Ocean: Thermohaline circulation I

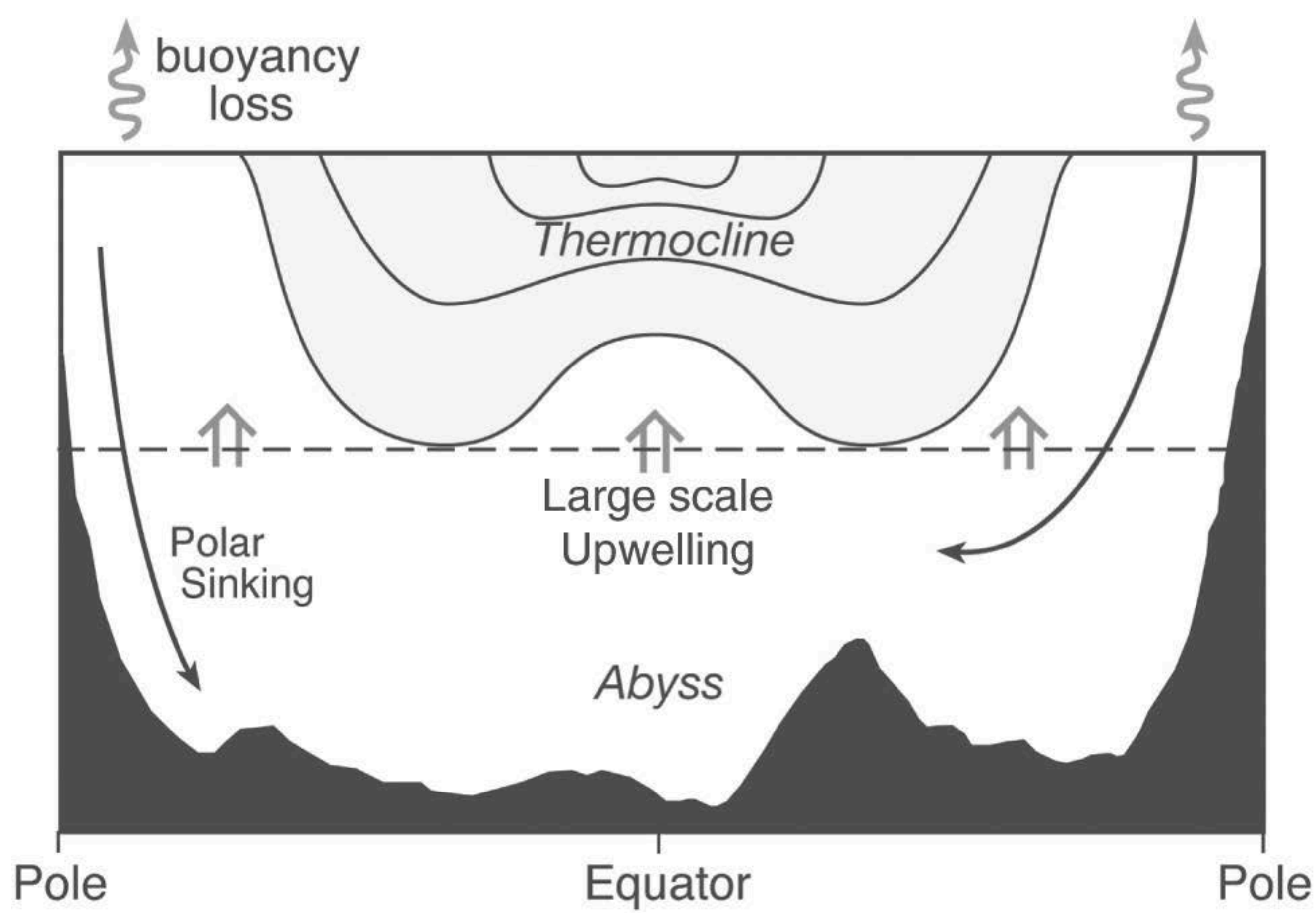
ATM2106

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

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

Shortwave — Q_{SW}; Longwave — Q_{LW}; Sensible heat — Q_S; Latent heat — Q_L

- 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 (Q_{SW}) Longwave (Q_{LW}) Sensible heat (Q_S) Latent heat (Q_L)

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

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

Coefficients for the heat transfer (c_S)

Specific heat of the air (c_p)

Density of the air at the surface (ρ_{air})

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.

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

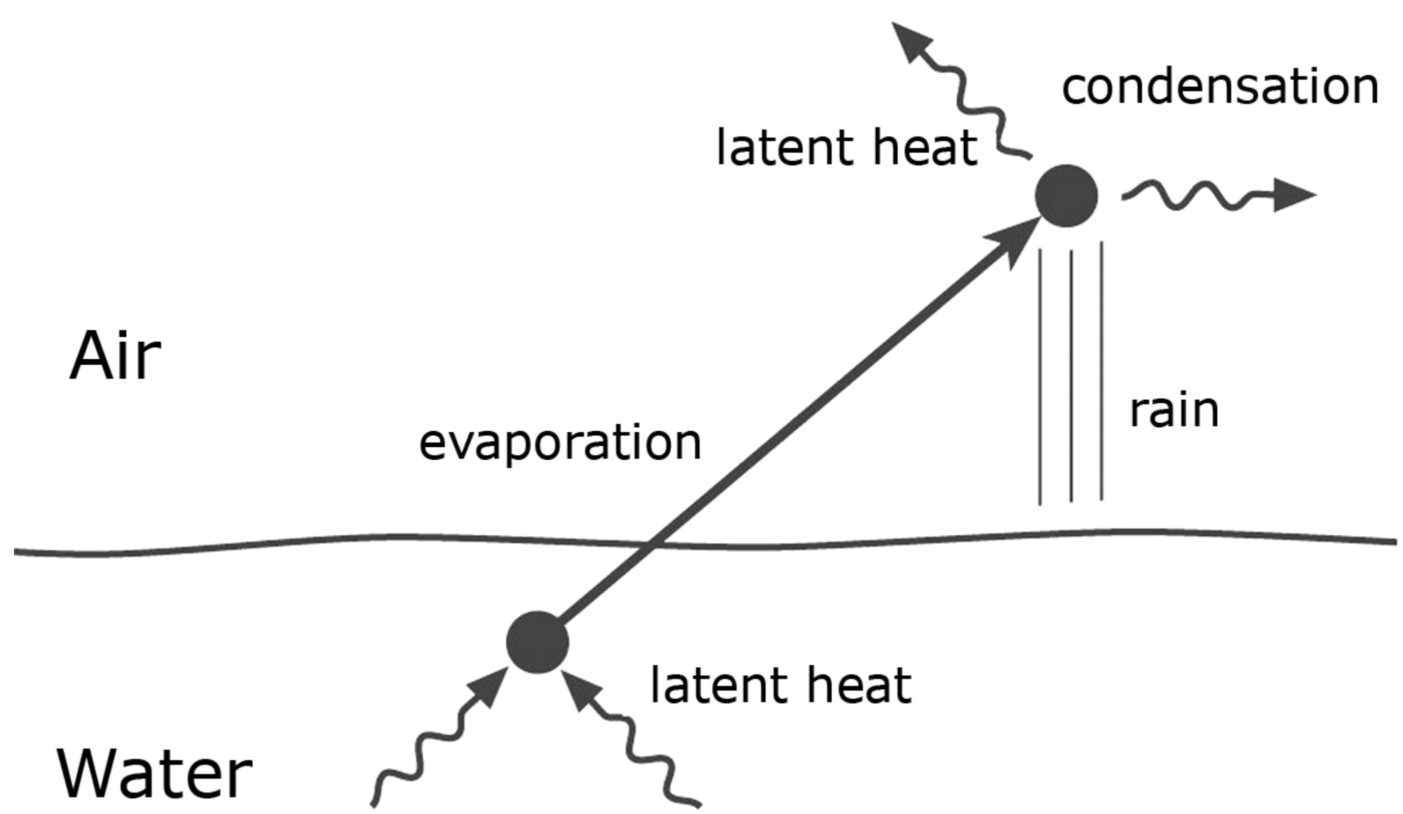
Density of the air at the surface
Latent heat of evaporation
Transfer coefficients for water vapor
Specific humidity at saturation
Specific humidity

Surface heat flux

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

Shortwave — Longwave — Sensible heat — Latent heat

- Latent heat flux is introduced from evaporation.



