Forcing of the Ocean: tides, winds, heat and freshwater

Tides

- Result from the gravitational forces of the moon and the sun
- For the Earth-moon-sun system there is a balance of gravitational forces very close to the center of the Earth.
- At any point on the Earth's surface there is a slight imbalance, giving a tide generating potential.
- The horizontal component of the tide generating potential gives TWO tidal bulges.

Tides

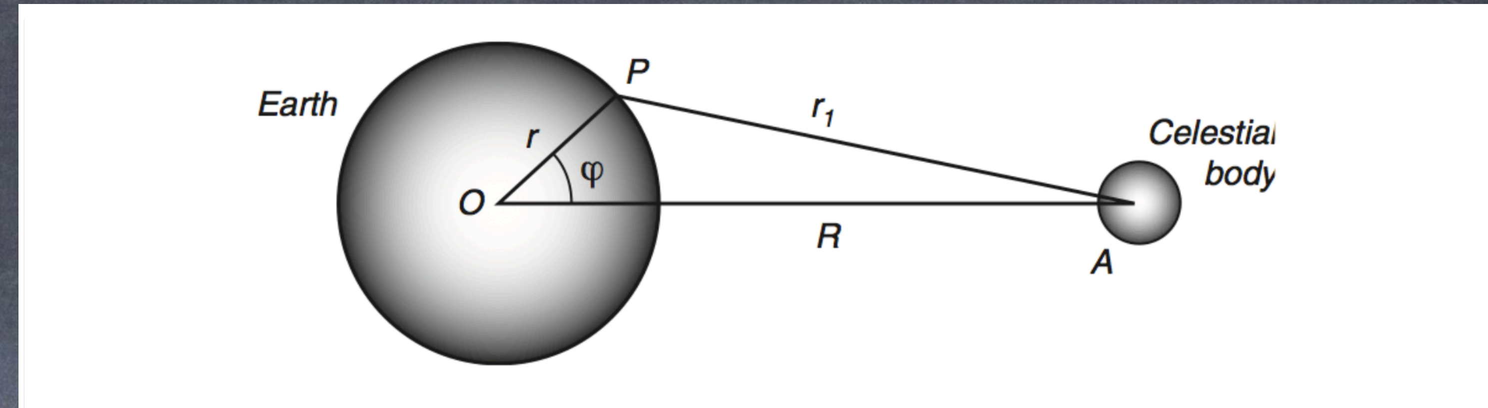
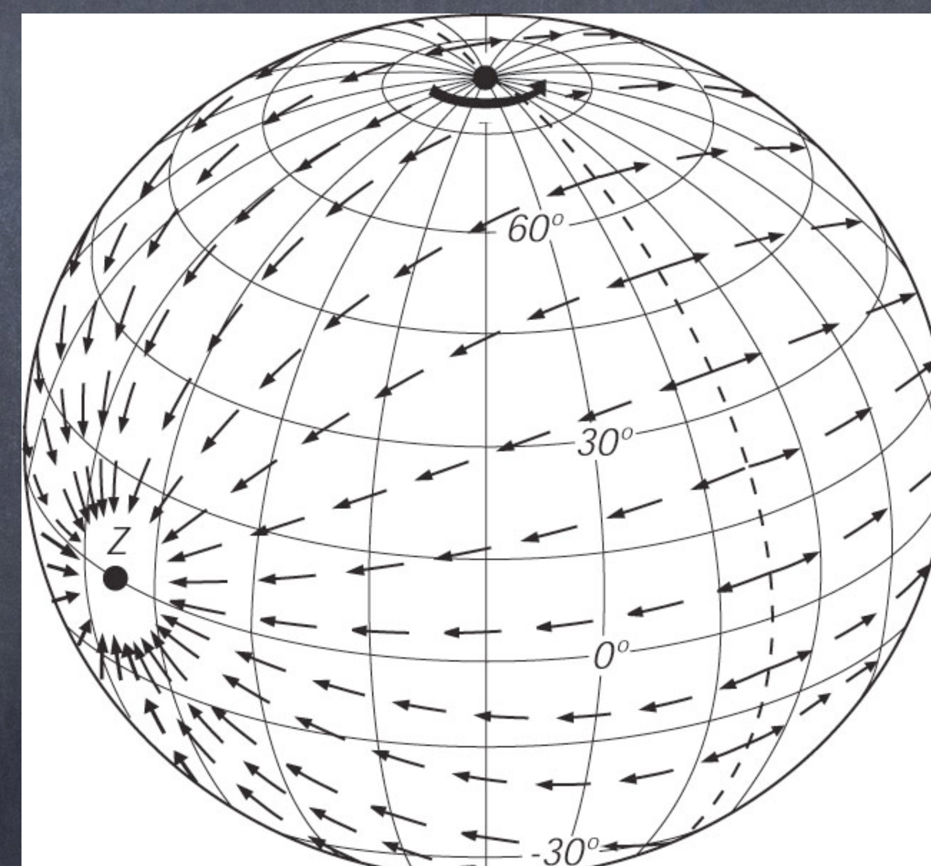


Figure 17.10 Sketch of coordinates for determining the tide-generating potential.

- The gradient of gravitational potential of the Earth-Moon-Sun system gives rise to tides
- There are two tidal bulges at any one time. These regions are planar with the Moon.
- Earth rotates once per day, so there are 2 major tides per day: Semi-diurnal
- Semi-diurnal solar tidal forces are about half that of the Moon.

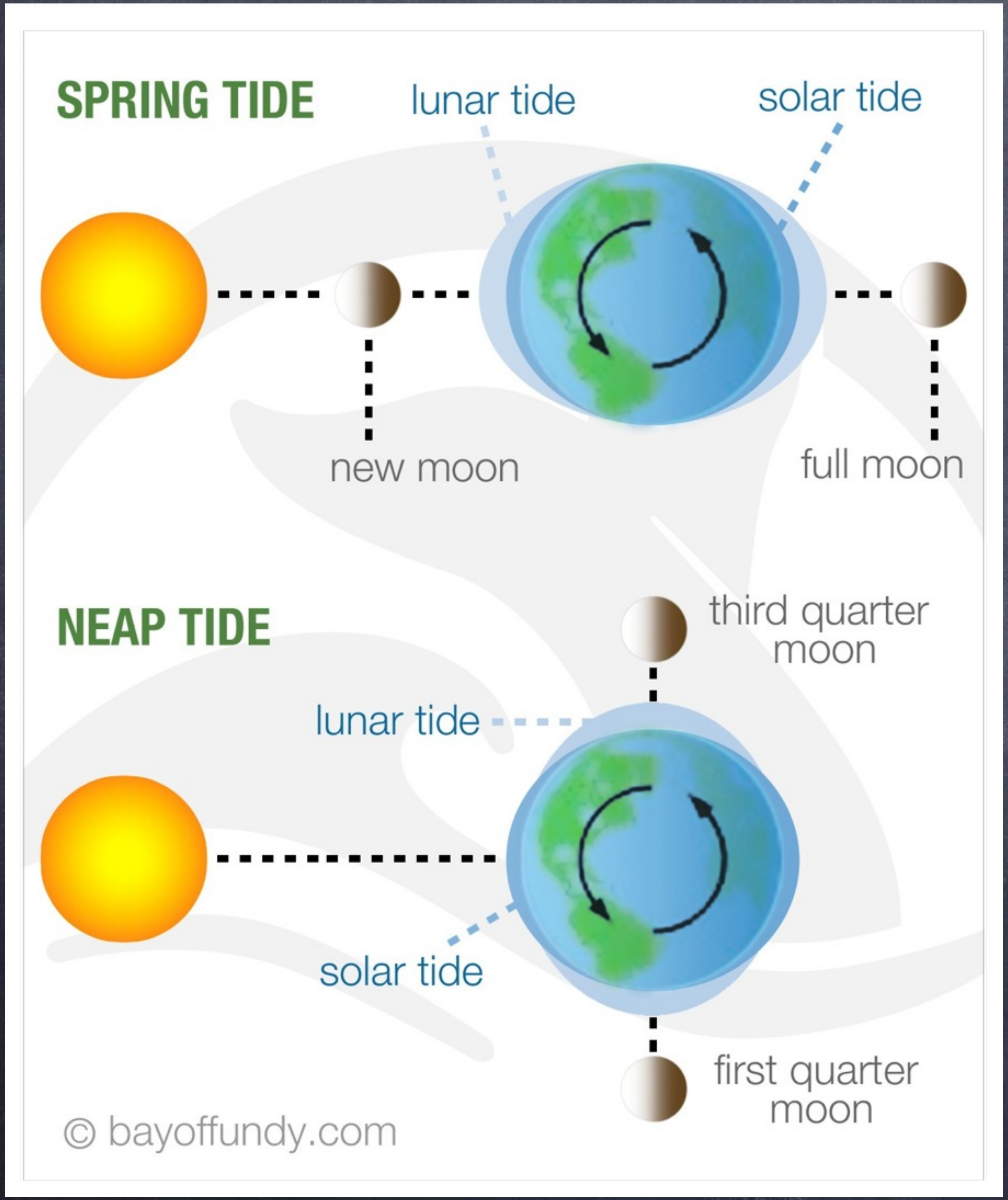
$V_m = -GM/r_1 \quad r_1^2 = r^2 + R^2 - 2rR\cos_\varphi$

full derivation RS p302



The horizontal component of the tidal force on Earth when the tide-generating body is above the Equator at Z. From Dietrich, et al. (1980).

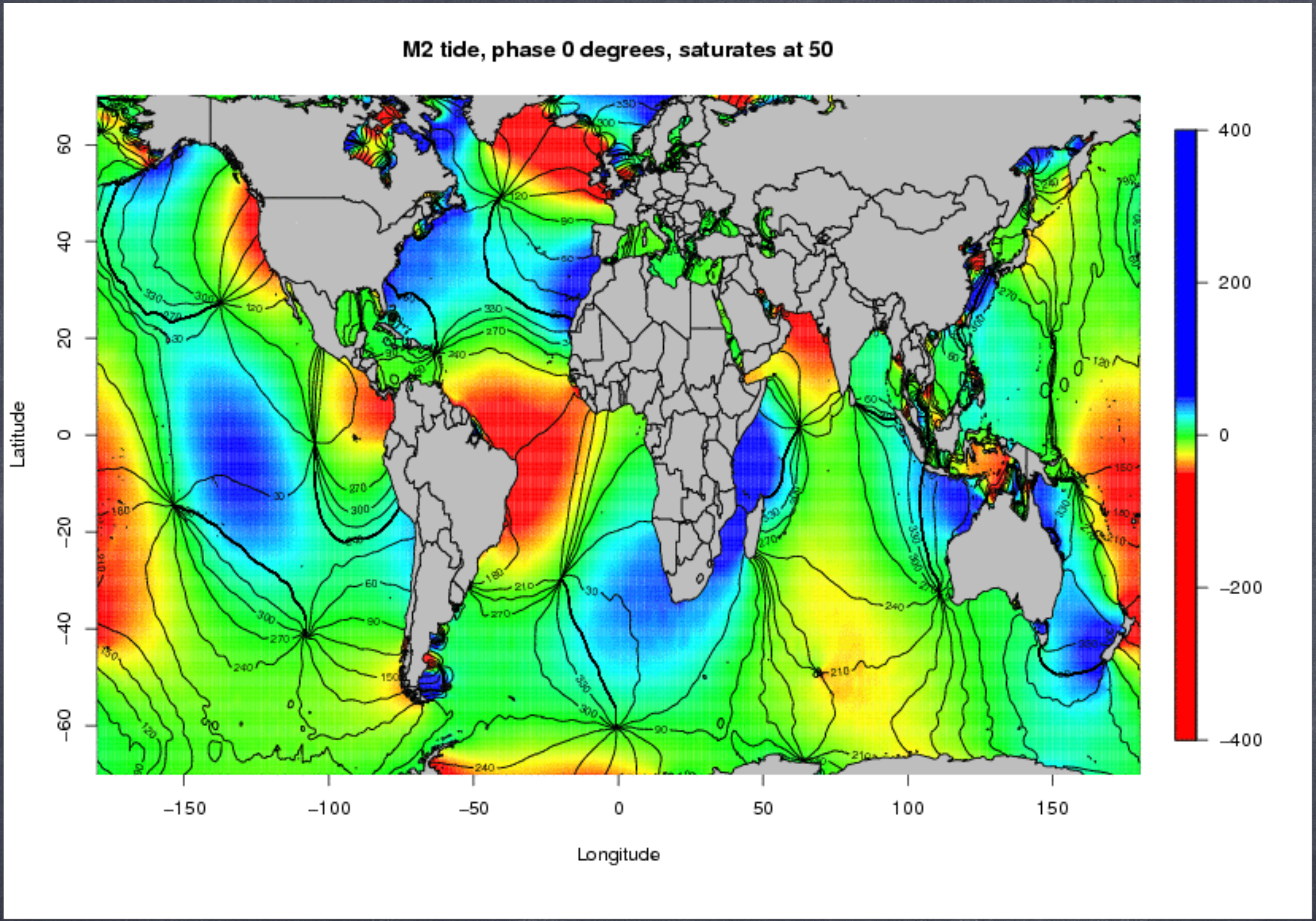
Spring-Neap cycle



Beating of lunar M_2 tide and solar S_2 tide leads to "spring" tides and "neap" tides with 14-day period

