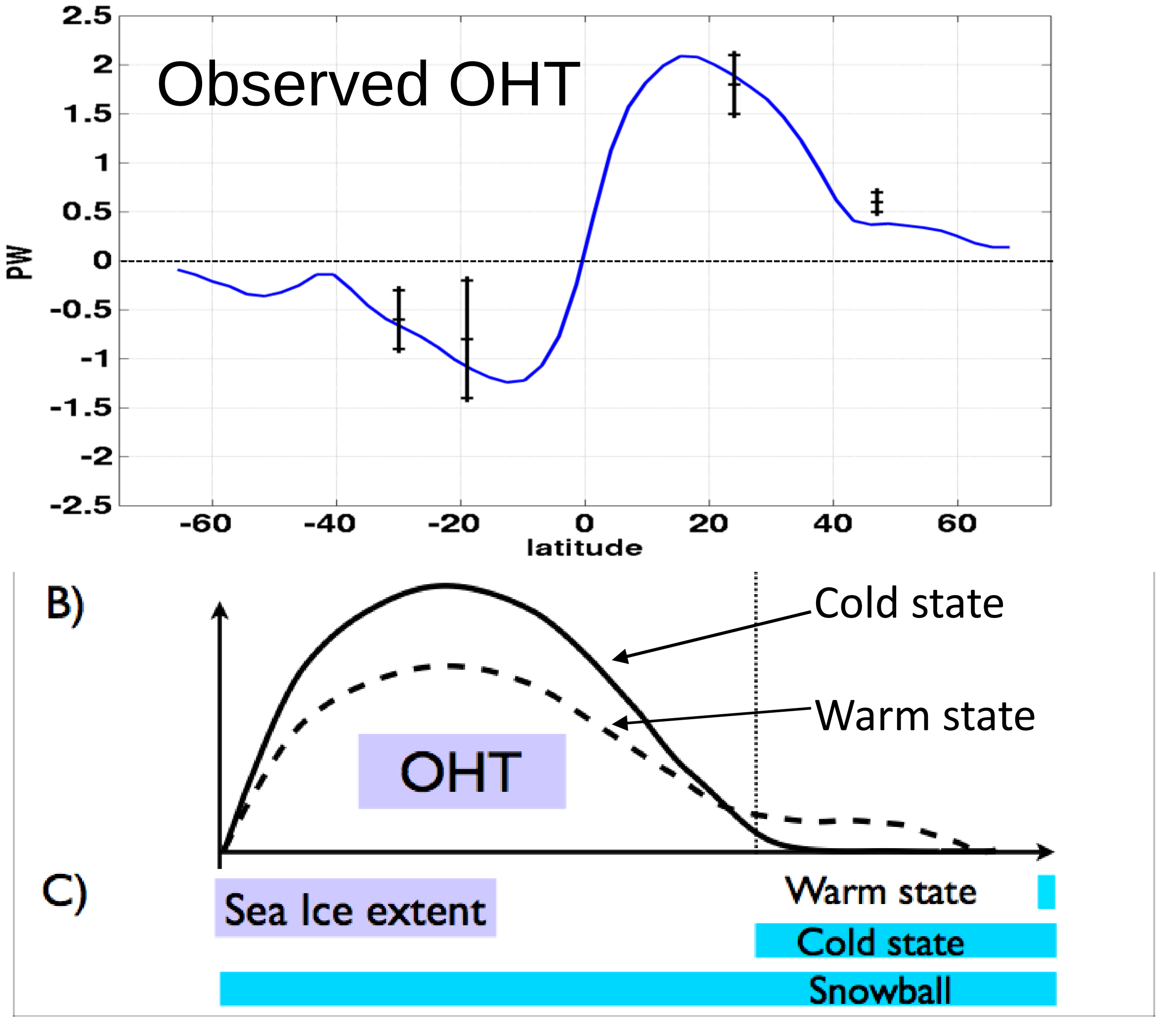


AquaPlanet

$\Delta T_{Pole}^{Eq} = 28^{o}C$ $\Delta T_{Pole}^{Eq} = 55^{o}C$

How are the multiple states maintained ?

<u>It's the shape of the OHT !</u>



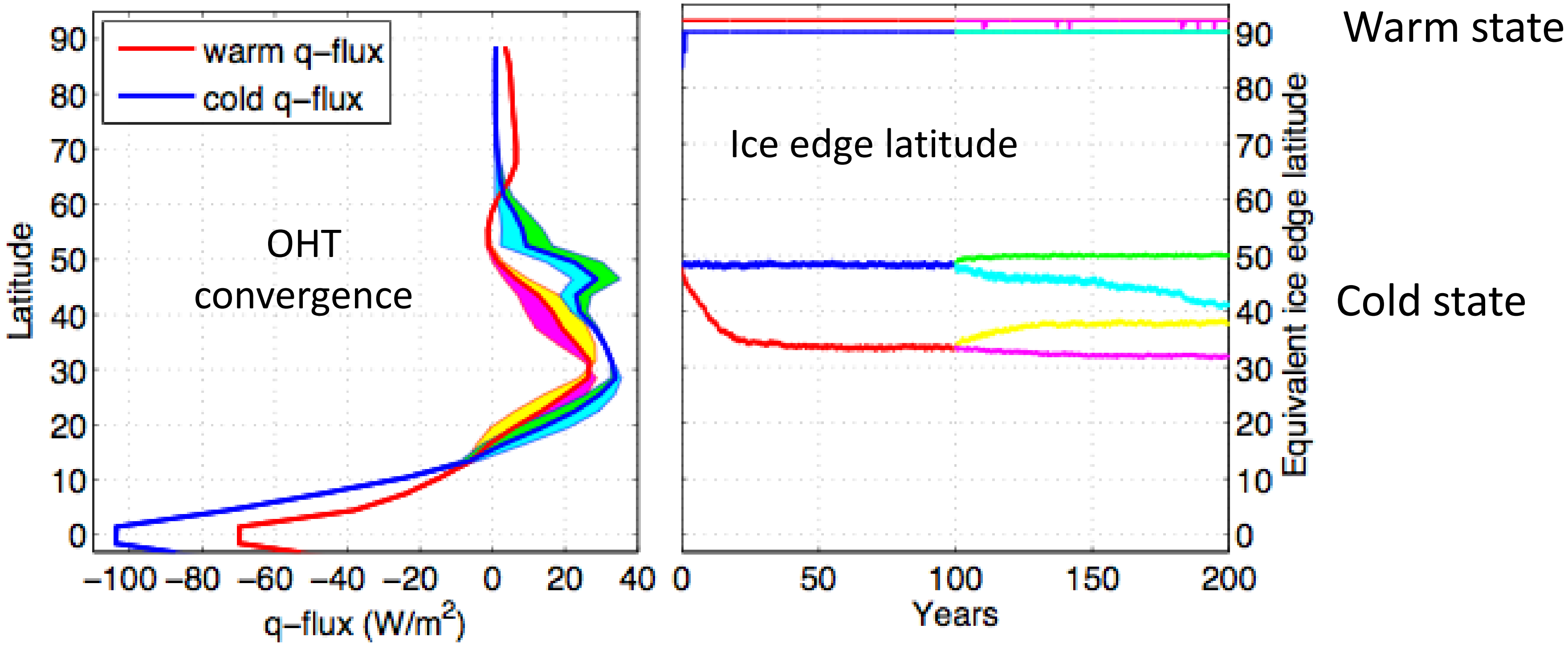
Cold State: OHT convergence arrests sea-ice expansion

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

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

Atmosphere + slab mixed-layer ocean

OHT is prescribed, 50 m deep mixed-layer



- Meridional structure of the OHT is key to obtain 3 stable states,
- OHT convergence controls ice edge location of Cold state,
- Existence of the multiples states does not depend on details of the OHT.

