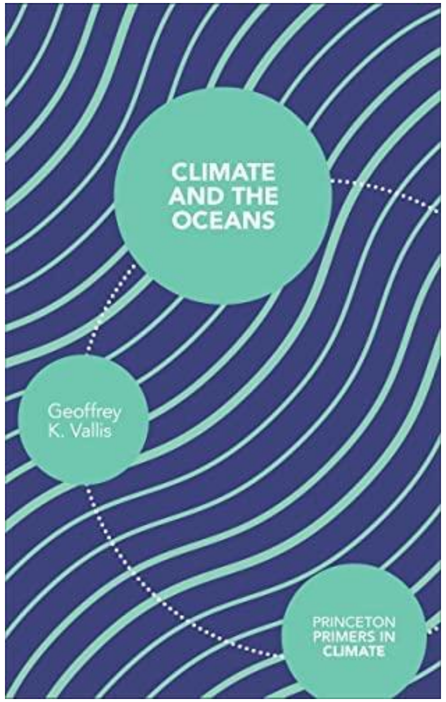
Dynamics and Ocean Circulation

Chapter 3 & 4

Climate and the Oceans



What you will know…

- The forces responsible for large-scale ocean dynamics
- The patterns of surface circulation in different ocean basins
- The nature of meridional overturning circulations
- Why landmasses are a nightmare!

What Forces affect the Ocean?

3 Categories of Forces

What’s New Here?

The major differences in atmospheric and oceanic dynamics are…

What is Surface Wind Stress?

- Winds push water by exerting a *stress* on the surface
- Due to Coriolis effects, the water moves slightly to the right (~ 45 degrees) of the wind
- Top layer exerts a stress on deeper layers

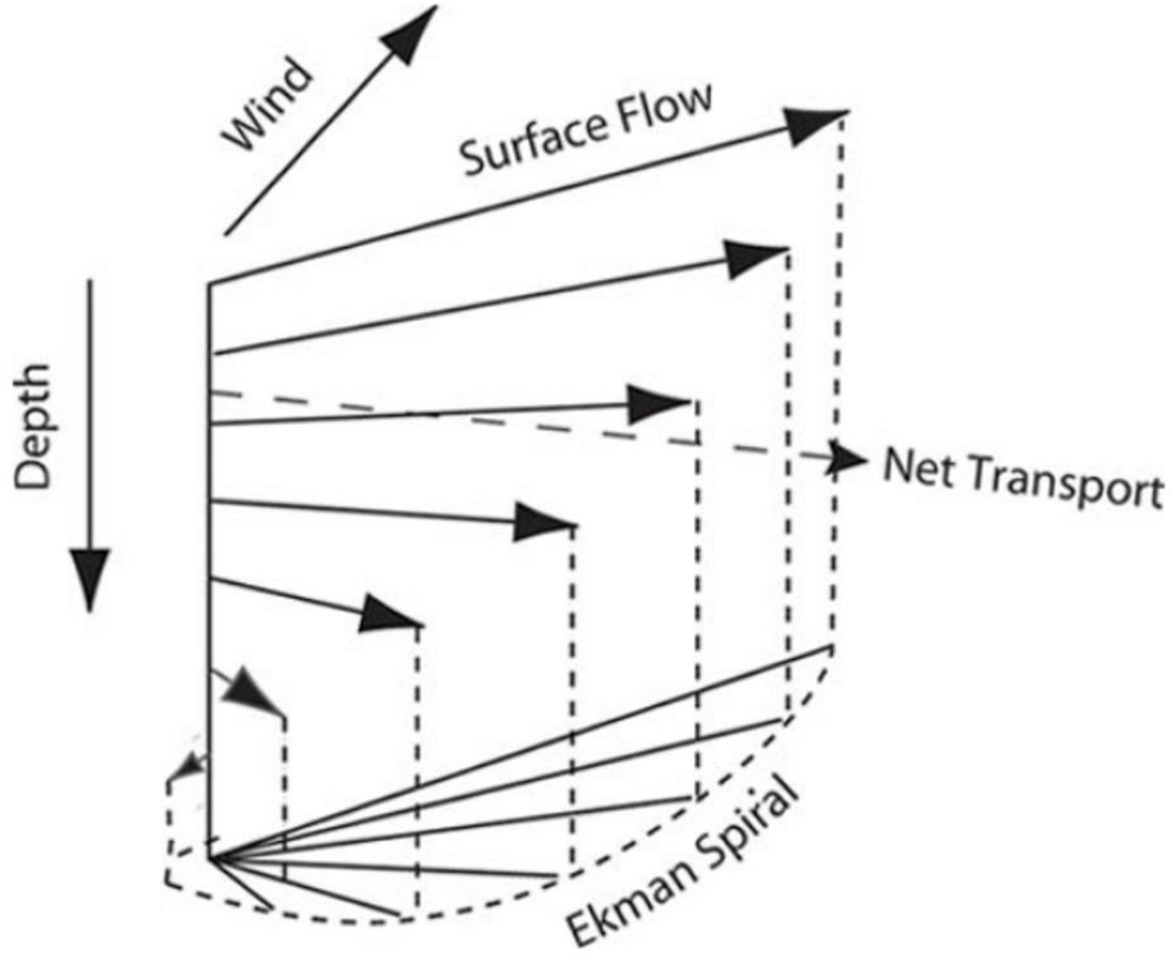


Figure 3.4. An idealized Ekman spiral in the northern Hemisphere.

Thermo-halo-what now?

Thermohaline forces are the equivalent of atmospheric buoyancy forces.

$$\rho - \rho_0 \approx \rho_0 \big[\alpha (T - T_0) + \beta (S - S_0) \big]$$

Thermal expansion coefficient

Haline contraction coefficient

Changes in Salinity (S) and temperature (T) affect the density (ρ) through the equation of state. ***Density differences lead to buoyancy forces.***

Approximations and Balances

Pressure forces and gravity forces are nearly balanced in the vertical, with very little exception

Hydrostatic Balance

$$\frac{\partial p}{\partial z} = -\rho g$$

The Coriolis force and pressure gradient force are the two largest forces in the horizontal, leading to geostrophic balance.