Surface heat flux

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

Shortwave (Q_{SW}), Longwave (Q_{LW}), Sensible heat (Q_S), Latent heat (Q_L)

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

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

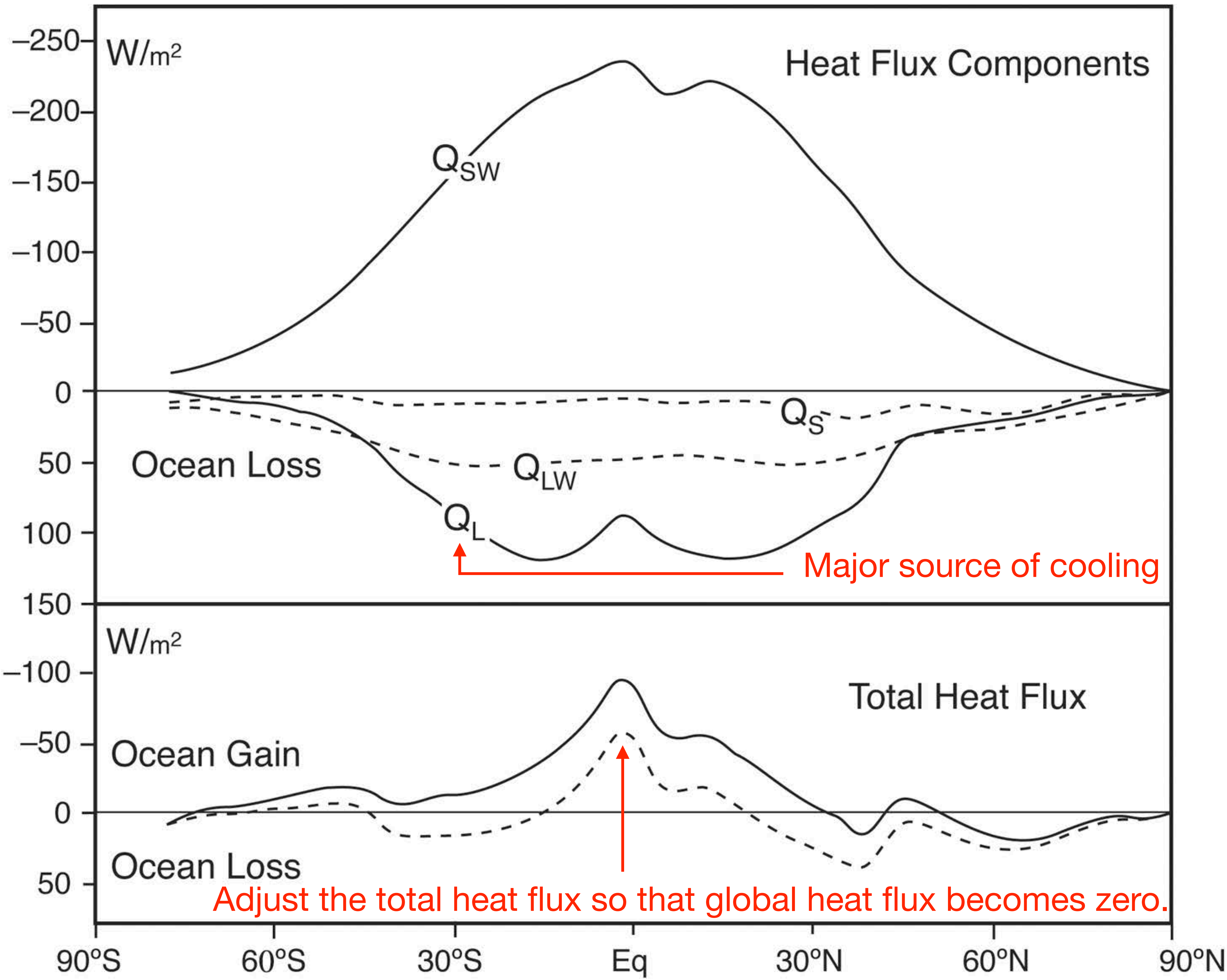
ρ_{air}: Density of the air at the surface

L_e: Latent heat of evaporation

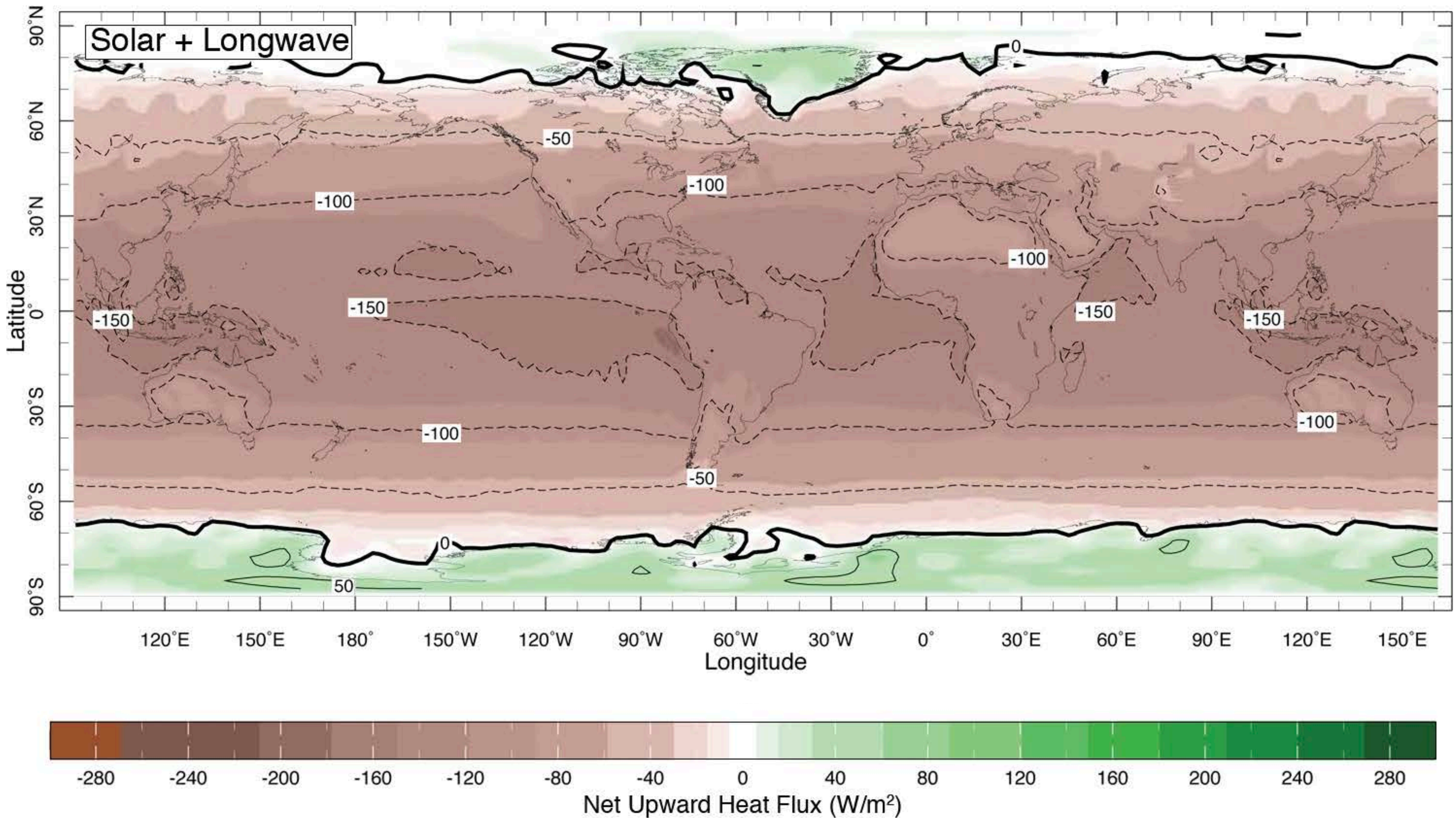
c_L: Transfer coefficients for water vapor