Ocean-Atmosphere EBM

Building on Rose and Marshall (2009), key differences with the “classical” EBM:

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

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

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

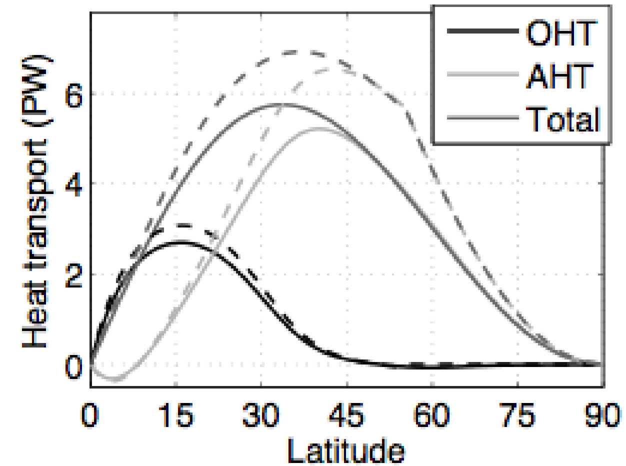
OHT has a diffusive form with a non-uniform K:

$$H_o = C_o K_o(y) \frac{\partial T_o}{\partial y}$$ with $$K_o(y) = fct(\tau_x(y))$$

Ocean-Atmosphere EBM

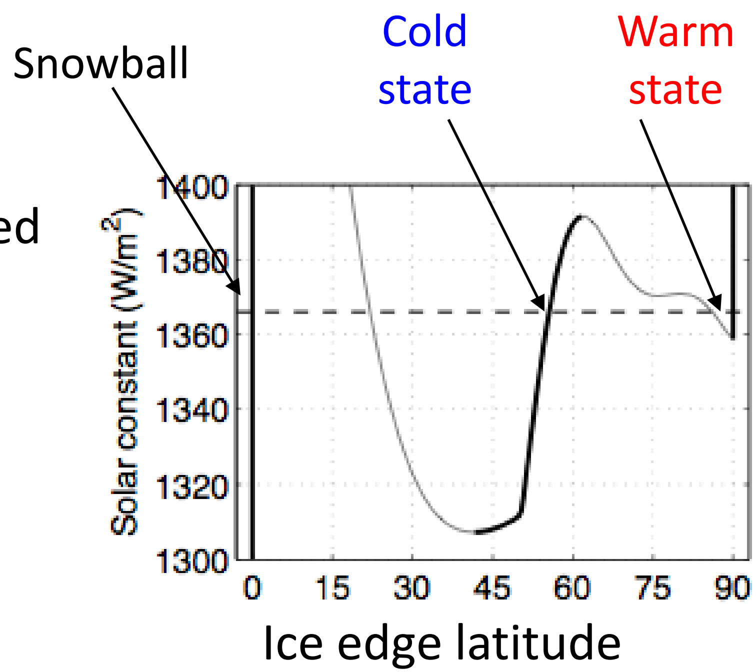
$$H_o \propto \psi_{res}\left(\frac{T_s - T_{deep}}{\Delta z}\right)$$ OHT due to MOC

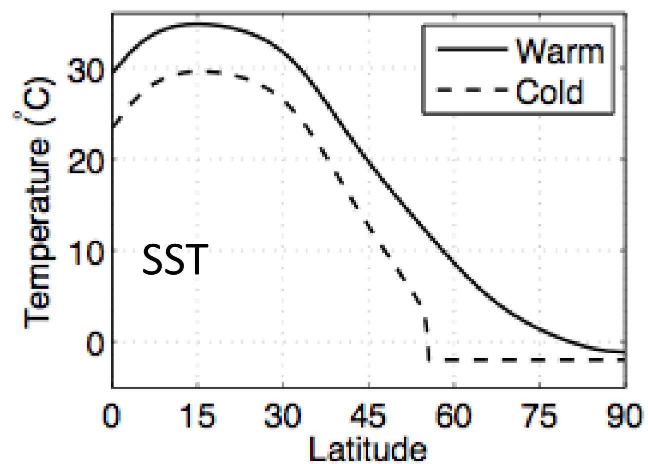
$$T_{deep} = T_s(y_{crit})$$ or freezing point