Geostrophic Balance

$$f\hat{k} \times \vec{u} = \underline{g\nabla\eta}$$

The Ocean is very nearly incompressible and thus non-divergent

Incompressibility

$$\nabla \cdot \vec{u} = 0$$

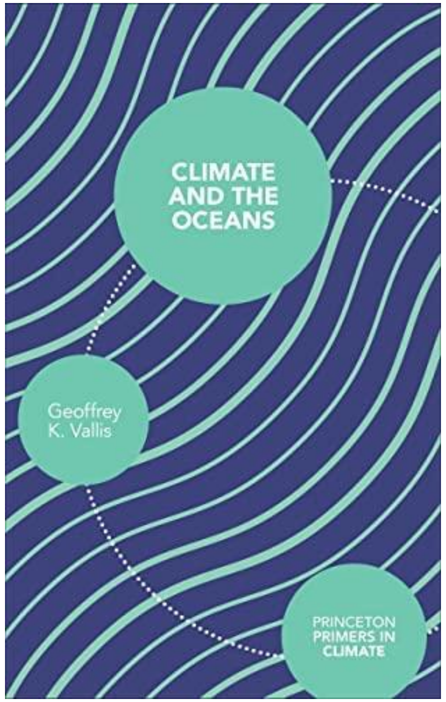
Summarizing Ocean Dynamics

- Vertical motion is very weak
- Horizontal motion is a response primarily to sea level/pressure gradients created by wind stress
- Any horizontal divergence must be compensated by vertical upwelling or downwelling

General Ocean Circulation

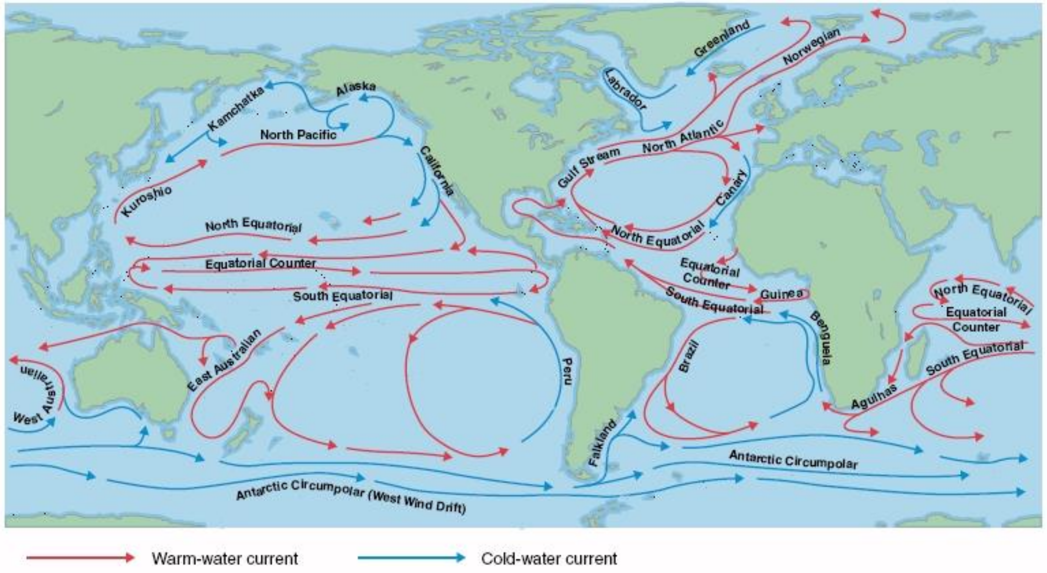
Chapter 4

Climate and the Oceans



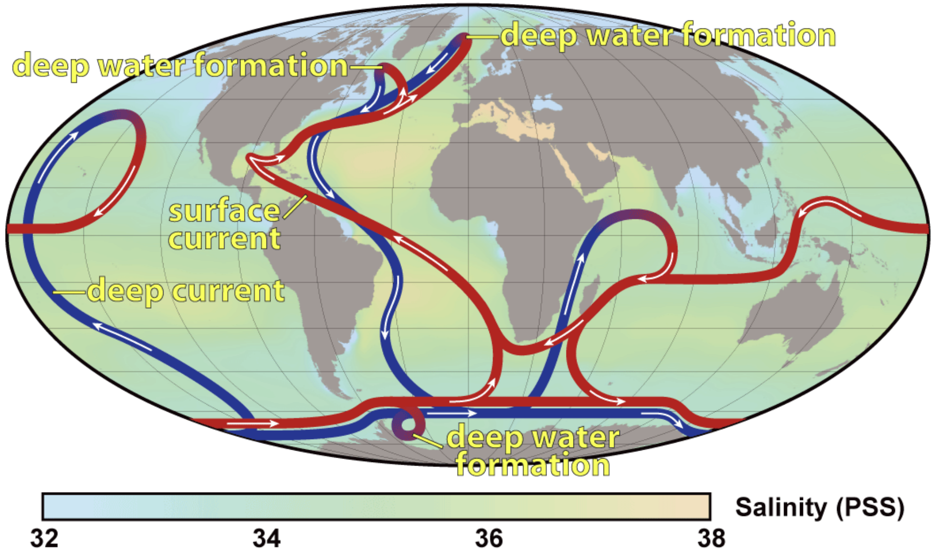
The Ocean Circulation consists of two main components. What are they?

Ocean Surface Circulation



- Wind-Driven
- Approximate Geostrophic Balance
- Relatively fast (10 cm/s to 100 cm/s)

Meridional Overturning Circulation



- Thermohaline driven
- Not in Geostrophic Balance
- Extremely slow (centuries to >1000 years)

https://www.nrdc.org/onearth/climate-running-amoc

https://www.researchgate.net/publication/357849856_Causes_and_Mechanisms_of_Global_WarmingClimate_Change

Ocean Surface Circulation

Surface Wind Stress generates torque

↓

Torque generates convergence/divergence

↓

Converge/Divergence creates compensating change in Sea Surface Height (SSH)

