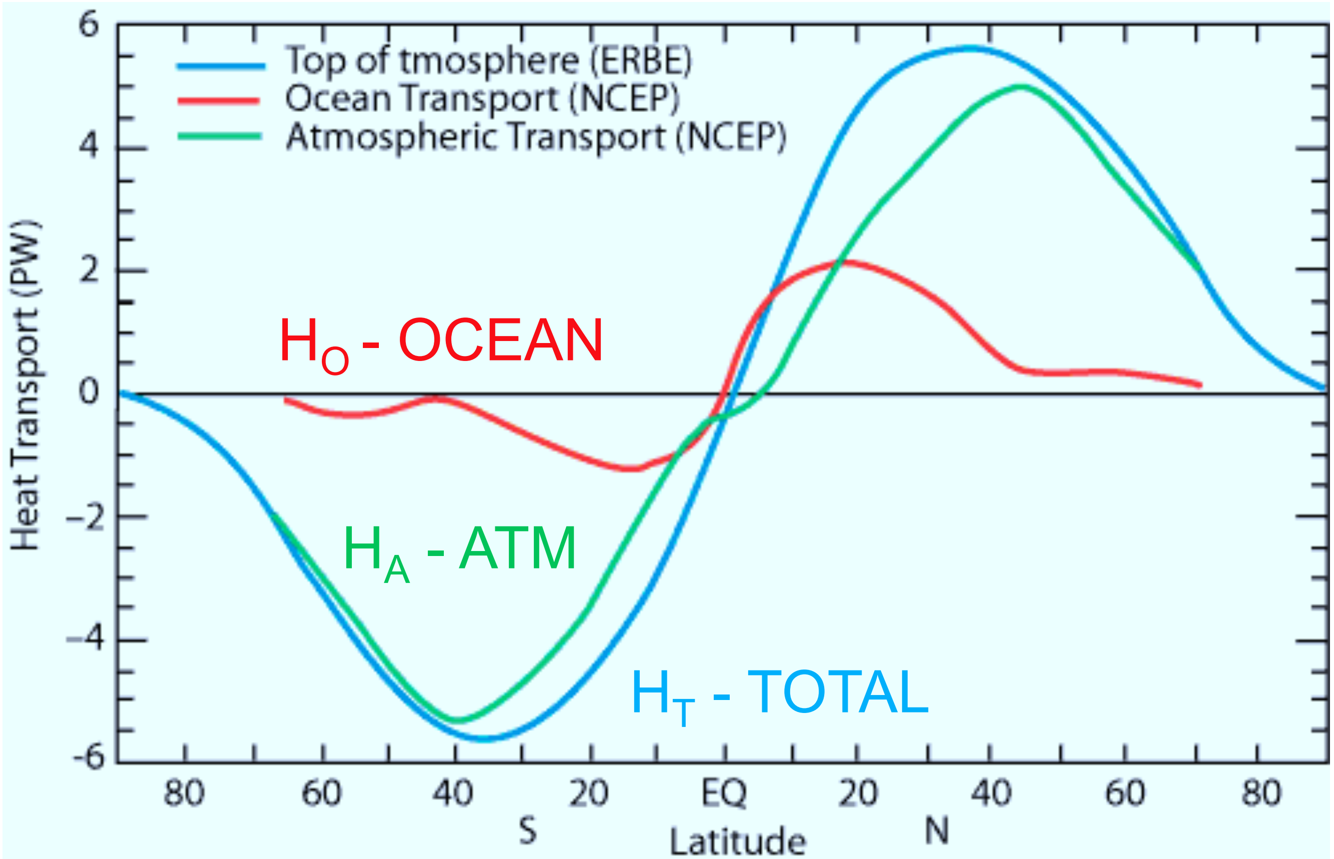
Earth's Energy Budget, Heat Transport, and Ice

Northward (or Meridional) Heat Transport

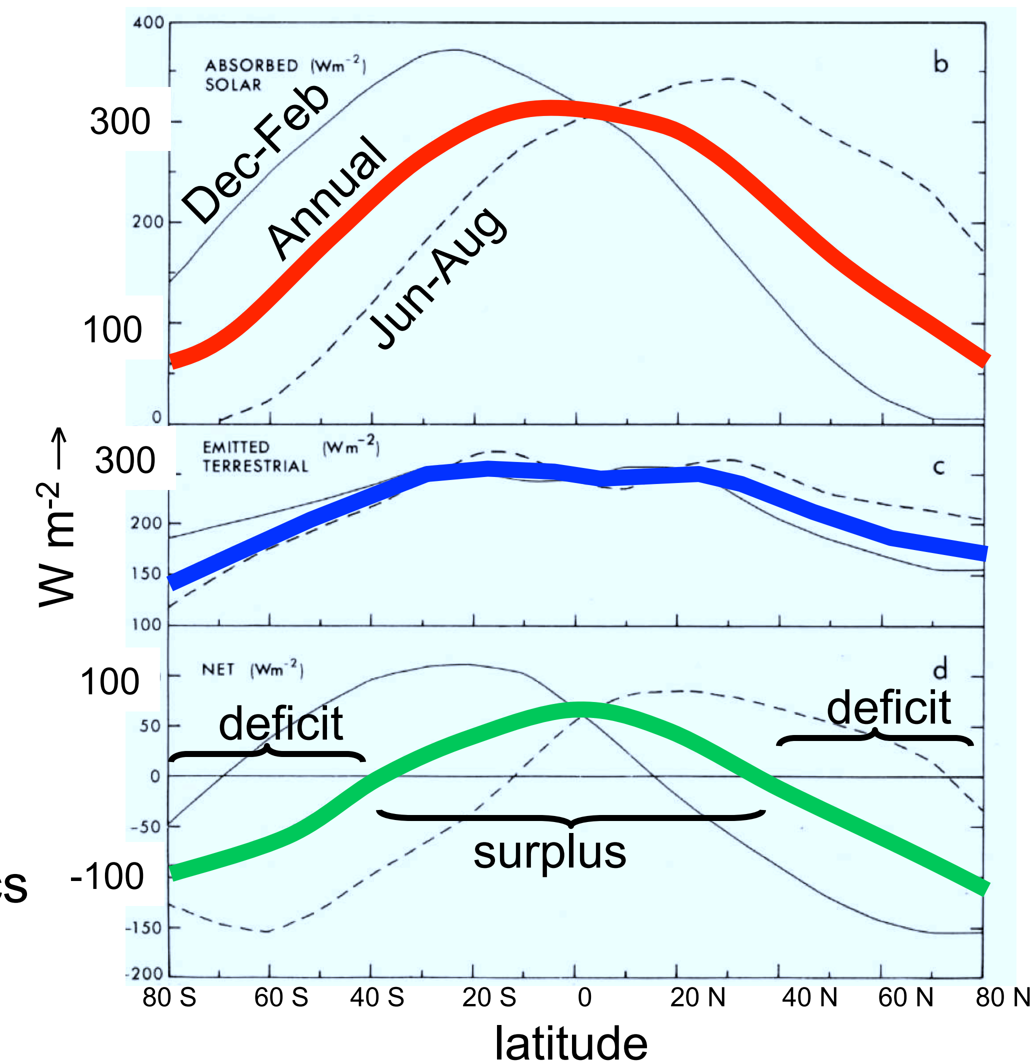


Annual mean Top Of Atmosphere (TOA) radiation budget of planet

Absorbed solar,
$Q_0(1-\alpha)$:
α = albedo

Longwave emitted
to space, F

The difference:
Drives climate dynamics
to alleviate imbalances



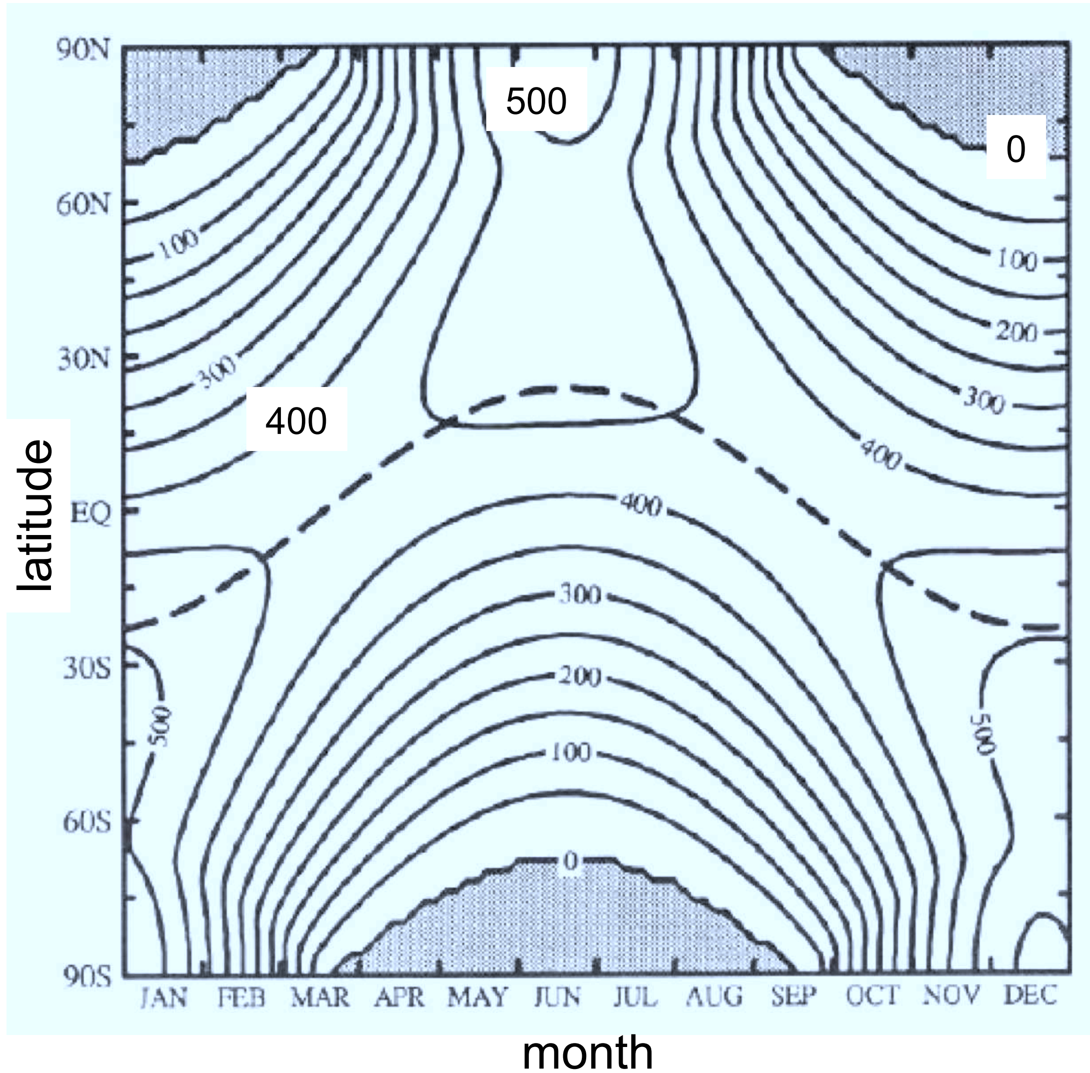
[Peixoto and Oort, 1992]

Daily mean insolation at top of atmosphere

-peaks at poles at summer solstice.

-is zero at poles at winter solstice.

- global average ~ 342 Wm^{-2}



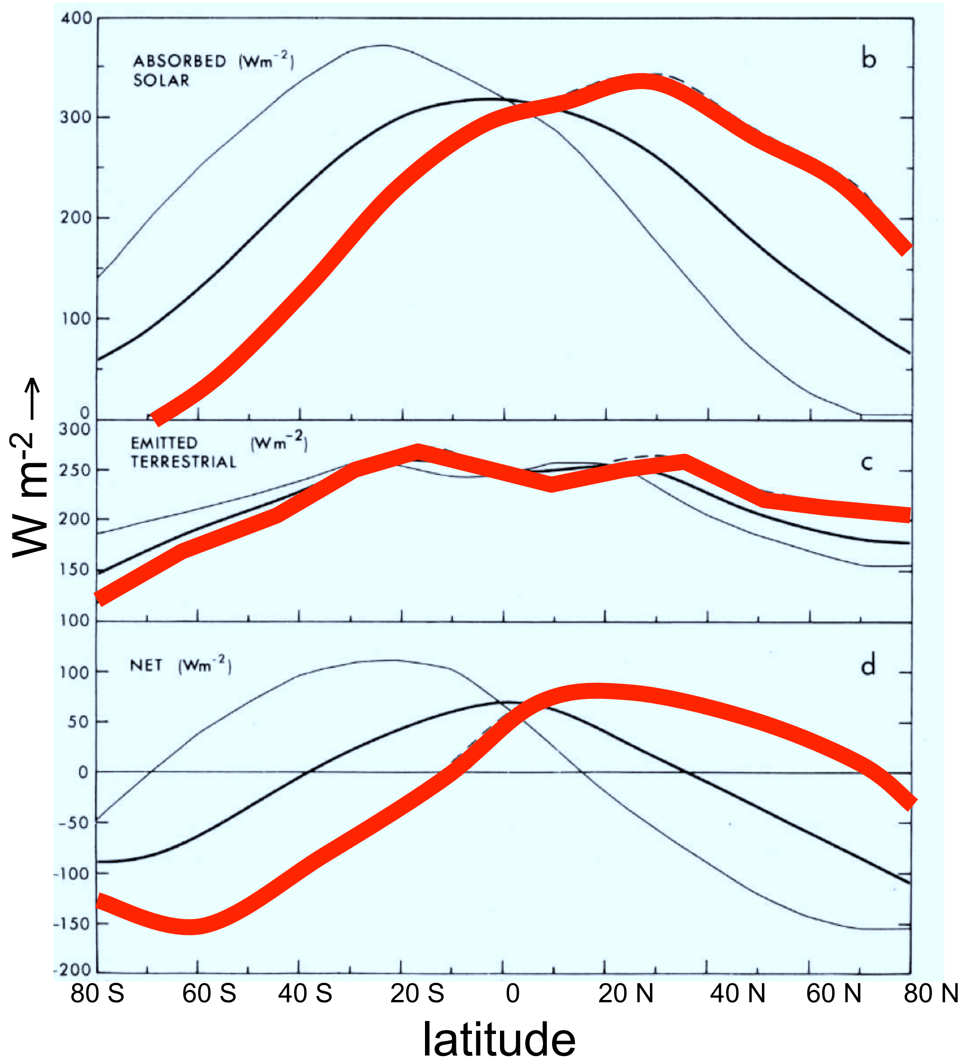
Hartmann, 1994

Northern summer radiation budget (Jun. Jul. Aug.)