Real tides are dynamic

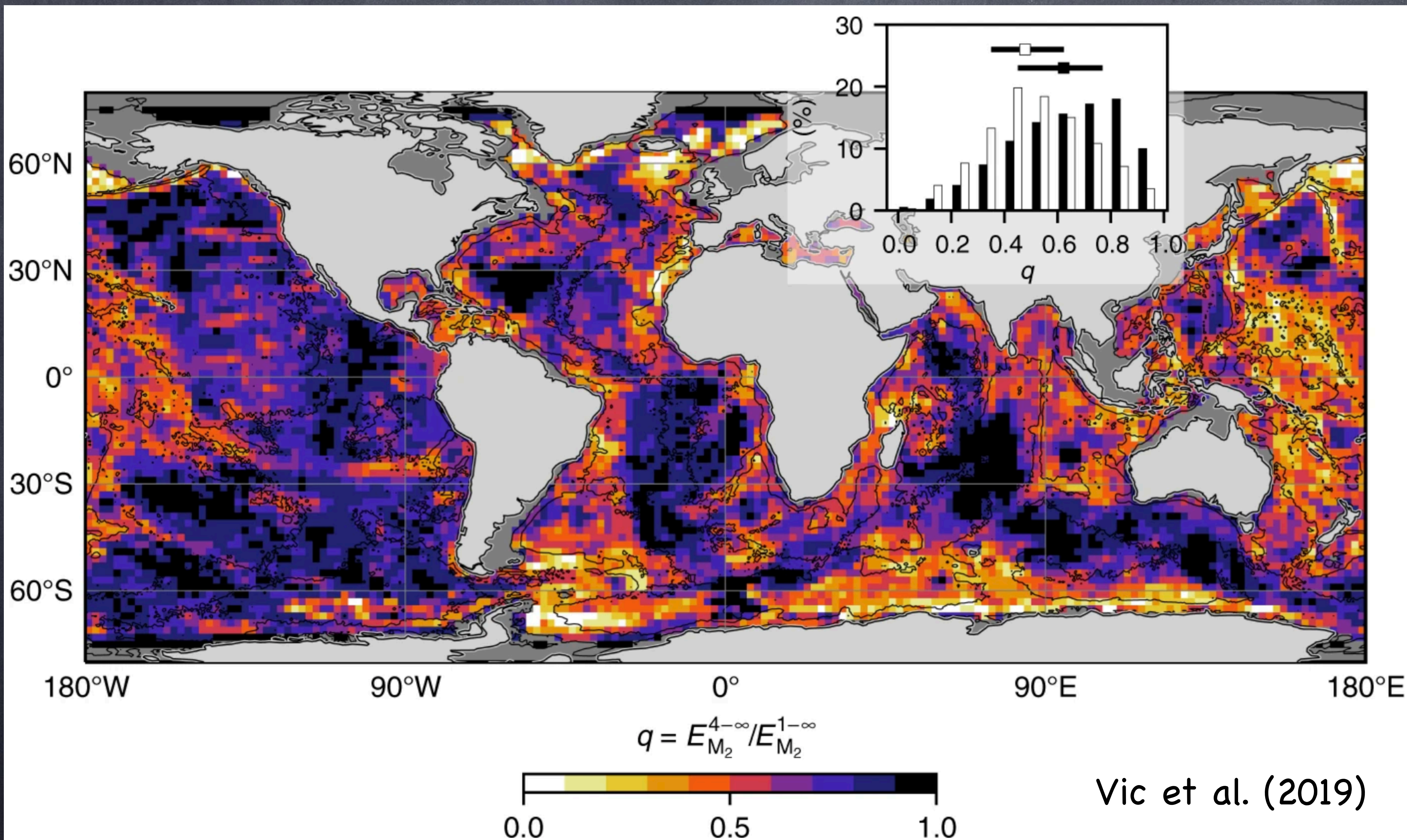
- Tidal "bulges" travel at the surface of the Earth as "shallow-water waves" of maximum speed 230 m s^{-1} which is half that predicted by celestial mechanics
- Bottom drag causes the dynamic tides to lag the equilibrium tides by several hours
- Shapes of ocean basin prevent the tidal bulges from circumnavigating the globe (except in the Southern Ocean)
- lateral ocean movements are subject to Coriolis effect



Animation **of M2 tidal constituent** (0-400 mm) from Tim Jupp. Cotidal lines indicating phase every 30 degrees originate at amphidromic points where the tidal range is zero.

http://empslocal.ex.ac.uk/people/staff/tej202/tideomatic/ani_World_M2.gif

Tidal energy is dissipated in the abyssal ocean around mid-ocean ridges, shaping abyssal circulation

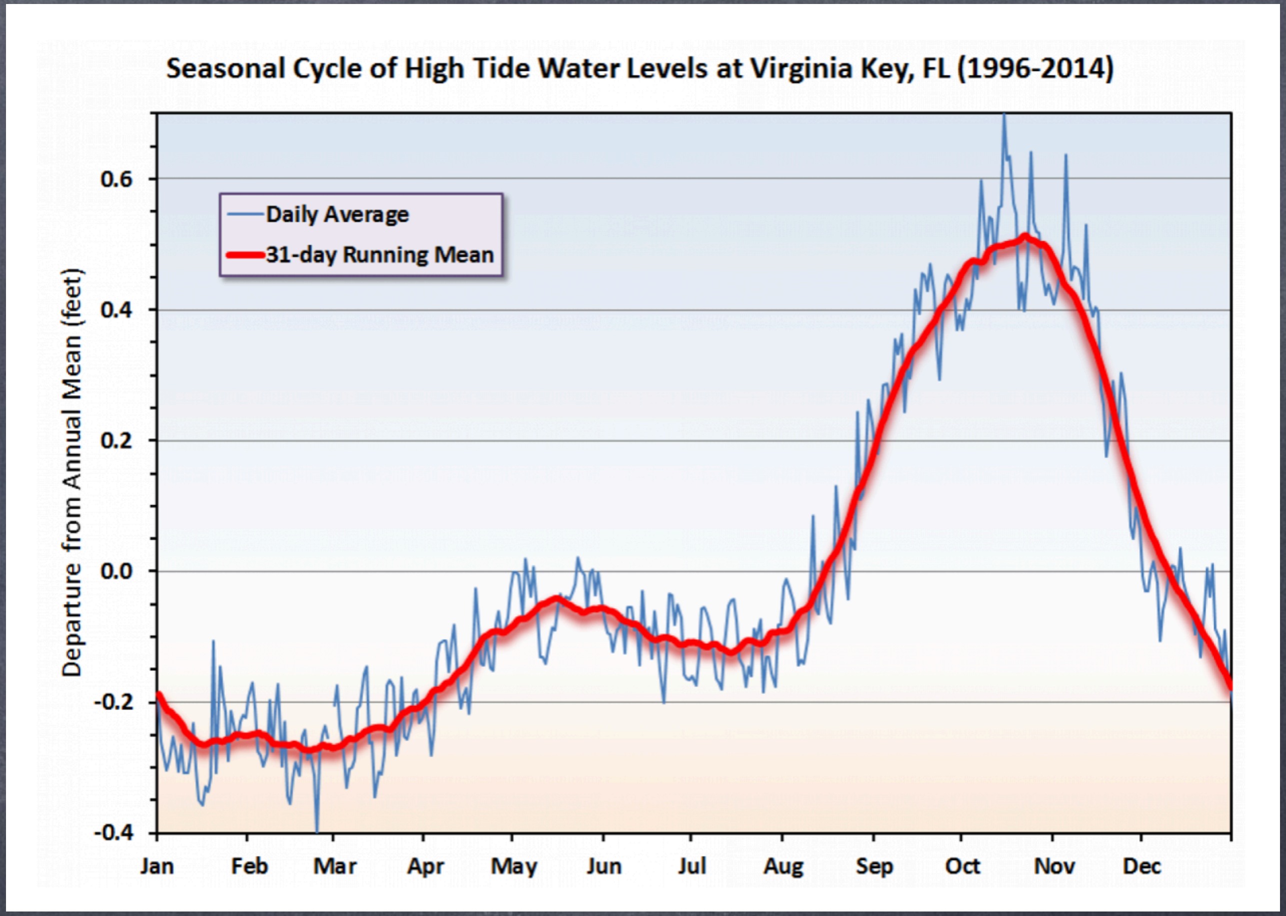


Geography of the ratio q of local tidal energy dissipation to total tidal energy conversion.

Why are water levels so high right now in Miami?

King Tides: Sept-Oct-Nov

- warmest ocean
- weakest Gulf Stream
- equinox - orbit of moon closest to Earth
- spring tide - moon-Earth-Sun aligned
- exacerbated by low atmospheric pressure

