

Ocean: Thermohaline circulation I

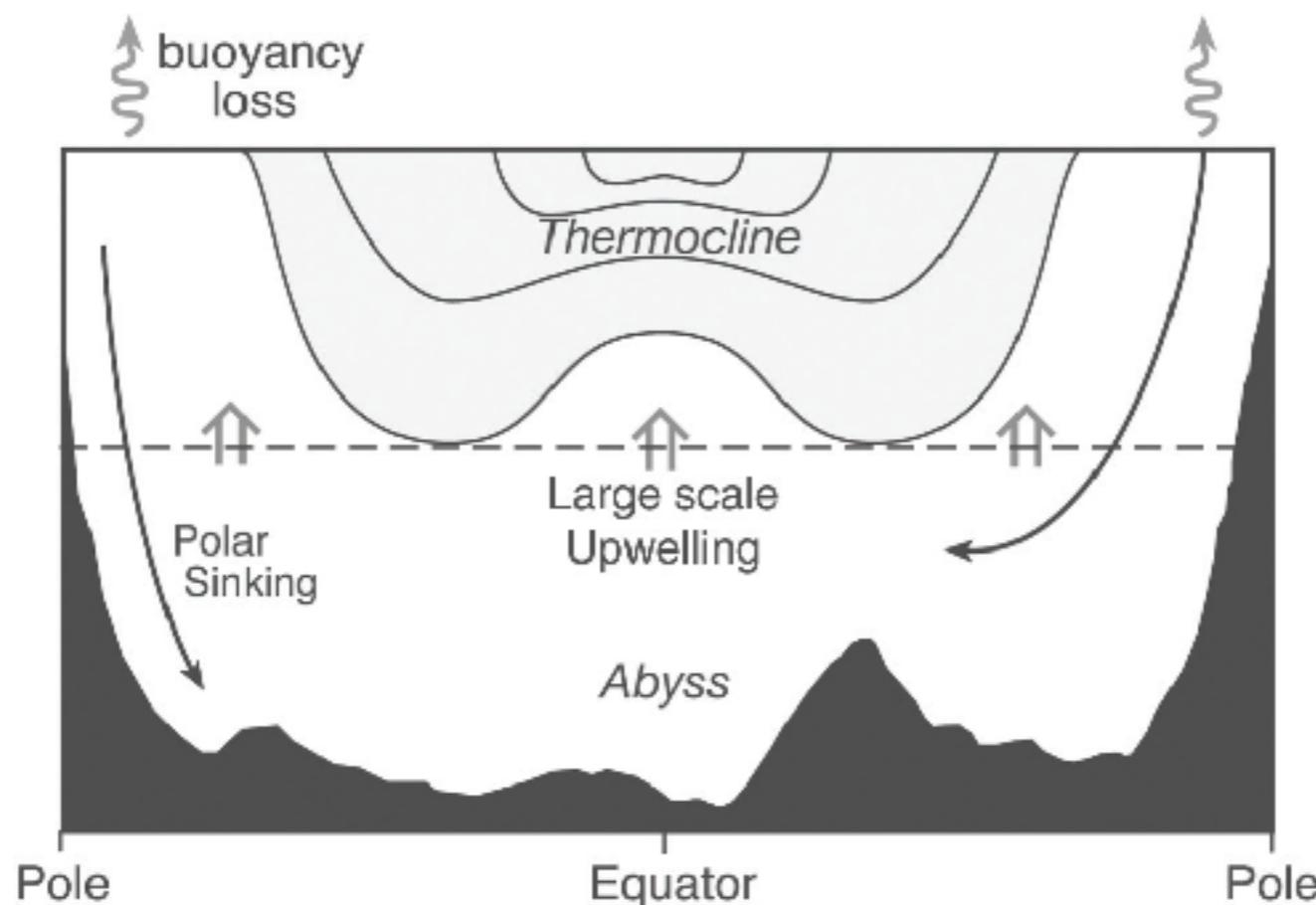
ATM2106

Two processes driving ocean circulation

- Stresses from the wind at the ocean's surface
- Convection induced by the loss of buoyancy
 - Due to cooling and/or salt input
 - Localized regions in polar latitudes
 - Causing surface waters to sink to depth
 - Global responses to the sinking
 - **Thermohaline circulation**

Thermohaline 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?

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

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

The diagram illustrates the components of surface heat flux. It shows four upward-pointing arrows of increasing length. Below each arrow is a label: 'Shortwave' under the shortest arrow, 'Longwave' under the second shortest arrow, 'Sensible heat' under the third arrow, and 'Latent heat' under the longest arrow. A horizontal brace groups the 'Sensible heat' and 'Latent heat' arrows together.

↑ ↑ ↑ ↑
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

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

The diagram illustrates the components of surface heat flux. It shows four upward-pointing arrows of increasing length. Below each arrow is a label: "Shortwave", "Longwave", "Sensible heat", and "Latent heat". The "Sensible heat" and "Latent heat" labels are grouped together under a single bracket, indicating they are components of the same physical process.

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

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

The diagram illustrates the components of sensible heat flux. It shows three upward-pointing arrows of increasing length. Below the first arrow is the label "Density of the air at the surface". Below the second arrow is the label "Specific heat of the air". Below the third arrow is the label "Coefficients for the heat transfer". The entire equation is enclosed in a red box.

Surface heat flux

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

↑ ↑ ↑ ↑
Shortwave Longwave Sensible heat Latent heat

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

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

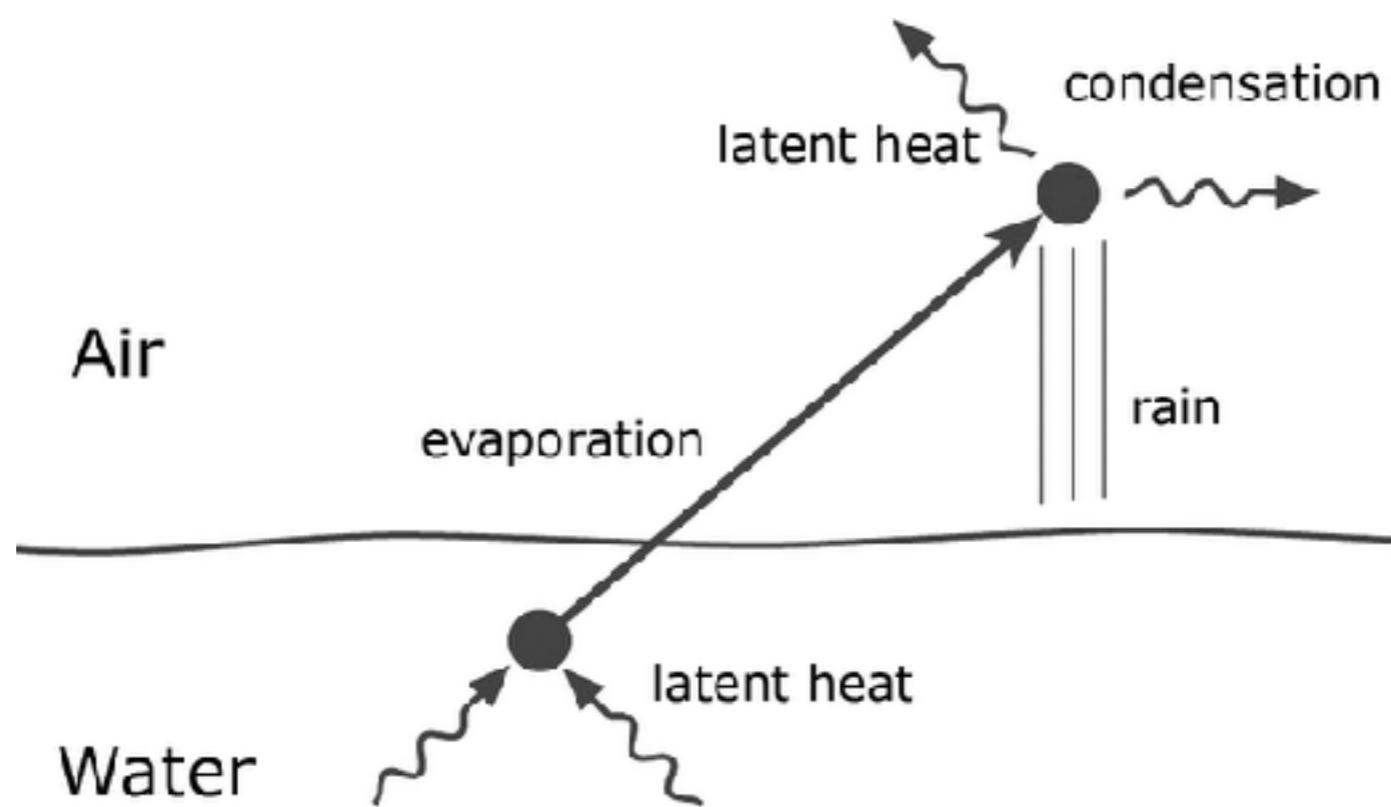
↑ ↑ ↑ ↑ ↑
Density of the air at the surface Latent heat of evaporation Transfer coefficients for water vapor Specific humidity at saturation Specific humidity

Surface heat flux

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

↑ ↑ ↑ ↑
Shortwave Longwave Sensible heat Latent heat

- Latent heat flux is by evaporation.



