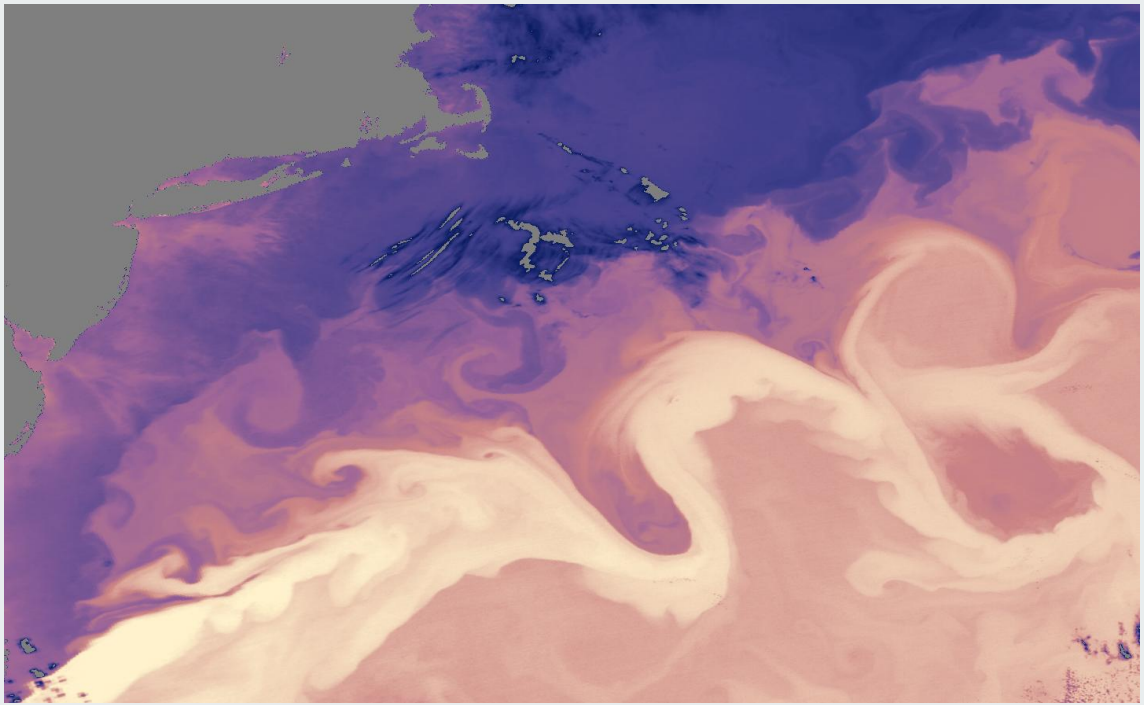
Dynamics and Circulation of the Ocean

From Chapters 3 and 4 of Climate and the Oceans by Geoffrey K. Vallis



Logan Knudsen
October 24, 2024

Image from NASA's visible Earth catalog, originally published April 20, 2008.

Goals of this presentation:

- Build an understanding of the basic dynamical principles of rotating, stratified fluid flow
  - Geostrophic Balance
  - Hydrostatic Balance
  - Ekman Layers
- Apply the basic dynamical principles to understand the flow of the ocean
  - Ocean gyres
  - Meridional Overturning Circulation

Centrifugal Force

- What is centrifugal force?
- Centripetal?
- How does the magnitude of centrifugal acceleration compare to gravitational acceleration?

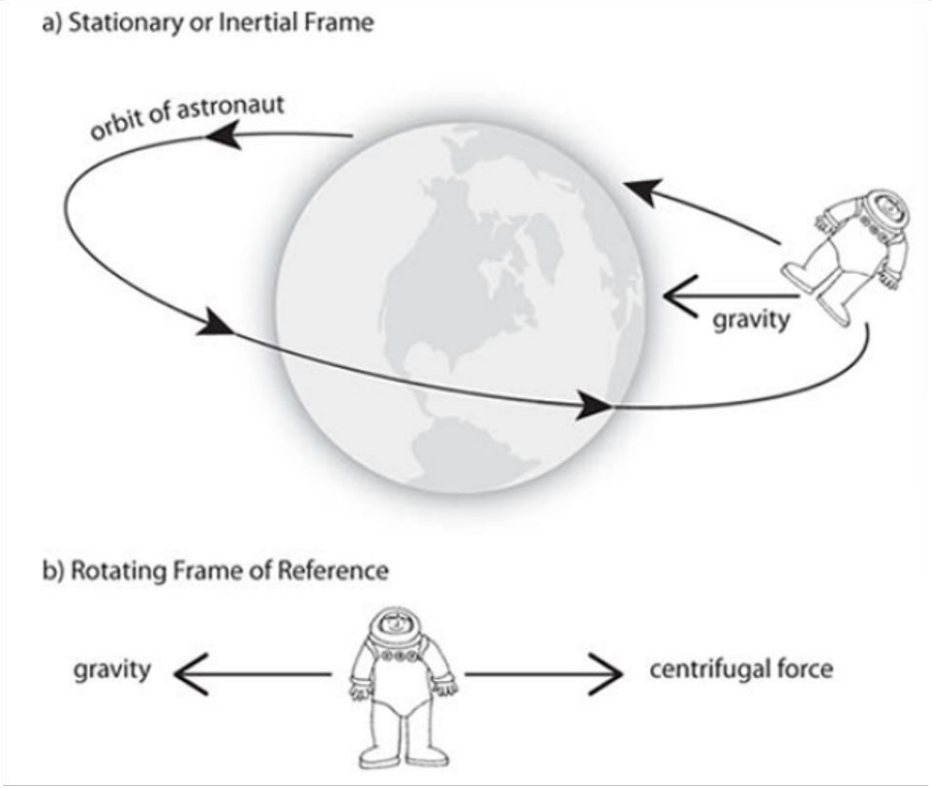
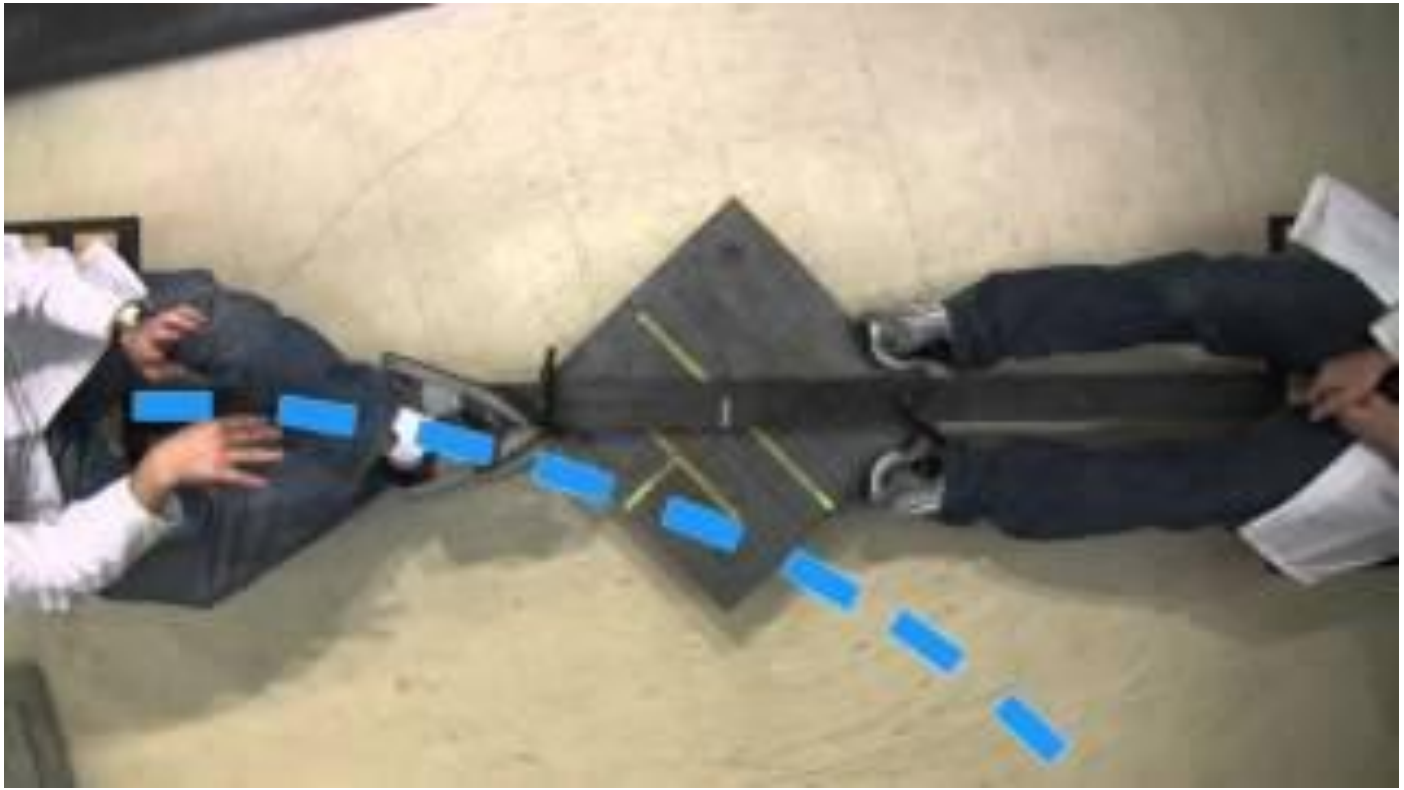


