Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Multiple Equilibria in the Climate System
ICTP, June, 2018

Monday Morning
Energy transport by A & O,
Climates of Aquaplanets
Oceans Climate Asymmetries
John Marshall (MIT, USA)

Monday Afternoon
Modeling Tutorials
Stephen Thomson (Exeter, U.K.)

Tuesday Morning
Fundamentals of Atmospheric Dynamics
In-Sik Kang (SNU, Republic of Korea)

Tuesday Afternoon
Multiple equilibria in the climate system: understanding the role of oceans and sea ice
Brian Rose (U. Albany, USA)

Wednesday Morning
Structure of the tropics and midlatitudes
Geoffrey Vallis (U. Exeter, U.K.)

Wednesday Afternoon
Multiple equilibria to and paleoclimate
David Ferreira (U. Reading, UK)

Thursday Morning
Tropical convection and large-scale circulation
Monsoons, tipping points
Simona Bordoni (CALTECH, USA)

Thursday Afternoon
Tropical ocean-atmospheric feedbacks
Shang-Ping Xie (SCRIPPS, USA)

Friday Morning
Regimes and Predictability of atmos flow
Franco Molteni (ECMWF, U.K.)

Friday Afternoon
Vegetation-Carbon-Cycle-Climate Feedbacks
Ning Zeng (U. Maryland, USA)

Coupled Climate Dynamics: Energy transport by the Atmosphere and Ocean

John Marshall, MIT

1. Energy transport by A & O
   Observations
   Importance of hierarchical modeling

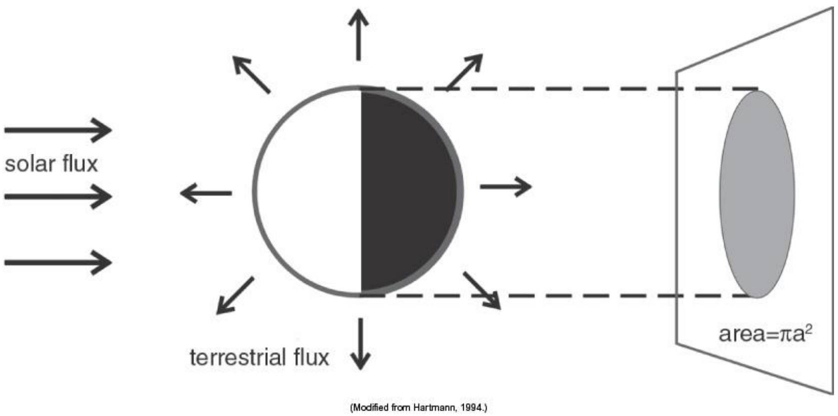
2. Climate of an Aquaplanet

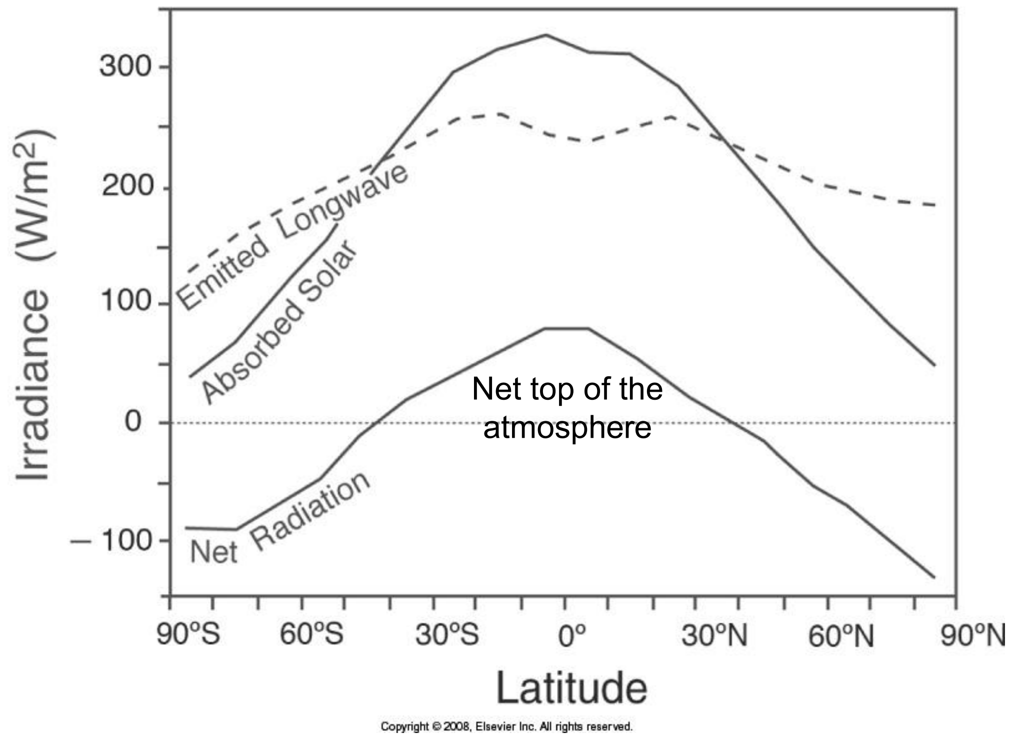
3. Oceans and Climate asymmetries

1. Energy transport by A & O
   Observations
   Importance of hierarchical modeling

Figs from Marshall and Plumb, 2008

Earth’s Energy Balance



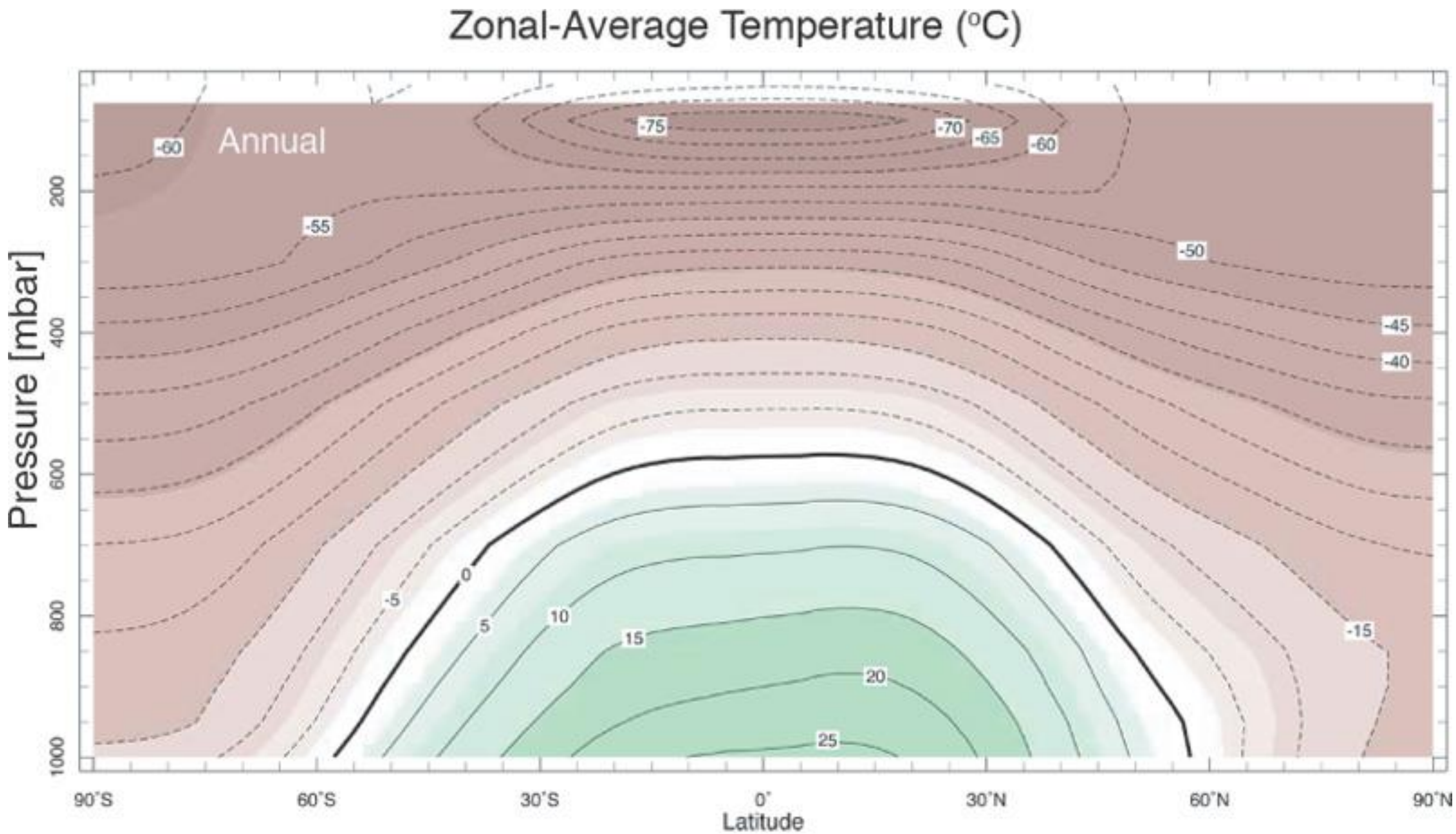


Two important consequences

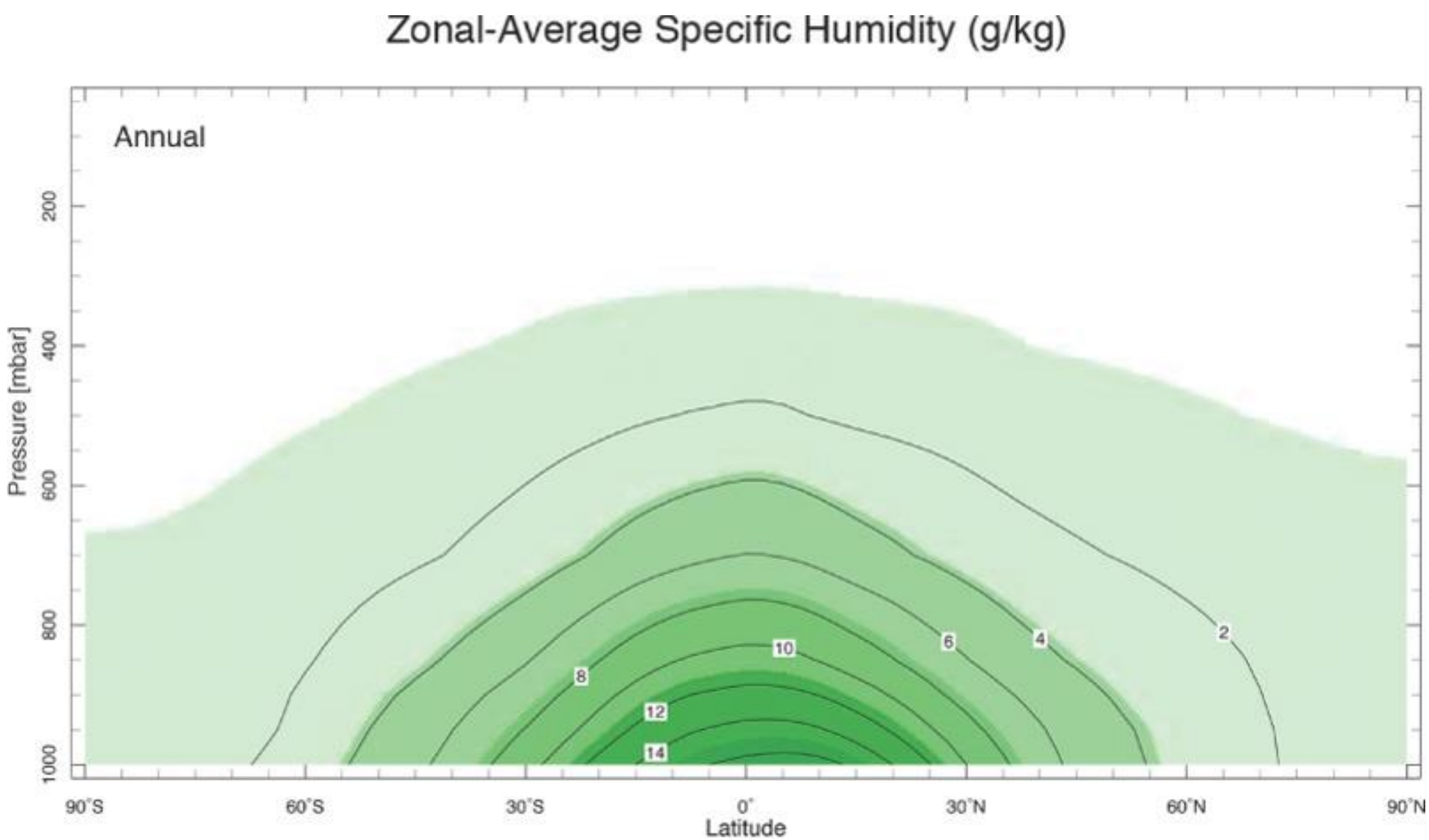
1. Warmer, and moister, in the tropics than at higher latitudes