Absorbed solar
$Q_0(1-\alpha)$:

Longwave
emitted to space, F:

The difference: drives
climate dynamics AND
heat storage



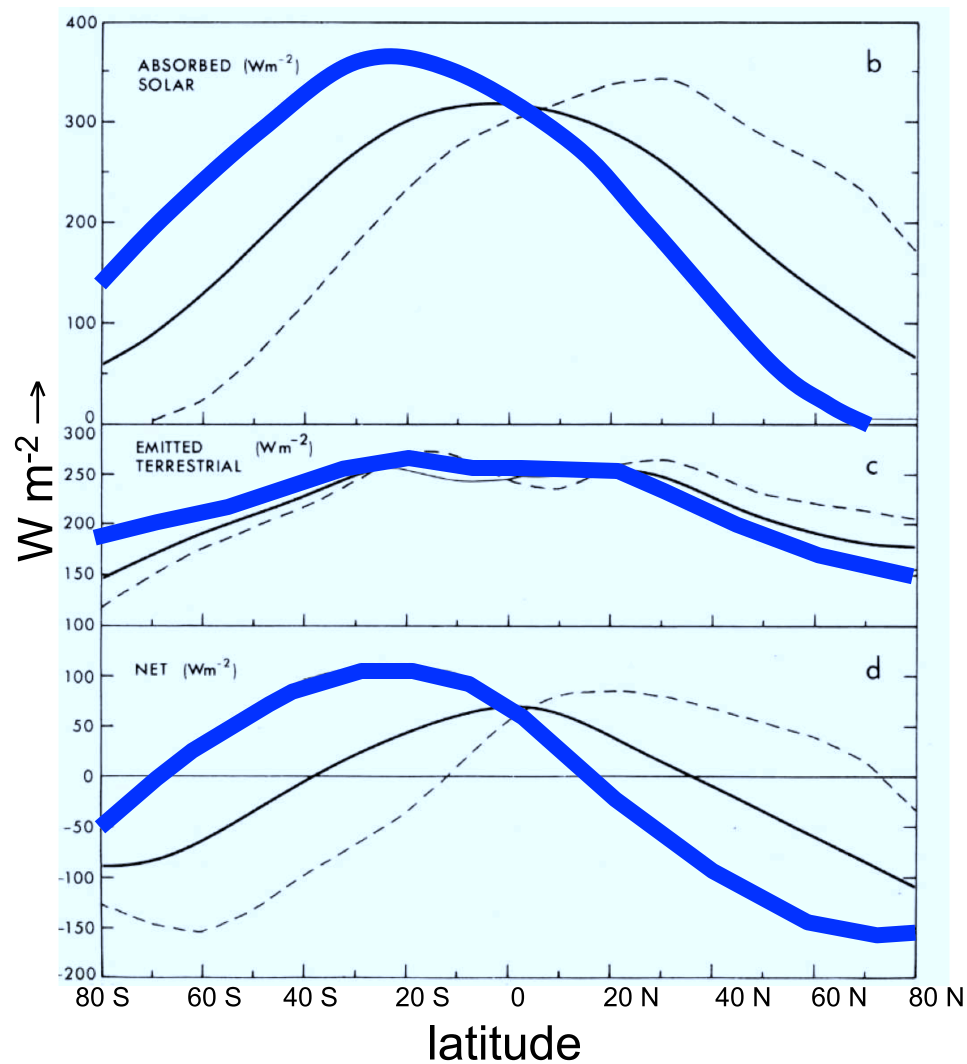
[Peixoto and Oort, 1992]

Northern winter radiation budget (Dec. Jan. Feb.)

Absorbed Solar
$Q_0(1-\alpha)$:

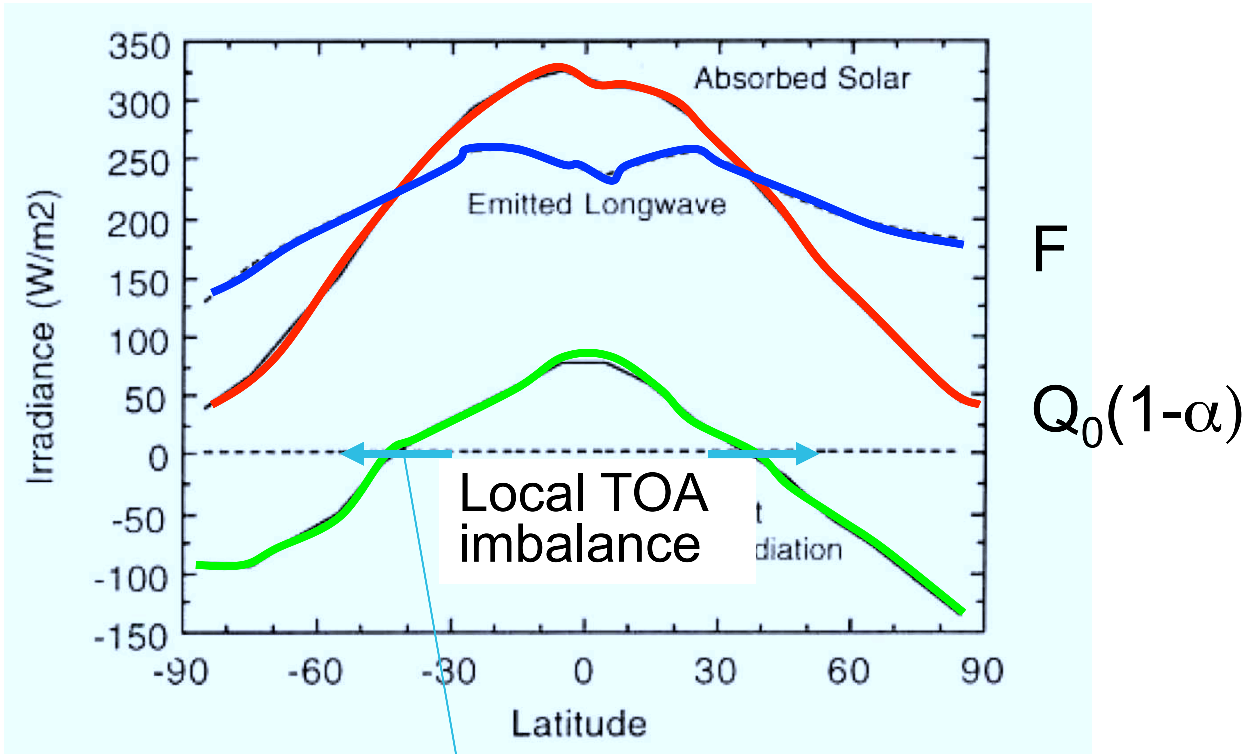
Longwave
emitted to space, F:

The difference: drives
climate dynamics AND
heat storage



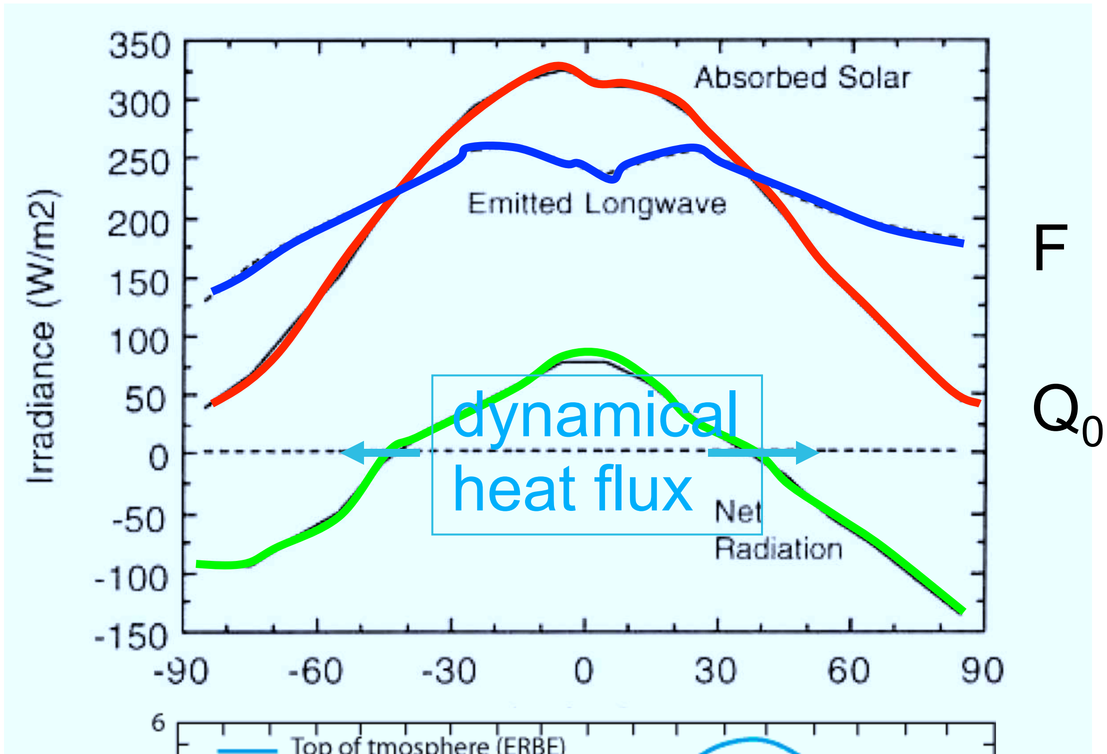
[Peixoto and Oort, 1992]

Top of Atmosphere (TOA) Flux Balance



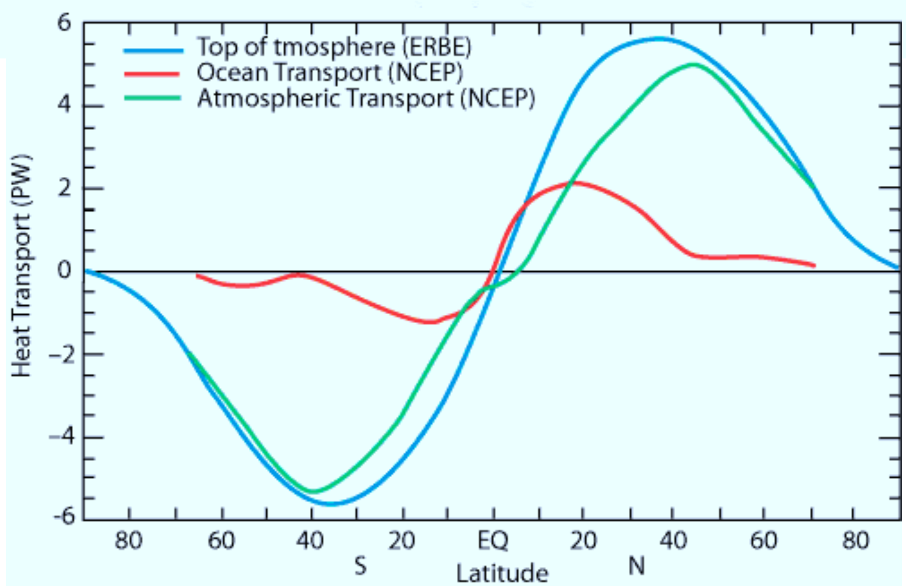
Local TOA imbalance drives dynamical heat flux such that the TOA imbalance is equal to the heat flux divergence. The imbalance is small relative to F or Qo(1-α) in most regions, except at the poles

Hartmann, 1994



F

$Q_0(1-\alpha)$

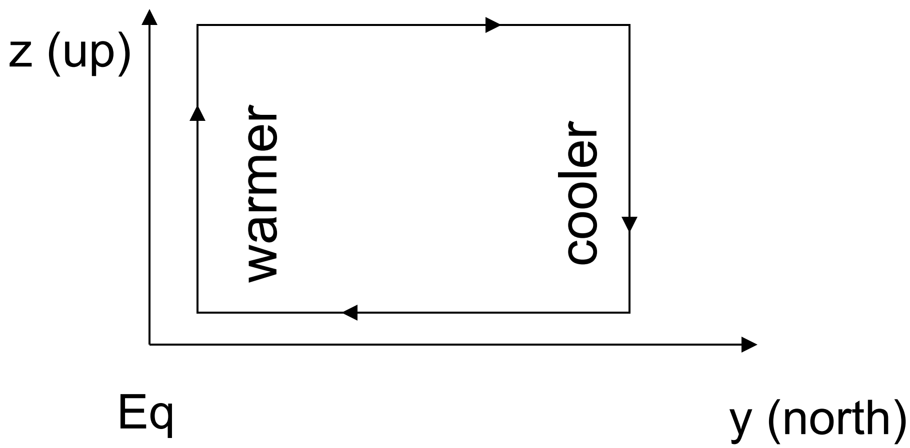


H_T Gradient
Seeks to
Balance TOA
Imbalance

Atmospheric General Circulation in <15 minutes

Point 1: Temperature gradient develops owing to differential heating

Hadley Circulation



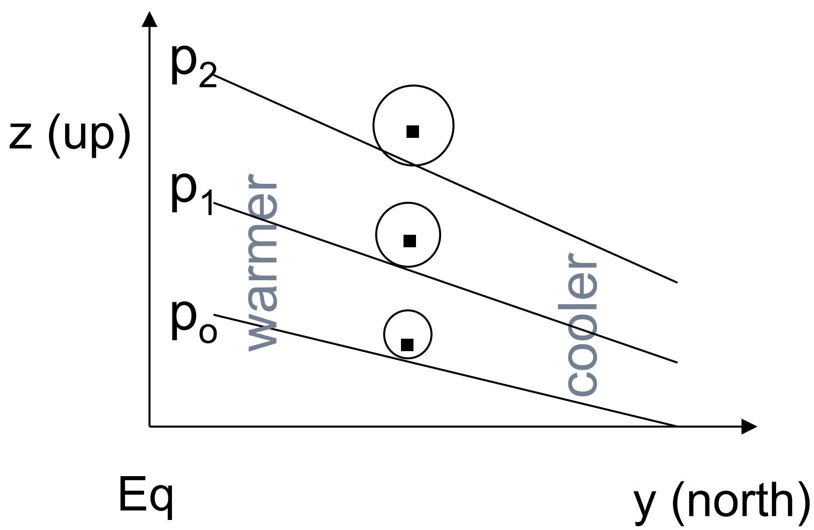
- "Thermally direct" meridional cell
  - Warmer air rises in the tropics (cooling it somewhat).
  - Cooler air sinks further north (warming it somewhat)
- Cooler air moves equatorward at surface
- Heat transport is primarily via potential energy

Point 2: Temperature gradient drives thermally direct cell, which moves heat poleward

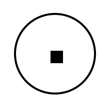
Point 3: Temperature gradients cause vertical shear of the horizontal wind (see intro meteorology text book)

$$\frac{\partial u}{\partial z} \sim \frac{\partial T}{\partial y}$$

u = westerly wind
T = temperature
z = up in atm, ? in ocn
y = north
x = east

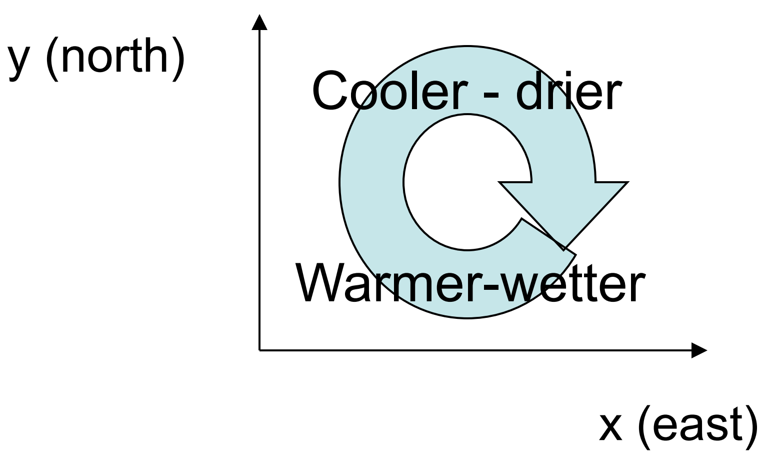


- Isobar slope increases with height
- Isobar slope determines geostrophic wind speed
- Westerly wind speed increases with height