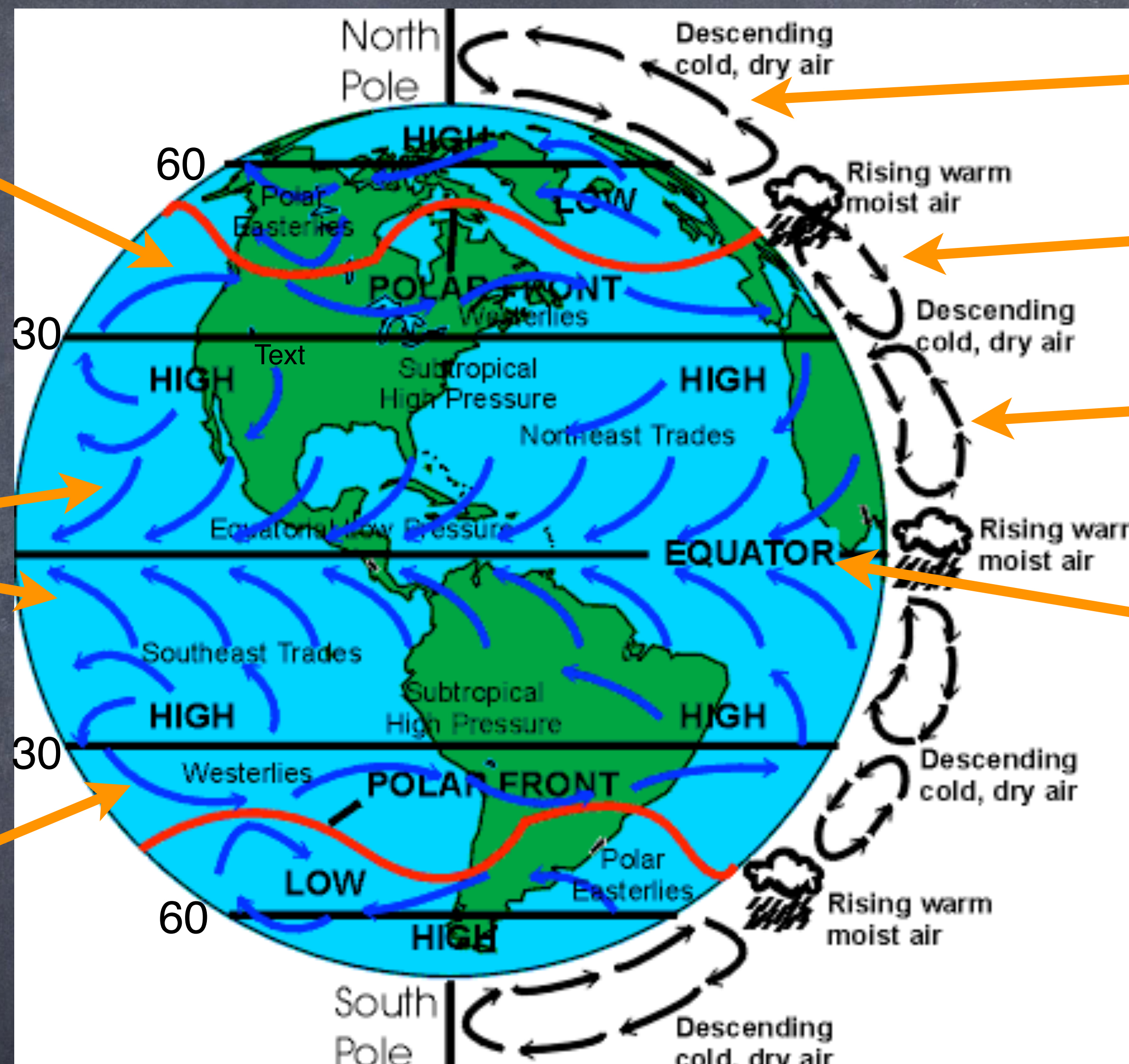


Winds

westerlies

trade winds

westerlies



Polar cell

Ferrel cell

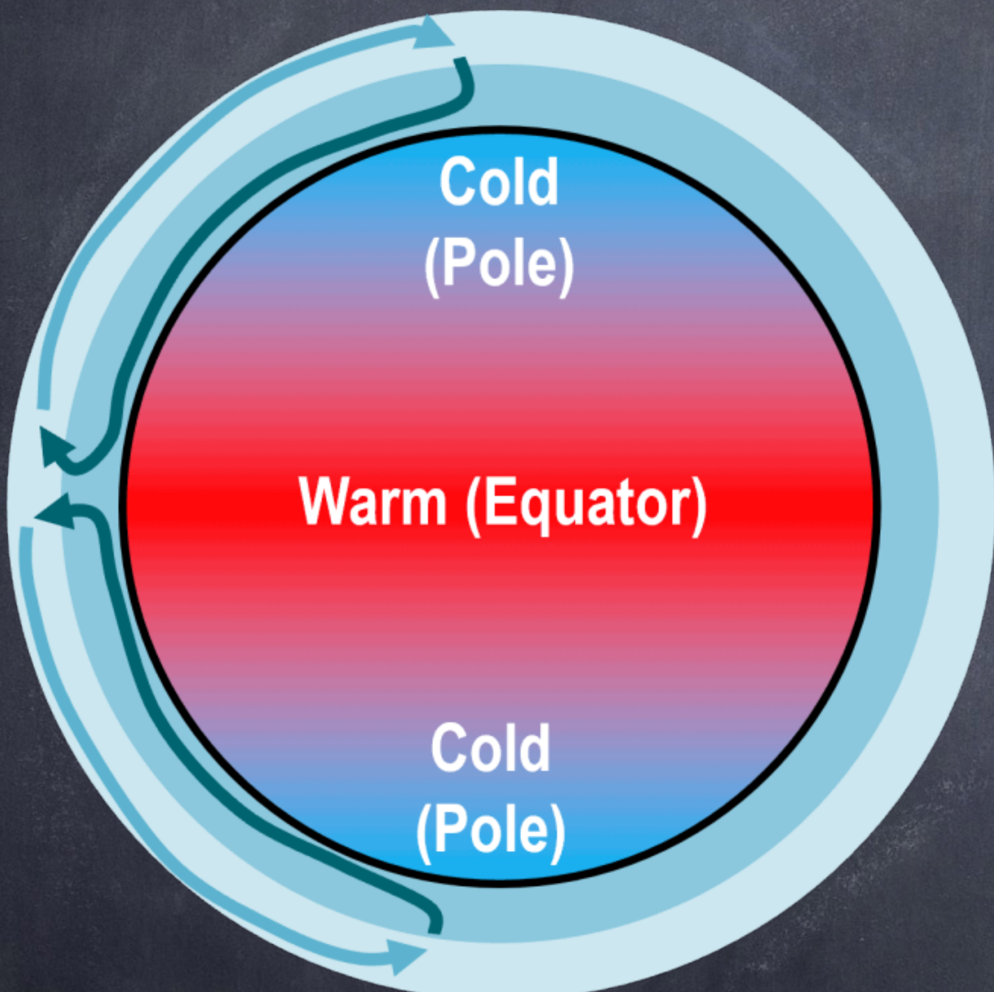
Hadley cell

ITCZ: Intertropical Convergence Zone

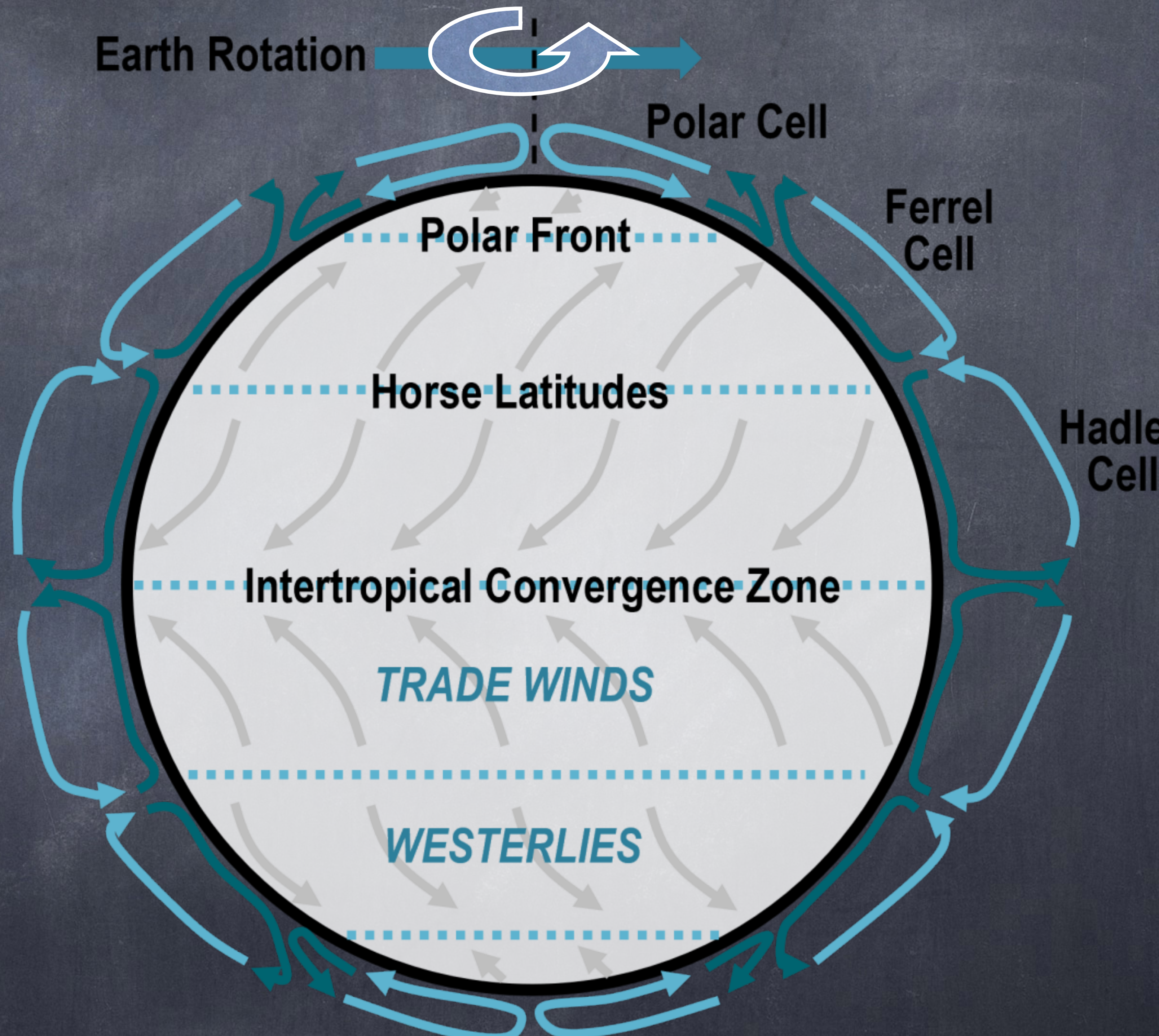
Circulation is deflected by Earth's rotation

Air circulation driven by uneven heating of Earth surface by Sun

Winds = thermodynamics + rotation



Principle



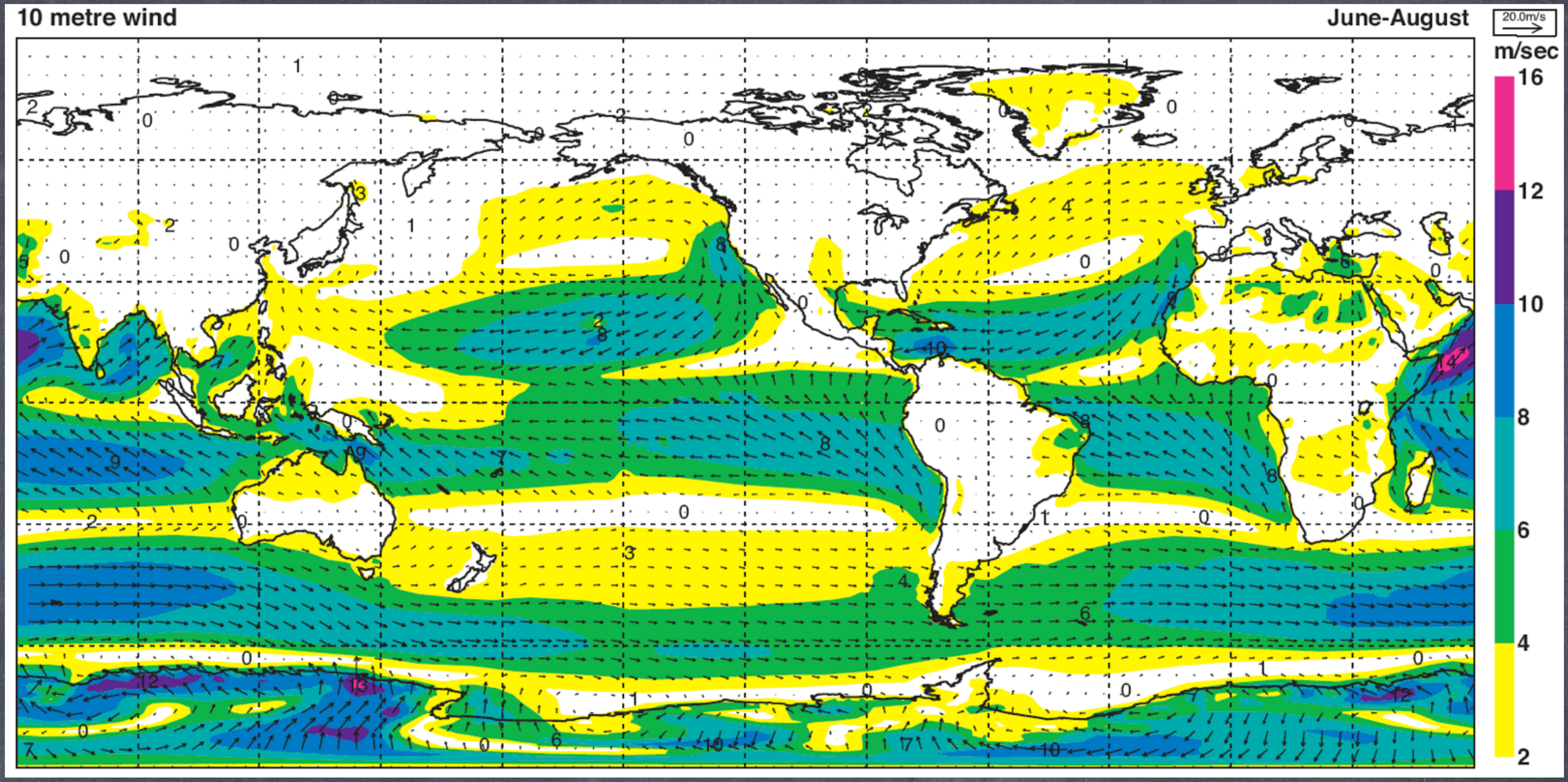
Global Structure

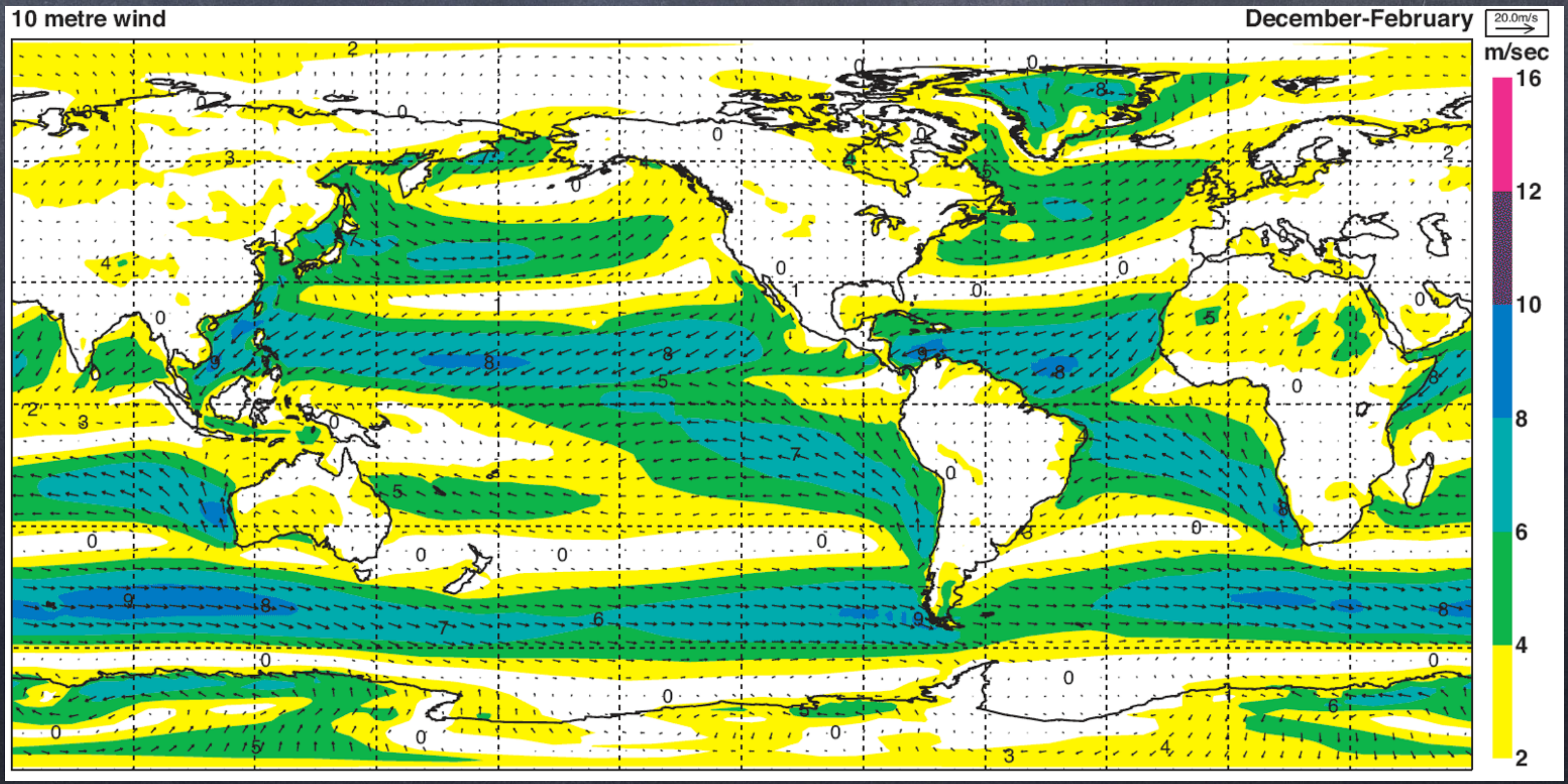
Mean 10-m winds in boreal summer (top) and winter (bottom) from ECMWF 40-year re-analysis. (Kallberg et al, 2005).