2. Atmosphere, and ocean, must transport, energy from low to high latitudes

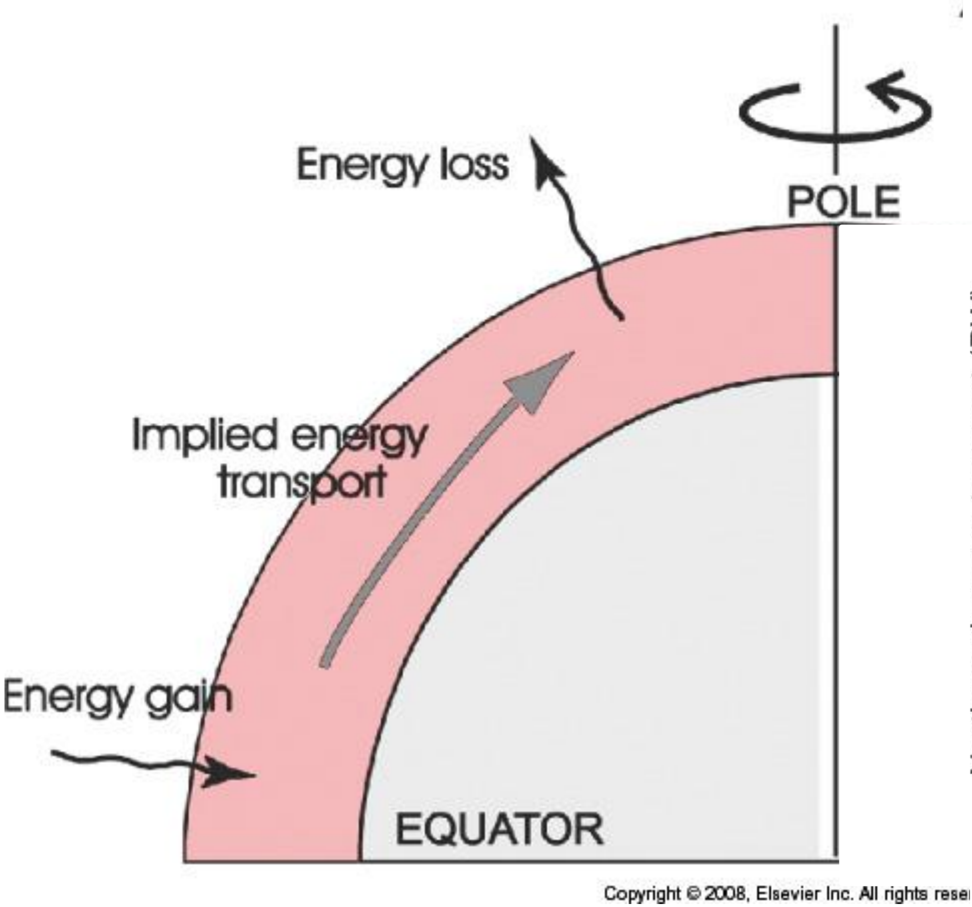
Warm, and moist in the tropics

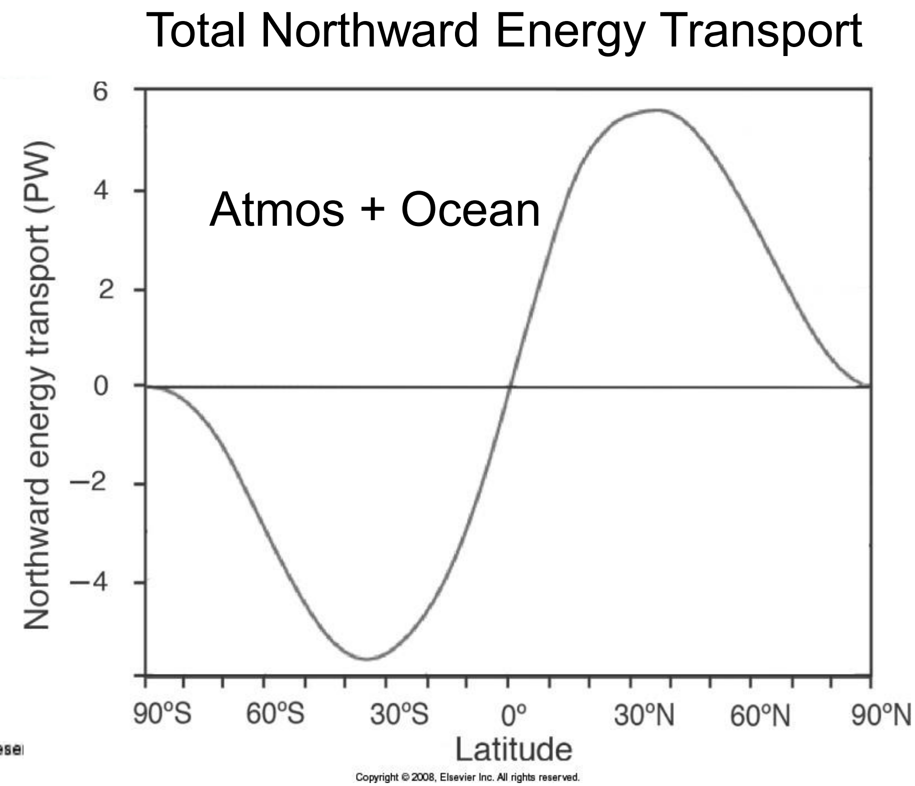


Warm, and moist in the tropics



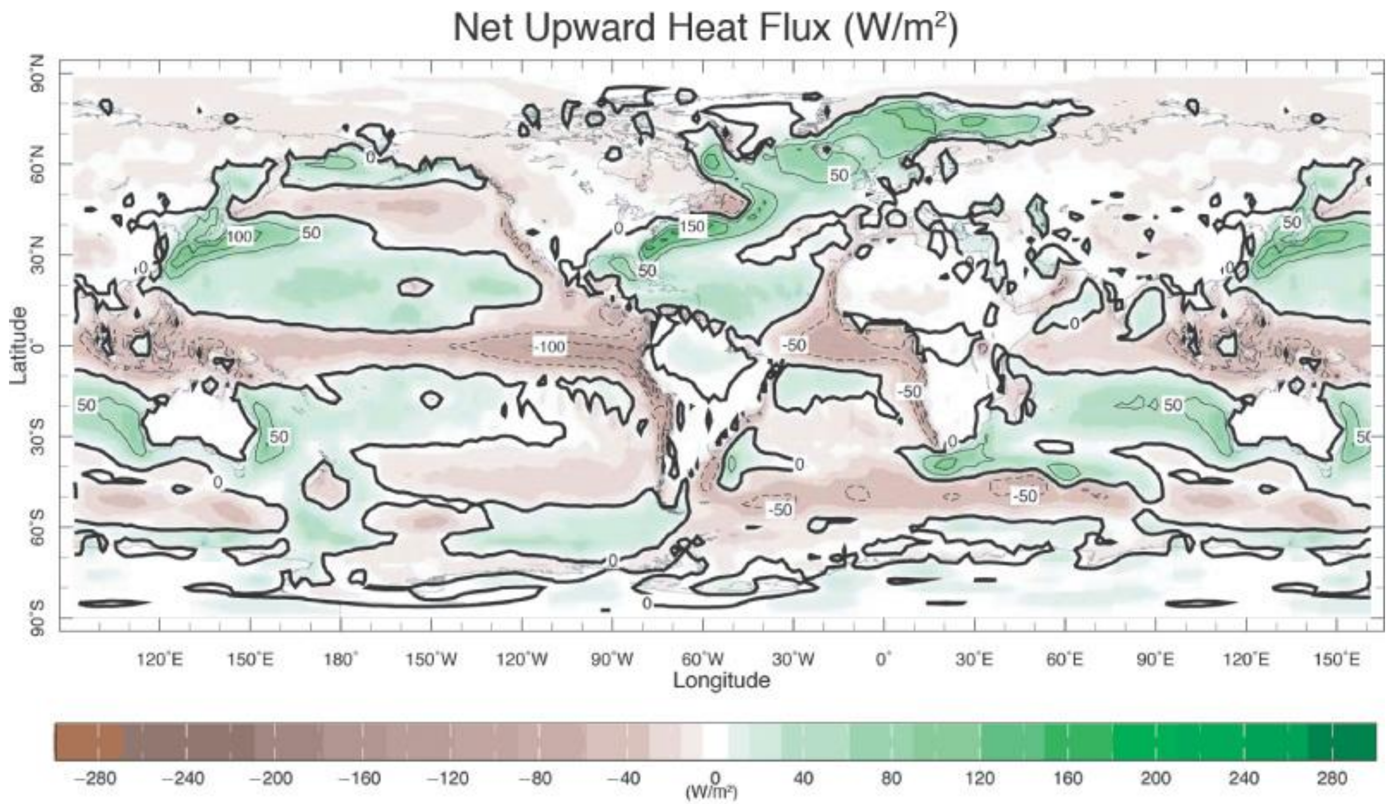
Energy budget of the atmosphere and ocean





Note: $\mathrm{PW} = 10^{15}\mathrm{W}$

Air-sea heat flux

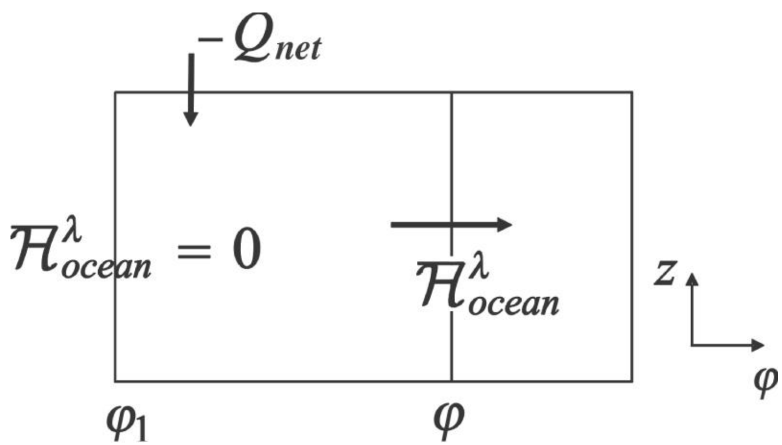


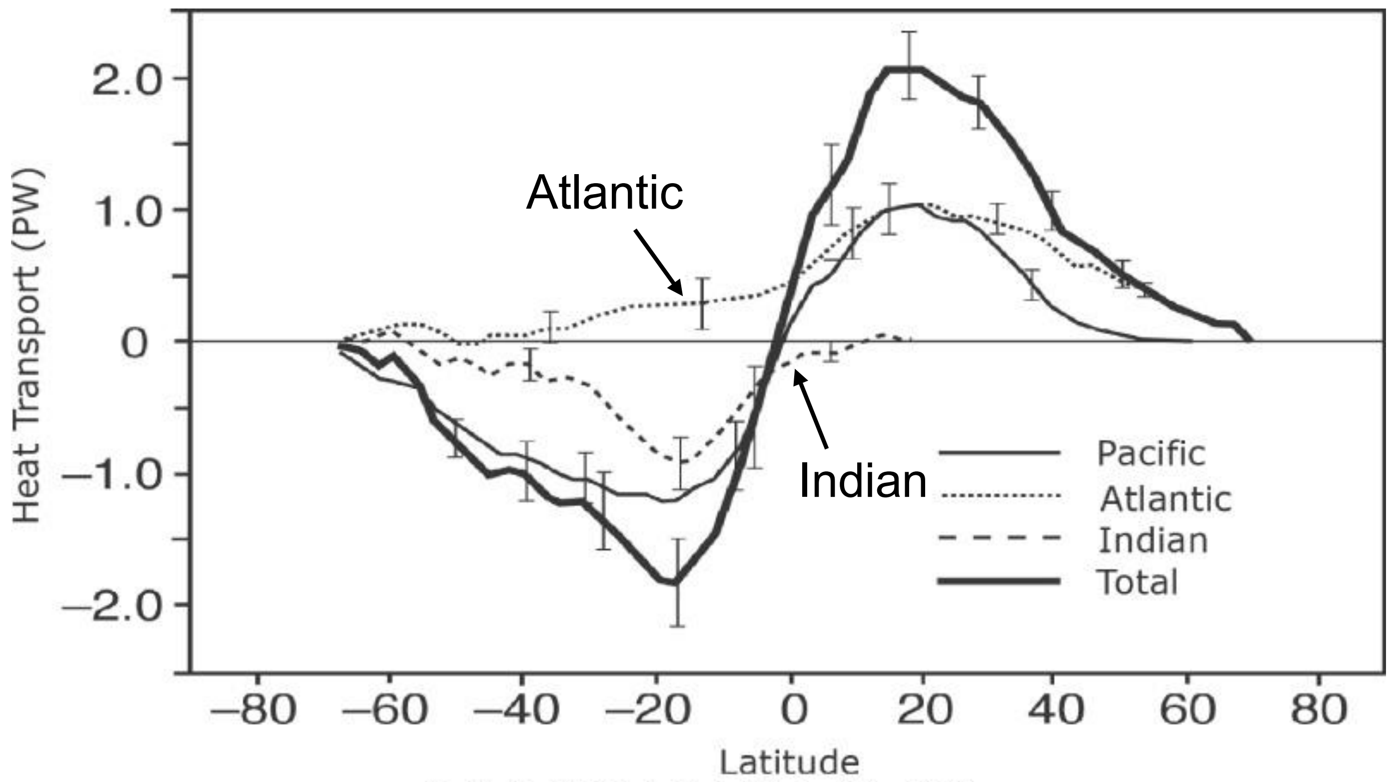
(From Kalnay et al. (1996).)