$y_{res}(y)$ prescribed from Aqua Cold

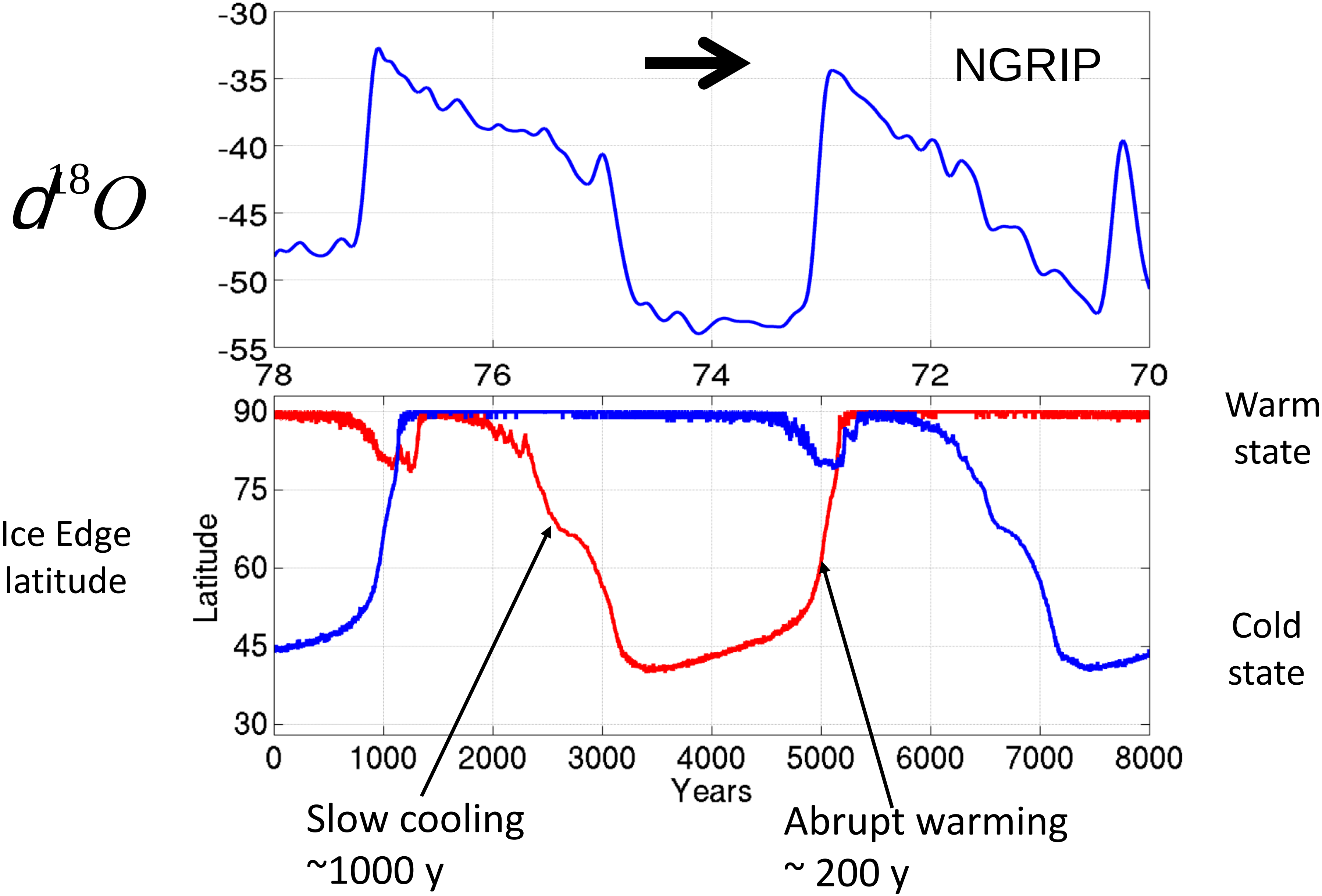
$$y_{crit} = 50^o N$$





Transition between states

RidgeWorld



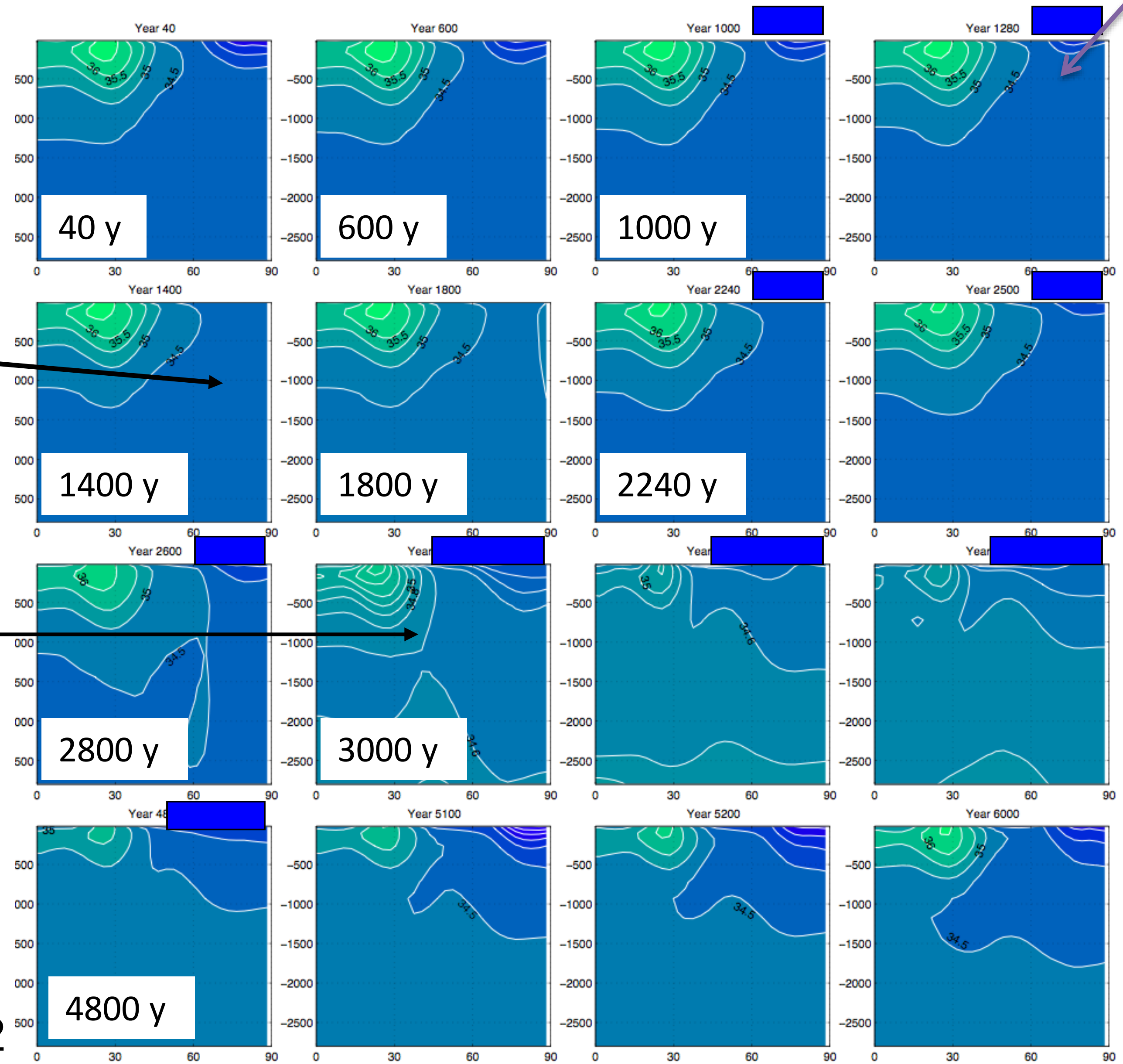
Evolution of Salt

Start from Warm State

Ice grows
Brine rejection

deep convection

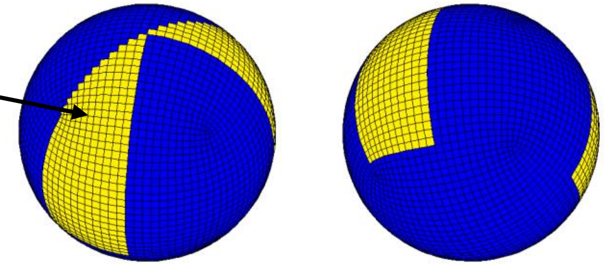