$q^*(SST)$: Specific humidity at saturation

q_{air}: Specific humidity


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

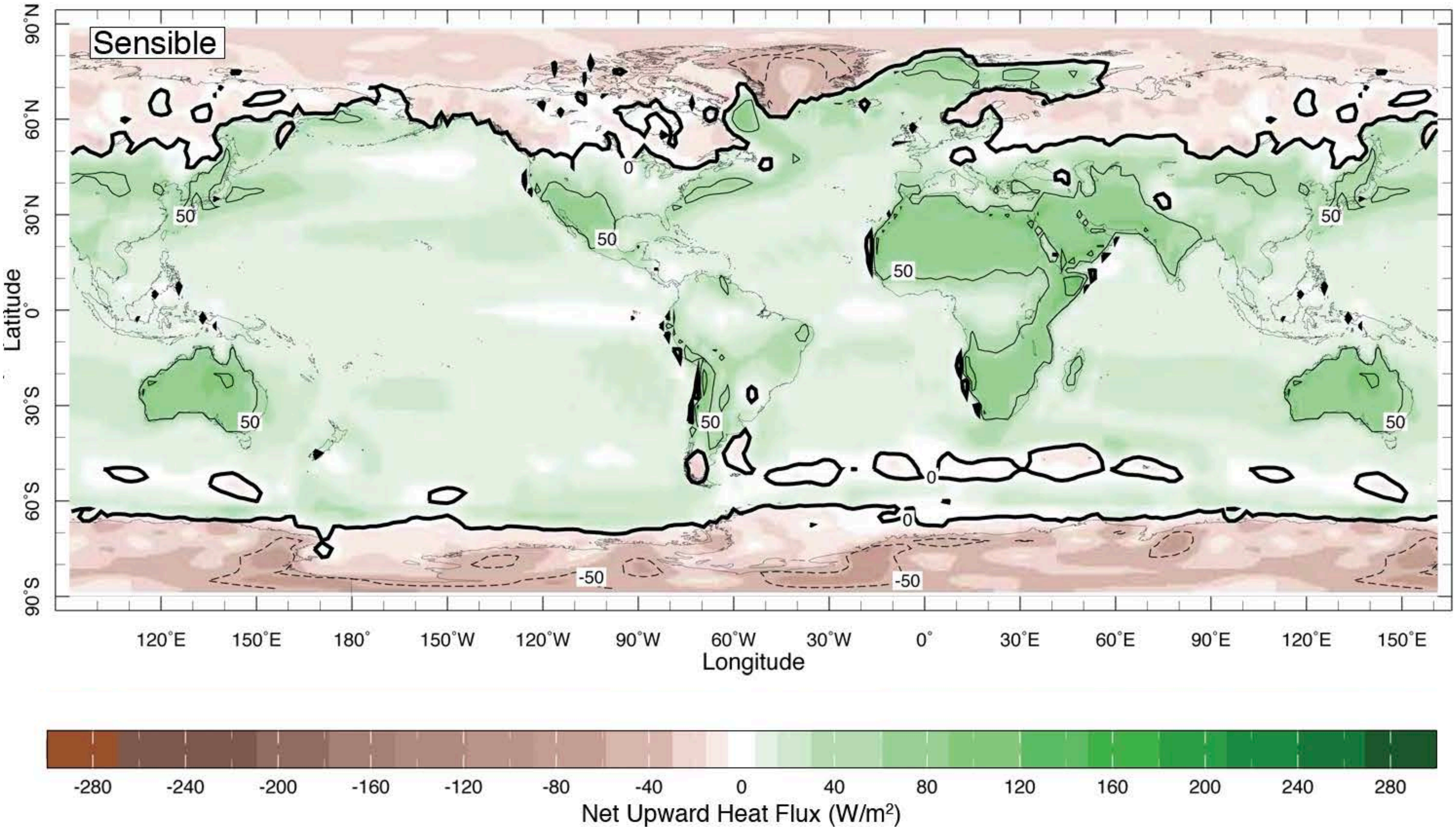
Net upward shortwave and longwave heat flux