↓

Currents Balance SSH changes Geostrophically

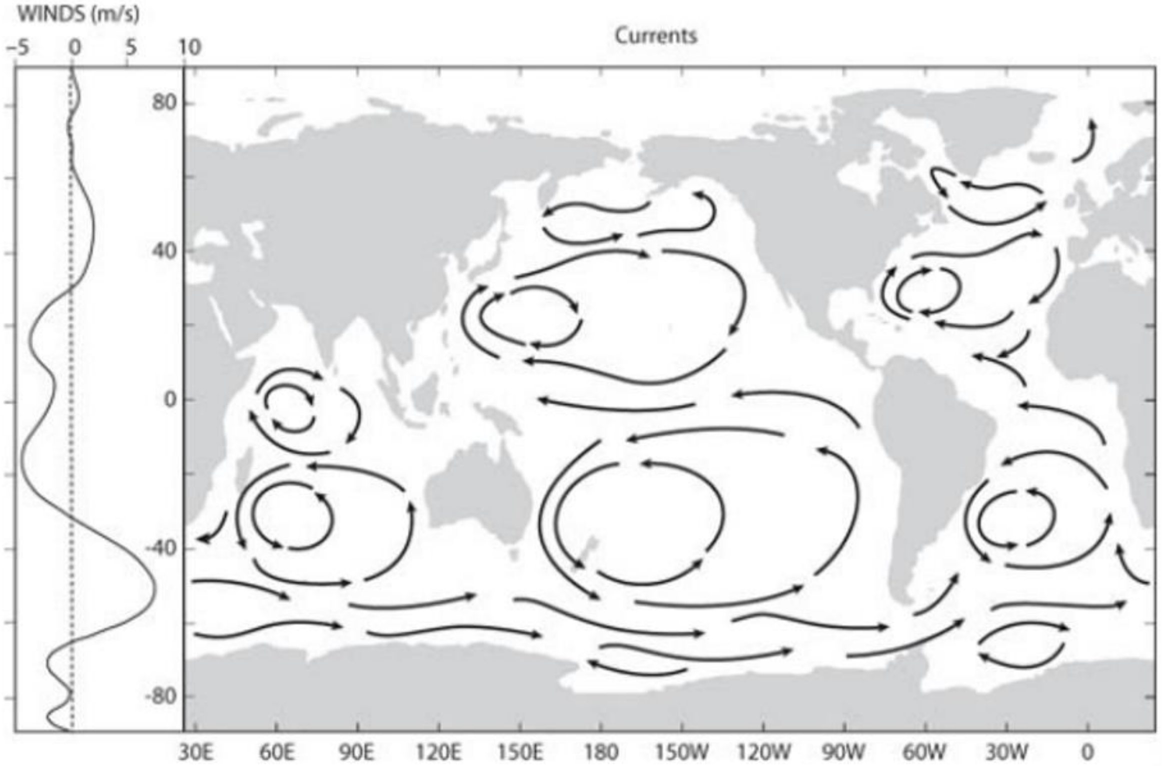
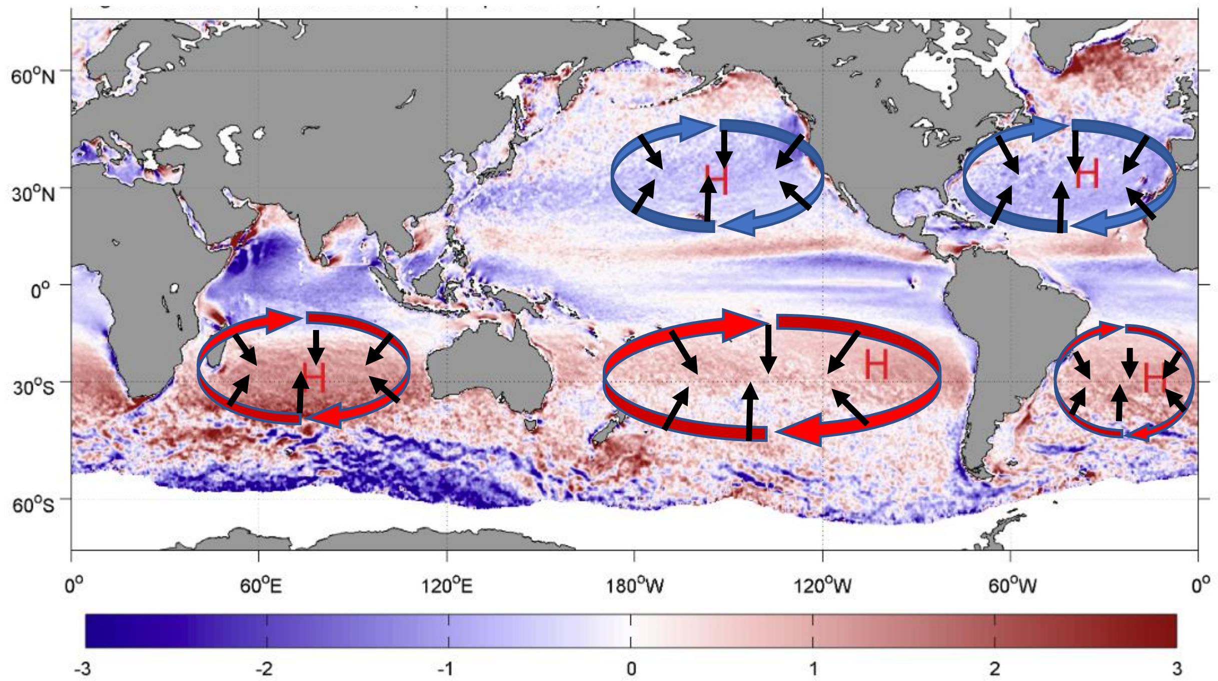


Figure 2.3. A schematic of the main surface currents of the world's oceans. The panel at the left shows the zonally averaged zonal (i.e., east–west) surface winds.

The ***net effects*** are circulating gyres that rotate in the direction of Wind Stress around regions of high or low SSH

