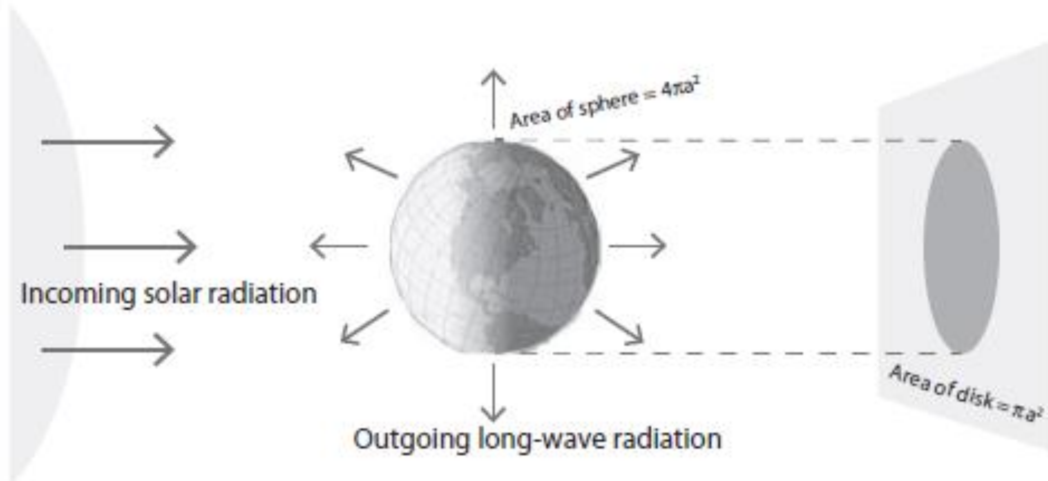
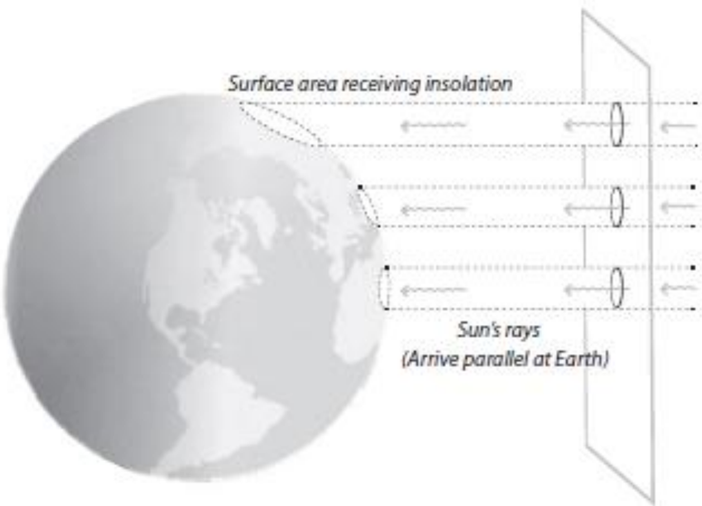
What makes the ocean circulate?

References:

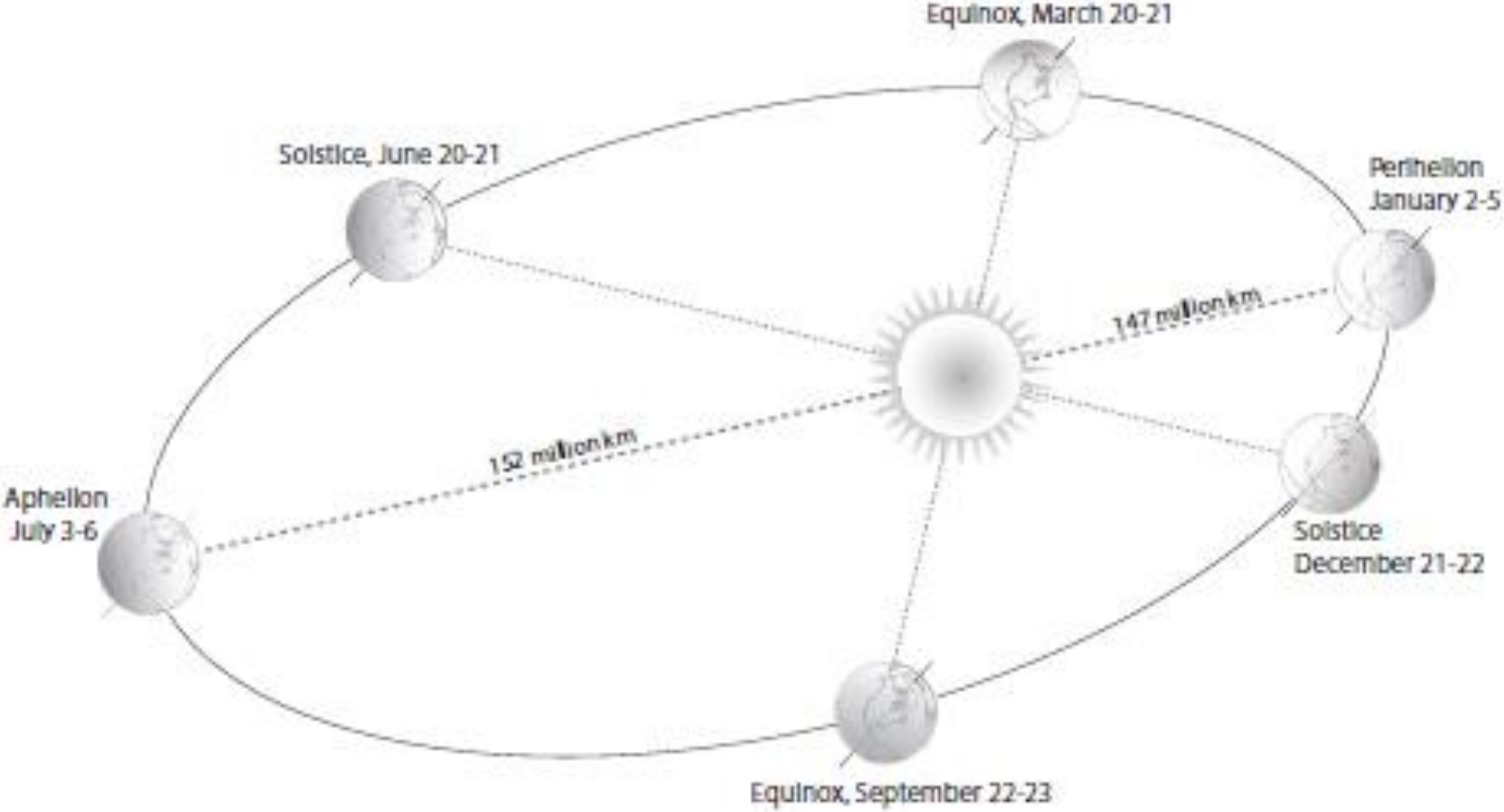
- Vallis (2012) Climate and the Oceans
- Vallis (2006) Atmospheric and Oceanic Fluid Dynamics
- Dommenget (2014) Lecture notes

http://users.monash.edu.au/~dietmard/teaching/dommenget.climate.dynamics.notes.pdf

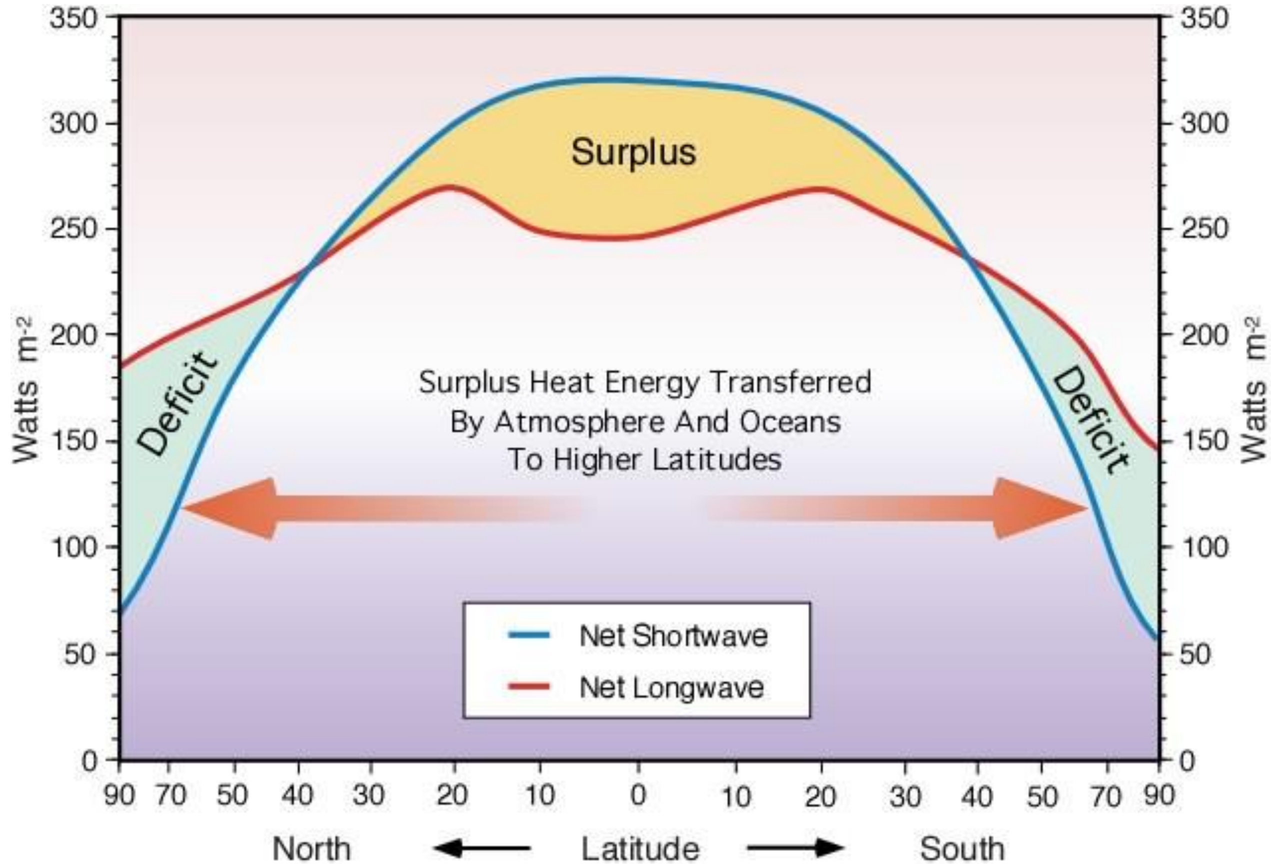




Source:Vallis (2012) Climate and the oceans



Source:Vallis (2012) Climate and the oceans



Surplus
Deficit
Deficit
Surplus Heat Energy Transferred
By Atmosphere And Oceans
To Higher Latitudes
Net Shortwave
Net Longwave
Watts m-2
Watts m-2
350
300
250
200
150
100
50
0
90 70 50 40 30 20 10 0 10 20 30 40 50 70 90
North
Latitude
South