Figure 3.6. An astronaut orbiting Earth. Panel a views the motion in a stationary frame of reference, in which Earth's gravitational force provides the centripetal force that causes the astronaut to orbit Earth. Panel b views the situation from the astronaut's frame of reference, in which the gravitational force is exactly balanced by the centrifugal force and the astronaut feels weightless.

Coriolis Force



https://www.youtube.com/watch?v=dt_XJp77-mk

Coriolis Force

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Wide of the mark by 100 yards: Textbooks and the Falklands Coriolis myth

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2 February 2022

A journey into primary sources debunks a commonly told story about the Coriolis effect.

Christopher M. Graney

DOI: https://doi.org/10.1063/PT.6.3.20220202b

Recently my boss—Guy Consolmagno, director of the Vatican Observatory—and I got into a disagreement regarding the accuracy of a story in one of my old textbooks about how the Coriolis effect allegedly played a role in the Battle of the Falkland Islands, a World War I naval engagement that occurred in December 1914. We were writing a popular article on how the Coriolis effect was first conceived by Jesuit astronomers and mathematicians in the 17th century. (Guy is a member of that religious order, formally known as the Society of Jesus.) Guy wanted to include the story about the effect's role in the battle as an example of a historical myth.

I was skeptical that such a commonly accepted story could be false. Somewhat to my surprise, however, and a little to my chagrin, Guy turned out to be right. Our argument and its resolution are an interesting illustration of how myths in science originate and propagate.

The Falkland Islands story

The Coriolis effect is named for Gaspard-Gustave de Coriolis, who worked out the math in the 19th century. It arises because Earth is a rotating sphere. At the equator, Earth's surface has a rapid eastward motion that carries it around

Coriolis Force

- Does coriolis force cause the flow to curve to the right or left in the northern hemisphere?

- What about the southern hemisphere?

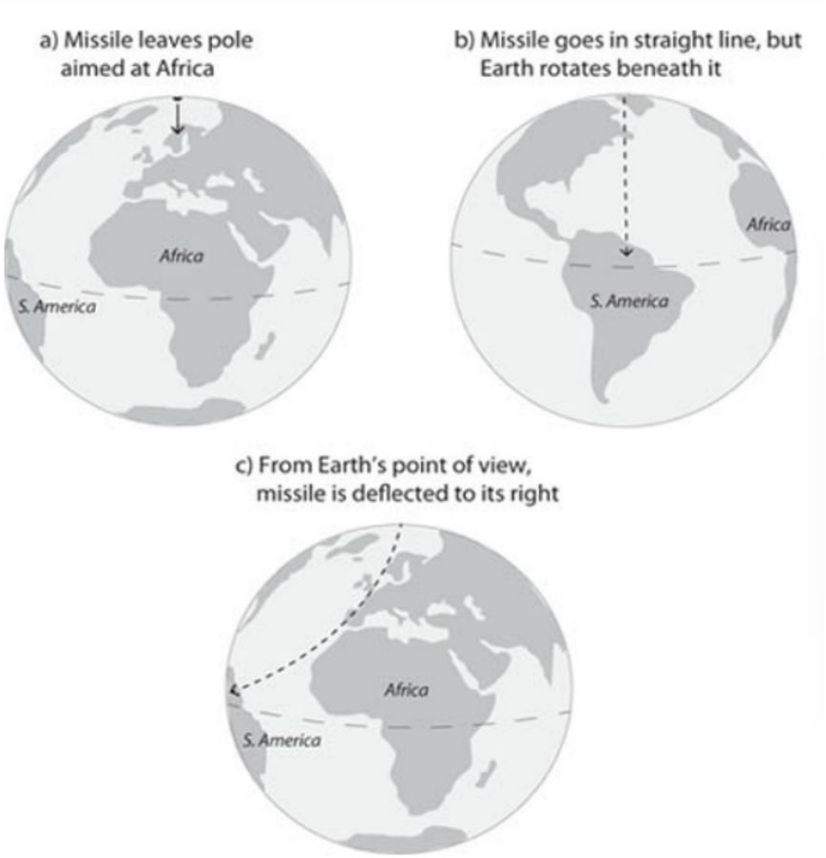
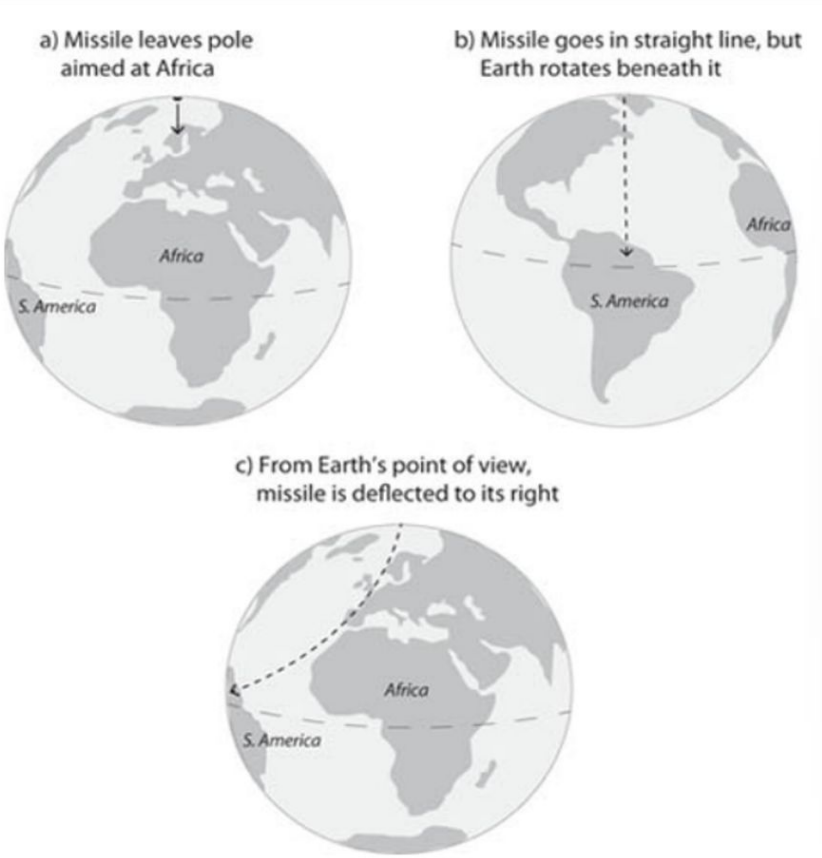


