Oceans in the Climate System

AOS660, Fall 2013, Prof. McKinley

- Earth, as a whole, is in radiative balance with space

- Uneven net radiation sets up a potential energy gradient that is damped by atmospheric and oceanic motion
  - Atmospheric winds drive the ocean
  - Ocean currents contribute to heat redistribution

- The ocean contributes to heat redistribution in 2 key ways
  - It supplies water vapor so that the atmosphere can carry latent heat
  - It moves sensible heat

First Law of Thermodynamics

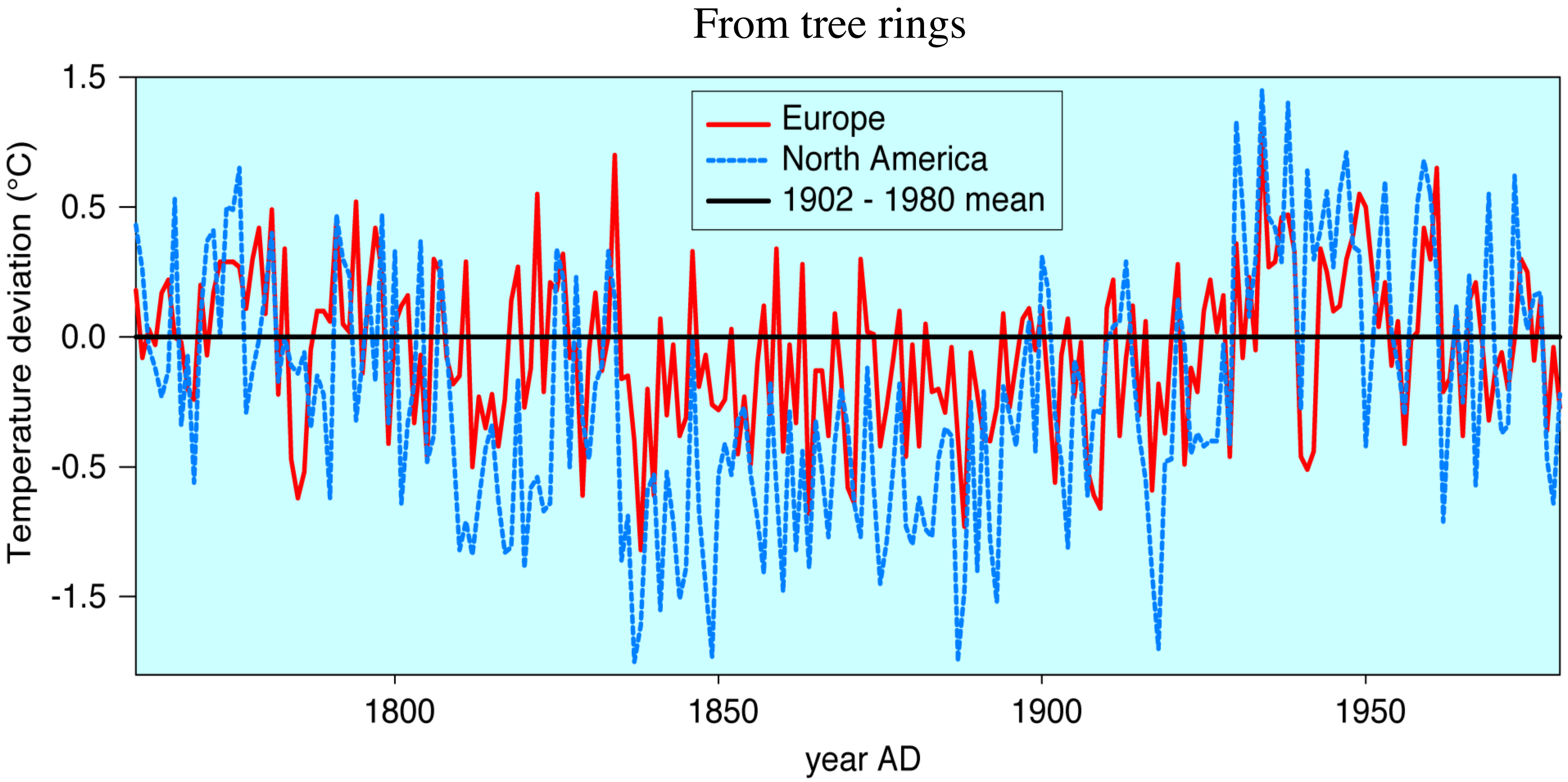
$$dQ = dU - dW$$

- “Heat added to a system is equal to the change in internal energy minus the work extracted”
- If there is no change in the internal energy, $dU = 0$

Is the Earth in radiative balance?

Considering multi-year / climate timescales ….

Reconstructed Mean Annual Temperatures for North America and Europe Since A.D. 1760



Paleoclimate, Global Change and the Future

Alverson, Bradley and Pederson eds., 2002

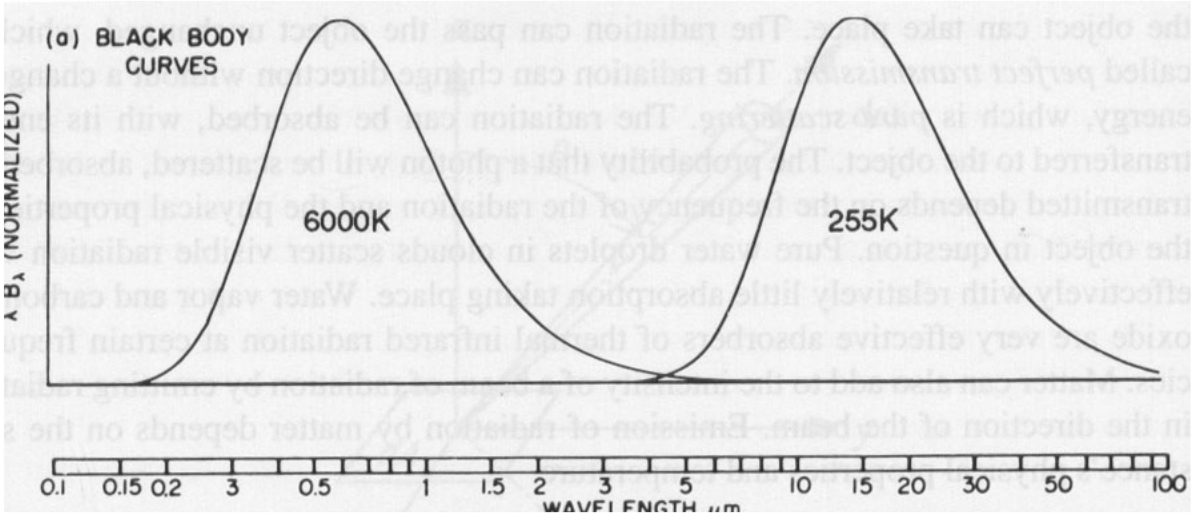
Chapter 6: R. S. Bradley et al., fig. 6.25 p. 136

Remember that the Earth receives ~350 W/m^2 of solar energy

Enough energy, at all times, on every m^2,
for 3+ 100W lightbulbs!

Earth maintains balance through radiation

GPC Fig 3.2a



Solar:

99% Visible and near IR

1% UV

Earth:

Thermal IR

Incoming Radiation

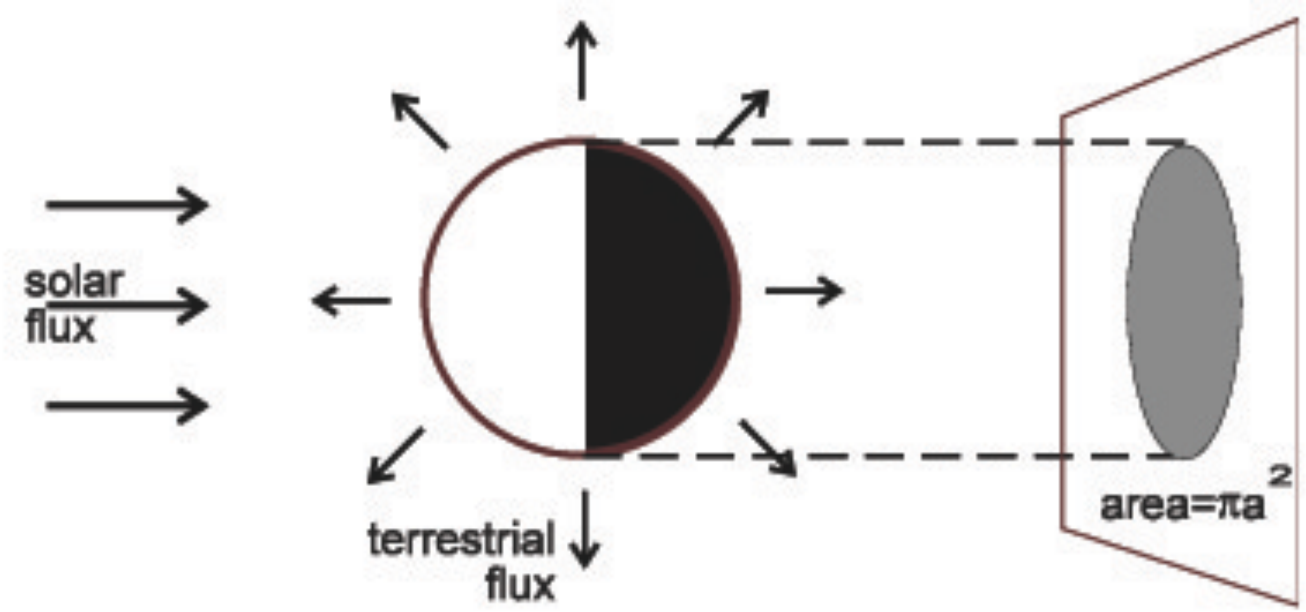
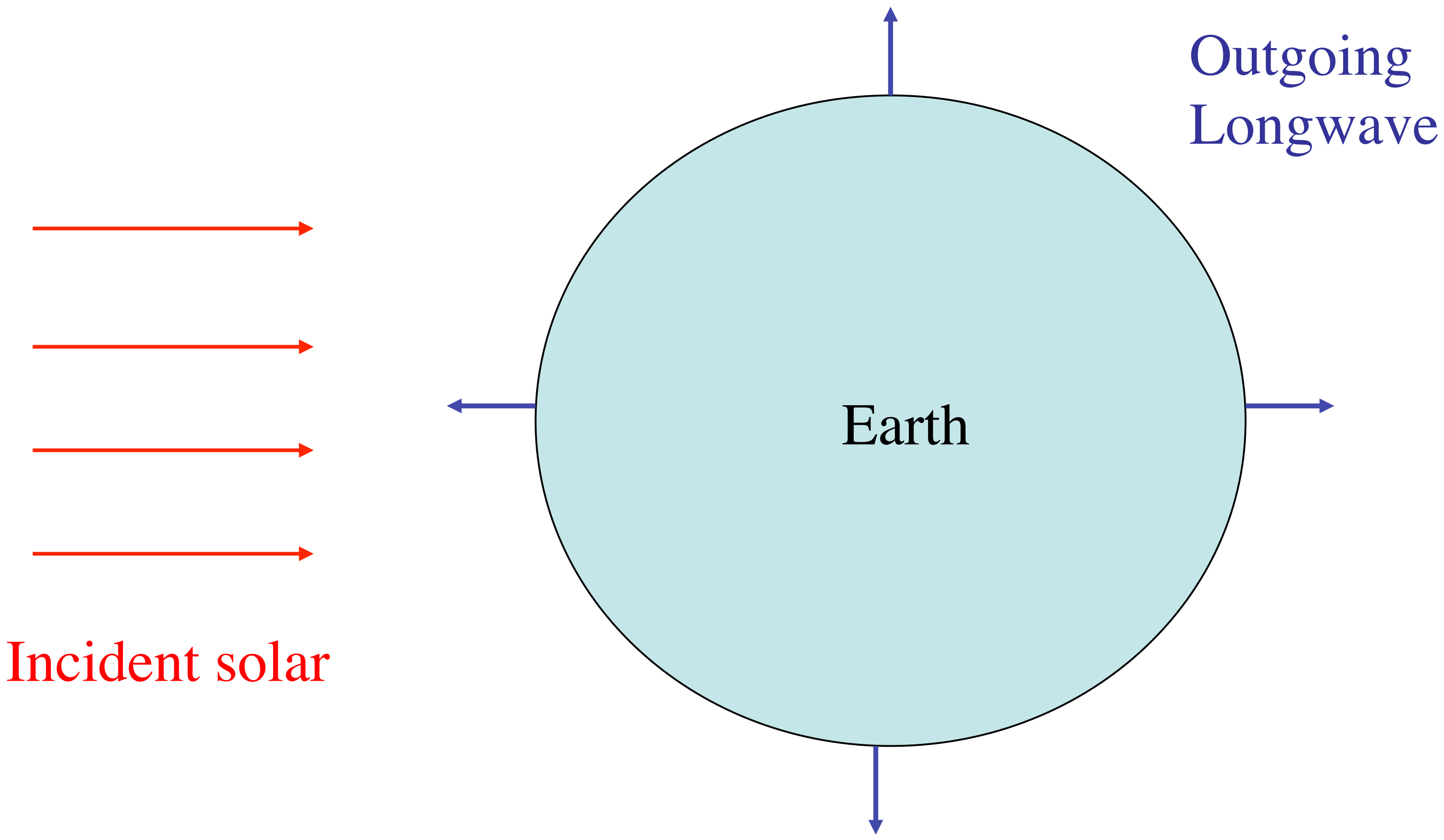


Figure 2.4: The spinning Earth is imagined to intercept solar flux over a disk and radiate terrestrial energy away isotropically from the sphere. Modified from Hartmann, 1994.

Marshall and Plumb, 2003

At what temperature does the Earth emit?