Ekman Pumping

August SCOW Wind Stress Curl



N m^{-2} per 10^4 km

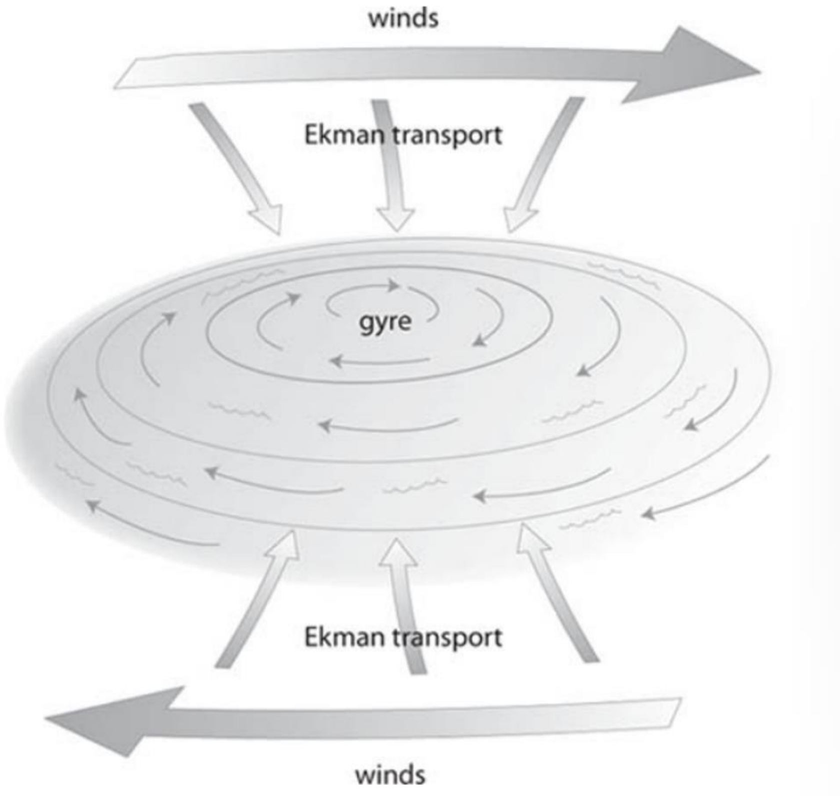
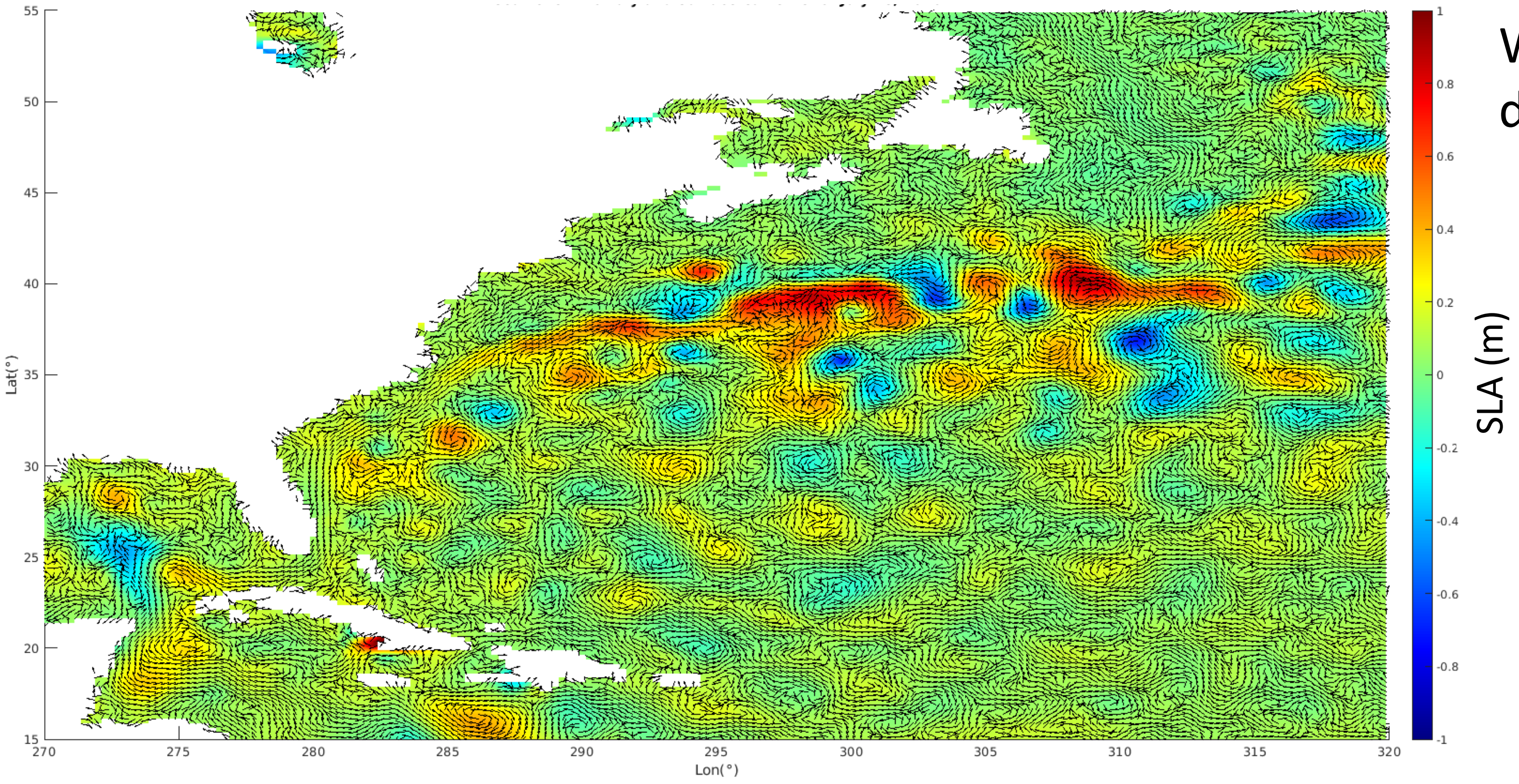


Figure 4.2. Production of gyres by winds. The winds blowing as shown induce a converging Ekman flow, causing the sea level to increase in the center, thus giving rise to a pressure gradient. This gradient in turn induces a geostrophic flow around the gyre, in the same sense as the winds themselves.

Circulating wind stress produces currents that either converge or diverge to the center of gyres. This is called ***Ekman Pumping***

https://chapman.ceoas.oregonstate.edu/scow/wind_stress_curl.html

Sea Level Anomaly and Surface Currents for July 18, 2020



What does this image demonstrate?

Altimetry data are provided by the NOAA Laboratory for Satellite Altimetry.
Surface Currents: http://globcurrent.ifremer.fr/products-data/data-catalogue

Why do surface currents intensify in the west?

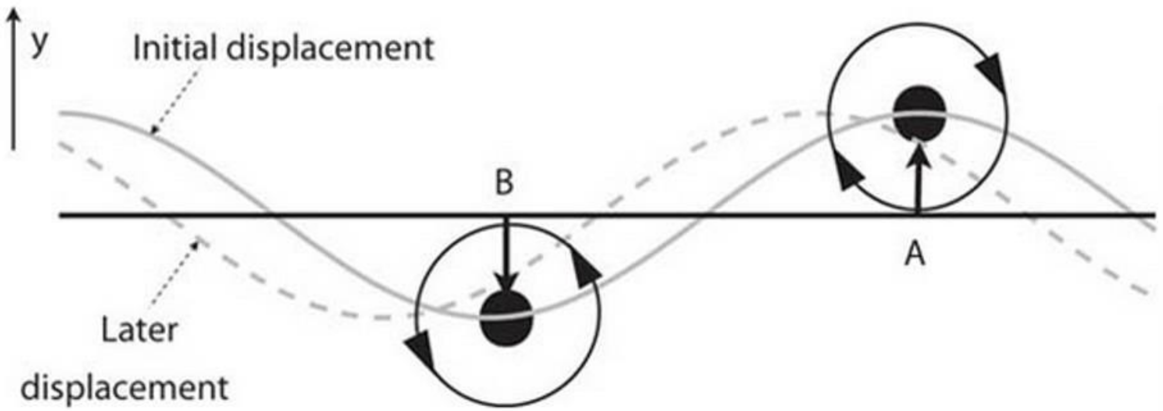
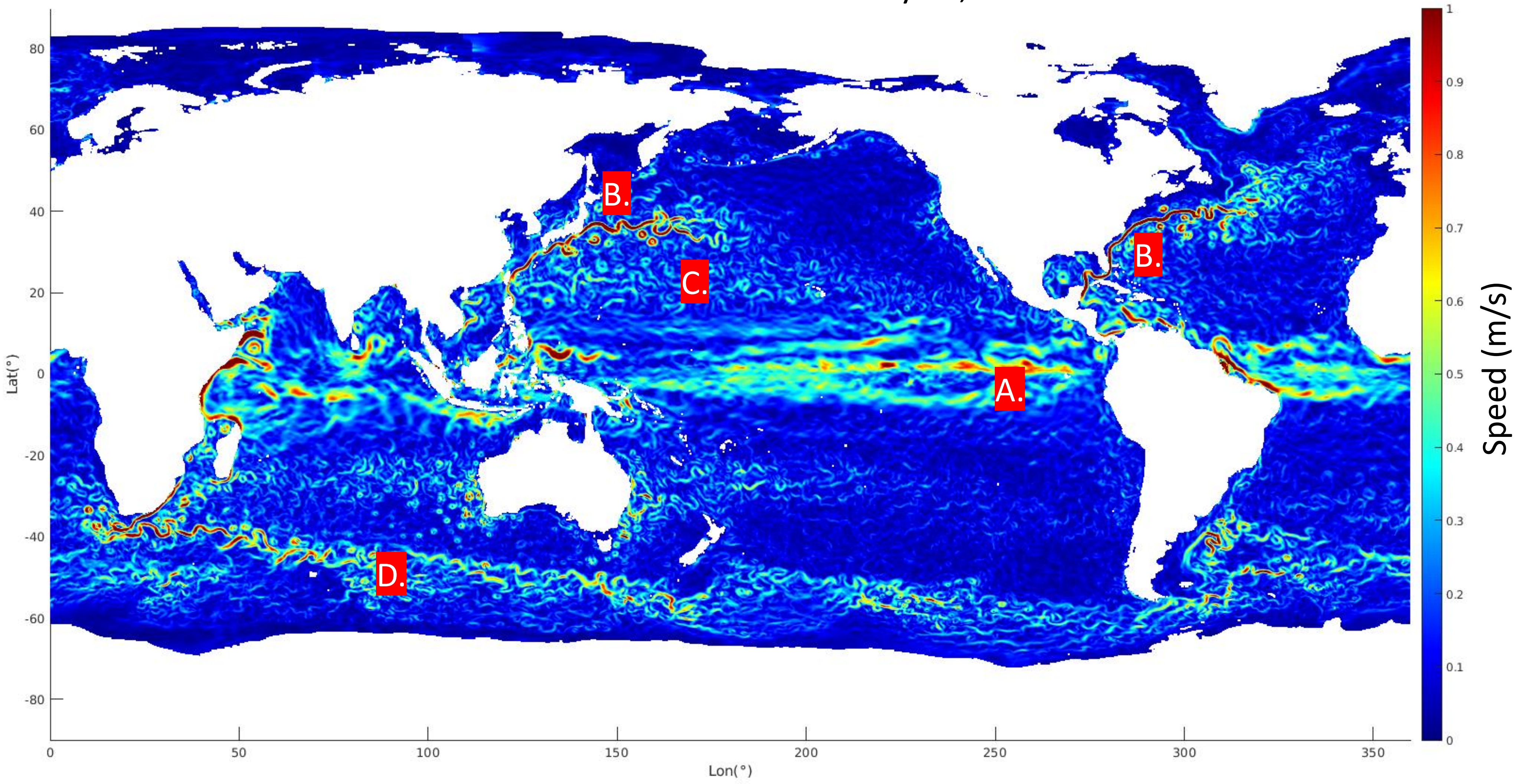