Surface heat flux

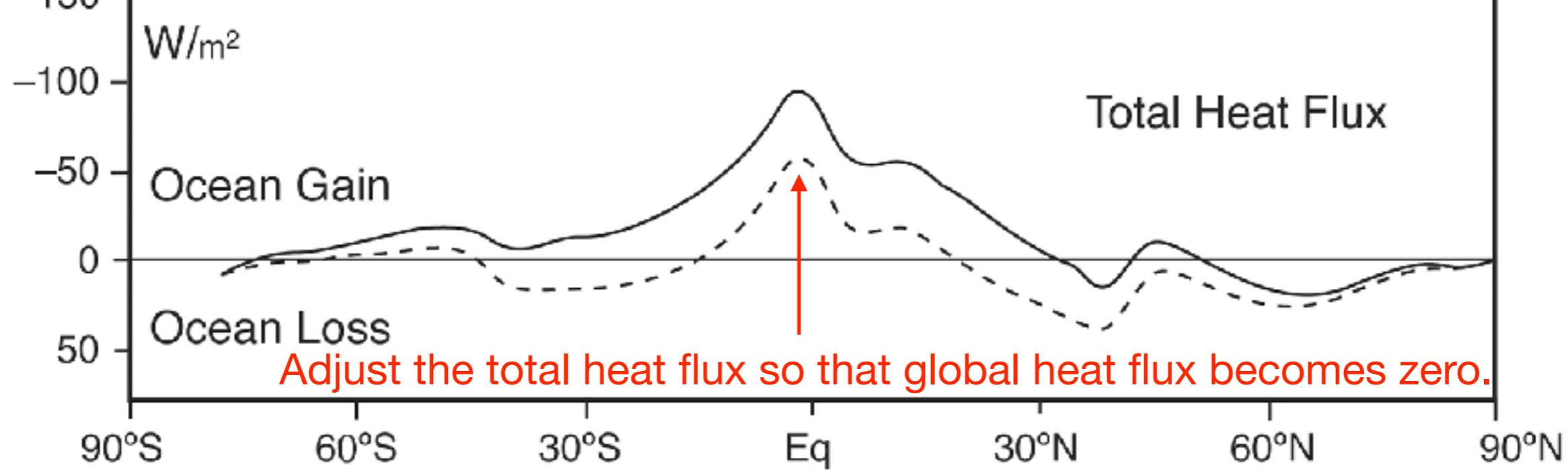
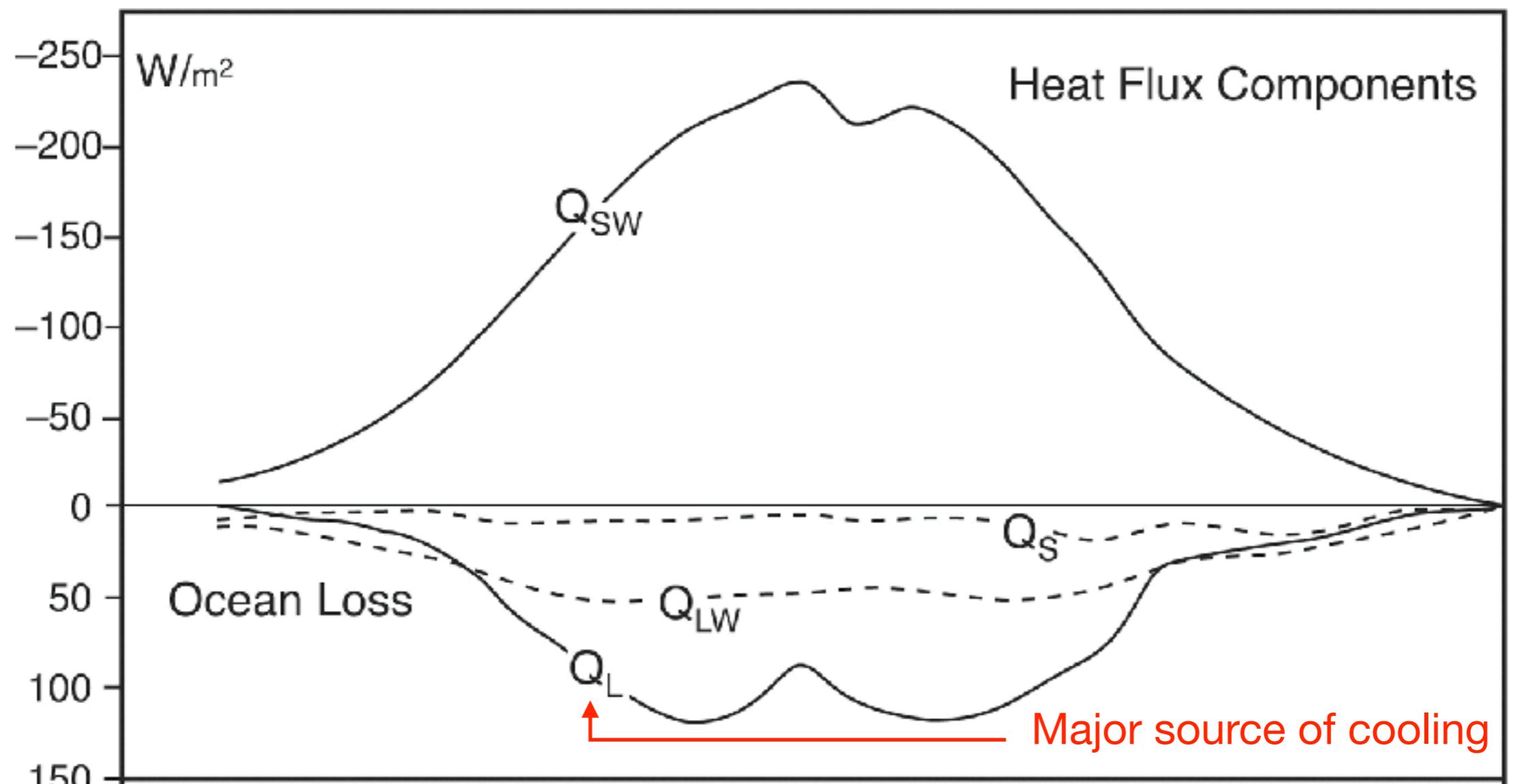
$$Q_{net} = Q_{SW} + Q_{LW} + Q_S + Q_L$$