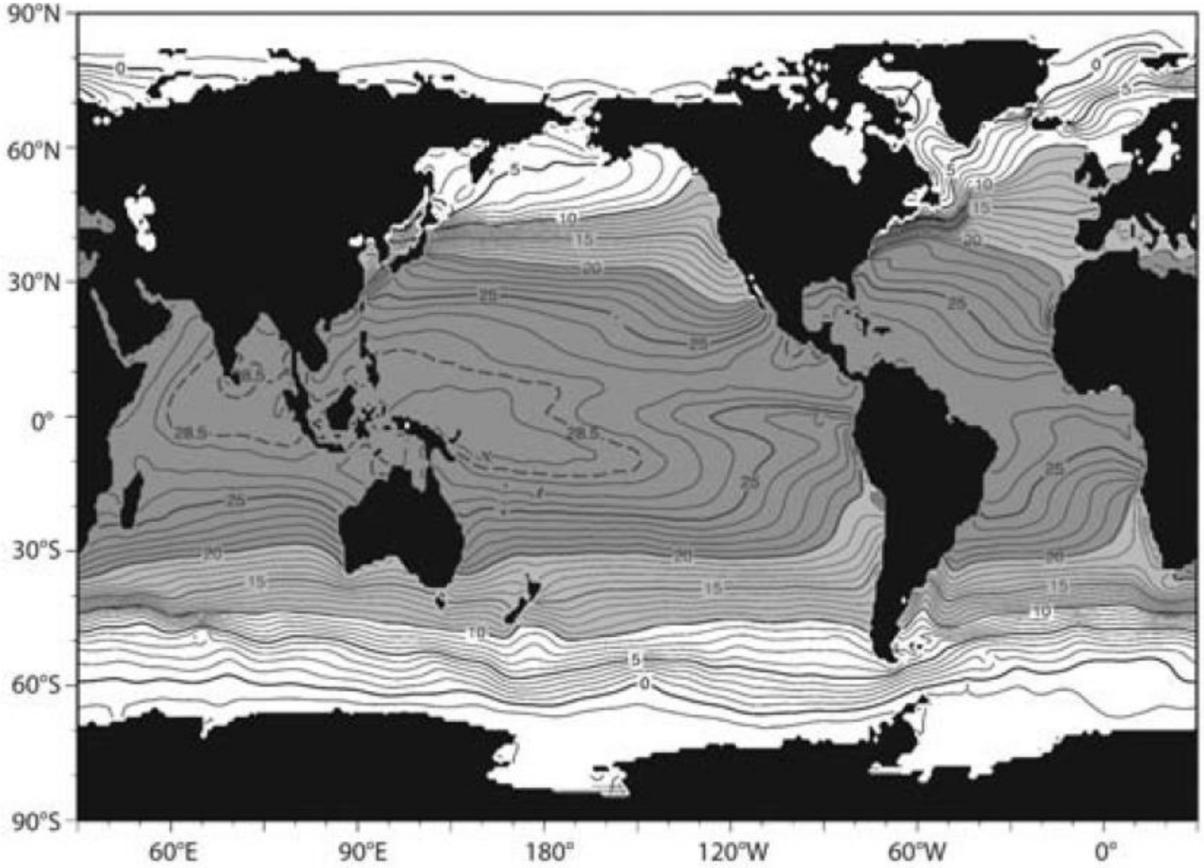


Figure 2.2. The annual average temperature at the ocean surface, in degrees centigrade. Adapted from World Ocean Atlas, 2009 of the National Oceanic and Atmospheric Administration (http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html).

Source:Vallis (2012) Climate and the oceans

Surface temperature in February

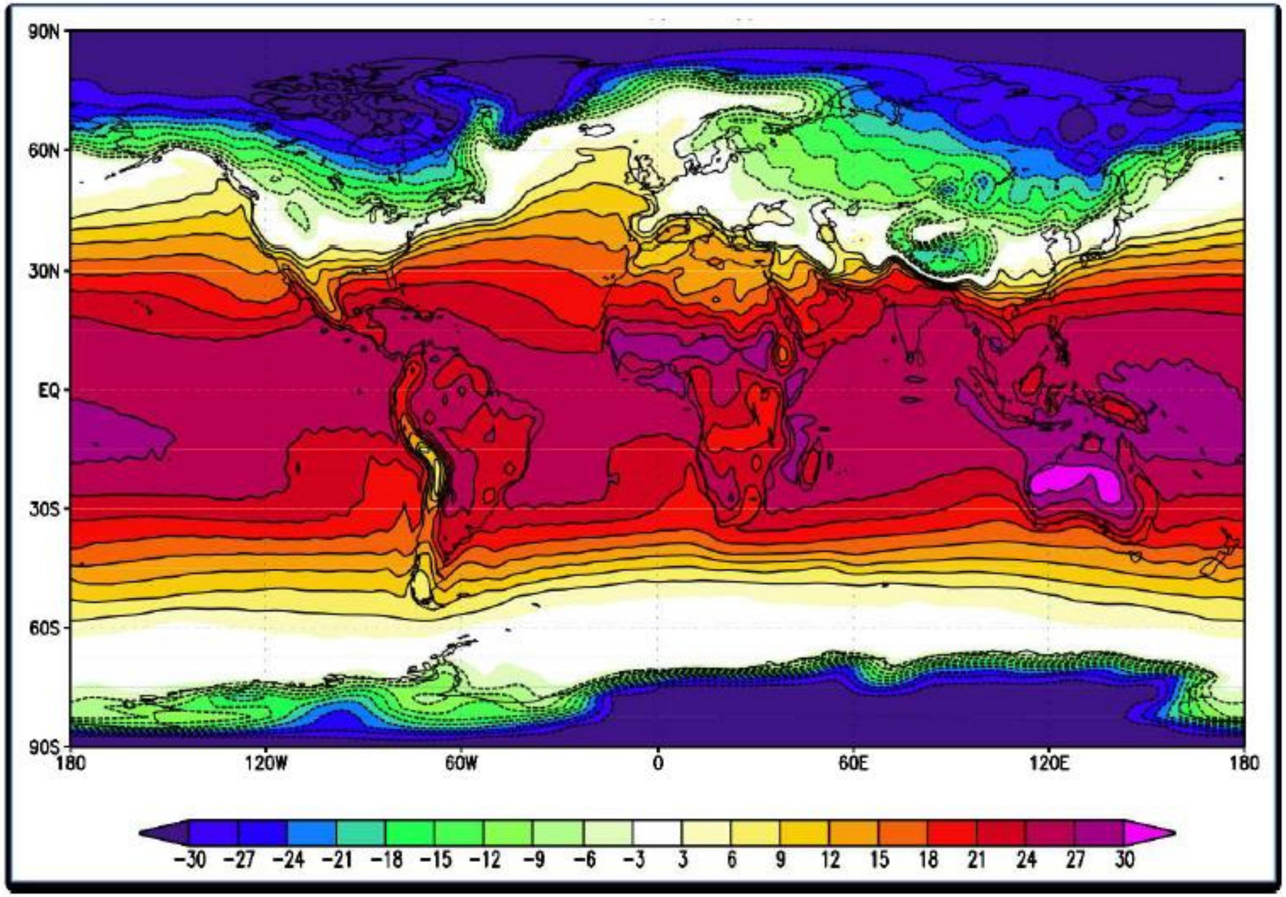


Figure 6.108: Surface temperature February: Note, that the northern North Atlantic (around $60^o N$) is much warmer than all other regions on the same latitude, which indicates that it is heating the other regions.

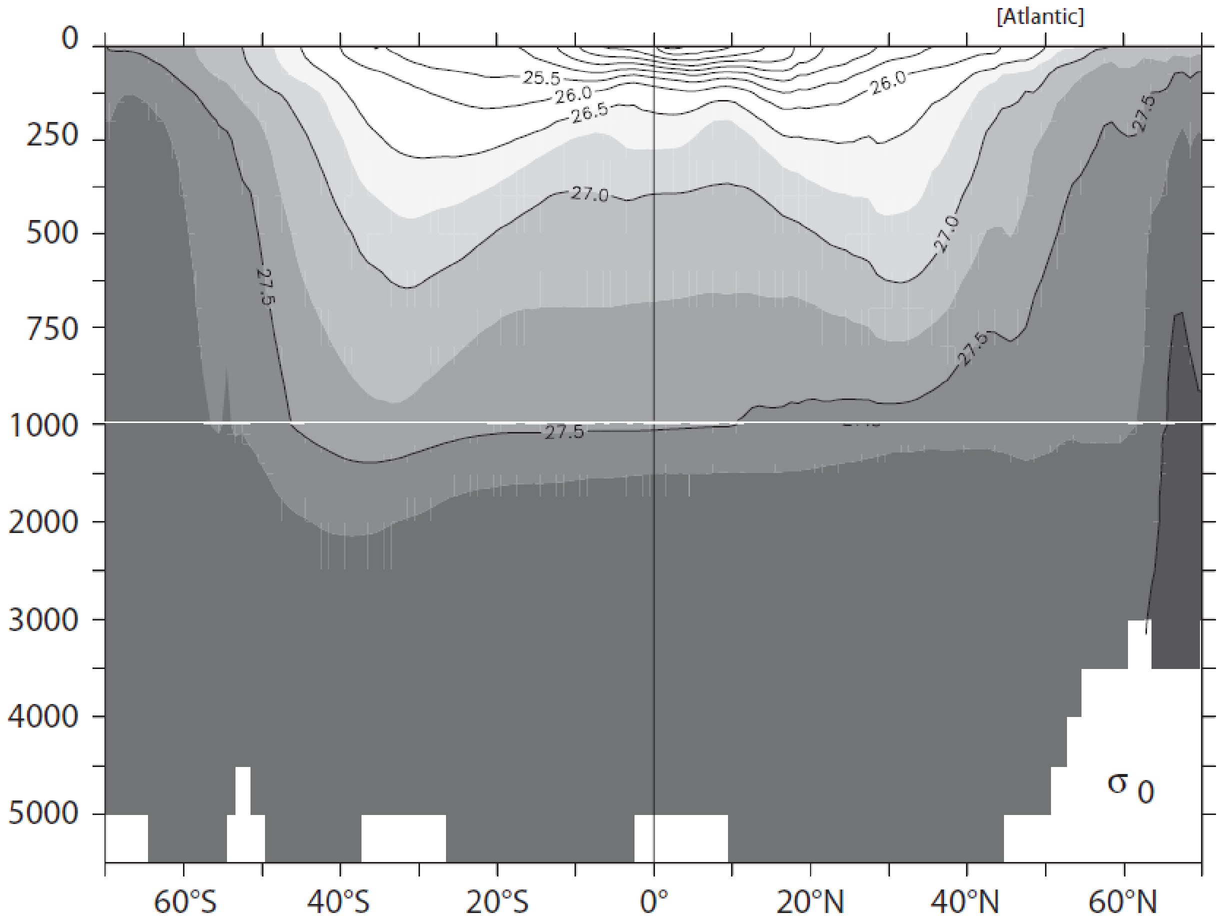


Figure 2.4. The zonally averaged density in the Atlantic Ocean. Note the break in the vertical scale at 1,000 m.[3]