 = Westerly wind

Vertical shear of horizontal wind is baroclinically unstable - encourages storm production, which limits the poleward reach of the Hadley Circulation to about 30 deg latitude

Midlatitude Baroclinic Eddies (aka Storms)



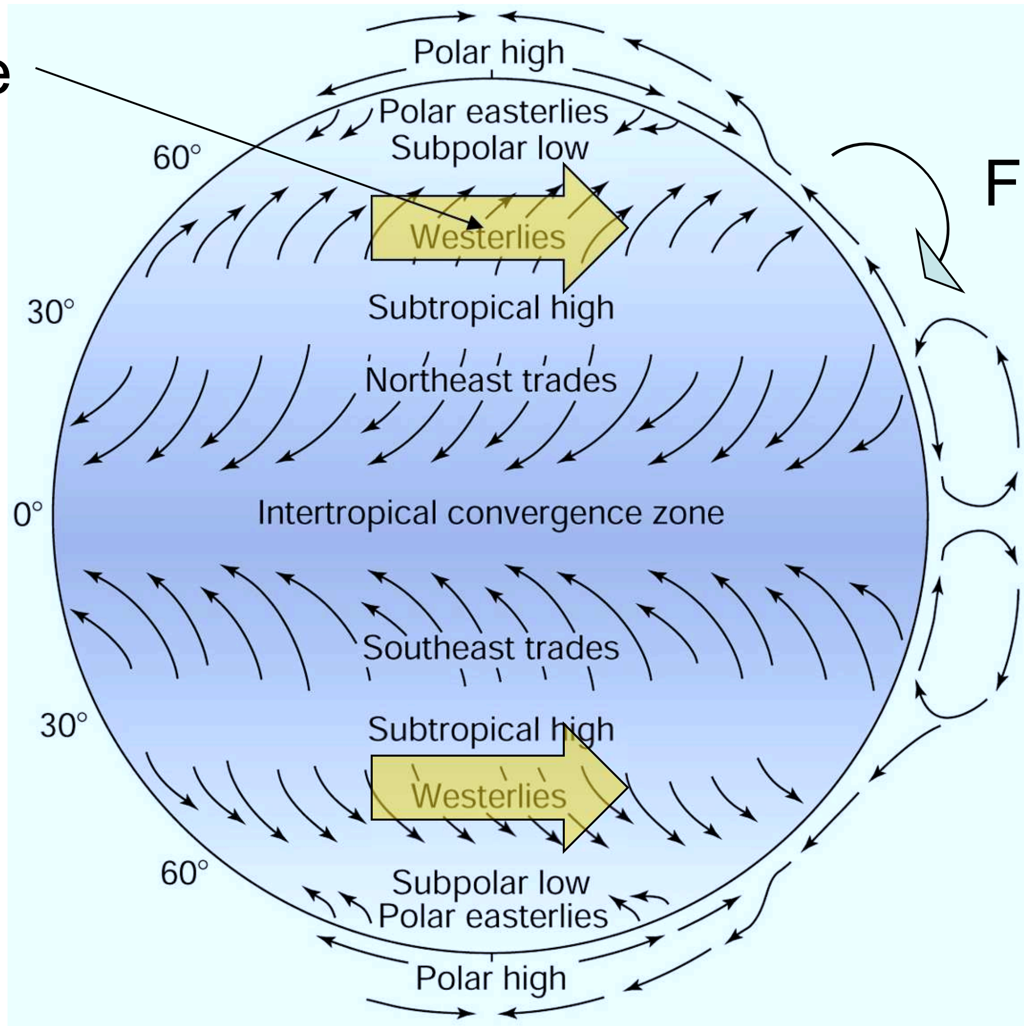
- •Eddies arise owing to horizontal temperature gradient
- •Eddies transport heat towards the pole
- •Eddies erode north-south temperature gradient and hence weaken their energy source

Point 4: Horizontal eddies move heat poleward and incidently produce a thermally **in**direct meridional cell known as the Ferrel cell (see intermediate meteorology text)

Ocean Circulation in <15 min

Surface Winds (crudely)

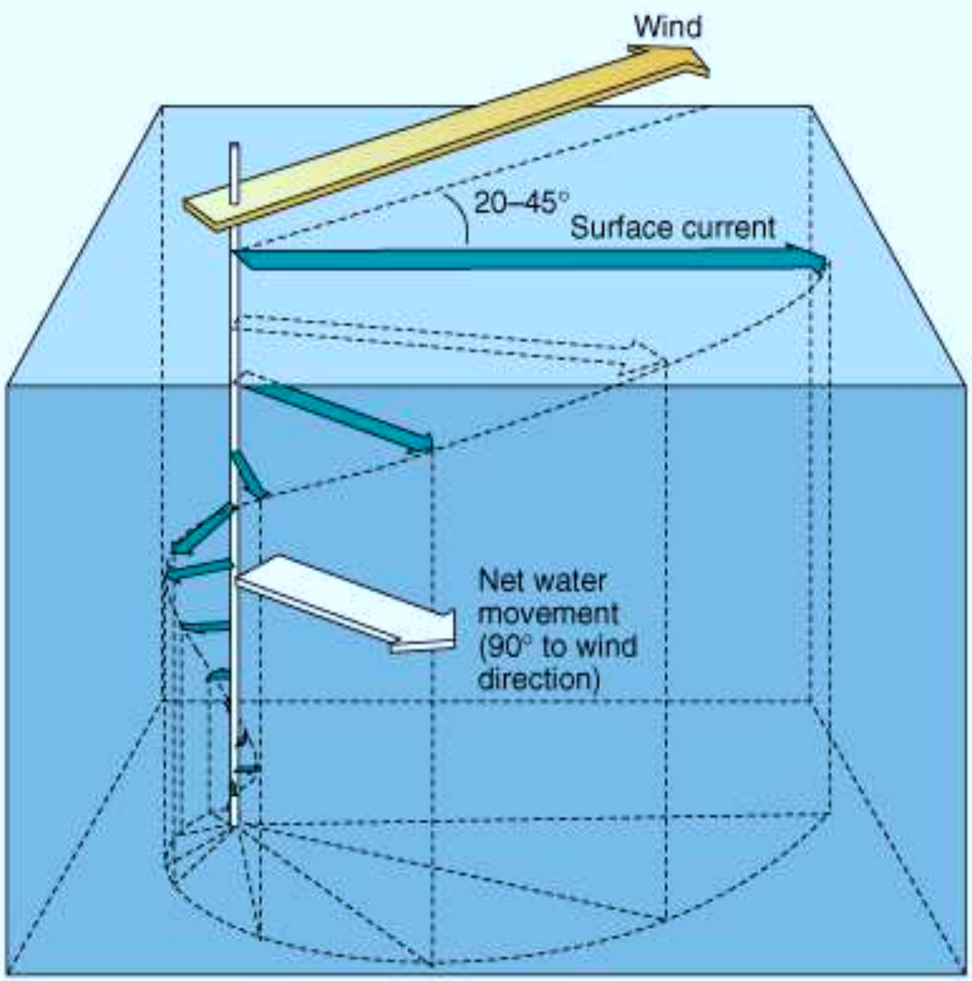
Midlatitude westerlies aloft



Ferrel Cell

Hadley Cell

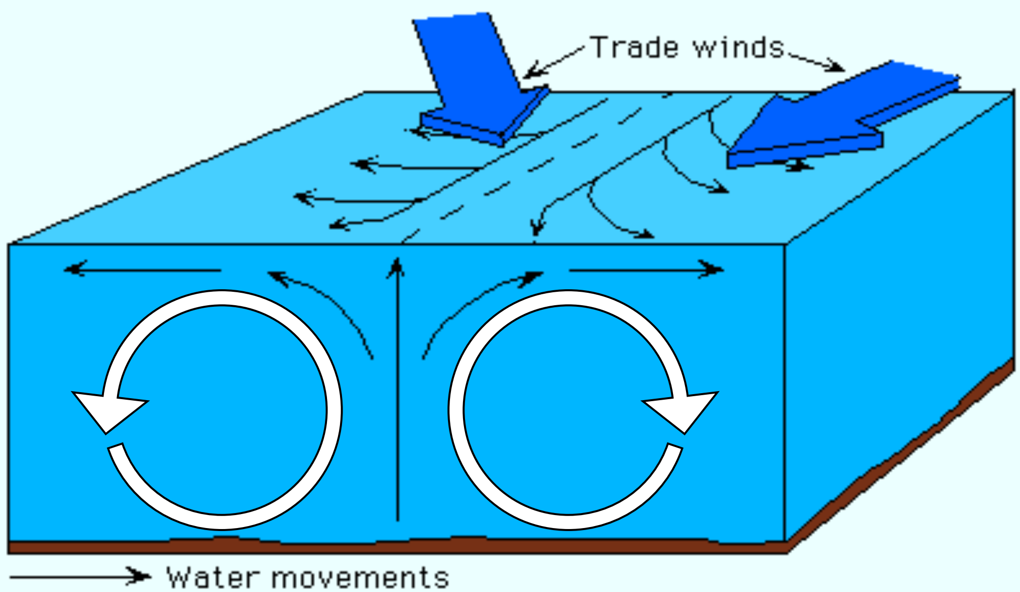
Ekman drift (in the NH)



- **Wind drags surface and friction drags layers beneath**
- **Deflected to the right by Coriolis Force**
- **Results in spiraling pattern**
- **Net transport of water to the right of the wind.**

Nansen's student Ekman solved this after Nansen saw icebergs moving at right angles to the wind

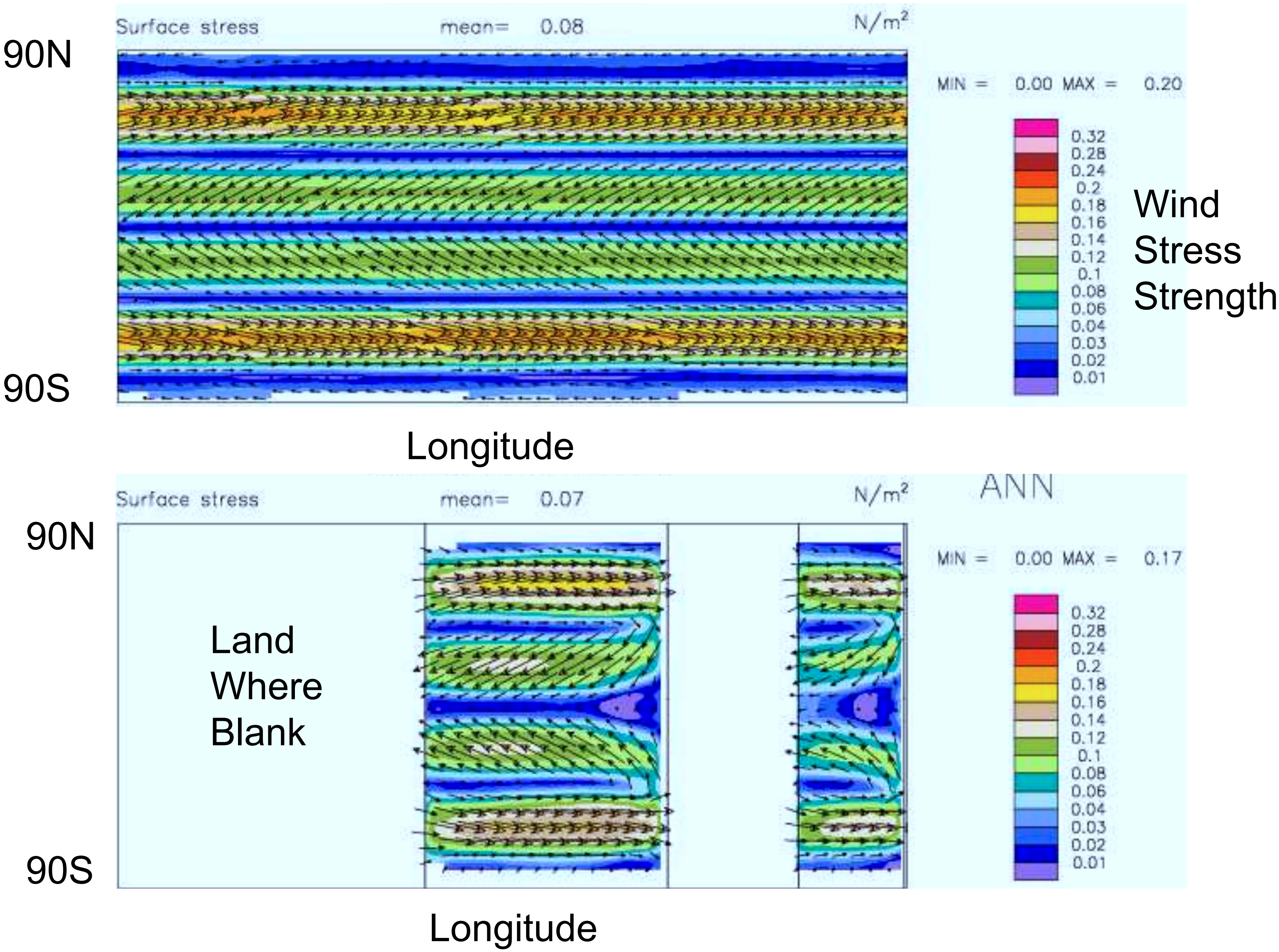
Equatorial Upwelling

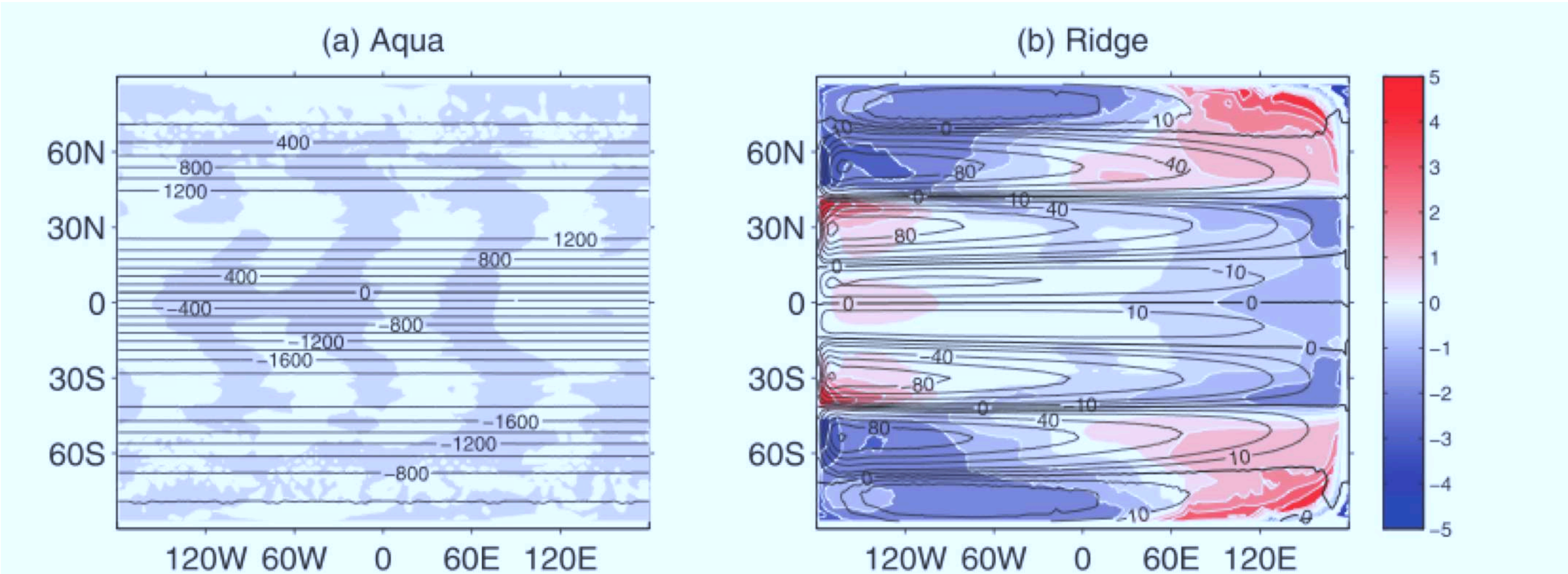


Adapted from Thurman, Harold V. (1997) **Introductory Oceanography, 8/E.** Prentice-Hall, Inc., New Jersey.