Figure 3.1. A missile launched from the North Pole toward Africa. Earth rotates beneath the missile, and the missile lands in South America. From the point of view of an observer on Earth, the missile has been deflected to its right, and the force causing that deflection is the Coriolis force.

Coriolis Force

- How do we formulate coriolis force?



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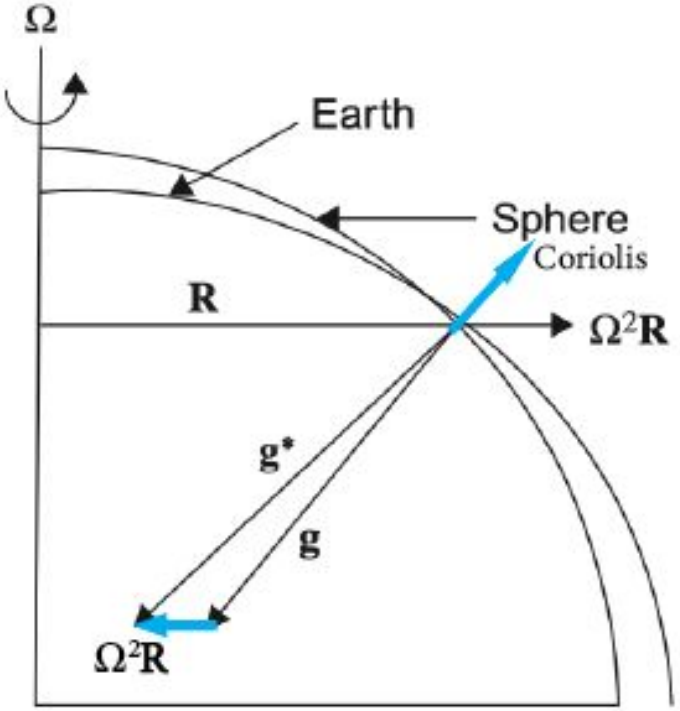
Coriolis Force

- What is the difference between coriolis force and centrifugal force?

- Why are we told to ignore the centrifugal force?



Force diagram for centrifugal and coriolis force. Adapted from Holton 2013.

Coriolis Force

- Note that coriolis force varies with latitude

- What is the formula for differential coriolis force?

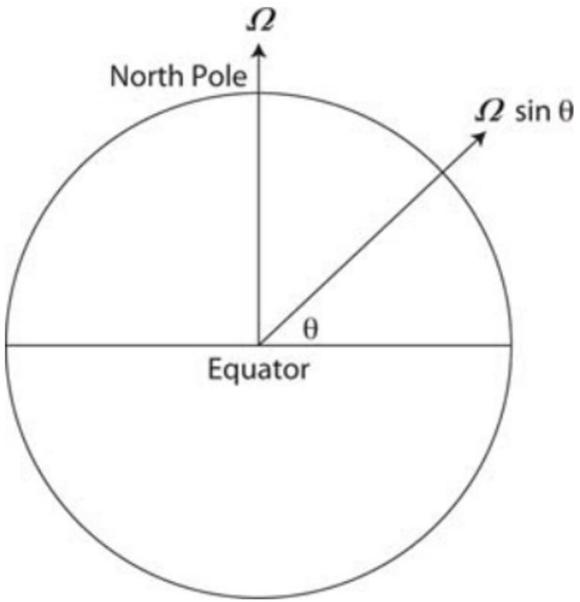


Figure 3.2. The component of Earth's rotation in the local vertical direction varies with latitude (θ) like $\Omega \sin \theta$. Its value is $+\Omega$ at the North Pole, zero at the equator, and $-\Omega$ at the South Pole. The Coriolis parameter f is given by $f = 2\Omega \sin \theta$.

Pressure Force

- What is the pressure gradient force?

- Does it act from high to low or low to high?

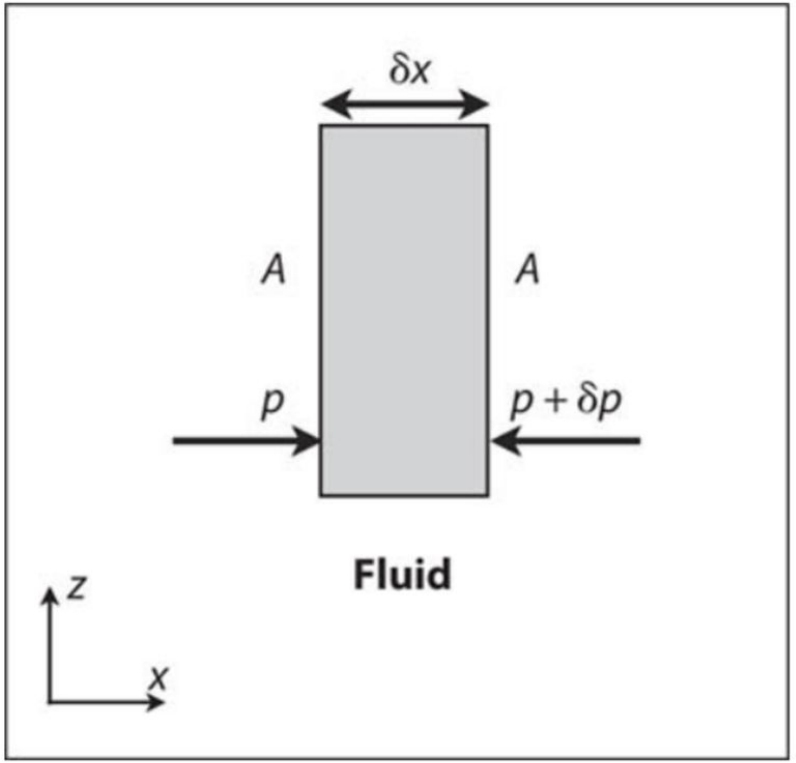


Figure 3.3. A slab (dark shading) floating within a fluid, with x and z the horizontal and vertical directions, respectively. The force to the right is just the difference of the pressure forces between the right and left surfaces of the slab, and so proportional to δp. Thus, the net force is proportional to the pressure gradient within the fluid.