Source:Vallis (2012) Climate and the oceans

Vertical structure of the ocean

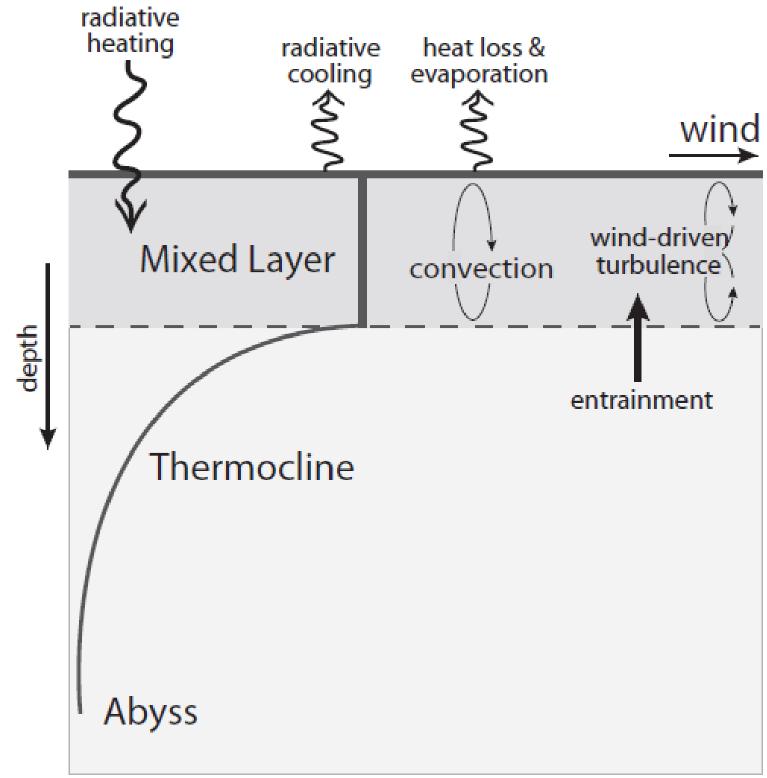
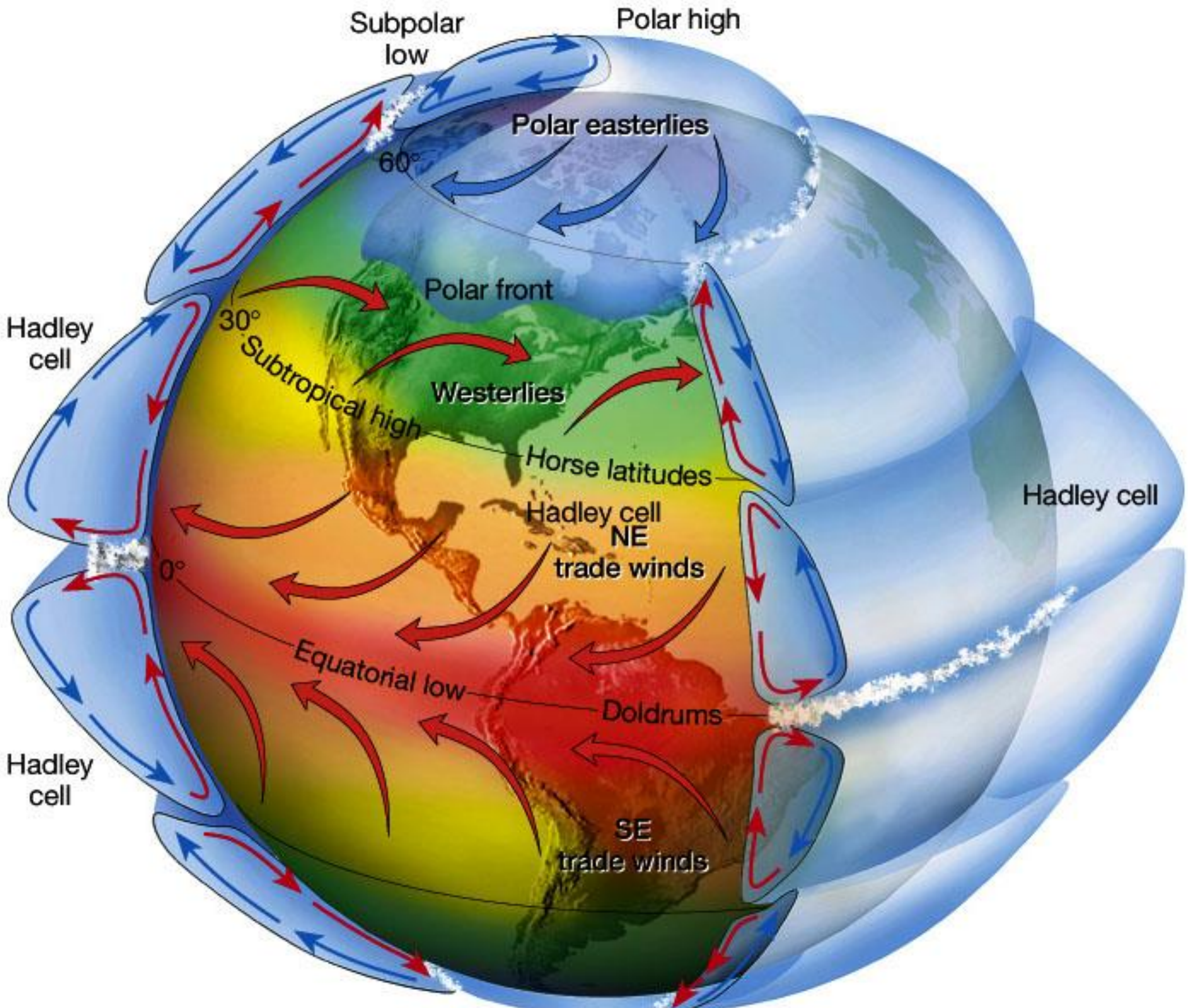


Figure 2.5. Schematic of the vertical structure of the ocean, emphasizing the mixed layer. In the mixed layer, typically 50–100 m deep, turbulence and convection act to keep the temperature relatively uniform in the vertical. Below this layer, temperature changes over a depth of a few hundred meters, in the *thermocline,* before becoming almost uniform at depth, in the *abyss*. Adapted from Marshall and Plumb, 2007.

Source:Vallis (2012) Climate and the oceans


Subpolar low
Polar high
Polar easterlies
60°
Polar front
Hadley cell
30°
Subtropical high
Westerlies
Horse latitudes
Hadley cell
NE trade winds
Hadley cell
0°
Equatorial low
Doldrums
Hadley cell
SE trade winds

Wind-driven ocean circulation

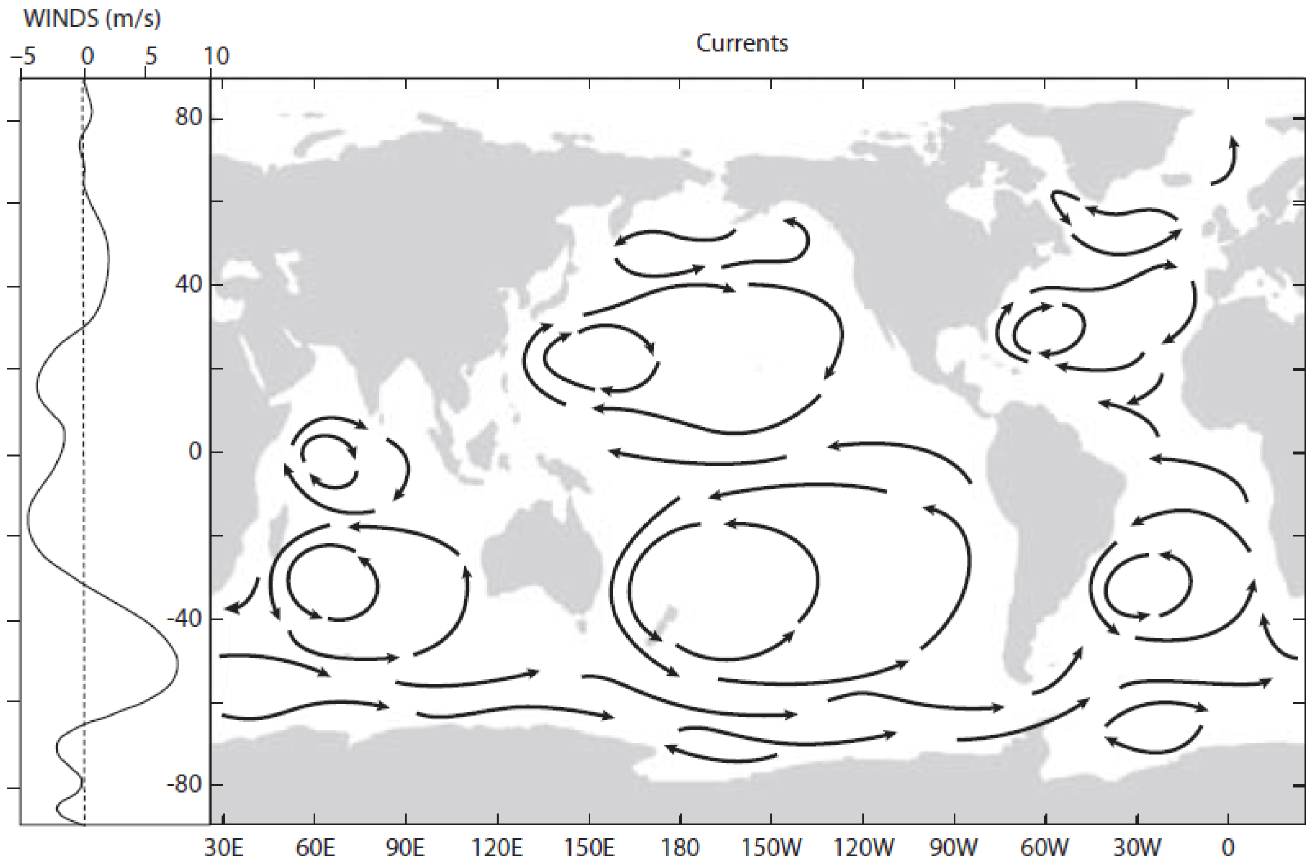


Figure 2.3. A schematic of the main surface currents of the world's oceans. The panel at the left shows the zonally averaged zonal (i.e., east–west) surface winds.

Source:Vallis (2012) Climate and the oceans

Westward propagation of Rossby waves

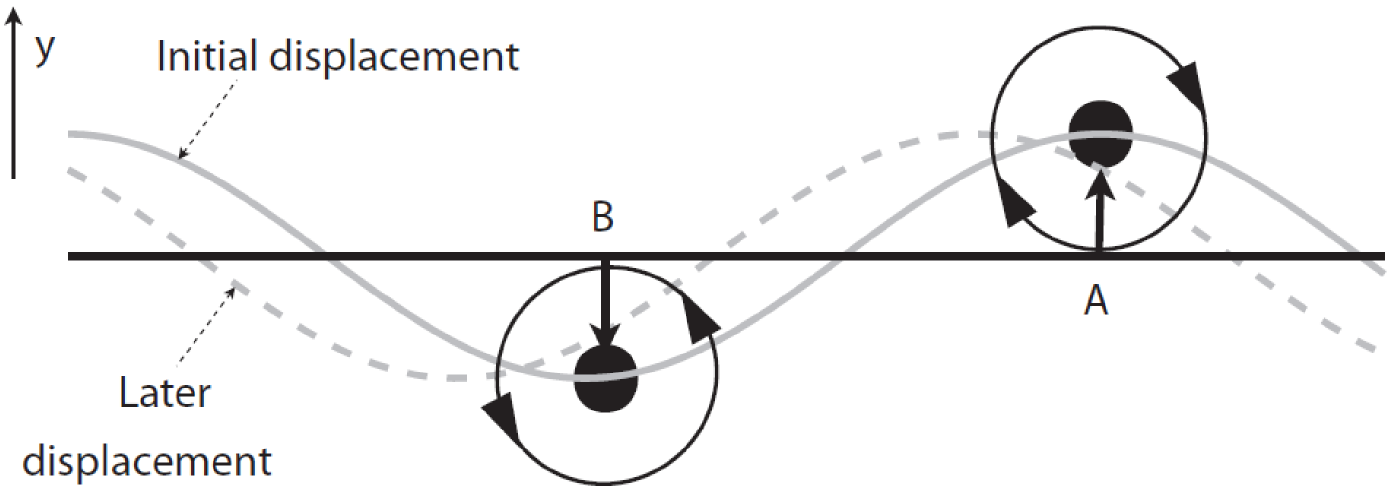


Figure 4.5. If parcel A is displaced northward, then its clockwise spin increases, causing the northward displacement of parcels that are to the west of A. A similar phenomenon occurs if parcel B is displaced south. Thus, the initial pattern of displacement propagates westward.

Absolute vorticity (spin) is conserved consisting of relative vorticity (clockwise) and planetary vorticity (anticlockwise)

Changing topography

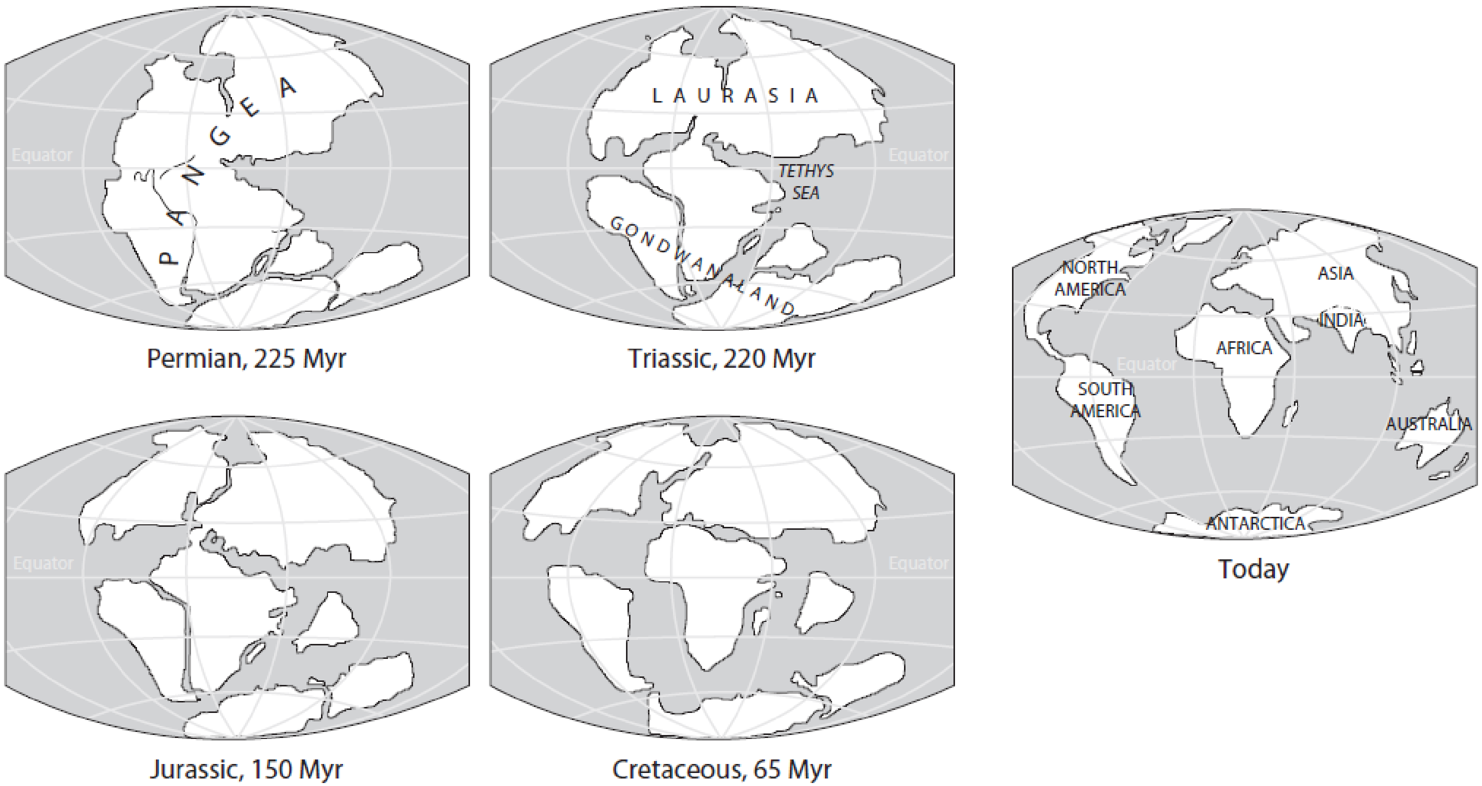


Figure 2.1. Schematic of the configuration of the oceans and continents over the past 225 million years, since the breakup of the supercontinent Pangea. Source: Adapted from USGS (http://pubs.usgs.gov/gip/dynamic/historical.html).