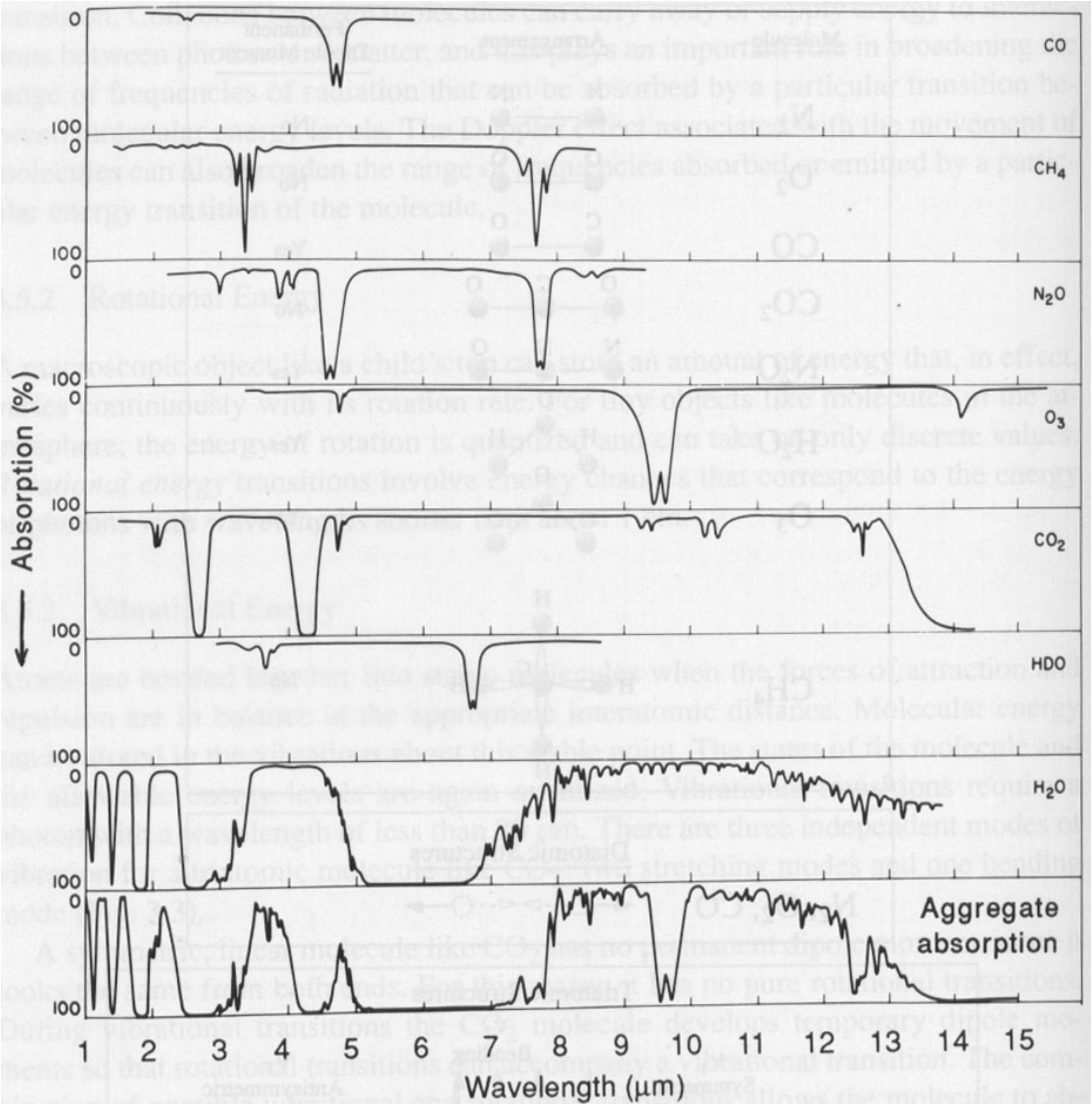
$T_s = 255K \ = -18C?$

Much colder than what is
observed at the surface…
(observed $T_s = 288K = 15C$)

We’ve left off the atmosphere

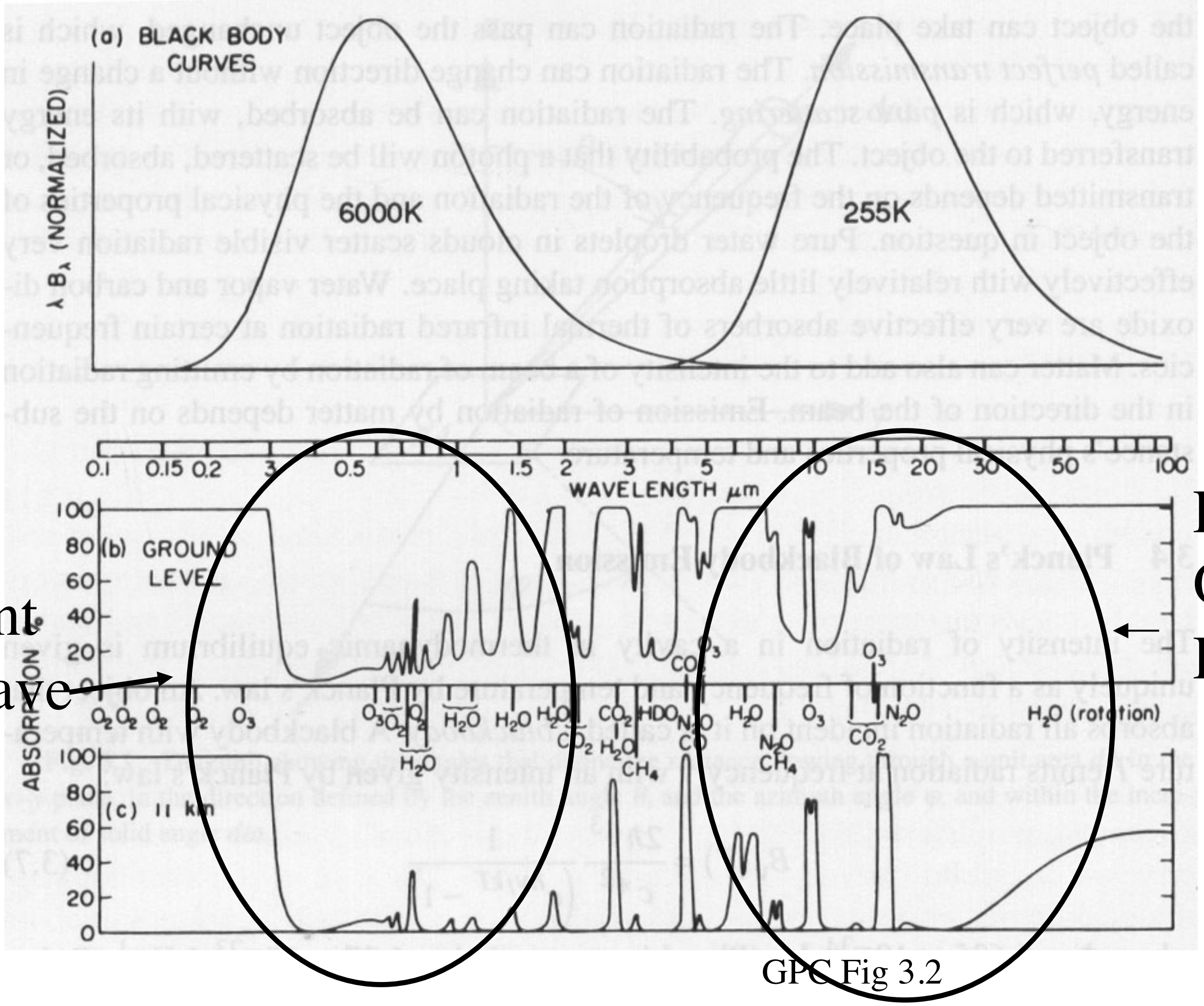
The atmosphere absorbs radiation

Spectra of Individual Molecules



GPC Fig 3.4

Combined absorption spectra and relation to emission



Relatively Transparent in Shortwave

Relatively Opaque in Longwave

GPC Fig 3.2

The Greenhouse Effect

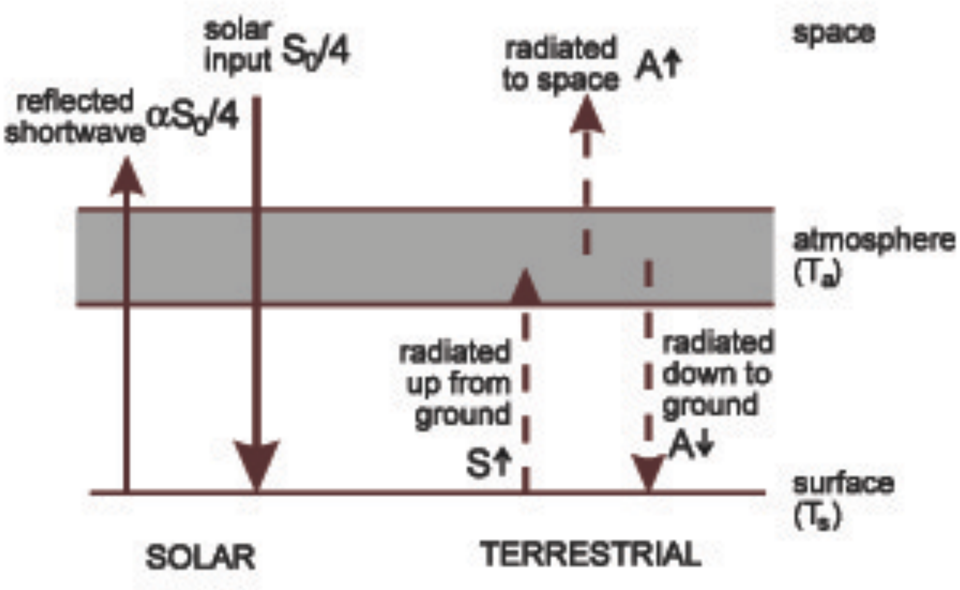


Figure 2.6: The simplest greenhouse model, comprising a surface at temperature T_s, and an atmospheric layer at temperature T_a, subject to incoming solar radiation $\frac{S_0}{4}$. The terrestrial radiation upwelling from the ground is assumed to be completely absorbed by the atmospheric layer.

Marshall and Plumb, 2003

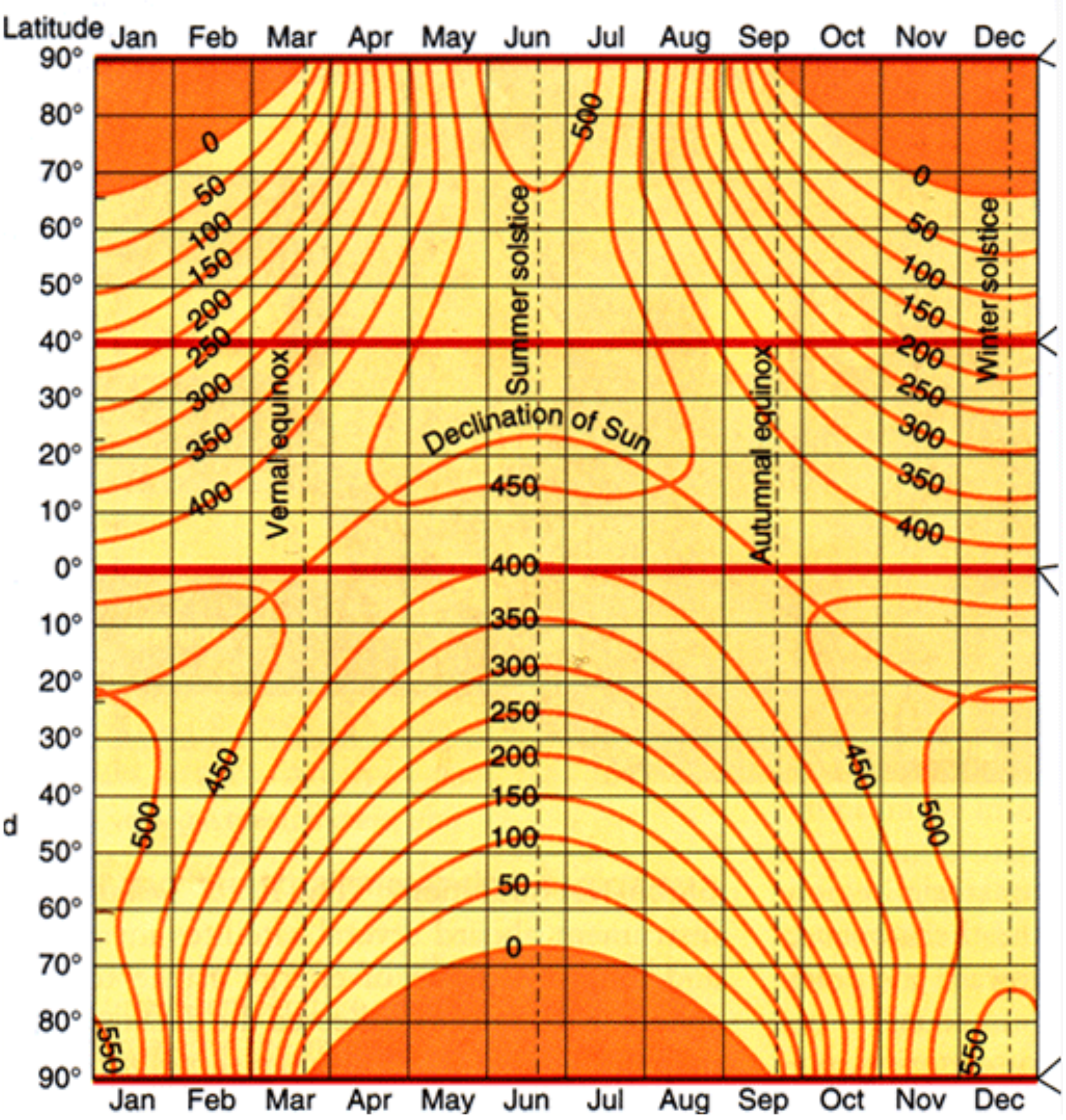
303K = 30C

Too warm, but not bad for a simple model.