Hydrostatic Balance

- Review: What is hydrostatic balance?

  How is it formulated?

- Is hydrostatic balance only valid for fluids at rest?

- How does pressure change in the ocean?

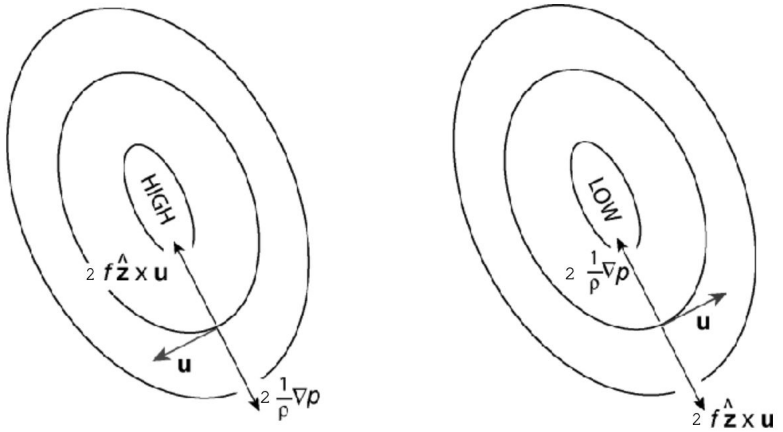
Image of Atmosphere from Atmosphere, Clouds and Climate by David A. Randall

Geostrophic Balance

- Geostrophic balance is when pressure gradient force and coriolis force balance
- How is it formulated?

- What field can we substitute pressure for?

- When can we approximate flows to be geostrophic?

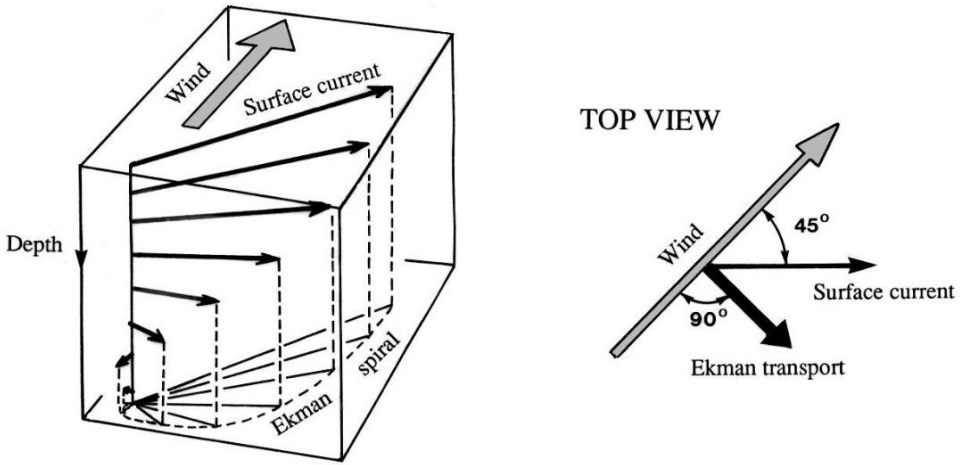


Geostrophic flow around a high and low pressure. Figure from Atmosphere, Ocean and Climate Dynamics by Marshall and Plumb

Ekman Layer

- Ekman layers are boundary layers driven by the surface wind stress.
- Does geostrophic balance apply?

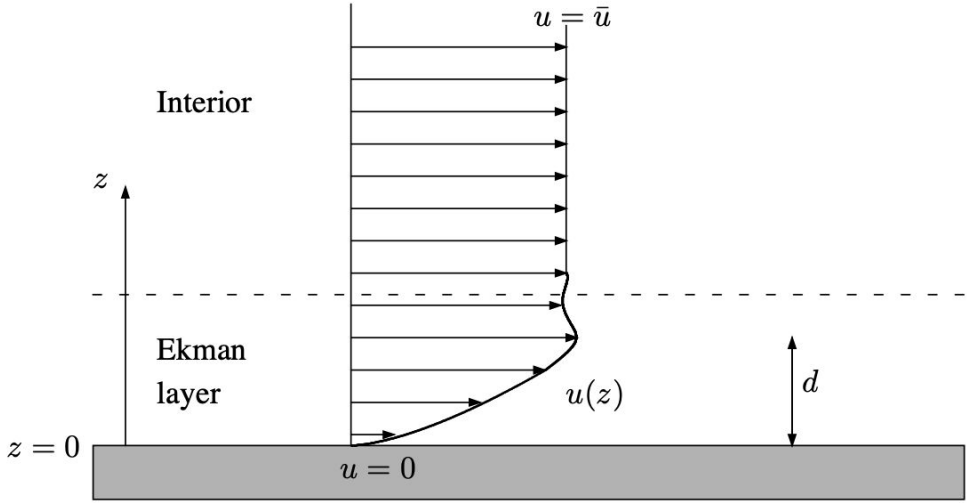
- What is the Ekman transport?



Ekman surface layer showing the signature Ekman spiral (right) and Ekman transport relative to surface wind. Figure from Introduction to Geophysical Fluid Dynamics by Cushman-Roisin and Beckers.