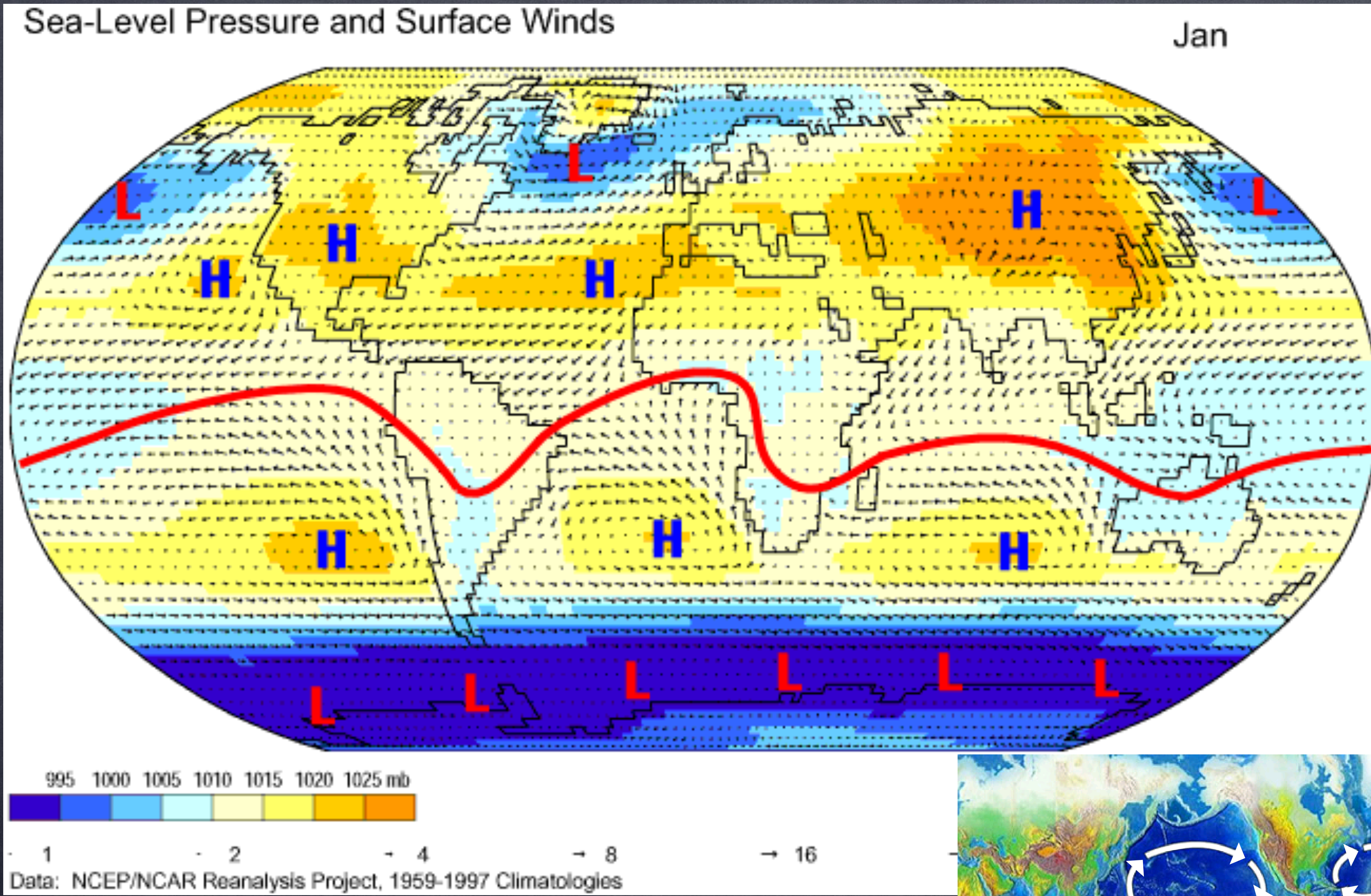
-Stronger westerlies in winter.

-Asian monsoon flips wind direction in N Indian Ocean and NW Pacific

-Strongest winds on Earth? Antarctic katabatic and Asian monsoons






Sea-Level Pressure and Surface Winds
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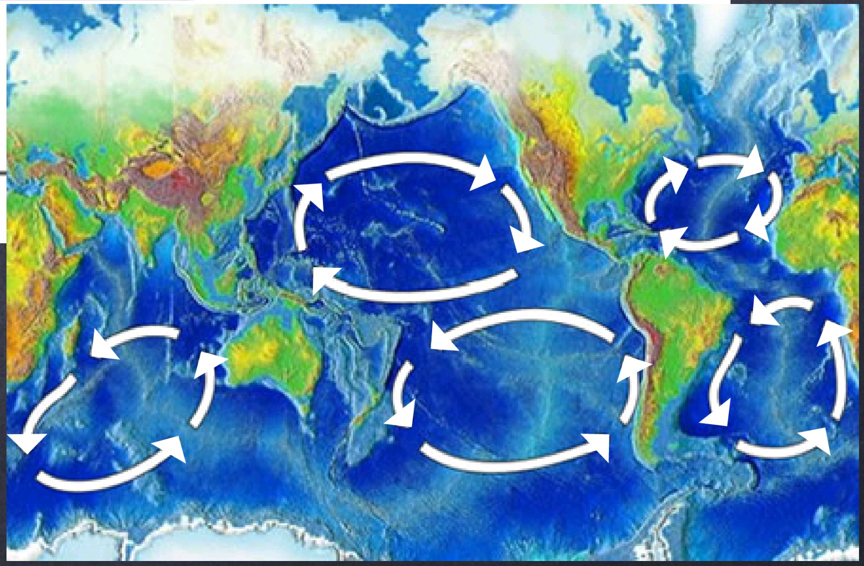
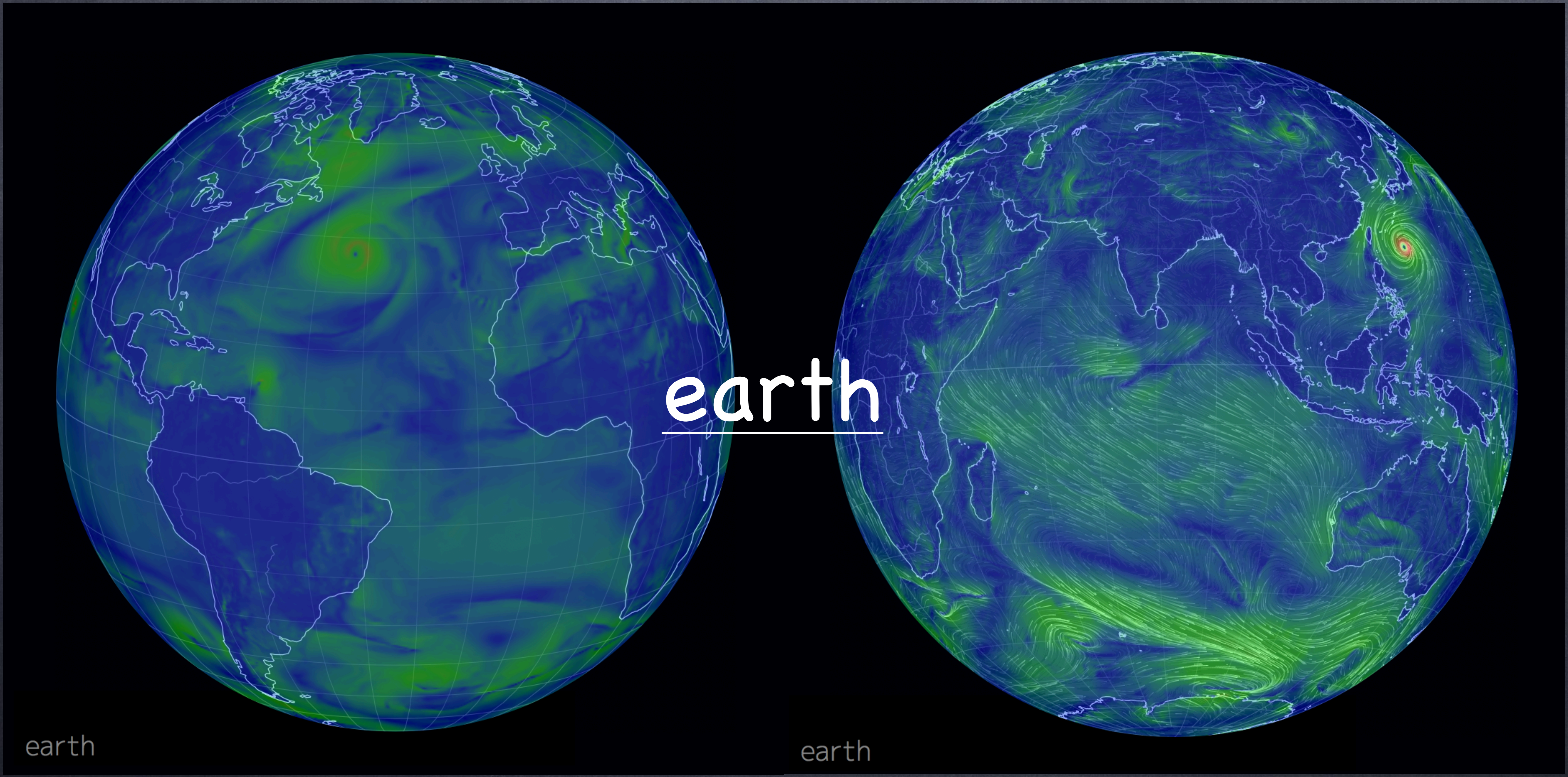
Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies



Winds Now!