Peak of glaciation



Rose et al. 2012

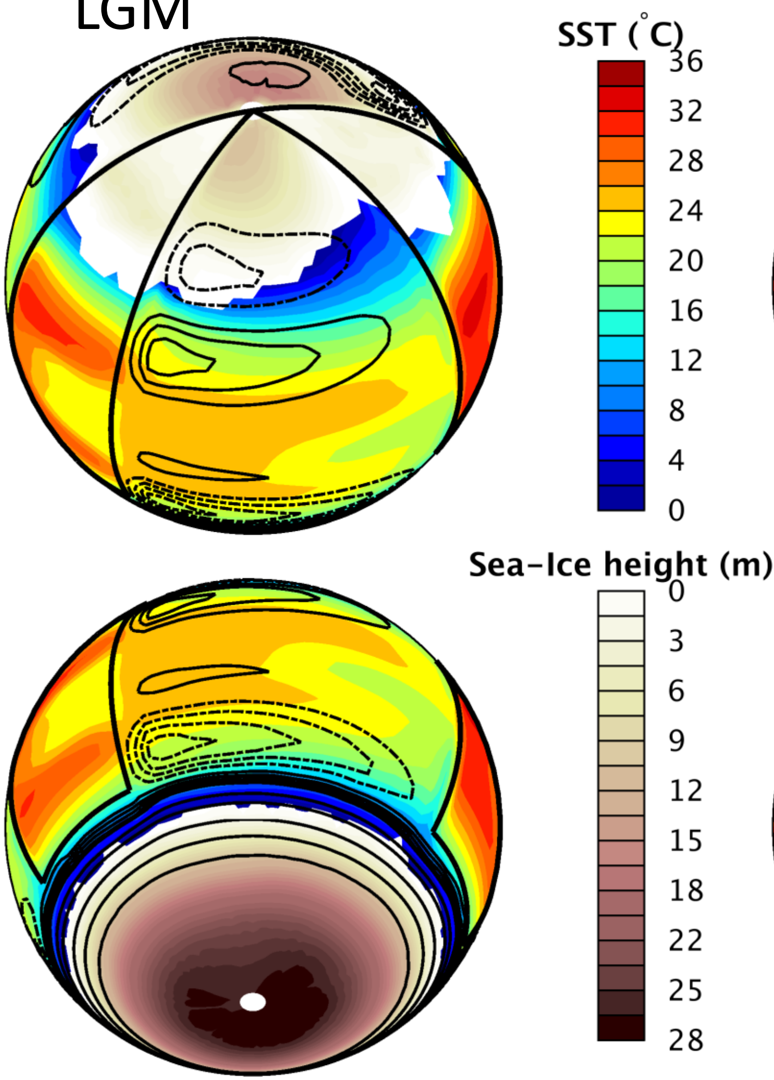
Boomerang

Continents

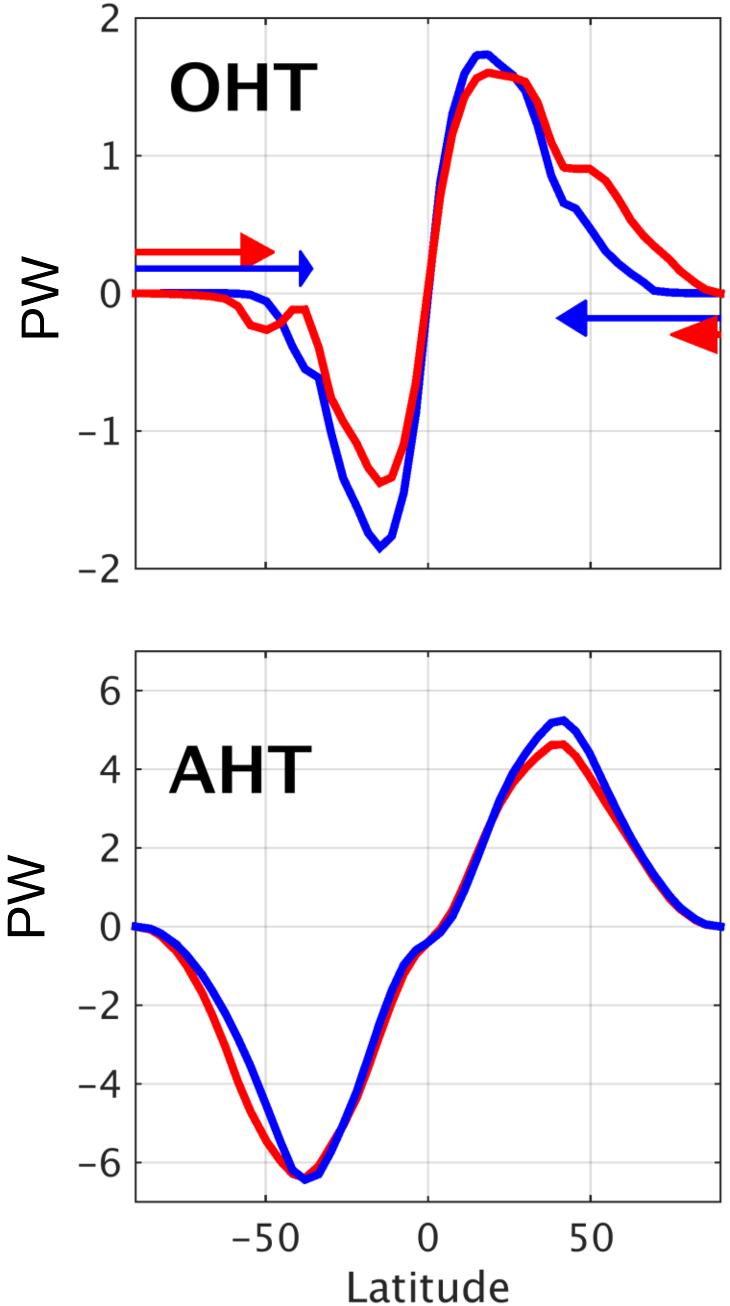


Glacial state
LGM

Interglacial state
Present day



- 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 : -118 ppm (from 268 to 150 ppm).