↑ ↑ ↑ ↑
Shortwave Longwave Sensible heat Latent heat

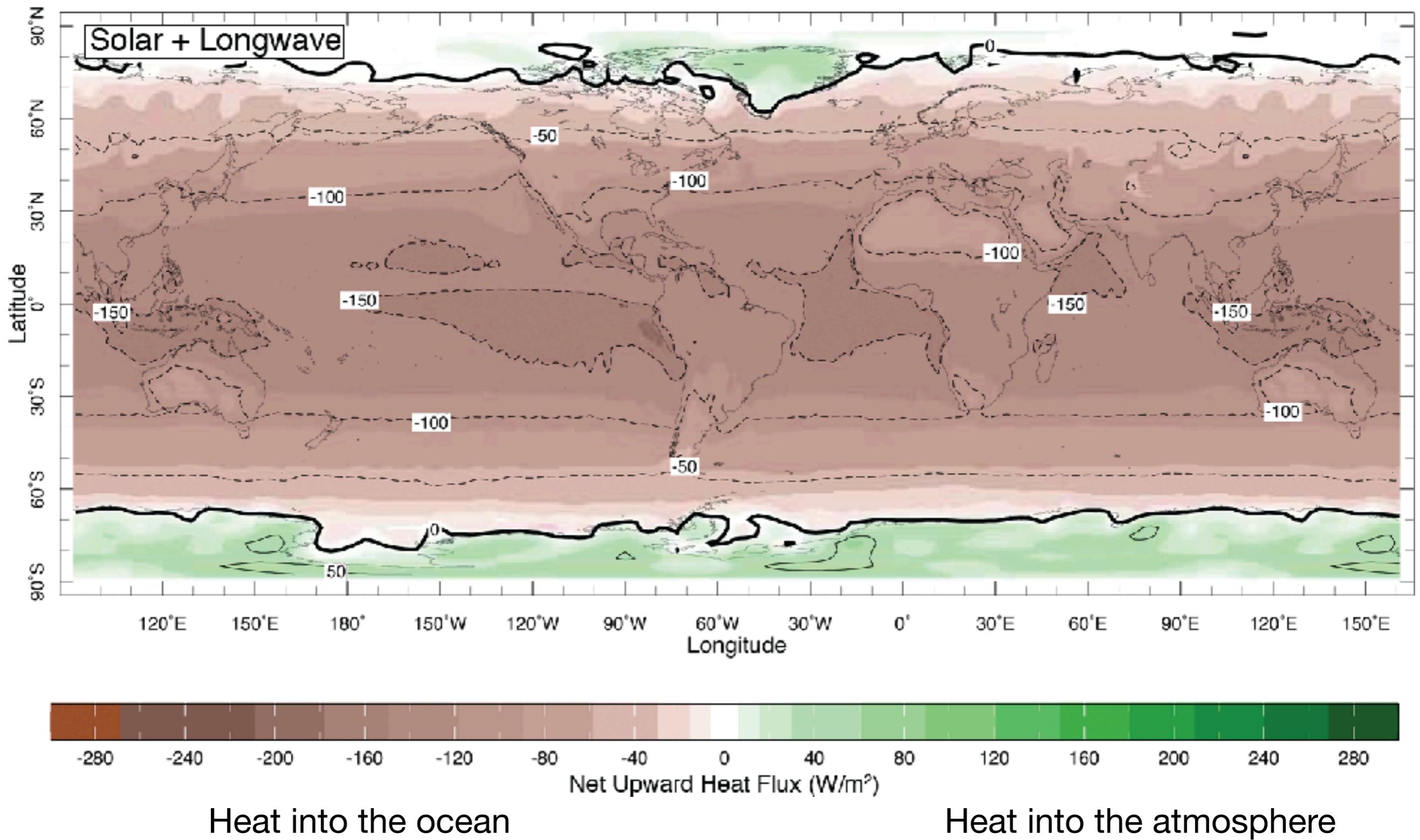
- High wind and dry air lead to more evaporation
- It is always positive.

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

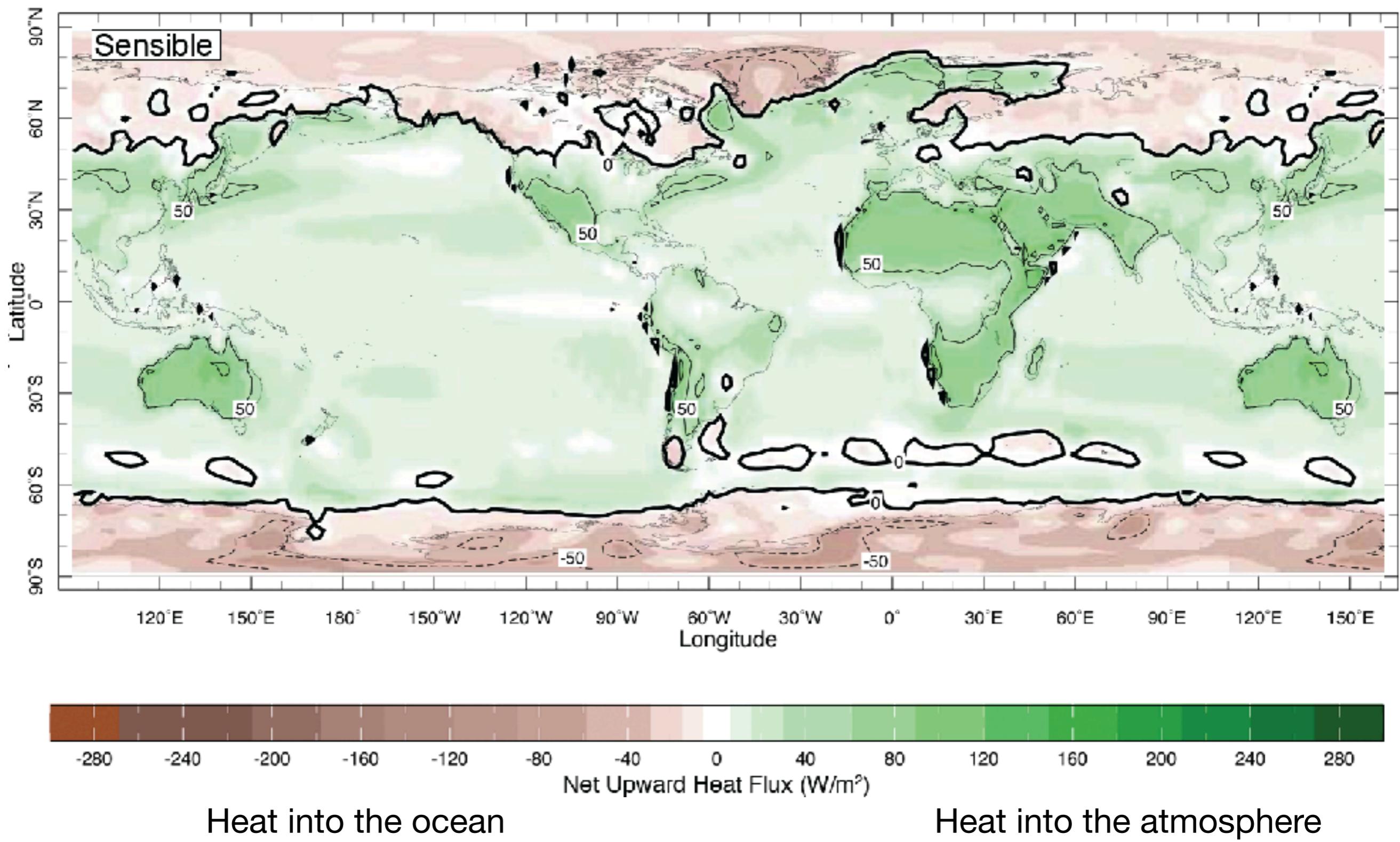
↑ ↑ ↑ ↑ ↑
Density of the air at the surface Latent heat of evaporation Transfer coefficients for water vapor Specific humidity at saturation Specific humidity



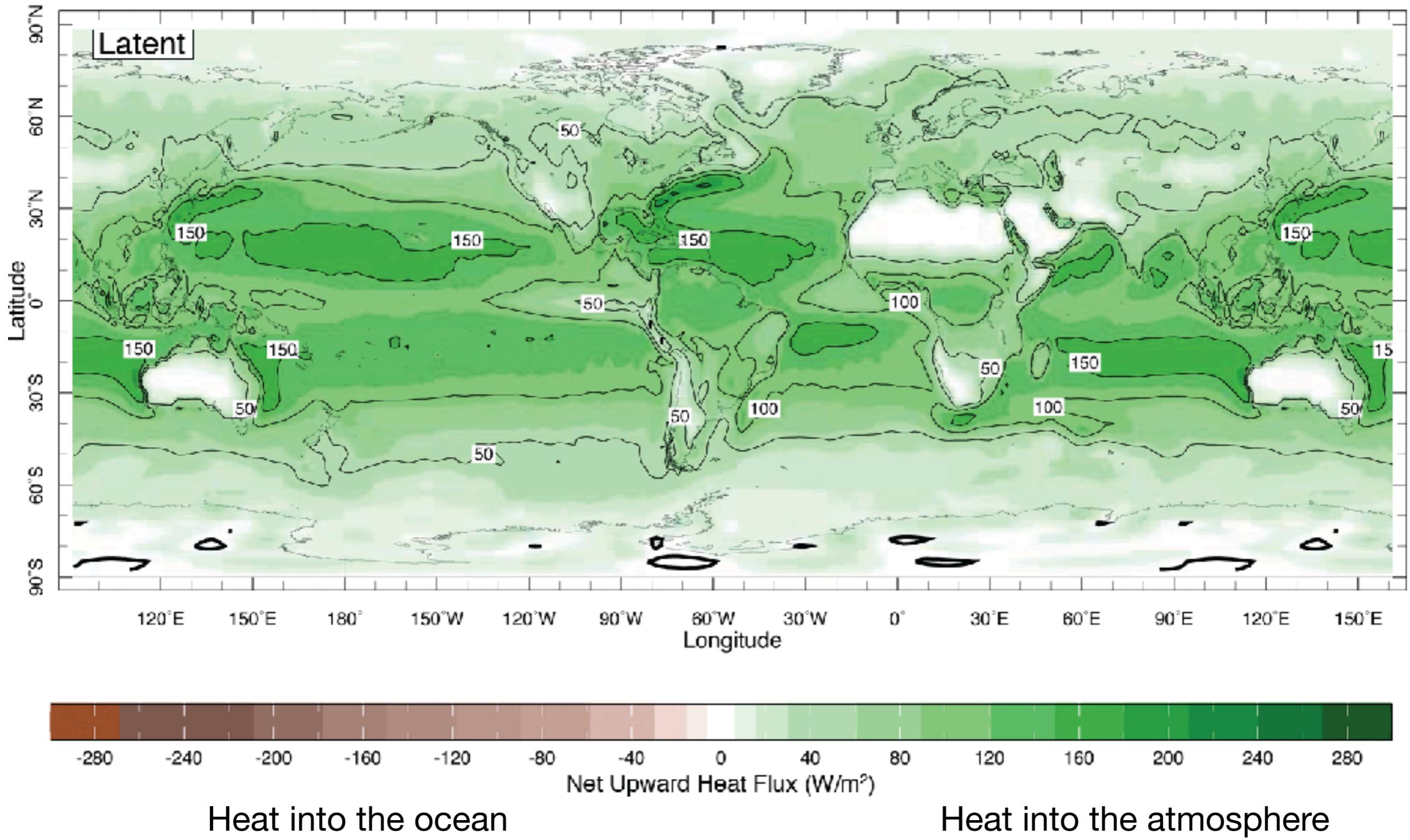
Net upward shortwave and longwave heat flux