If we relax assumptions about complete transparency in Shortwave and complete opacity in Longwave, we can do better

The global distribution of incoming radiant energy

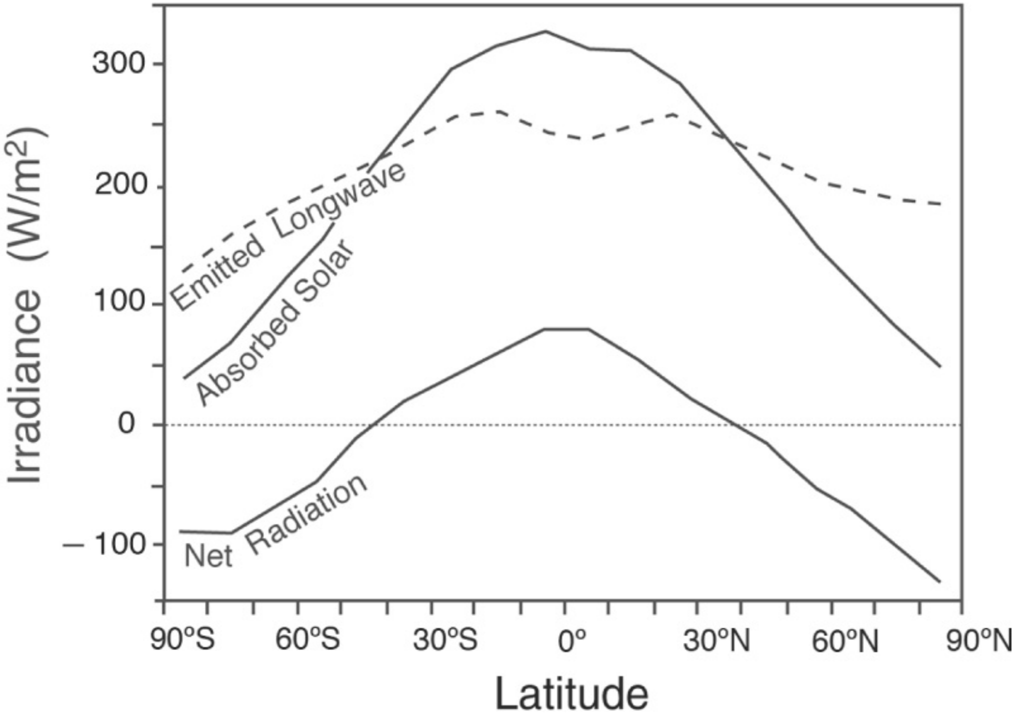
At TOA: Top of the Atmosphere



Daily Receipt of Insolation(W/m^2) at Top of the Atmosphere

Georgia Tech

Net Radiation at Top of Atmosphere
Excess at Equator, Deficit at Pole

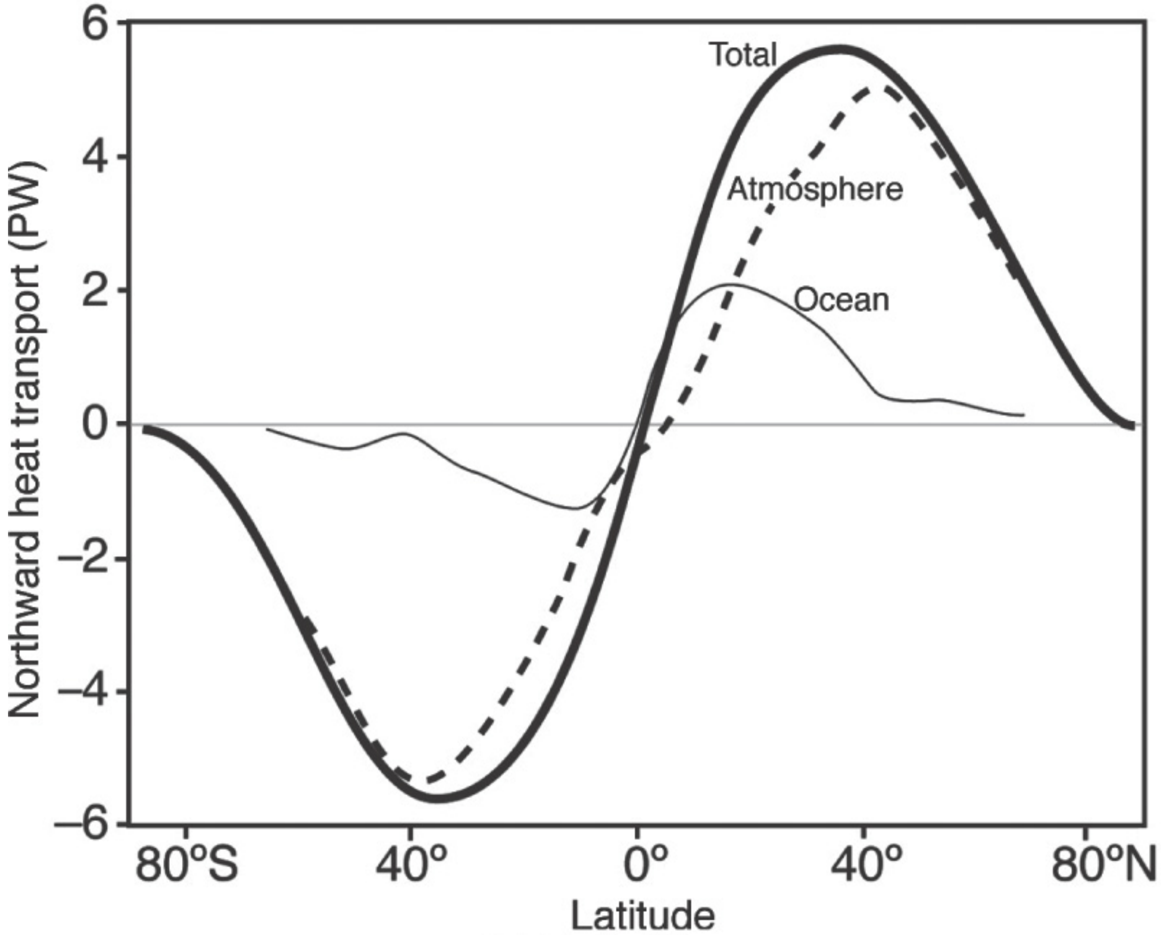


M&P Fig 5.5

- NASA Net Radiation Animation

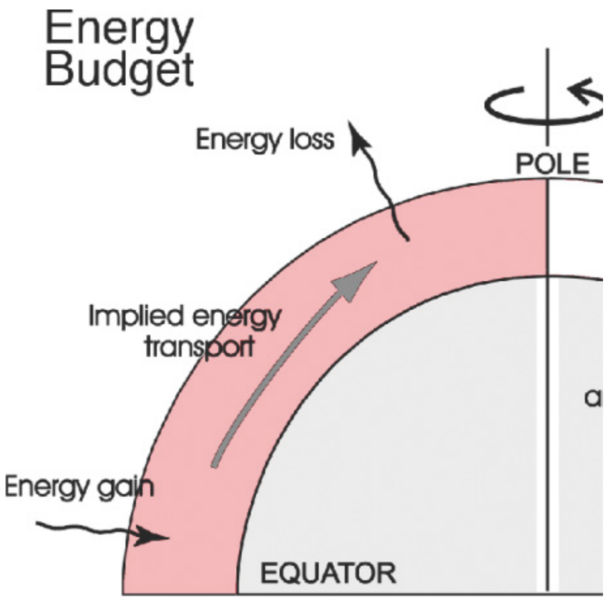
http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=CERES_NETFLUX_M

Equator to Pole Heat Transport Required



(From Trenberth and Caron (2001).)

M&P fig 8.13

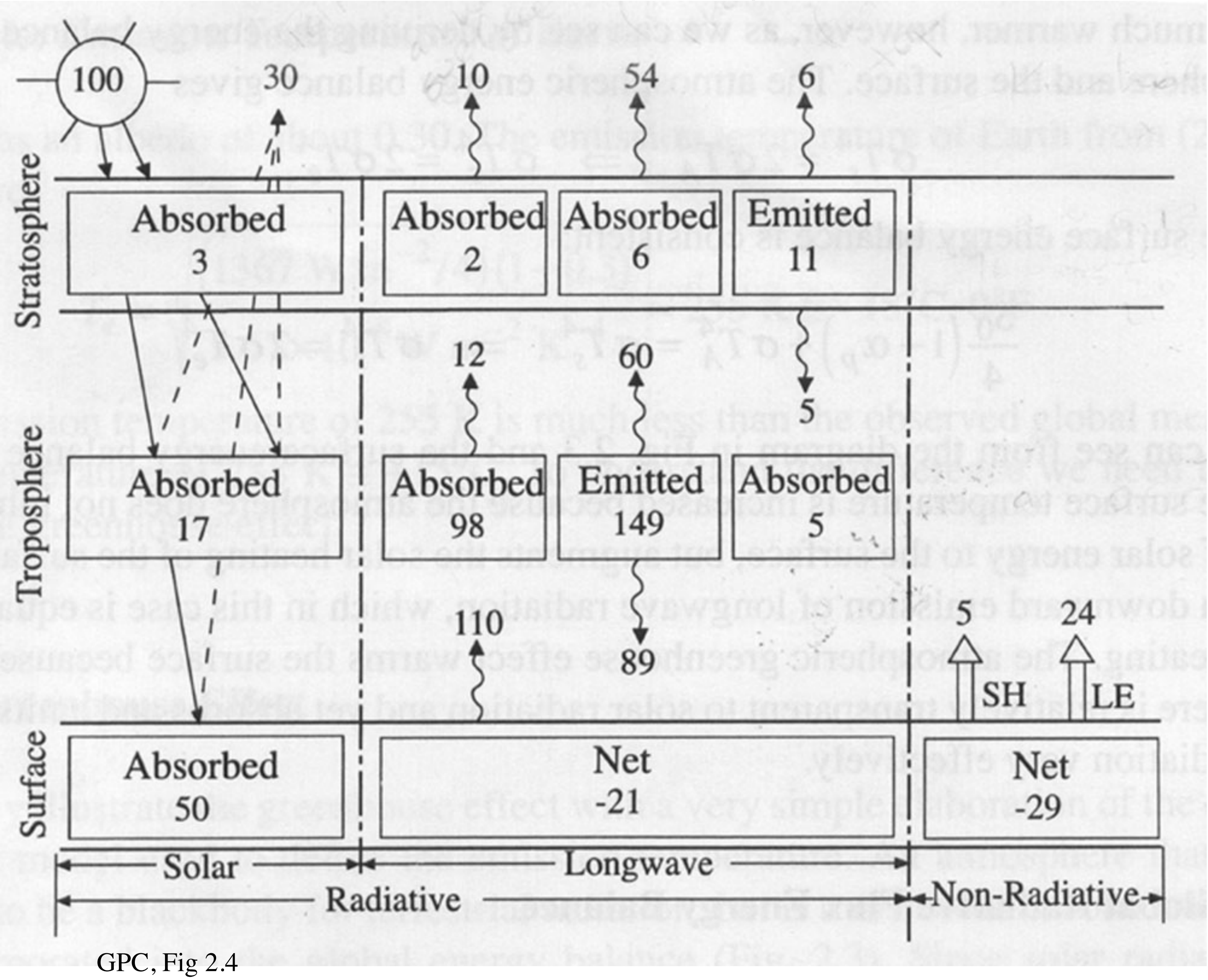


How is this heat moved within the atmosphere / ocean system?

Global Energy Flow:

Space/Atmosphere/Surface, 1D column

$100 = 342\ \mathrm{W/m^2}$

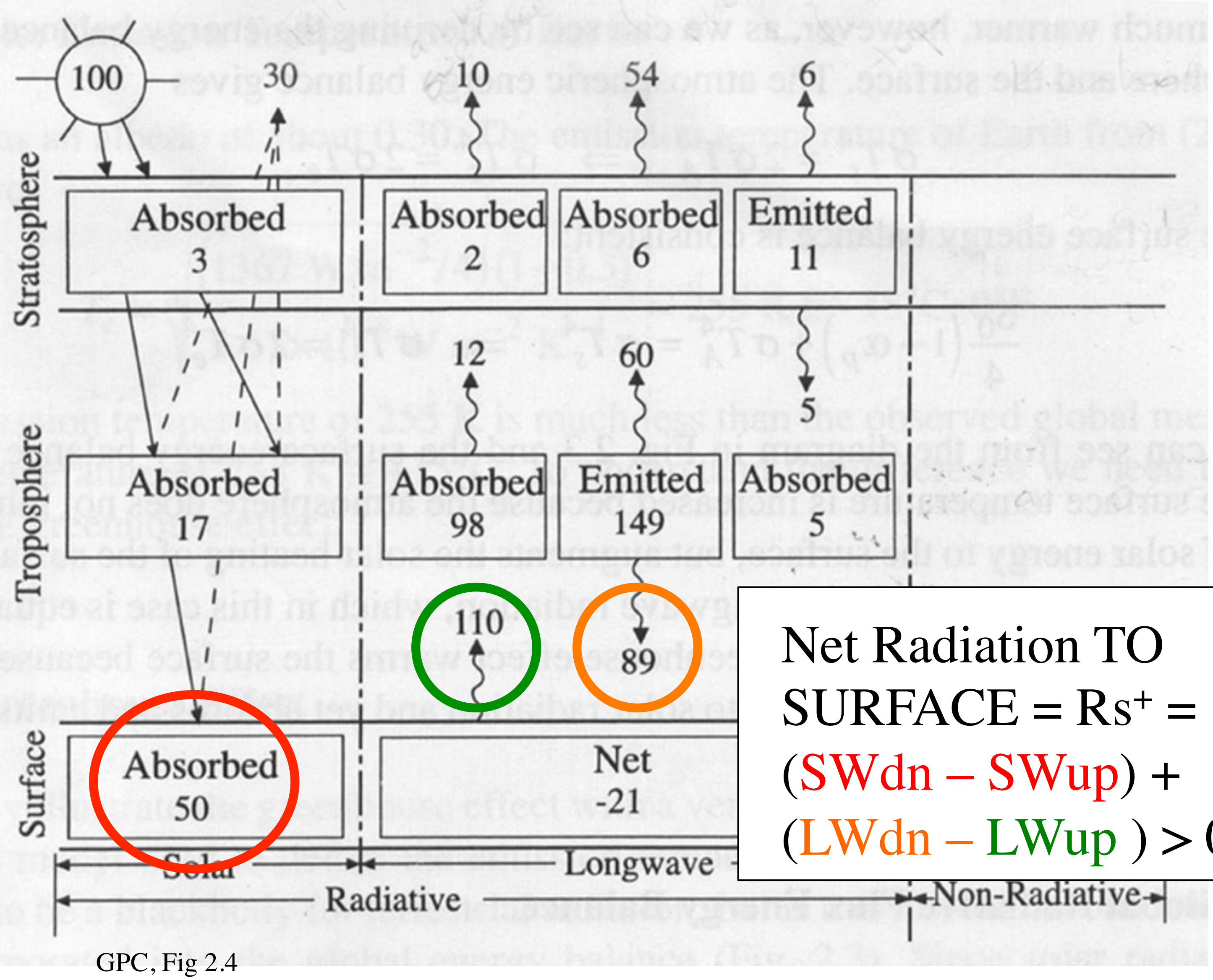


GPC, Fig 2.4

Global Energy Flow:

Space/Atmosphere/Surface, 1D column

$100 = 342\ W/m^2$



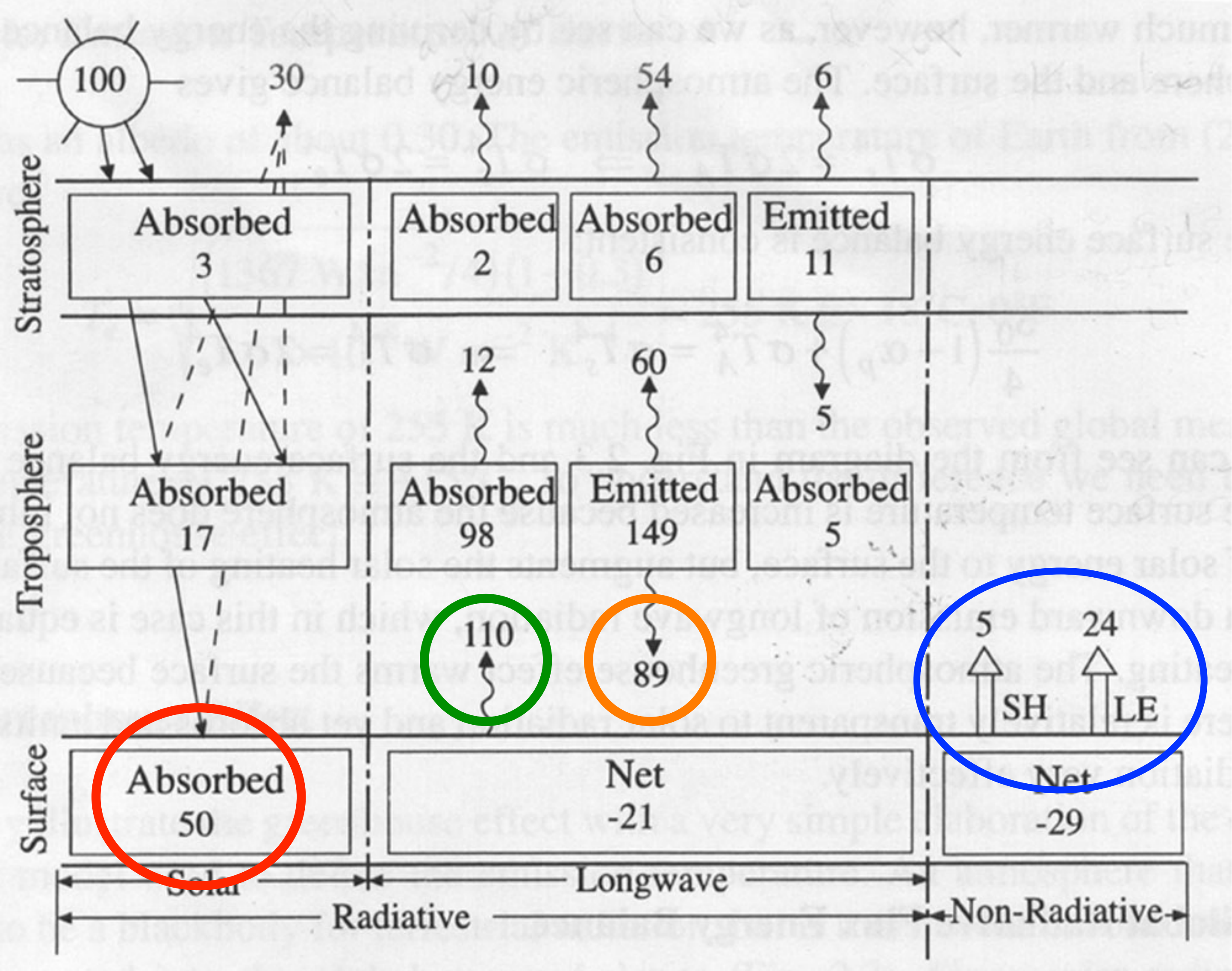
GPC, Fig 2.4

Net Radiation TO SURFACE = R_s^+ =
(SWdn – SWup) +
(LWdn – LWup) > 0

Global Energy Flow:

Space/Atmosphere/Surface, 1D column

$100 = 342\ \mathrm{W/m^2}$



GPC, Fig 2.4

Latent and Sensible Heat

- Latent Heat =“Energy in Evaporated Water”
  - Energy required to evaporate (cooling surface)
  - Energy released with condensation (warming in the atmosphere with precipitation)
- Sensible heat
  - Direct, conductive heat
  - Molecular motions

Radiative and Non-Radiative Fluxes to/from the Ocean

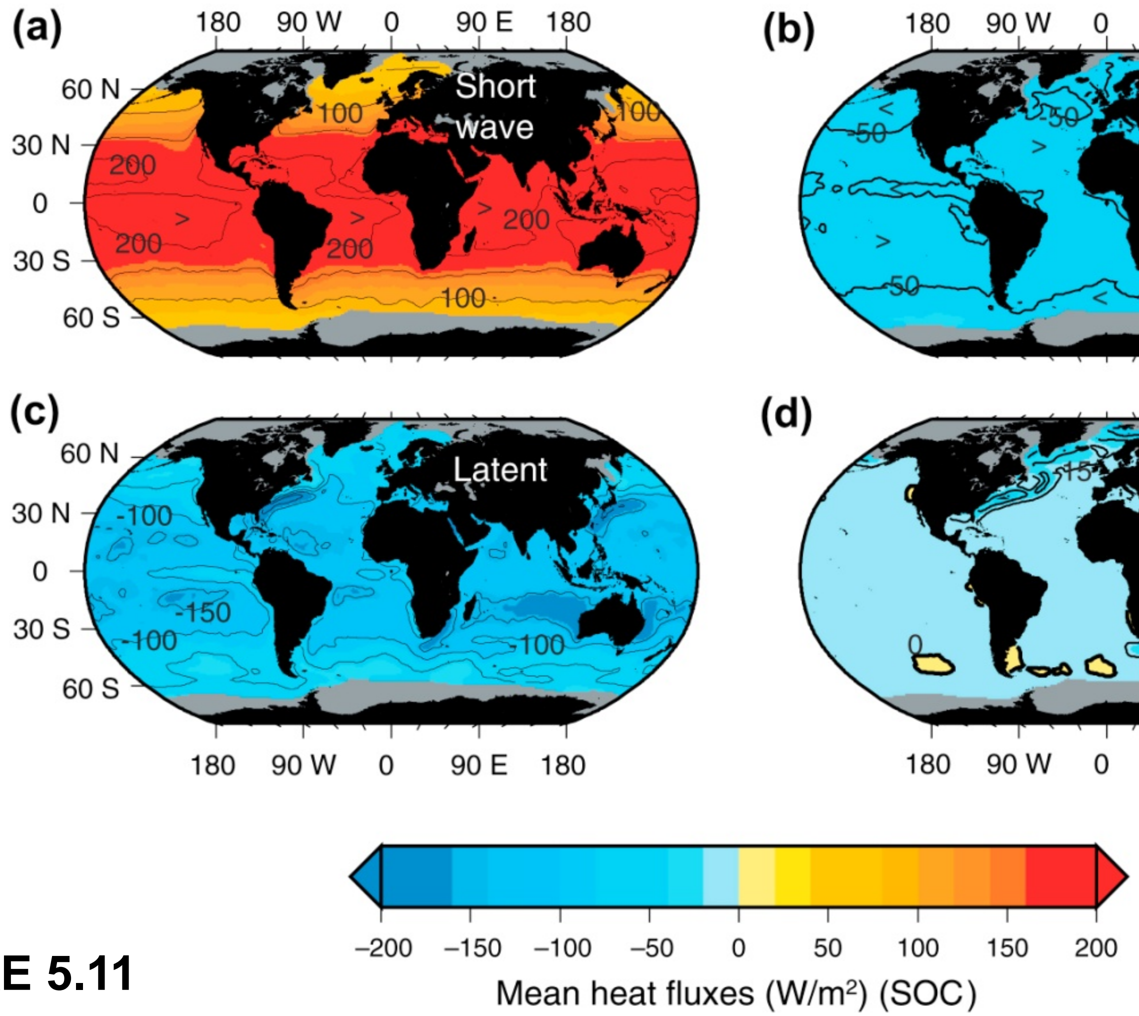


FIGURE 5.11

Annual average heat fluxes (W/m^2). (a) Shortwave heat flux Q_s. (b) Longwave (back radiation) heat flux Q_b. (c) Evaporative (latent) heat flux Q_e. (d) Sensible heat flux Q_h. Positive (yellows and reds): heat gain by the sea. Negative (blues): heat loss by the sea. Contour intervals are 50 W/m^2 in (a) and (c), 25 W/m^2 in (b), and 15 W/m^2 in (d). Data are from the National Oceanography Centre, Southampton (NOCS) climatology (Grist and Josey, 2003). This figure can also be found in the color insert.

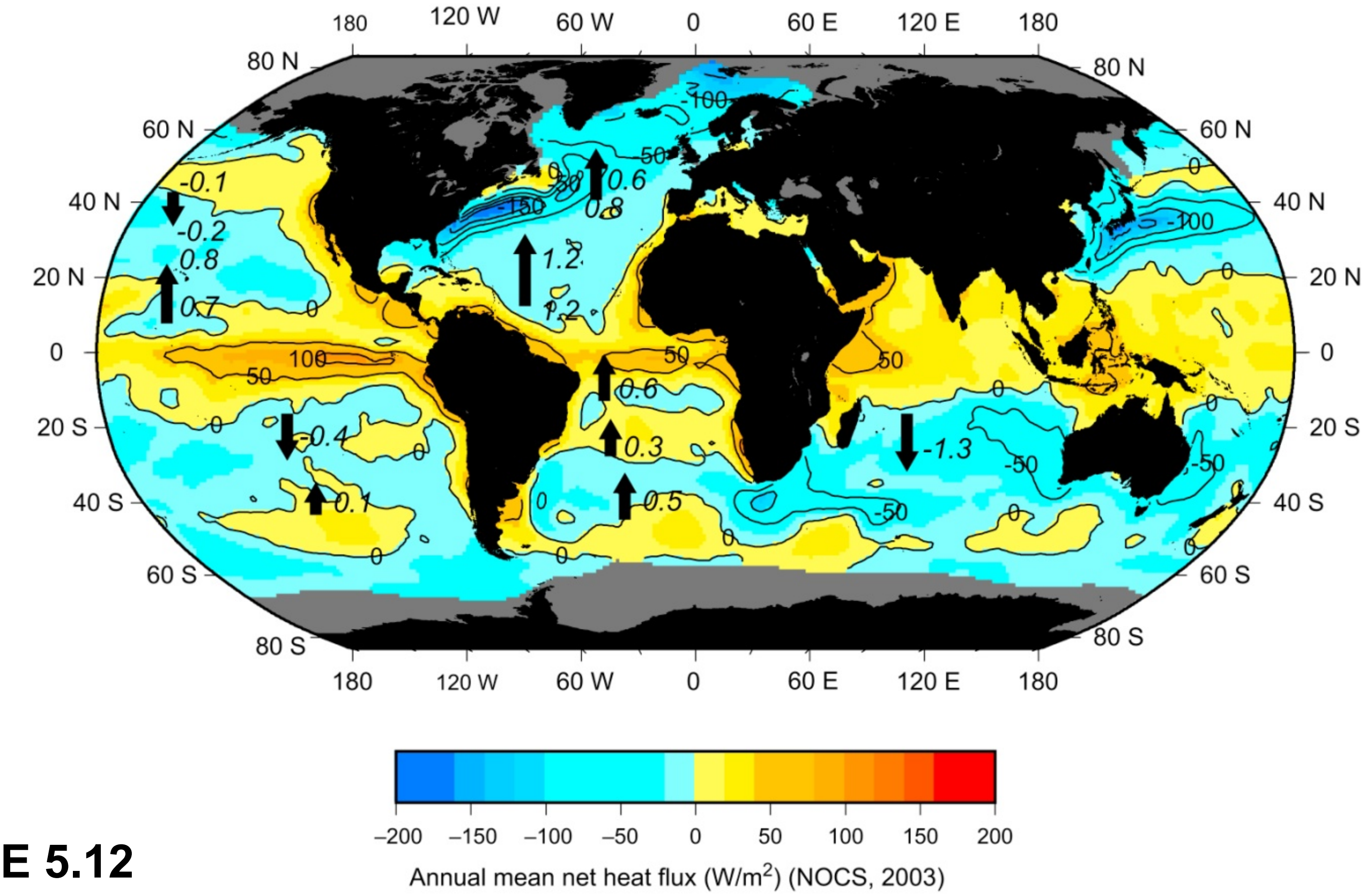


FIGURE 5.12

Annual average net heat flux (W/m^2). Positive: heat gain by the sea. Negative: heat loss by the sea. Data are from the NOCS climatology (*Grist and Josey, 2003*). Superimposed numbers and arrows are the meridional heat transports (PW) calculated from ocean velocities and temperatures, *based on Bryden and Imawaki (2001) and Talley (2003)*. Positive transports are northward. The online supplement to Chapter 5 (Figure S5.8) includes another version of the annual mean heat flux, from Large and Yeager (2009). This figure can also be found in the color insert.