In to ocean

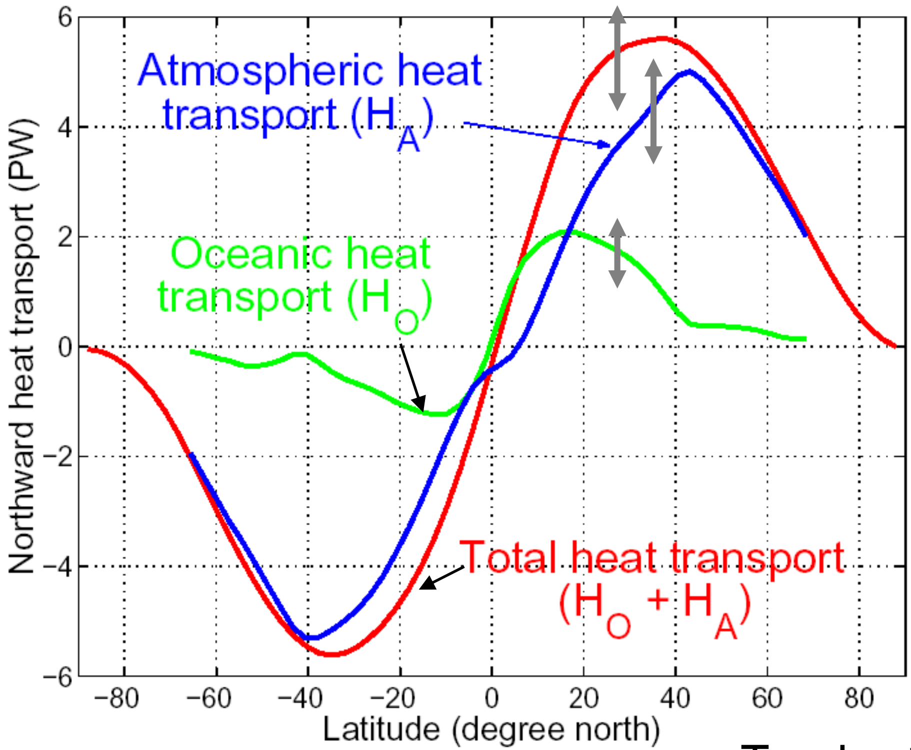
Out of ocean

Ocean heat transport, basin by basin





Northward Energy Transport by Atmosphere and Ocean



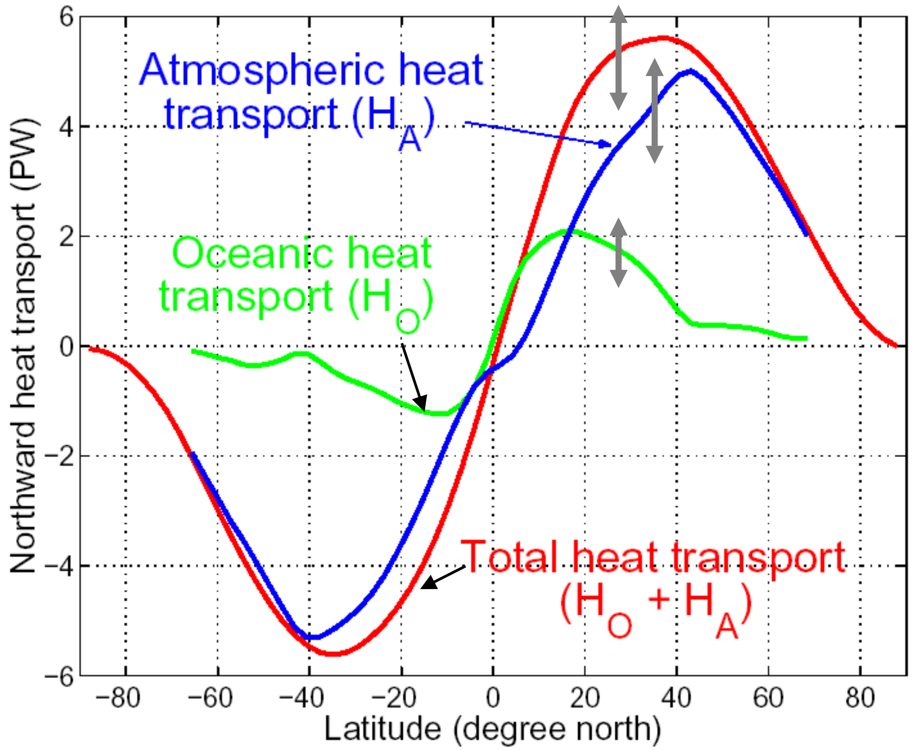
Trenberth and Caron, 2001

Notes:

- Atmosphere dominates over ocean in middle to high latitudes
- Ocean transports substantial amounts of heat out of the tropics
- Error bars are considerable

Key climate questions

- What determines the total meridional energy transport and its partition between the atmosphere and ocean?
- What sets the pole-equator temperature gradient?
- What determines the extent of polar ice caps?
- To what extent is the ocean ‘slaved’ to the atmosphere?
- Can more than one climate state exist for the same external forcing?

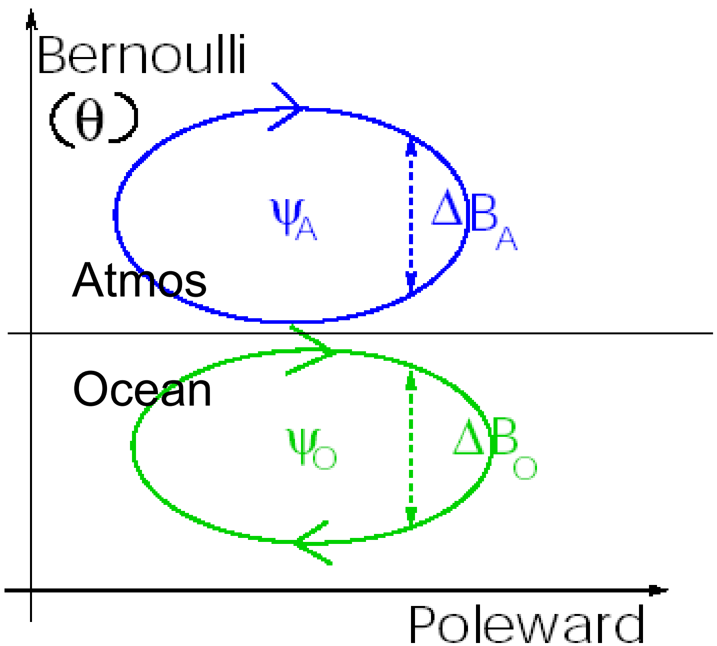


Trenberth and Caron, 2001

See afternoon sessions by Brian Rose and by David Ferreira

Framework for thinking about Energy Partition between A and O

Plot mass transport in energy space



Meridional energy transport is:

$$H = \Psi \times \Delta B$$

Mass transport $\mathrm{kg\ s^{-1}}$

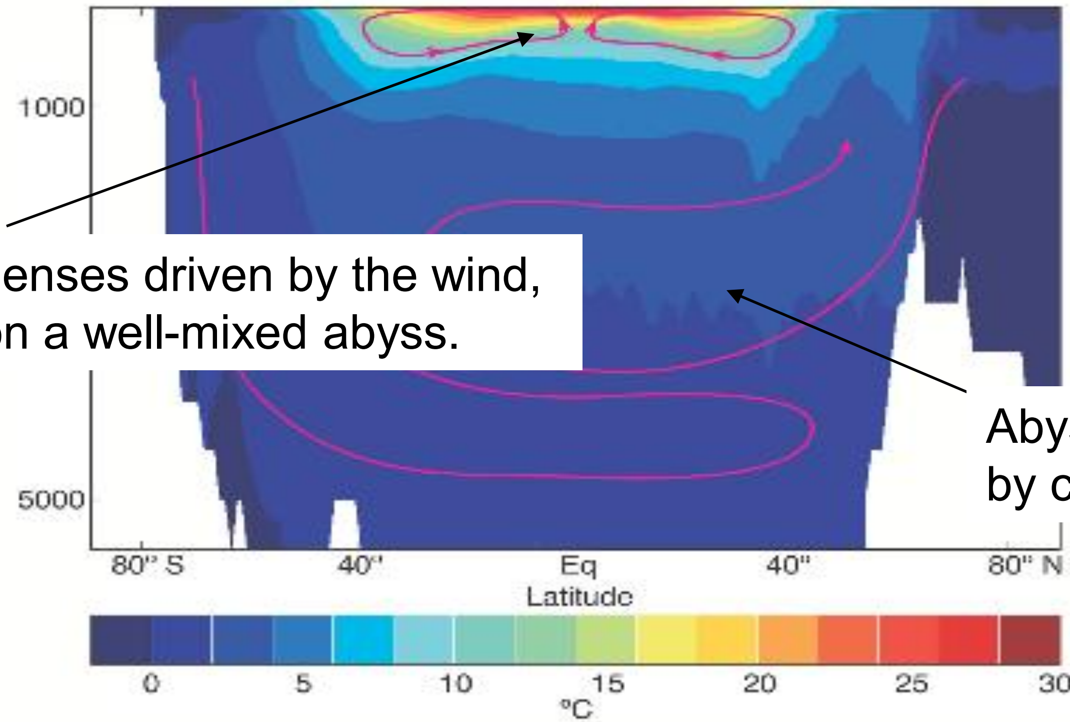
Energy contrast $\mathrm{J\ kg^{-1}}$

$$\frac{H_A}{H_O} = \frac{\Psi_A}{\Psi_O} \times \frac{\Delta B_A}{\Delta B_O}$$

Note: If we define a Sverdup (Sv) as $10^9\,\mathrm{kg\,s^{-1}}$ then can readily compare the mass transports in each fluid.

Example

Ocean circulation



Warm, salty lenses driven by the wind, floating on a well-mixed abyss.