Net upward sensible heat flux

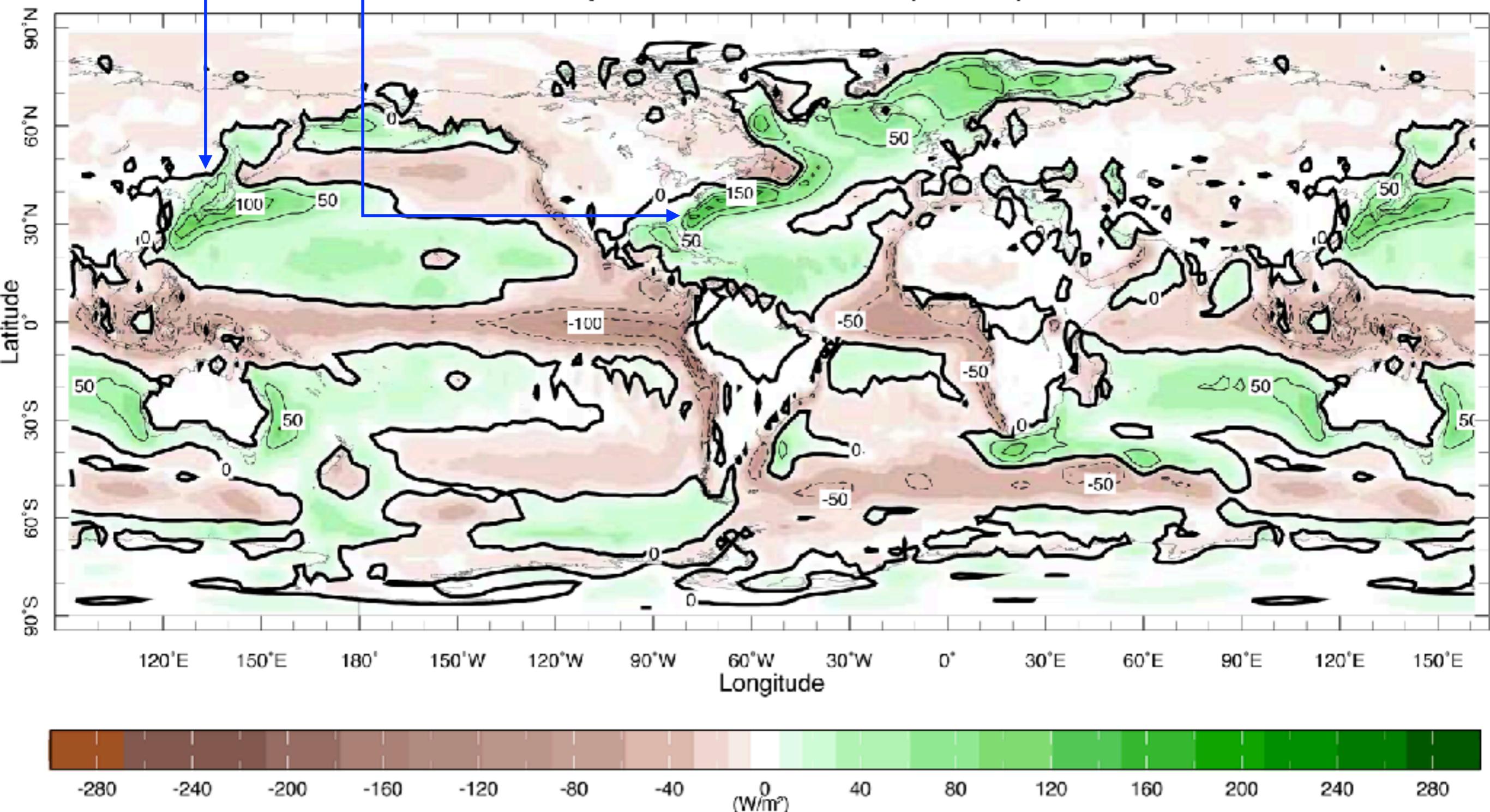


Net upward latent heat flux



Warm water + Cold air from the land in winter

Net Upward Heat Flux (W/m^2)