- Trade winds blow surface toward the west
- Ekman flow transports water poleward in both hemispheres
- Upwelling cold water fills gap
- Causes a meridional circulation that moves heat poleward, "Eulerian mean"

Wind variations cause gyres provided there is land





Sverdrupian gyre circulation on right only

Enderton and Marshall, 2009
Figure 9

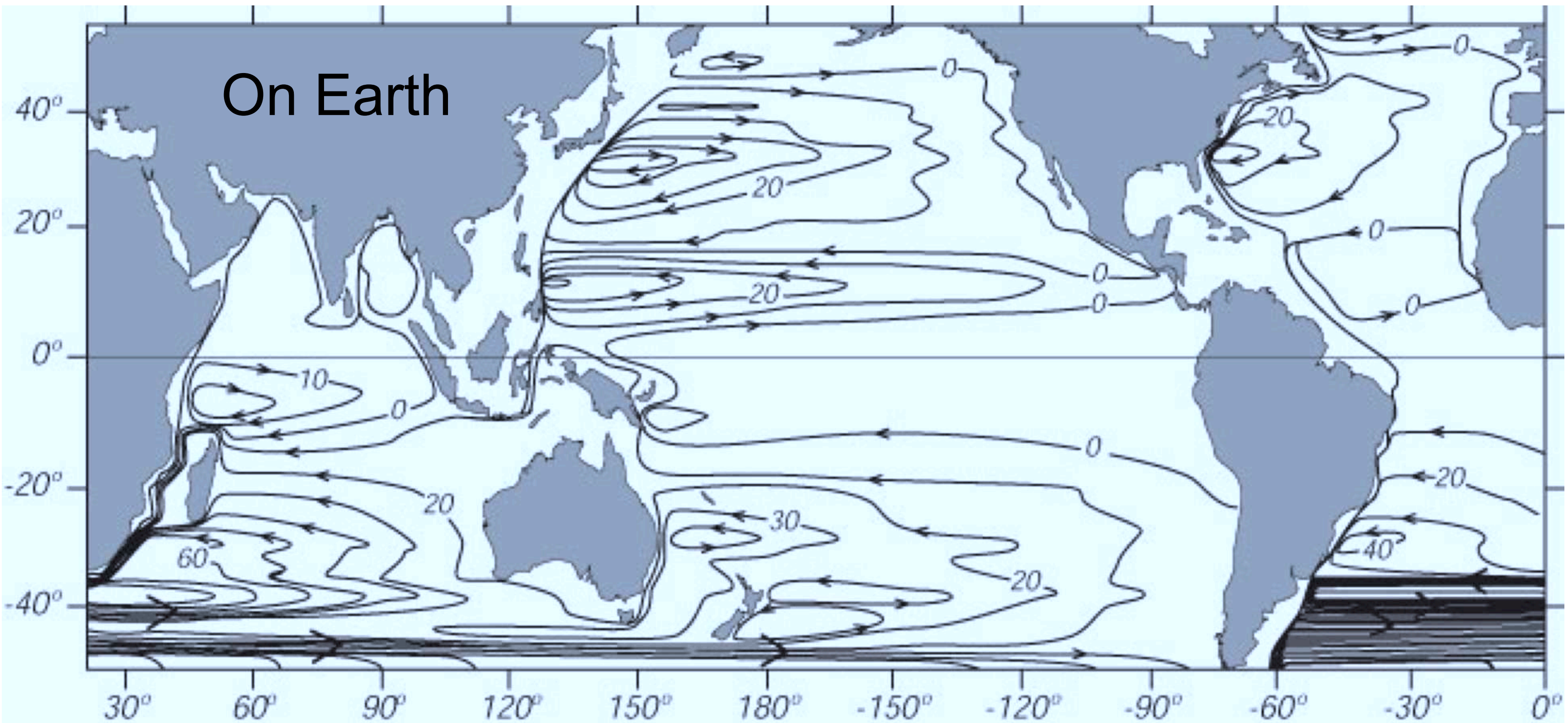
Sverdrup Balance

$$M_y \approx -\frac{1}{\beta}\frac{\partial T_x}{\partial y}$$

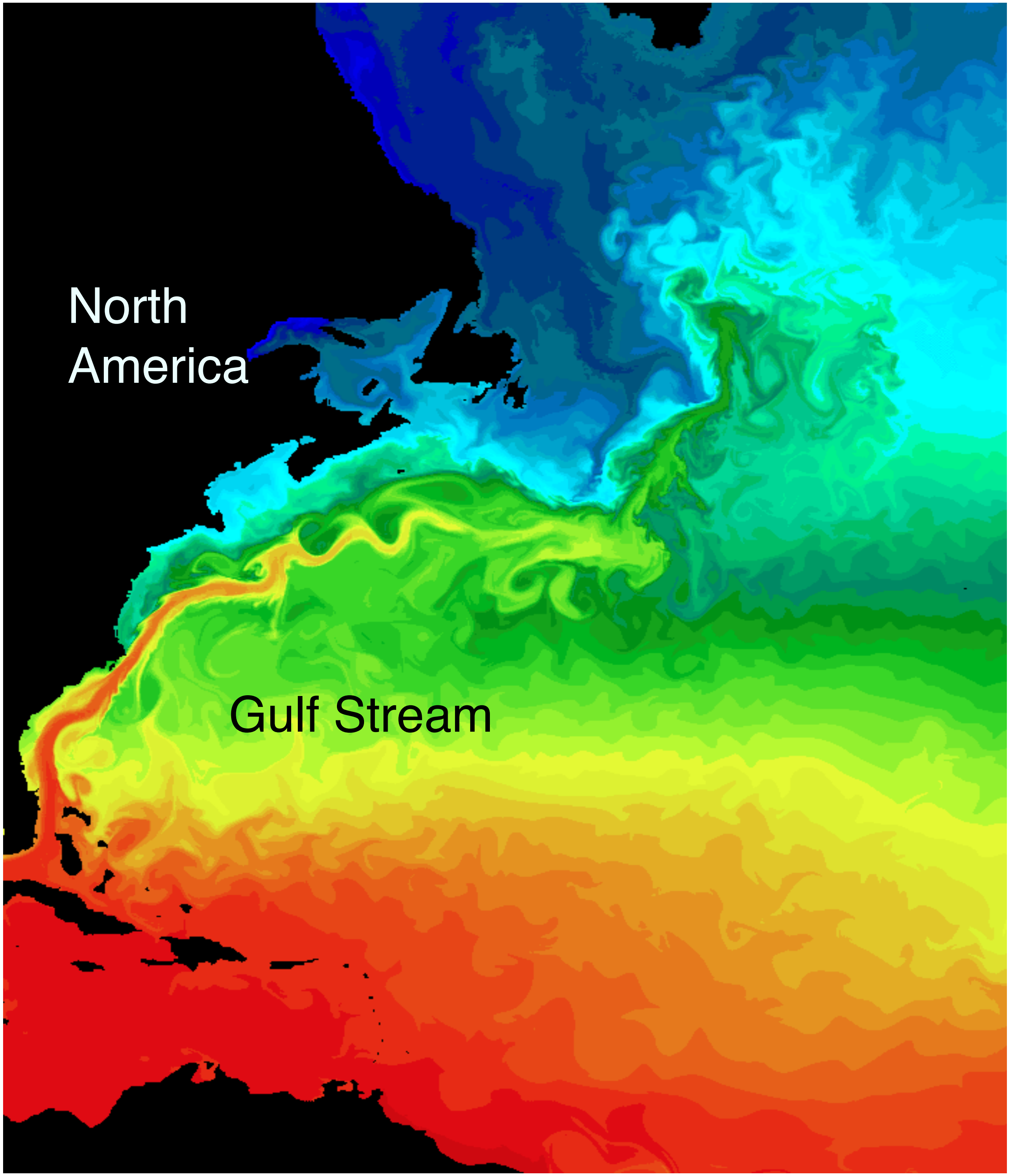
$$\frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y} = 0$$

M = vertically integrated mass transport
T = wind stress
β = ∂f/∂y is the rate of change of Coriolis parameter with latitude
recall x=east, y=north

Requires Boundary Condition M_x = *0 at eastern boundary*



http://oceanworld.tamu.edu/resources/ocng_textbook/chapter11/chapter11_01.htm

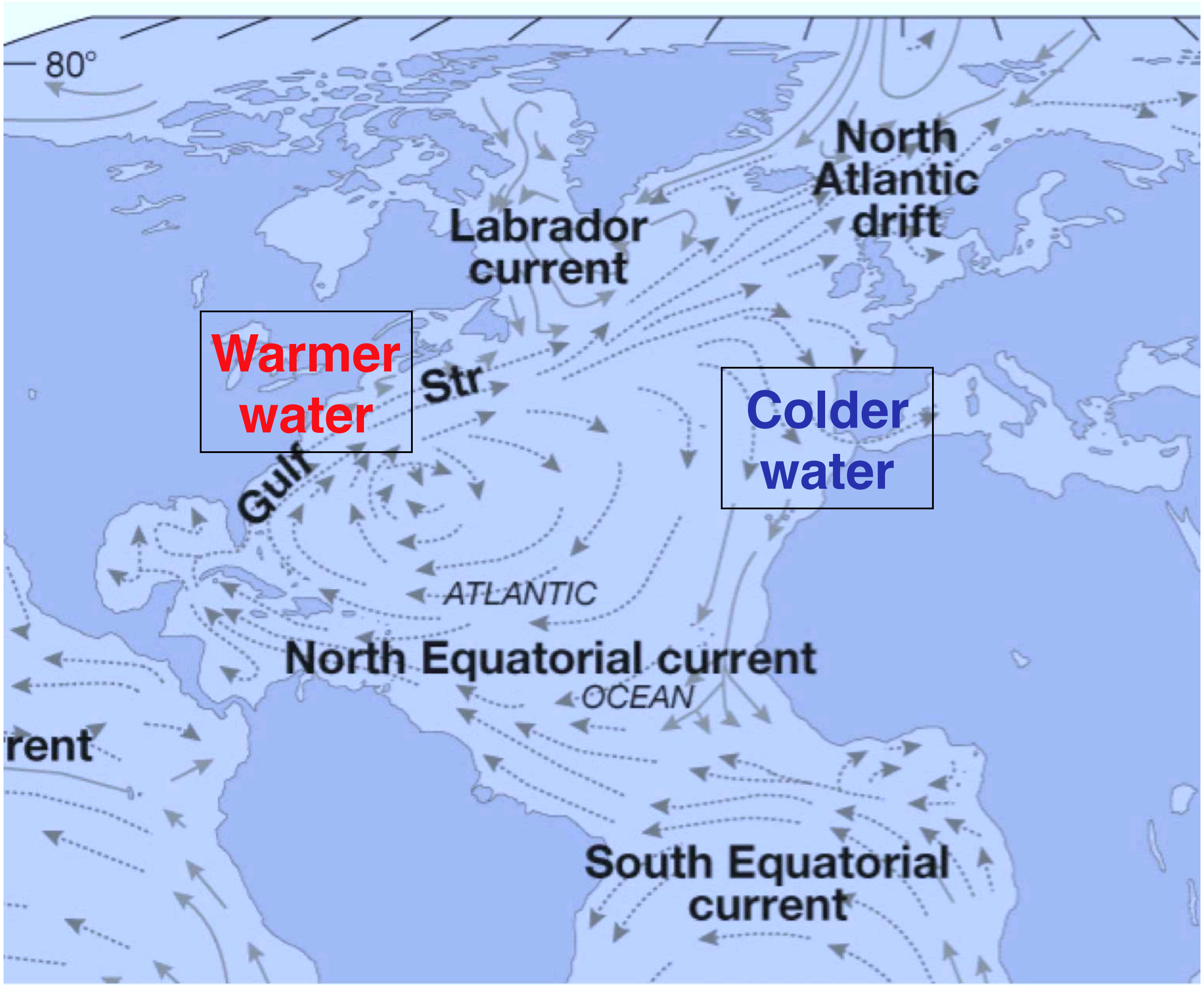


Gyres transport heat

Colors show Temperature

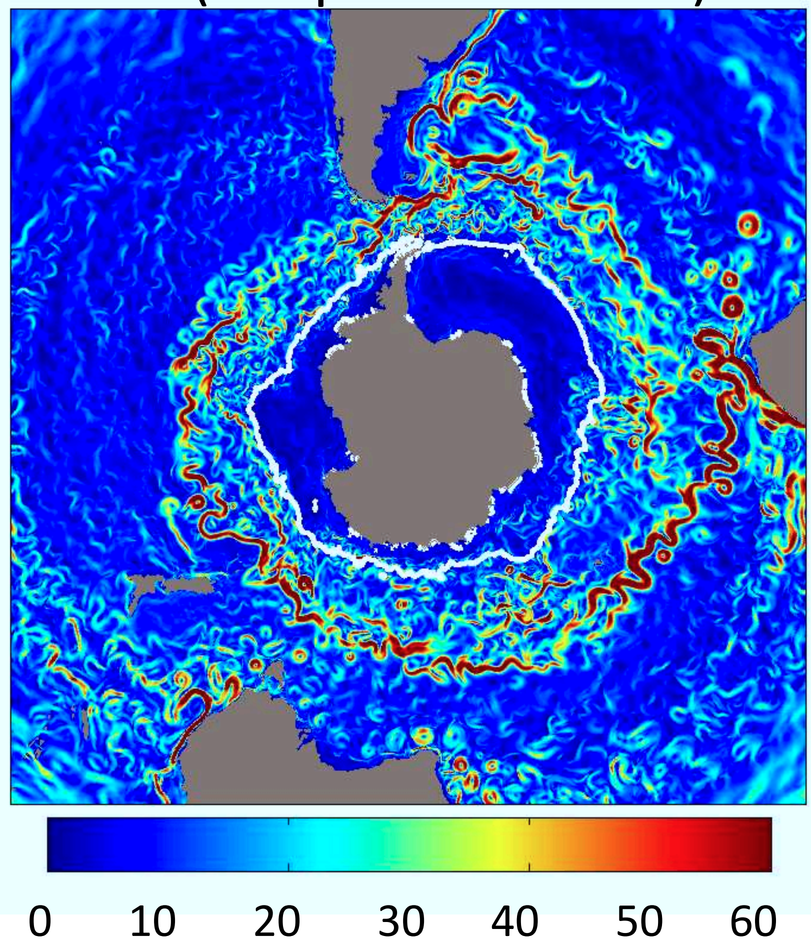
AVHRR satellite

Gyres move heat and also cause meridional flow (Sverdrup Balance)