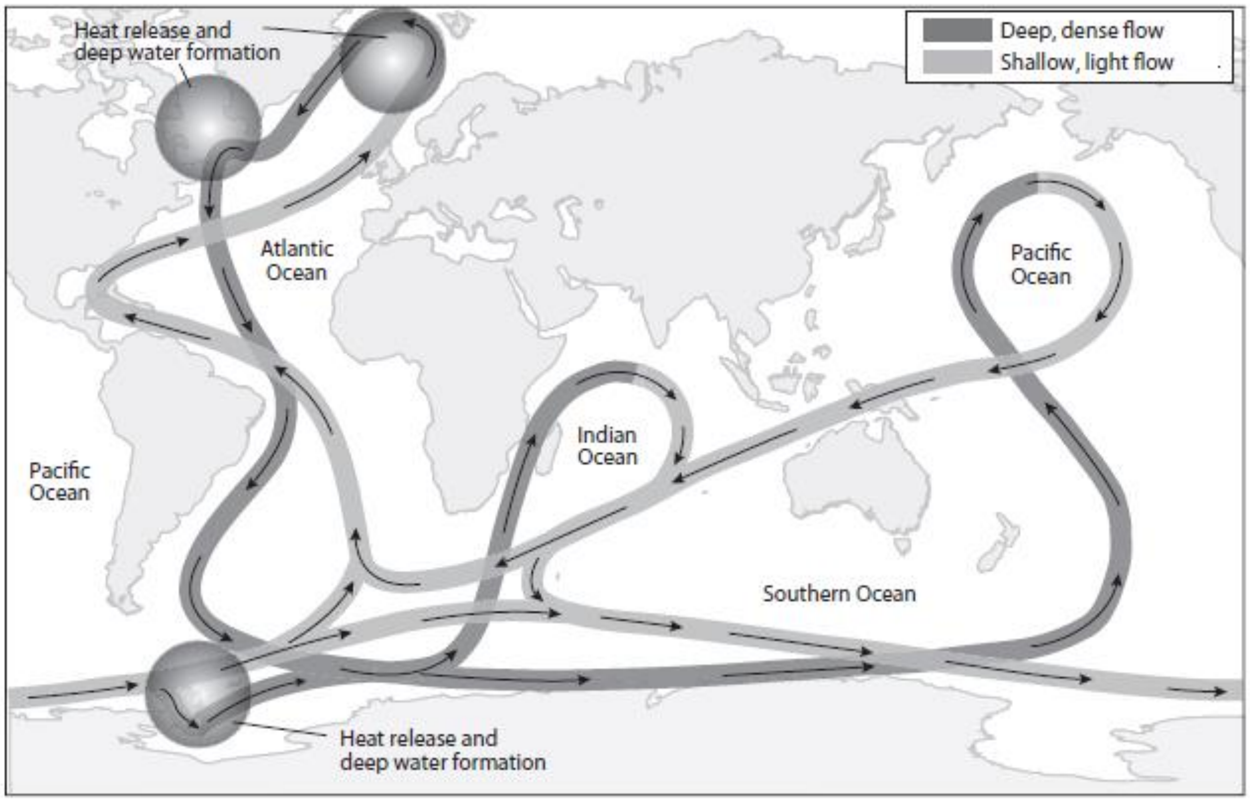
Source:Vallis (2012) Climate and the oceans

Some numbers

- Ocean covers 70% of the Earth surface
- 57% of the oceans are in the Southern Hemisphere (80% ocean)
- Average depth 3.7 km
- Volume of the ocean 1.3×10^{18} m^3 (density of sea water 1.03×10^3 kg m^{-3})
- Total mass of the ocean 1.4×10^{21} kg
- Mass of the atmosphere 5×10^{18} kg
- Specific heat of seawater 4,180 J kg^{-1} K^{-1} resulting in an overall heat capacity of the ocean which is 1,000 times that of the atmosphere (ocean‘s moderating effect on climate)

Source:Vallis (2012) Climate and the oceans

Ocean conveyor belt



Source:Vallis (2012) Climate and the oceans

Transports in the ocean

- 1 Sv = 10^6 m^3 s^{-1} (Harald Sverdrup)
- Antarctic Circumpolar Current (ACC) 120 Sv (in some places up to 150 Sv)
- Gulf Stream (30 Sv off the coast of Florida, 150 Sv at Cape Hatteras in North Carolina)
- Amazon River 0.2 Sv
- All the world's rivers into the ocean 1 Sv
- Westerly winds in the atmosphere carry up to 500 Sv of air

Source:Vallis (2012) Climate and the oceans

What makes the ocean circulate?

- **Wind: (1) wind-driven gyres, (2) wind plays also a role for the interhemispheric MOC (upwelling)**
- **Buoyancy effects (temperature, salinity)**
- **Mixing brings heat down to the abyss at low latitudes and enables an overturning circulation to be maintained**

— Mixing warms the deep water at low latitudes, which may then rise through the thermocline, maintaining a circulation of sinking at high latitudes and rising at low latitudes.

— Strong westerly winds in the Antarctic Circumpolar Current can draw water up from the deep and induce an interhemispheric circulation, which is particularly strong in the Atlantic.

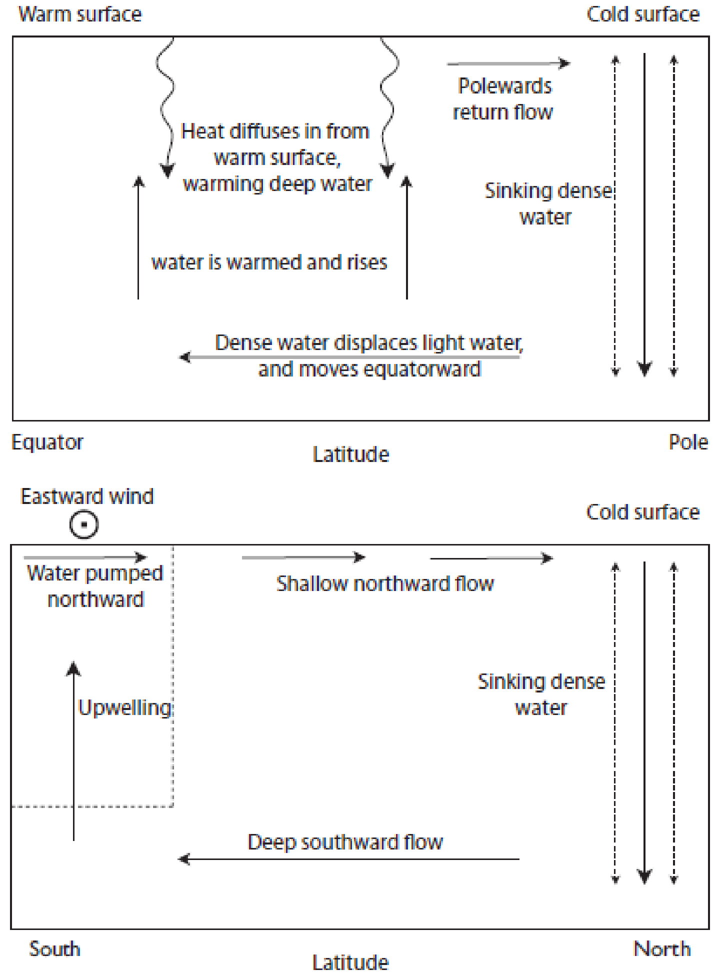
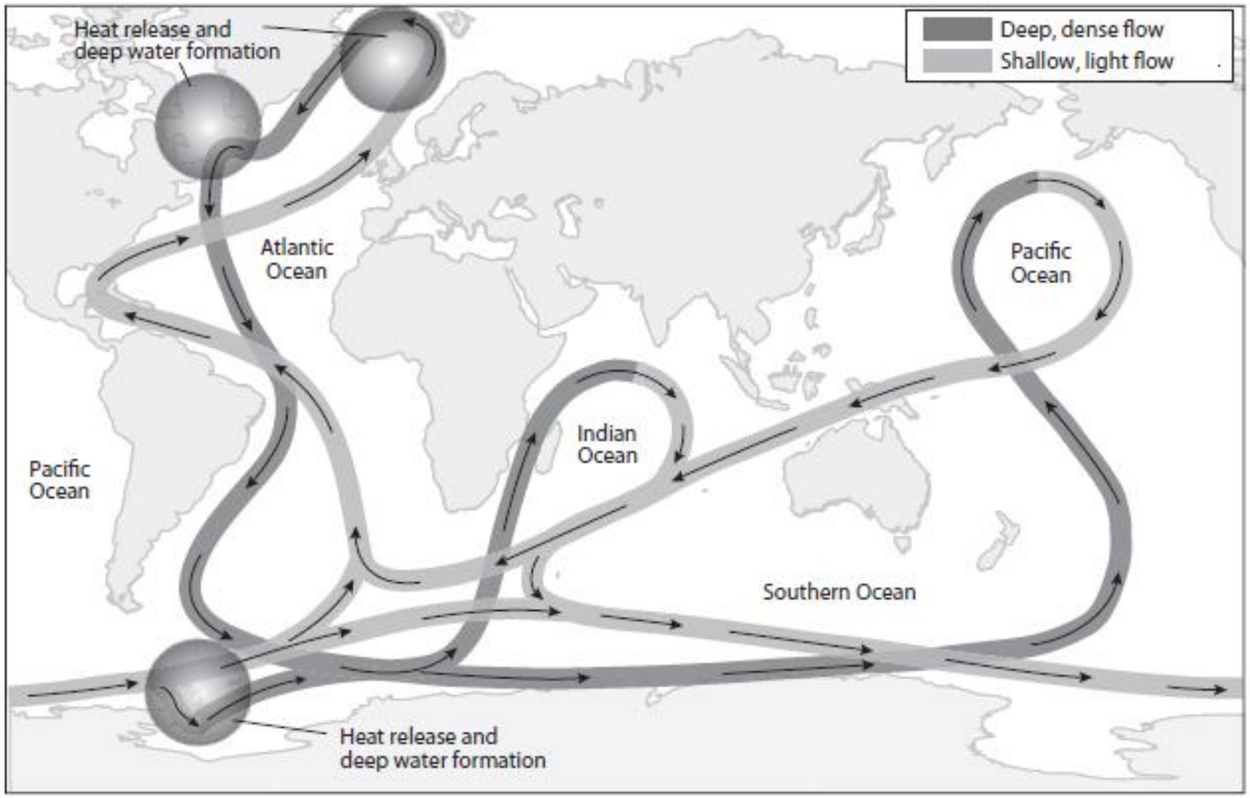


Figure 4.6. Schema of the two main components of the MOC. Top: The mixing-maintained circulation. Dense water at high latitudes sinks and moves equatorward, displacing warmer, lighter water. The cold, deep water is slowly warmed by diffusive heat transfer (mixing) from the surface in mid- and low latitudes, enabling it to rise and maintain a circulation. Bottom: Winds over the Antarctic Circumpolar Current (outlined by dashed lines) pump water northward, and this pumping enables deep water to rise and maintain the circulation. In the absence of both wind and mixing, the abyss would fill up with the densest available water and the circulation would cease.

