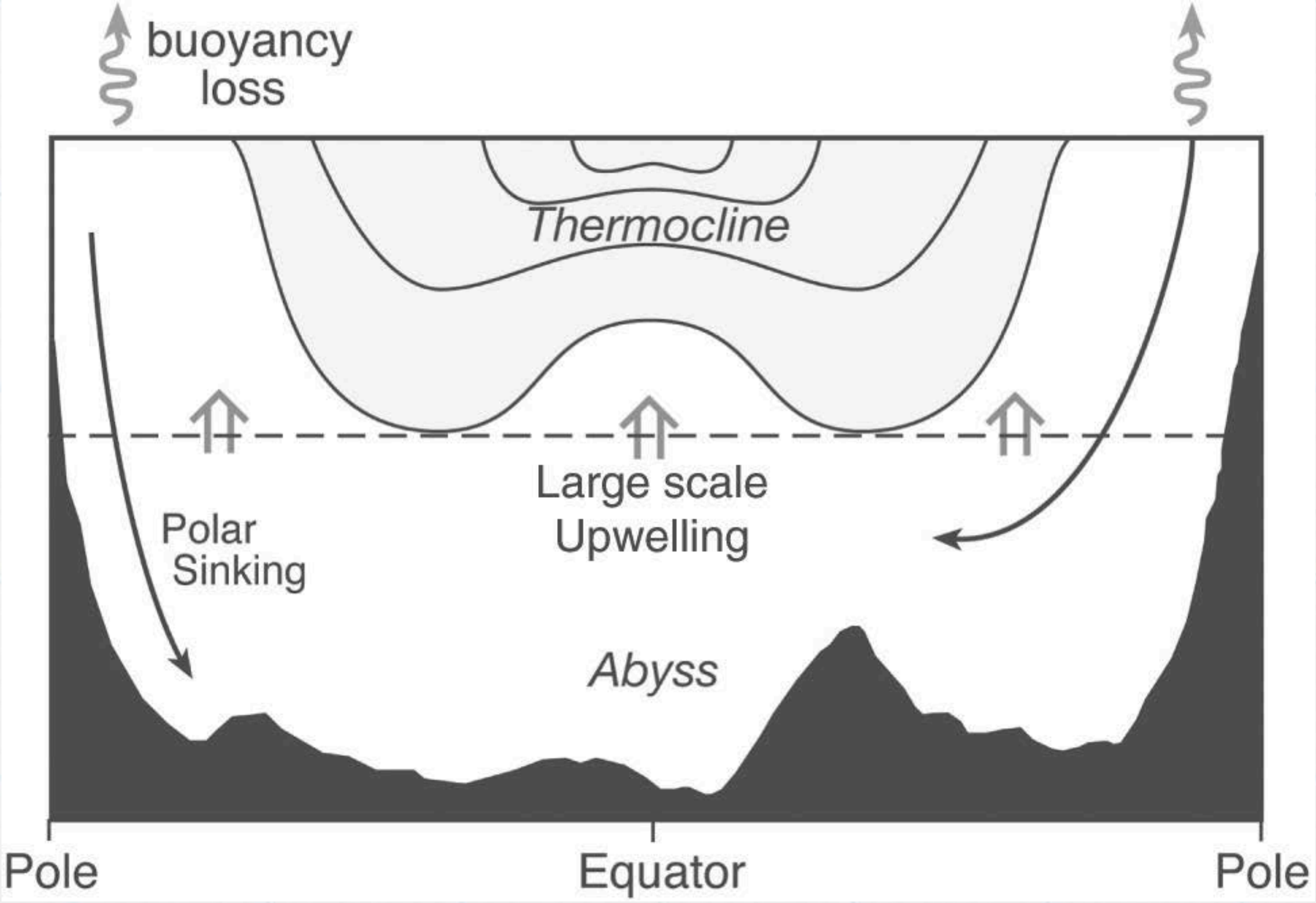
Ocean: #4
Buoyancy driven circulation

Buoyancy driven circulation

- Setting up properties of the abyssal ocean
- Very long timescale and weak current
- Hard to observe directly
- Tracer distributions (e.g. oxygen) reflect the circulation



Ocean convection is most prevalent in…

- The coldest regions where the interior stratification is small.
- High latitudes in winter where surface density increases by
    - direct cooling, reducing temperature
    - brine rejection in sea-ice formation, increasing salinity

Buoyancy loss

- Temperature and salinity changes at the surface result in the density change.
- Either cooling or sea-ice formation is associated with buoyancy loss.
- What processes control the surface temperature and salinity in general?

Buoyancy in oceanography

- $b = -g\dfrac{\sigma - \sigma_0}{\rho_{ref}}$
- $\sigma = \sigma_0 + \rho_{ref}\left(\alpha_T[T - T_0] + \beta_S[S - S_0]\right)$
- The equations governing the evolution of T and S
- $\dfrac{DT}{Dt} = -\dfrac{1}{\rho_{ref}c_w}\dfrac{\partial Q}{\partial z}$
- $\dfrac{DS}{Dt} = S\dfrac{\partial \mathcal{E}}{\partial z}$

Buoyancy flux

- $$\frac{Db}{Dt} = -\frac{g}{\rho_{ref}}\left[\frac{\alpha_T}{c_w}\frac{\partial Q}{\partial z} + \rho_{ref}\beta_S S\frac{\partial \mathscr{E}}{\partial z}\right] = -\frac{\partial B}{\partial z}$$
- $$B_{surface} = \frac{g}{\rho_{ref}}\left[\frac{\alpha_T}{c_w}Q_{net} + \rho_{ref}\beta_S S(E-P)\right]$$
- This is called surface buoyancy flux (m/s^2 x m/s)

Surface temperature change

$$\frac{DT}{Dt} = -\frac{1}{\rho_{ref} c_w} \frac{\partial Q}{\partial z}$$

- c_w is the heat capacity of water.
- Q is the turbulent vertical flux of heat.
- At the surface, $Q = Q_{net}$, which is net heat flux.
- When Q_{net} is positive (upward, out of the ocean into the atmosphere), T decreases.

Surface heat flux

$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

Shortwave Longwave Sensible heat Latent heat

- Shortwave flux (Q_{SW}) heats up the surface and also down to a depth of 100-200 m.
- Longwave flux (Q_{LW}) cools the ocean's surface following the black-body law.

Surface heat flux

$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

Shortwave Longwave Sensible heat Latent heat

- Sensible heat flux is due to turbulent heat exchange that depends on the wind speed and air-sea temperature difference.

$$Q_S = \rho_{air} c_p c_S \boxed{u_{10}(SST - T_{air})}$$

Coefficients for the heat transfer

Specific heat of the air

Density of the air at the surface

Surface heat flux

$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

Shortwave Longwave Sensible heat Latent heat

- Latent heat flux is introduced from evaporation.
- It depends on the wind speed and relative humidity.