Abyssal ocean, ventilated by convection from poles

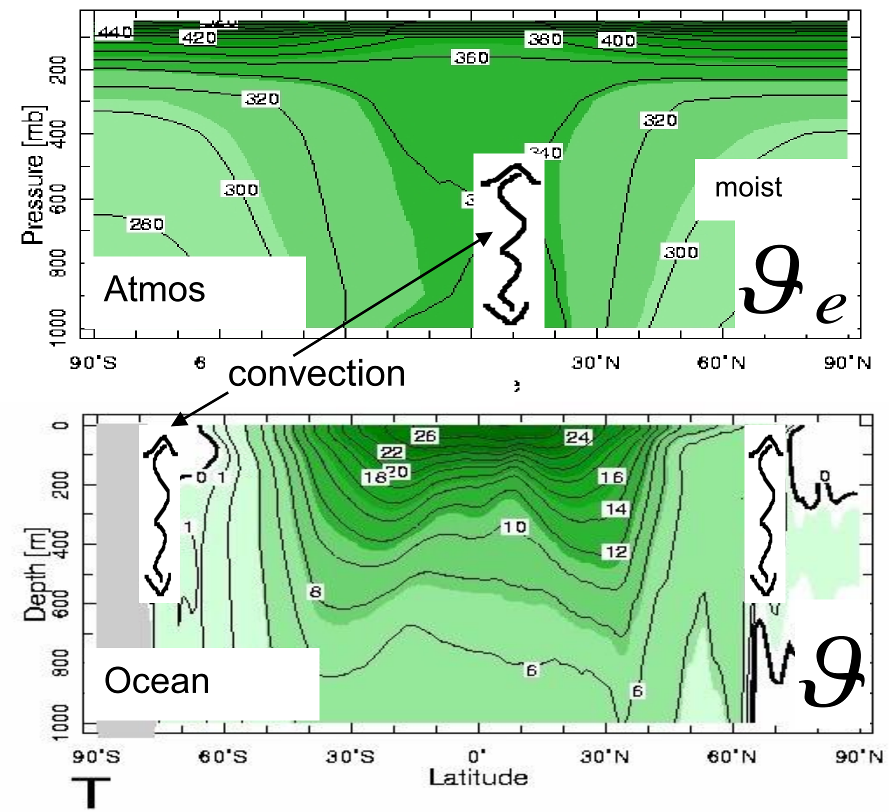
Meridional energy transport

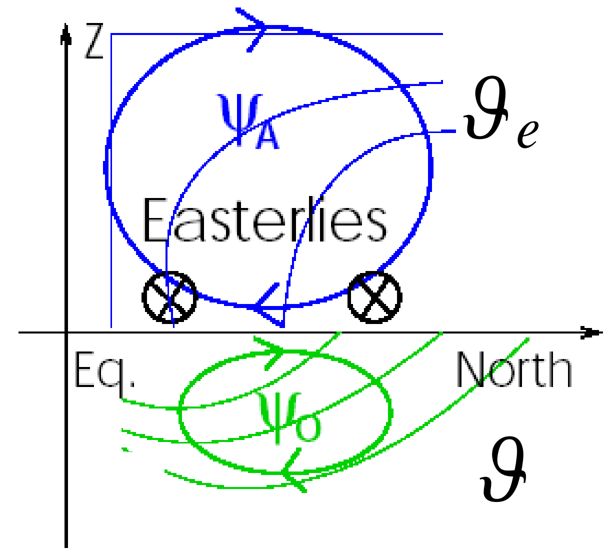
$$H_O = \rho_o \Psi_{vol} \times C_o \Delta\vartheta = 10^3 \times 20 \times 10^6 \times 4000 \times 15$$

$$\rho_o: kg\ m^{-3} \qquad \Psi_{vol}: m^3 s^{-1}$$

$$\Psi \times \Delta B = 1.2 \times 10^{15} \text{W}$$

Asymmetry of stratification of A and O in deep tropics





Ratio of energy transports | Ratio of mass transports | Ratio of stratifications

$$\frac{H_A}{H_O} = \frac{\Psi_A}{\Psi_O} \times \frac{\Delta B_A}{\Delta B_O}$$

$$\frac{\Psi_A}{\Psi_O} \longrightarrow 1$$

$$\frac{H_A}{H_O} \sim \frac{\Delta B_A}{\Delta B_O} < 1$$

Note – in atmosphere need
to consider moist static energy

$$B_A = C_A T + gz + Lq$$

Held, 2001
Czaja and Marshall, 2006

Observational estimates

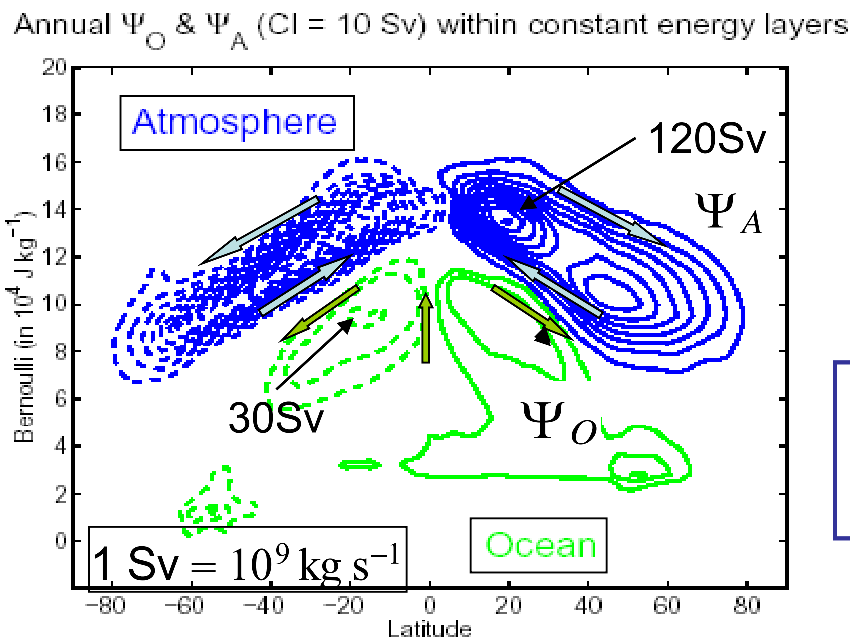
$p + \delta p$ ——— $\vartheta + \delta\vartheta$

p ——— ϑ

$\rho v \Delta z = \frac{v \Delta p}{g}$

Ψ_A & ΔB_A from NCEP re-analyzed

Moist static energy $B_A = C_A T + gz + Lq$



$$\frac{H_A}{H_O} = \frac{\Psi_A}{\Psi_O} \times \frac{\Delta B_A}{\Delta B_O}$$

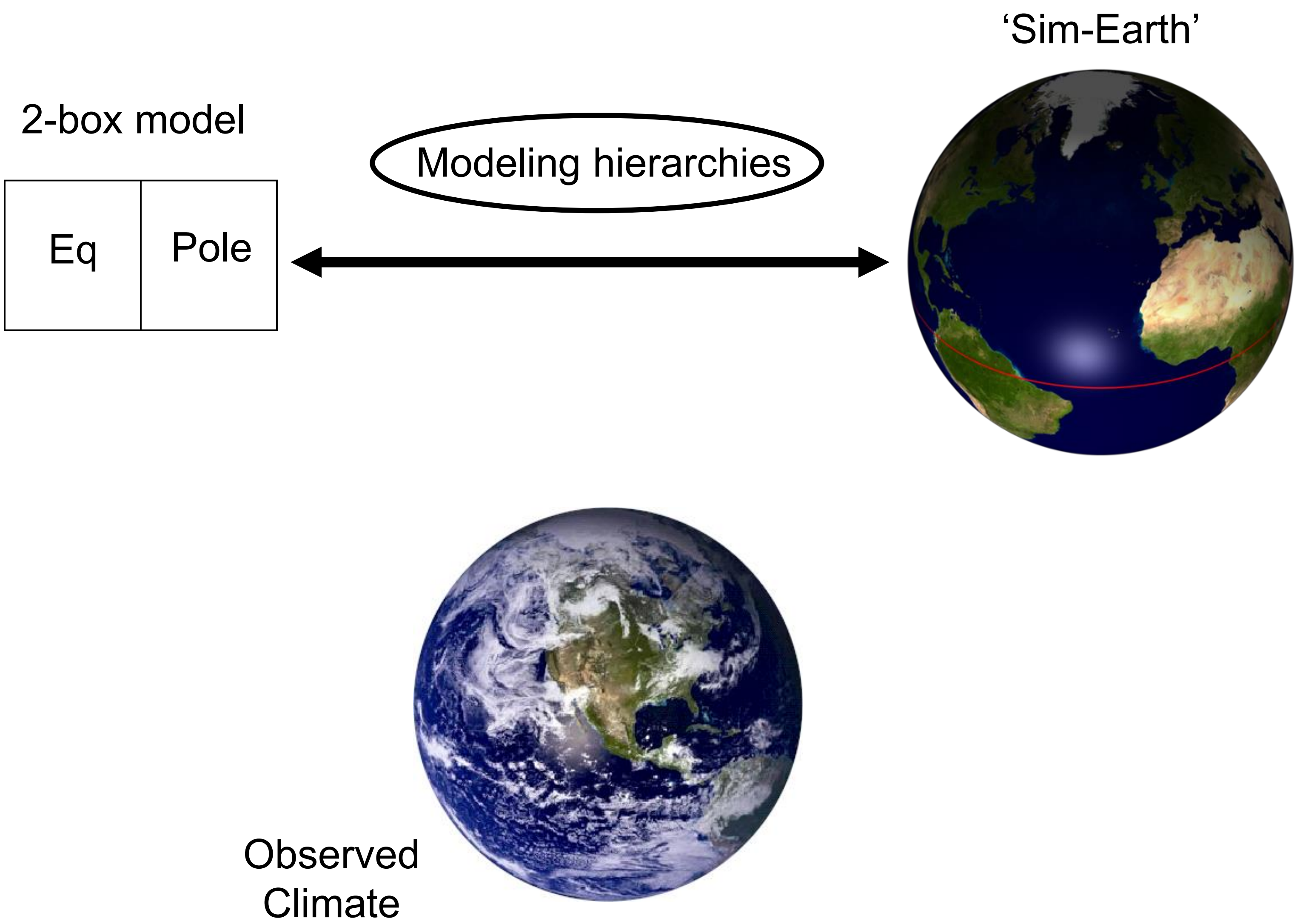
Dominance of H_A over H_O

is a consequence of $\Psi_A >> \Psi_O$

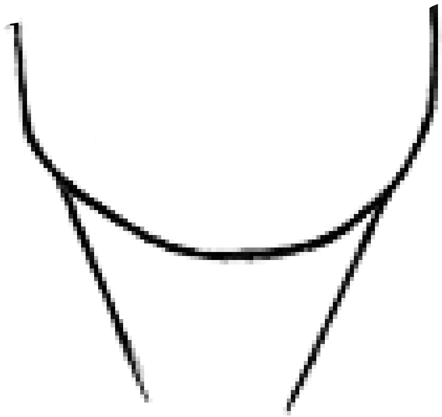
Czaja and Marshall, JAS, 2006

How robust is this partition?
Could it have been different in past, in future?