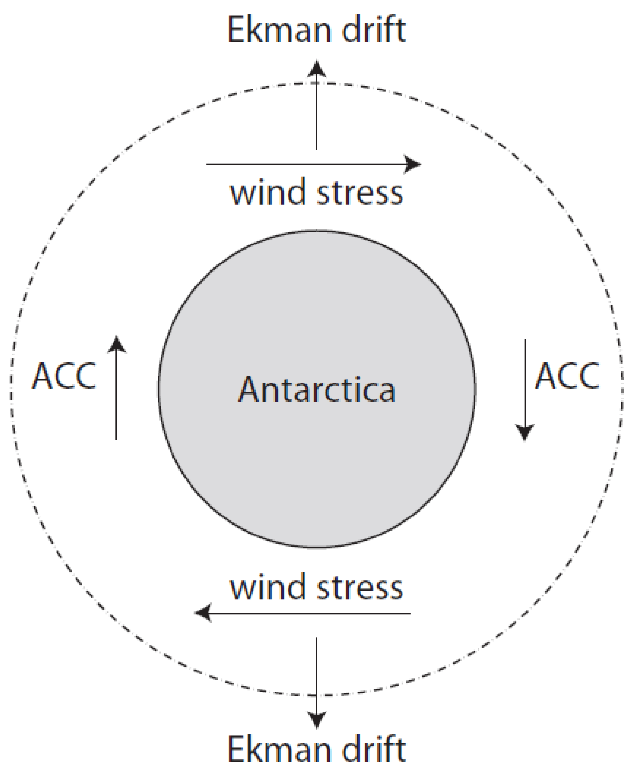
Source:Vallis (2012) Climate and the oceans

Ocean conveyor belt



Source:Vallis (2012) Climate and the oceans

Antarctic Circumpolar Current



Source:Vallis (2012) Climate and the oceans

Driving mechanisms of the meridional overturning circulation (MOC)

- If there would be no mixing (turbulent diffusion generated by mechanical forcing – wind and tides) and no upwelling around Antartica (Ekman transport), the ocean would be in the „cold death“ steady state
- In today‘s climate, the circulation is thermally driven, rather than salt driven
- Salinity explains the difference between the MOC of the Atlantic (NA is saltier) and the Pacific

Source:Vallis (2012) Climate and the oceans

Atlantic Ocean's MOC

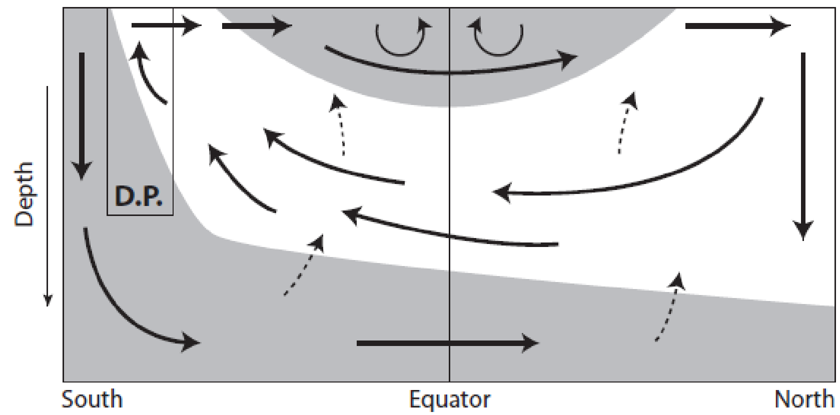


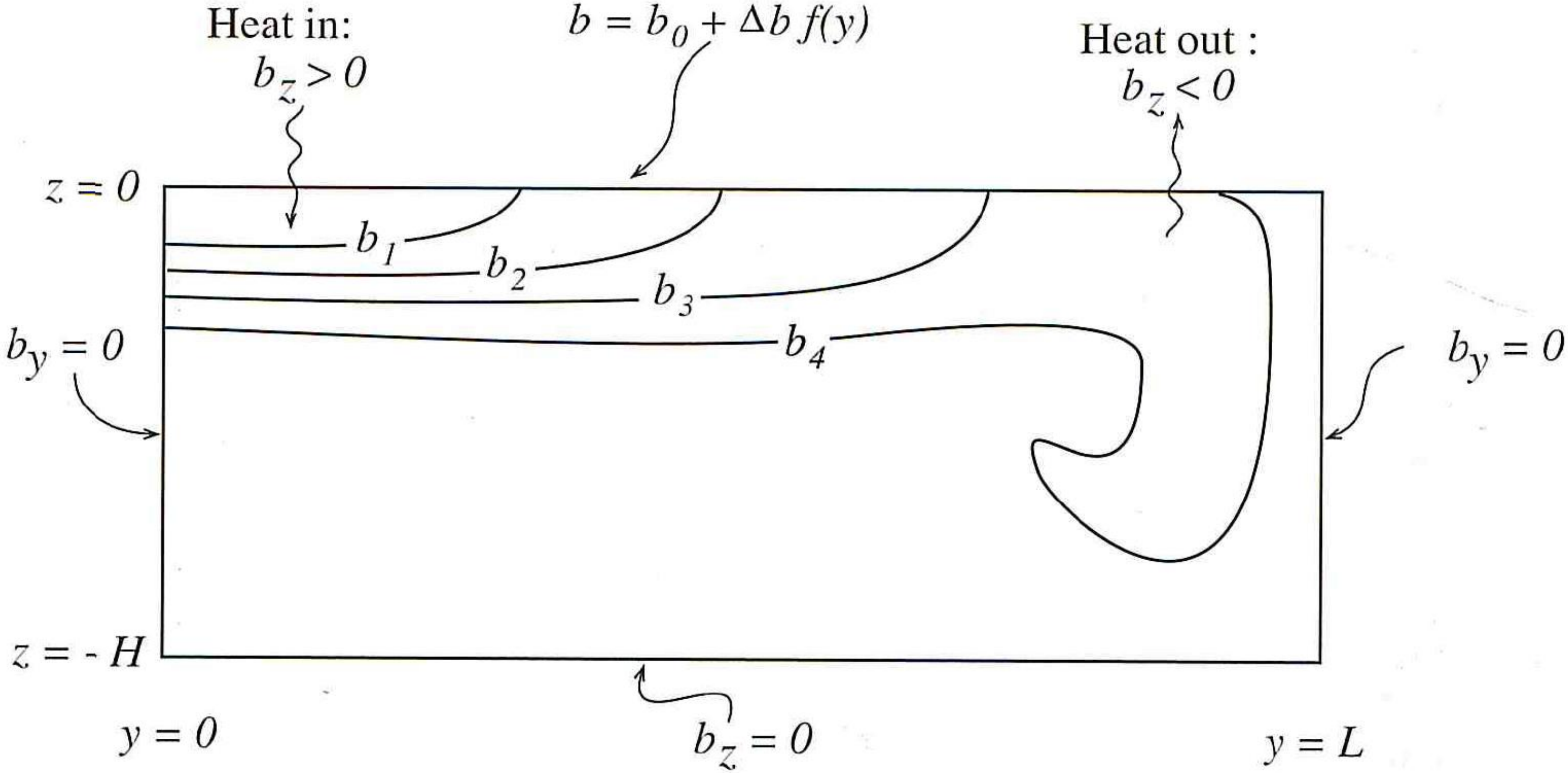
Figure 4.8. Schematic of the meridional overturning circulation, most applicable to the Atlantic Ocean (D.P. indicates the Drake Passage, the narrowest part of the ACC). The arrows indicate water flow, and dashed lines signify water crossing constant-density surfaces, made possible by mixing. The upper shaded area is the warm water sphere, including the subtropical thermocline and mixed layer, and the lower shaded region is Antarctic Bottom Water. The bulk of the unshaded region in between is North Atlantic Deep Water.

Source:Vallis (2012) Climate and the oceans

Time scales

- Currents in the abyssal ocean 1 mm s^{-1}, i.e. it takes 300 years for a parcel from ist high-latitude source to move to the equator
- If the surface conditions change, it will take several hundred years for the deep ocean to re-equilibrate

Buoyancy-driven ocean circulation - a schema of sideways convection



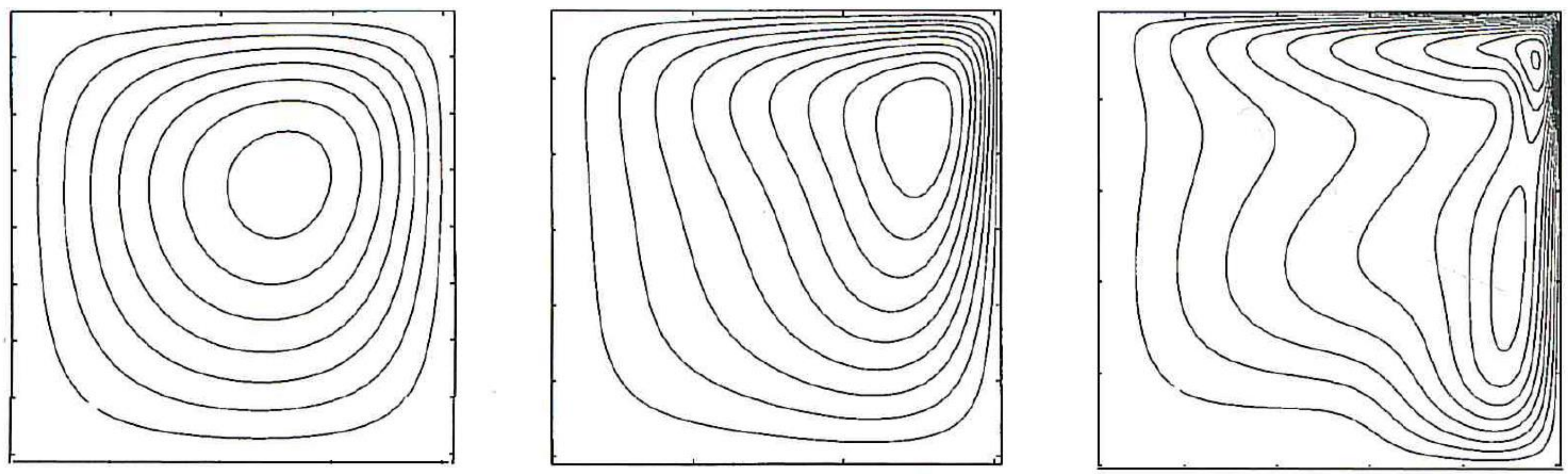
Source:Vallis (2006)

Buoyancy-driven ocean circulation - sideways convection

- Rayleigh number: ratio between buoyancy forcing and viscous term
- Prandtl number: ratio between viscosity and diffusivity (seawater Pr=7)
- Aspect ratio: ratio between H and L

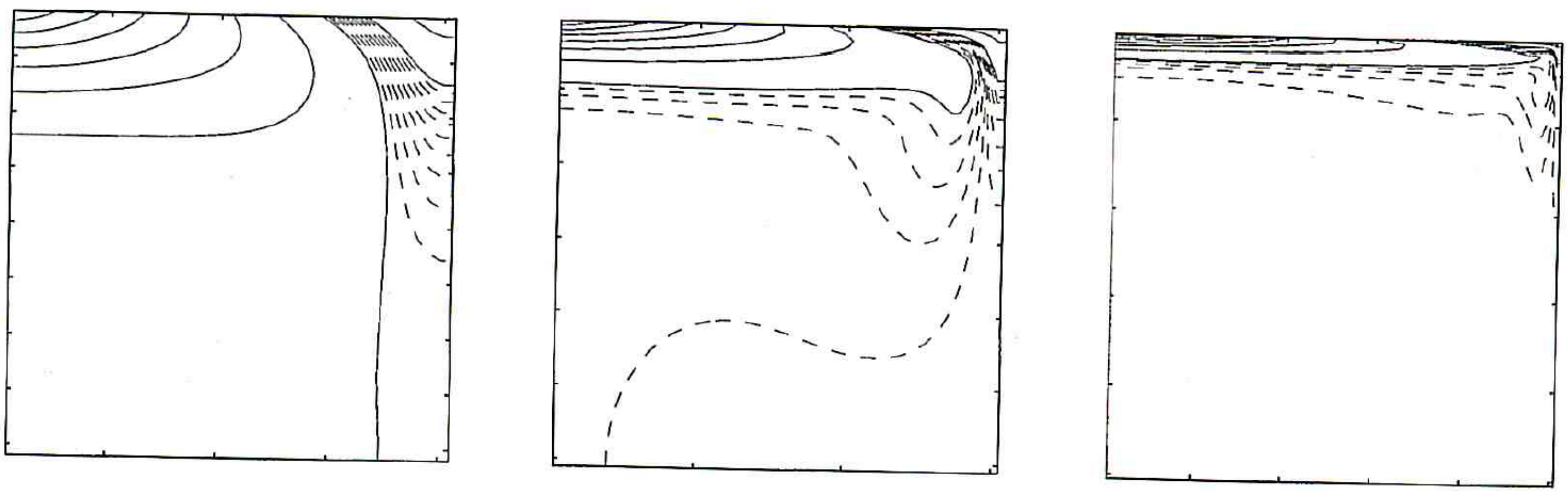
Source:Vallis (2006)