$$Q_L = \rho_{air} L_e c_L u_{10}(q^*(SST) - q_{air})$$

Density of the air at the surface

Latent heat of evaporation

Transfer coefficients for water vapor

Specific humidity

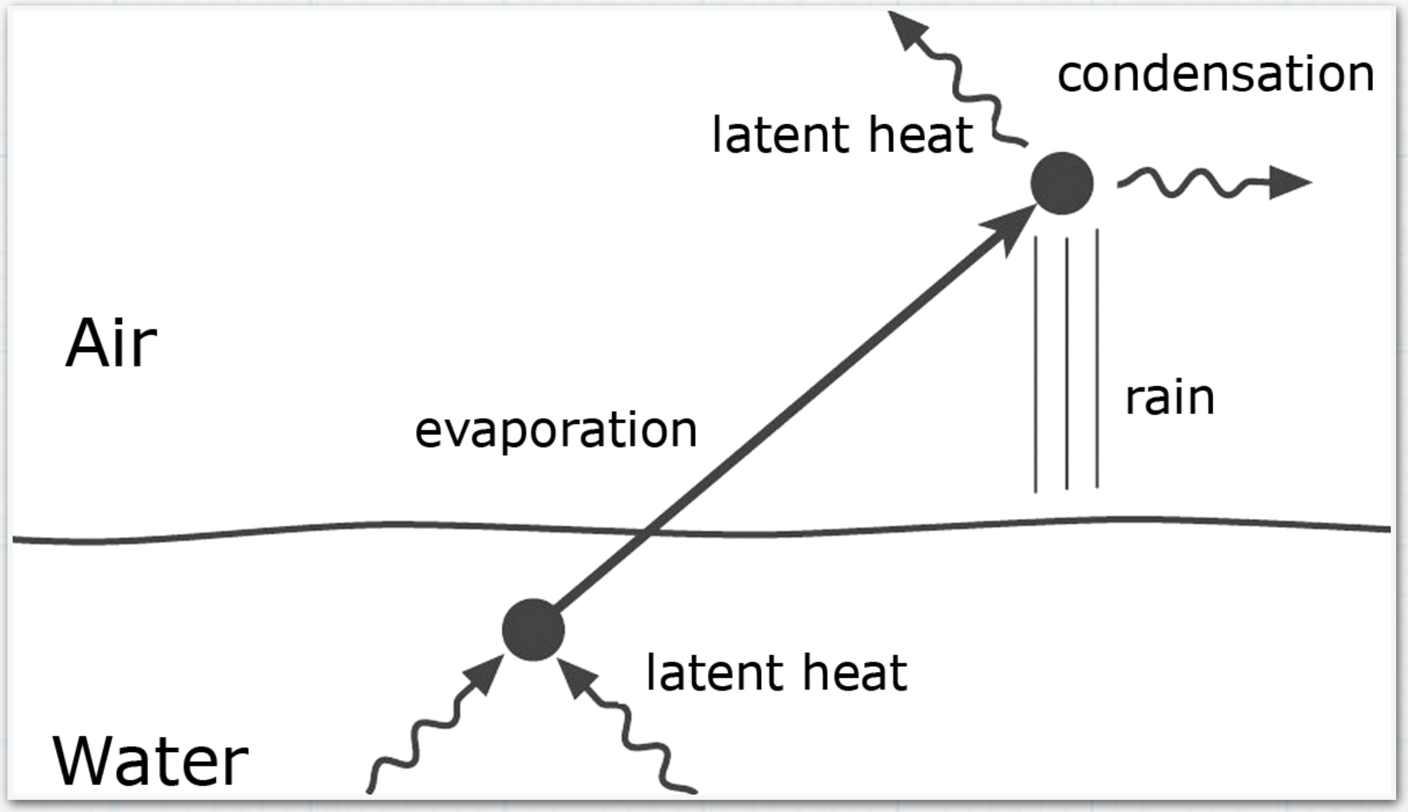
Specific humidity at saturation

Surface heat flux

$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

Shortwave Longwave Sensible heat Latent heat

- Latent heat flux is introduced from evaporation.



Surface heat flux

$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

Shortwave Longwave Sensible heat Latent heat

- High wind and dry air lead to more evaporation
- It is always positive.