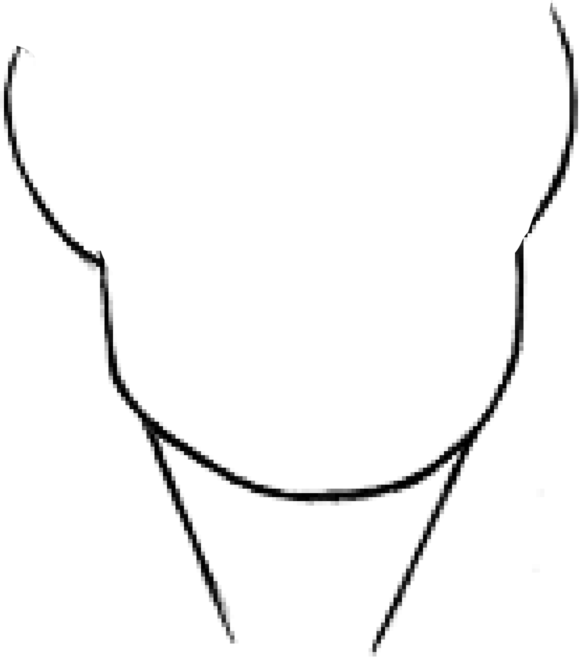
Modeling hierarchies



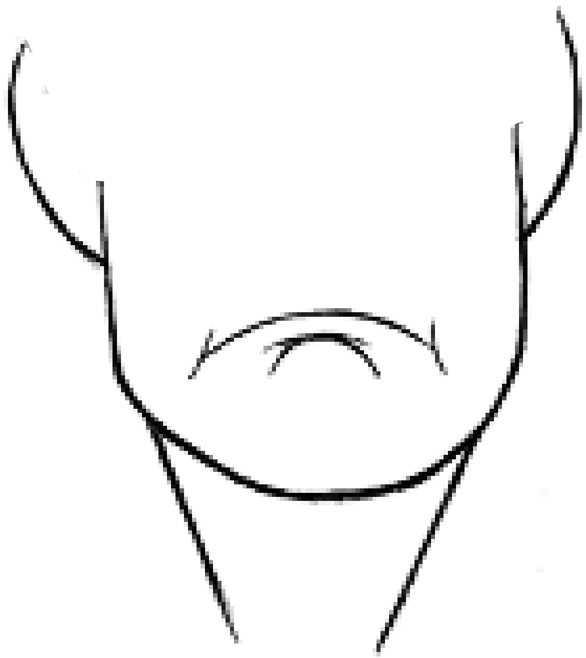
Modeling hierarchies



Modeling hierarchies

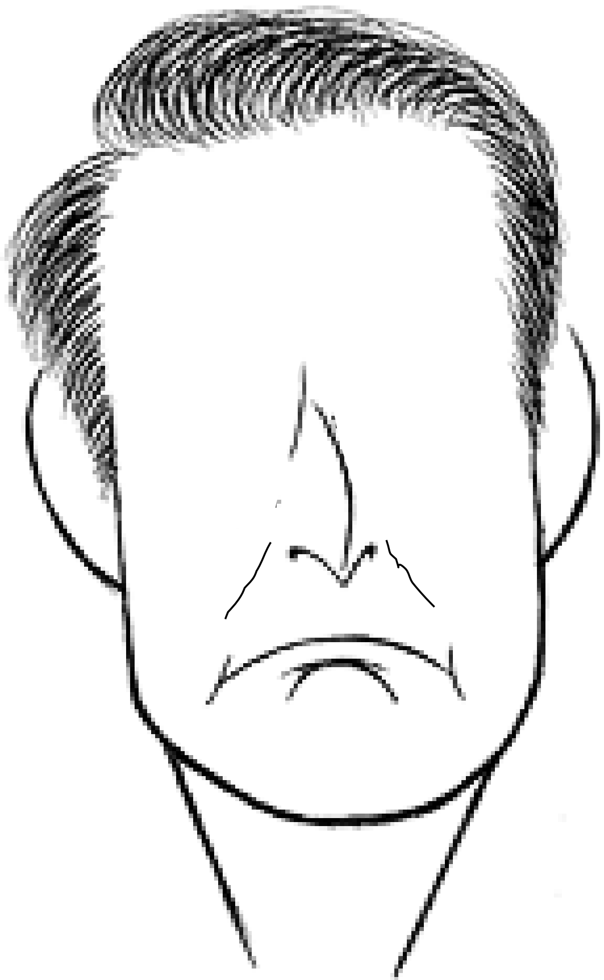


Modeling hierarchies

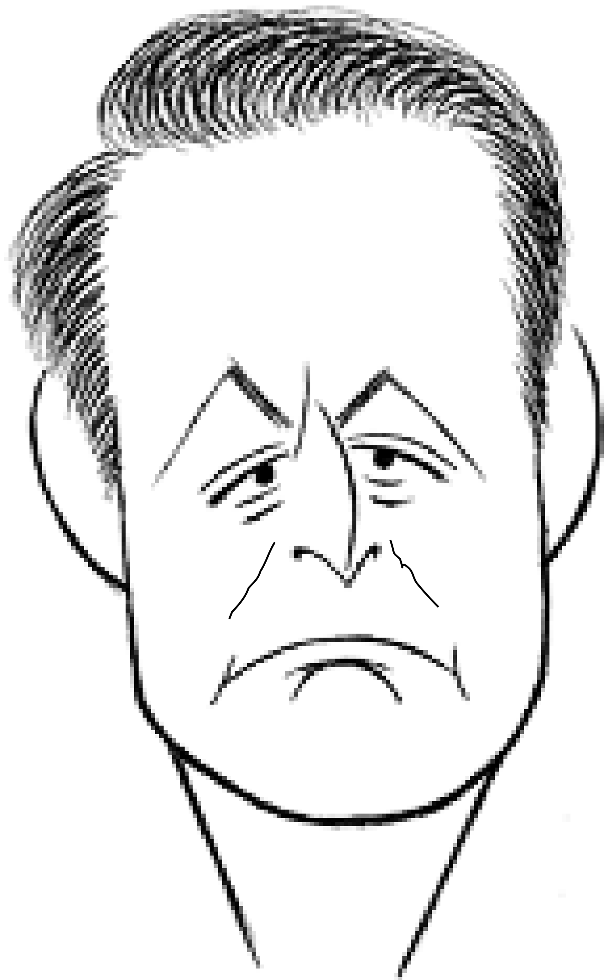


Modeling hierarchies

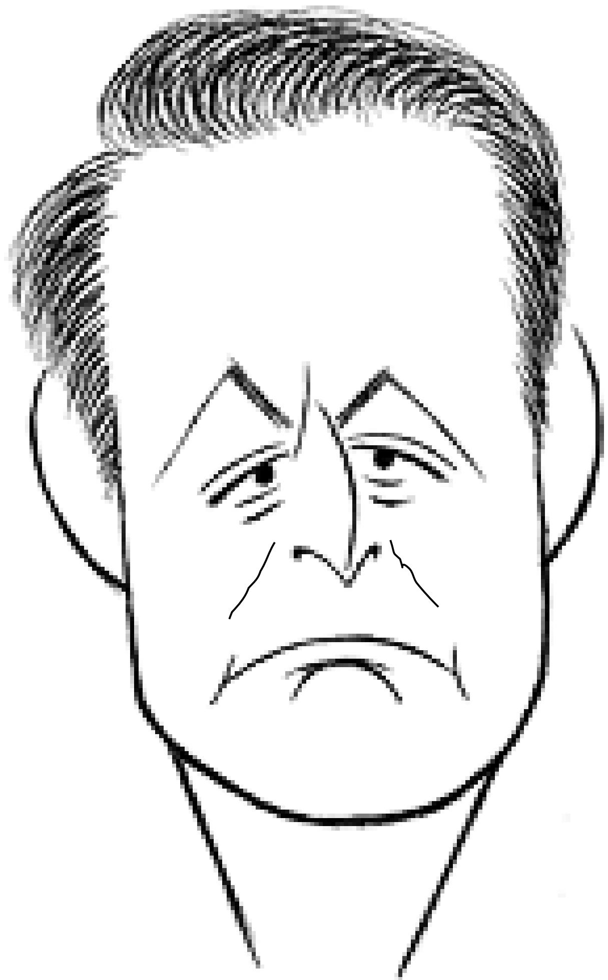
Modeling hierarchies



Modeling hierarchies



Ken Fallin



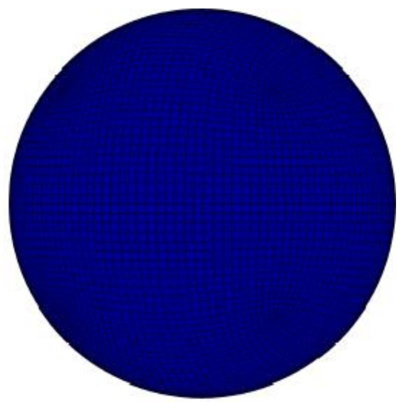
Ken Fallin

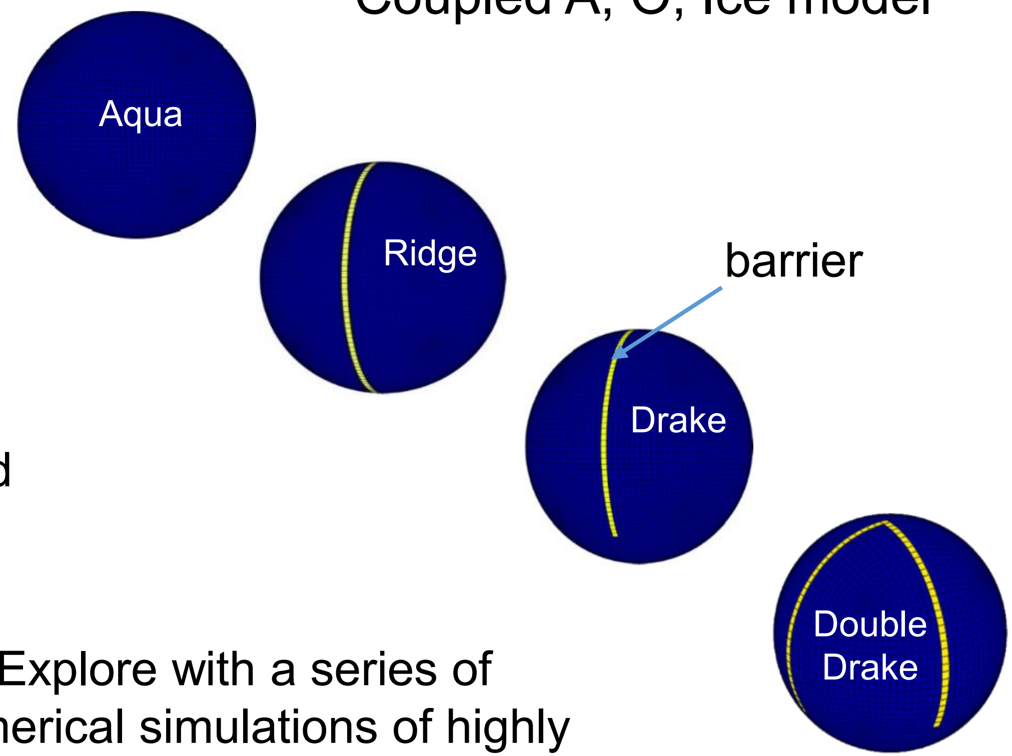
‘Ken takes a sharp look, brandishes his steel quill, and traces in ink the essence of a living soul’

Climate of a Water World

What would the climate of earth be like if there were no land?

Coupled A, O, Ice model





A, O, possibility of Ice, but no land

Explore with a series of numerical simulations of highly idealized water worlds

Coupled Climate Dynamics: Energy transport by the Atmosphere and Ocean

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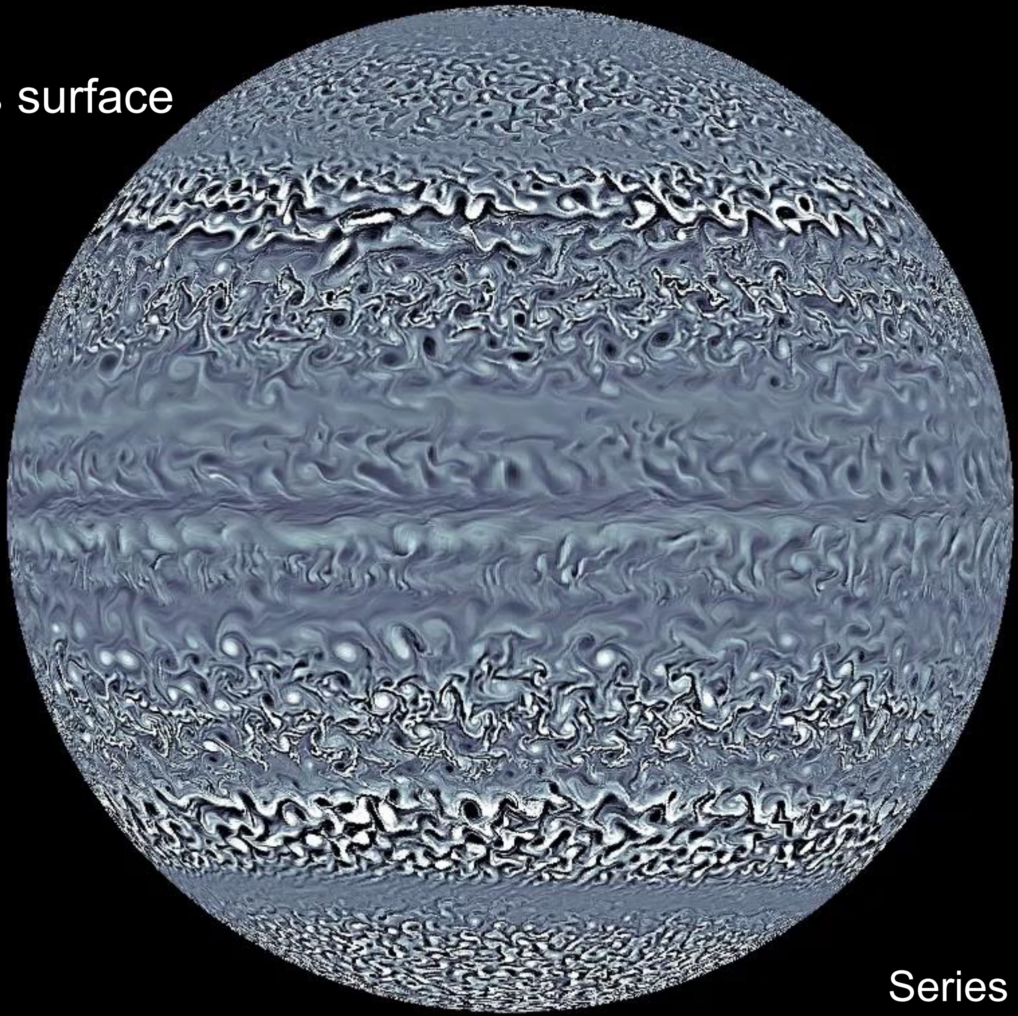
Aqua-planet Project

Vorticity at ocean's surface



Aqua-planet Project

Thanks to:

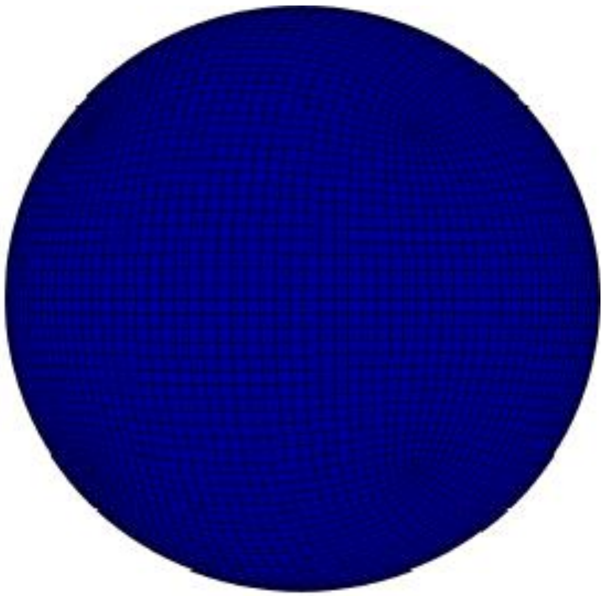
Martha Buckley
J-M Campin
Aaron Donohoe
Daniel Enderton
David Ferreira
Brian Green
Mukund Gupta
Chris Hill
David McGee
Paul O'Gorman
Brian Rose
Sara Seager