Streamfunction of two-dimensional sideways convection for Raleigh numbers 10^4, 10^6 and 10^8



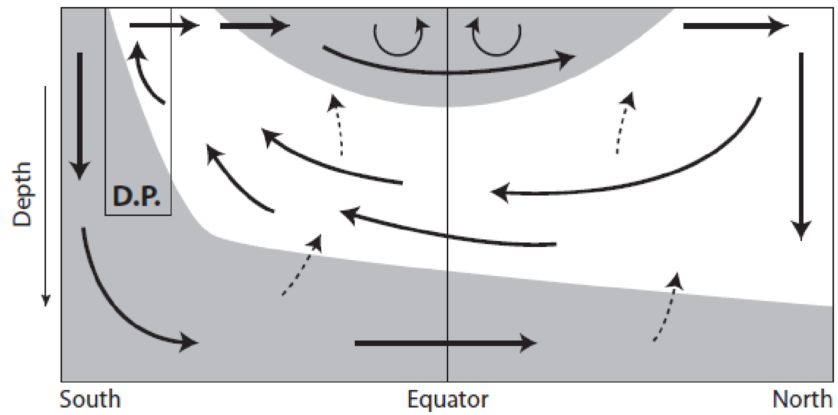
Source:Vallis (2006)

Corresponding temperature or buoyancy field



Source:Vallis (2006)

Atlantic Ocean‘s MOC



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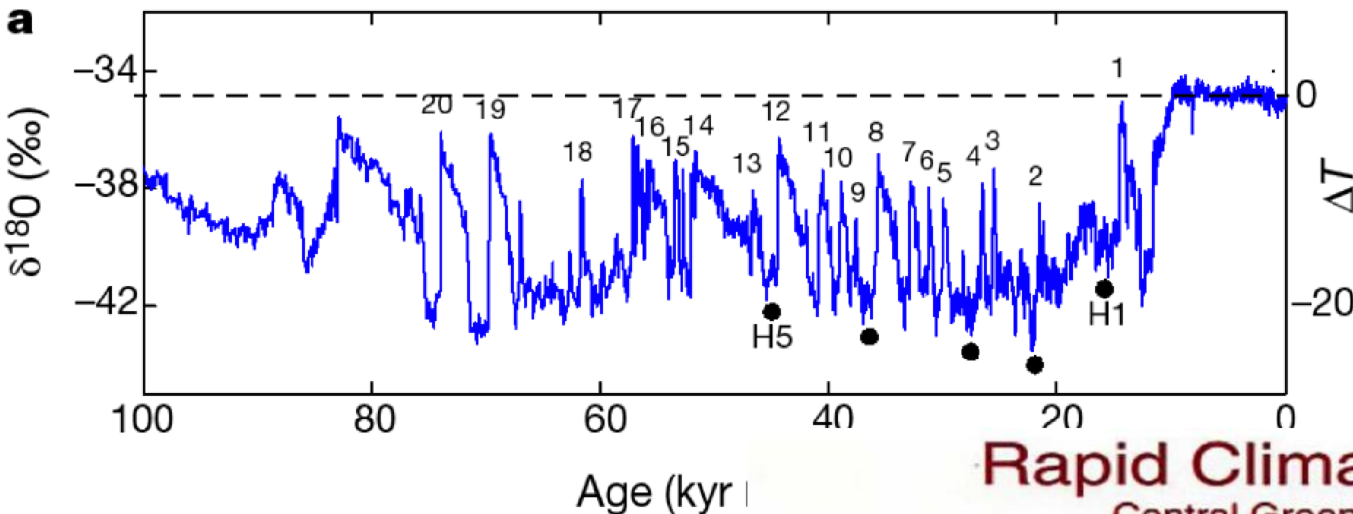
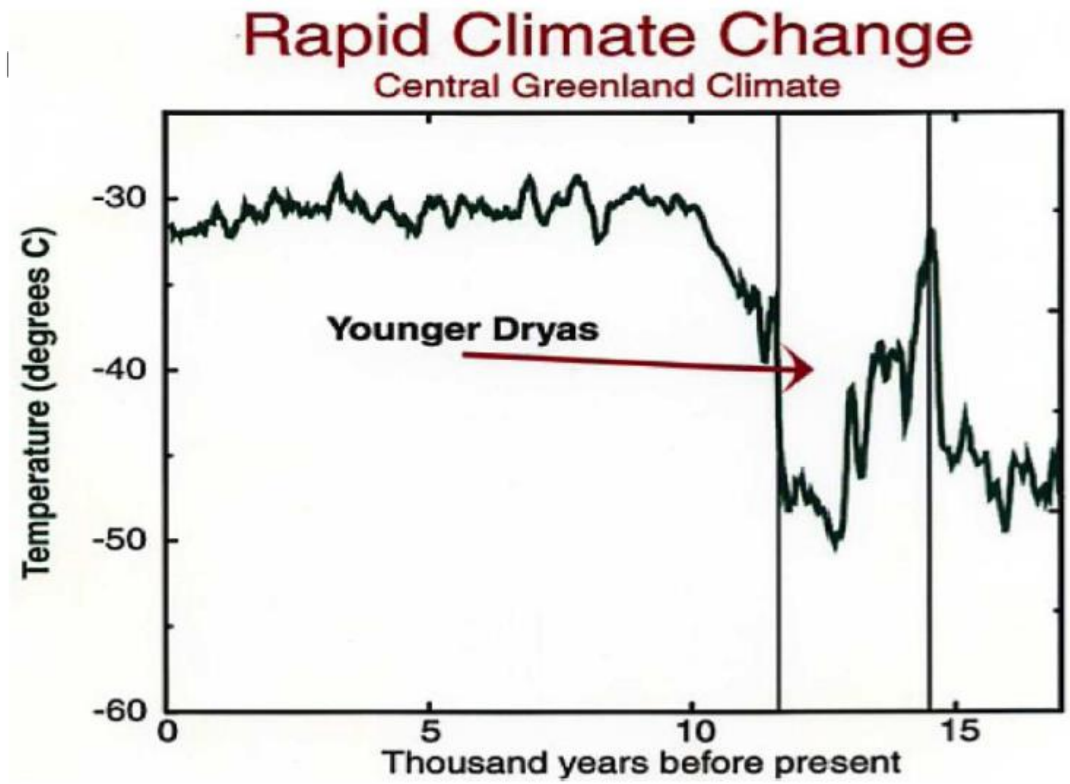
Source:Vallis (2012) Climate and the oceans

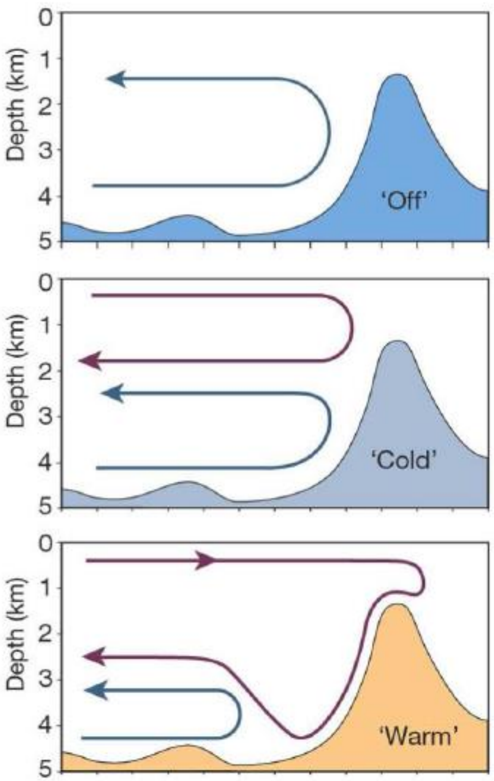
Paleo-climate variability





Source: Dommenget (2014)

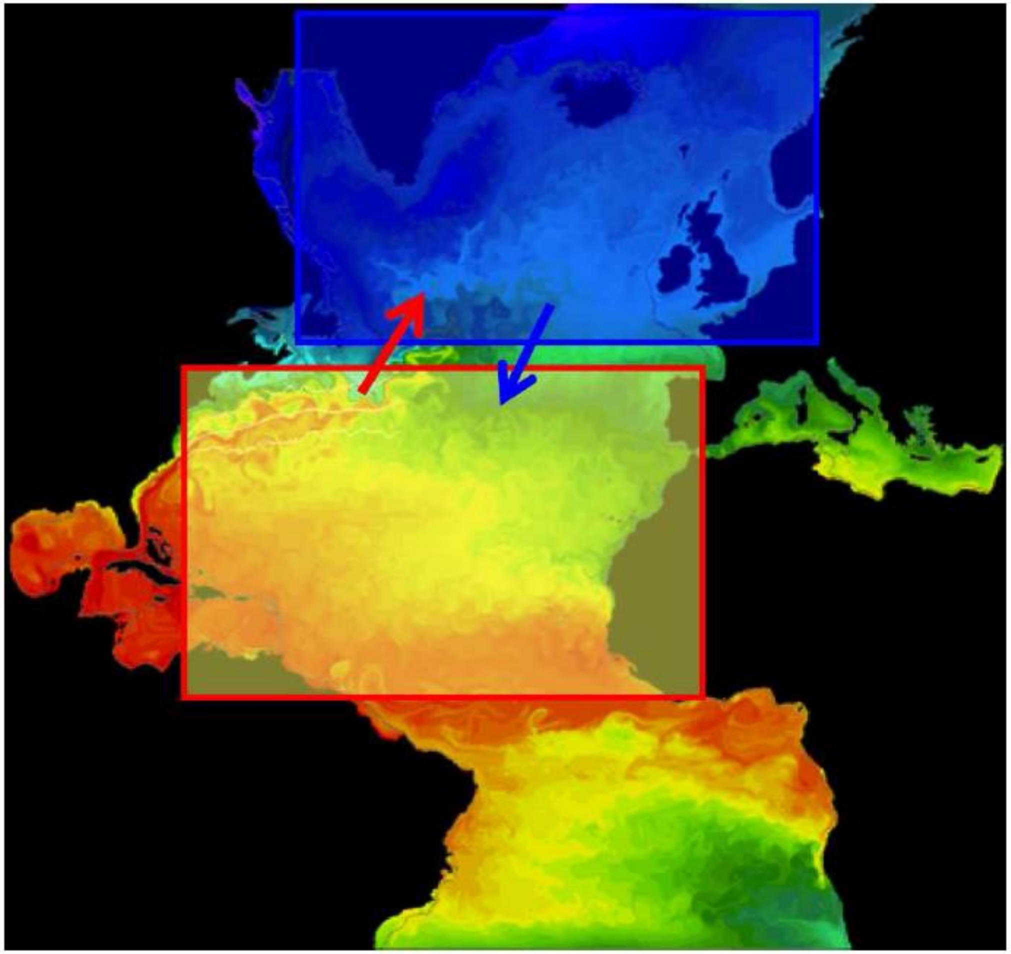
MOC in the North Atlantic at different climate states



Source: Dommenget (2014)