Heat into the ocean

Heat into the atmosphere

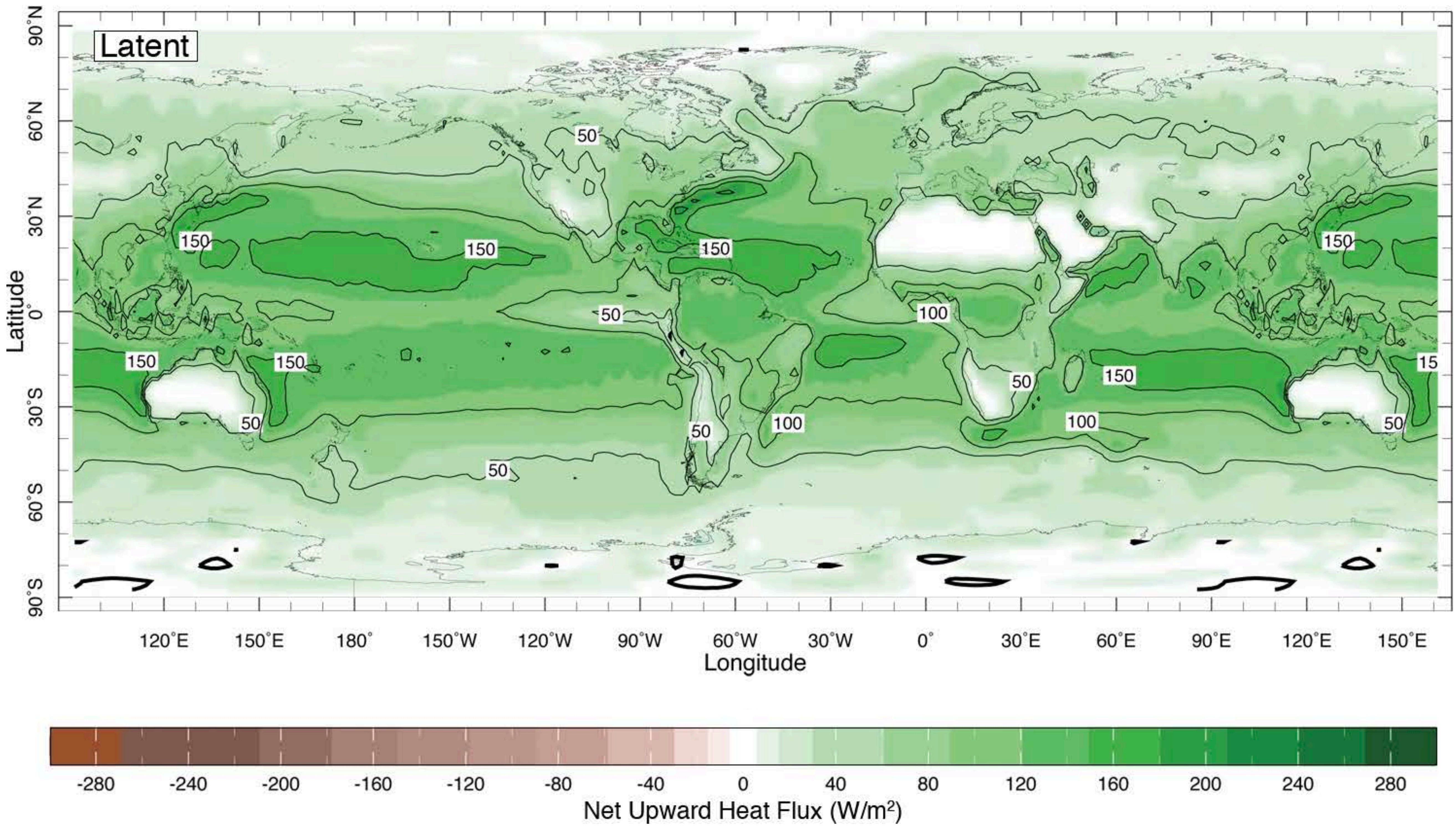
Net upward sensible heat flux



Heat into the ocean

Heat into the atmosphere

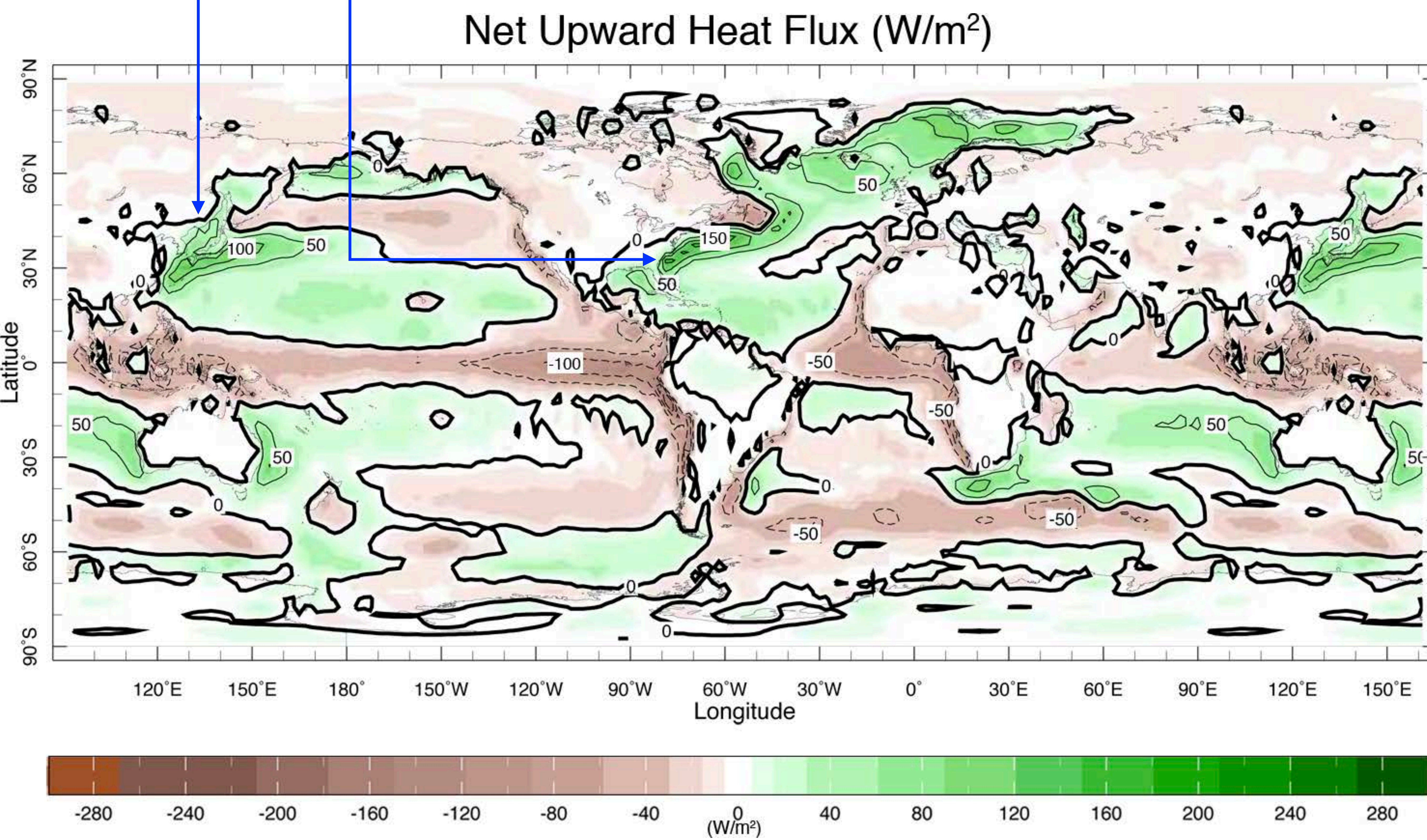
Net upward latent heat flux



Heat into the ocean

Heat into the atmosphere

Warm water + Cold air from the land in winter