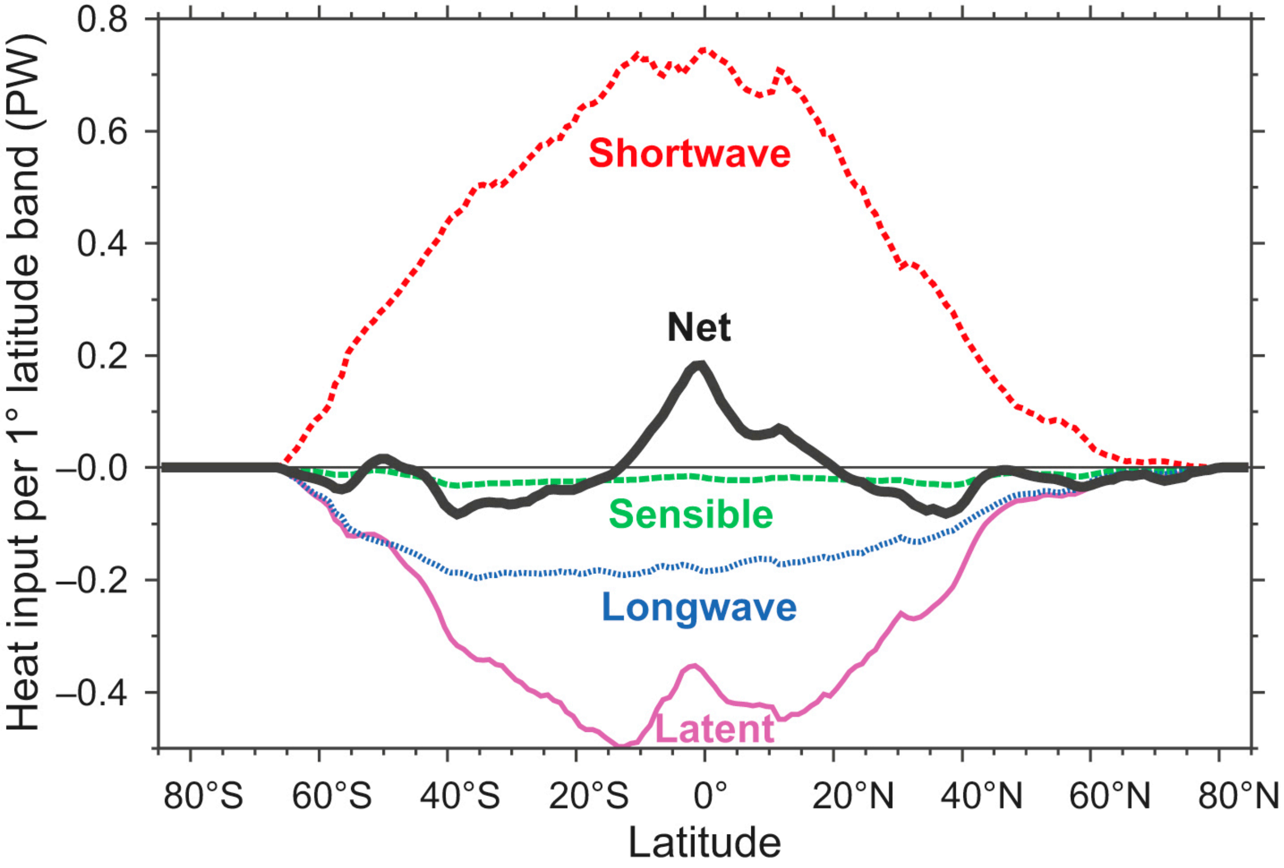


FIGURE 5.13

Heat input through the sea surface (where 1 PW = 10^{15} W) (world ocean) for 1° latitude bands for all components of heat flux. *Data are from the NOCS climatology (Grist and Josey, 2003).*

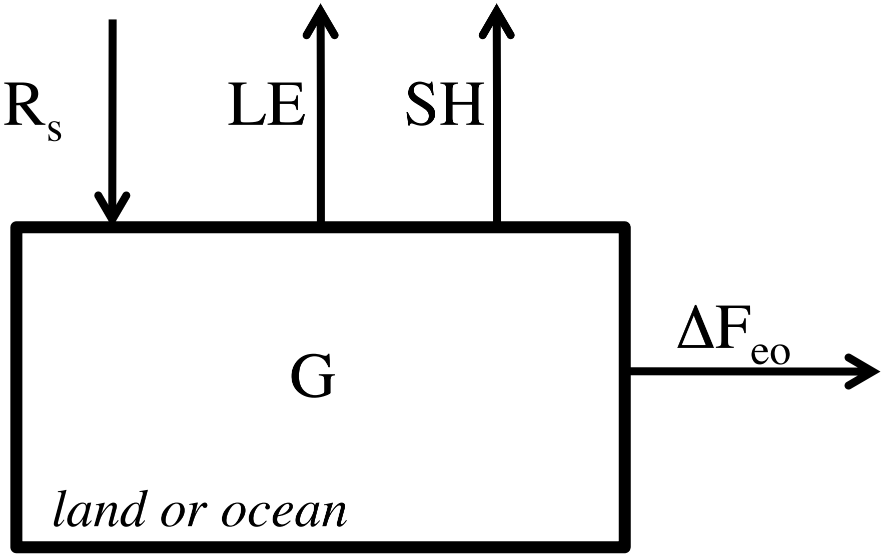
Energy Balance of the Surface

- Apply first law of thermo to the surface (as opposed to atmosphere)
- G = Storage = d(Surface Energy)/dt = dE_s/dt
- R_s = Net Radiation