Applied to:
Understand present climate
Paleo climate
Multiple equilibria of climate
Exoplanets

Series of papers by
John Marshall, Brian Rose,
David Ferreira & collaborators

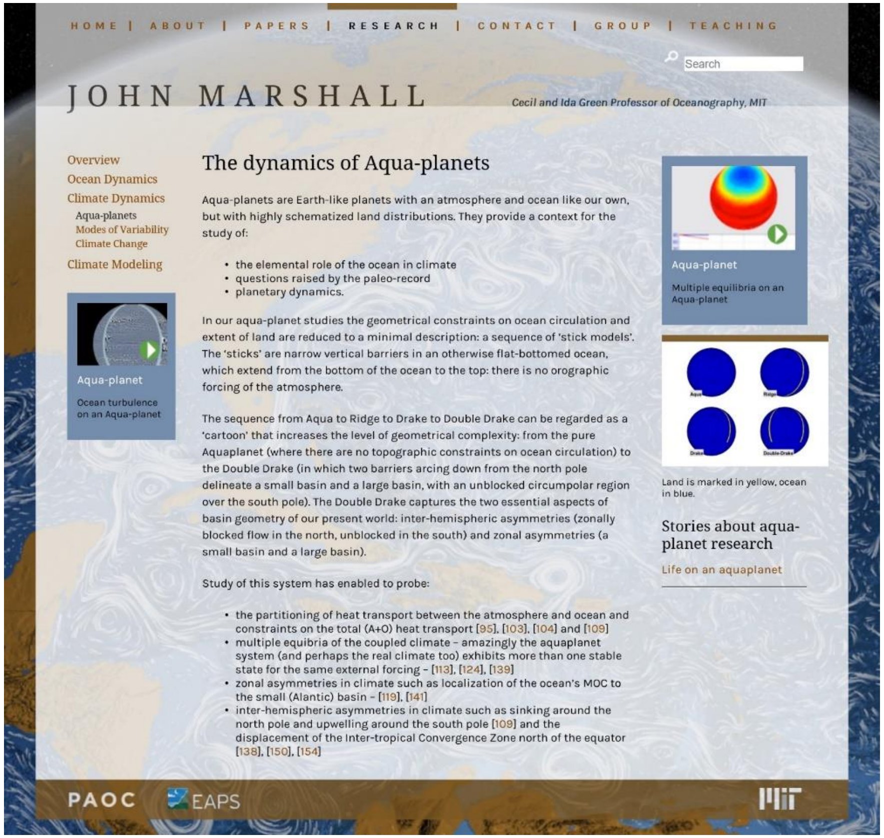
Riccardo Farneti & Geoff Vallis

Climate of an Aquaplanet



What would the climate of earth be like if there were no land?

How would it achieve the requisite meridional energy transports?



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JOHN MARSHALL

Cecil and Ida Green Professor of Oceanography, MIT

Overview
Ocean Dynamics
Climate Dynamics
Aqua-planets
Modes of Variability
Climate Change
Climate Modeling

Aqua-planet

Ocean turbulence on an Aqua-planet

The dynamics of Aqua-planets

Aqua-planets are Earth-like planets with an atmosphere and ocean like our own, but with highly schematized land distributions. They provide a context for the study of:

- the elemental role of the ocean in climate
- questions raised by the paleo-record
- planetary dynamics.

In our aqua-planet studies the geometrical constraints on ocean circulation and extent of land are reduced to a minimal description: a sequence of 'stick models'. The 'sticks' are narrow vertical barriers in an otherwise flat-bottomed ocean, which extend from the bottom of the ocean to the top: there is no orographic forcing of the atmosphere.

The sequence from Aqua to Ridge to Drake to Double Drake can be regarded as a 'cartoon' that increases the level of geometrical complexity: from the pure Aquaplanet (where there are no topographic constraints on ocean circulation) to the Double Drake (in which two barriers arcing down from the north pole delineate a small basin and a large basin, with an unblocked circumpolar region over the south pole). The Double Drake captures the two essential aspects of basin geometry of our present world: inter-hemispheric asymmetries (zonally blocked flow in the north, unblocked in the south) and zonal asymmetries (a small basin and a large basin).

Study of this system has enabled to probe:

- the partitioning of heat transport between the atmosphere and ocean and constraints on the total (A+O) heat transport [95], [103], [104] and [109]
- multiple equibria of the coupled climate – amazingly the aquaplanet system (and perhaps the real climate too) exhibits more than one stable state for the same external forcing – [113], [124], [139]
- zonal asymmetries in climate such as localization of the ocean's MOC to the small (Alantic) basin – [119], [141]
- inter-hemispheric asymmetries in climate such as sinking around the north pole and upwelling around the south pole [109] and the displacement of the Inter-tropical Convergence Zone north of the equator [138], [150], [154]

Aqua-planet

Multiple equilibria on an Aqua-planet

Land is marked in yellow, ocean in blue.