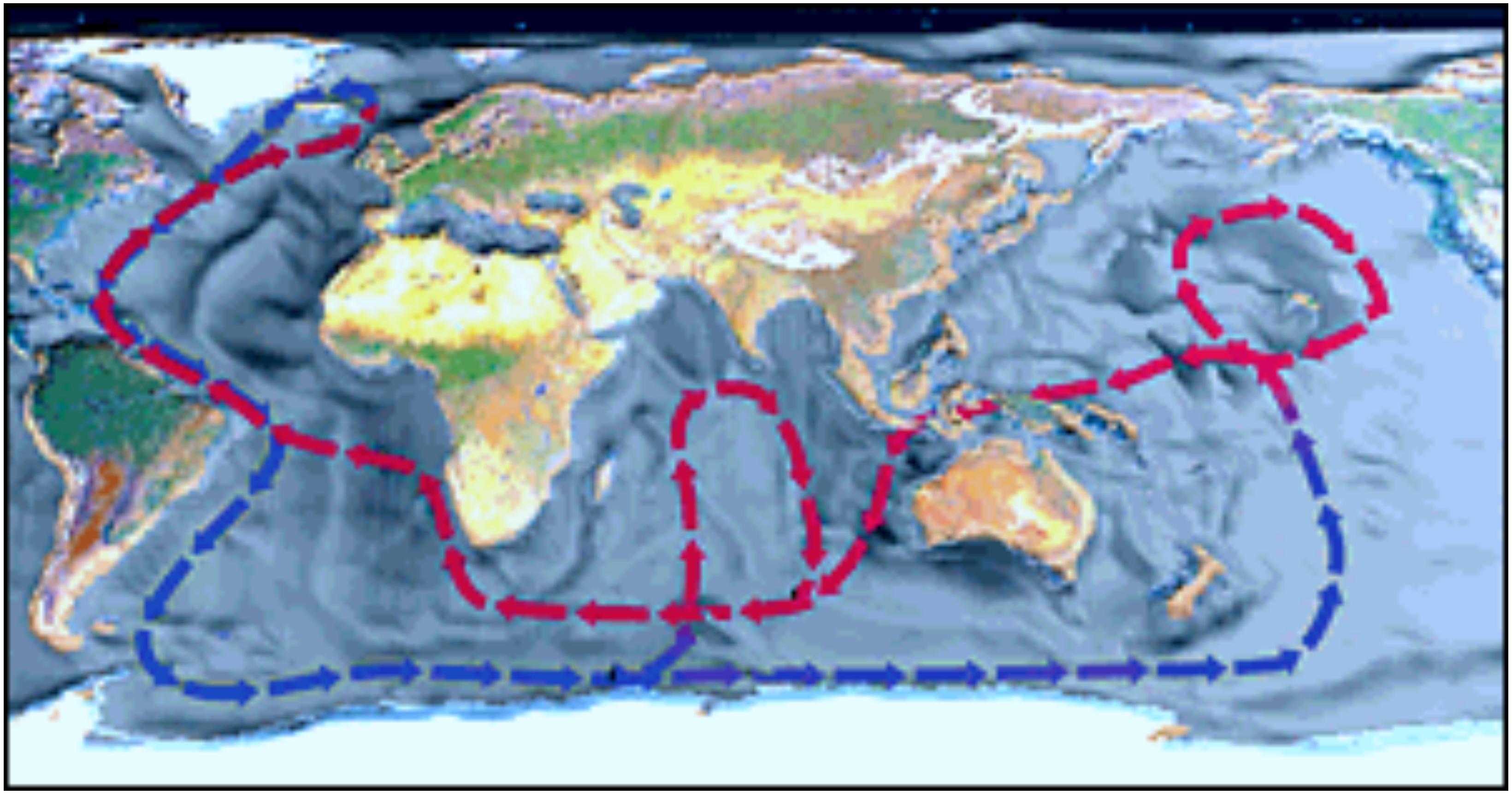
Eddies move heat
like mini-gyres

0.1° Simulation
resolved (not parameterized) eddies



Current Speed in cm/s for randomly chosen October

Mean Meridional Circulation also moves heat



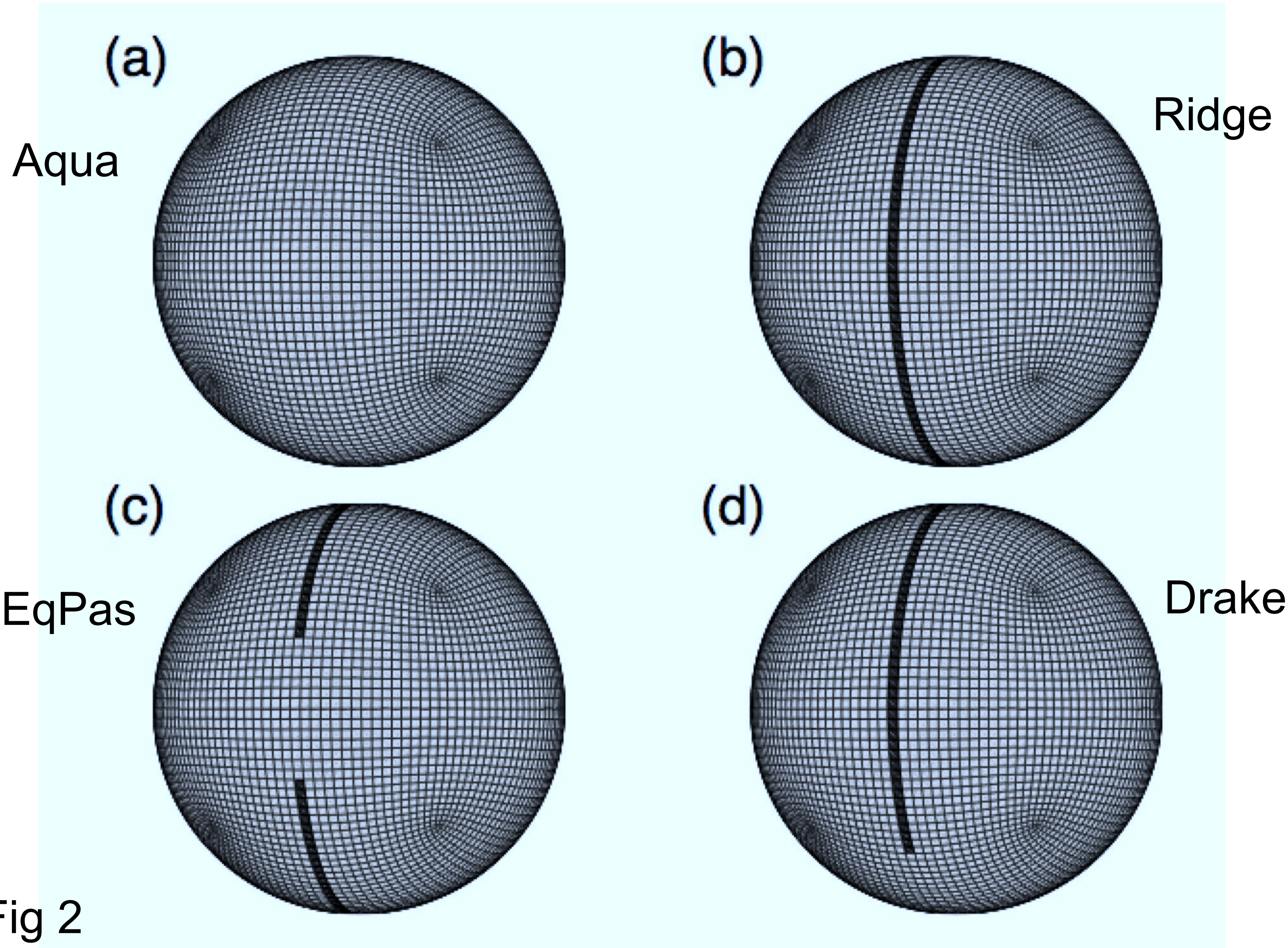


Fig 2

θ - Potential Temperature

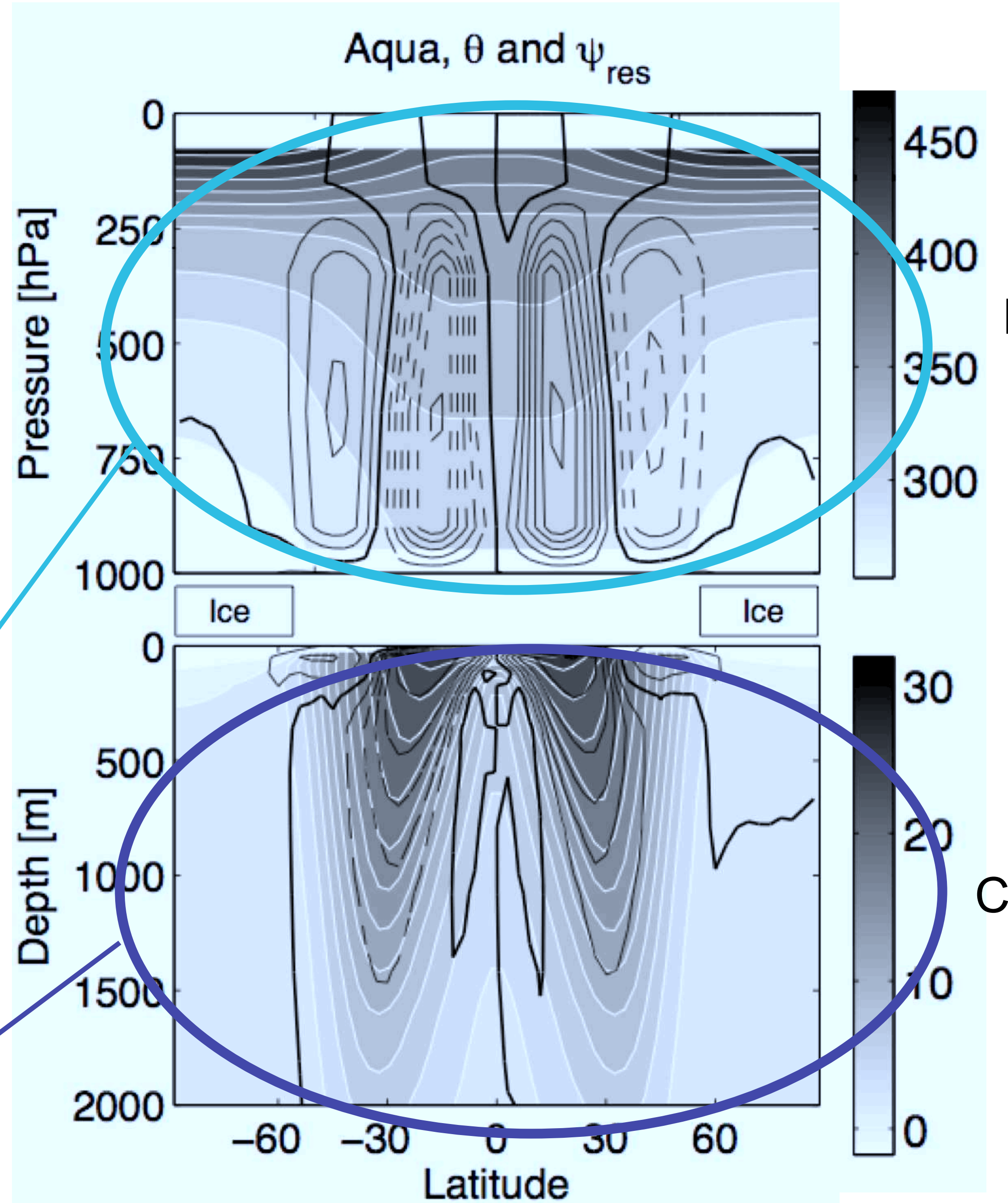
(shaded) temperature if air sinks adiabatically to surface, stratosphere has large θ and is very stable

Ψ_{res}- streamfunction (lines)

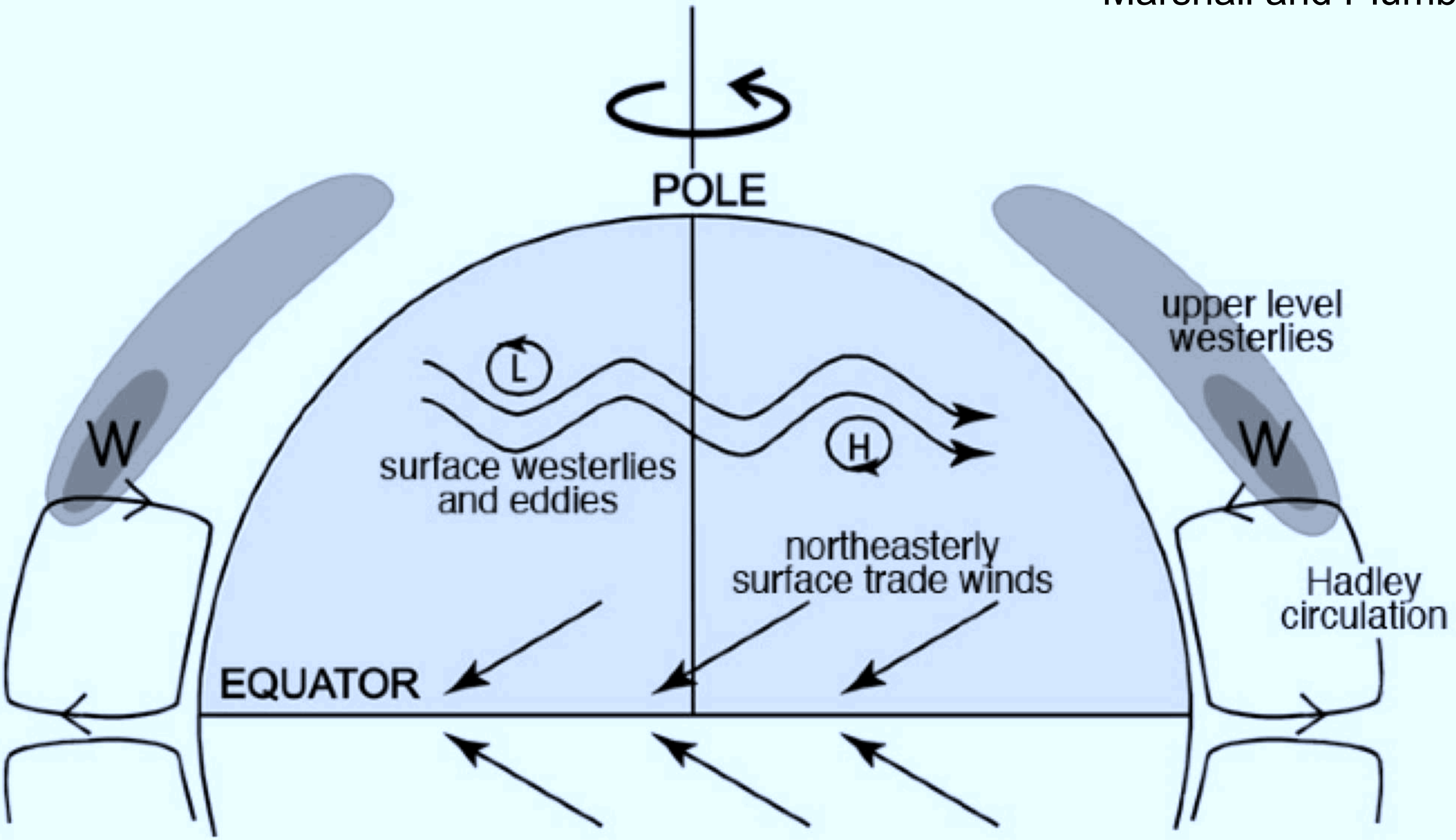
denotes circulation

Atmosphere is in thermal wind balance, has Hadley and Ferrel Cells, strong midlatitude grad θ and jets, etc

Ocean has sinking in the high latitudes and upwelling in the tropics. Little circulation under sea ice.