  = SW-LW
- LE = Latent
- SH = Sensible
- ΔF_{eo} = Transport

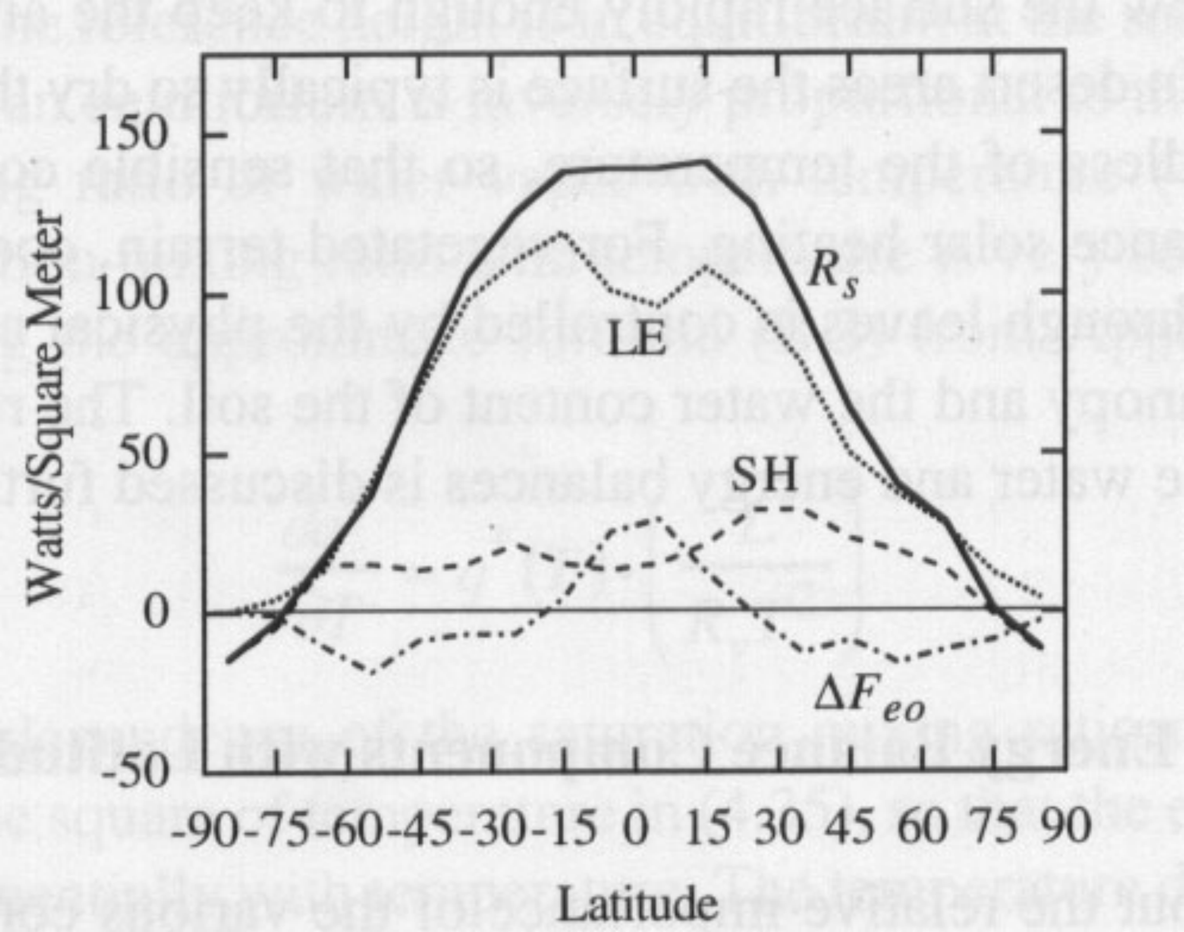
BALANCE EQUATION for next few plots

$$\boxed{G = Rs^{+} - LE - SH - \Delta F_{eo}}$$



Global Surface Balance

$G = Rs^{+} - LE - SH - \Delta F_{eo}$

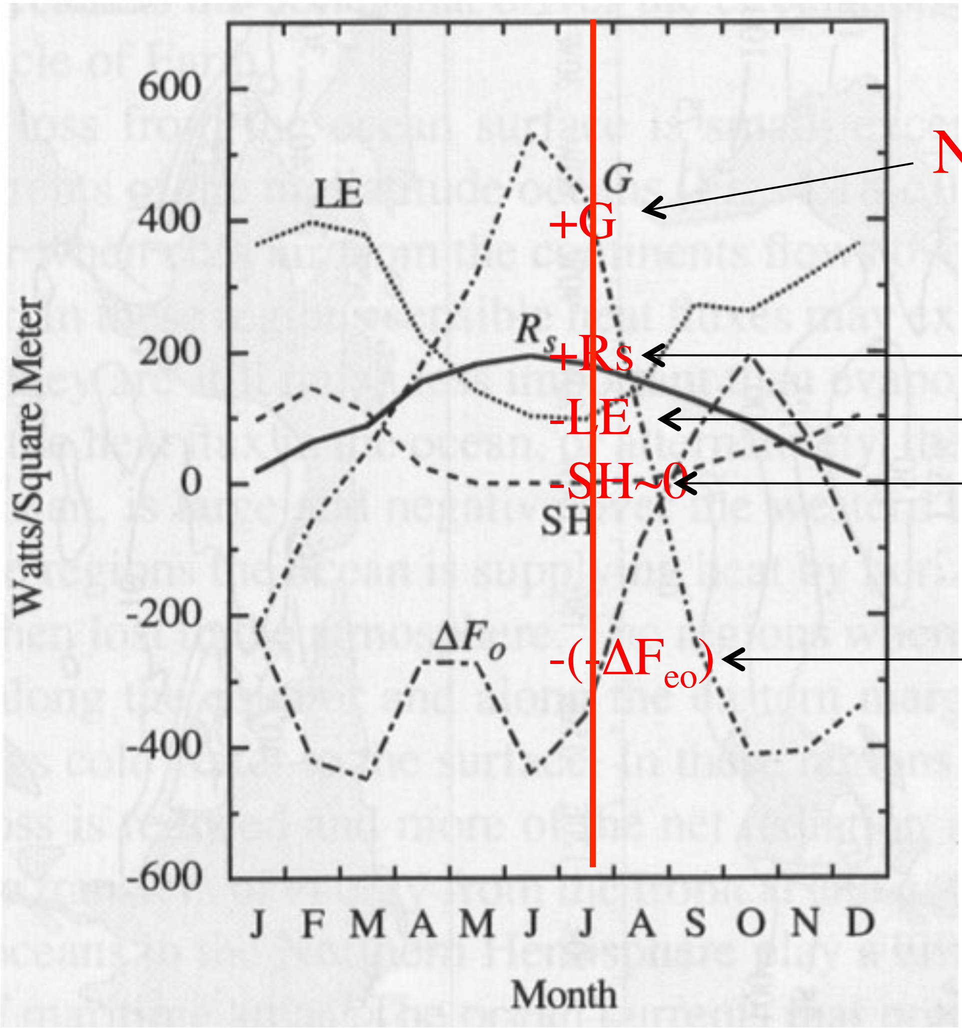


GPC, Fig 4.11

G=0 for long-term, global mean

Ocean Surface, 38N in Gulf Stream, seasonal

$$G = Rs^{+} - LE - SH - \Delta F_{eo}$$



GPC, Fig 4.17

Net heat gain = 400

Warming = 200

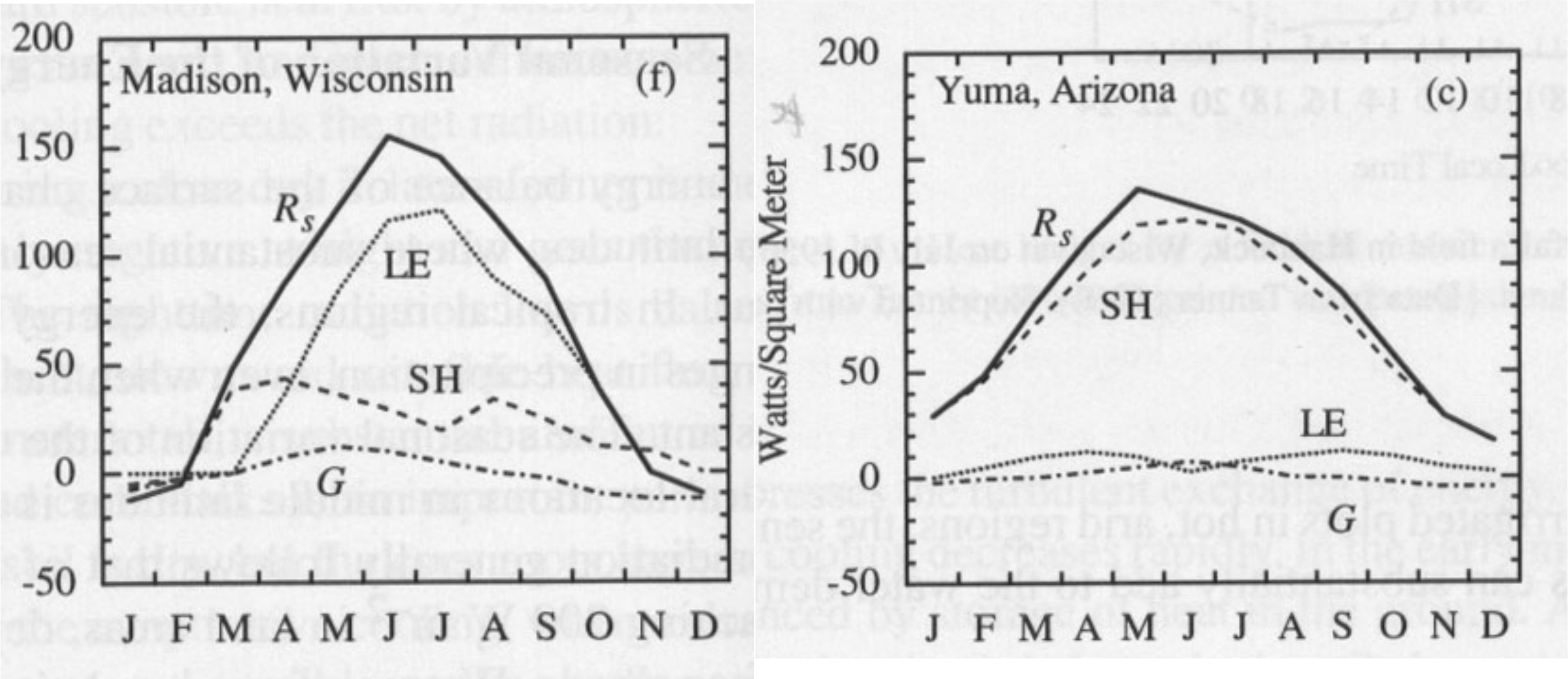
Cooling = -100

Neutral = 0

Warming = -(-300)

400

Seasonal:
Madison vs. Arizona desert
$G = Rs^+ – LE – SH - \Delta F_{eo}$



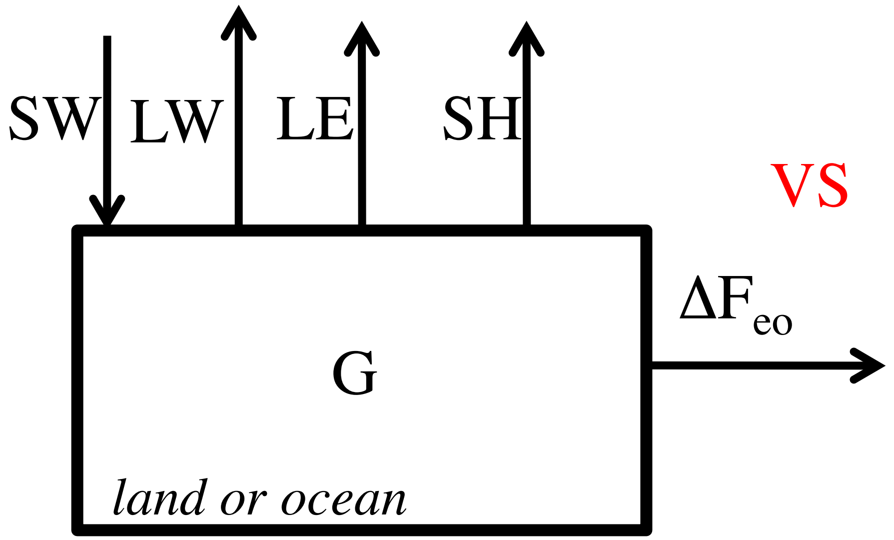
GPC, Fig 4.16 (c,f)

Flux Notation – Must take care!

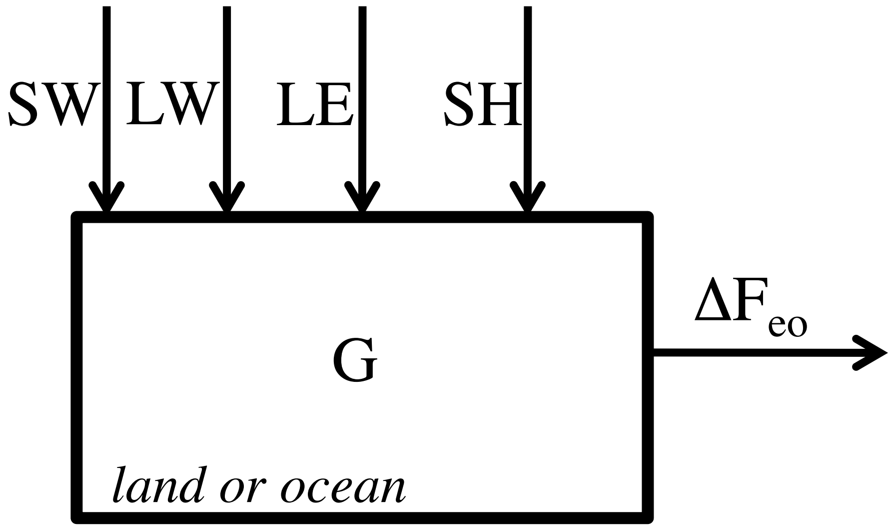
- Shortwave
  - Usually positive down at the surface (as in Talley)
  - BUT the fields in exercise from NCEP are positive up

- Longwave and non-radiative
  - May be positive up or positive down (Talley et al. 2011)

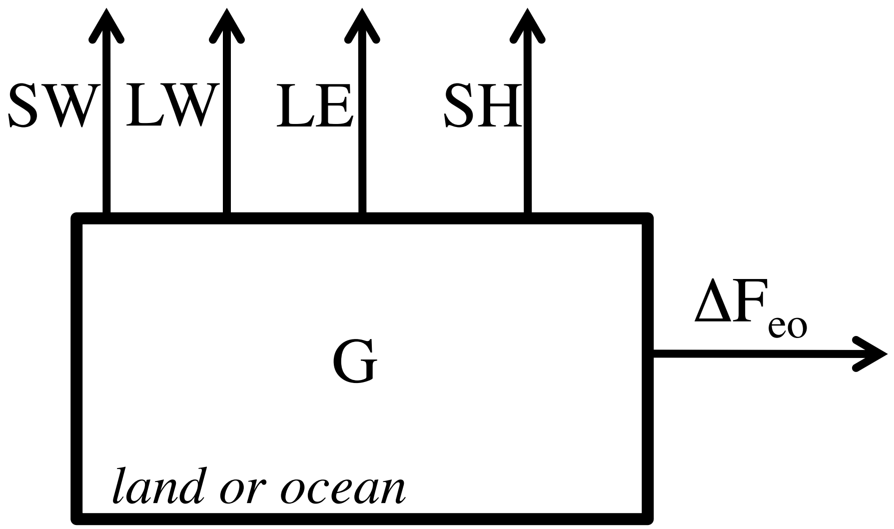
- When you look at a plot, first orient yourself to the sign convention


SW
LW
LE
SH
ΔF_{eo}
G
land or ocean

VS


SW
LW
LE
SH
ΔF_{eo}
G
land or ocean

VS

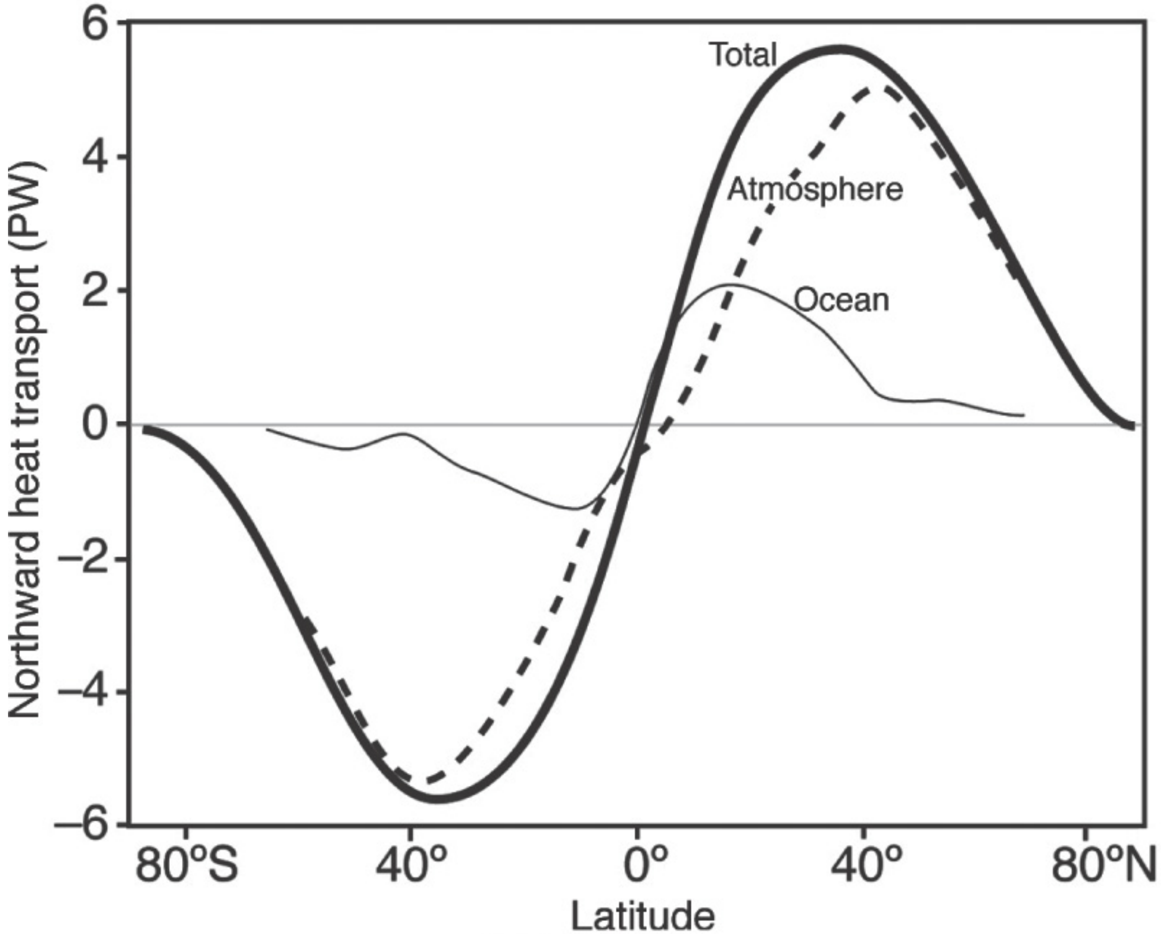

SW
LW
LE
SH
ΔF_{eo}
G
land or ocean

Heat Capacity Calculation

The ocean stores and moves sensible heat (much of which returns to atmosphere as LW);

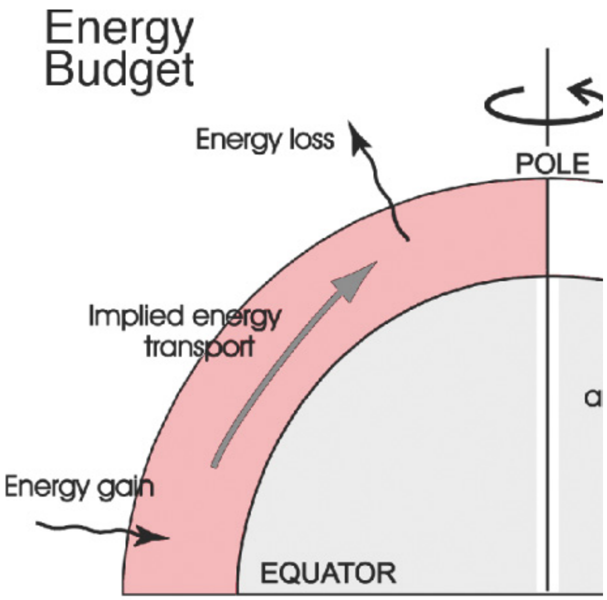
the ocean also provides the water critical to latent fluxes.