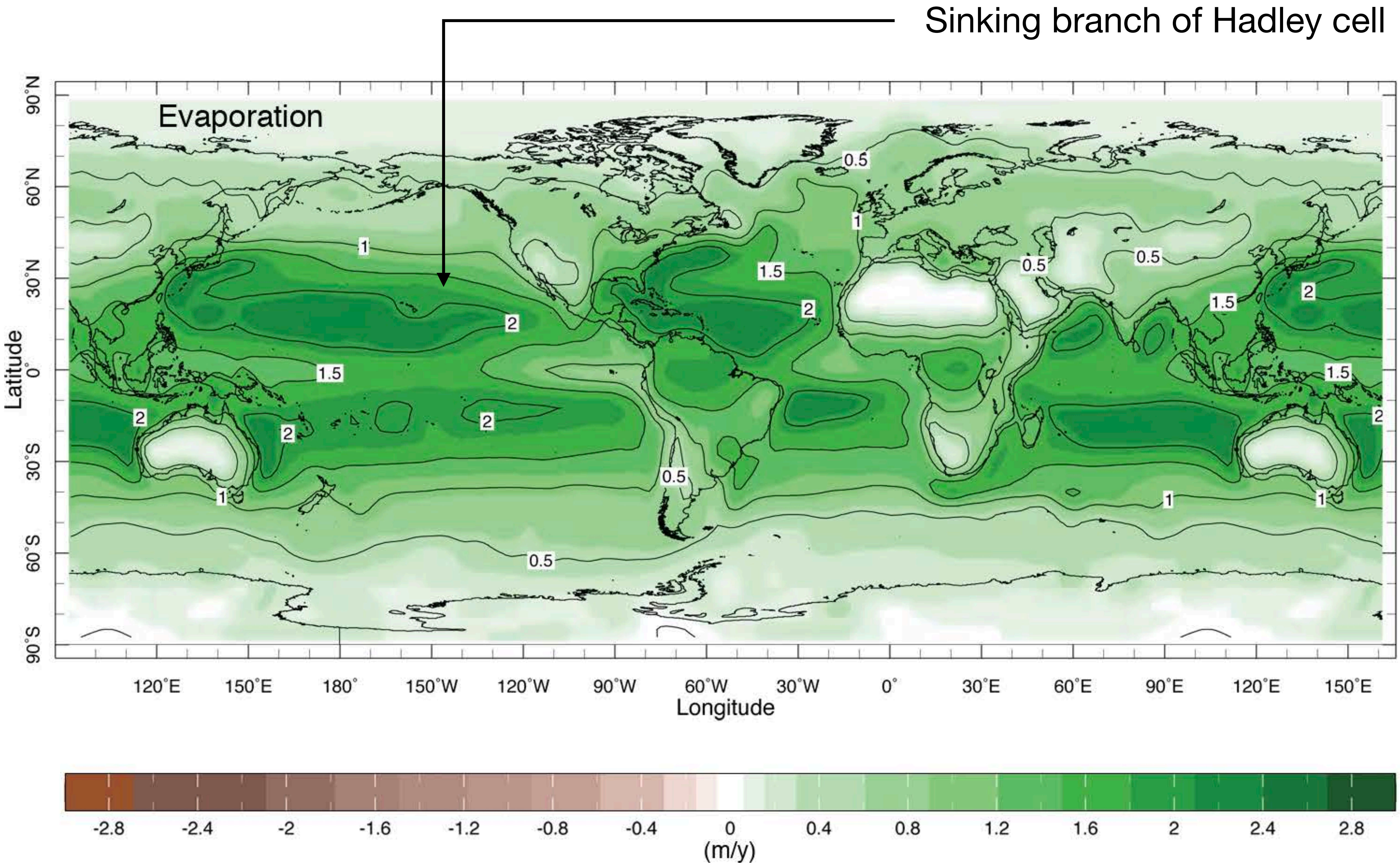
Heat into the ocean

Heat into the atmosphere

Surface salinity change

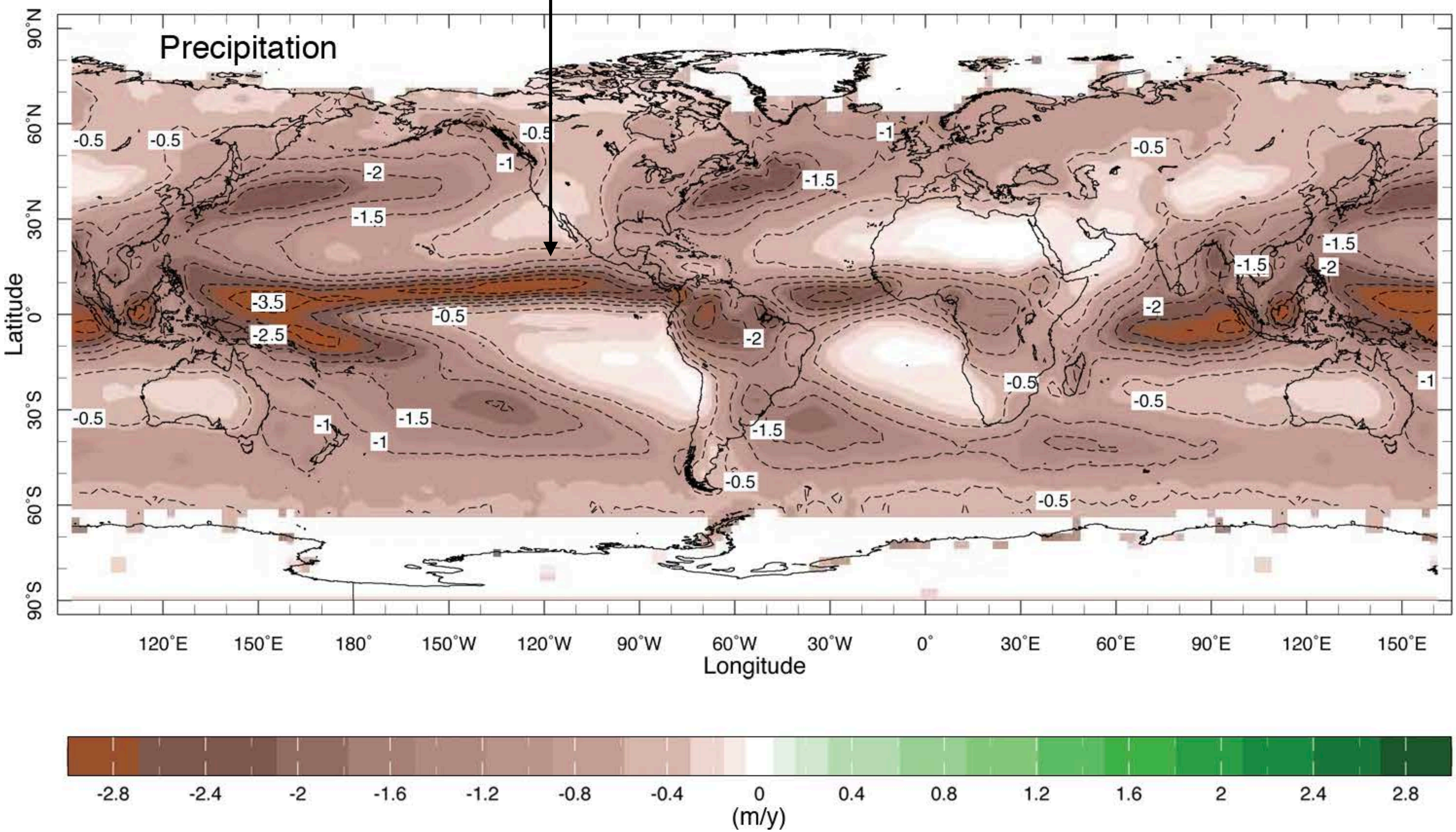
$$\frac{DS}{Dt} = S\frac{\partial \mathcal{E}}{\partial z}$$

- $\mathcal{E}$ 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)