Heat into the ocean

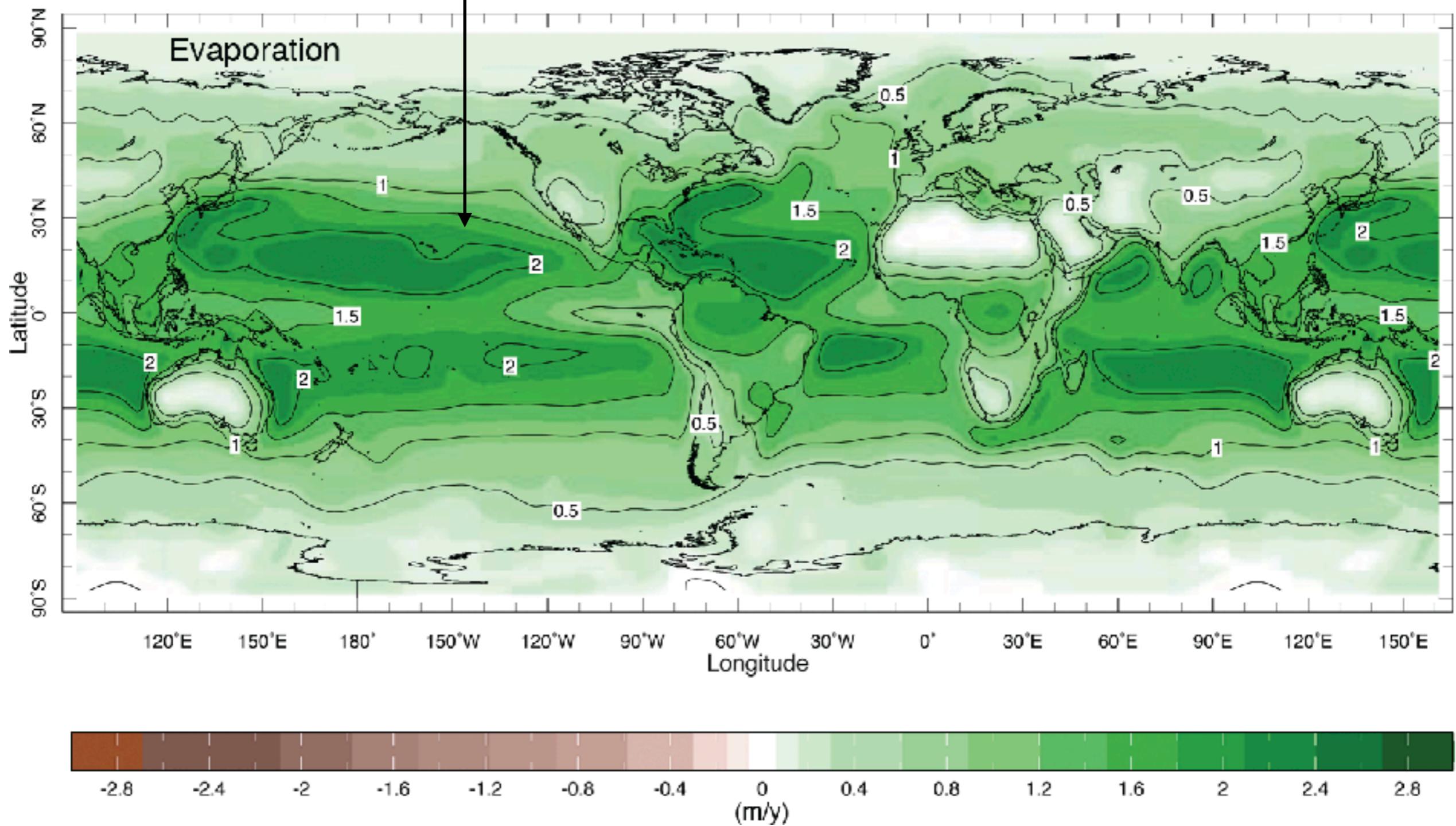
Heat into the atmosphere

Surface salinity change

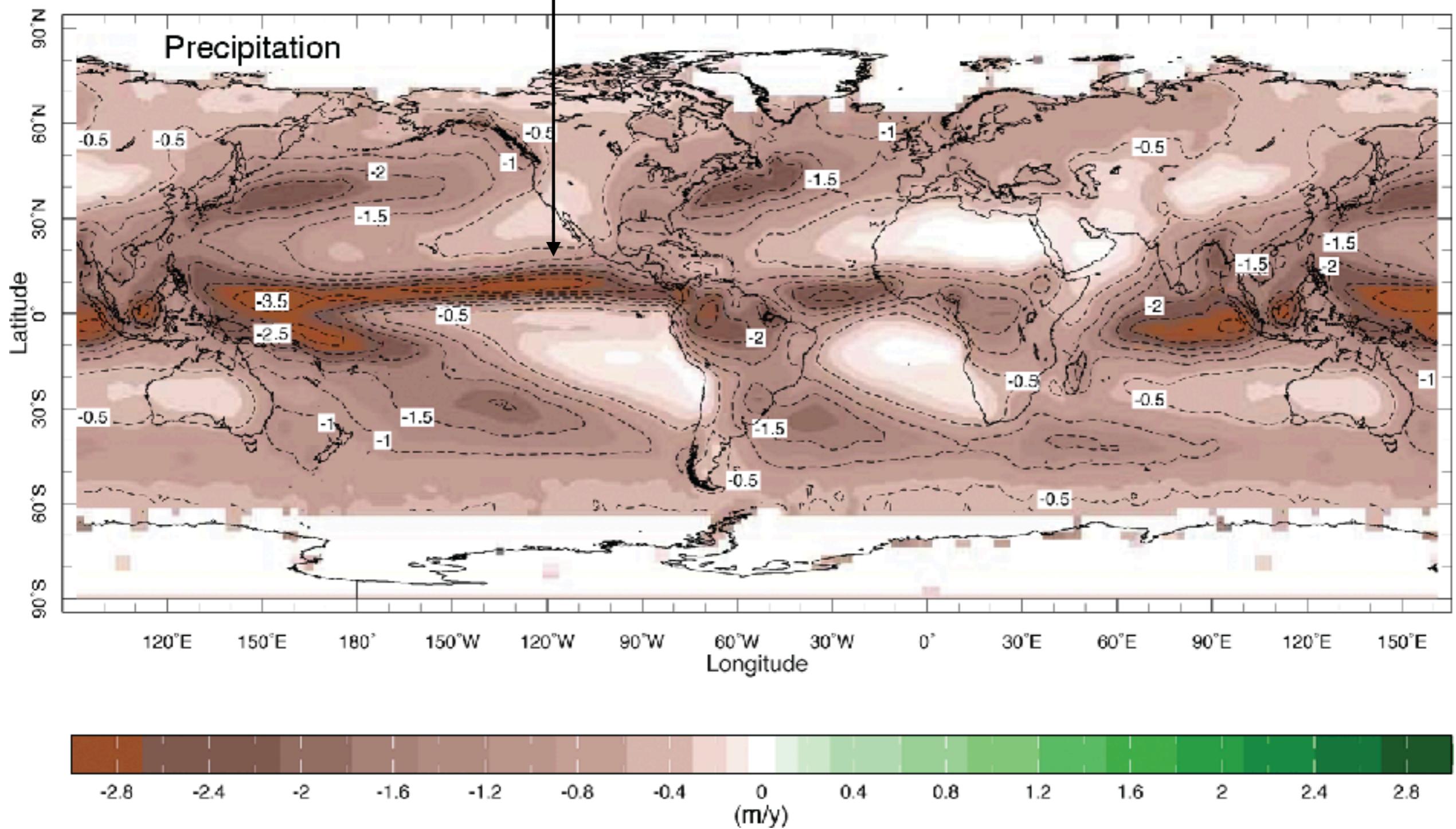
$$\frac{DS}{Dt} = S \frac{\partial \mathcal{E}}{\partial z}$$