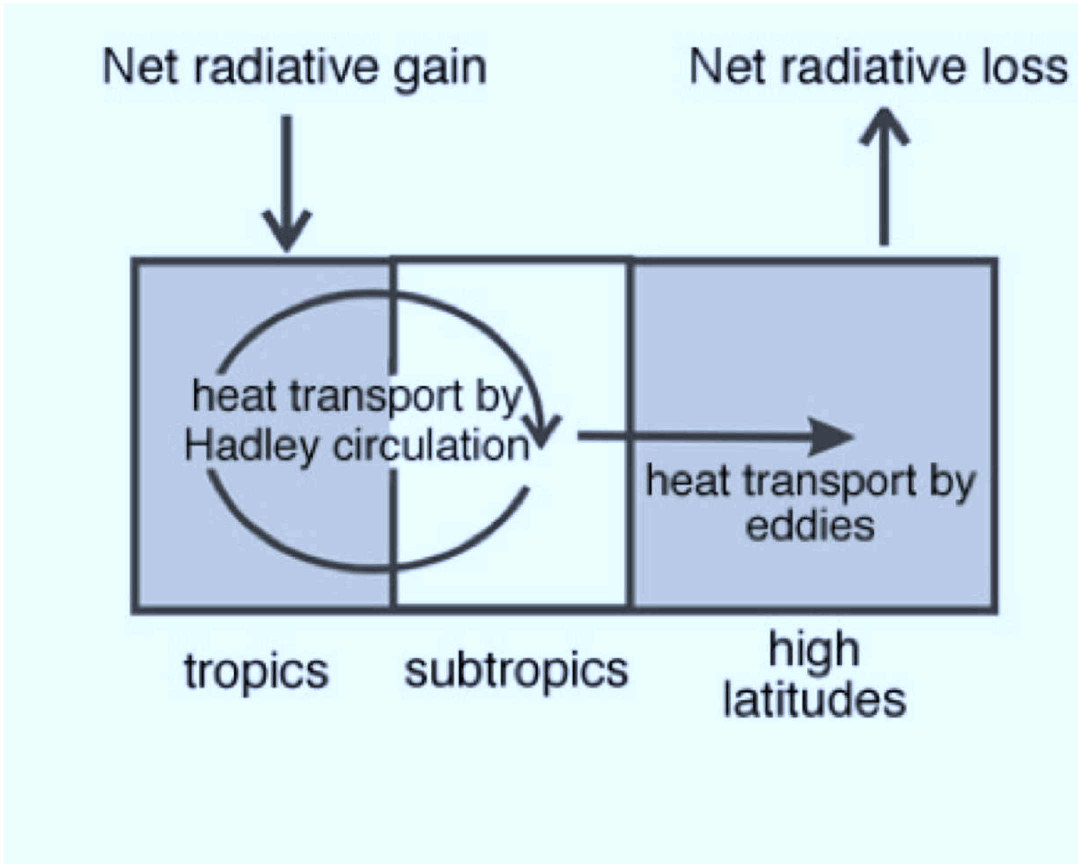


Marshall and Plumb

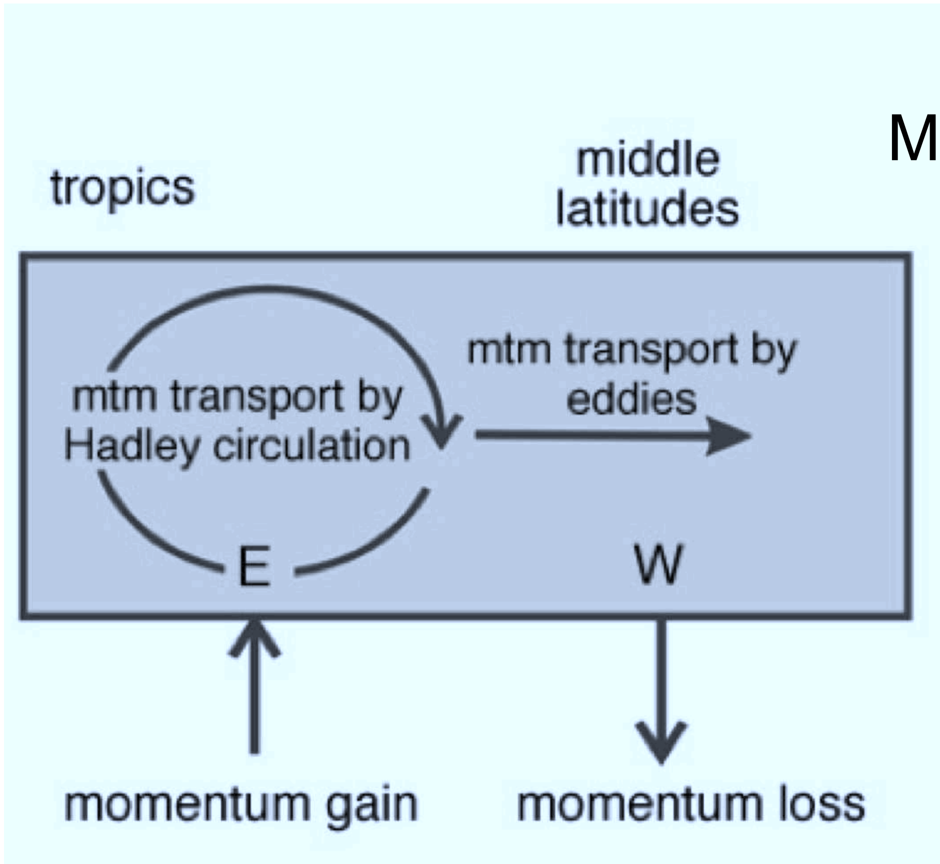


Ferrel cell in mid latitude (opposite sense of Hadley circ), results from momentum and heat budgets driven by eddies… see favorite meteorology text

Marshall and Plumb



Weaker eddies also has implications for momentum transport



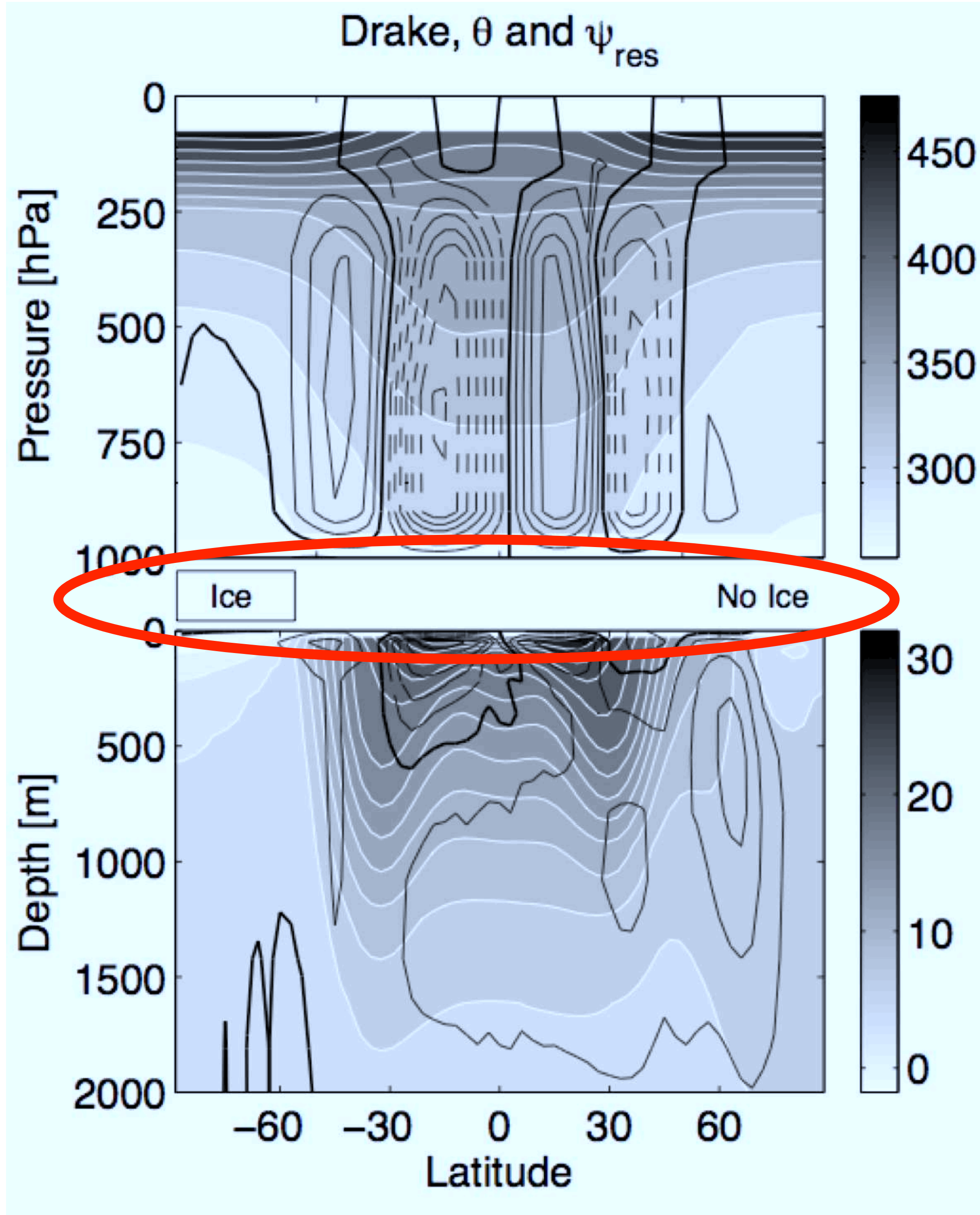
Marshall and Plumb

where winds are easterly

where winds are westerly

Wave dispersion causes shape of eddies to be non-circular
in the horizontal such that they transport westerly momentum towards the pole, thus requiring easterlies in the tropics