Figure 4.5. If parcel A is displaced northward, then its clockwise spin increases, causing the northward displacement of parcels that are to the west of A. A similar phenomenon occurs if parcel B is displaced south. Thus, the initial pattern of displacement propagates westward.

This is the same mechanism that generates ***Rossby Waves***. These are the result of an interaction between the Coriolis force and the conservation of angular momentum. Rossby waves *<u>always propagate westward</u>* and carry fluid parcels westward with them as well.

Western Boundary Currents occur when Rossby Waves propagate energy and fluid into a boundary or coastline, increasing the available kinetic energy.

Ocean Surface Currents for July 18, 2020

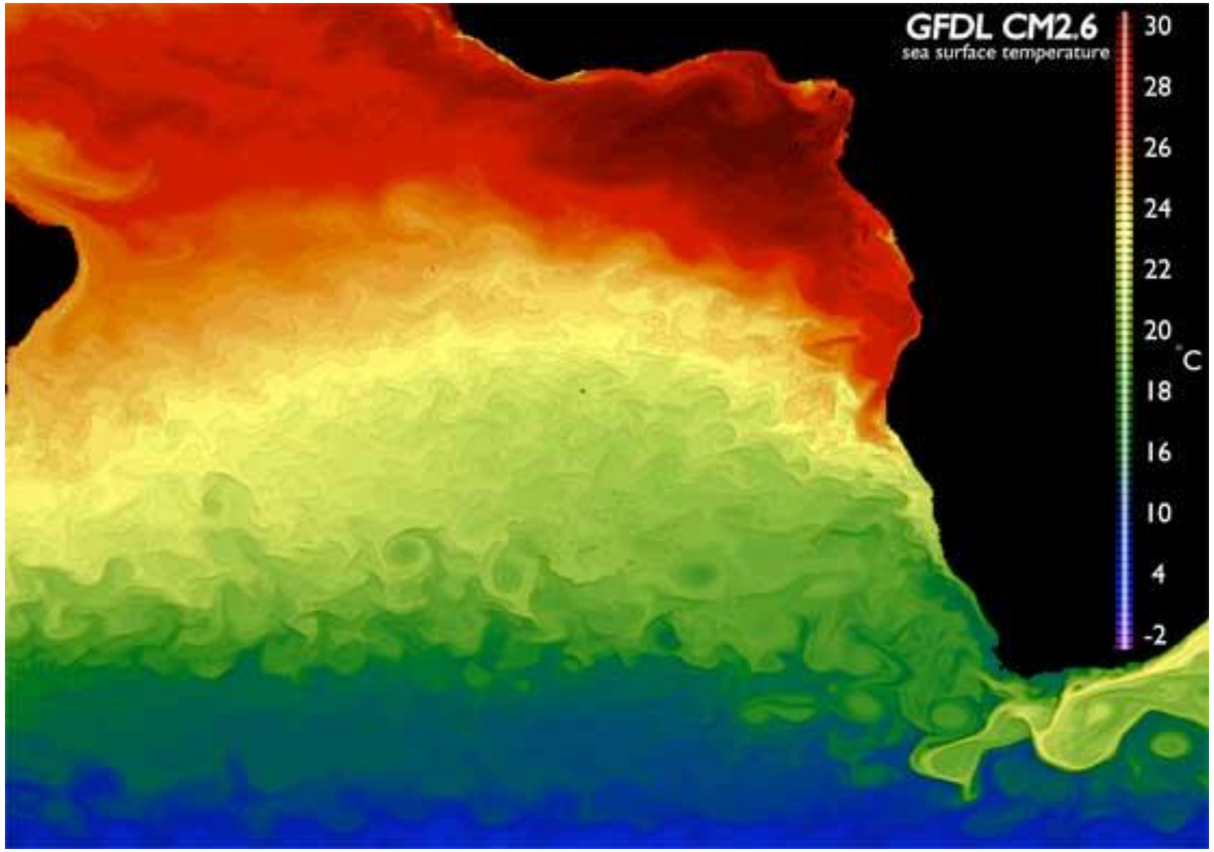


Are there any strange features we didn't discuss?

Surface Currents: http://globcurrent.ifremer.fr/products-data/data-catalogue

Mesoscale Eddies – What are they?