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

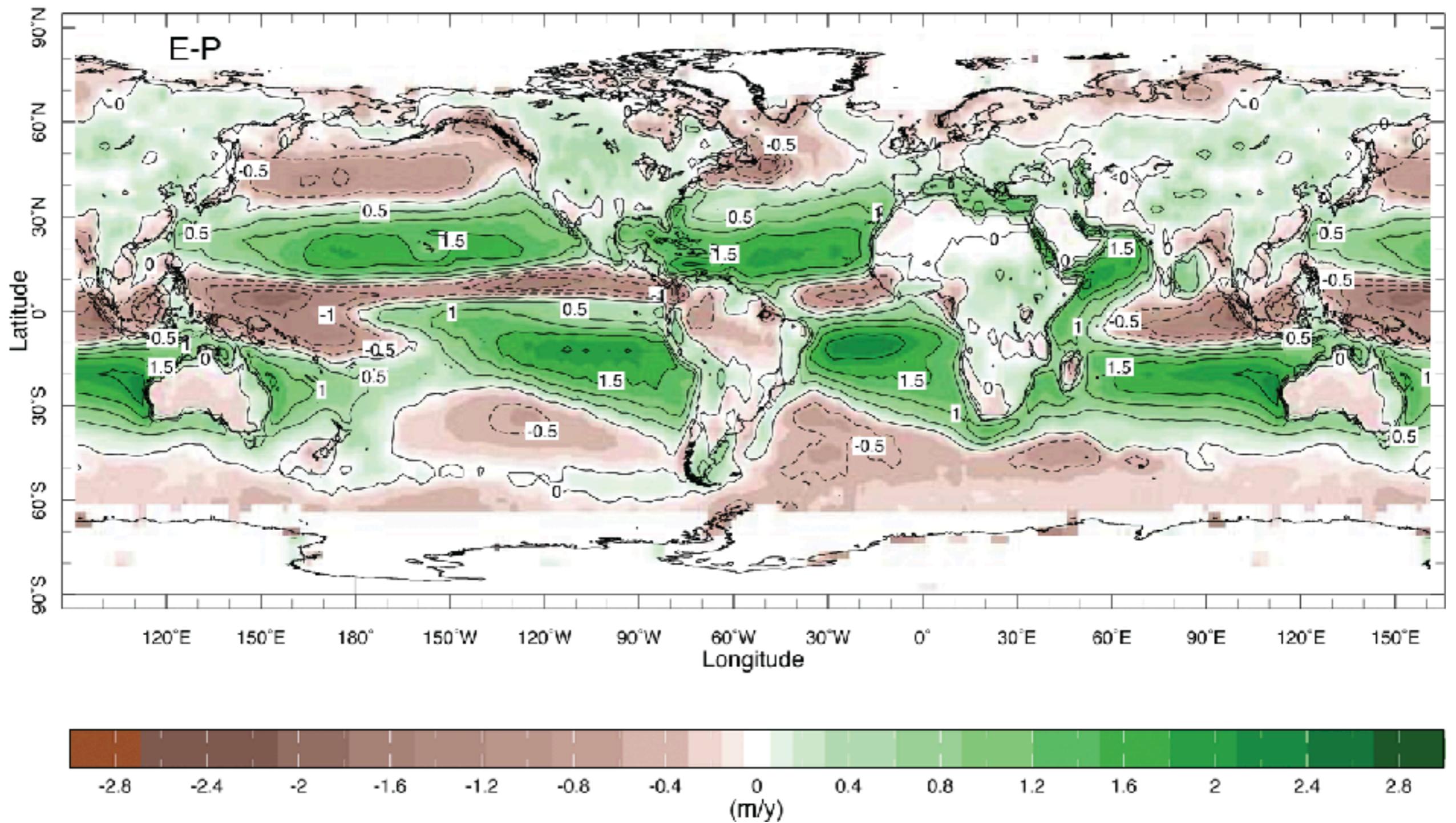
Sinking branch of Hadley cell



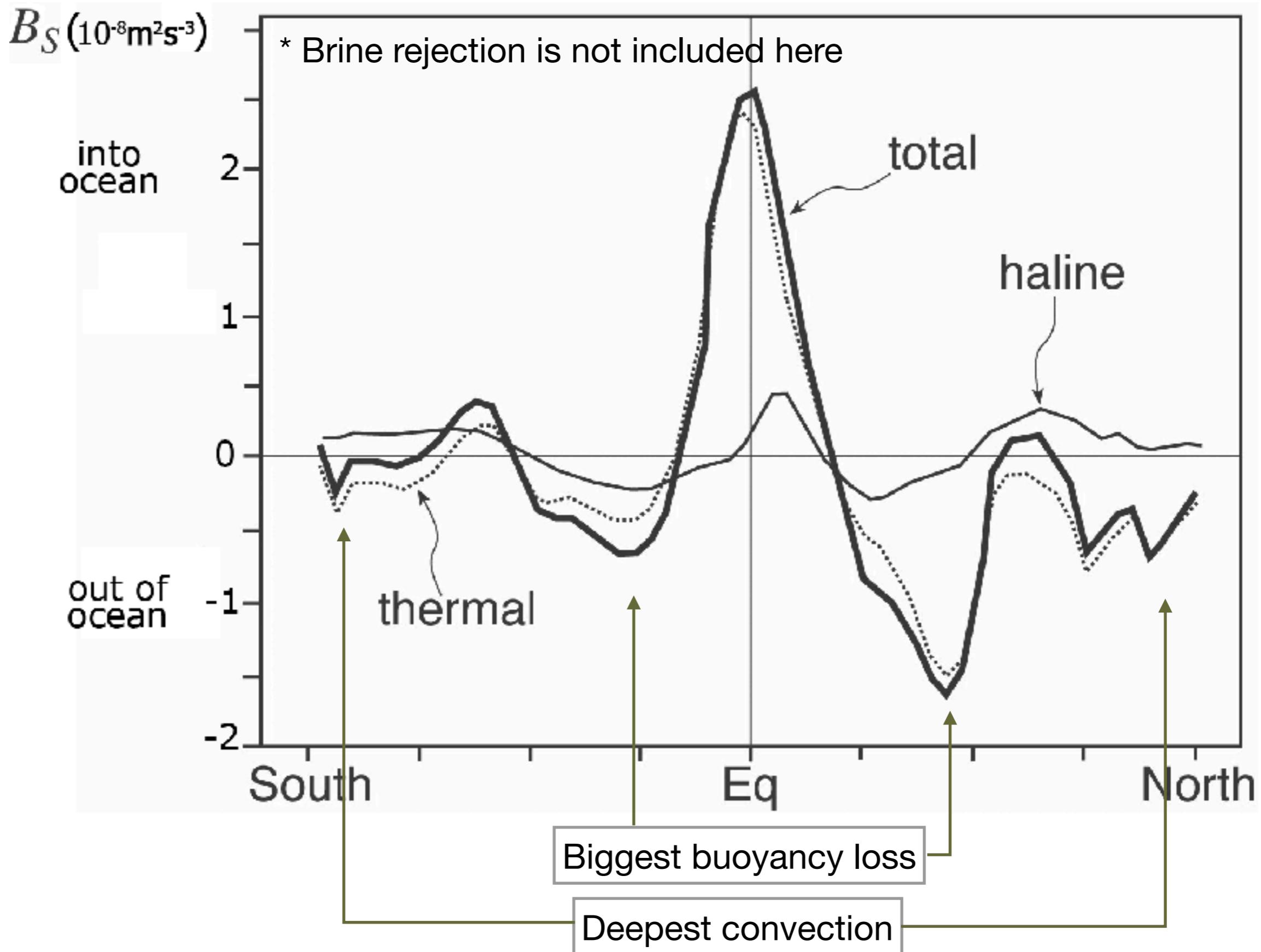
Rising branch of Hadley cell



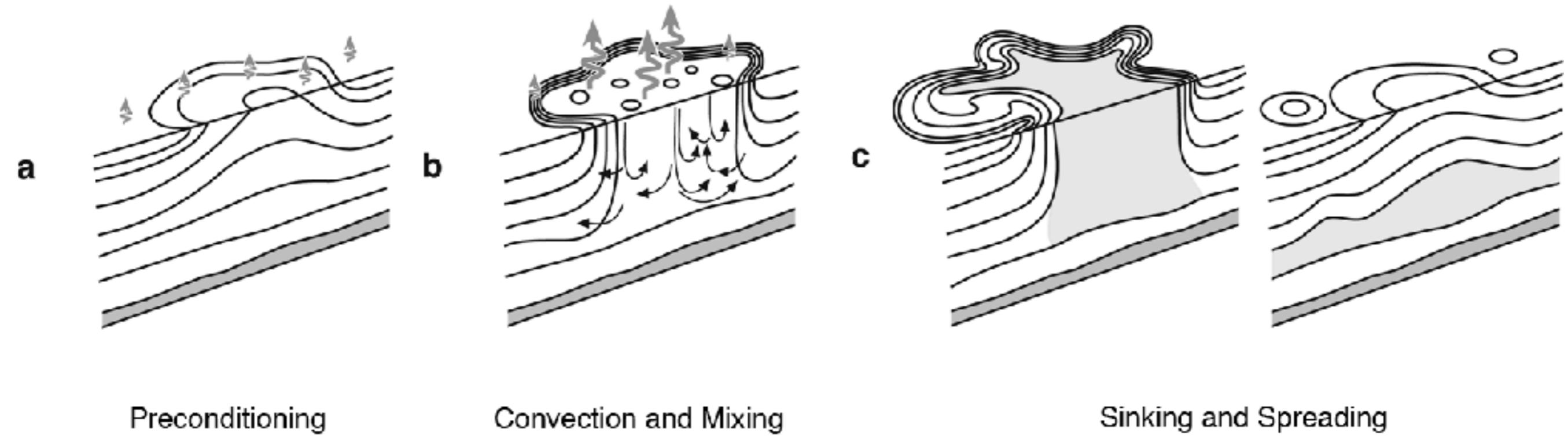
Green : net evaporation
Brown : net precipitation



The zonally-averaged buoyancy forcing



Phases of deep convection



Schematic diagram of the three phases of open-ocean deep convection:

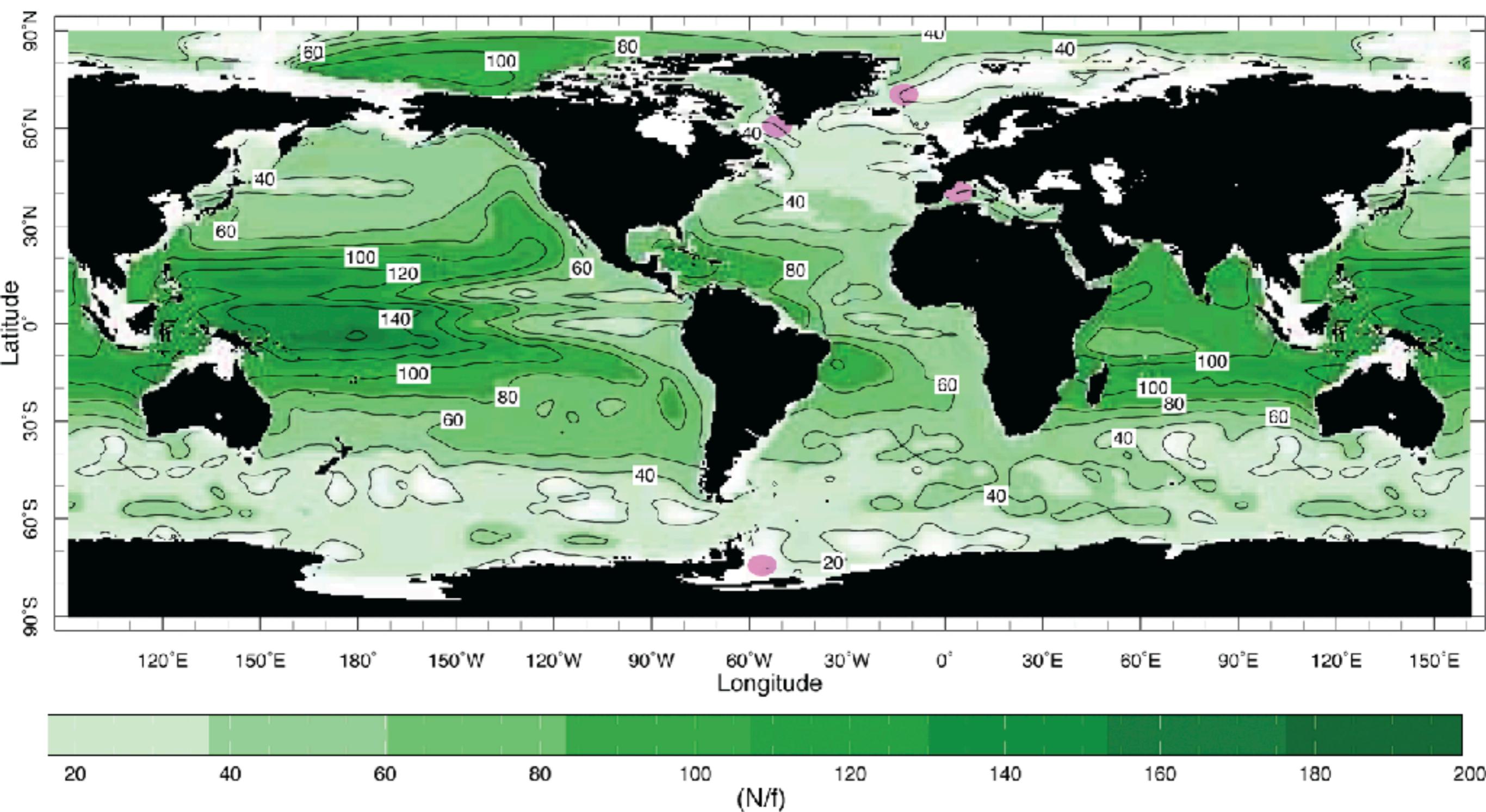
- (a) preconditioning,
- (b) deep convection and mixing
- (c) sinking and spreading.