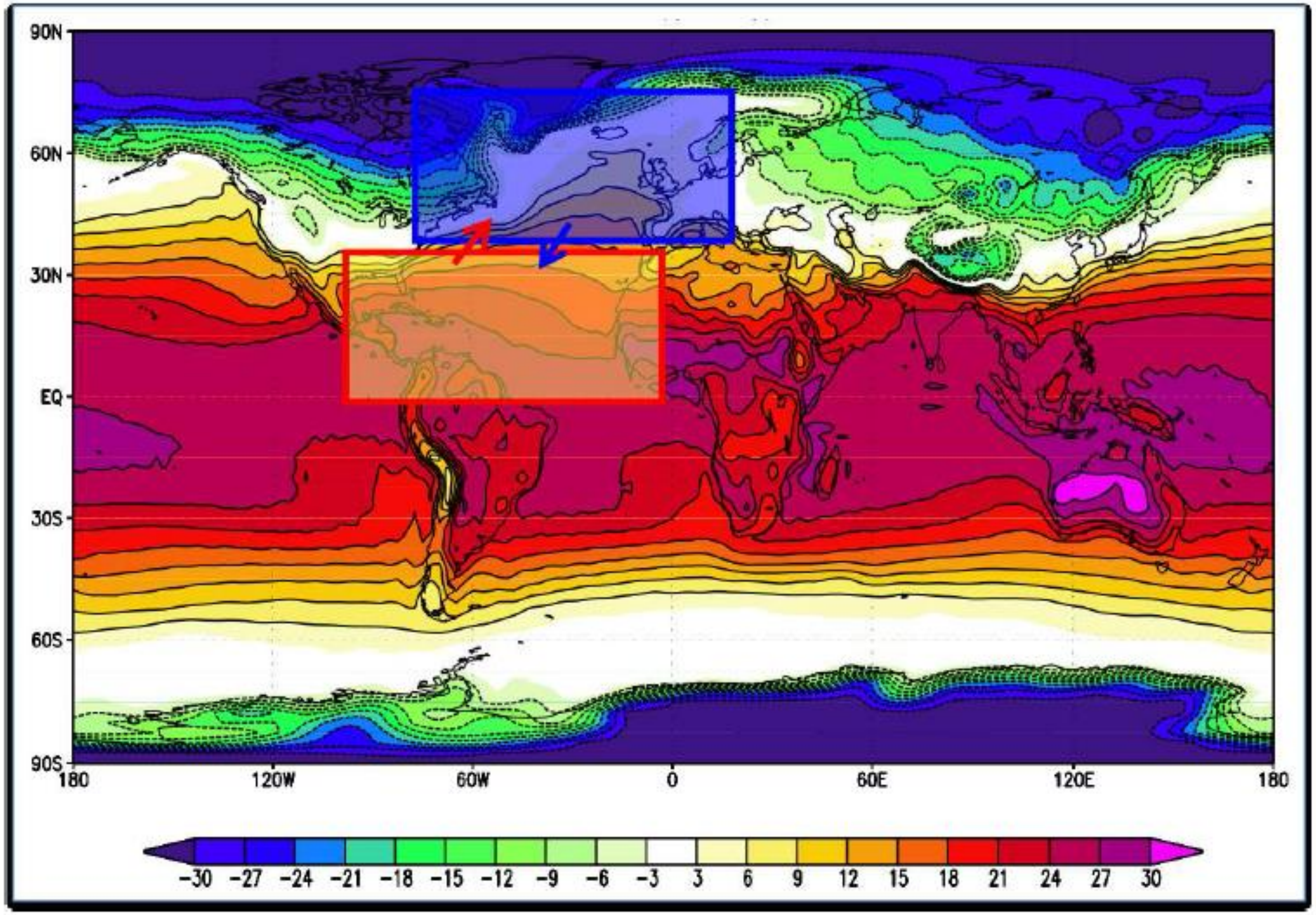
Iceland-Faroe Ridge

Simple box models:
Stommel's two-box model (1961)



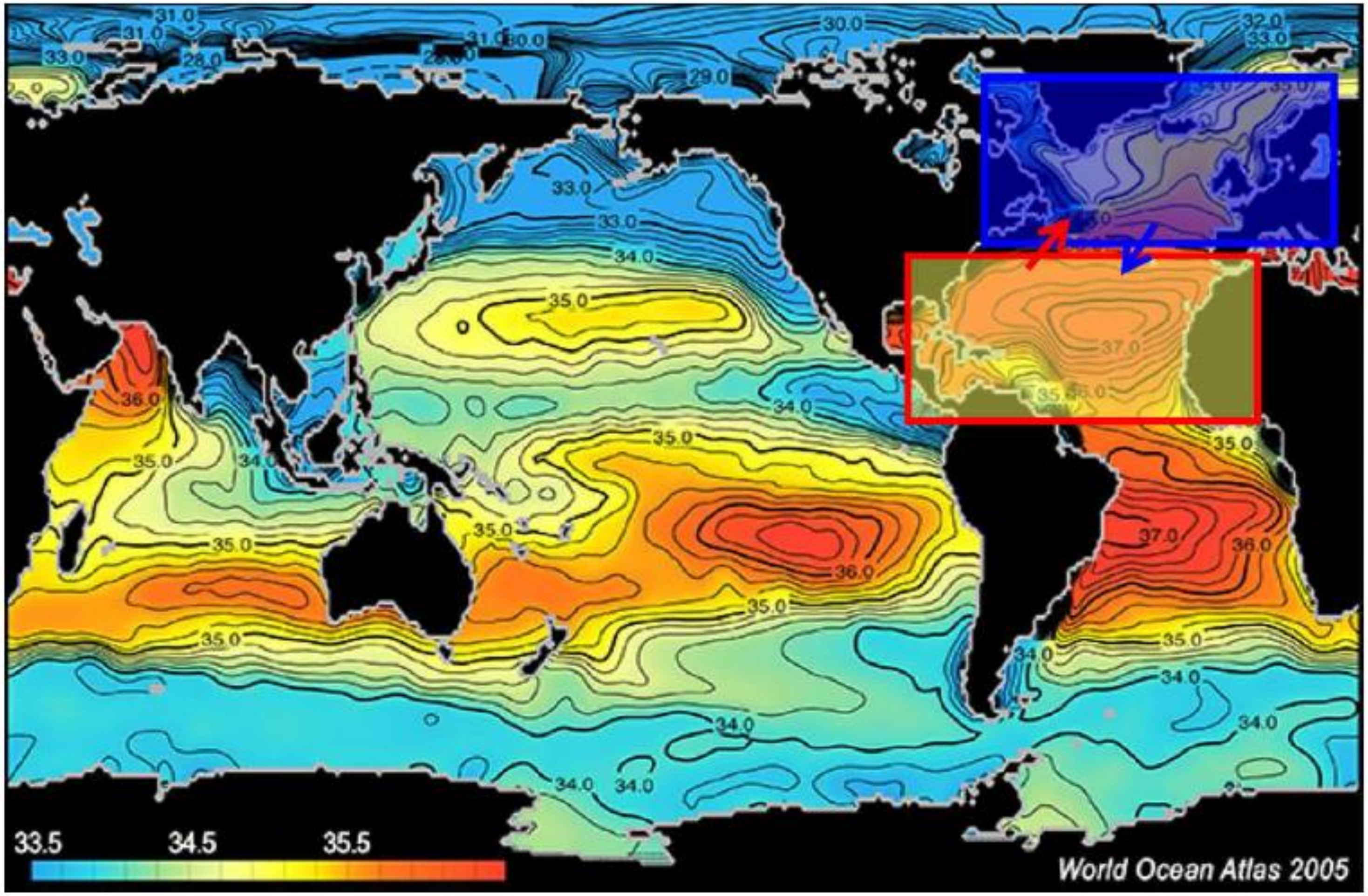
Source: Dommenget (2014)

Surface temperature in February

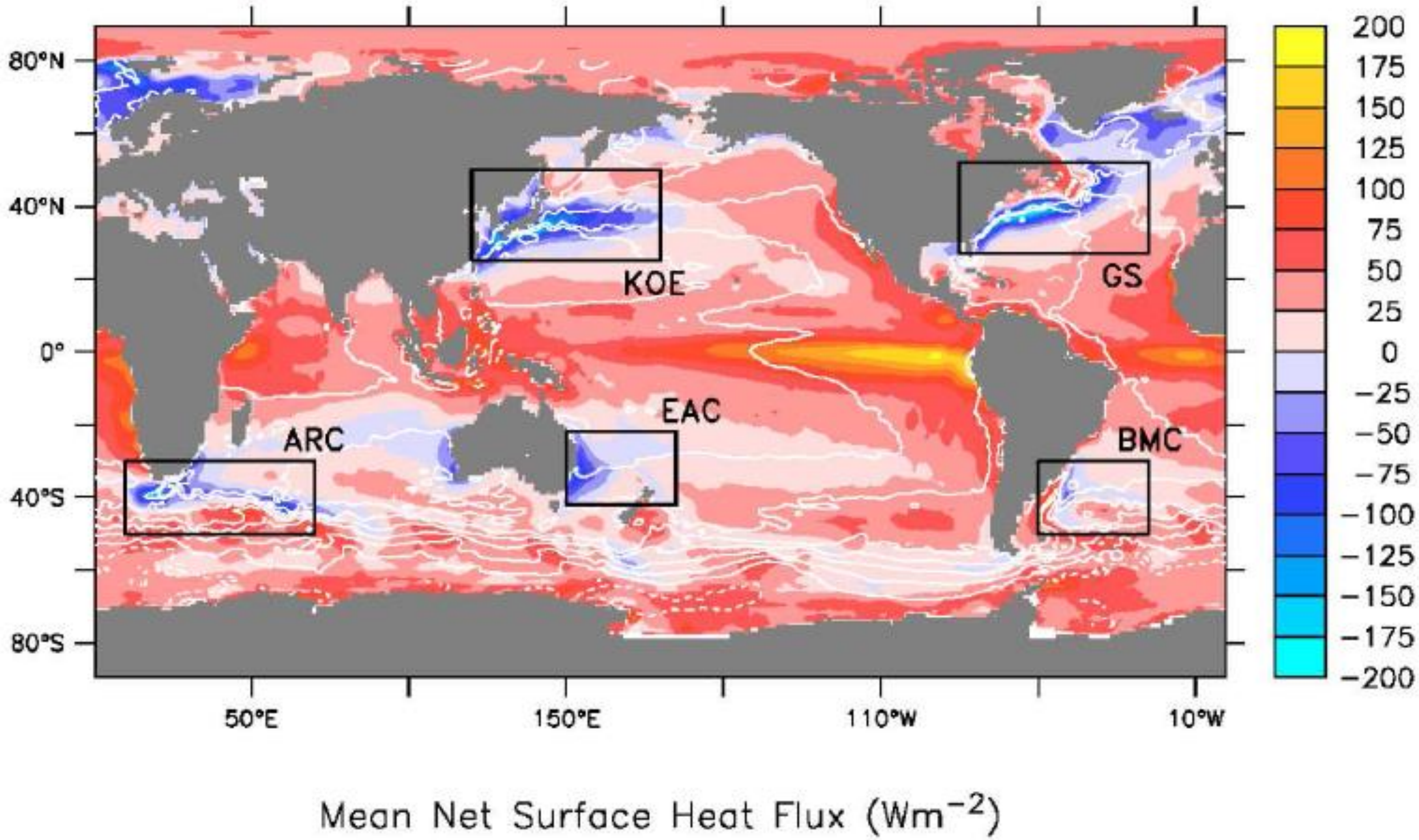


Source: Dommenget (2014)