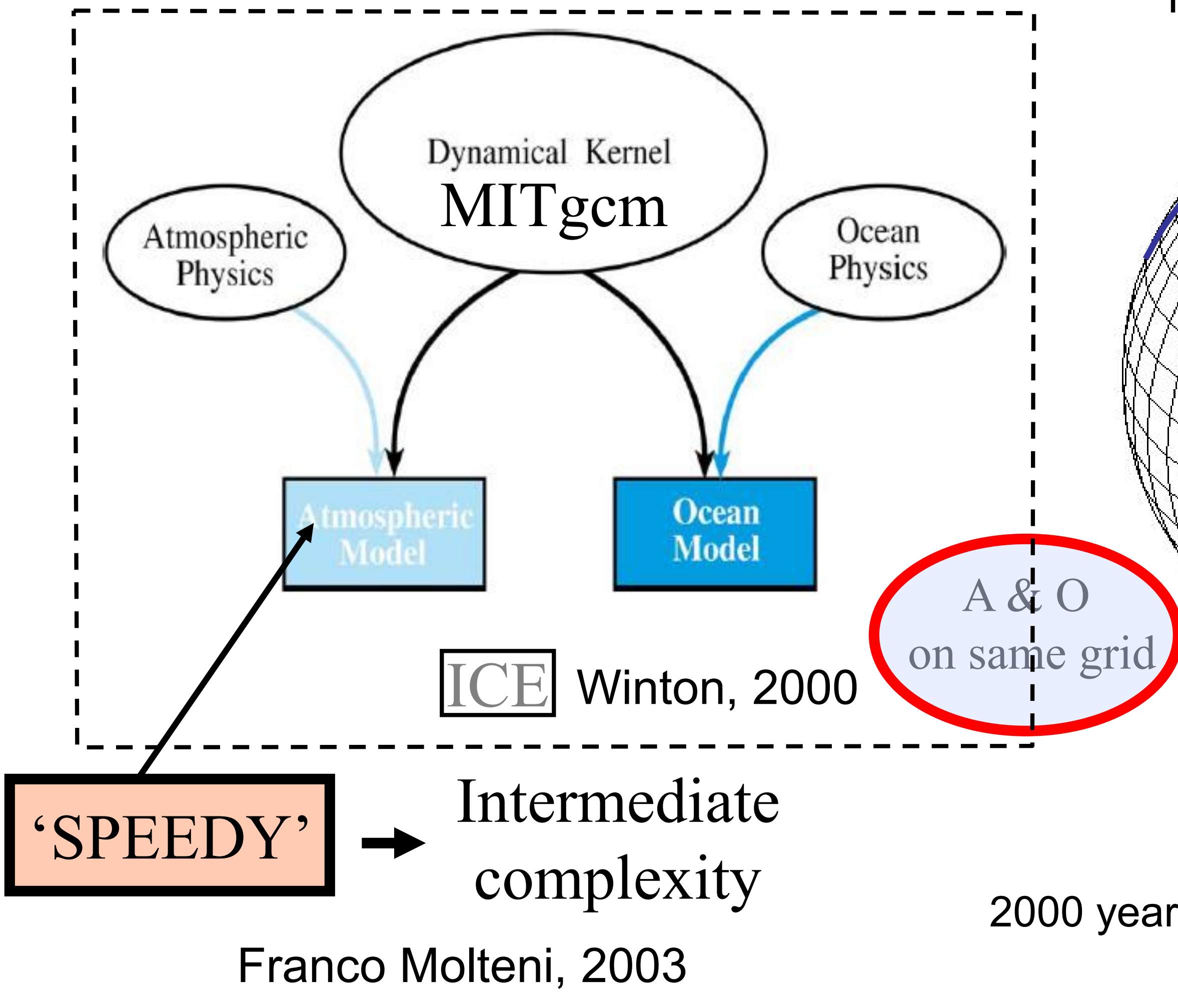
Stories about aqua-planet research

Life on an aquaplanet

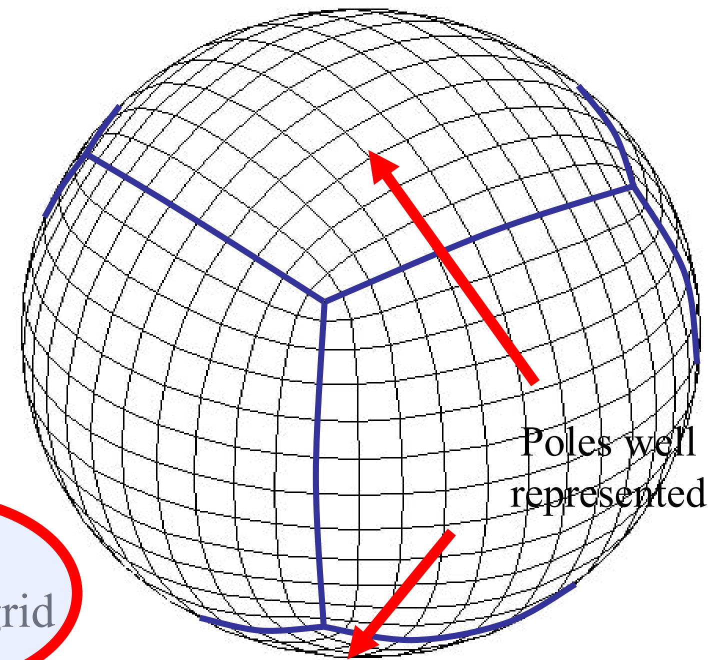
PAOC EAPS

http://oceans.mit.edu/JohnMarshall/research/climate-dynamics/page-1/

Coupled Climate Model



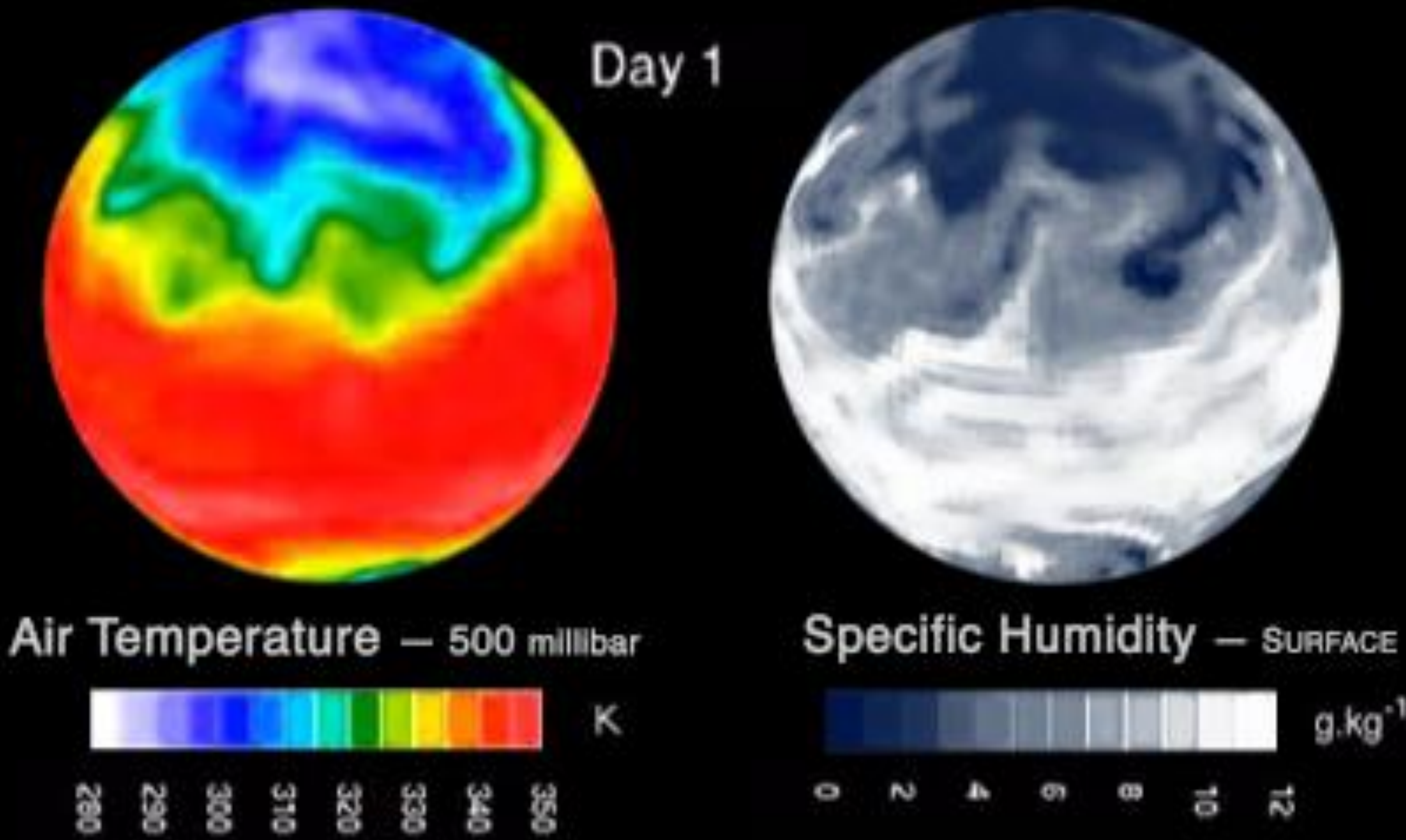
Fully coupled:
no adjustments



2000 years in 1 week of CPU time
(synchronous)

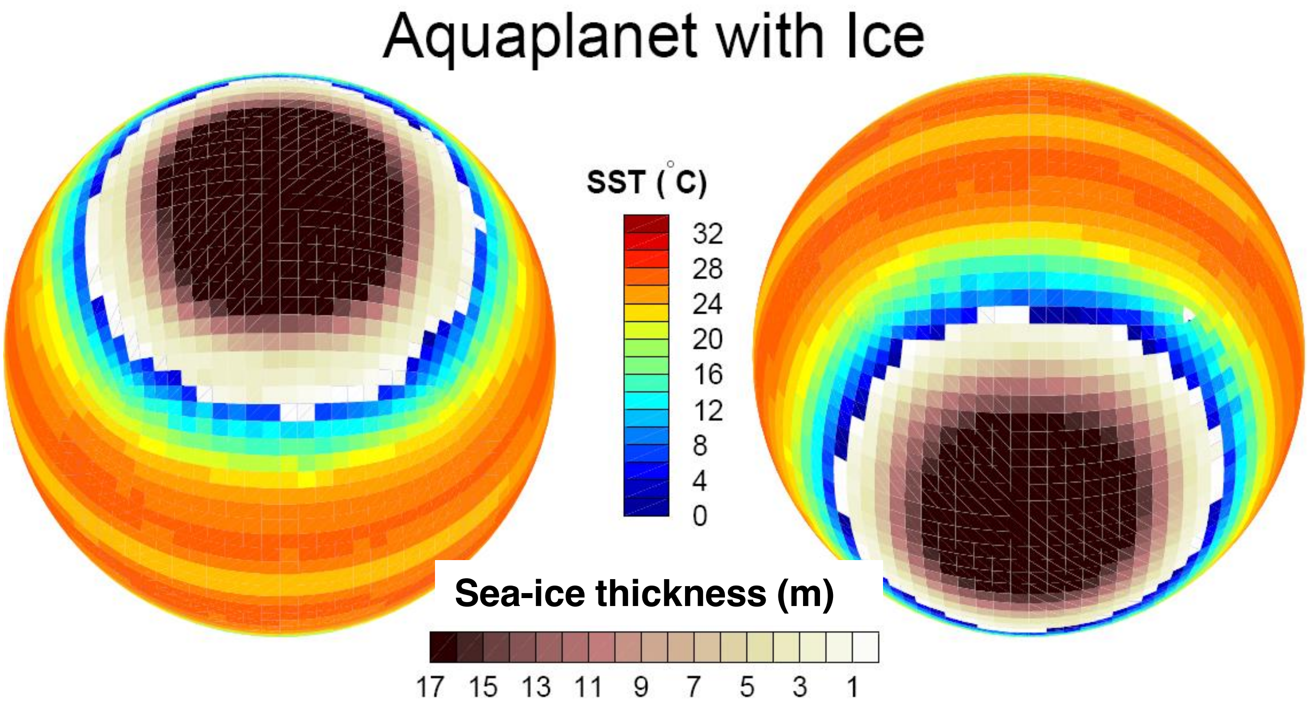
J-M Campin and Chris Hill built the model
David Ferreira helped drive forward the science

Aqua-planet



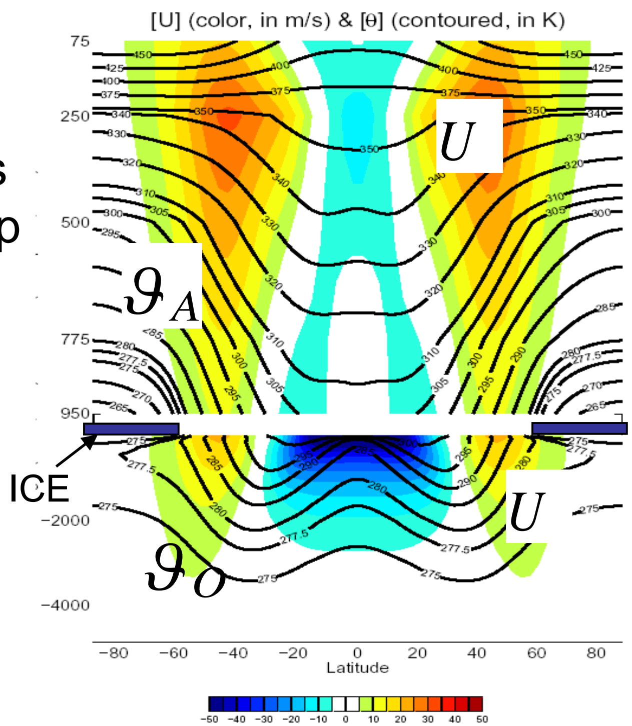
Day 1
Air Temperature – 500 millibar
K
280 290 300 310 320 330 340 350
Specific Humidity – SURFACE
g.kg-1
0 2 4 6 8 10 12