$$Q_L = \rho_{air} L_e c_L u_{10}(q^*(SST) - q_{air})$$

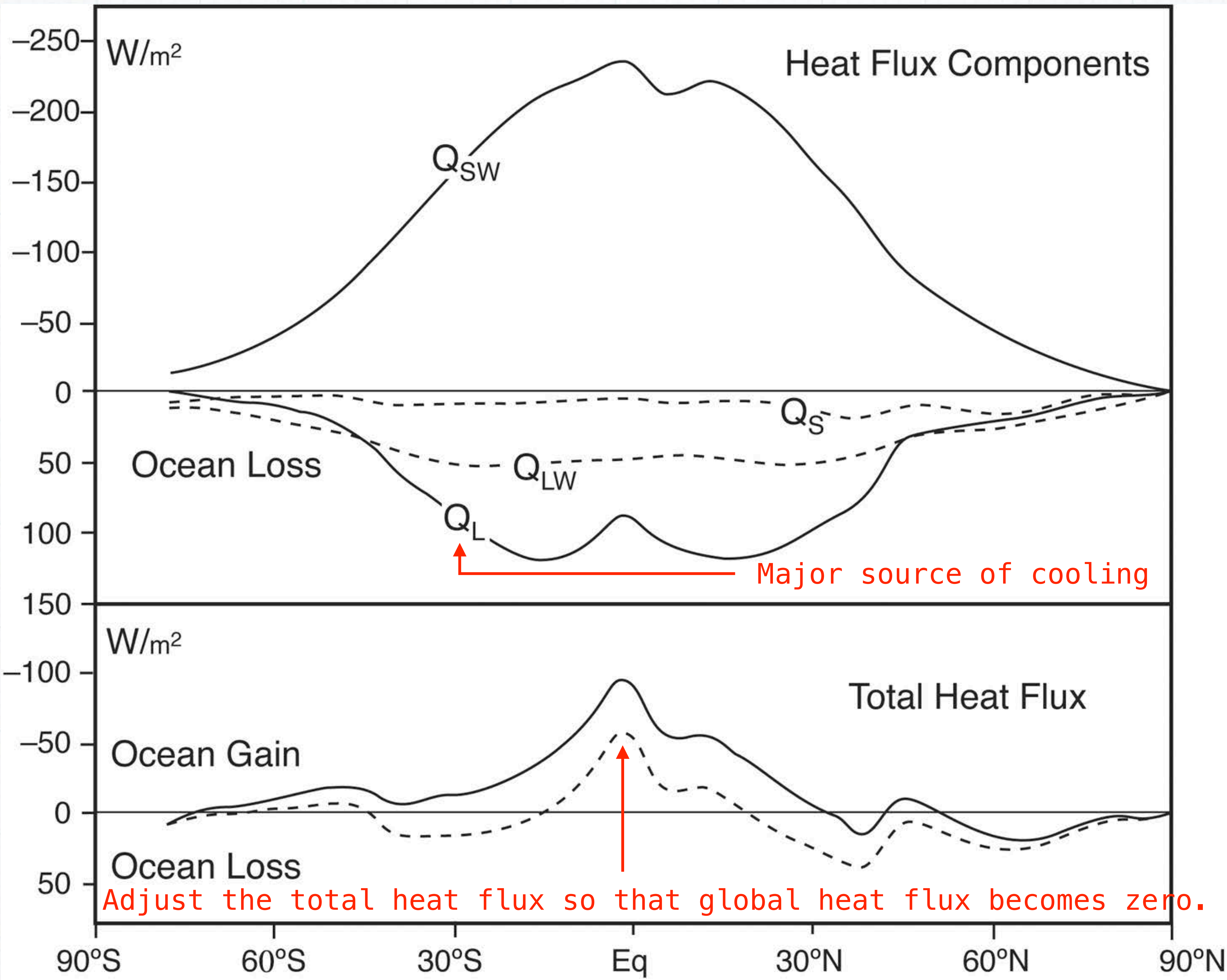
Density of the air at the surface

Latent heat of evaporation

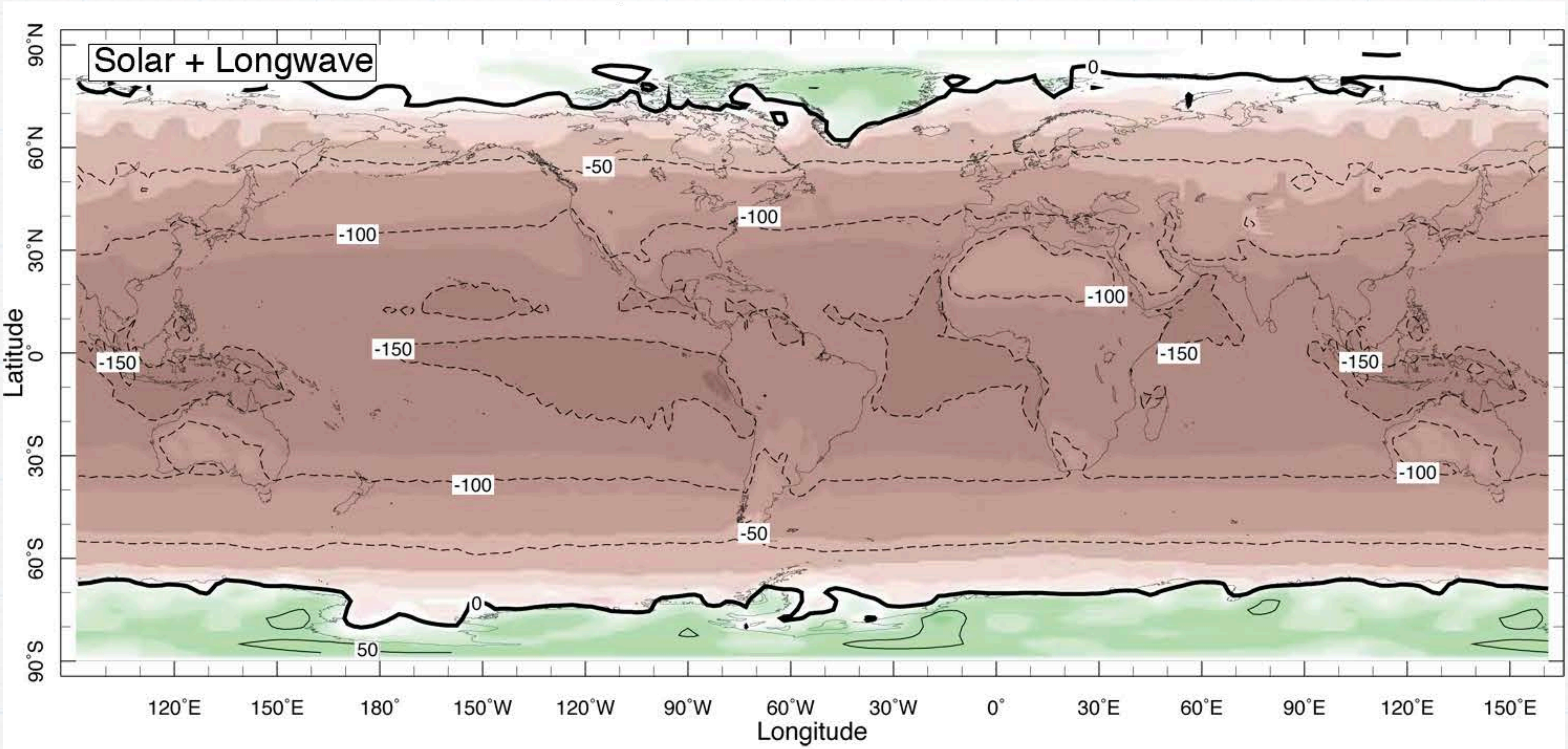
Transfer coefficients for water vapor

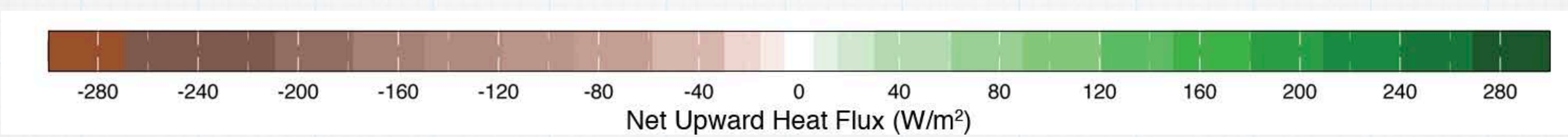
Specific humidity

Specific humidity at saturation


W/m2
Heat Flux Components
−250
−200
−150
−100
−50
0
50
100
150
QSW
QS
QLW
QL
Ocean Loss
Major source of cooling
W/m2
Total Heat Flux
−100
−50
0
50
Ocean Gain
Ocean Loss
Adjust the total heat flux so that global heat flux becomes zero.
90°S
60°S
30°S
Eq
30°N
60°N
90°N