earth

https://earth.nullschool.net/

Heat

short wave long wave

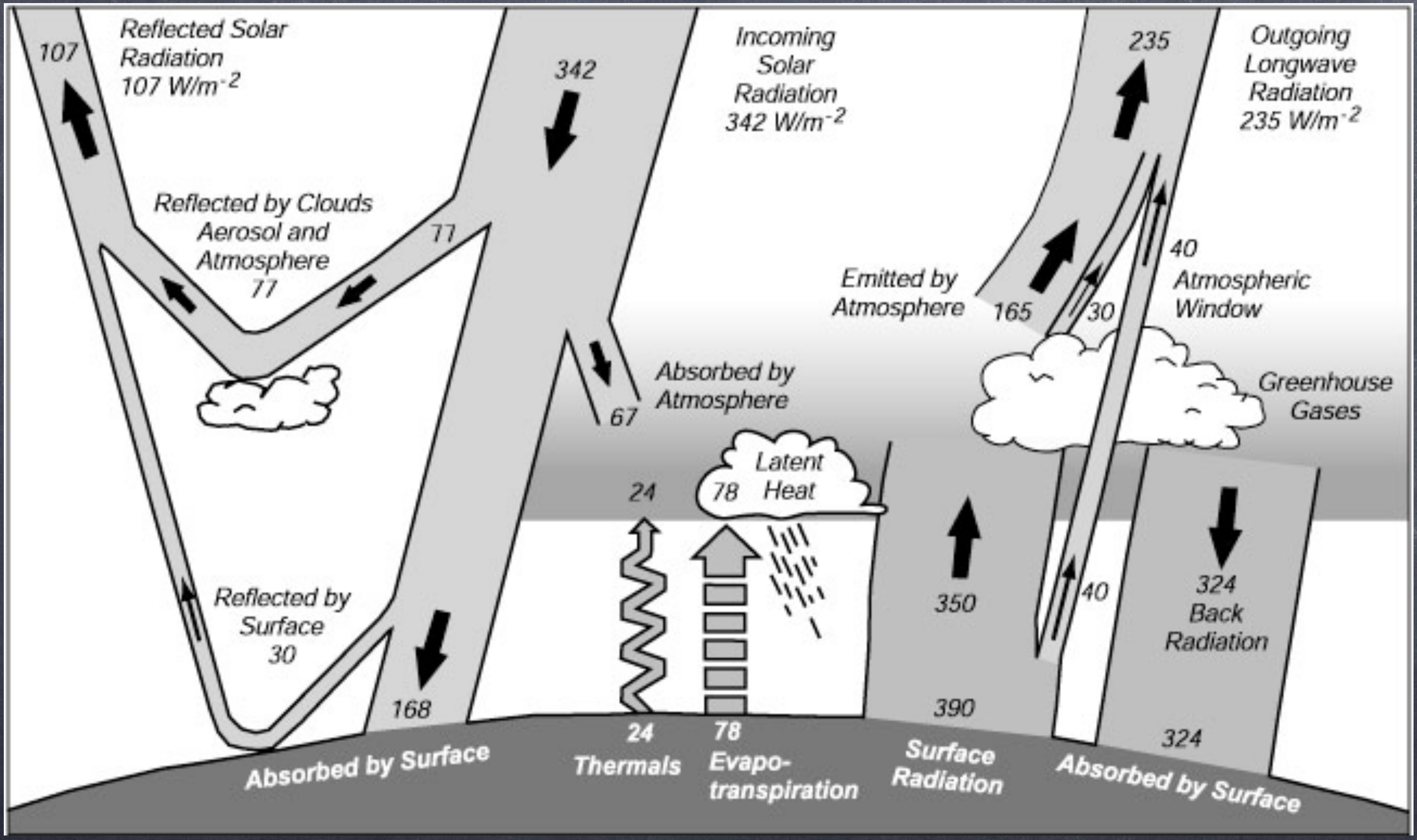
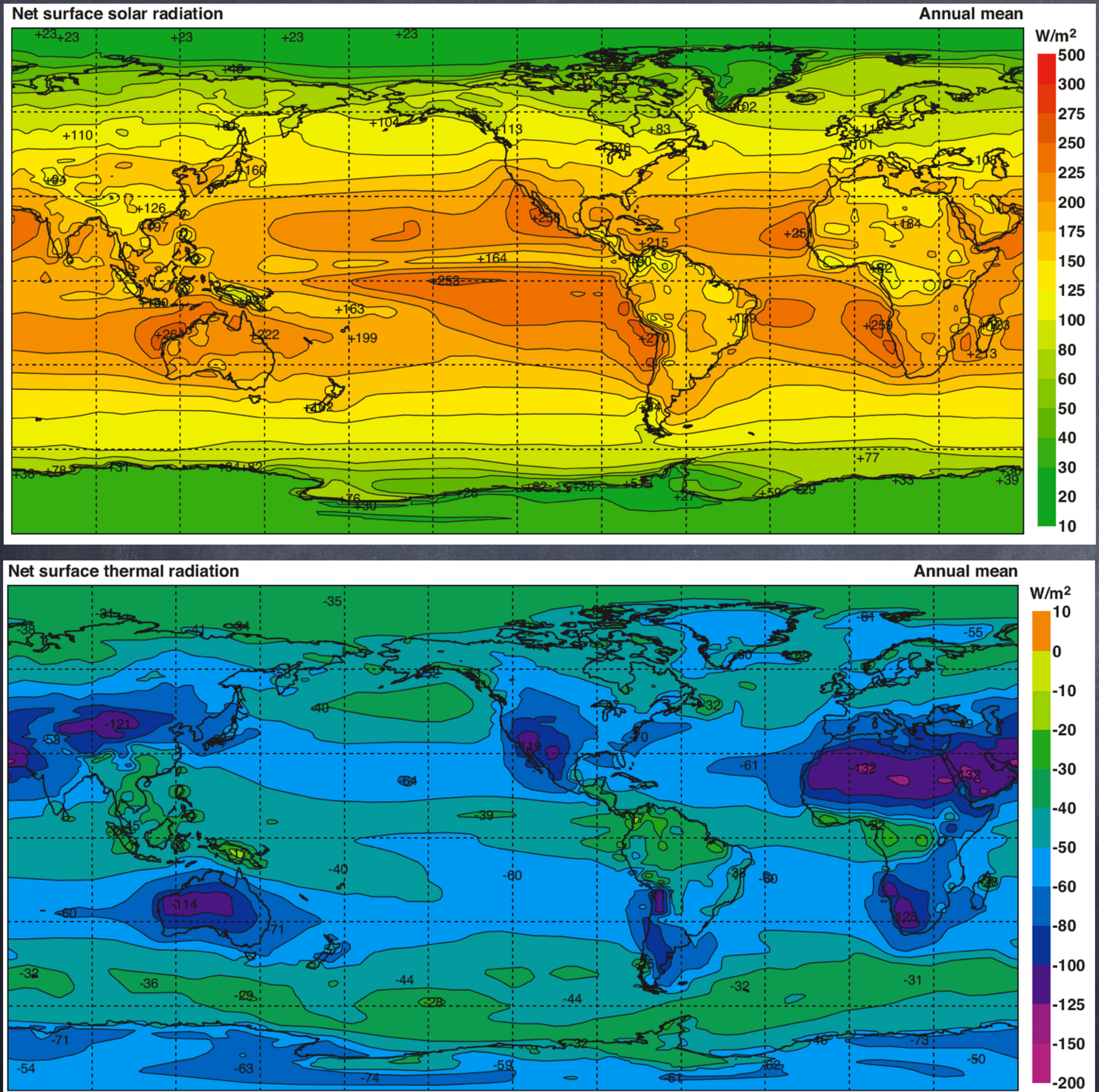


Figure 5.6 The mean annual radiation and heat balance of the Earth. From Houghton et al., (1996: 58), which used data from Kiehl and Trenberth (1996).

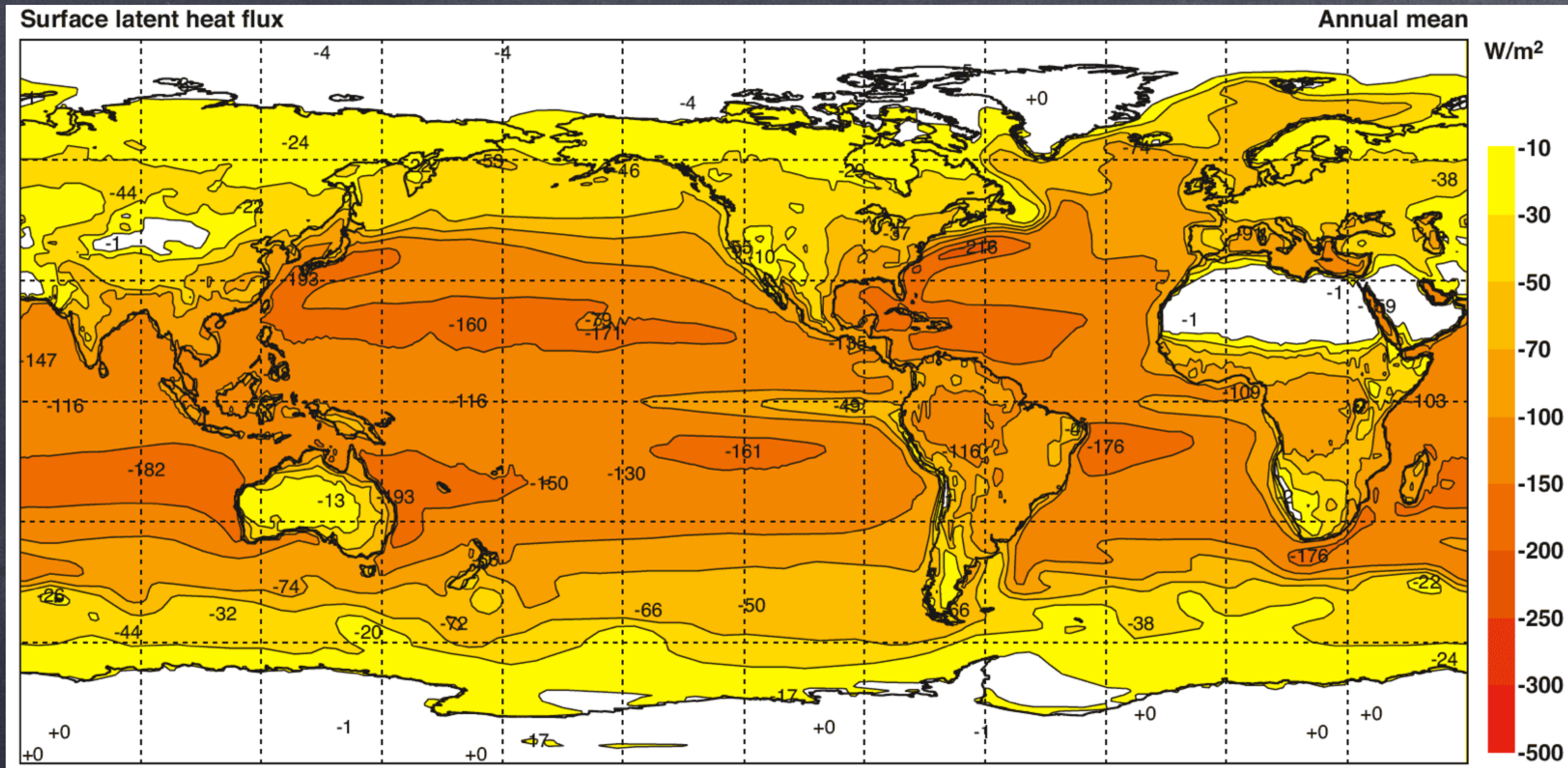


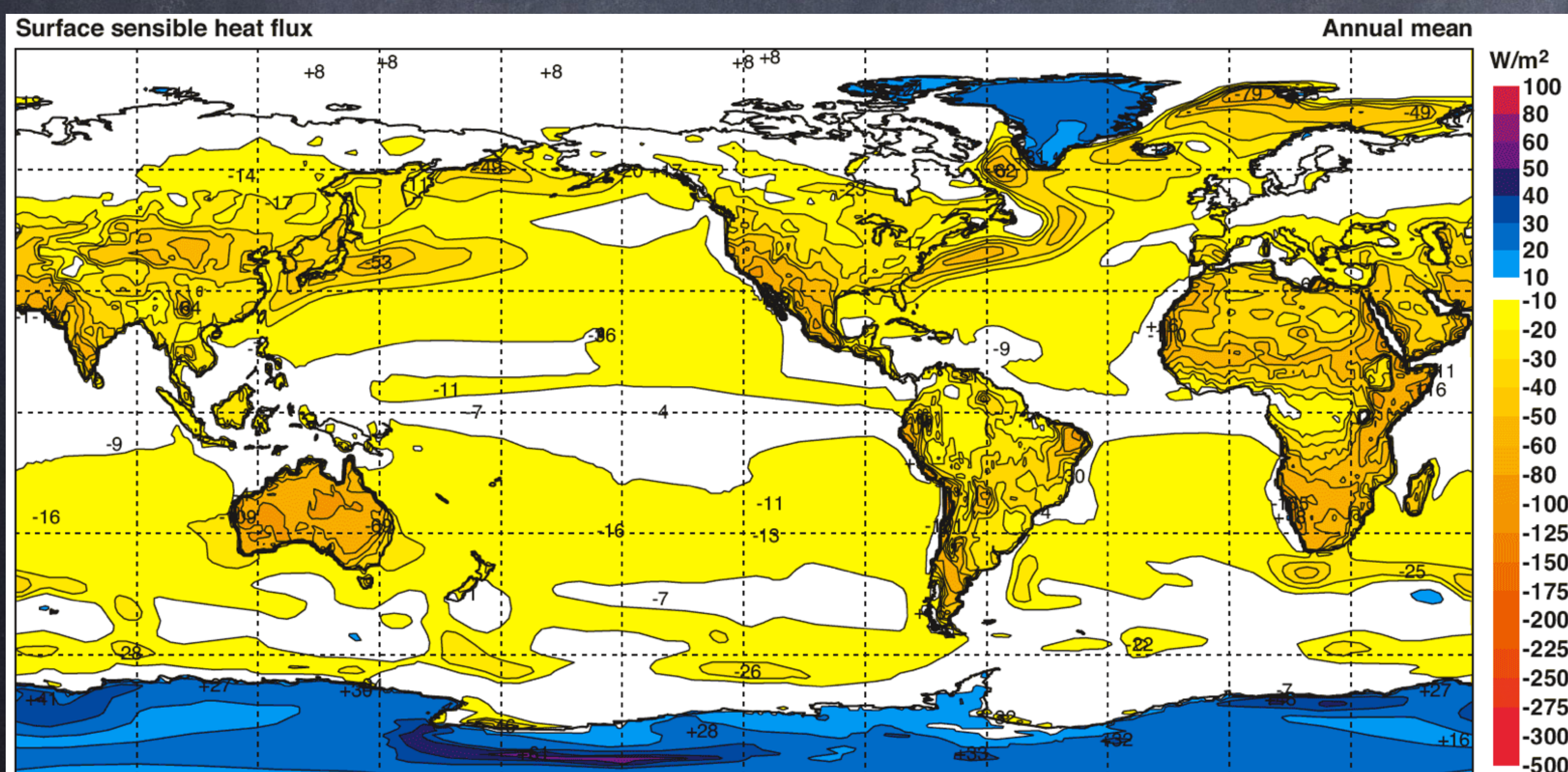
Annual-mean short-wave and long-wave radiation at surface

Top: net solar, Q_{SW} = incoming-reflected

Bottom: net infrared, Q_{LW} = greenhouse-outgoing

From the ECMWF 40-year reanalysis. Units are W m^{-2}. From Kallberg et al 2005.