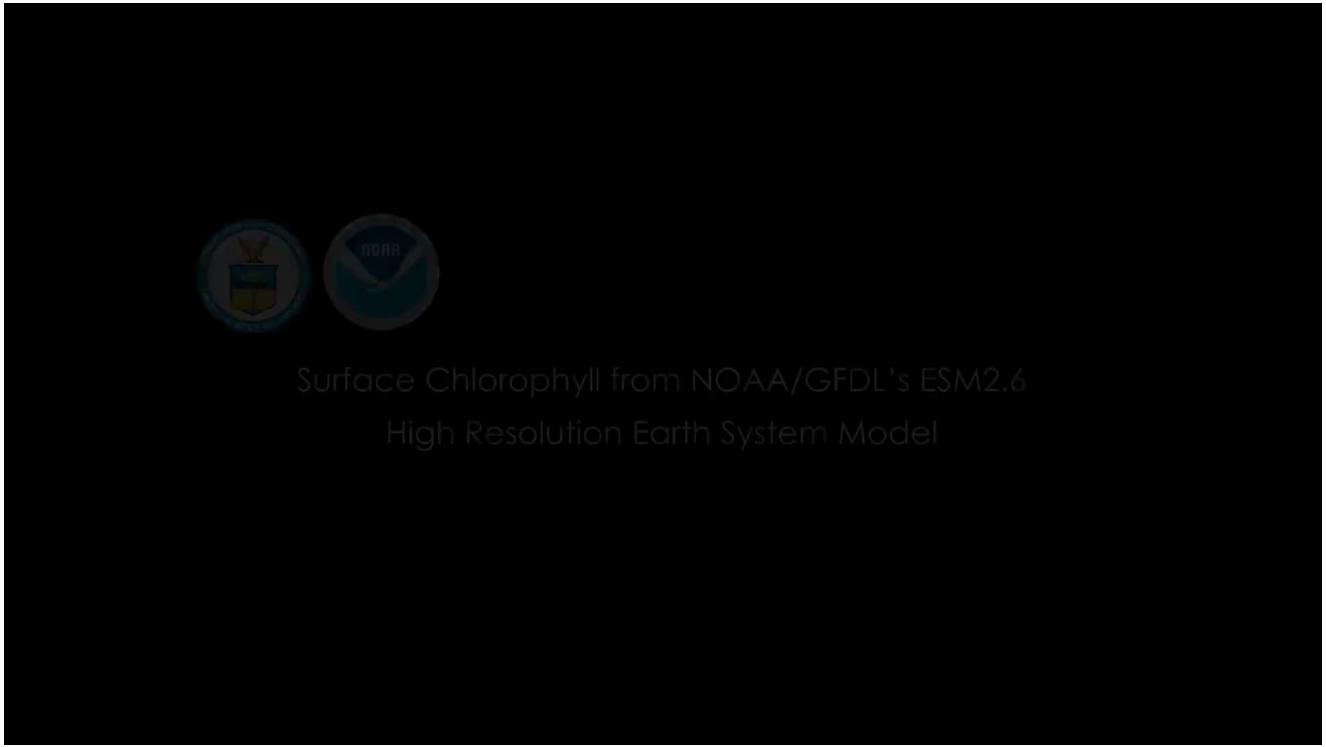
Ekman Layer

- Ekman layers also exist in bottom boundary layers
- Ekman Transport is **not** 90° to the right of the direction of the interior flow
- Not a good model in the atmosphere, but performs better in the oceanic bottom boundary layer



Velocity profile for bottom Ekman layer. Figure from Introduction to Geophysical Fluid Dynamics by Cushman-Roisin and Beckers.

Ocean Circulation



Video of Surface Chlorophyll from NOAA/ESM2.6, Video from Geophysical Fluid Dynamics Laboratory Large Scale Ocean Dynamics Visualization. https://www.gfdl.noaa.gov/visualization/visualizations-oceans/

Ocean Gyres

- Why do ocean gyres exists?

- Why is friction not included as a primary driver of circulation?

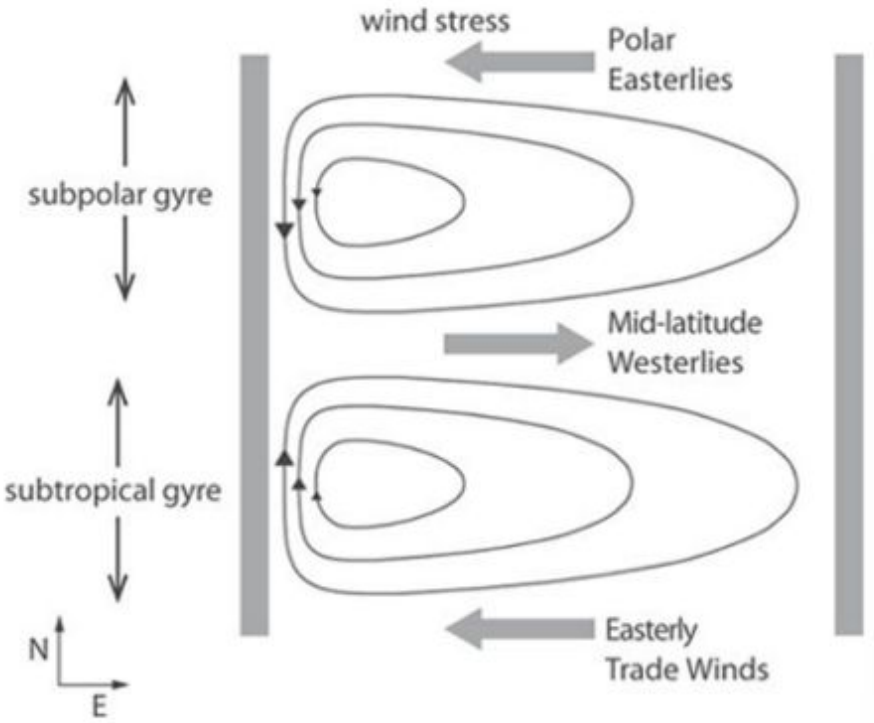
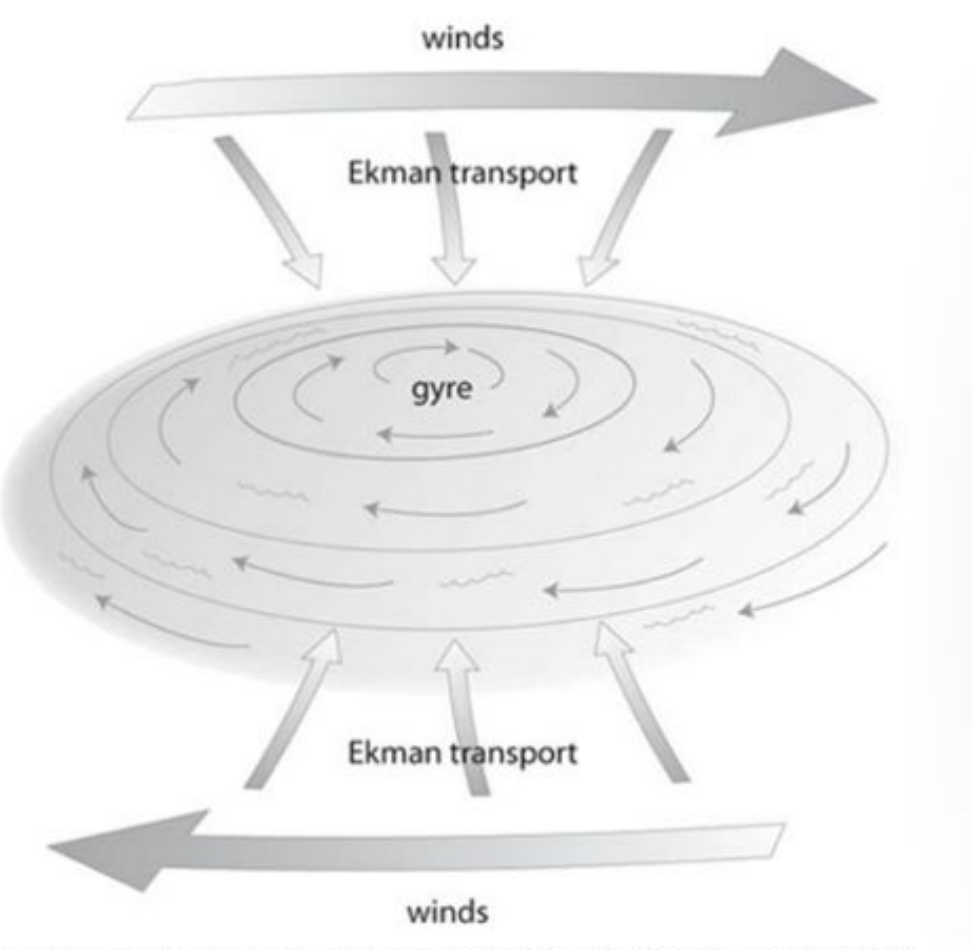
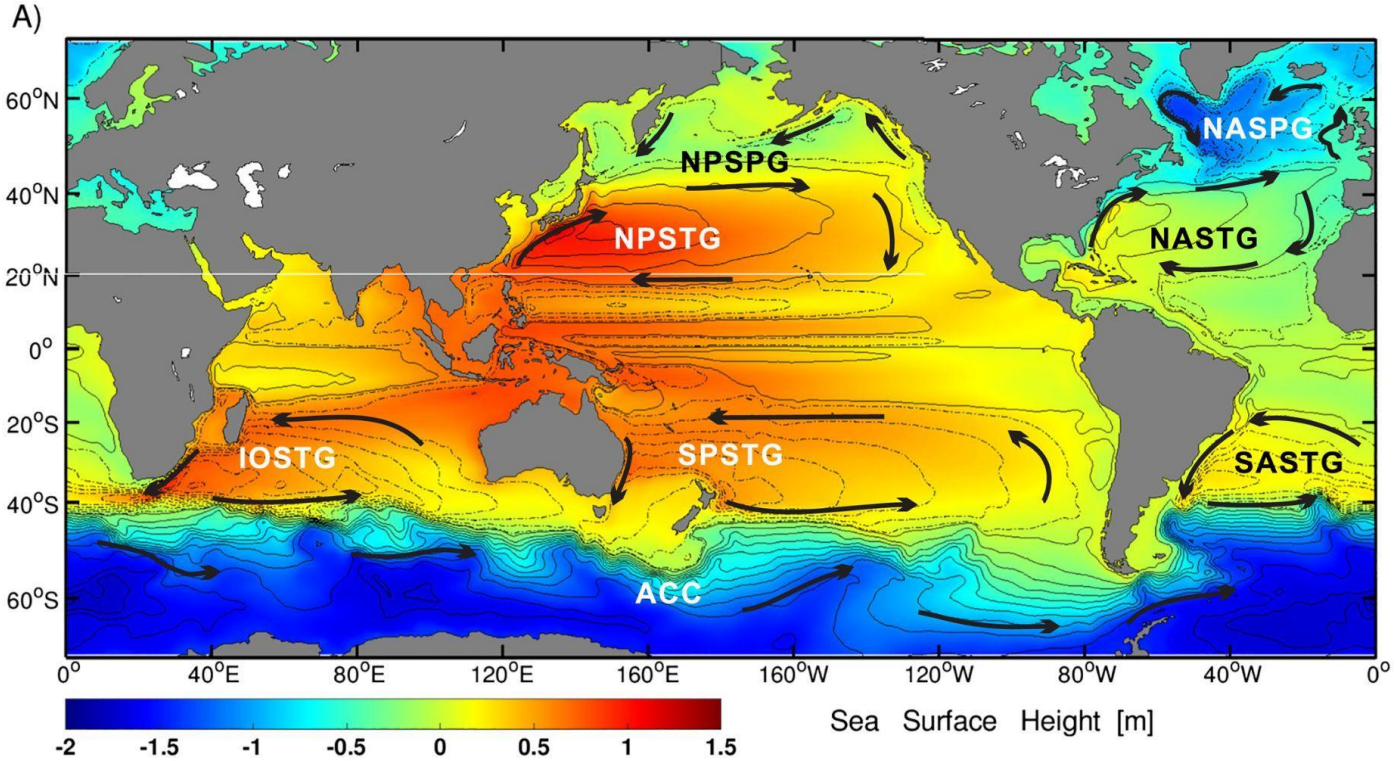