Net upward shortwave and longwave heat flux

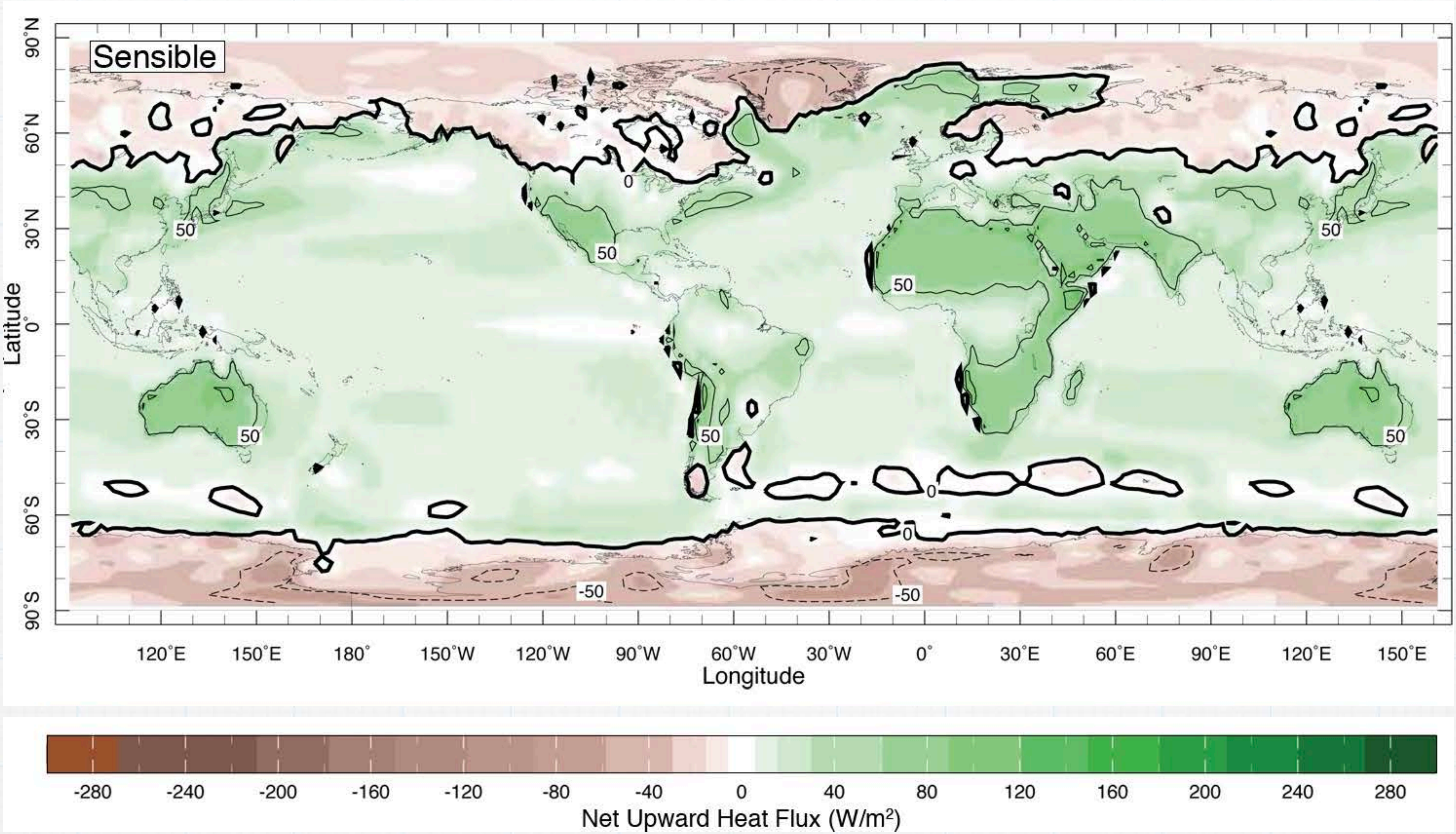




Heat into the ocean

Heat into the atmosphere

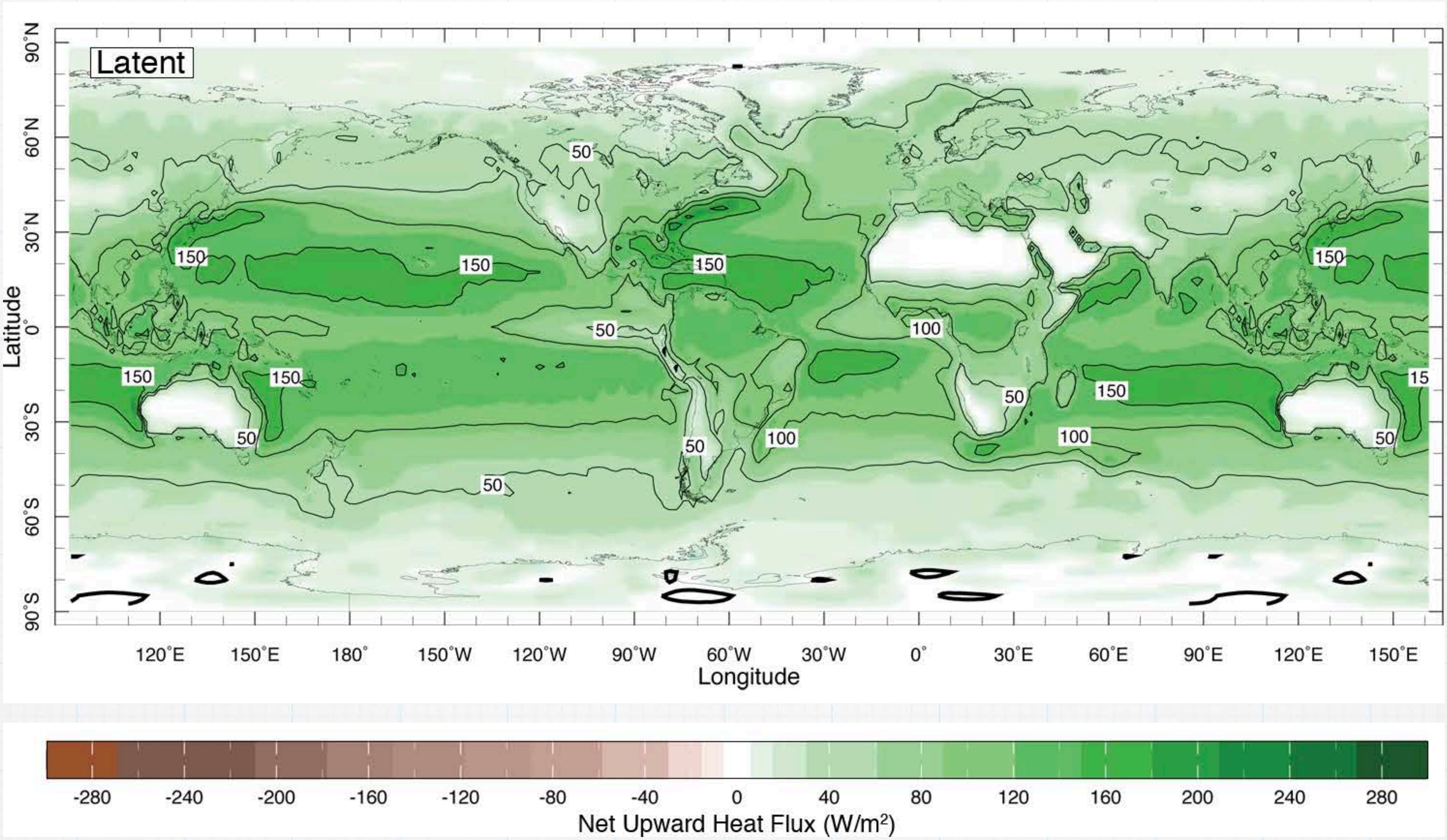
Net upward sensible heat flux



Heat into the ocean

Heat into the atmosphere

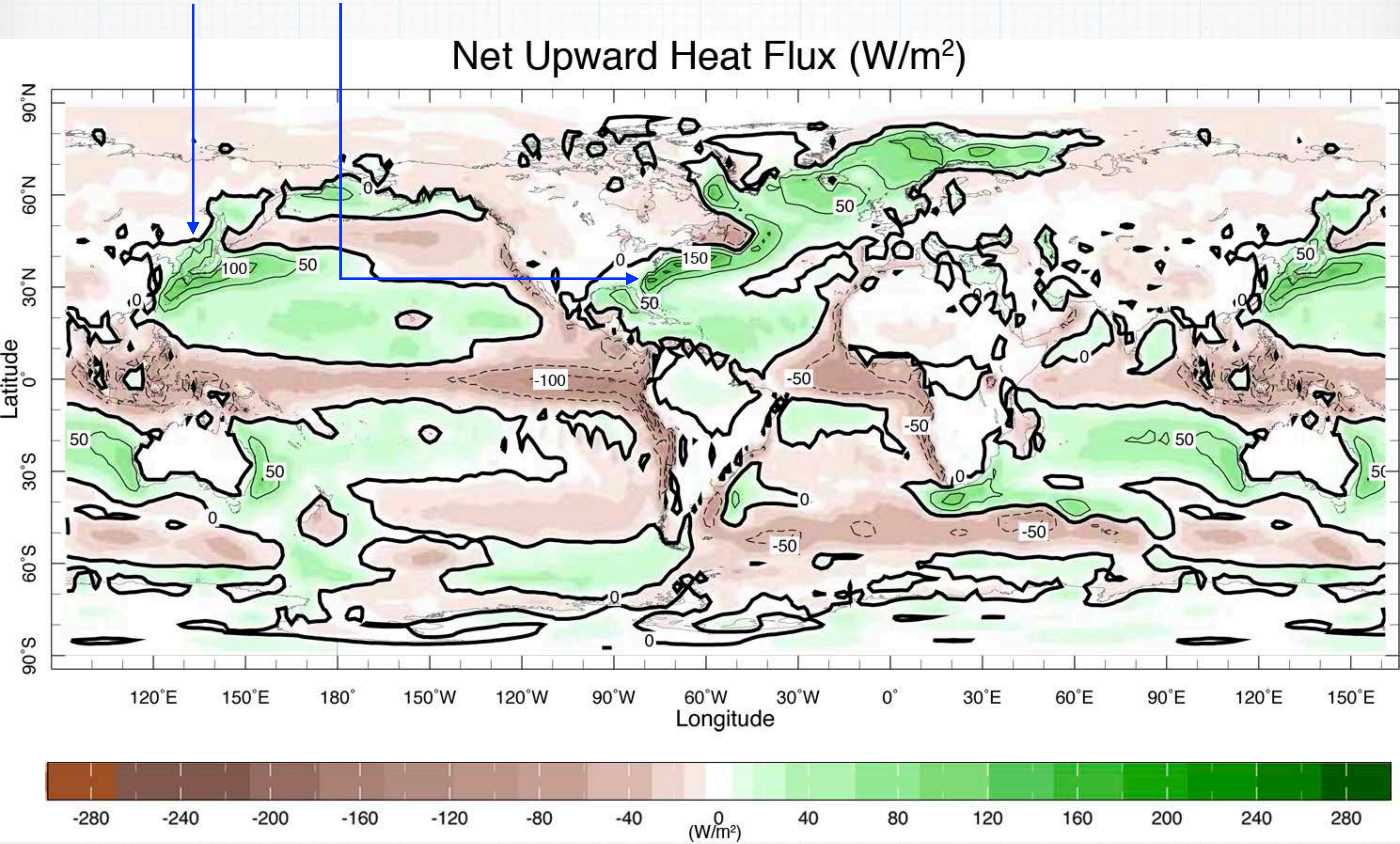
Net upward latent heat flux



Heat into the ocean

Heat into the atmosphere

Warm water + Cold air from the land in winter

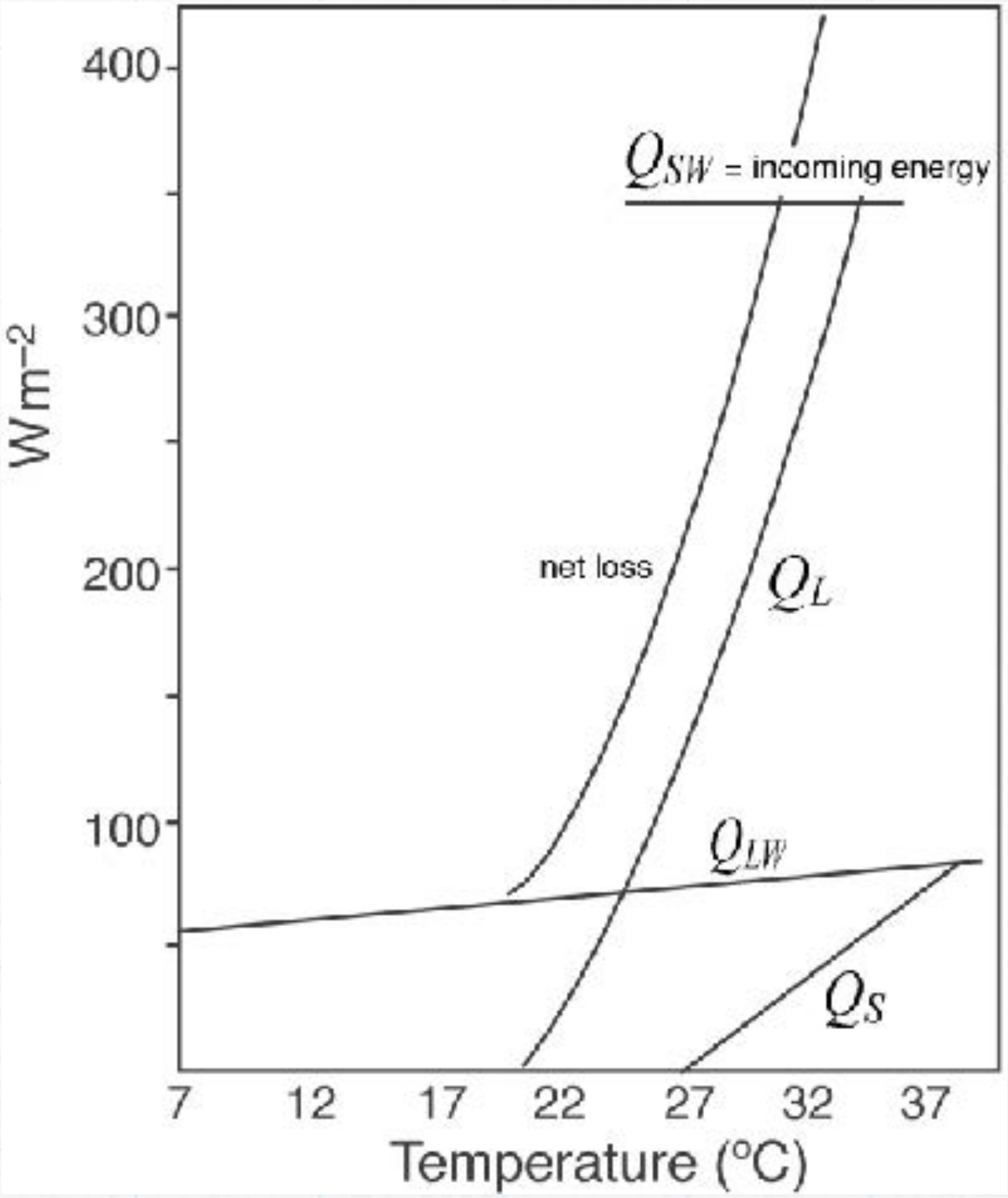


Heat into the ocean

Heat into the atmosphere

Temperature at the tropics

- Air temperature = 27 degC
- Specific humidity at 70% RH = 15 g/kg
- Wind speed = 3 m/s
- Solar radiation = 341
- Surface ocean temperature cannot go beyond a certain value due to the feedback.