Global energy transports

- Global OHT : complex pattern of strengthening and weakening

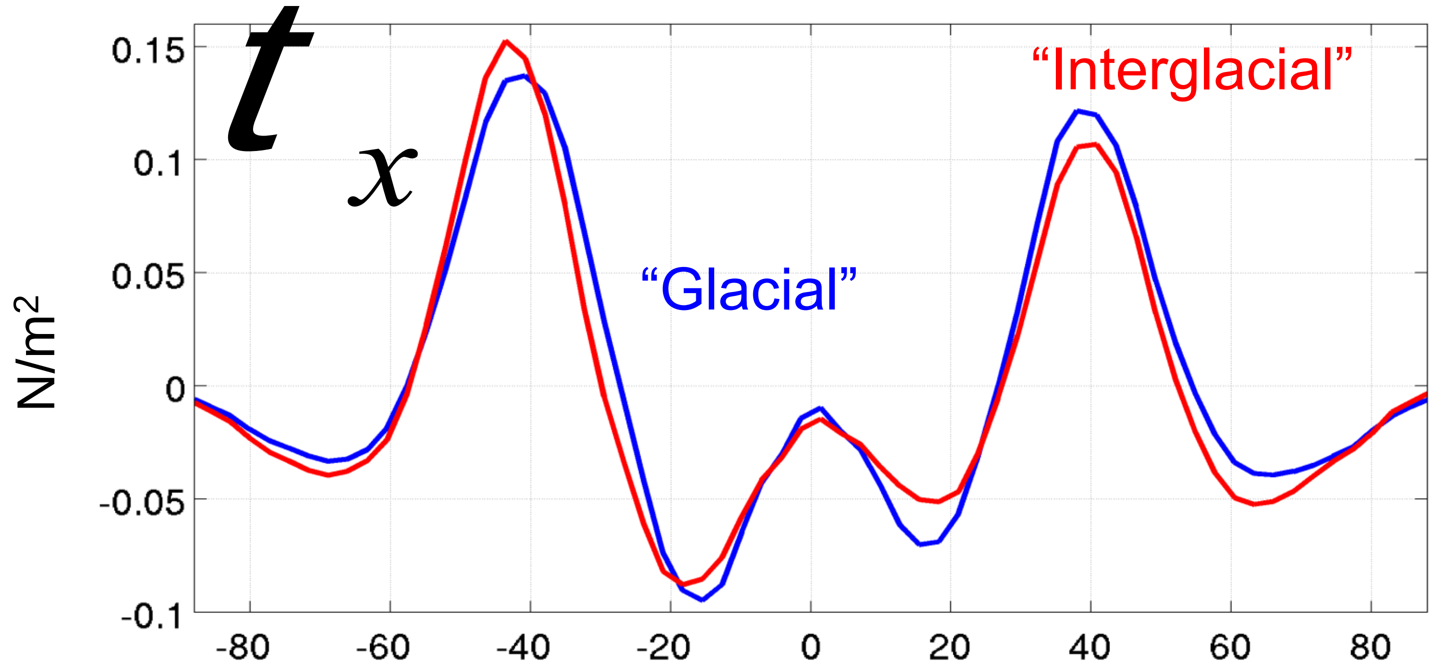
- AHT: Compensating changes in latent/sensible heat transports

→ Opposite changes in the 2 hemispheres

→ strong (non-linear) effects of the sea ice edge

→ Increased "storminess" in SH

Surface Winds

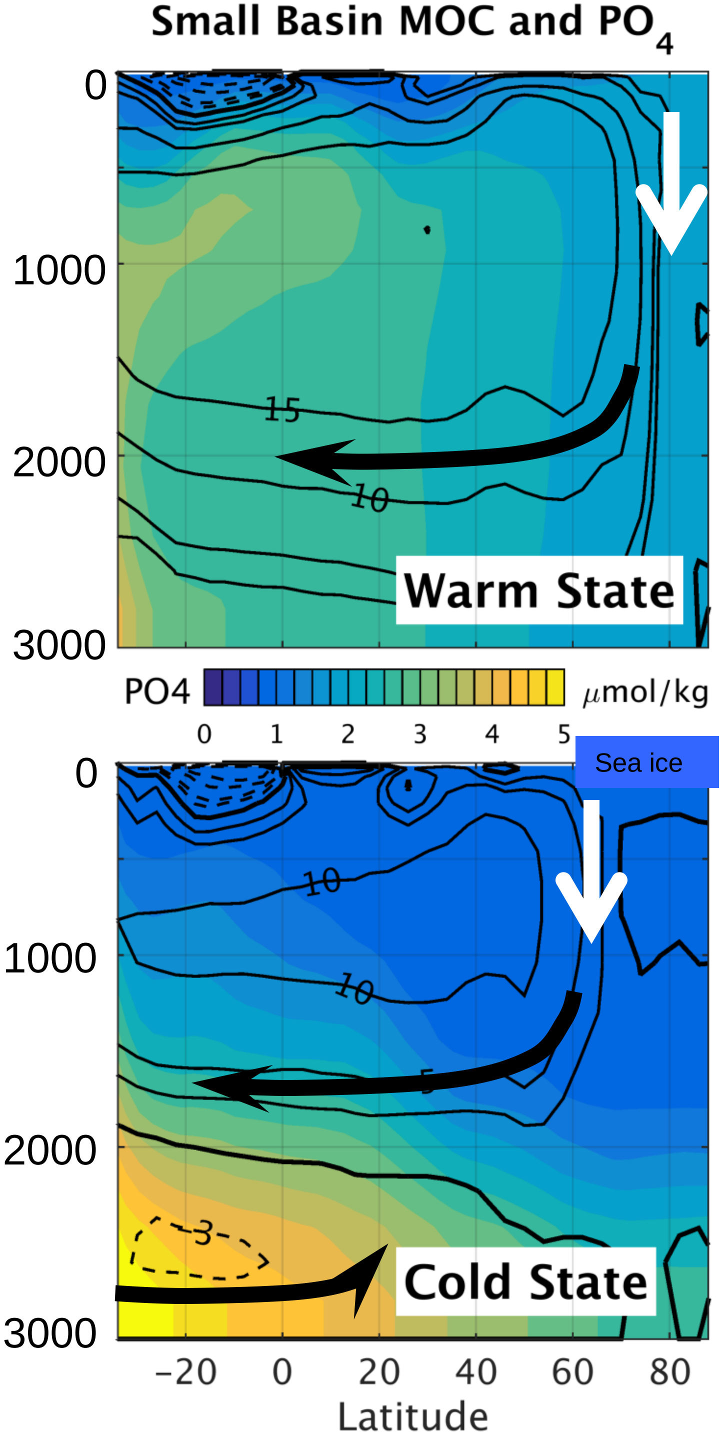


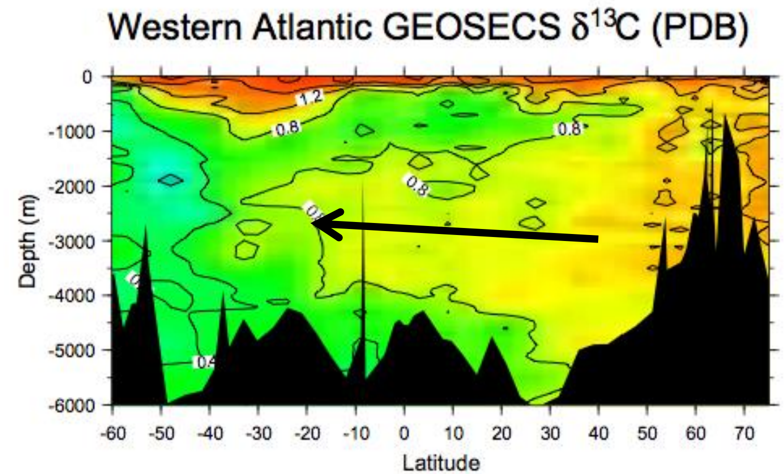
In glacial climate:

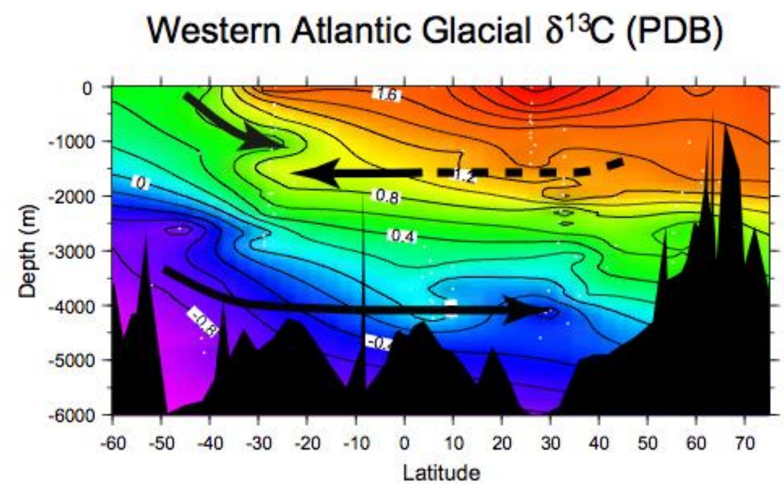
- Trade winds strengthen (as do the Hadley circulation)
- SH westerly winds shift equatorward ~1.5 deg
- and weaken ~10%

→ 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)





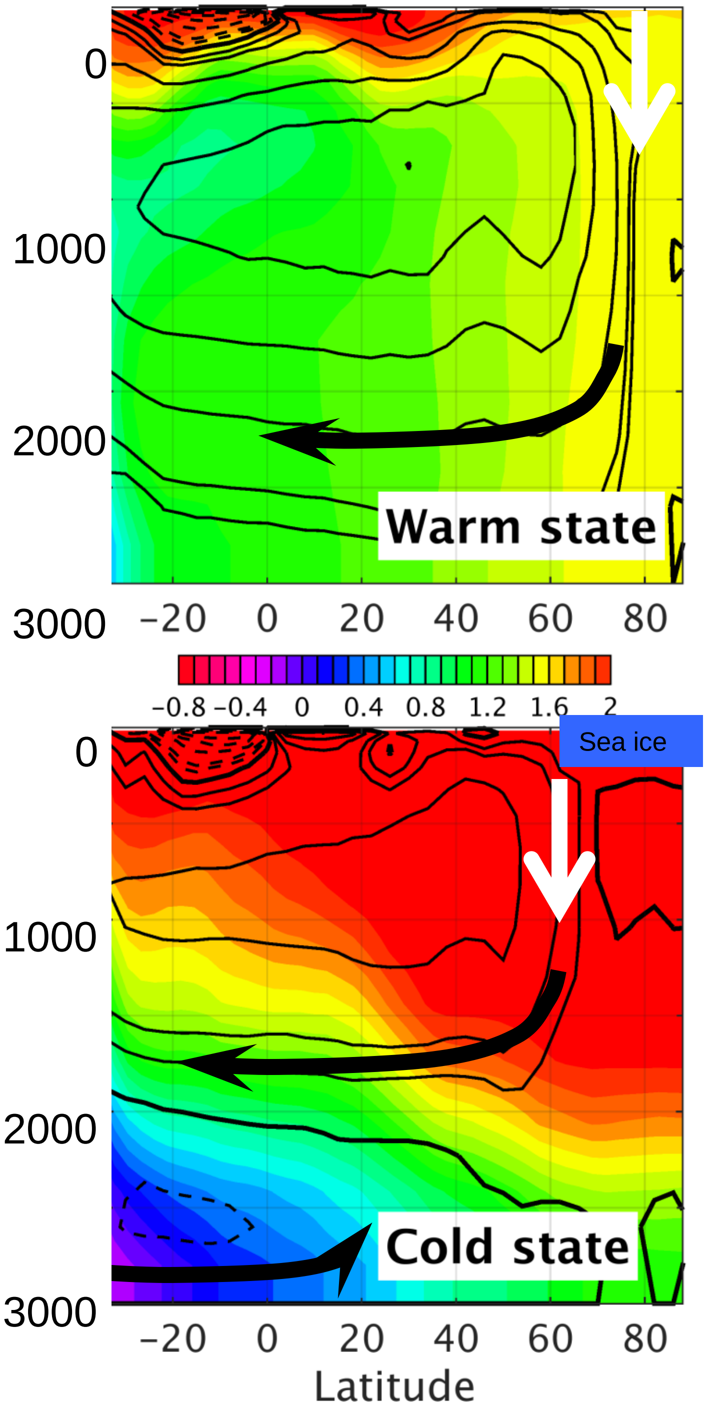


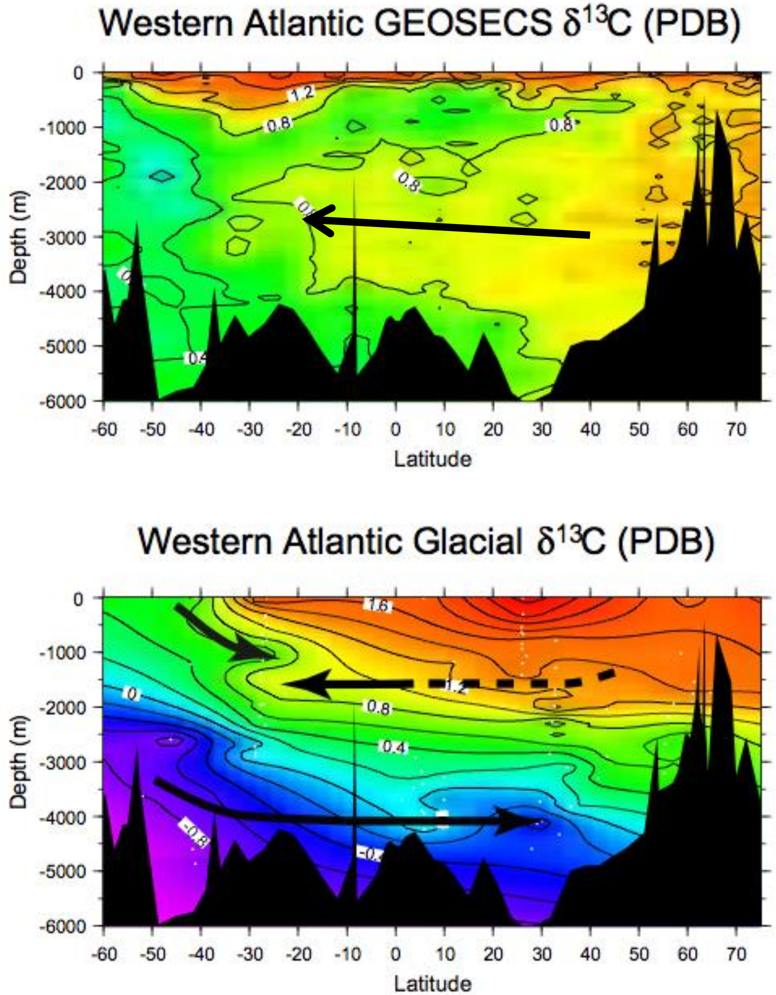
Curry and Oppo 2005

In "Glacial" state:

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

See also Lynch-Stieglitz etal. 2007





Curry and Oppo 2005

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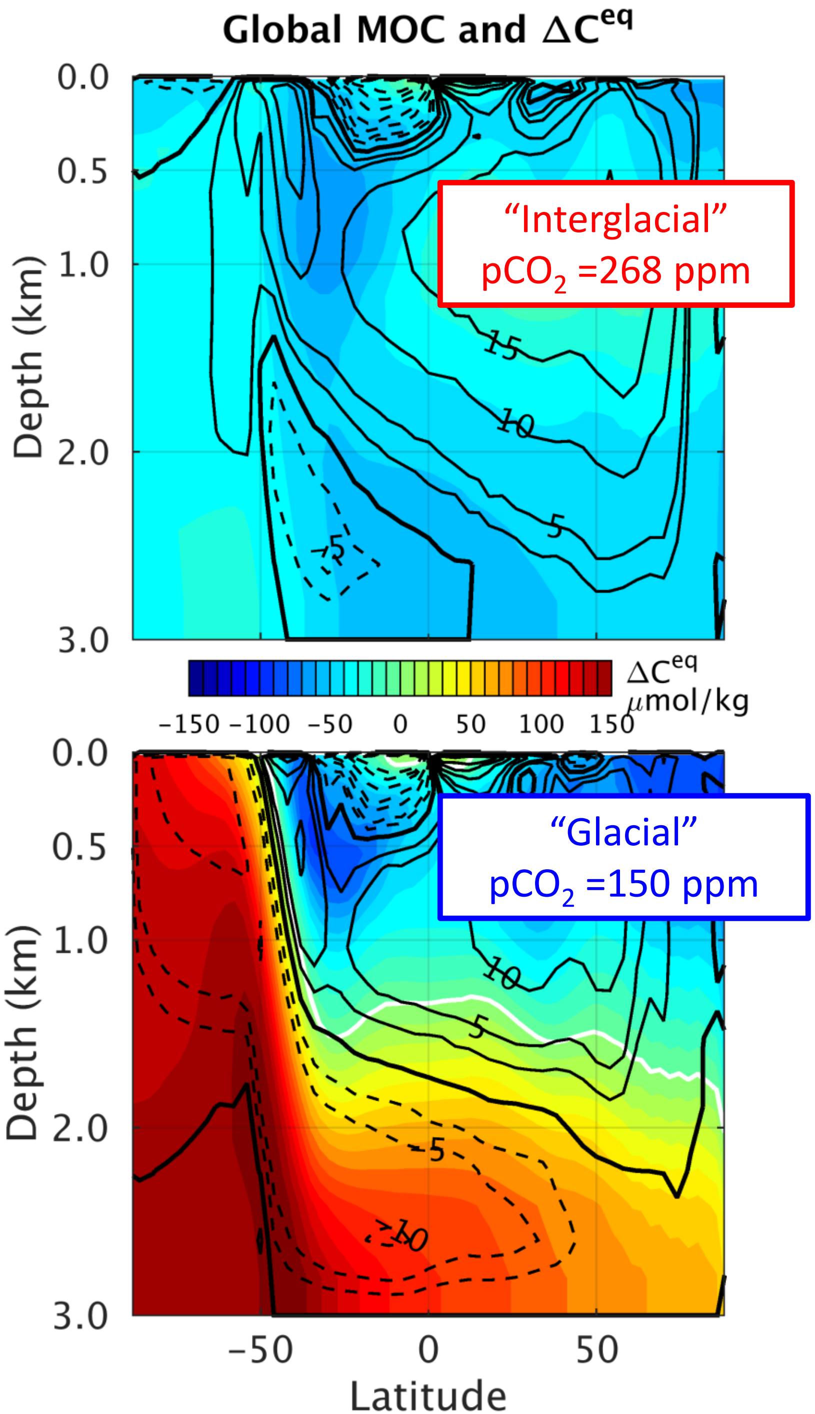


How is carbon stored in the "Glacial" ocean?: Mechanism

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

- Winds and upwelling rate in the Southern Ocean play little role (≠ Toggweiler and collaborators' mechanism)

- Other mechanisms in literature, no consensus

How is carbon stored in the "Glacial" ocean?

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

Change ("InterGlacial" → "Glacial") in 3 carbon reservoirs:

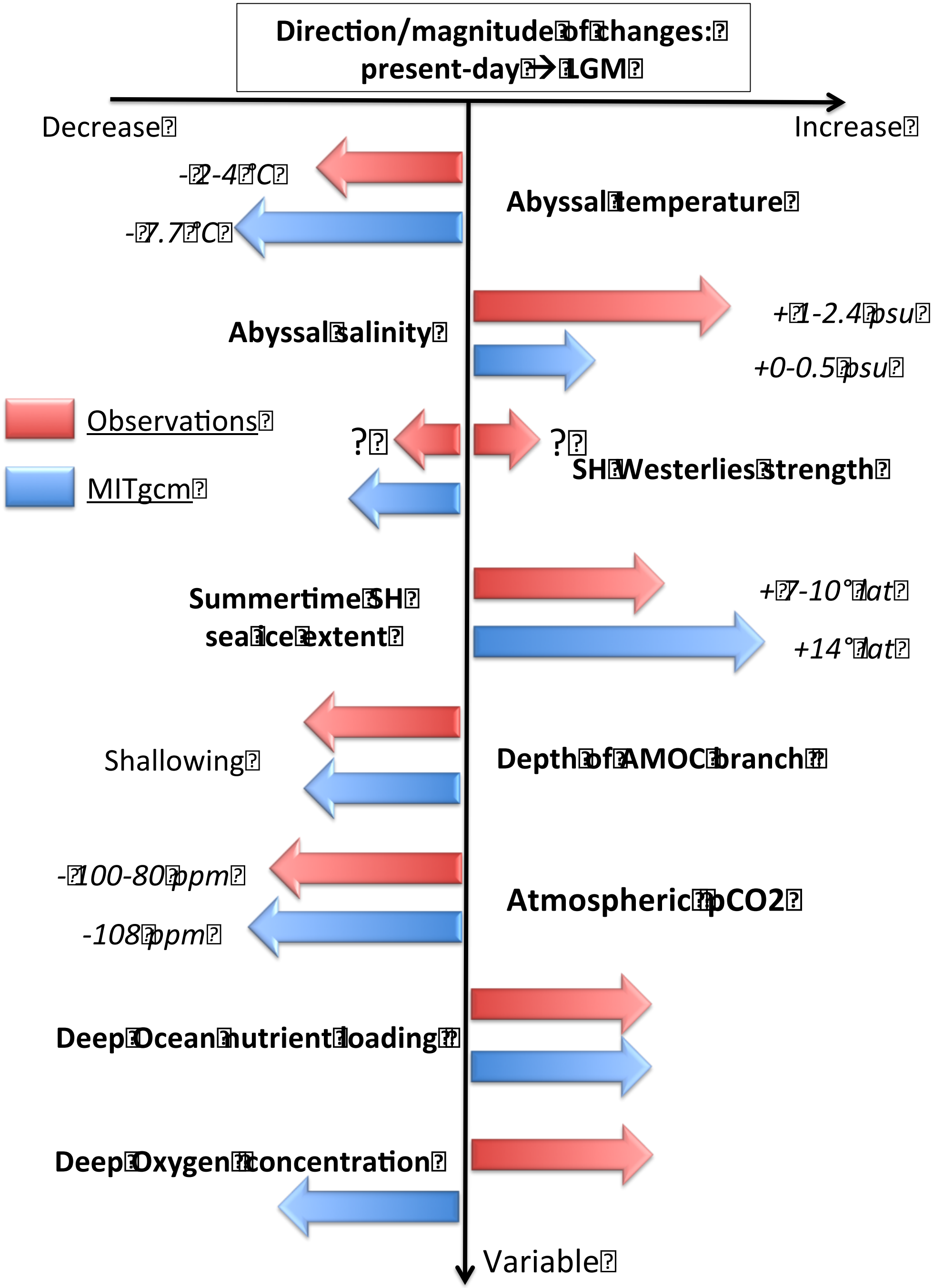
$$DC_{tot} = DC_{sat} + DC_{bio} + DC_{dis}$$