Aqua had ice at both poles, but Drake only has ice at Drake passage pole



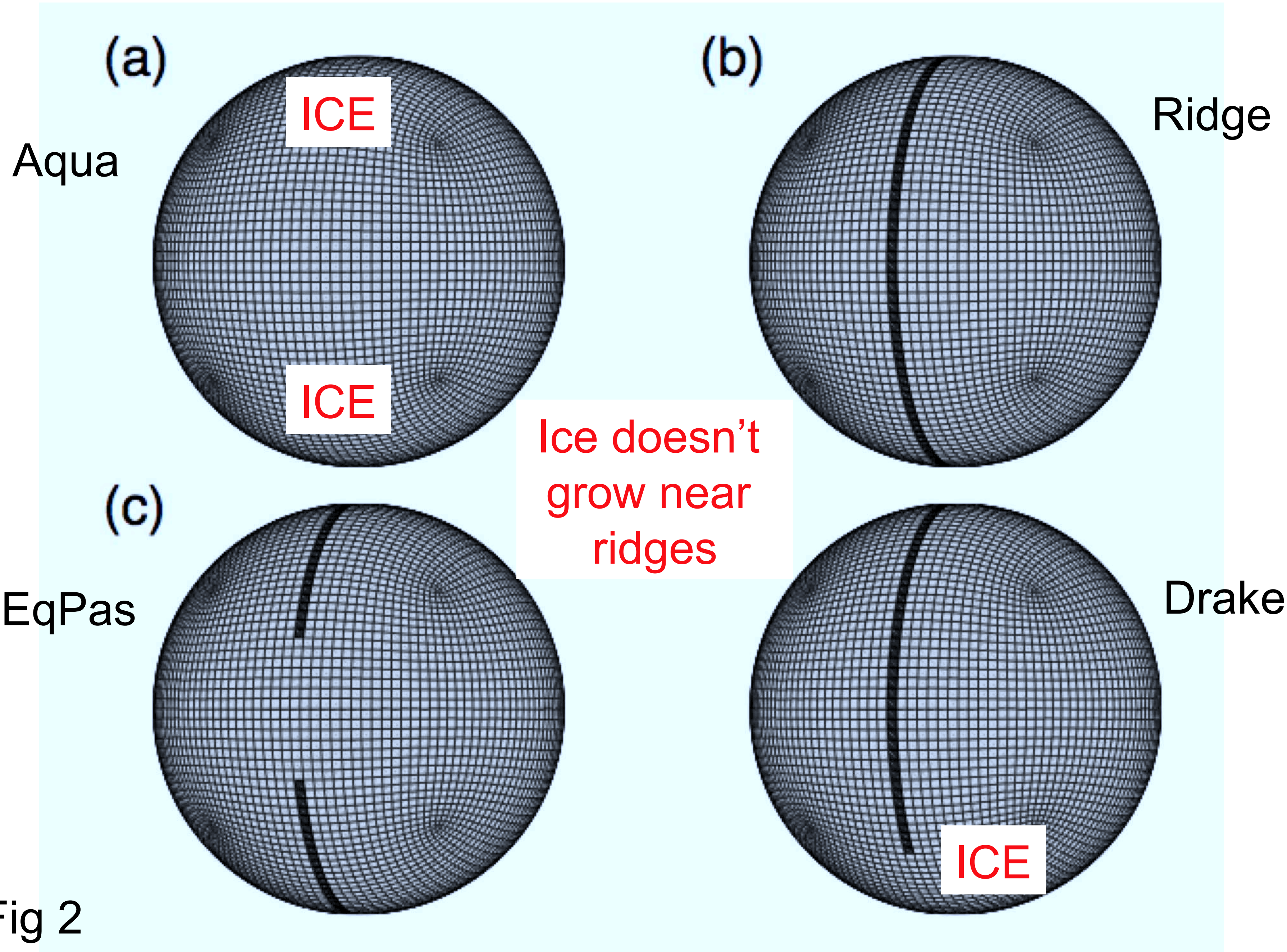

(a)
Aqua
ICE
ICE
(b)
Ridge
(c)
EqPas
Ice doesn't grow near ridges
Drake
ICE

Fig 2

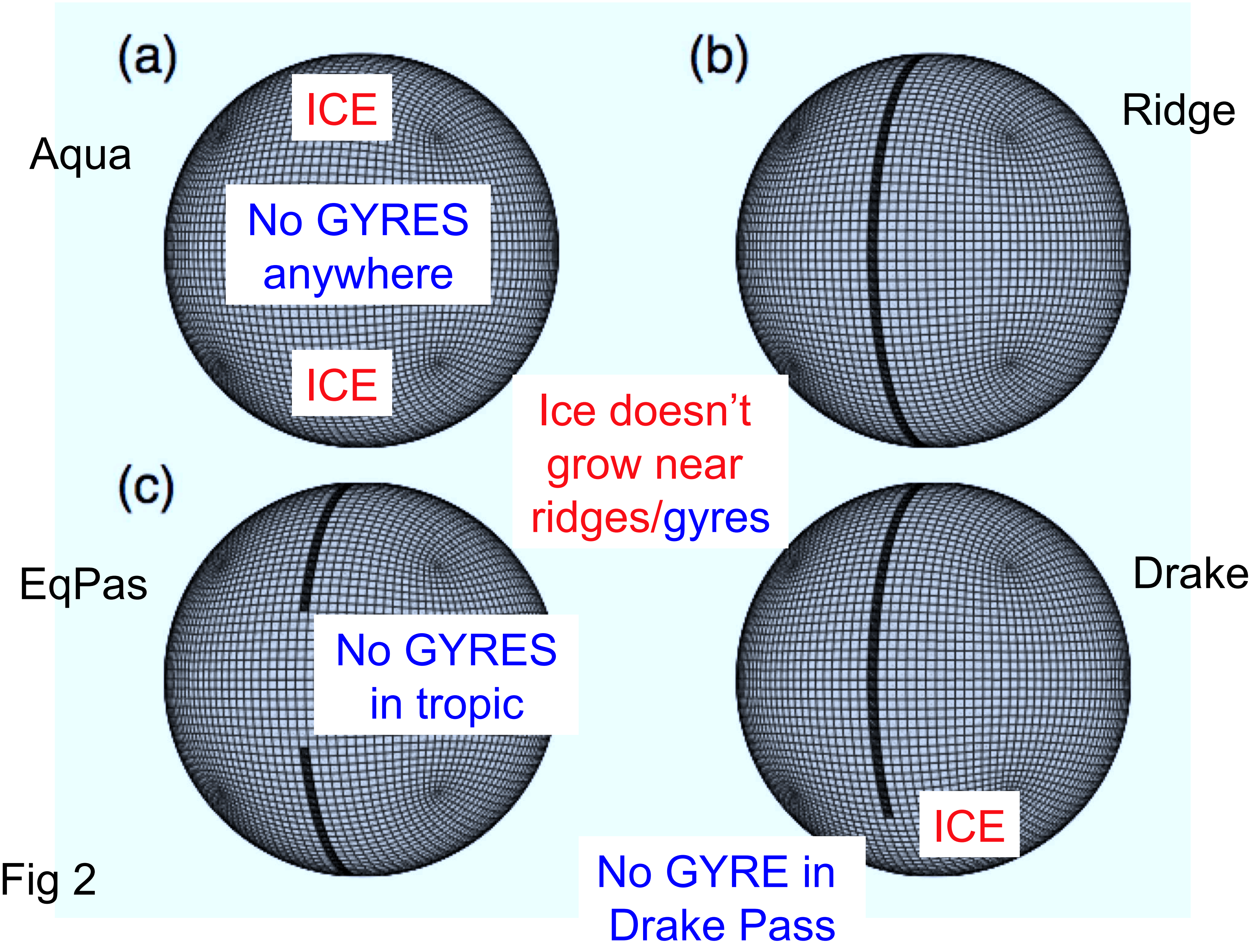
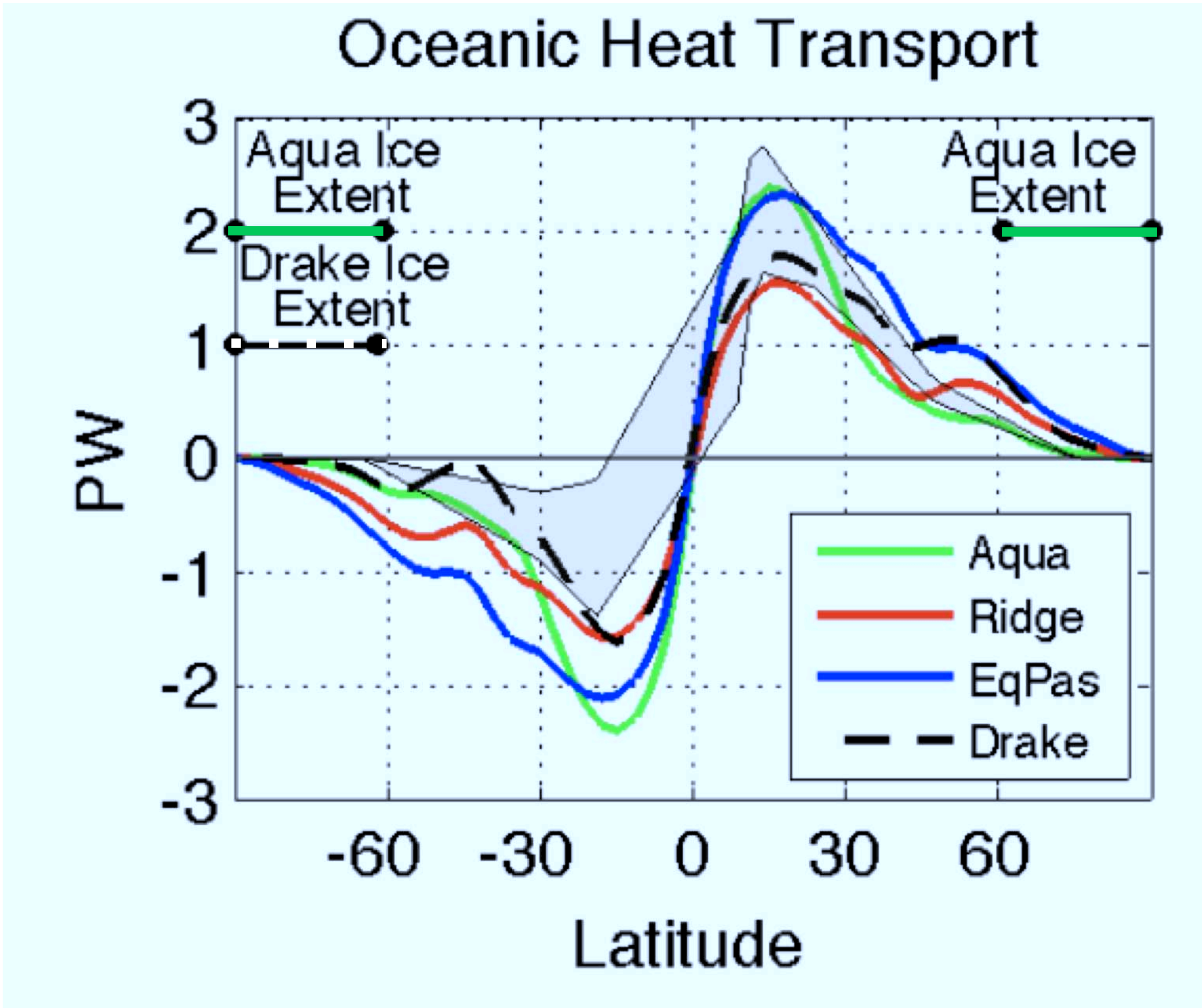
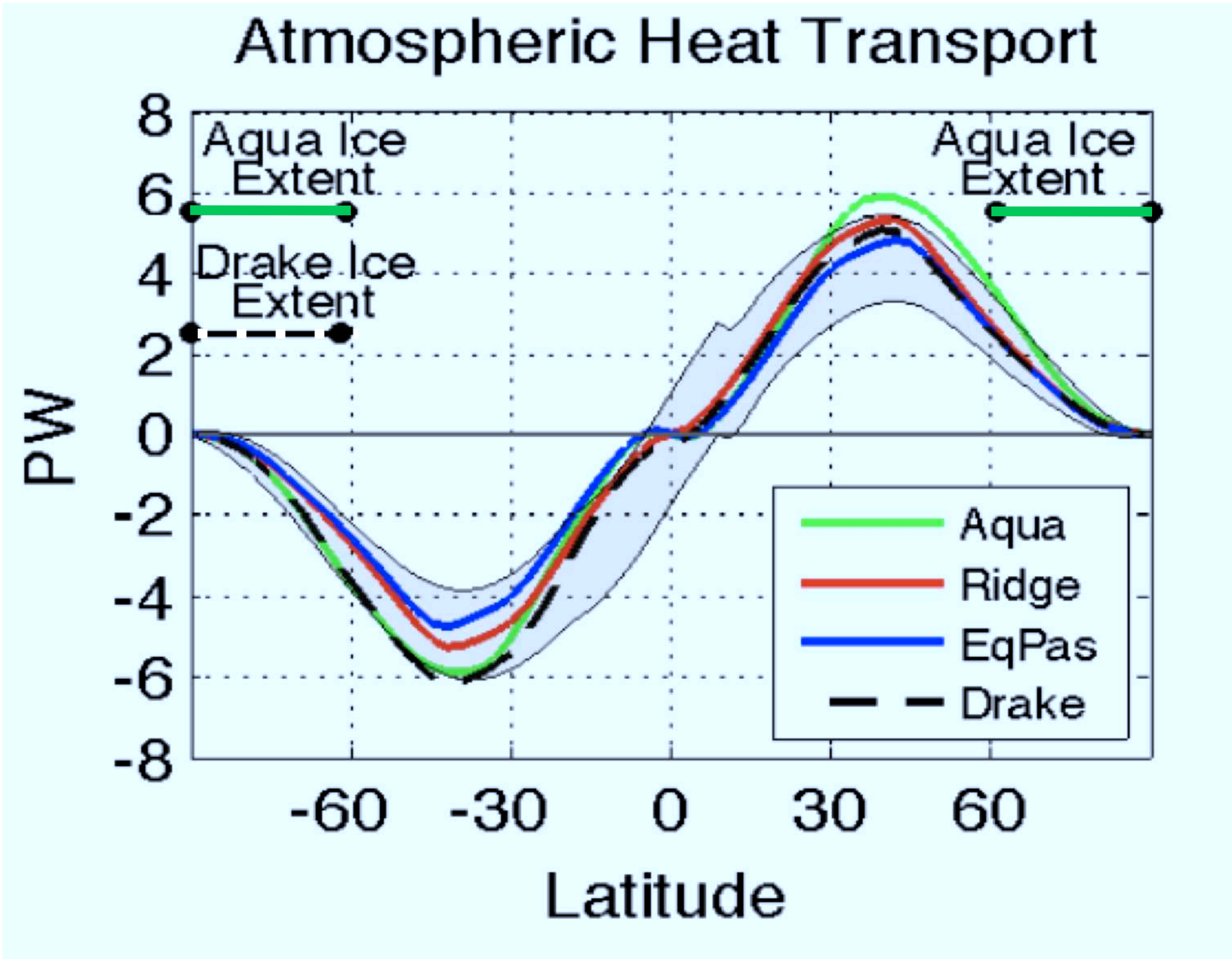

(a)
Aqua
ICE
No GYRES anywhere
ICE
(b)
Ridge
Ice doesn't grow near ridges/gyres
(c)
EqPas
No GYRES in tropic
Drake
ICE
No GYRE in Drake Pass

Fig 2

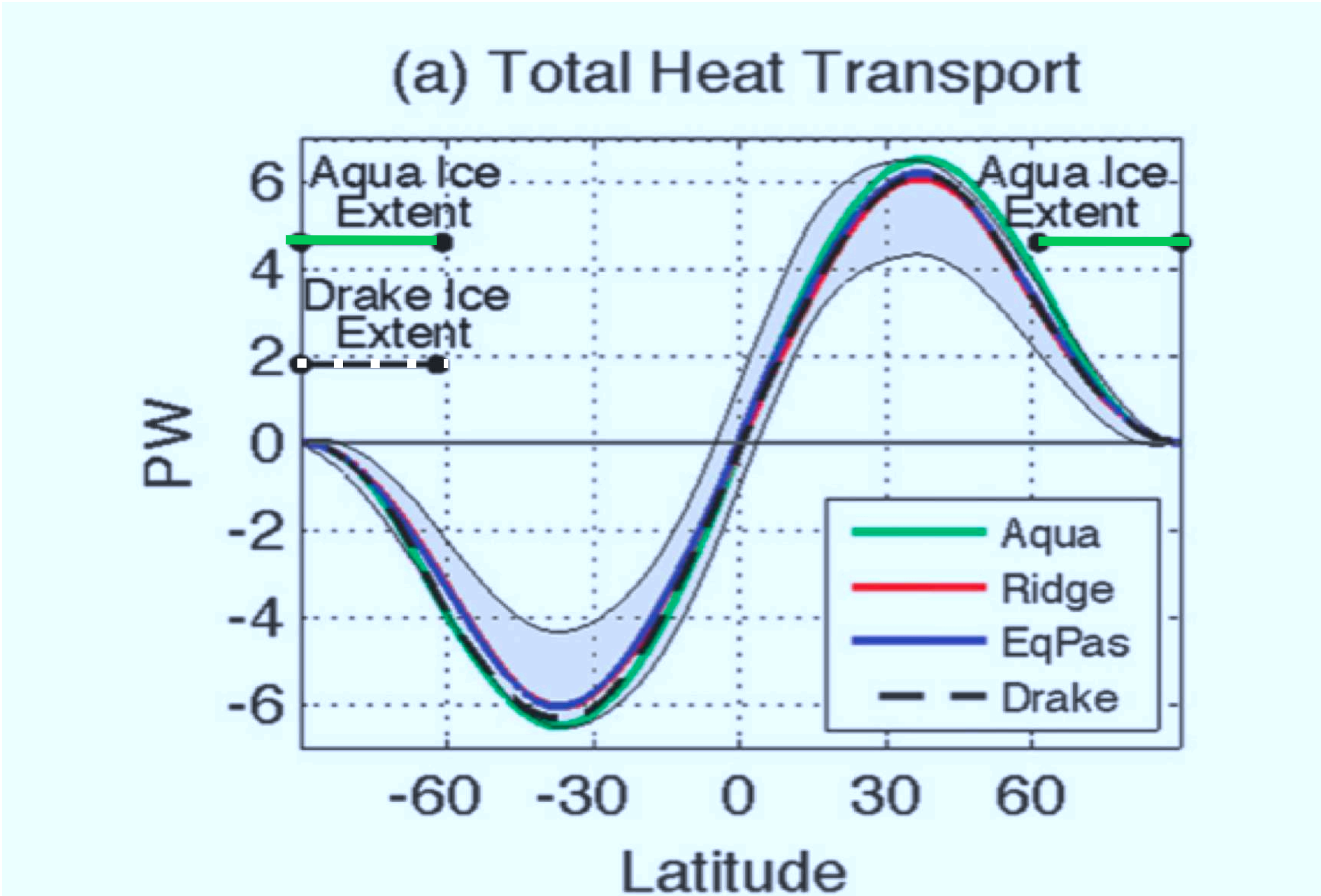
Without gyres, ocean heat transport at 60 N/S is inadequate to prevent ice