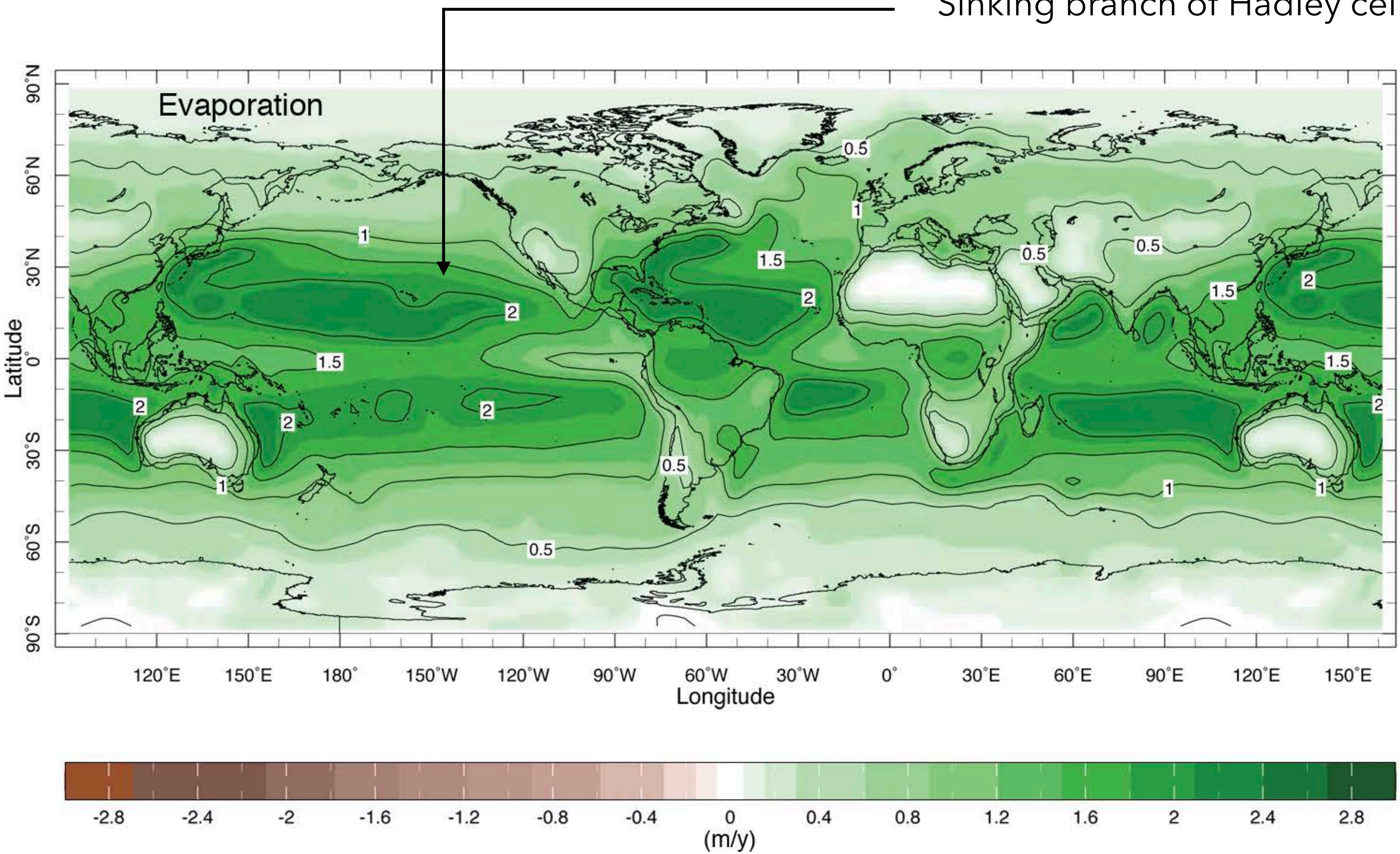


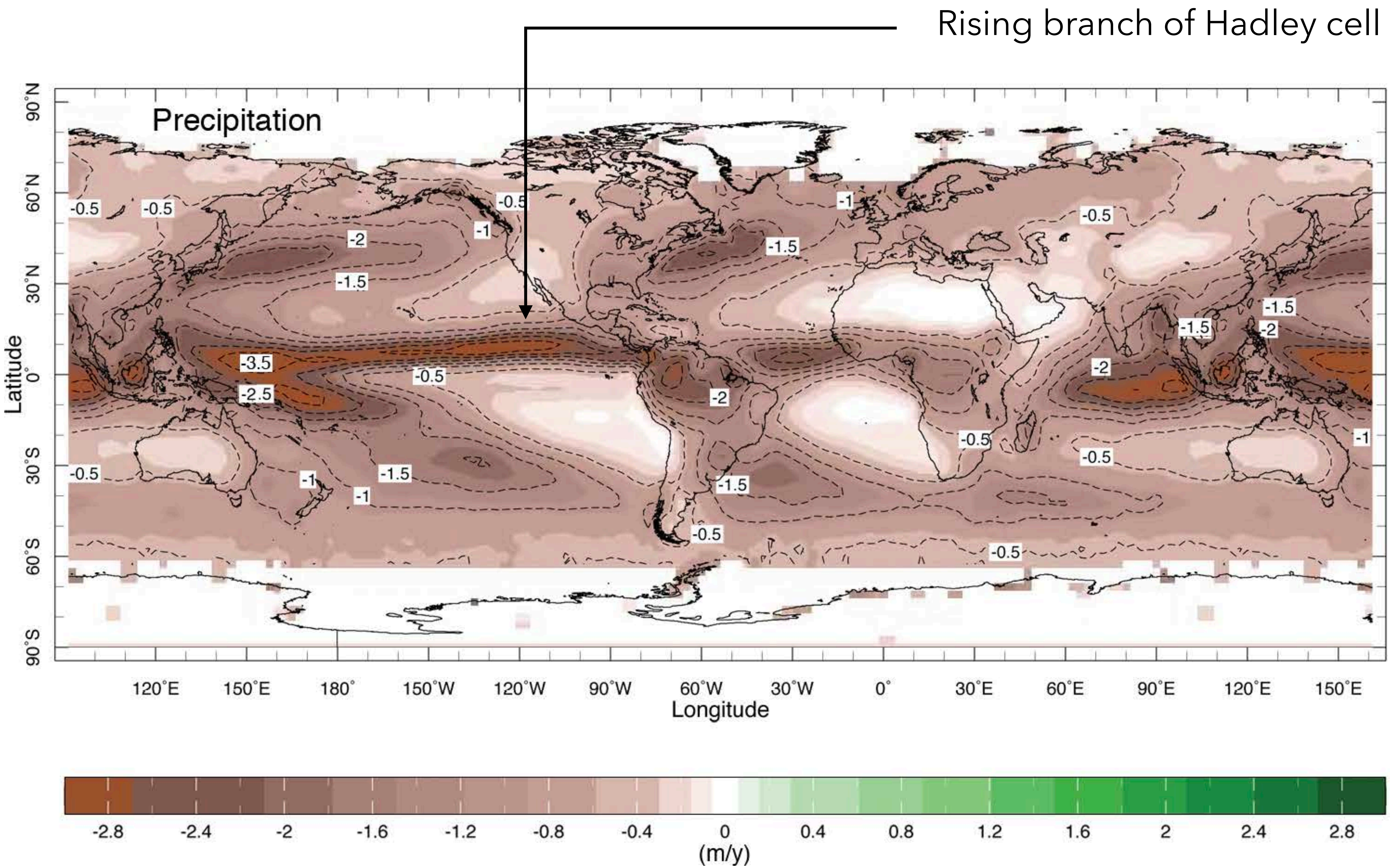
Surface salinity change

$$\frac{DS}{Dt} = S\frac{\partial \mathscr{E}}{\partial z}$$

- $\mathscr{E}$ is the turbulent vertical flux of freshwater.
- At the surface, $\mathscr{E} = \mathscr{E}_{surface} = E - P$ (Evaporation - Precipitation, including river runoff and ice formation)