Buoyancy flux through the sea surface is represented by curly arrows, and the underlying stratification/outcrops are shown by continuous lines. The volume of fluid mixed by convection is shaded.

Sites of deep convection

- There is no direct relationship between air-sea buoyancy forcing and the pattern of deep mixed layer depth.
- Underlying stratification plays important role in preconditioning of the ocean for deep convection.
- Labrador and Greenland Seas in the north Atlantic have convection deeper than 1 km.
- No deep convection in the North Pacific (because it is fresh.)

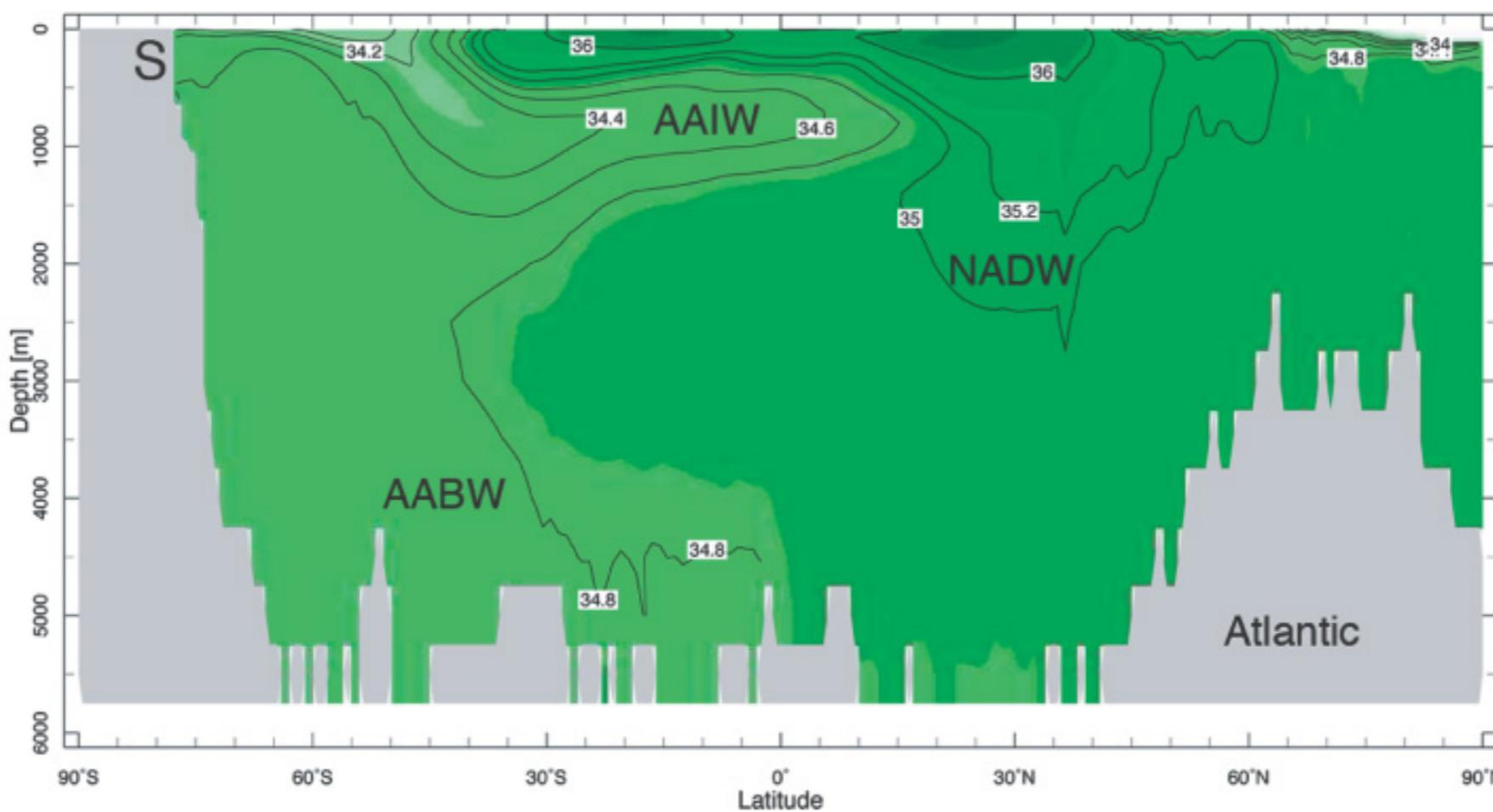
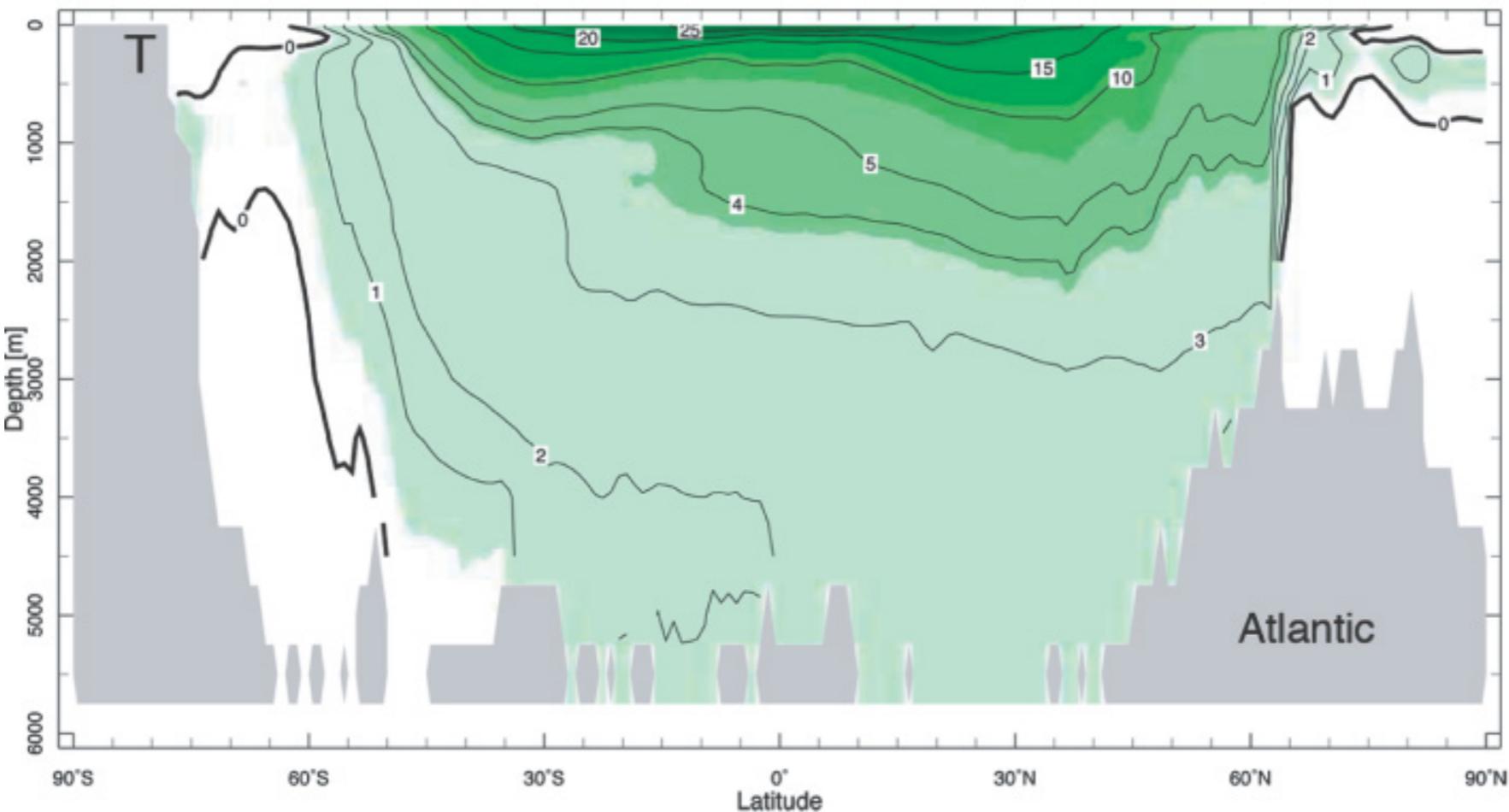
Mean Ocean Stratification at 200m