Equator to Pole Heat Transport Required

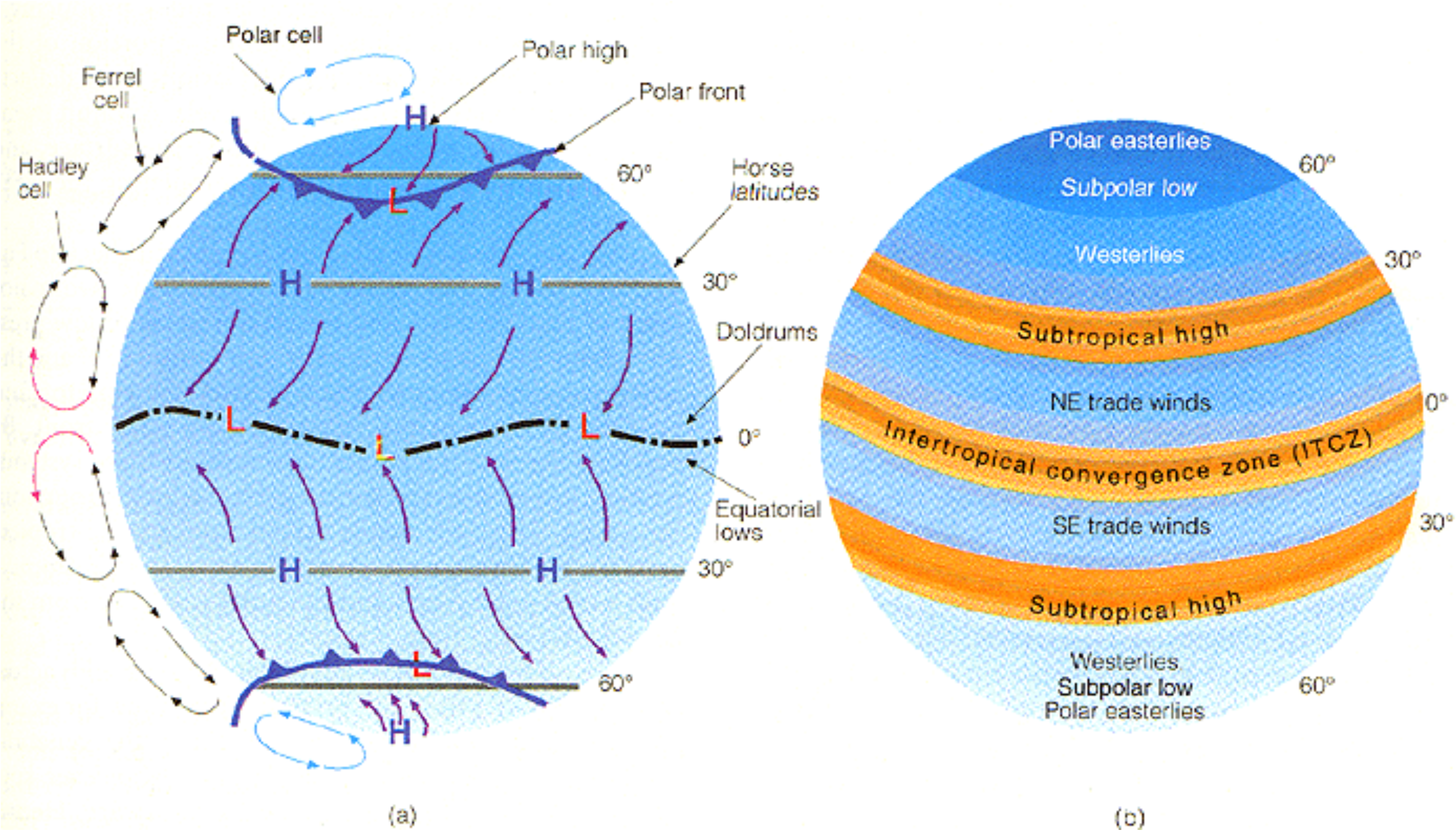


(From Trenberth and Caron (2001).)

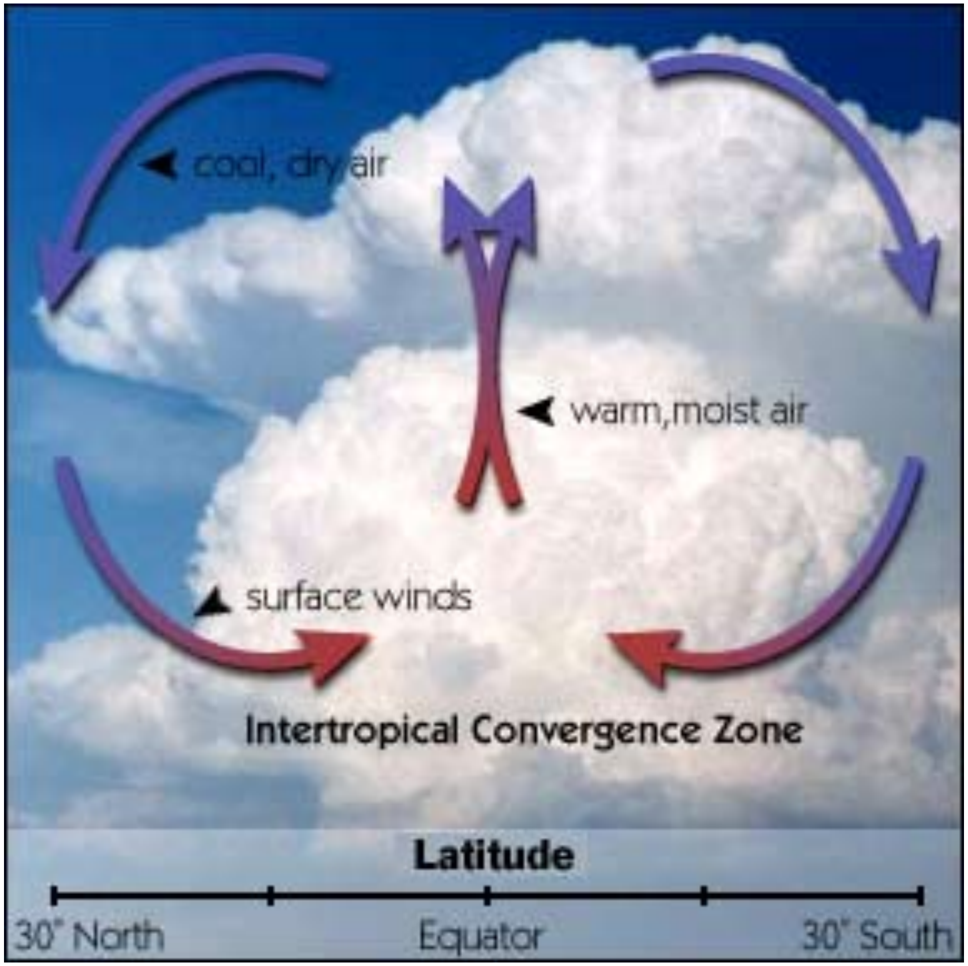
M&P fig 8.13



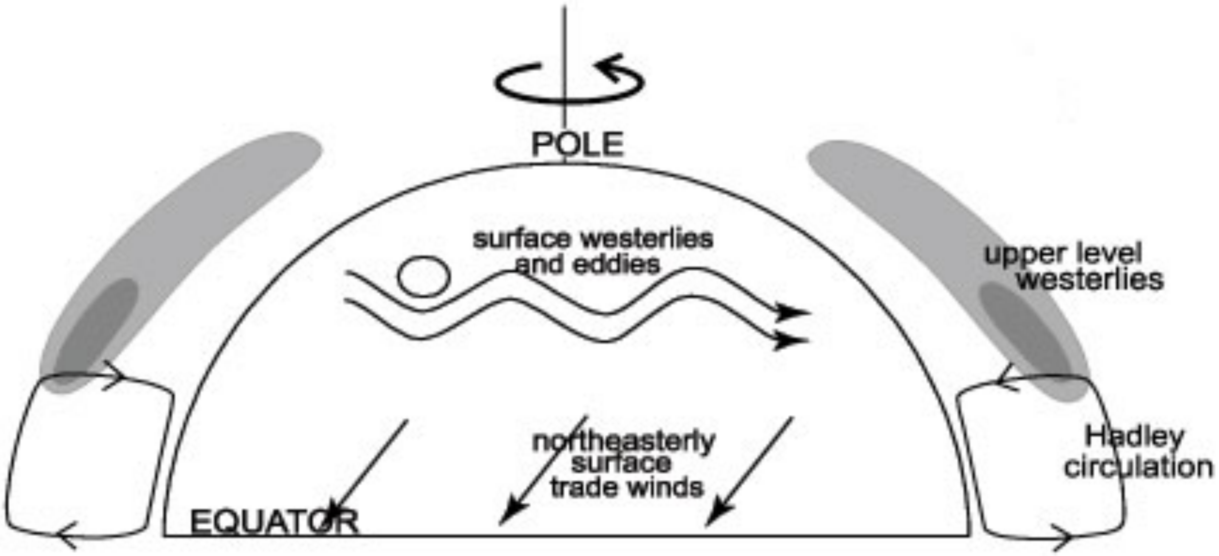
General Circulation



Hadley Cell 0-30^o

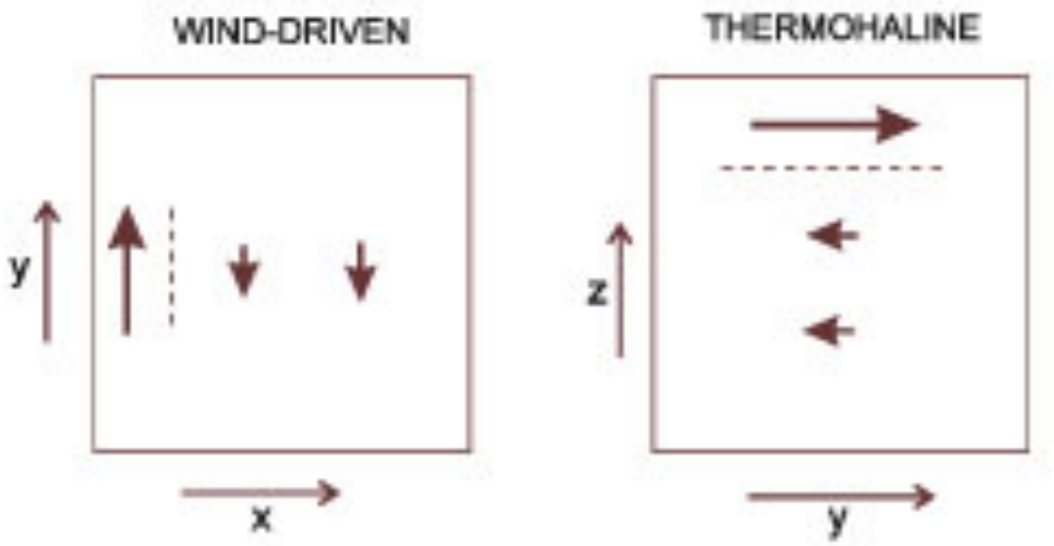


Observed general circulation

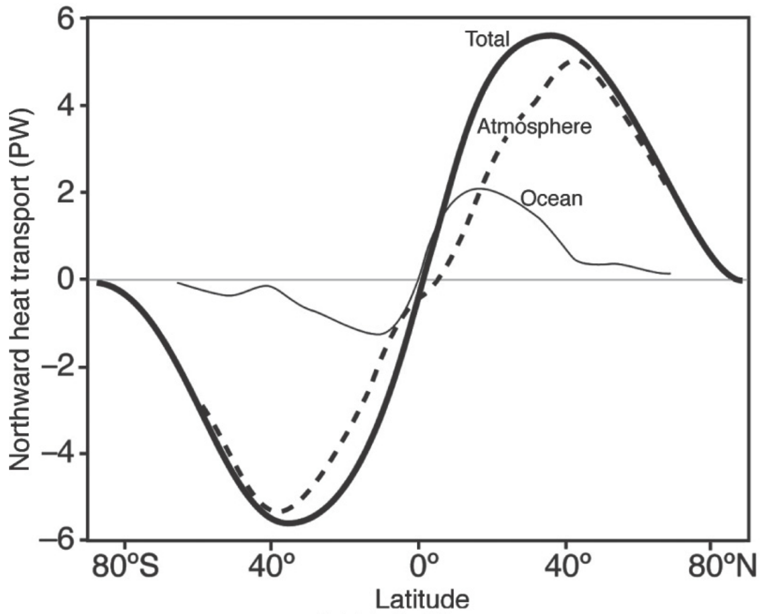


MP Fig 8.2

Heat Transport in Ocean

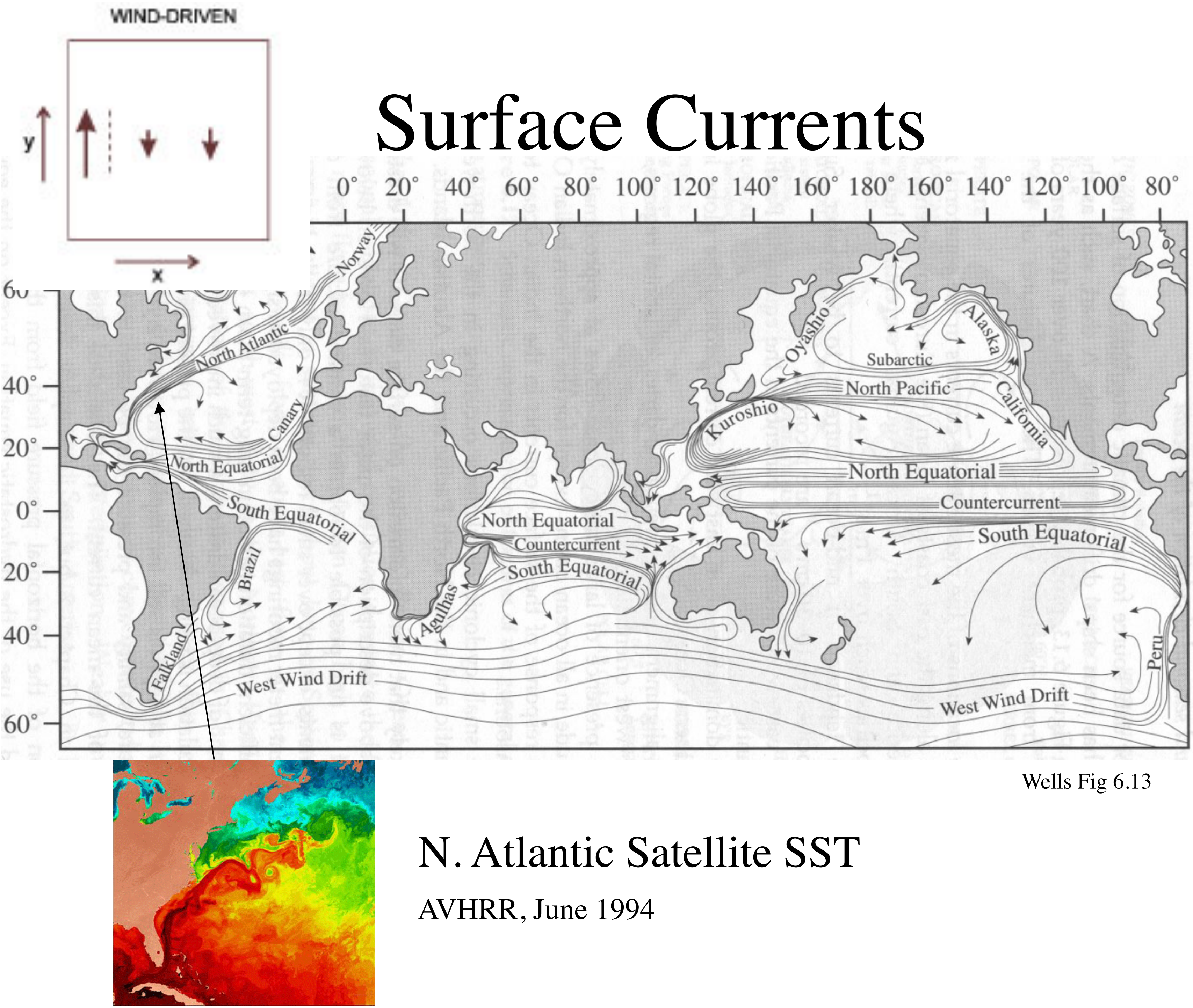


Marshall and Plumb, 2003



(From Trenberth and Caron (2001).)