Saturation pump:
+56 µmol/kg
or
-58 ppm

Net biological
pump:
-36 µmol/kg
Or
+36 pm

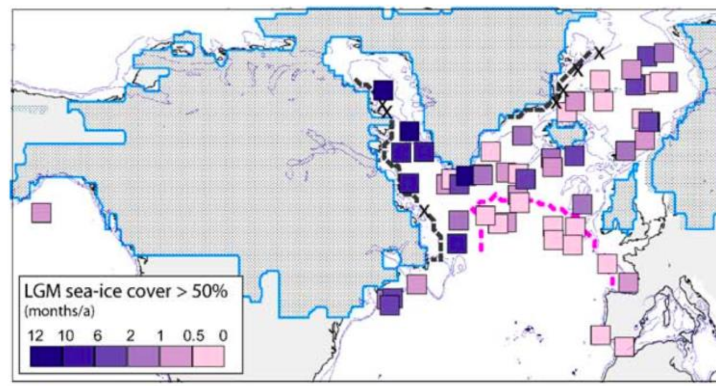
Air-sea
disequilibrium
pump:
+85 µmol/kg
or
-87 ppm

Overestimated C_{sat} (ΔT=-7.7 ° C):
-23±8 ppm for ΔT=- 2-4 ° C



Summary of the changes: Simulation versus Paleoproxy

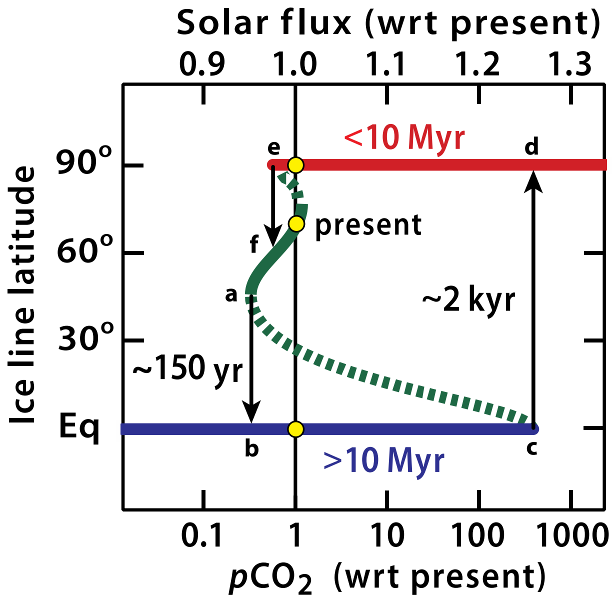
NH large sea expansion : consistent with paleproxies (de Vernal et al. 00)



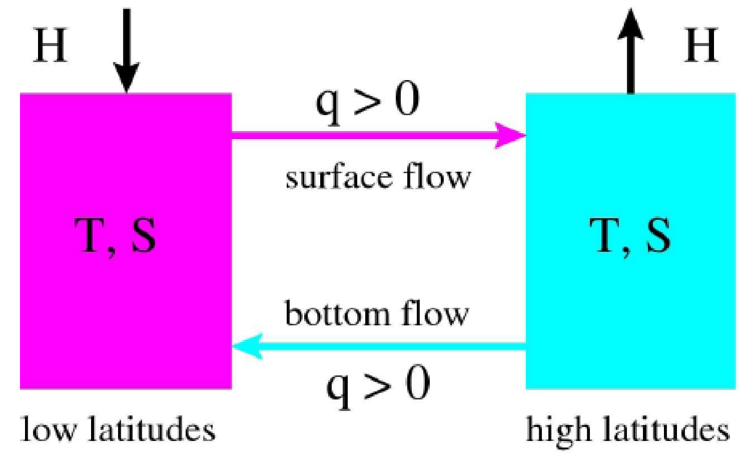
Curry and Oppo 05, Lynch-Stieglitz et al. 07, but Gebbie 14

Easy to find in simple "toy" models ...

Multiple states of ice edge

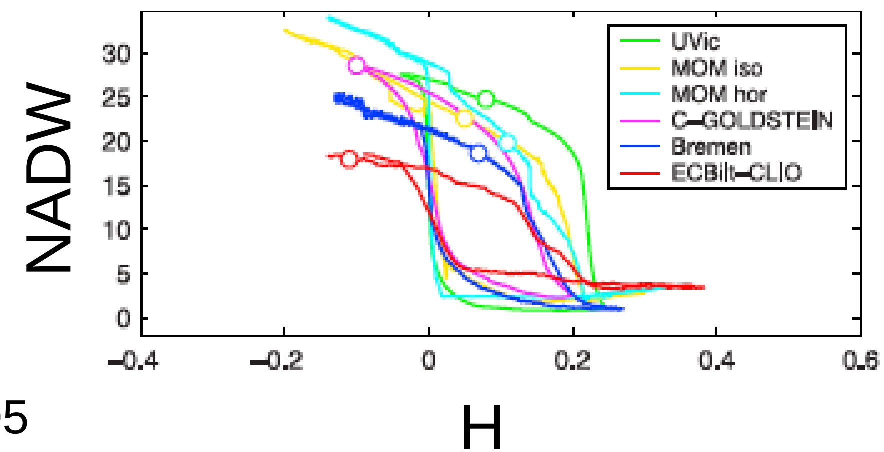


Multiple states of the Meridional Overturning Circulation



Stommel (1961)

… more complicated in GCMs



Rahmstorf et al. 2005