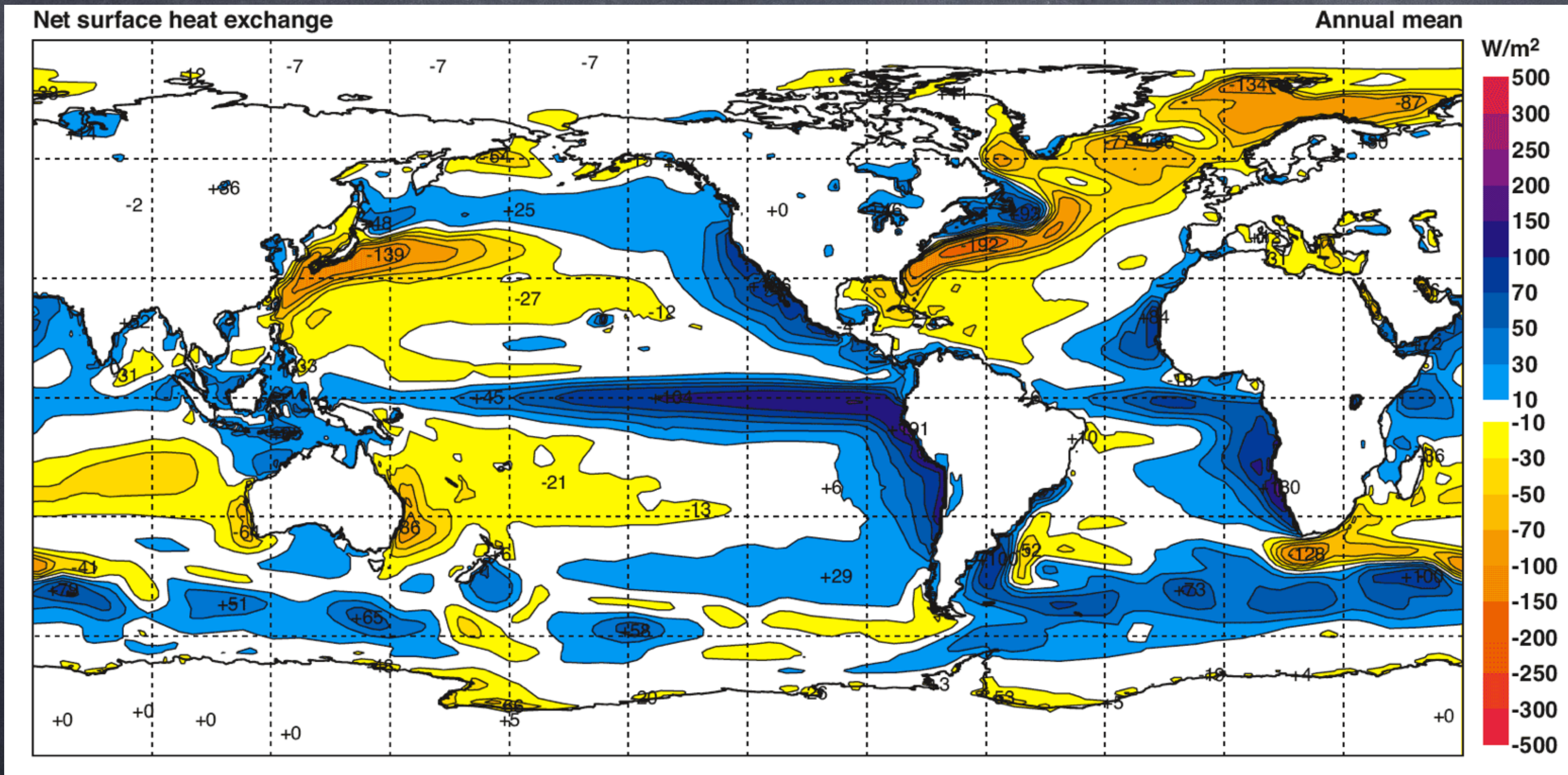
Annual-mean latent and sensible heat fluxes at surface

Top: latent heat flux, Q_L

Bottom: sensible heat flux, Q_S

From the ECMWF 40-year reanalysis. Units are W m^{-2}. From Kallberg et al 2005.

Net Annual-mean heat flux Q through the sea surface in W m^{-2}, calculated from the ECMWF 40-year reanalysis. Kallberg et al 2005.



Max into ocean in tropics and upwelling regions.
Max loss from ocean over WBCs and sub-Arctic.
(Need more measurements in Southern Ocean)

Global Heat flux through sea surface

- -insolation greatest in tropics
- -evaporation + LW primarily balances insolation
- -sensible heat flux is smallest
- -what balances total heat flux?

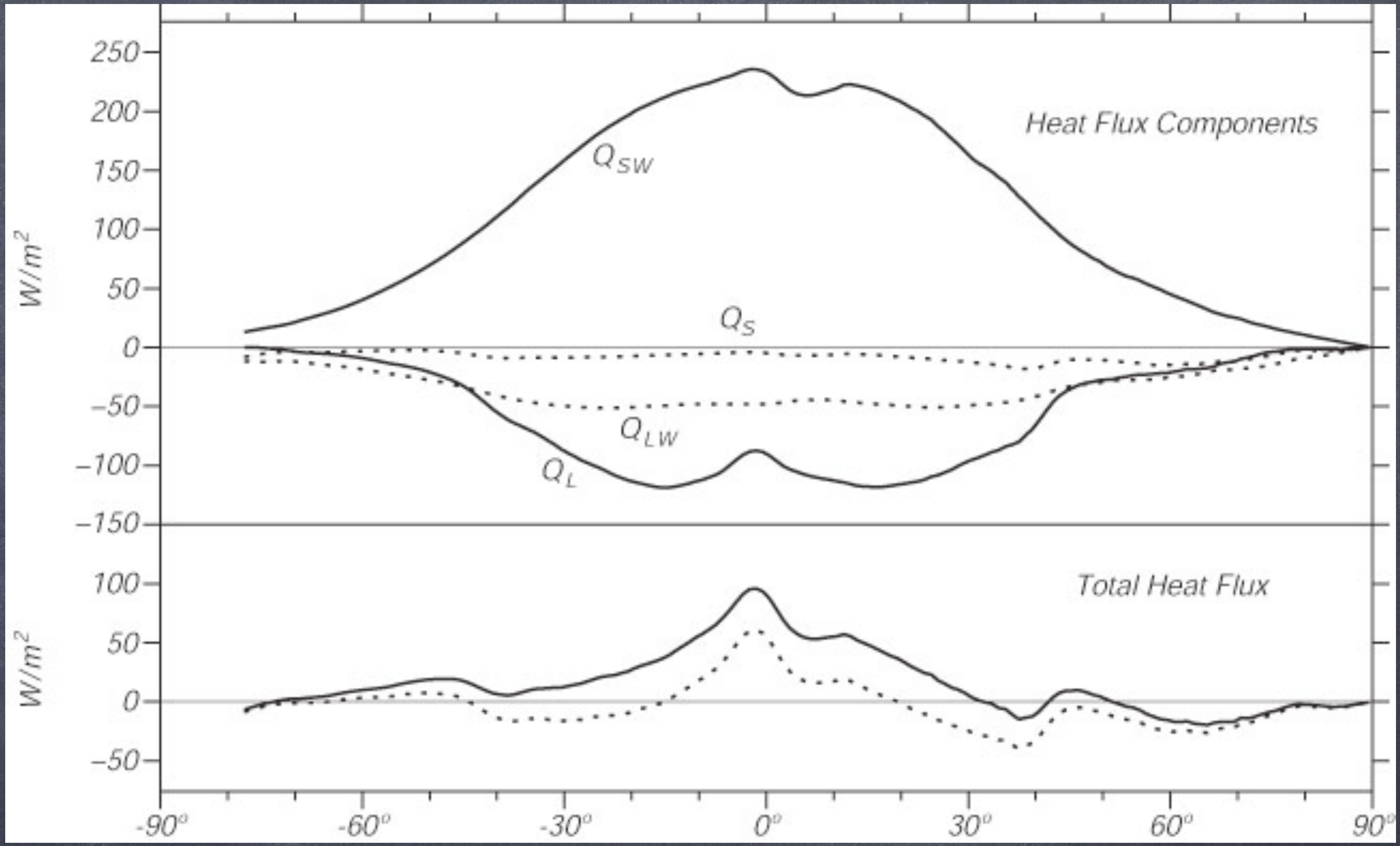
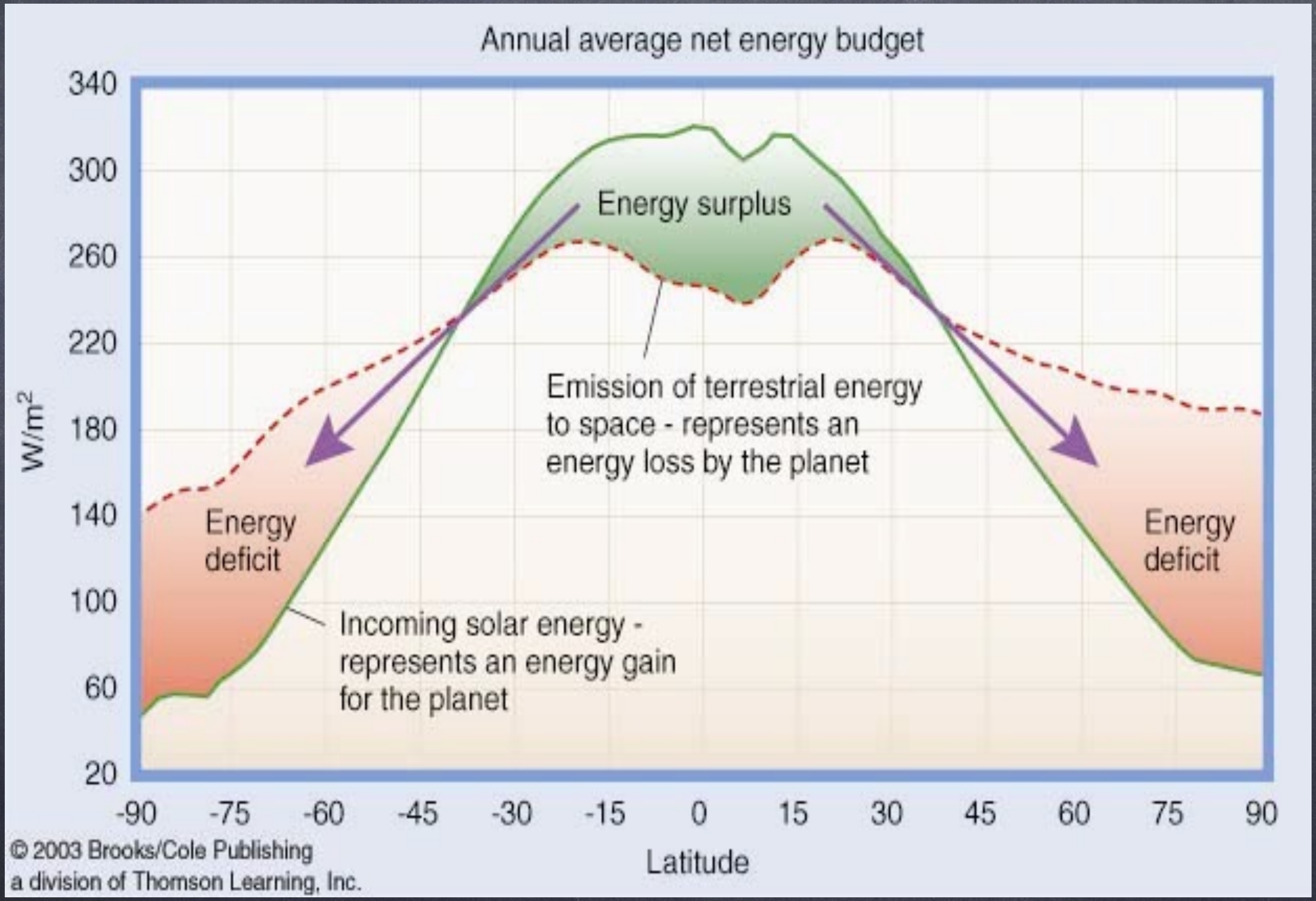
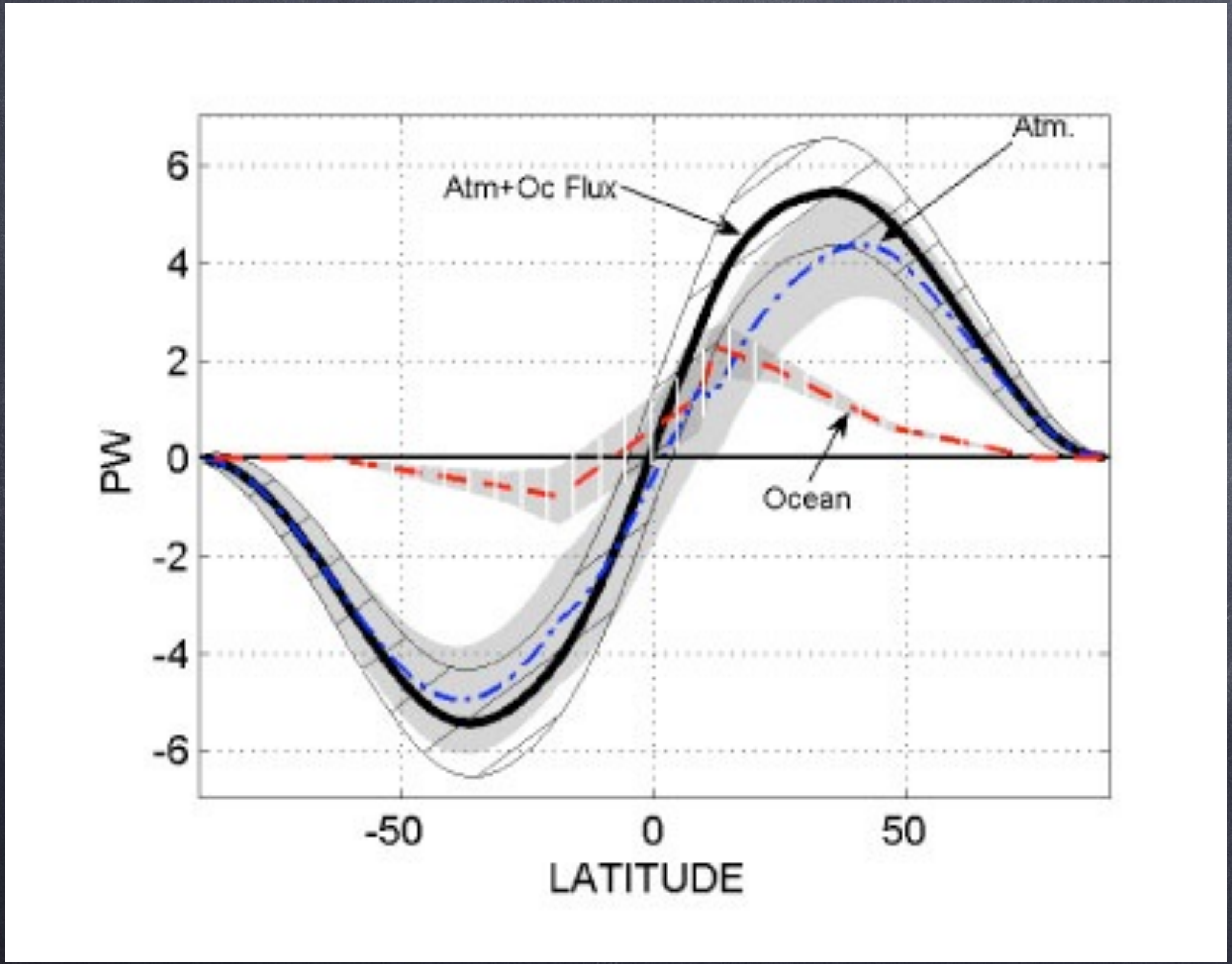


Figure 5.7 Upper: Zonal averages of heat transfer to the ocean by insolation Qsw, and loss by longwave radiation Qlw, sensible heat flux Qs, and latent heat flux Ql, calculated by DaSilva, Young, and Levitus (1995) using the COADS data set.
Lower: Net heat flux through the sea surface calculated from the data above (solid line) and net heat flux constrained to give heat and fresh-water transports by the ocean that match independent calculations of these transports.