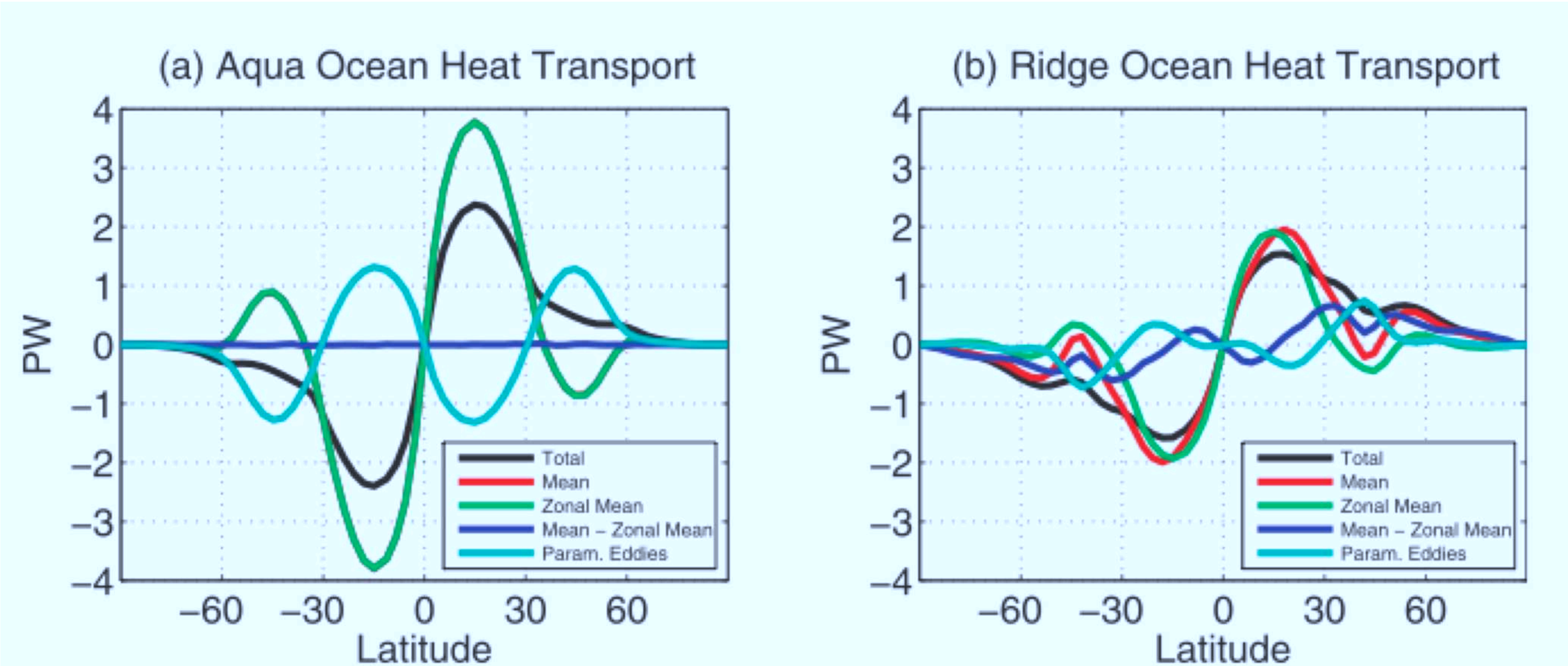


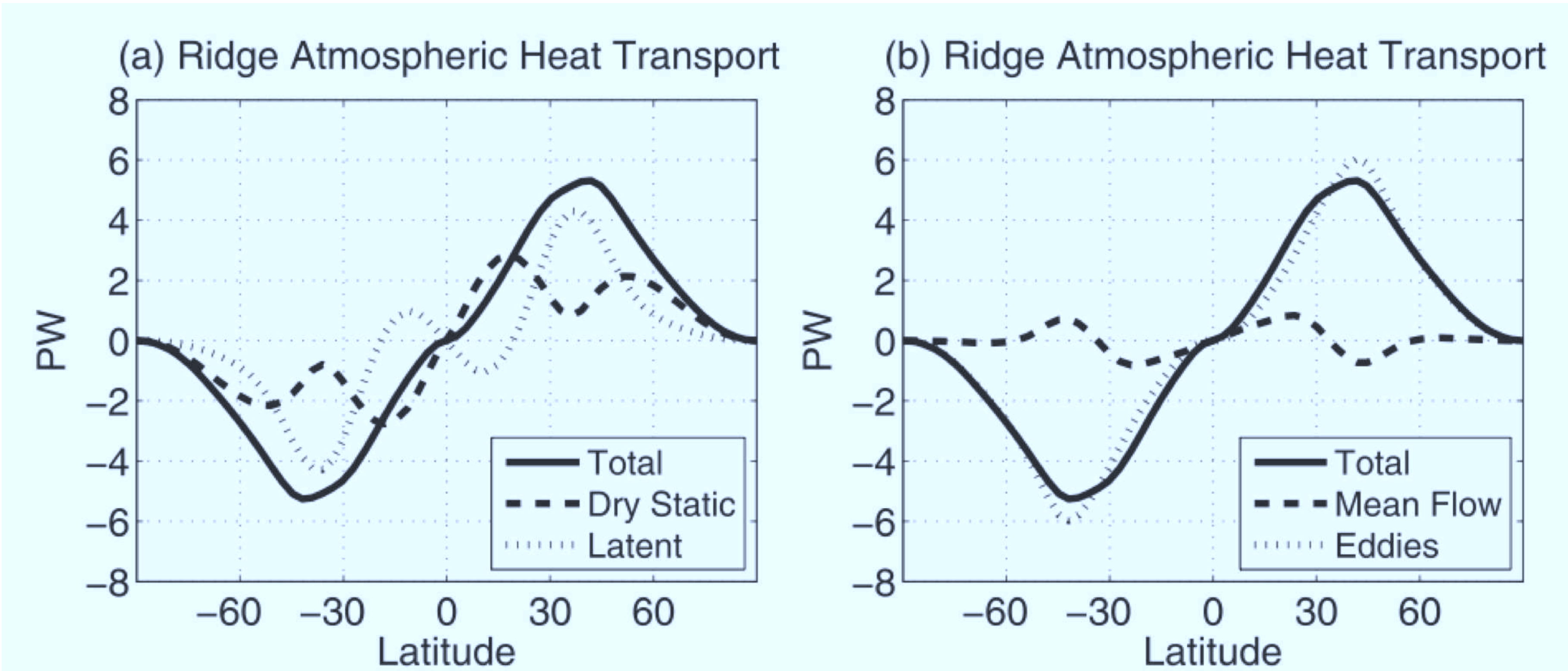
But atmospheric heat transport at 60 N/S over compensates



Ocean Heat Transport varies by X2 but total varies little




(a) Aqua Ocean Heat Transport
PW
Latitude
Total
Mean
Zonal Mean
Mean – Zonal Mean
Param. Eddies
(b) Ridge Ocean Heat Transport
PW
Latitude
Total
Mean
Zonal Mean
Mean – Zonal Mean
Param. Eddies



(a) Ridge Atmospheric Heat Transport
PW
8
6
4
2
0
−2
−4
−6
−8
−60
−30
0
30
60
Latitude
Total
Dry Static
Latent
(b) Ridge Atmospheric Heat Transport
PW
8
6
4
2
0
−2
−4
−6
−8
−60
−30
0
30
60
Latitude
Total
Mean Flow
Eddies

The rest of the paper is about why the total heat transport is slightly larger when the poles are icy.

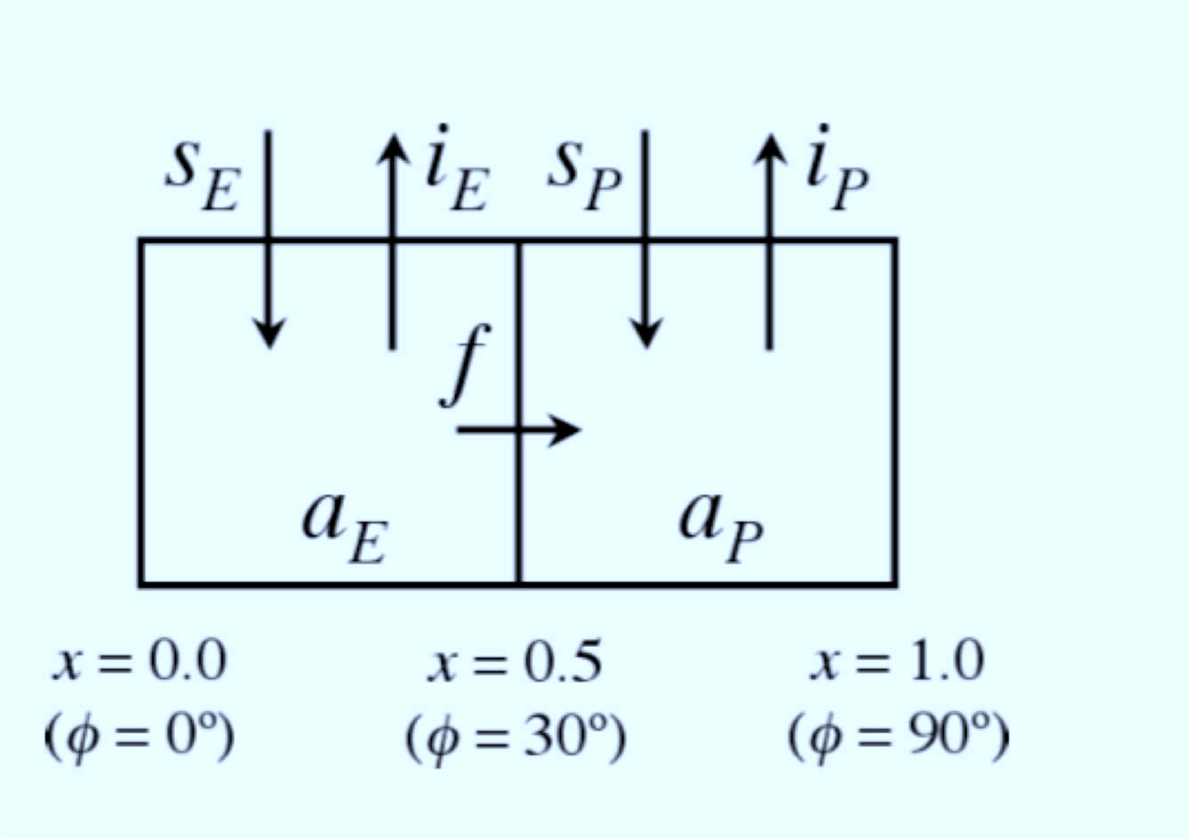
Never says why circulation details affect ice!!!

$$\frac{dH_T}{d\phi} = 2\pi R^2 \cos\phi [S(\phi)a(\phi) - I(\phi)]$$

total heat transport change with latitude	=	Absorbed solar	-	Outgoing longwave

Circulations are wildly different but analysis is only in terms of top of atmosphere energy balance!

2-Box model of one hemisphere



Fluxes are divided by total incoming solar

s = absorbed solar

i = outgoing longwave radiation

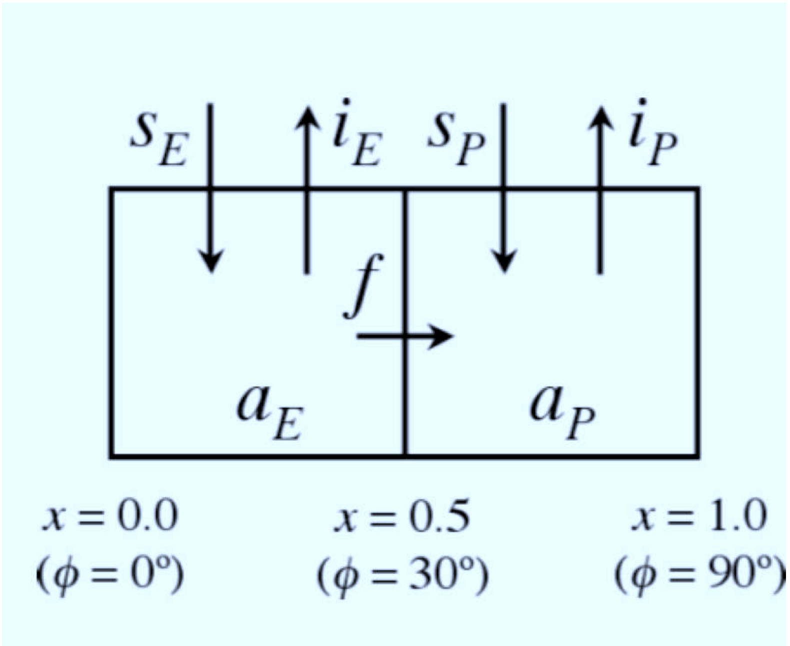
f = transport at 30 deg

a = co-albedo = 1-albedo

x = sin ϕ

Hemispheric energy balance requires the mean absorbed solar must equal mean OLR

$\overline{s\,a} = \overline{i}$ (bar means box avg)



$$\Delta s = \overline{s_P} - \overline{s_E}$$

$$\Delta a = \overline{a_P} - \overline{a_E}$$

$$\Delta i = \overline{i_P} - \overline{i_E}.$$

Hemispheric energy balance also requires

$$f = -\left(\Delta s \overline{a} + \overline{s} \Delta a + \frac{1}{2} \Delta s \Delta a - \Delta i\right) \frac{\Delta x}{2}$$

After some algebra recognizing strong cancelation between solar absorption and outgoing longwave …

	$-\Delta s\bar{a}$	$-\bar{s}\Delta a$	$-\frac{1}{2}\Delta s\Delta a$	$+\Delta i$	*Sum*	Two-box model H_T at 30° (PW)	Coupled model H_T at 30° (PW)
Aqua NH	0.240	0.086	-0.016	-0.021	0.289	6.30	6.25
Ridge NH	0.249	0.023	-0.004	0.002	0.270	5.88	5.81
Drake NH	0.250	0.024	-0.004	0.007	0.277	6.03	5.86
Drake SH	0.239	0.087	-0.016	-0.026	0.285	6.21	6.11

Biggest term is from differential heating by sun

But Δs and s are same for all cases - hence H_T differences are due primarily to co-albedo mean and pole-to-equator difference