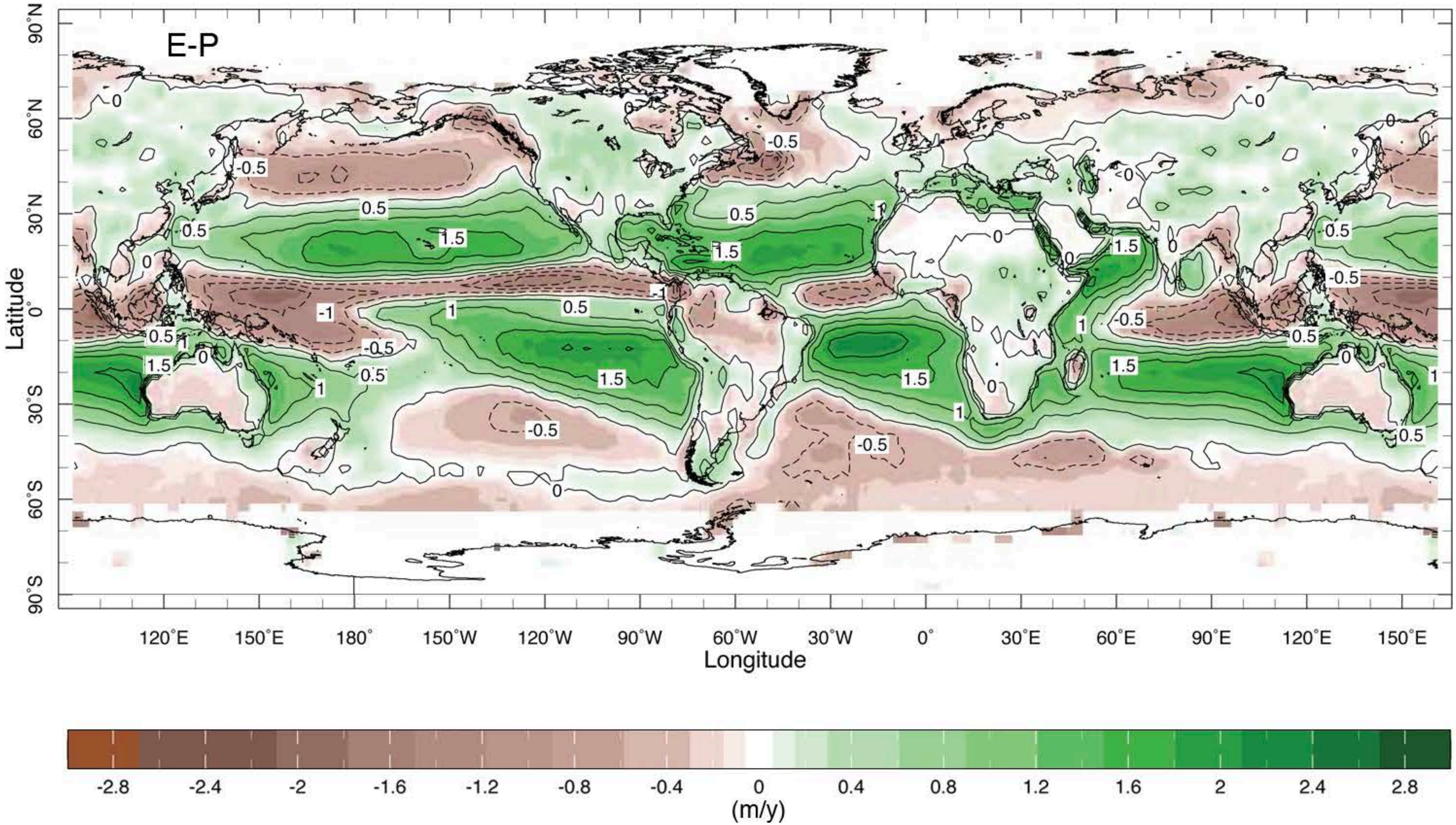
Sinking branch of Hadley cell



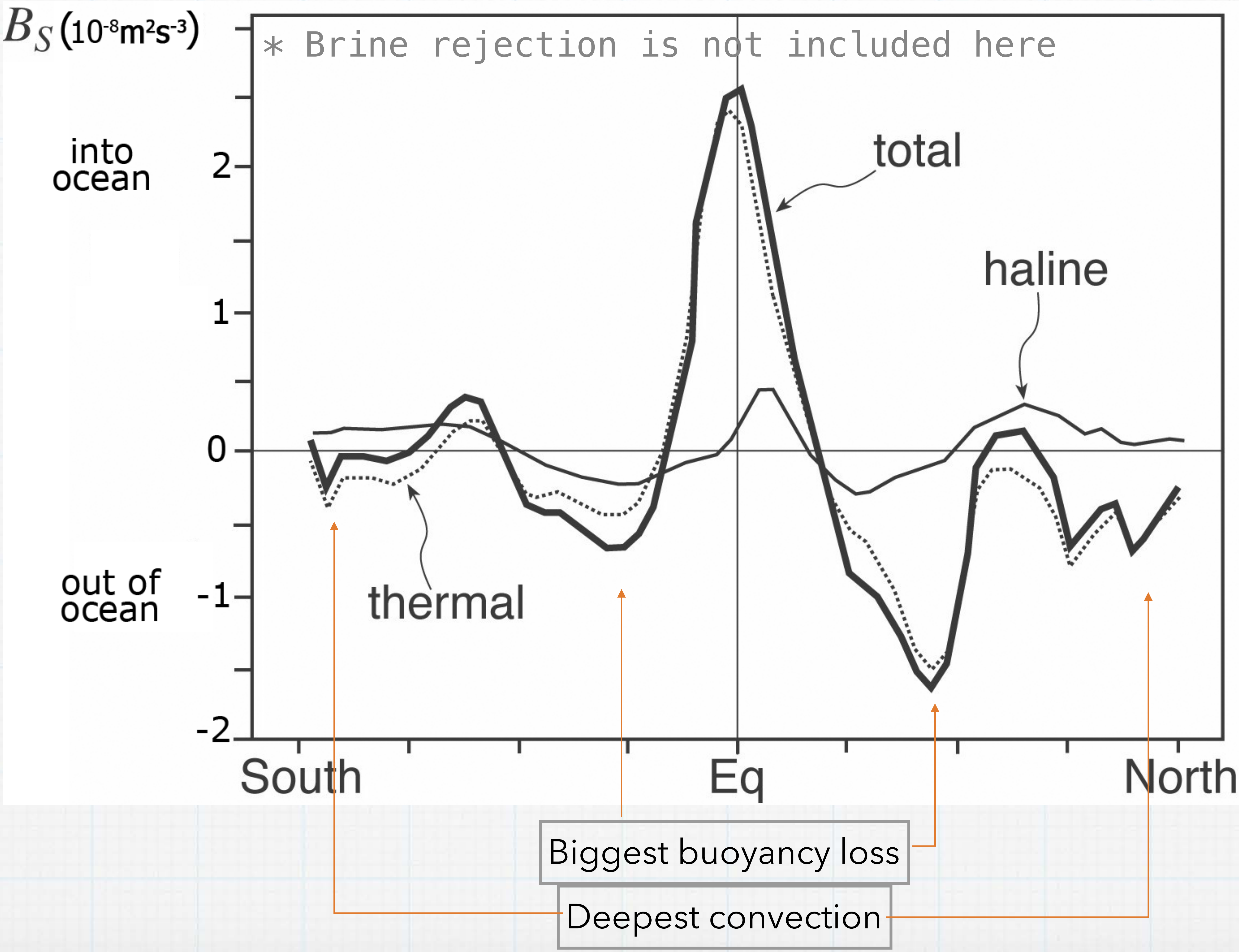

Rising branch of Hadley cell
Precipitation
Latitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
Longitude
-2.8
-2.4
-2
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
(m/y)