Global energy budget at top of atmosphere with latitude

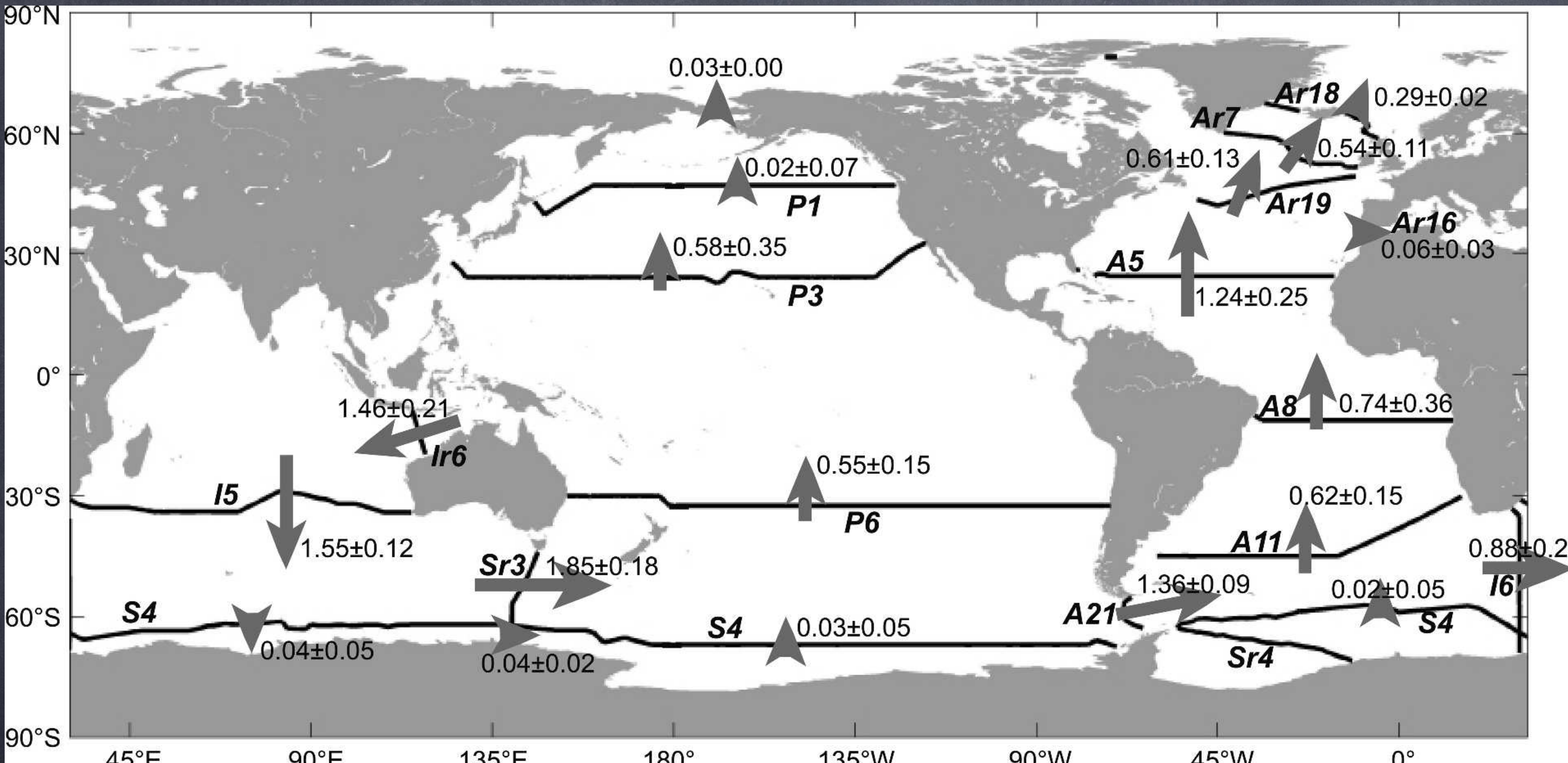


Oceanic and atmospheric meridional heat flux



Oceanic heat flux skewed northward

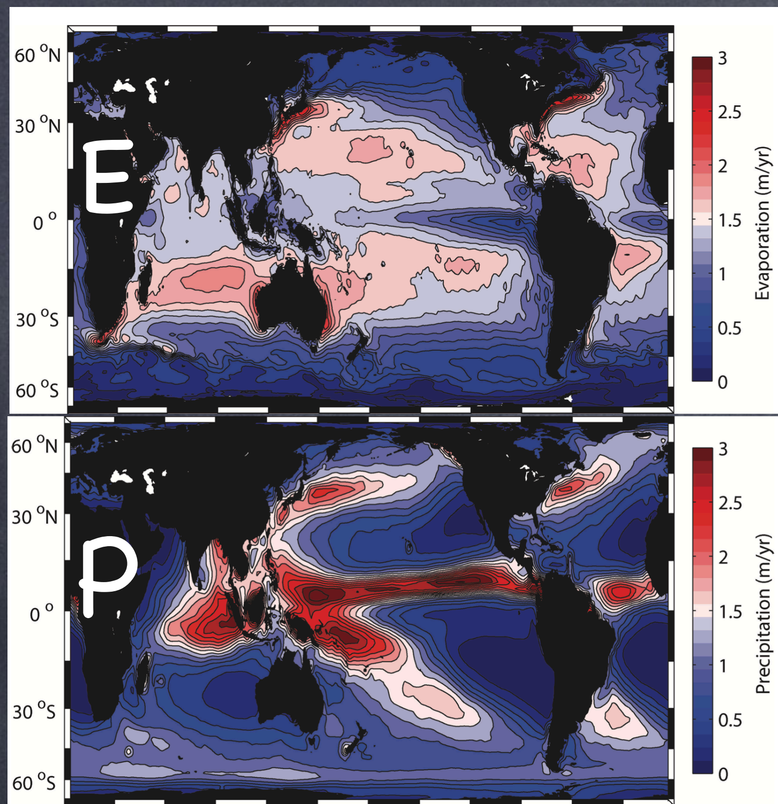
Meridional oceanic heat fluxes

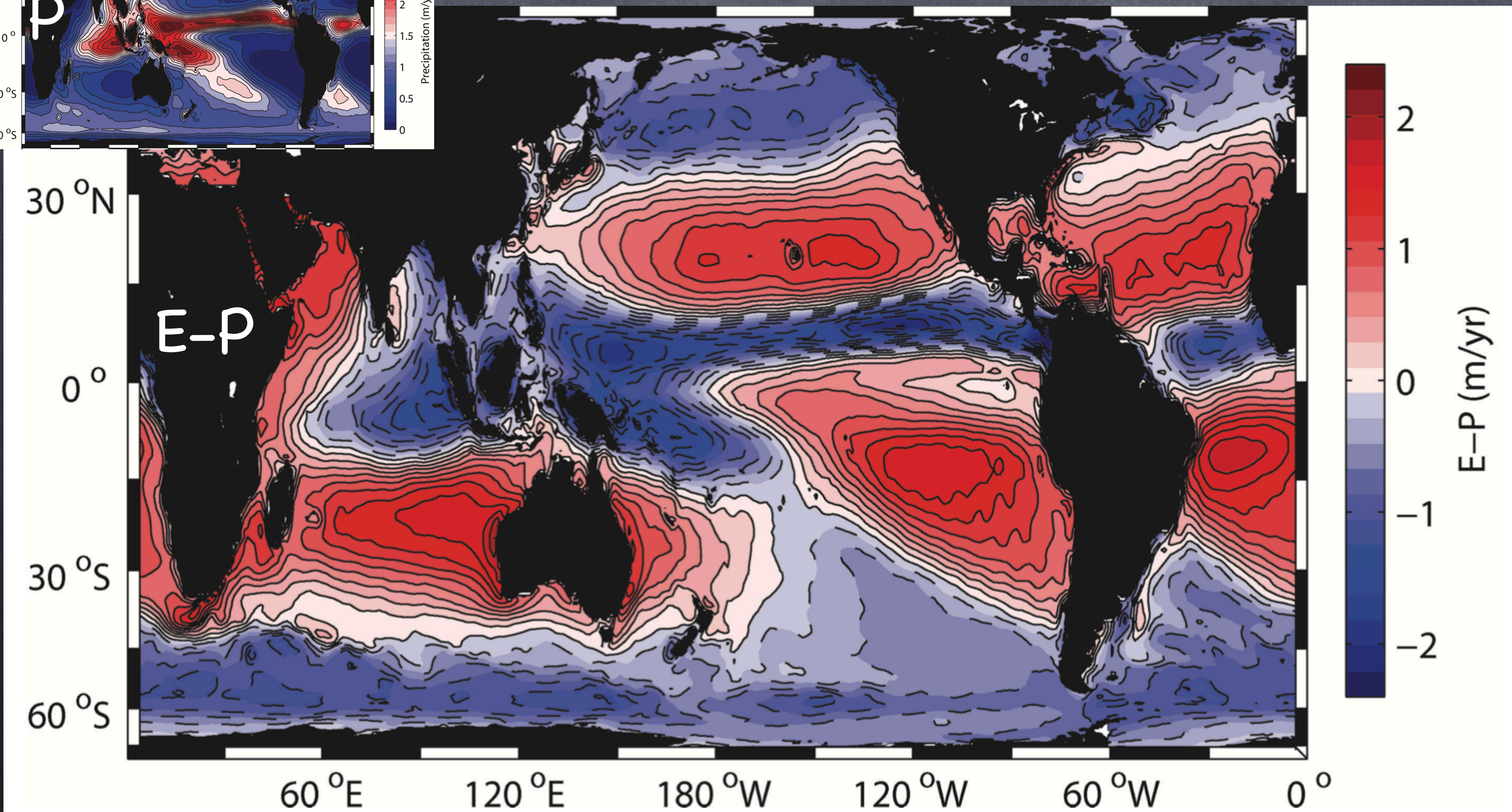


Lumpkin and Speer (2007)