Model Output of SST in the South Atlantic



SST (C)

Mesoscale Eddies are ~100km in size and last for ~1 month. They are ***coherent regions of vorticity independent of the surrounding flow***. As a result, MEs often have different physical properties than the surrounding flow.

MEs are the result of *instabilities in ocean currents* and are responsible for nearly all exchange of heat, salinity, etc across boundary currents.

https://www.gfdl.noaa.gov/ocean-mesoscale-eddies/

Meridional Overturning Circulation

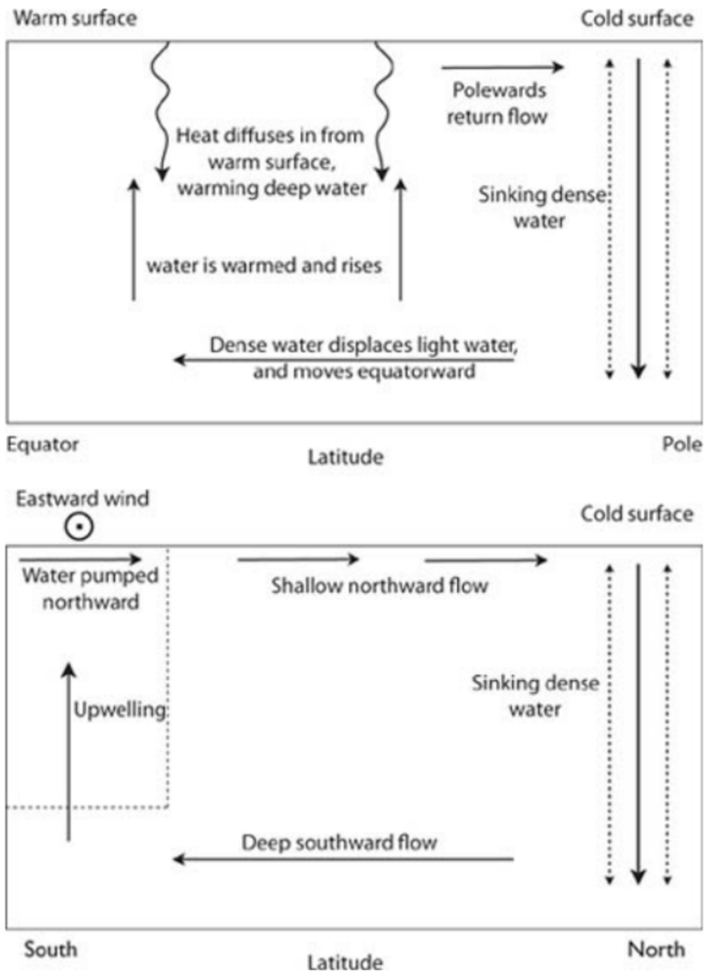


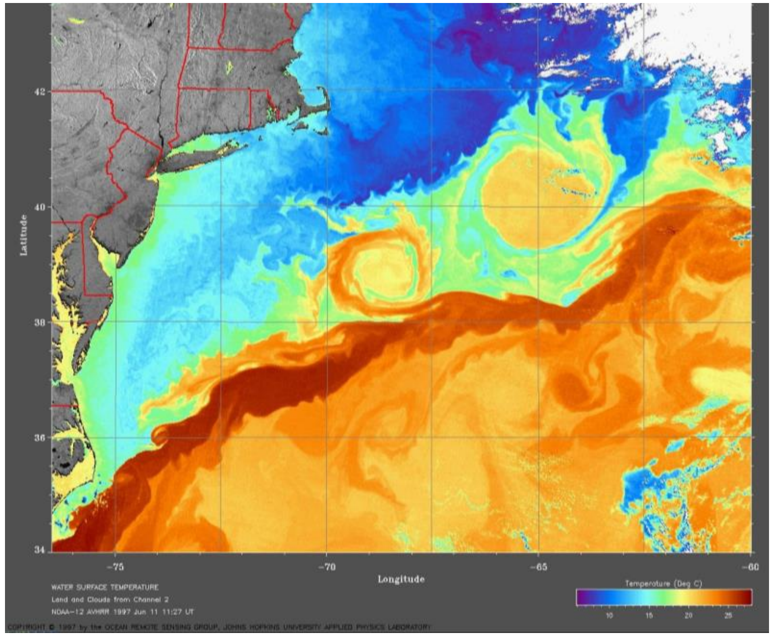
Figure 4.6. Schema of the two main components of the MOC. Top: The mixing-maintained circulation. Dense water at high latitudes sinks and moves equatorward, displacing warmer, lighter water. The cold, deep water is slowly warmed by diffusive heat transfer (mixing) from the surface in mid- and low latitudes, 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.

The **Meridional Overturning Circulations** are the result of interactions between *wind-driven surface flow*, and *thermohaline circulation*.

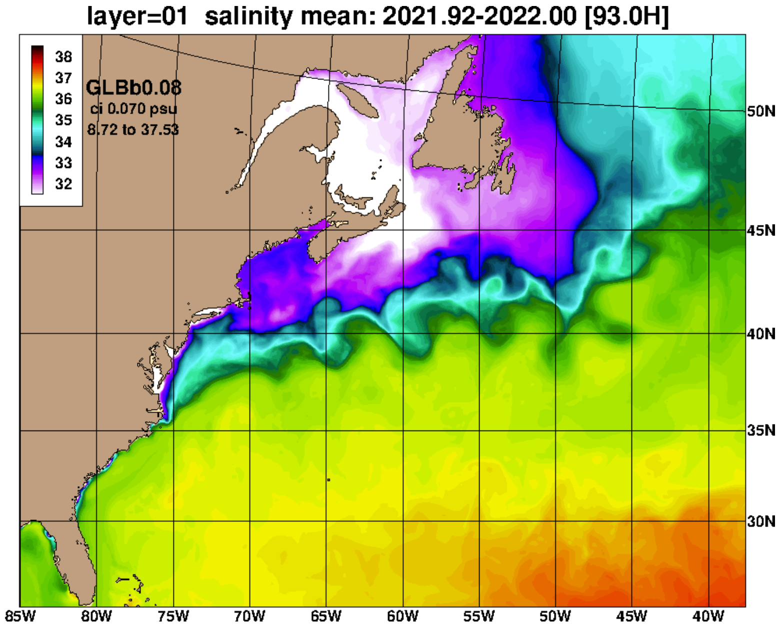
A long time ago, at an equator not so far away…

We know that surface currents carry equatorial water poleward. Why?

What physical properties do you notice about the water?