Surface salinity

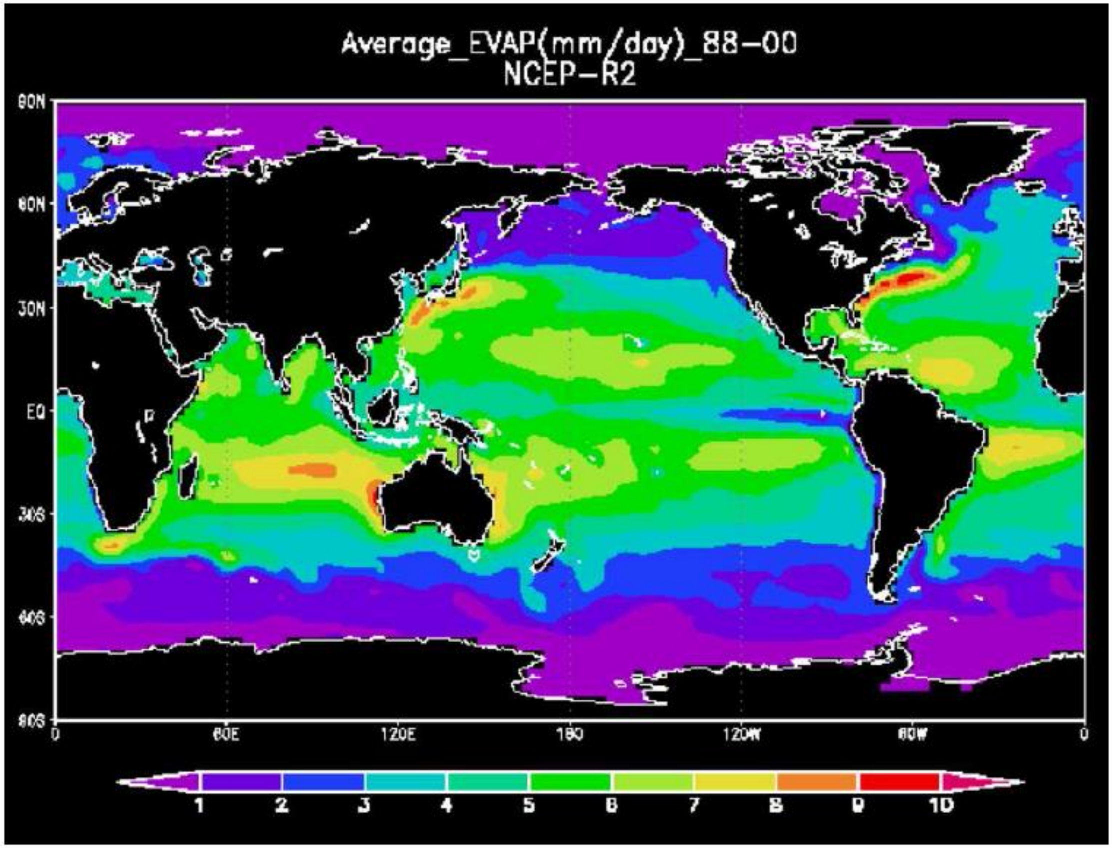


Source: Dommenget (2014)



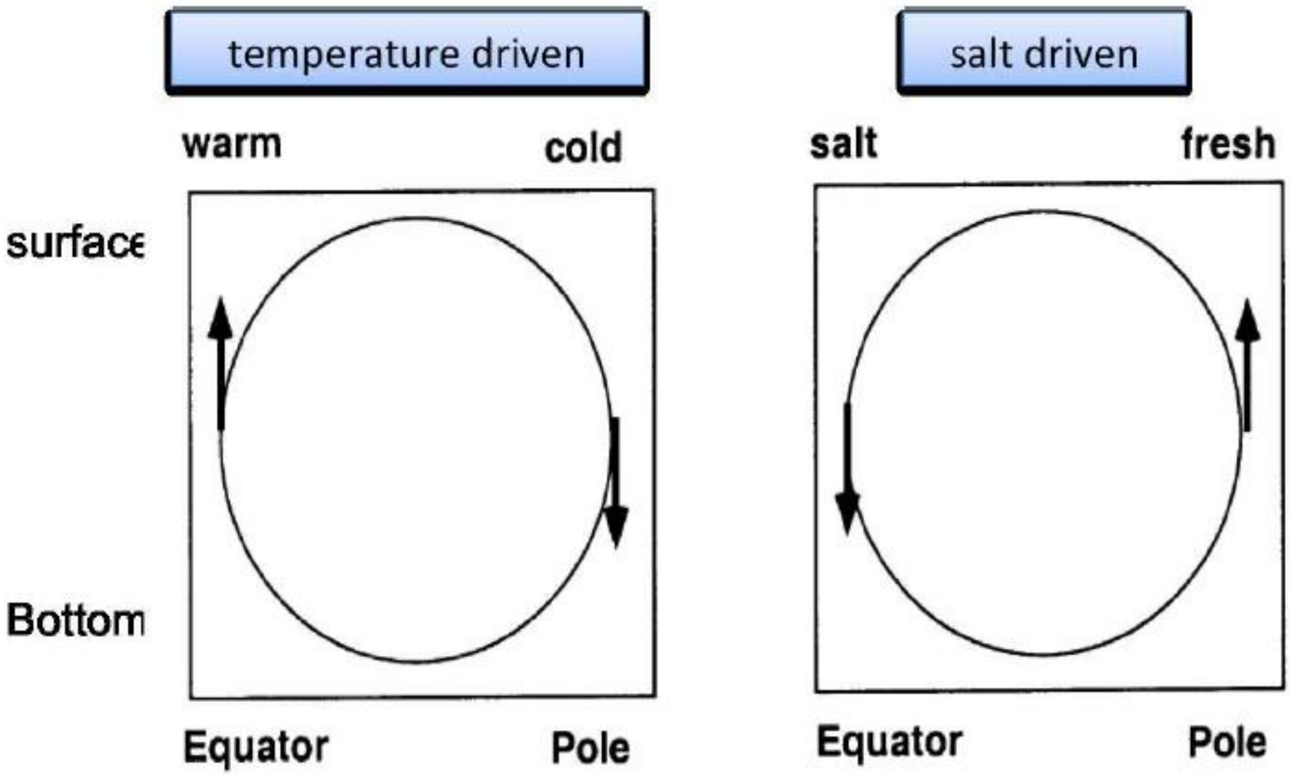
Source: Dommenget (2014)

Net evaporation



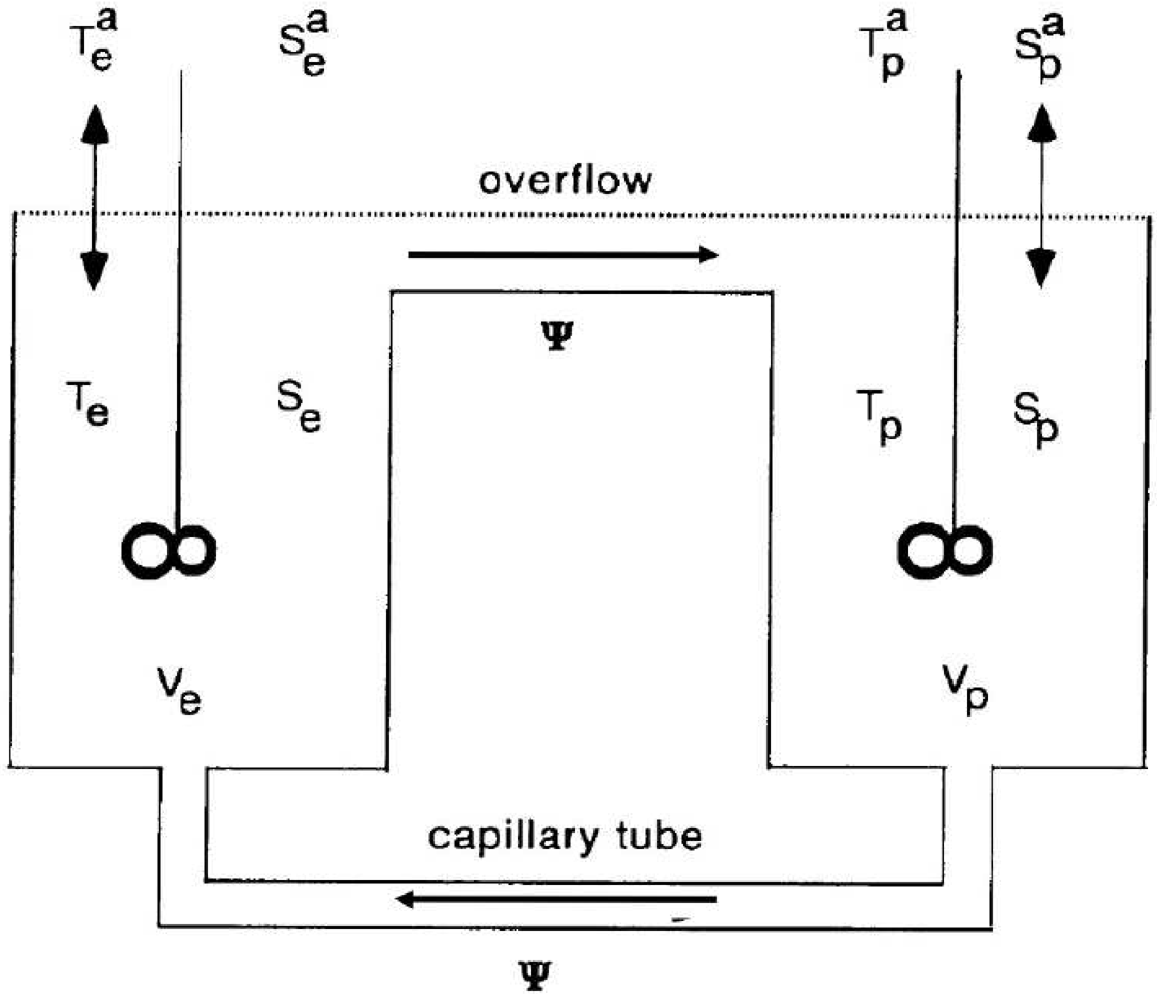
Source: Dommenget (2014)

Two competing regimes in Stommel's two-box model



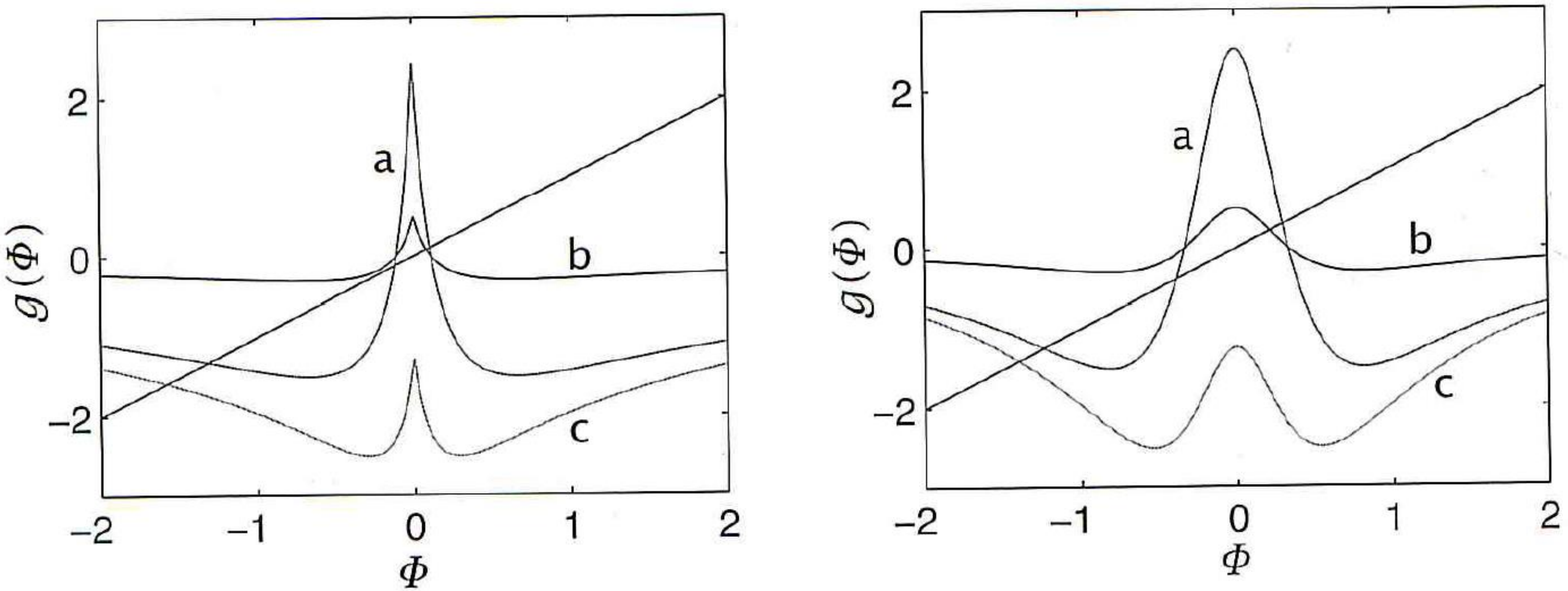
Source: Dommenget (2014)

Stommel‘s two-box model



Source: Dommenget (2014)

Stommel‘s two-box model



Graphical solution of the two-box model.
a: (γ=5, δ=1/6, μ=1.5), b: (γ=1, δ=1/6, μ=1.5), c: (γ=5, δ=1/6, μ=0.75)

Source: Vallis (2006)