Green : net evaporation

Brown : net precipitation



The zonally-averaged buoyancy forcing



The heat budget for a column of ocean

$$\frac{\partial \mathrm{H}}{\partial t} = -Q_{net} - \left(\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y} \right)$$

$$\mathrm{H} = \rho_{ref} c_w \int_{bottom}^{top} T dz$$

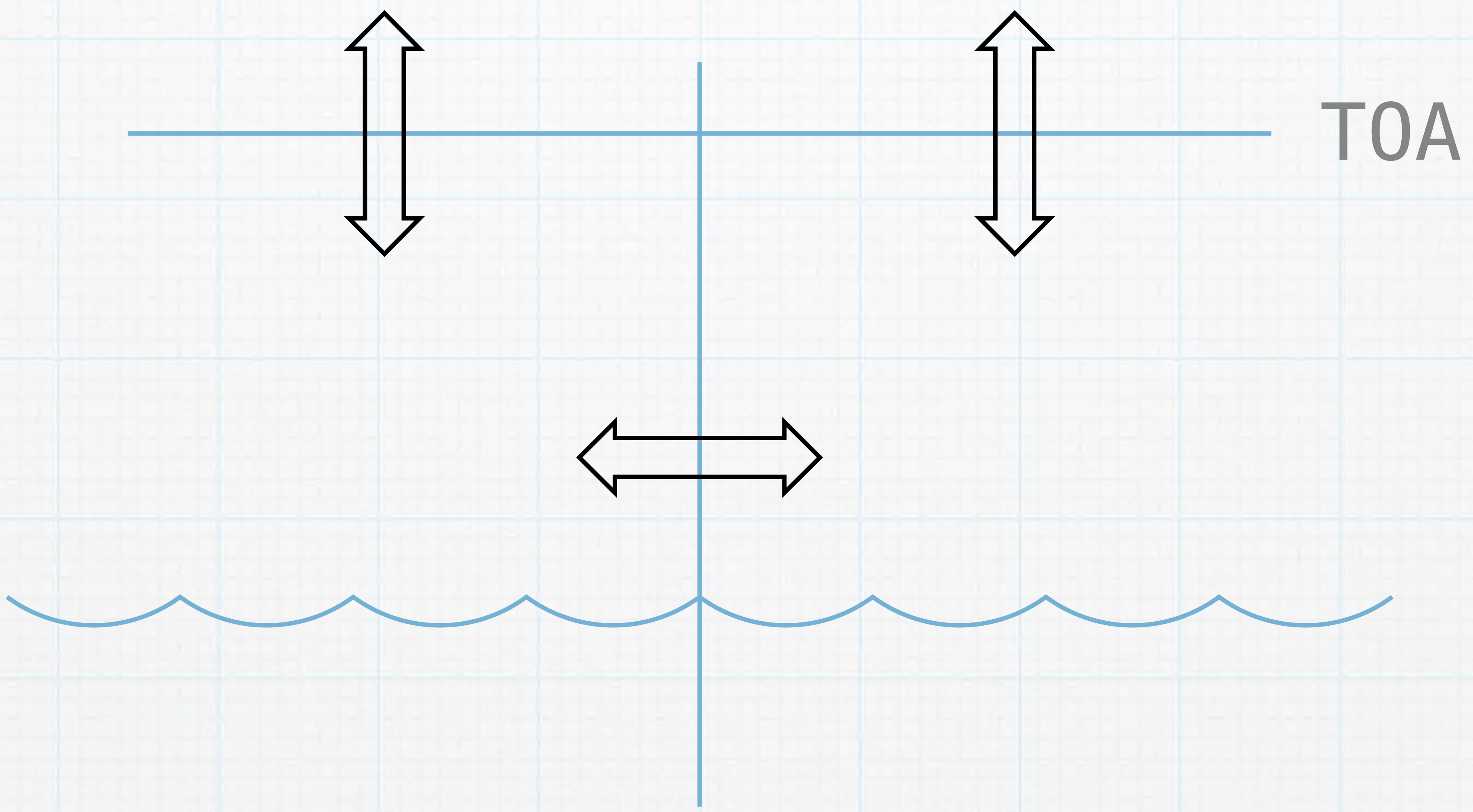
$$H_x = \rho_{ref} c_w \int_{bottom}^{top} uT dz$$

$$H_y = \rho_{ref} c_w \int_{bottom}^{top} vT dz$$

Changes in heat stored in a column of the ocean = surface heat flux + horizontal heat flux by ocean currents

How to measure ocean heat transport?

- By subtracting atmospheric heat transport from the total heat transport measured at the top of the atmosphere.

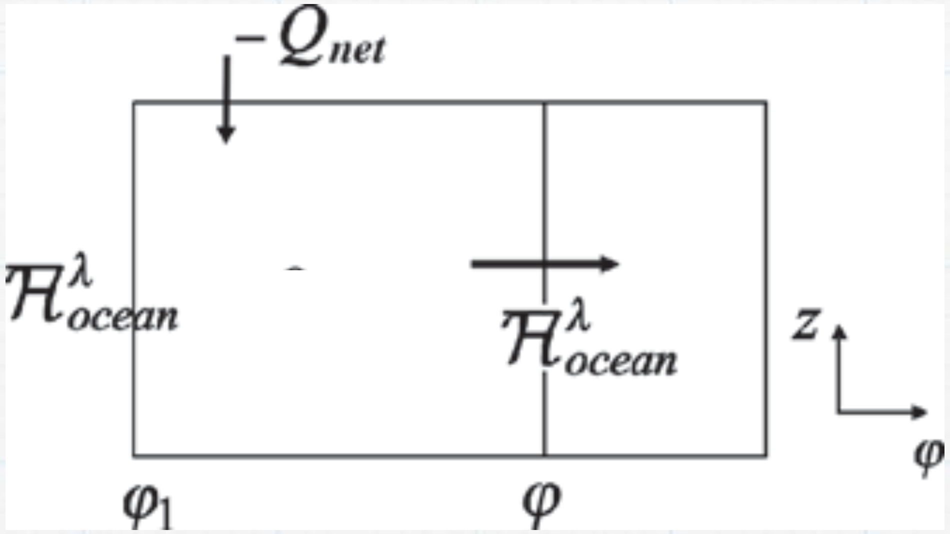


How to measure ocean heat transport?

- By subtracting atmospheric heat transport from the total heat transport measured at the top of the atmosphere.

- By finding the heat transport that balances the surface heat flux under the assumption of steady state.

$$H^{\lambda}_{ocean}(\phi) - H^{\lambda}_{ocean}(\phi_1) = -a^2 \cos\phi \int_{\phi_1}^{\phi} \int_{\lambda_{west}}^{\lambda_{east}} Q_{net} d\lambda d\phi$$

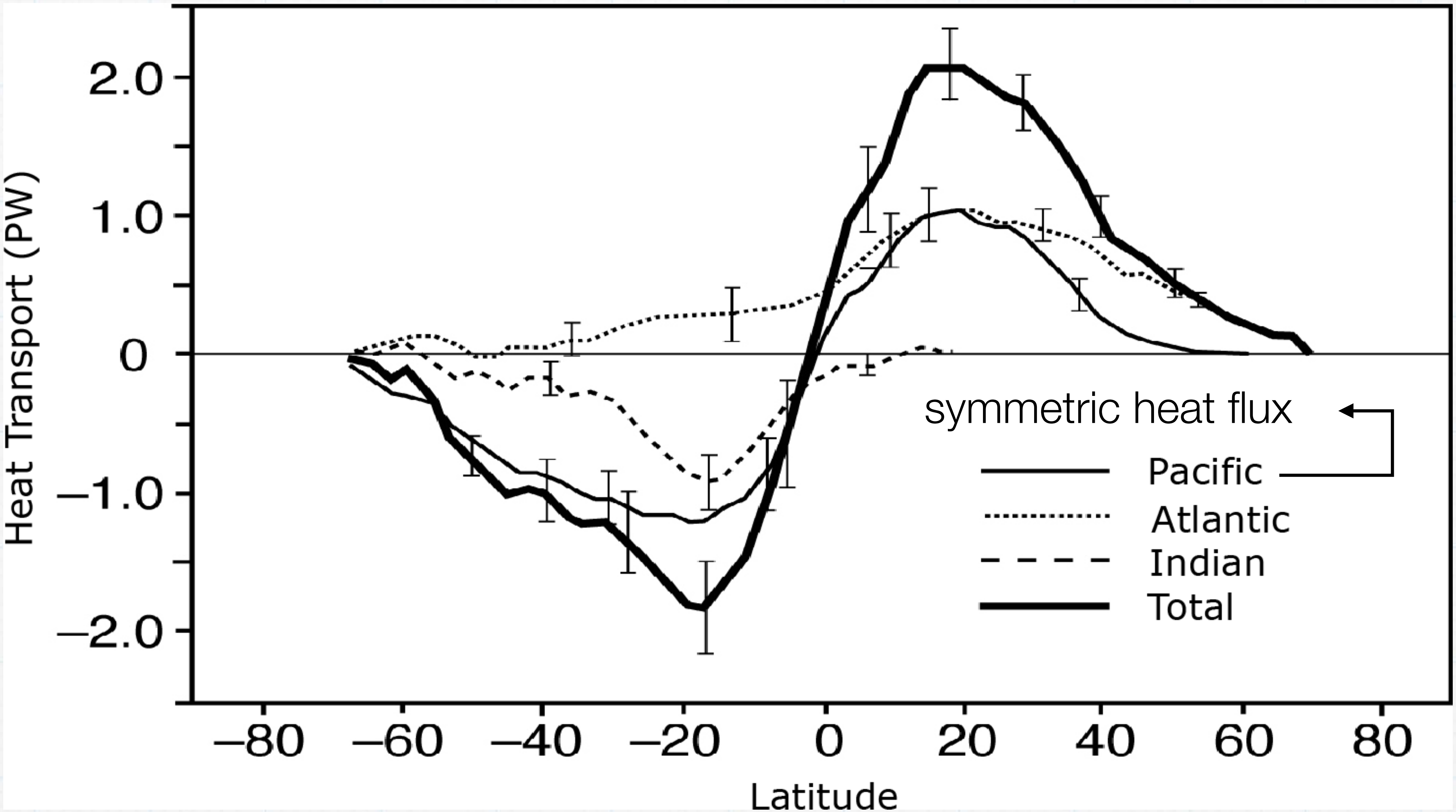


How to measure ocean heat transport?