Figure 4.1. An idealized gyre circulation in a rectangular ocean basin in the Northern Hemisphere, showing the subtropical gyre (lower, typically extending from about 15°N to 45°N), the subpolar gyre (upper), and the intense western boundary currents on the left.

Ocean Gyres



Ocean Gyres



Map of Sea Surface Height with streamlines. From Yang et al. 2020

Western Intensification

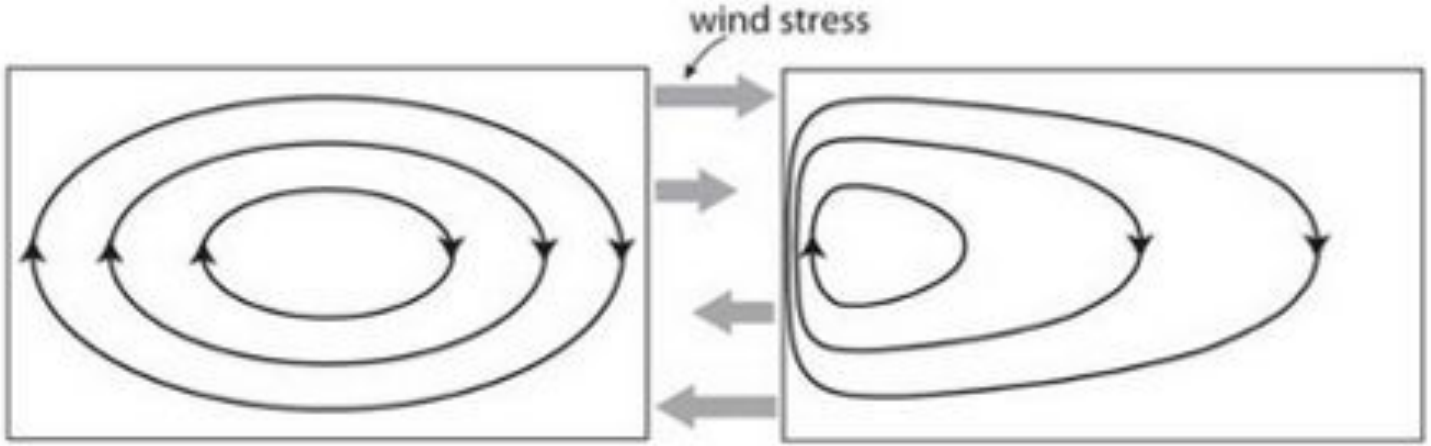
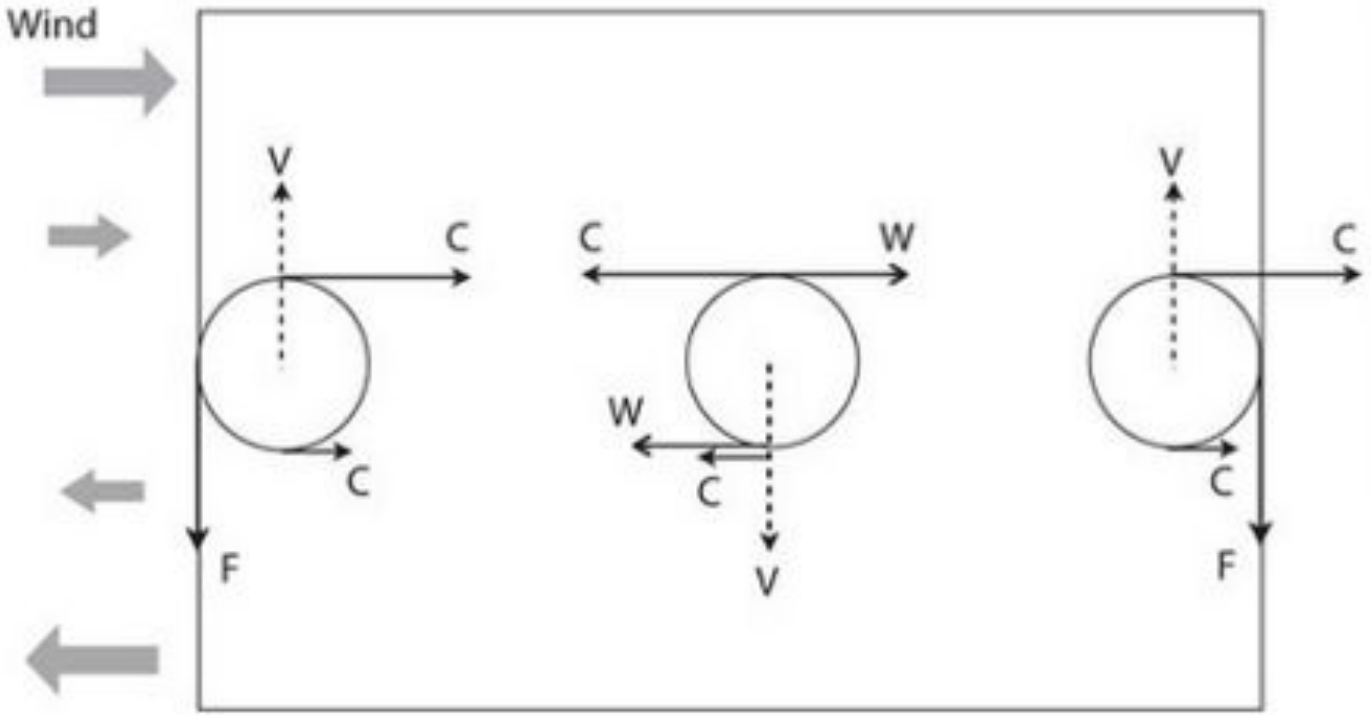