Temperature (Celsius)



Salinity (psu)

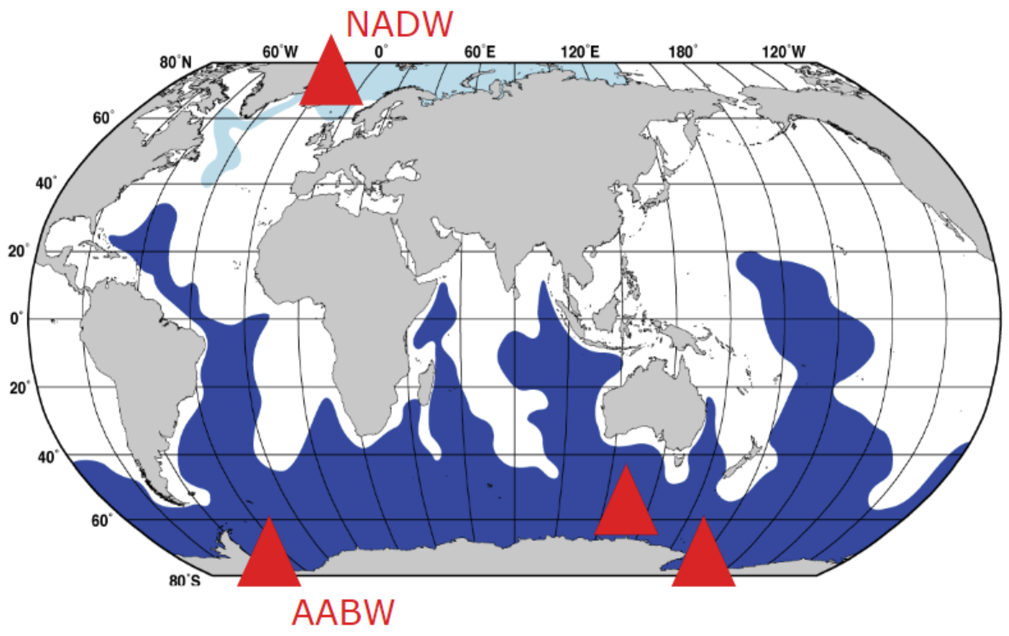
https://fermi.jhuapl.edu/avhrr/gs/averages/index.html
https://www7320.nrlssc.navy.mil/GLBhycomcice1-12_mnsd/navo/arc_list_glfstrsssMN.html

To the poles and back again…

The northward flow gets rapidly cooled by the cold winds that are moving it northward. Due to constant contact with the subarctic and arctic winds, this water becomes colder and thus denser. This water also maintains it's high salinity!

Now this water is saltier and colder than the surrounding surface water, so it sinks.

As the water sinks, it spreads out along the ocean floor.



This figure shows the extent of AABW (dark blue) and NADW (light blue) in an idealized model at a certain depth.

https://oceanwiki.ethz.ch/doku.php?id=lecture3:watermasses

The newly formed deep water slowly makes it’s way towards the equator. ***But then what happens?***

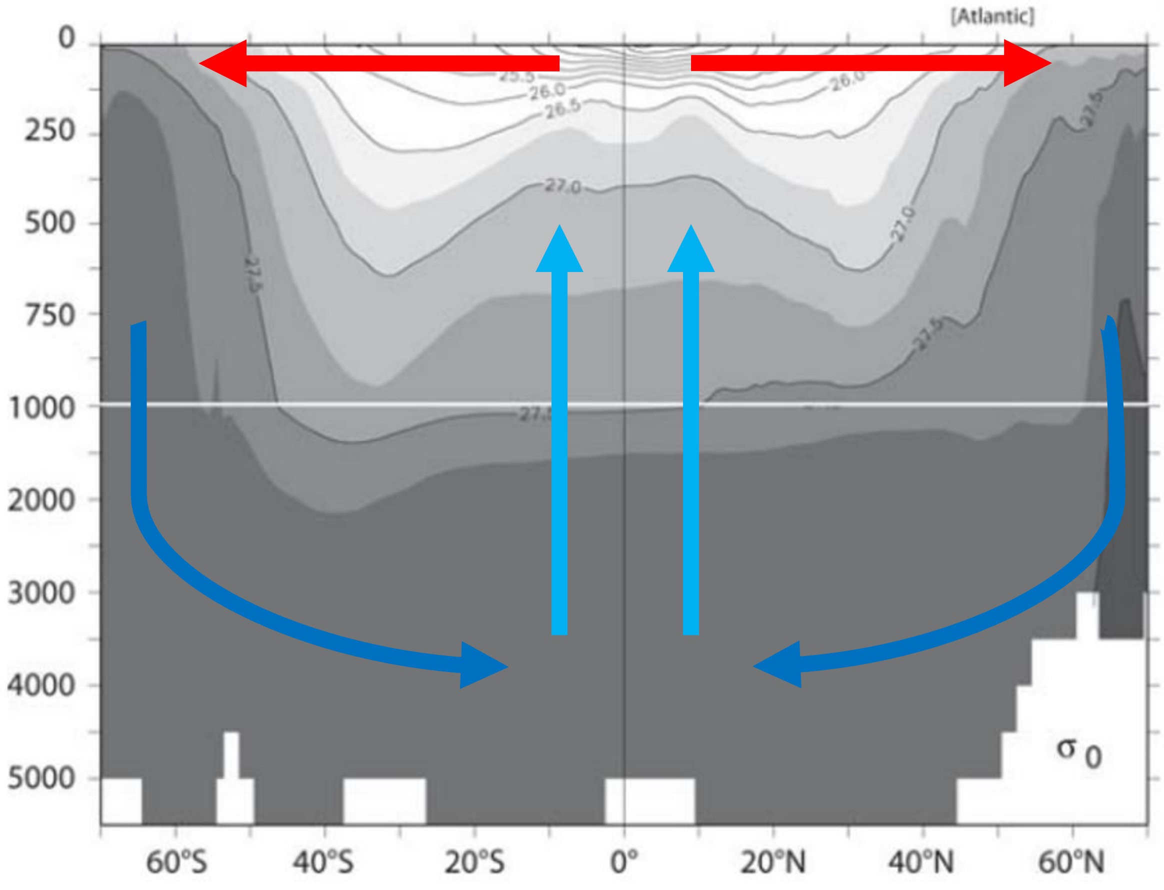
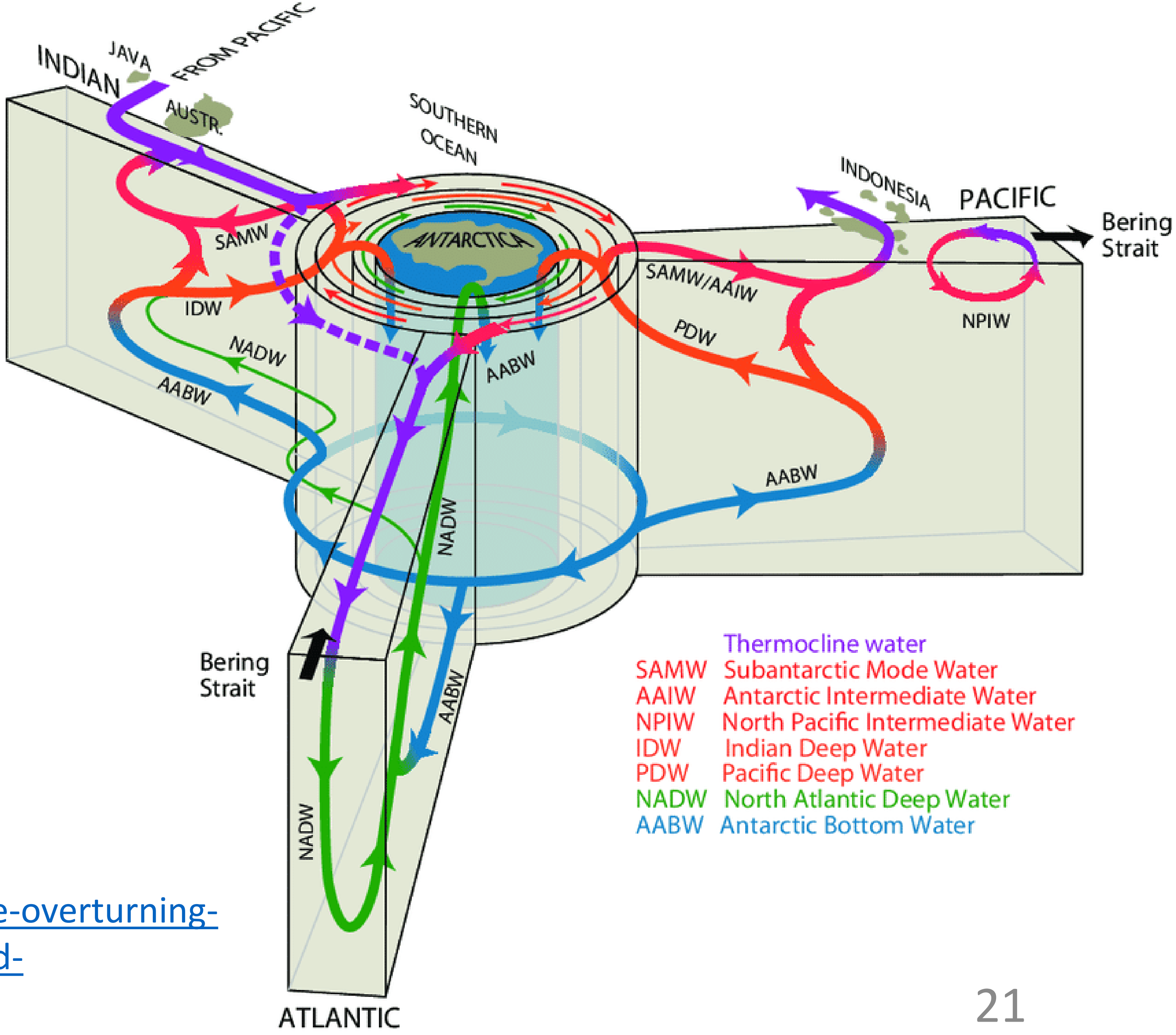