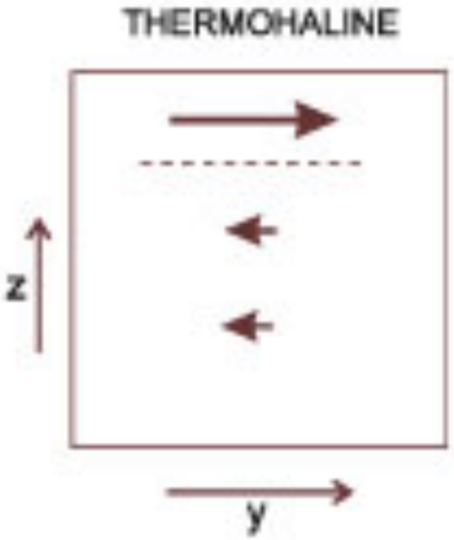
Surface Currents



Wells Fig 6.13

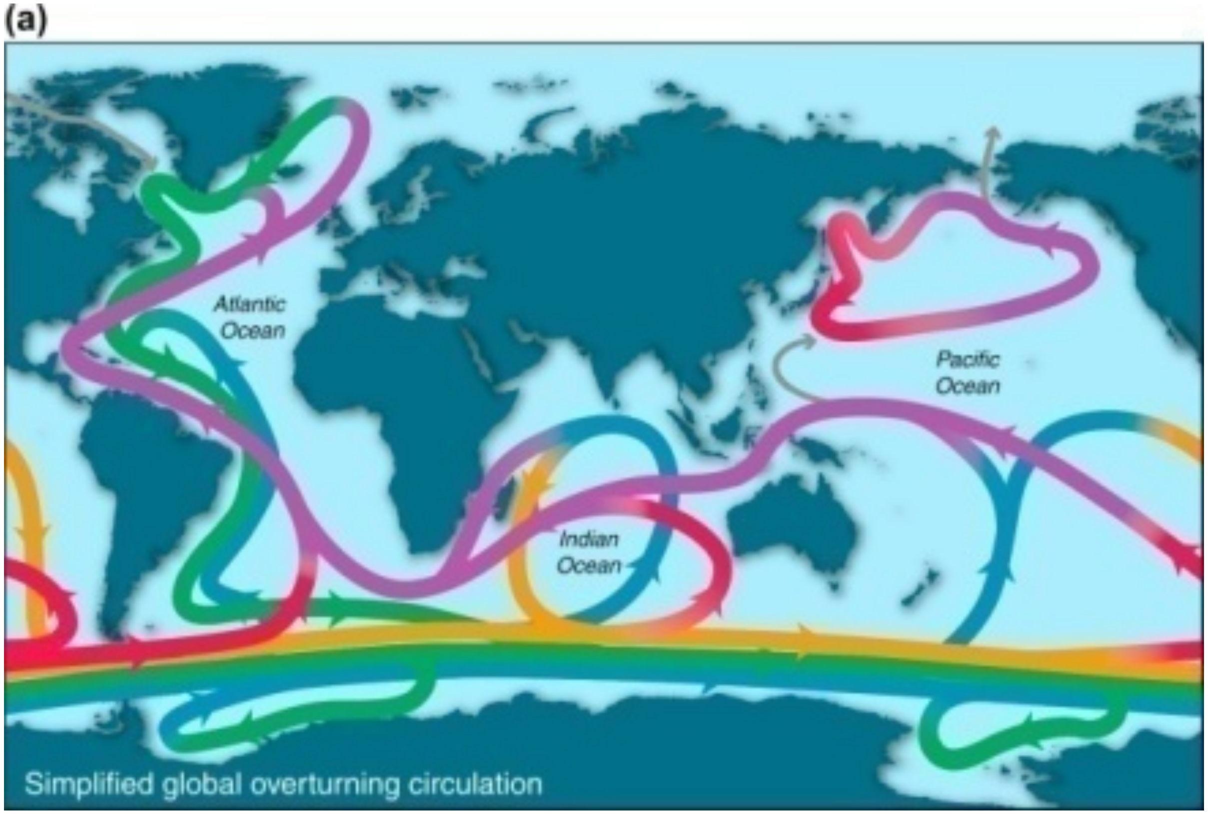
N. Atlantic Satellite SST

AVHRR, June 1994



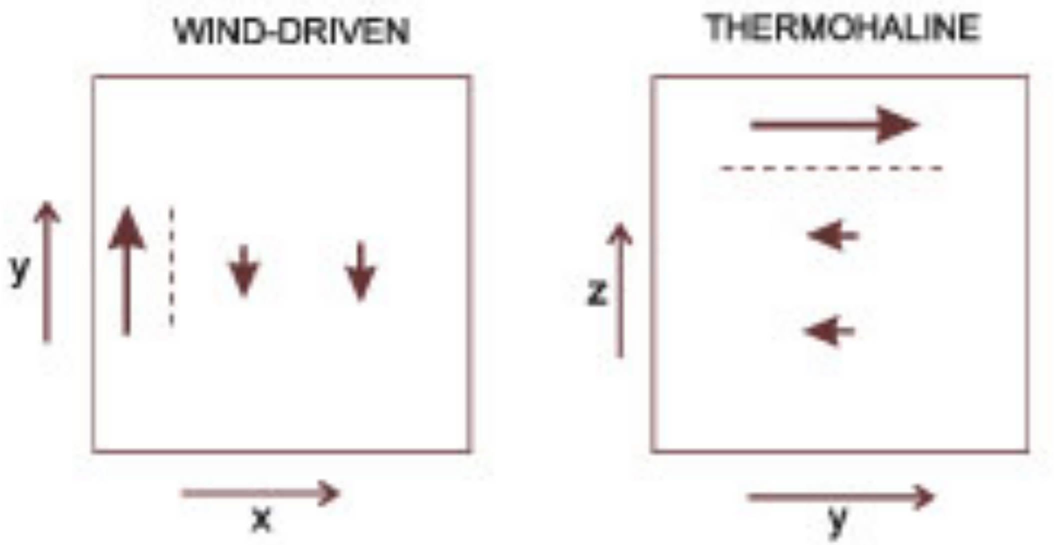
Thermohaline Circulation

(simplified)

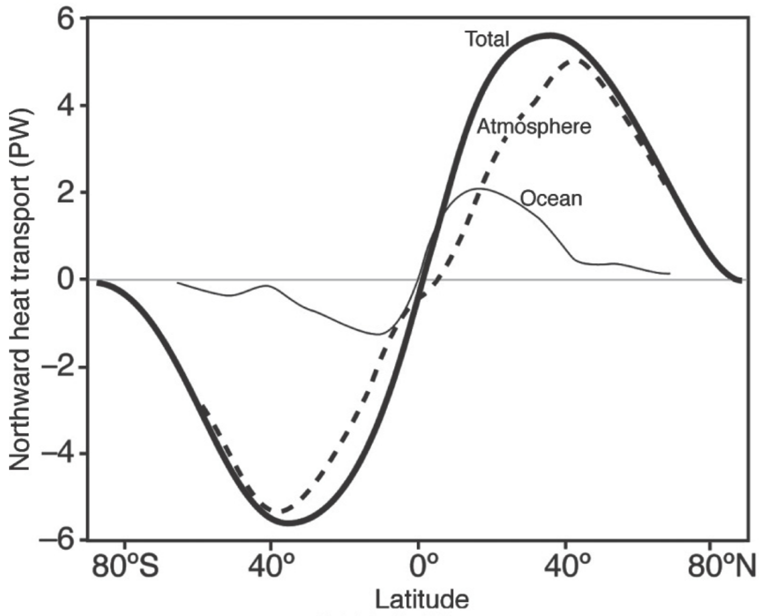


Talley et al 2011

Heat Transport in Ocean



Marshall and Plumb, 2003



(From Trenberth and Caron (2001).)

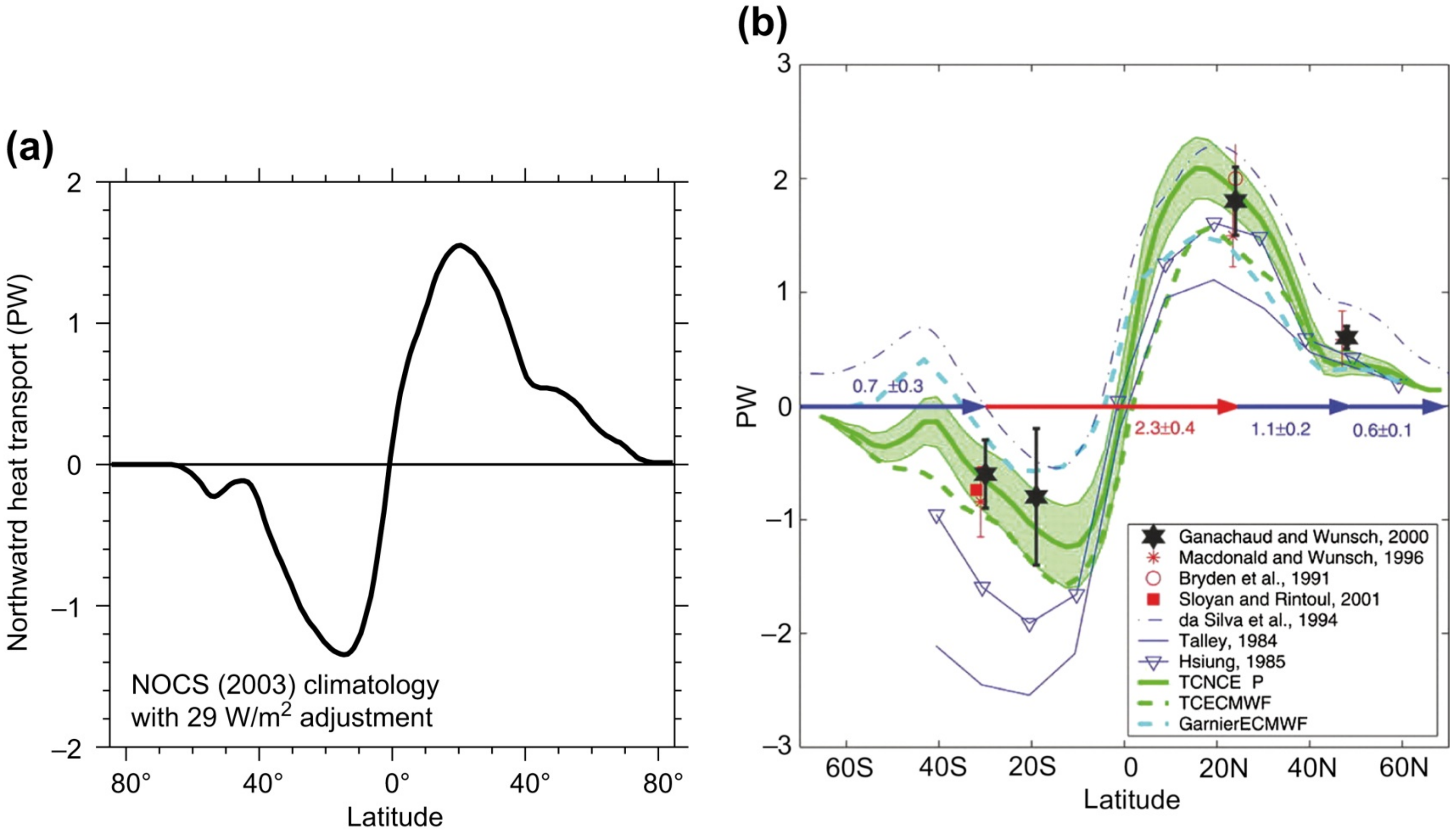


FIGURE 5.14

Poleward heat transport (W) for the world's oceans (annual mean). (a) Indirect estimate (light curve) summed from the net air–sea heat fluxes of Figures 5.12 and 5.13. Data are from the NOCS climatology, adjusted for net zero flux in the annual mean. *Data from Grist and Josey (2003)*. A similar figure, based on the Large and Yeager (2009) heat fluxes is reproduced in the online supplement (Figure S5.9). (b) Summary of various direct estimates (points with error bars) and indirect estimates. The direct estimates are based on ocean velocity and temperature measurements. The range of estimates illustrates the overall uncertainty of heat transport calculations. © American Meteorological Society. Reprinted with permission. *Source: From Ganachaud and Wunsch (2003)*.