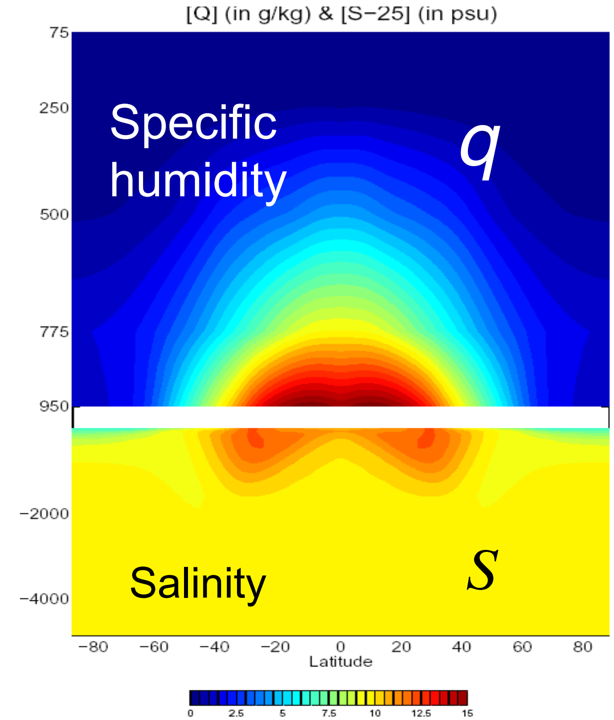
Sea Surface Temperature & Sea Ice

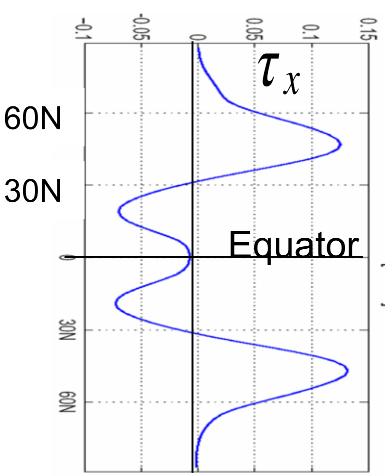


Climate of aqua-planet

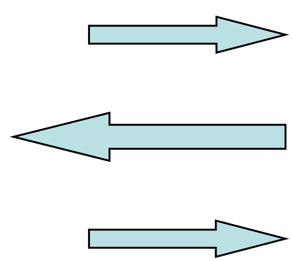
Winds, Currents and Temp



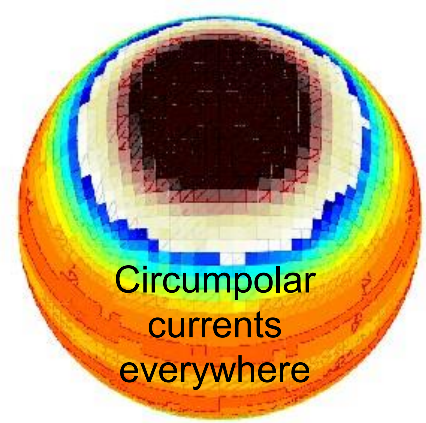




Surface Winds

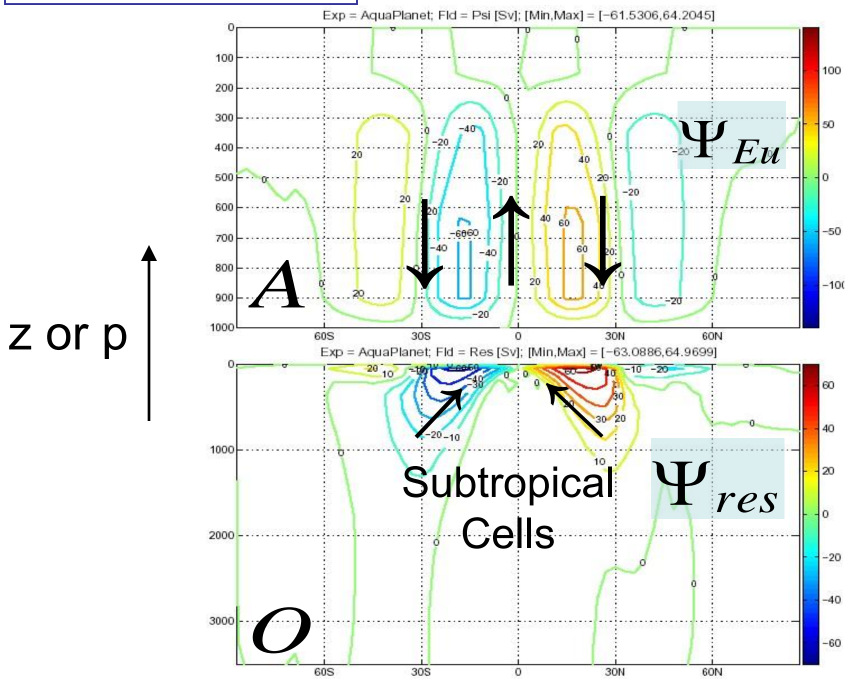


Zonal jets in ocean

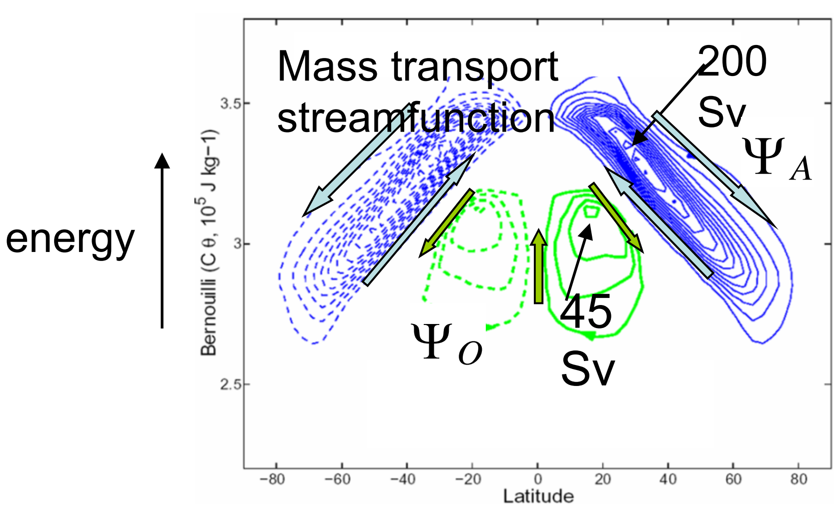


Aquaplanet solution discussed in Marshall, Ferreira et al JAS, 2007

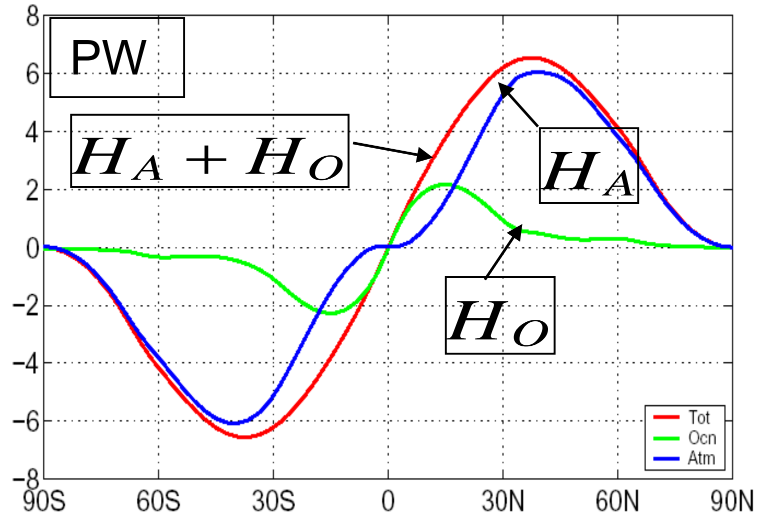
Eulerian view



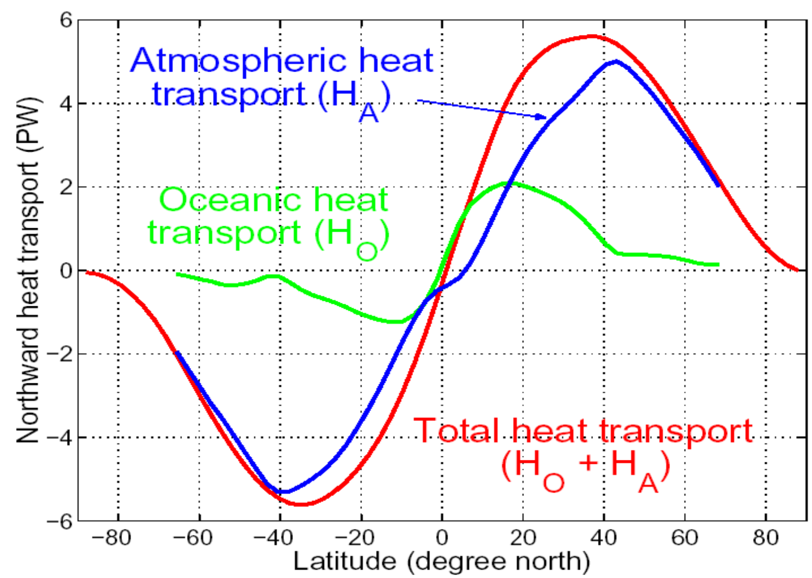
Residual view



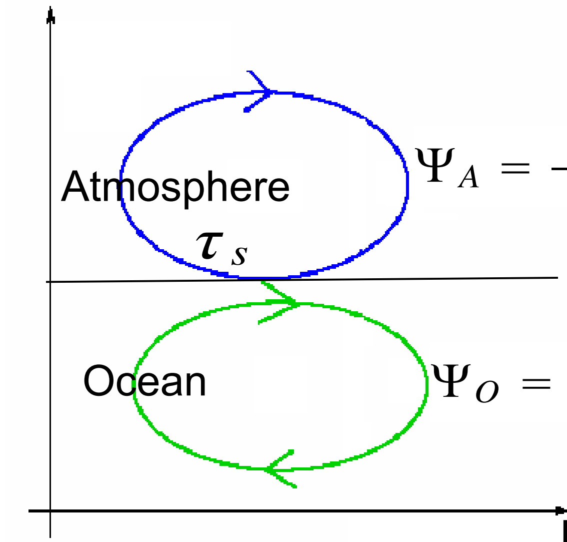
Aqua planet



Today's climate



Interpretation



Dominates in extra-tropics

$$\Psi_A = -\frac{\tau_s}{f} + \rho_A \overline{v'h'}_A$$

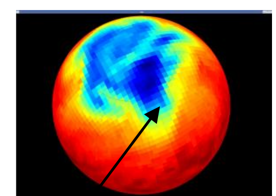
bolus transport

$$\Psi_O = -\frac{\tau_s}{f} + \rho_O \overline{v'h'}_O$$

Balance one-another in extra-tropics

In tropics $\quad \frac{\Psi_O}{\Psi_A} \sim 1$

In extra-tropics $\quad \frac{\Psi_O}{\Psi_A} \lesssim \frac{\rho_O \overline{v'h'}_O}{\rho_A \overline{v'h'}_A}$



Now $\quad \overline{v'h'} \simeq \frac{\overline{v'\theta'}}{\overline{\theta}_z} = K s_\theta$

where K is an eddy diffusivity.

If isentropic slopes in the two fluids are comparable, then

$$\boxed{\frac{\Psi_O}{\Psi_A} \lesssim \frac{\rho_O K_O}{\rho_A K_A}} \simeq \frac{1}{4}$$

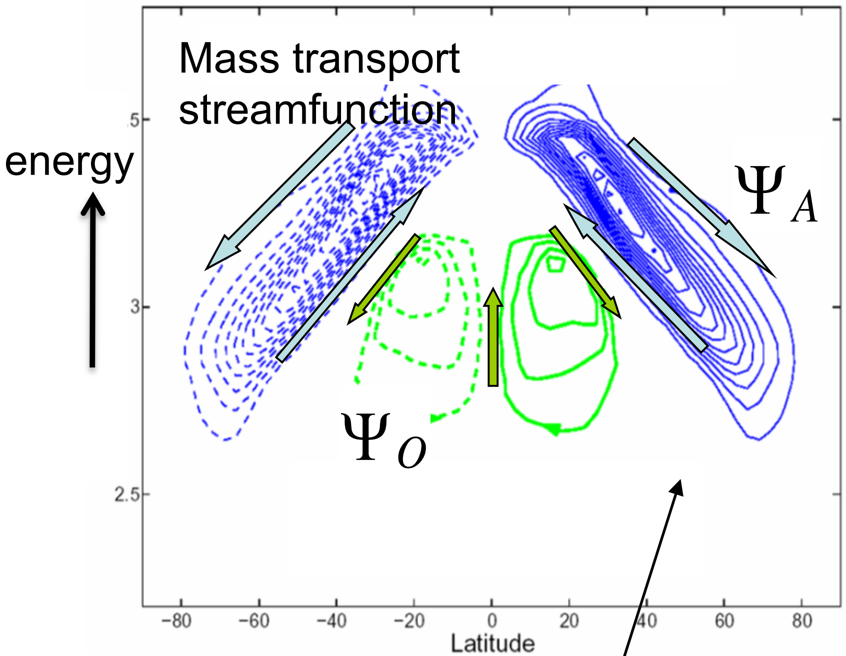
supposing that $\quad K_A = 4 \times 10^6\,\mathrm{m}^2\,\mathrm{s}^{-1}$

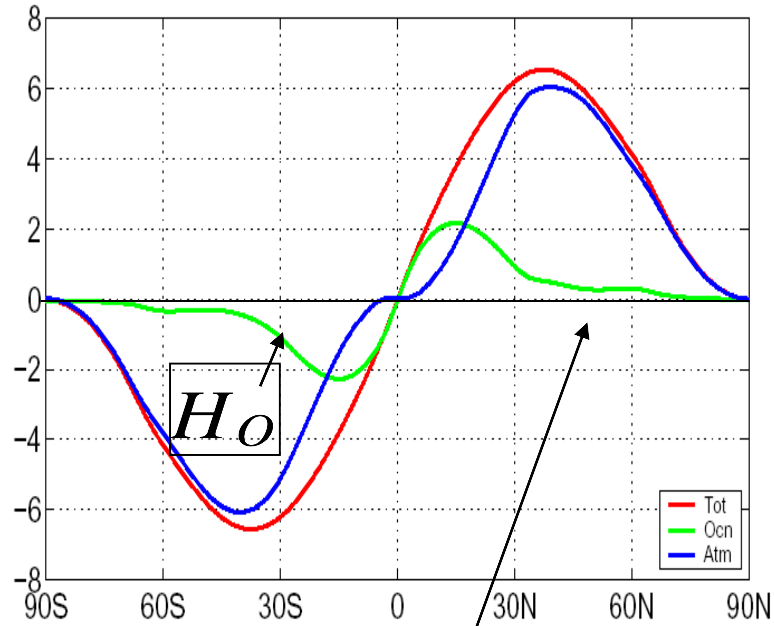
$K_O = 10^3\,\mathrm{m}^2\,\mathrm{s}^{-1}$

typical of turbulent diffusivities in A and O

Why ice at the poles in aqua?

$$H = \Psi \times \Delta B$$





Poleward mass transport in the ocean all but vanishes at high latitudes

Very small high latitude meridional energy flux

Pole freezes over

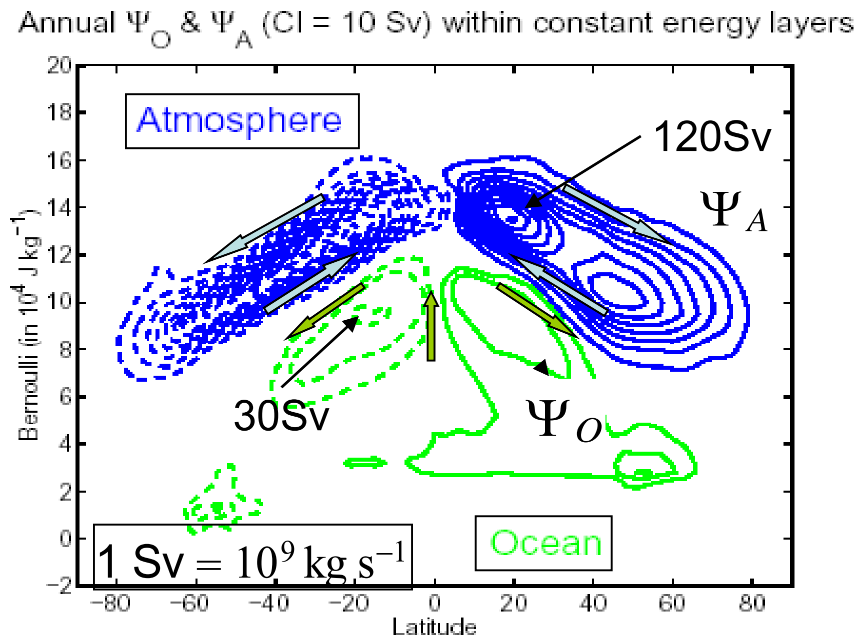
Conclusions

• Energy flux partition can be rationalized by

$$\frac{H_A}{H_O} = \frac{\Psi_A}{\Psi_O} \times \frac{\Delta B_A}{\Delta B_O}$$

Dominance of H_A over H_O

is a consequence of $\Psi_A >> \Psi_O$



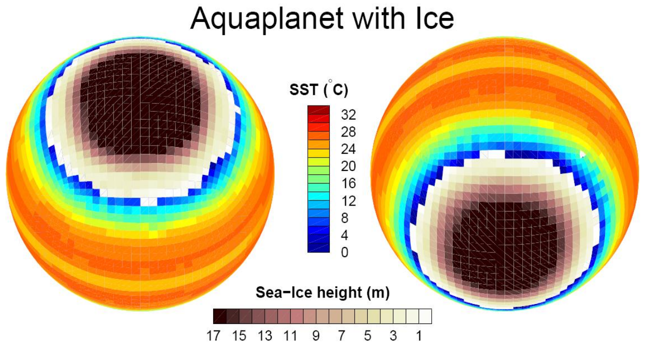
• Partition of heat transport on aqua-planet remarkably similar to present climate

Can interpret using zonal-average theory

• Ocean energy transport on aqua-planet very small at high latitudes

Vanishing of residual flow at high latitudes

Ice builds up over the poles



As we shall see, the aqua-planet supports multiple equilibria