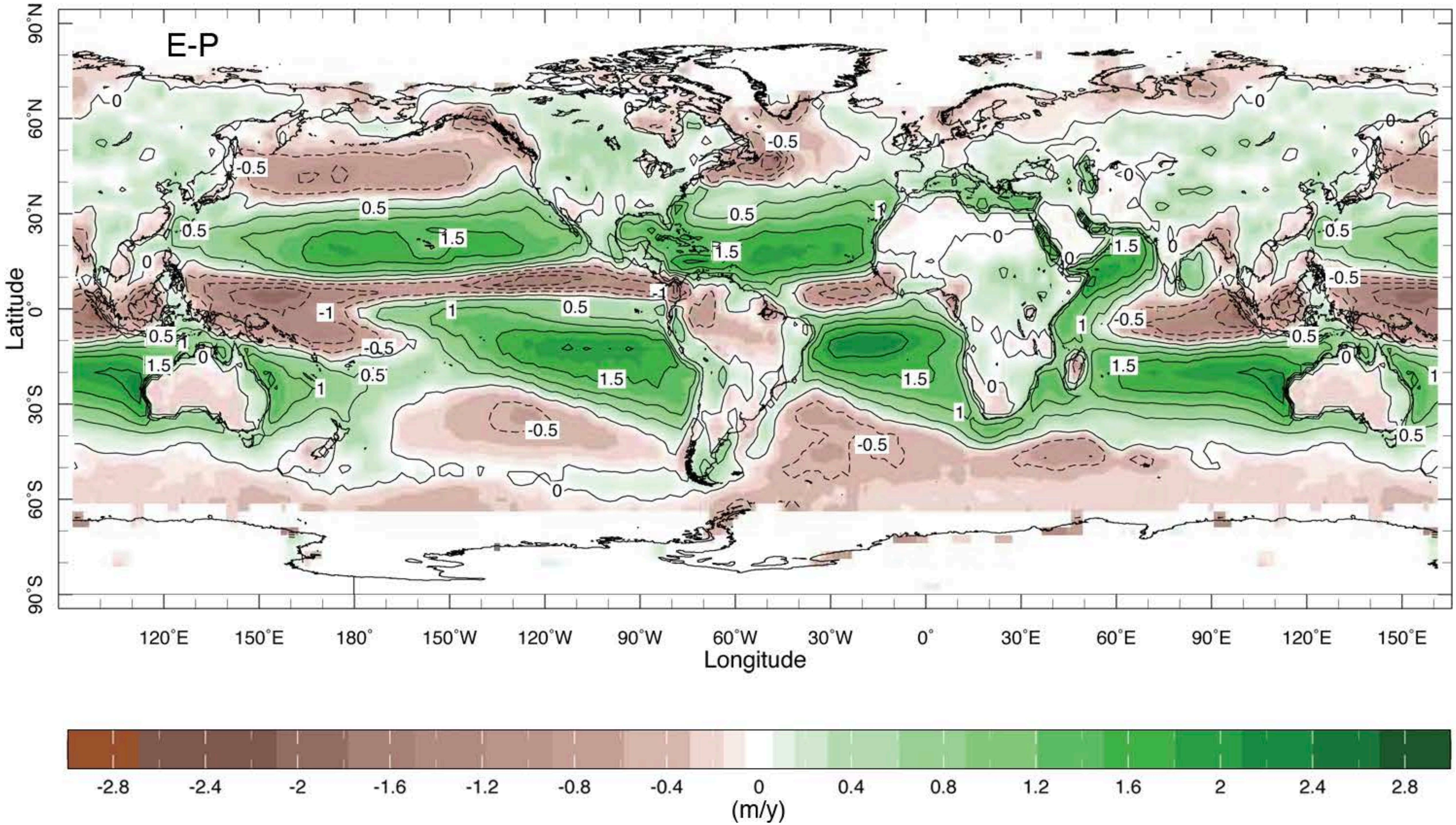


Sinking branch of Hadley cell
Evaporation
Latitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
Longitude
0.5
1
1.5
2
-2.8
-2.4
-2
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
(m/y)