Figure 2.4. The zonally averaged density in the Atlantic Ocean. Note the break in the vertical scale at 1,000 m.[3]

A more complete overturning picture…

What can we see that we recognize?

- Deep Water formation (NADW, AABW)
- Equatorial upwelling
- Poleward heat transport
- Shallow Northern flow of Antarctic water



https://www.researchgate.net/figure/Schematic-of-the-overturning-circulation-from-a-Southern-Ocean-perspective-revised-from_fig3_269730919

Summarizing what we learned…

What are the primary kinds of Ocean Circulation?

- *Wind-driven* and *Geostrophically maintained* surface circulation
- *Thermohaline-driven* and *Wind maintained* meridional overturning circulation

What Forces drive Ocean Circulation?

- *Ekman surface wind stress*
- *Thermohaline/Buoyancy Forces*
- *Coriolis Force*
- *Interaction with landmasses*

A note on the Antarctic Circumpolar Current

The AACC and the winds that drive it are actually strong enough that they generate a global wind circulation that maintains the meridional overturning circulation.

The strong winds that circulate around Antarctica generate upwelling in the South Sea that is forced northward in a shallow flow. This water is replaced by poleward flowing deep water.

When this flow meets the warmer waters of the subarctic, it sinks down to form the ***Antarctic Intermediate Water.***

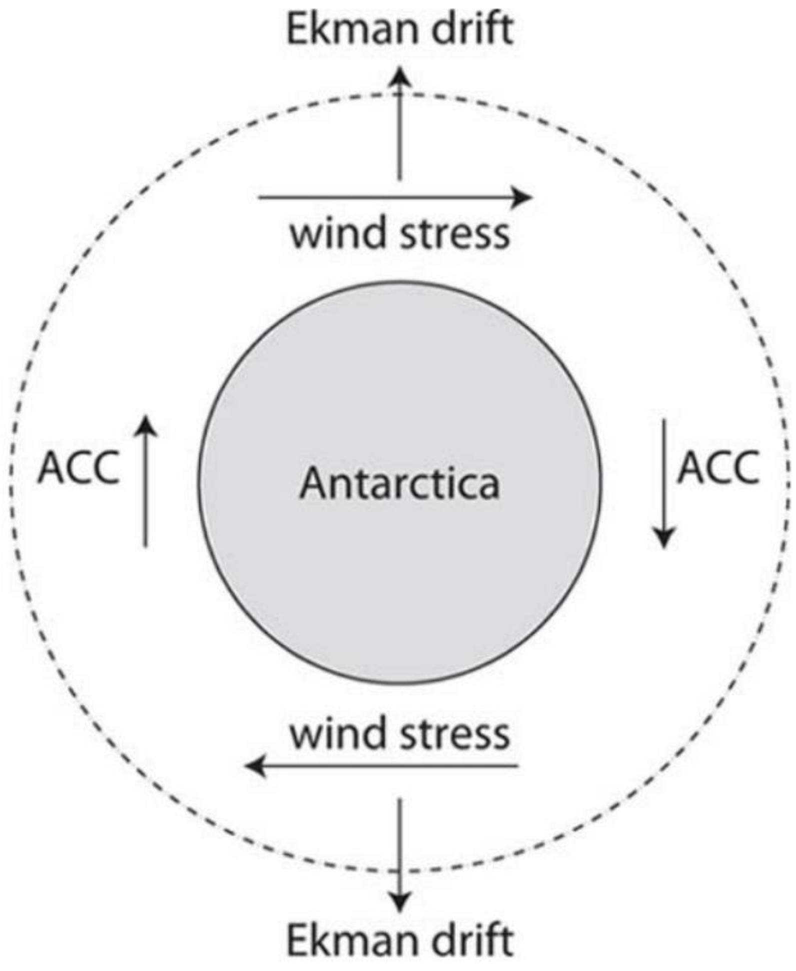


Figure 4.7. Schematic of the flow in the Antarctic Circumpolar Current (ACC). The wind predominantly blows in a zonal direction around the Antarctic continent, generating an Ekman flow toward the north and a net loss of water from the channel. The water returns at depth, generating a deep overturning circulation, as illustrated in the bottom panel of figure 4.6.