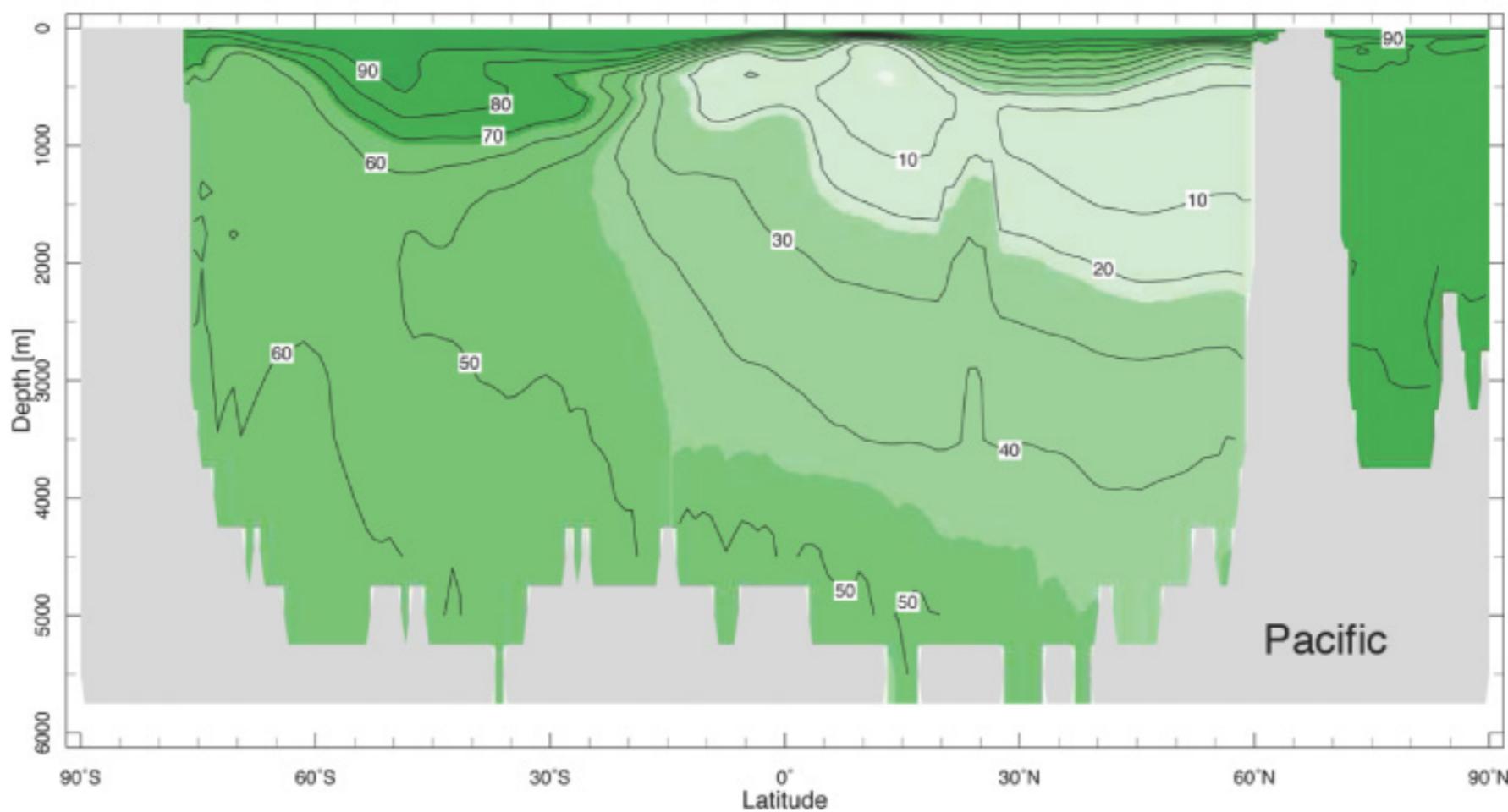
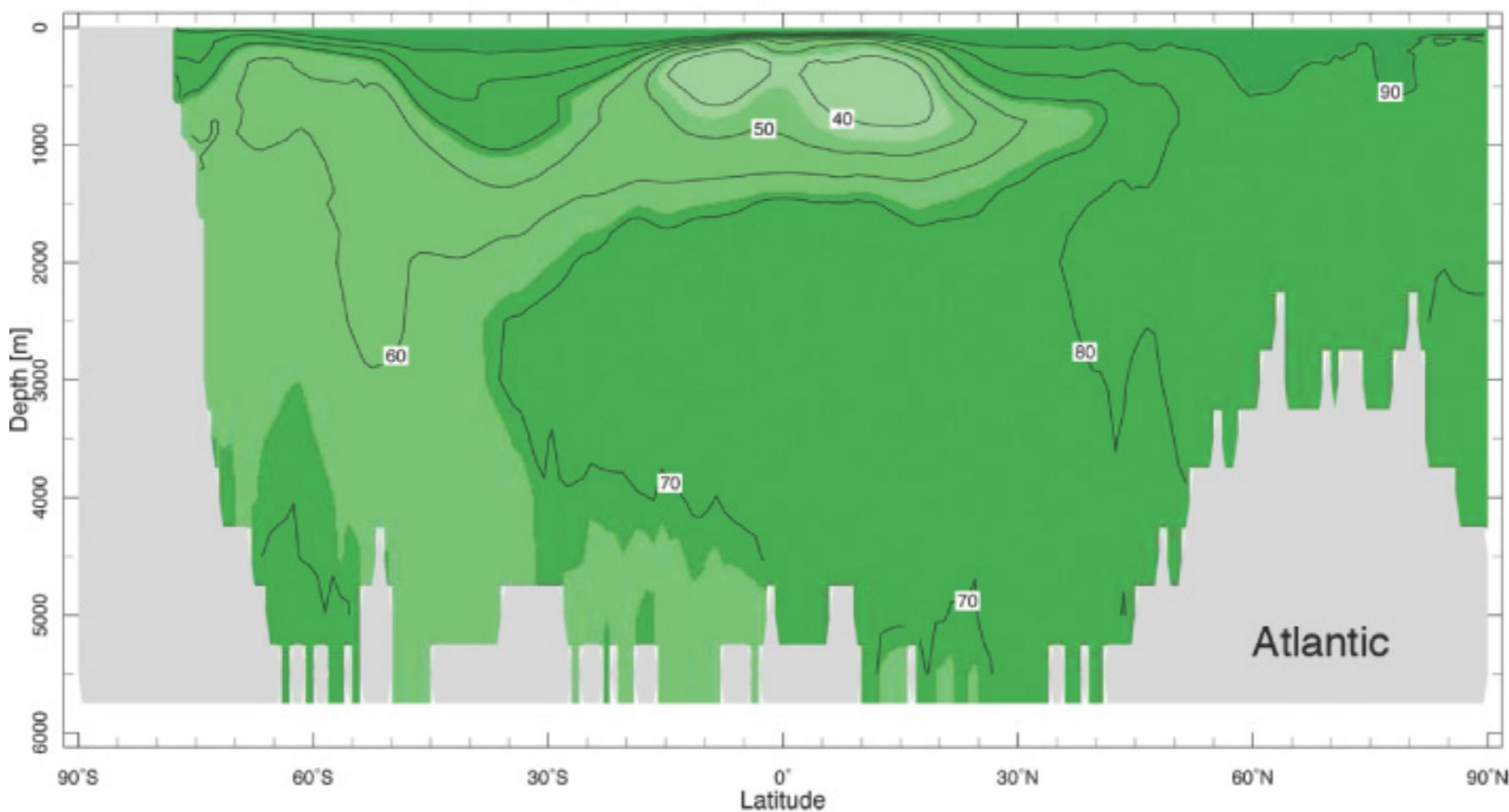
Buoyancy frequency normalized by a reference value of the Coriolis parameter. Note that $N/f < 20$ in regions where deep mixed layers are common. Sites of deep-reaching convection are marked in the Labrador Sea, the Greenland Sea, the Western Mediterranean and the Weddell Sea.

The observed thermohaline circulations

Zonal-Average T ($^{\circ}$ C) And S (psu) across The Atlantic



Zonal Average Oxygen (ml/l) across Atlantic and Pacific



Observations of CFCs at a depth of 2 km in ocean

- Chlorofluorocarbons (CFCs) from industrial and household use can be used to track the ocean circulation patterns.
- The concentration of CFCs reveals the flow in the ocean interior along the western boundaries.