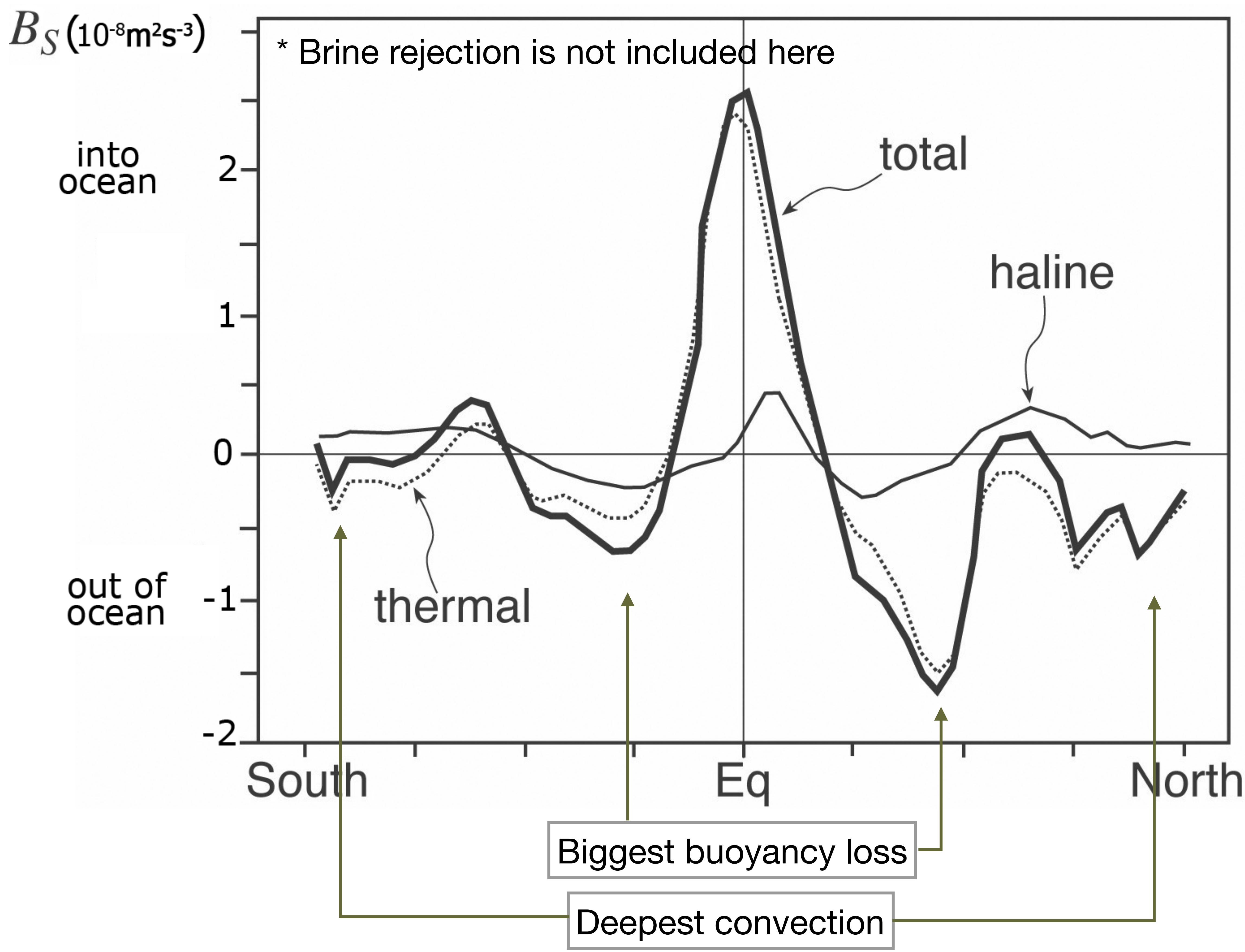
Rising branch of Hadley cell



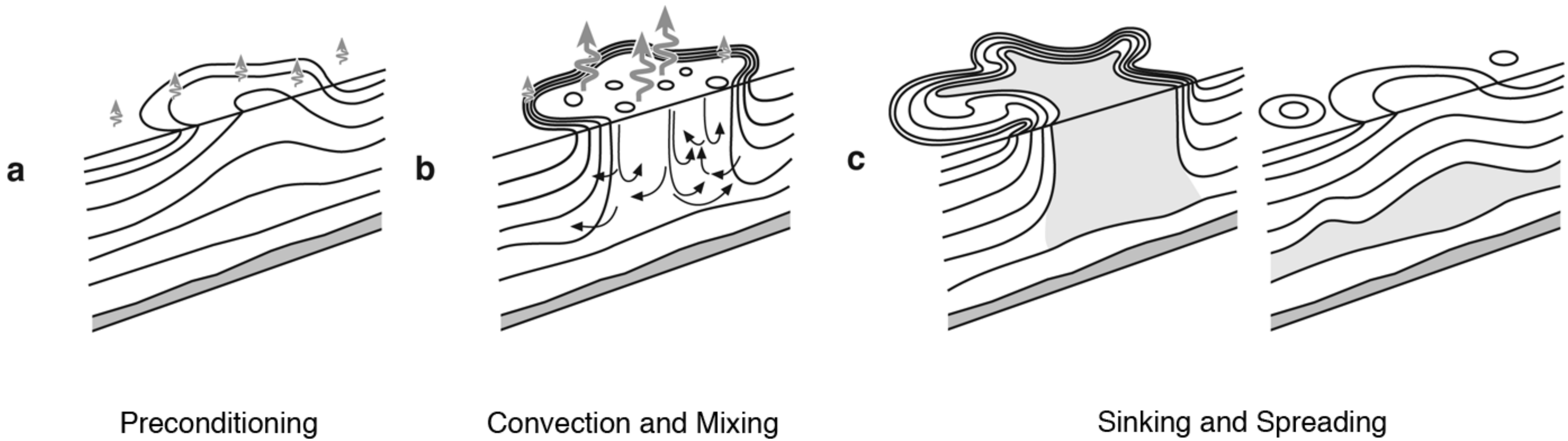
Green : net evaporation
Brown : net precipitation



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

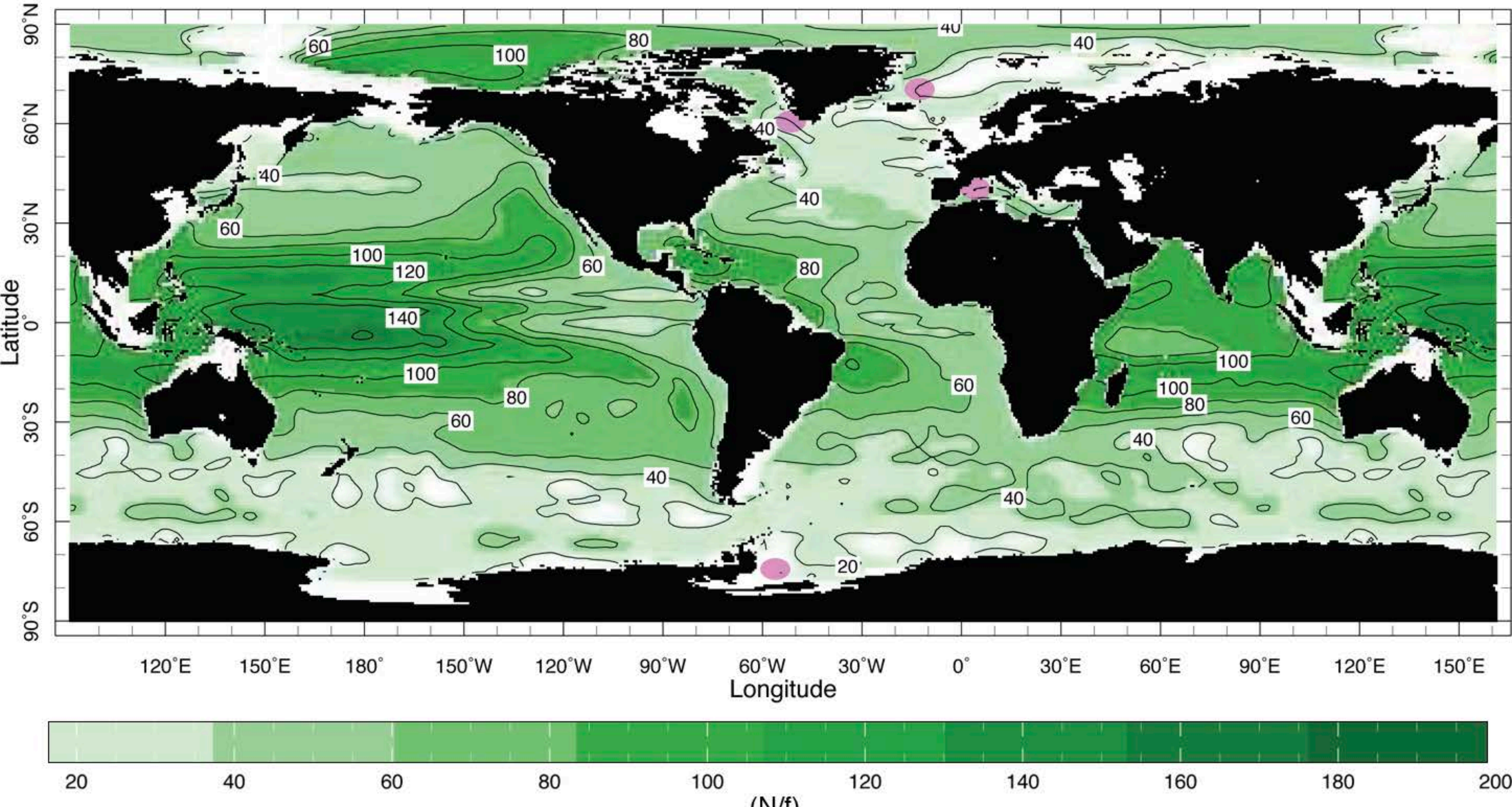
(c) sinking and spreading.

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.)