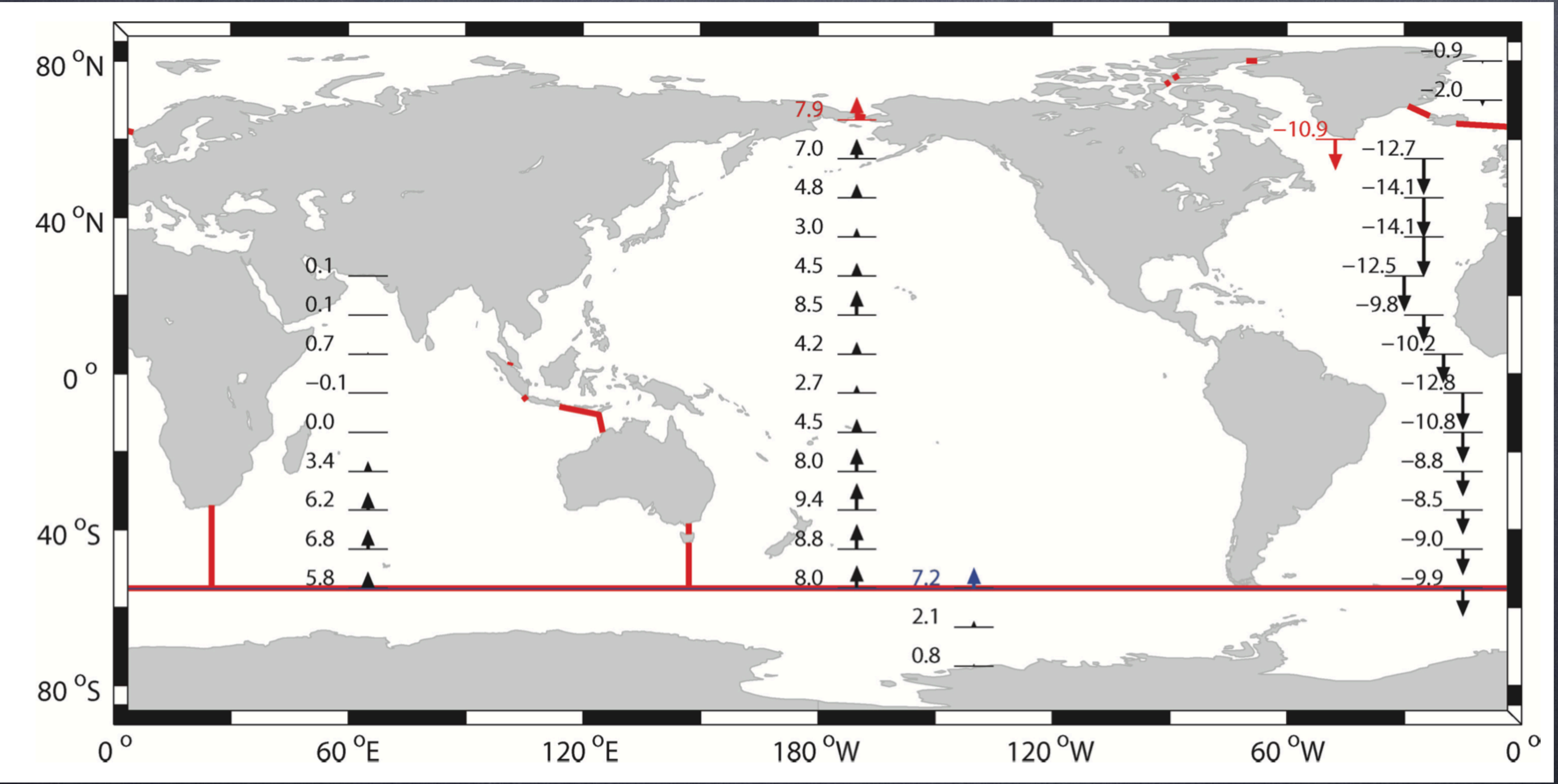
Freshwater Budget

Annual mean precipitation into ocean = 12.2 ± 1.2 Sv,
Evaporative loss = 13.0±1.3 Sv
Total freshwater input from land = 1.25±0.1 Sv. Imbalance = 0.5 ± 1.8 Sv (Schanze et al., 2010)



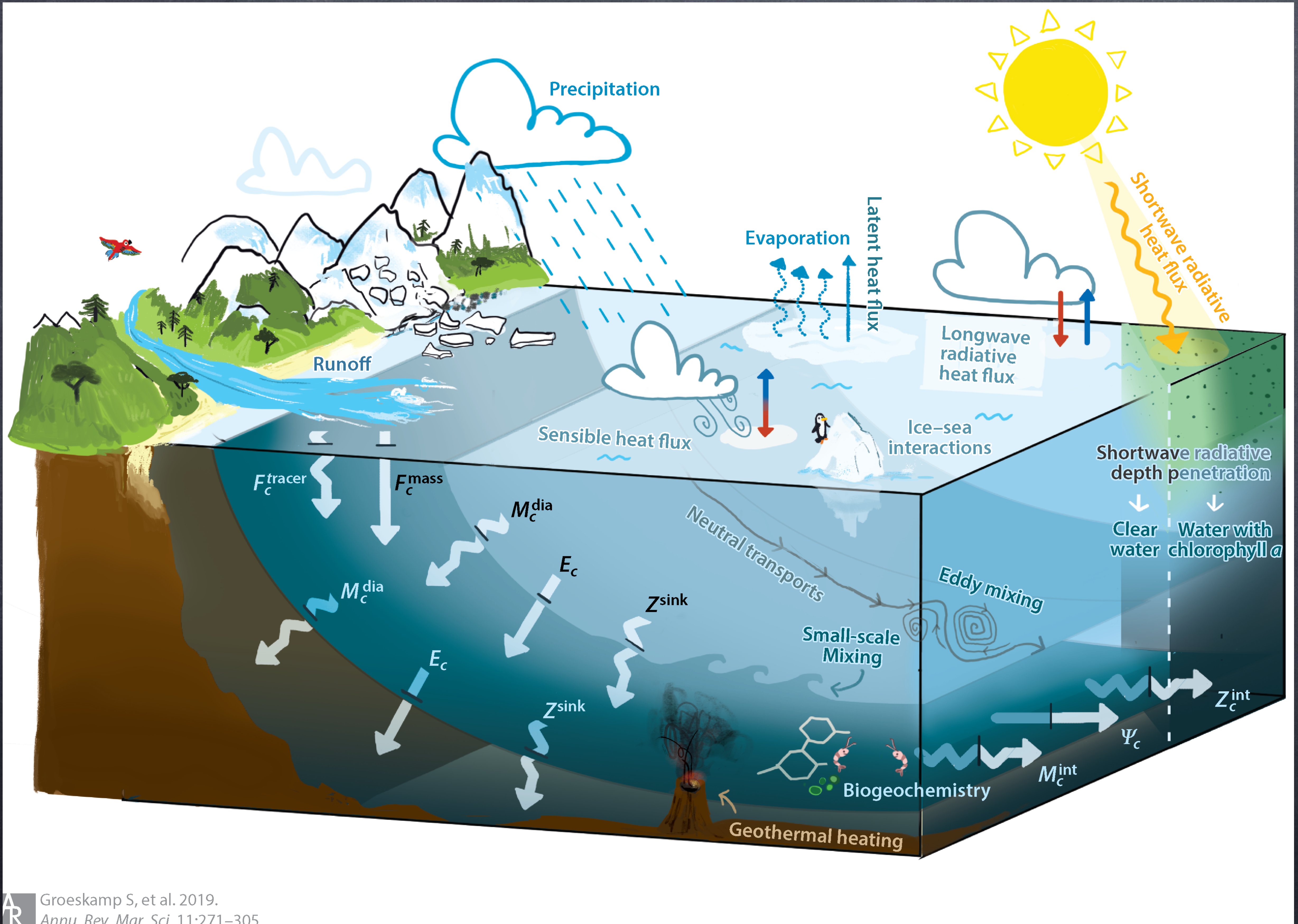


Oceanic freshwater transport
(Schanze et al., 2010)

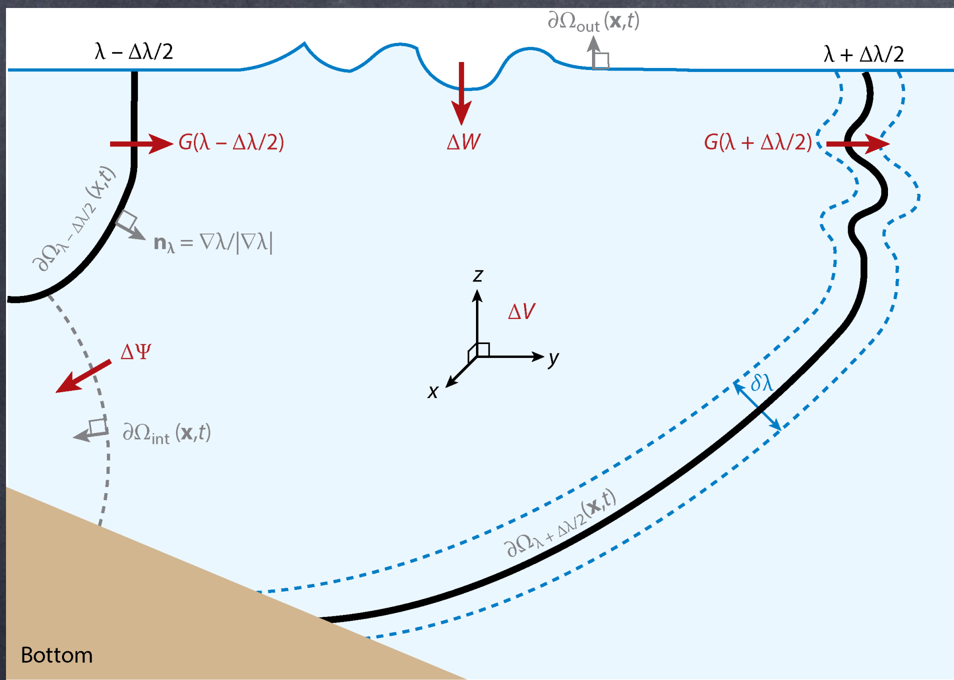


North-South integrated basin freshwater balance in 10^5 m^3 s^{-1} (0.1 Sv)

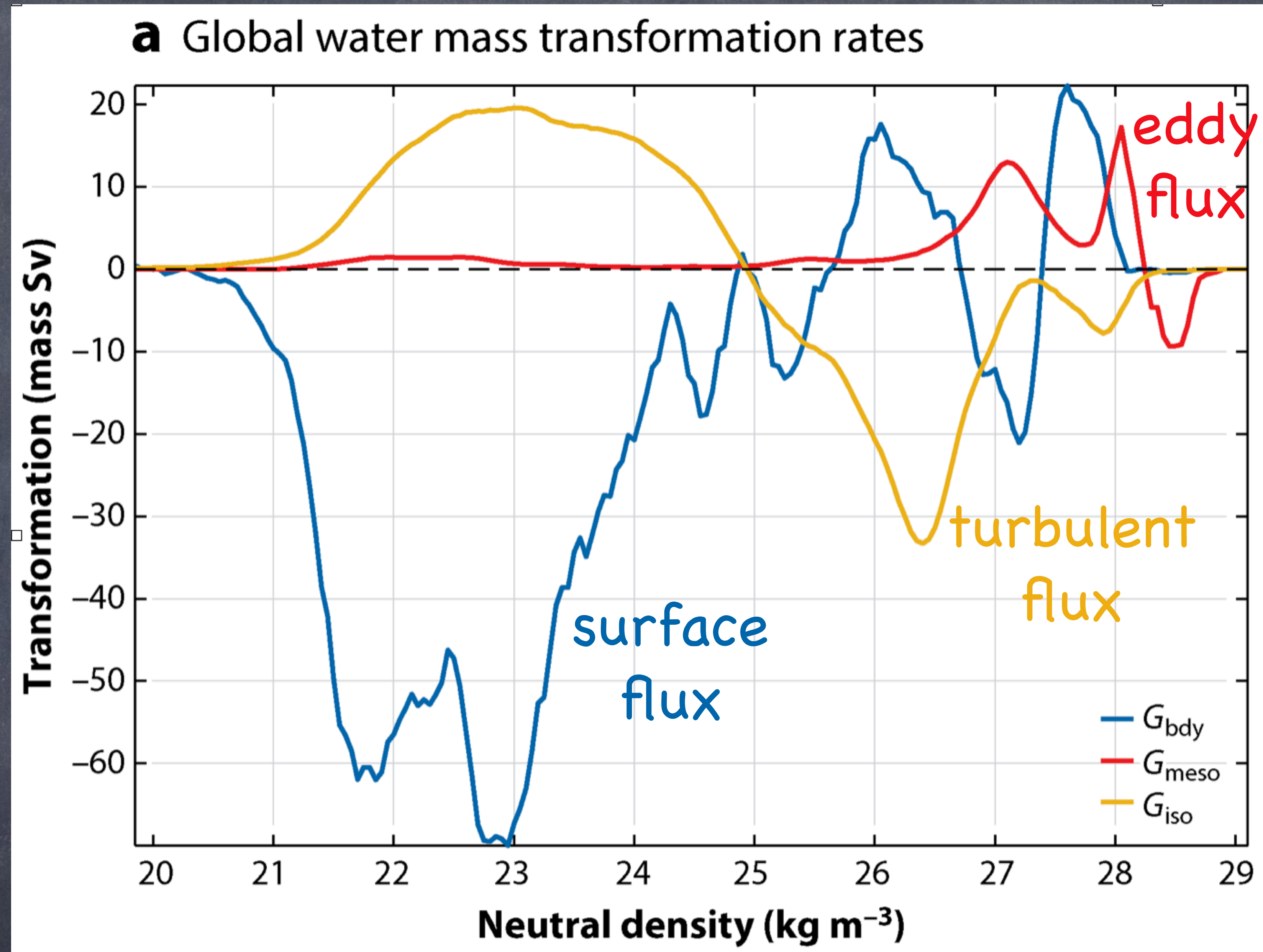
Buoyancy flux = heat + freshwater forcing



Global ocean buoyancy fluxes



Groeskamp S, et al. 2019.
Annu. Rev. Mar. Sci. 11:271–305



$$\dot{\rho}_l = \underbrace{F^{\rho}_{\text{mass}} + F^{\rho}_{\text{surface}} + F^{\rho}_{\text{swr}} + F^{\rho}_{\text{geo}}}_{\text{boundary fluxes}} + \underbrace{\left(\dot{\rho}_l\right)_{\text{hor}} + \left(\dot{\rho}_l\right)_{\text{iso}} + \text{Cab} + \text{Thb}}_{\text{diffusive fluxes}},$$

Water mass transformation is quantified by conserving mass (material derivative of density) over a volume defined by the ocean surface, sea bed, and isoneutral surfaces
(Groeskamp et al., 2019)

$$G(\gamma) = \frac{\partial}{\partial \gamma} \iiint_{\gamma' \le \gamma} \gamma' \, b \, \dot{\rho}_l \, \mathrm{d}V$$