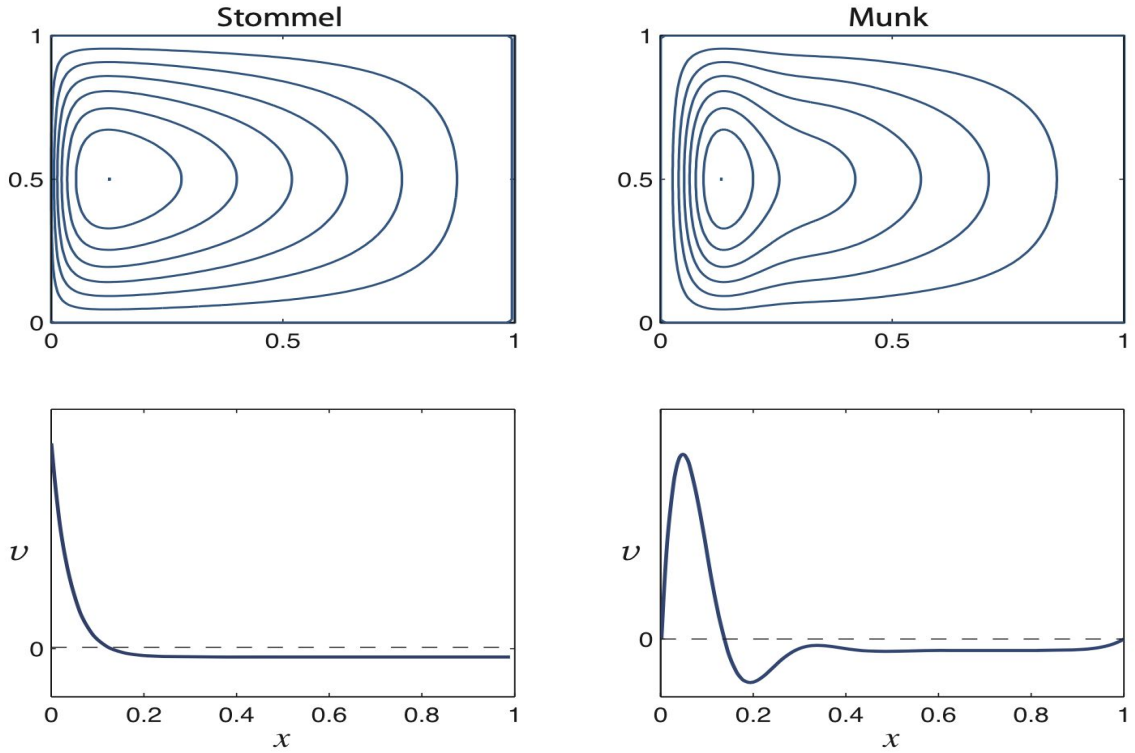
Figure 4.3. Two schematics of a subtropical gyre. The left panel shows the basic response of the circulation to the winds shown, and the right panel shows the gyres in the presence of differential rotation, with western intensification.

- Ocean gyres are asymmetrical, with western boundary currents of intense flow.
- What causes this asymmetry?

Western Intensification



Western Intensification



Streamlines and meridional velocity for Stommel and Munk models. From Atmospheric and Oceanic Fluid Dynamics by Vallis