- By subtracting atmospheric heat transport from the total heat transport measured at the top of the atmosphere.
- By finding the heat transport that balances the surface heat flux under the assumption of steady state.
- By directly measuring the heat transport at a few locations.

Northward heat transport in the world ocean

Peaks at 20°   Using method 1

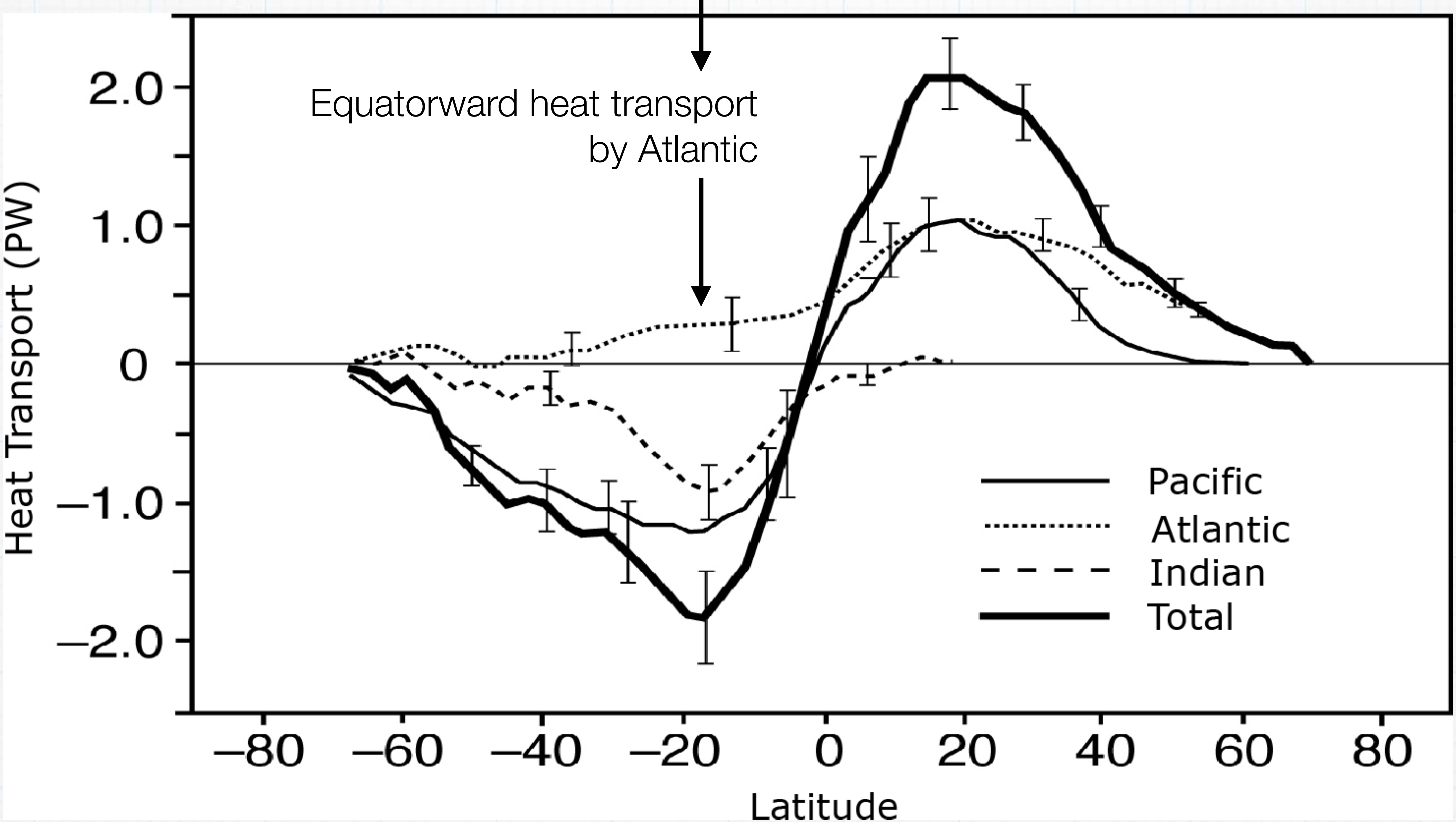


Northward heat transport in the world ocean

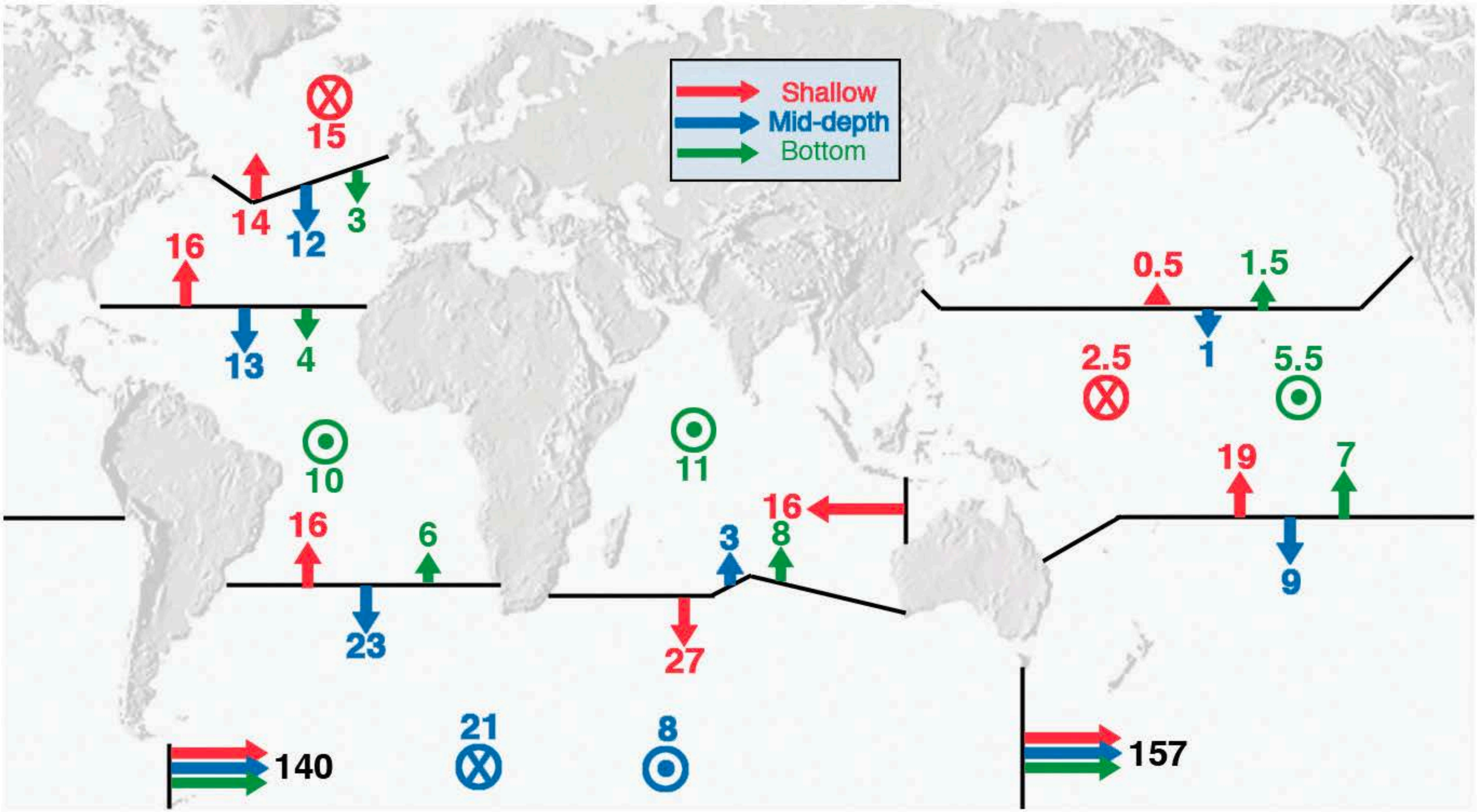
Atlantic Meridional Overturning Circulation

Peaks at 20°

Using method 1



The estimate of global ocean circulation pattern



The ocean’s meridional circulation