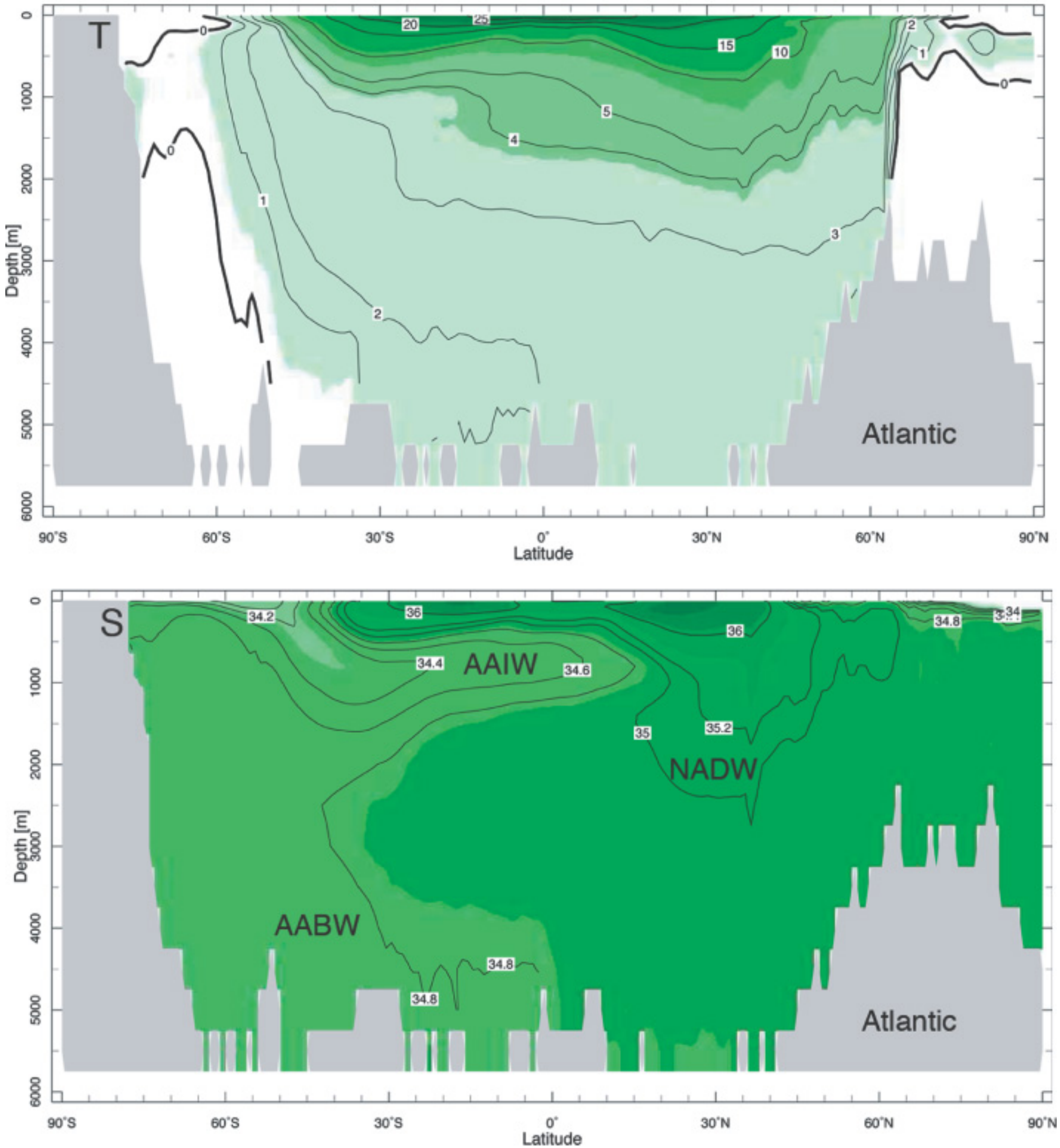
Mean Ocean Stratification at 200m



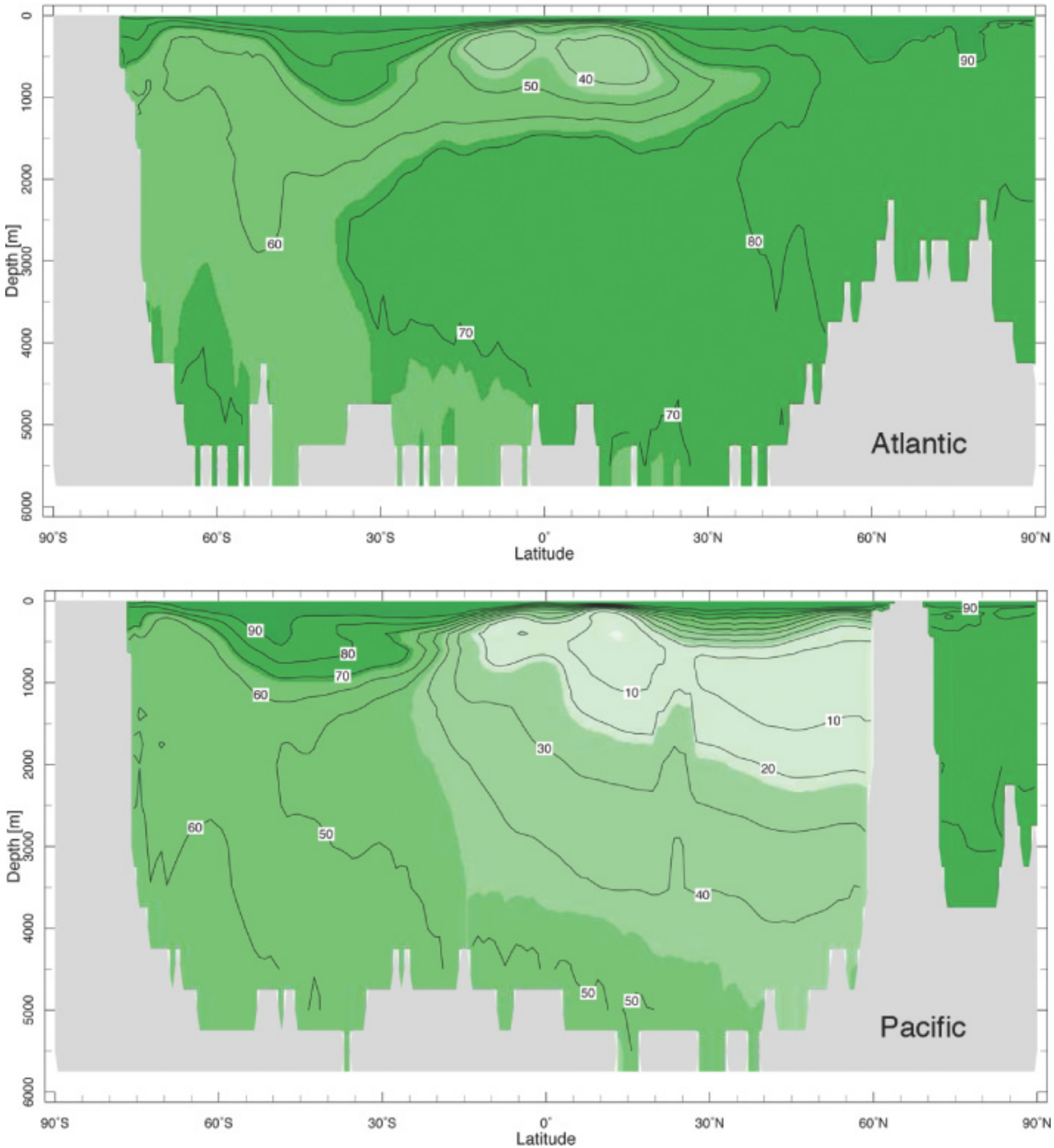
Buoyancy frequency normalized by a reference value of the Coriolis parameter. Note that N/f < 20 in regions where deep mixed layers are common Sites of deep-reaching convection are marked in the Labrador Sea, the Greenland Sea, the Western Mediterranean and the Weddell Sea.

The observed thermohaline circulations

Zonal-Average T (°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

- Chloroflourocarbons (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.