Westward Drift

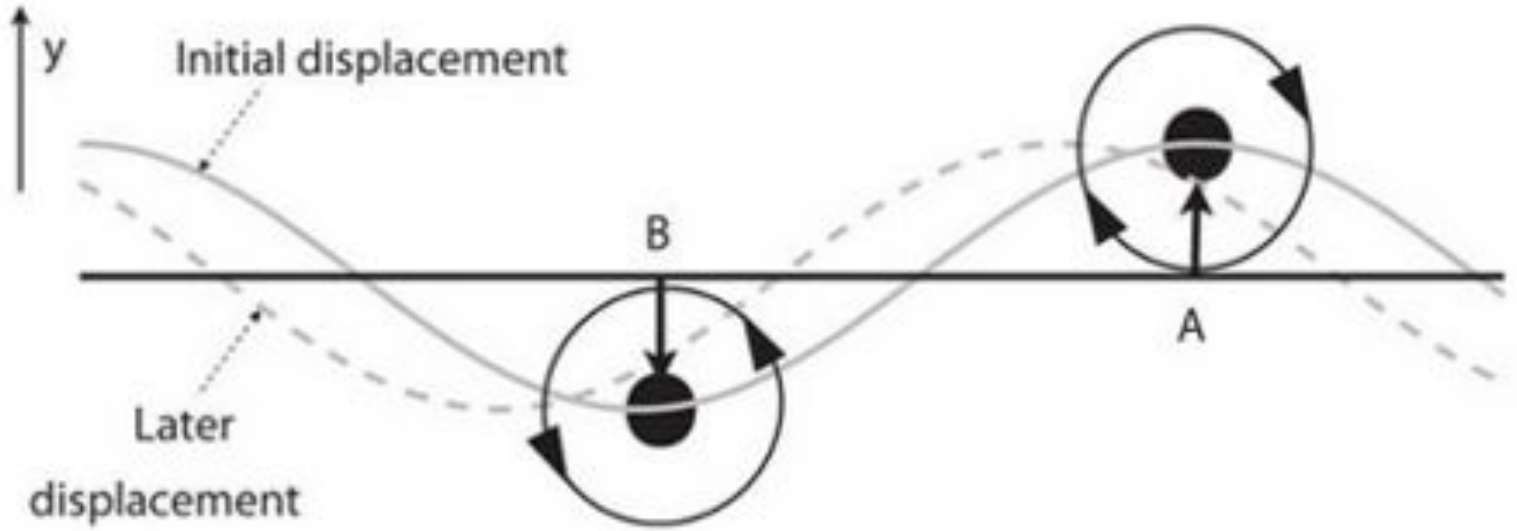


Figure 4.5. If parcel A is displaced northward, then its clockwise spin increases, causing the northward displacement of parcels that are to the west of A. A similar phenomenon occurs if parcel B is displaced south. Thus, the initial pattern of displacement propagates westward.

Buoyancy

- What is buoyancy?

- Draw buoyancy profiles for stable, unstable and neutral buoyancy cases.

Meridional Overturning Circulation

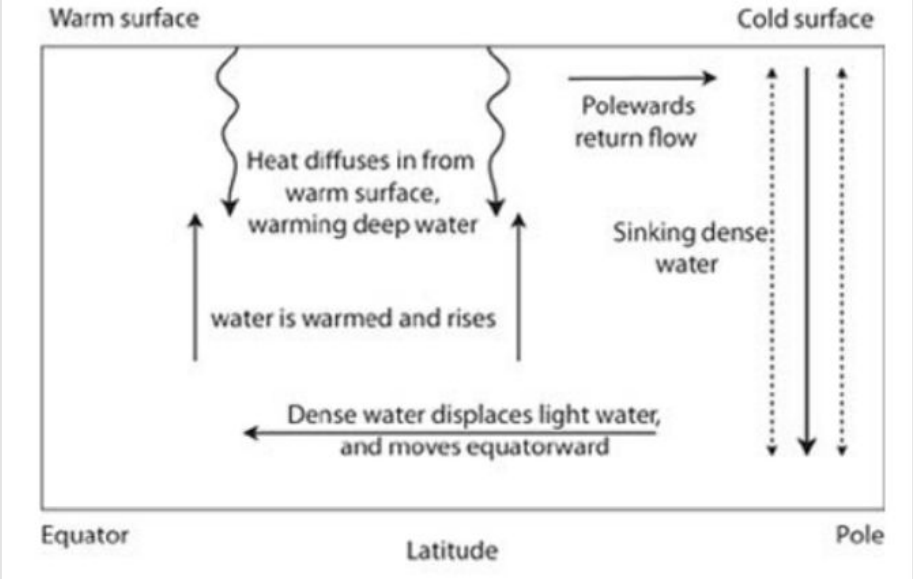
https://www.youtubeeducation.com/watch?v=eZzpvLz4yAk

Meridional Overturning Circulation

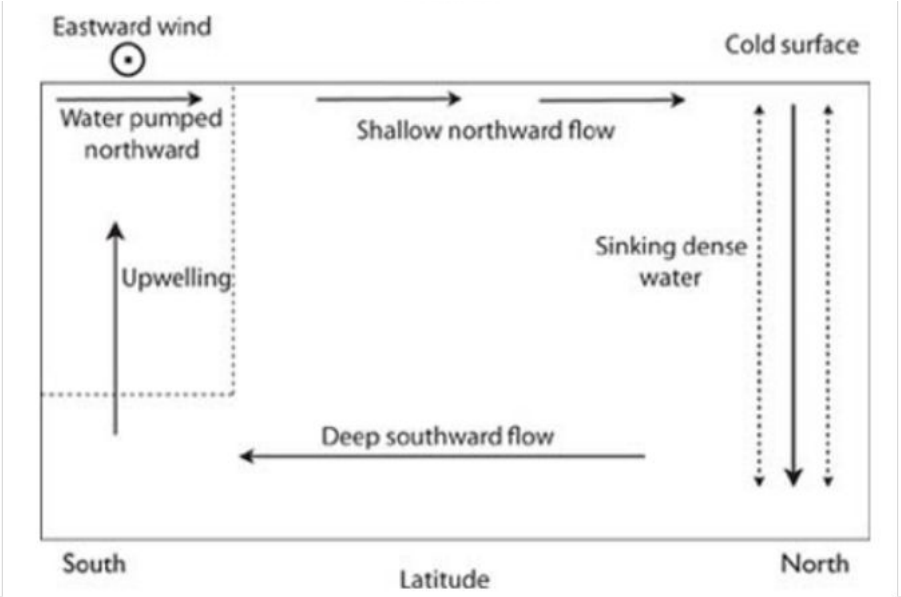
- What are the components of the Meridional Overturning Circulation?

- Can you describe the mechanisms of these two processes?

Meridional Overturning Circulation



(a.) Mixing component of the MOC



(b.) Wind-driven component of the MOC

Meridional Overturning Circulation

- Why is the Antarctic Circumpolar Current (ACC) important to maintaining MOC?
- Is the ACC in geostrophic balance?
- Why not?

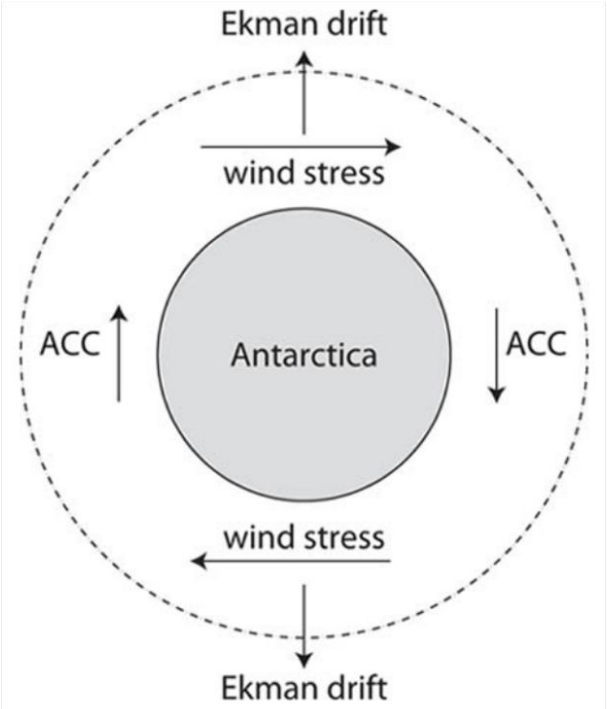


Figure 4.7. Schematic of the flow in the Antarctic Circumpolar Current (ACC). The wind predominantly blows in a zonal direction around the Antarctic continent, generating an Ekman flow toward the north and a net loss of water from the channel. The water returns at depth, generating a deep overturning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

Meridional Overturning Circulation

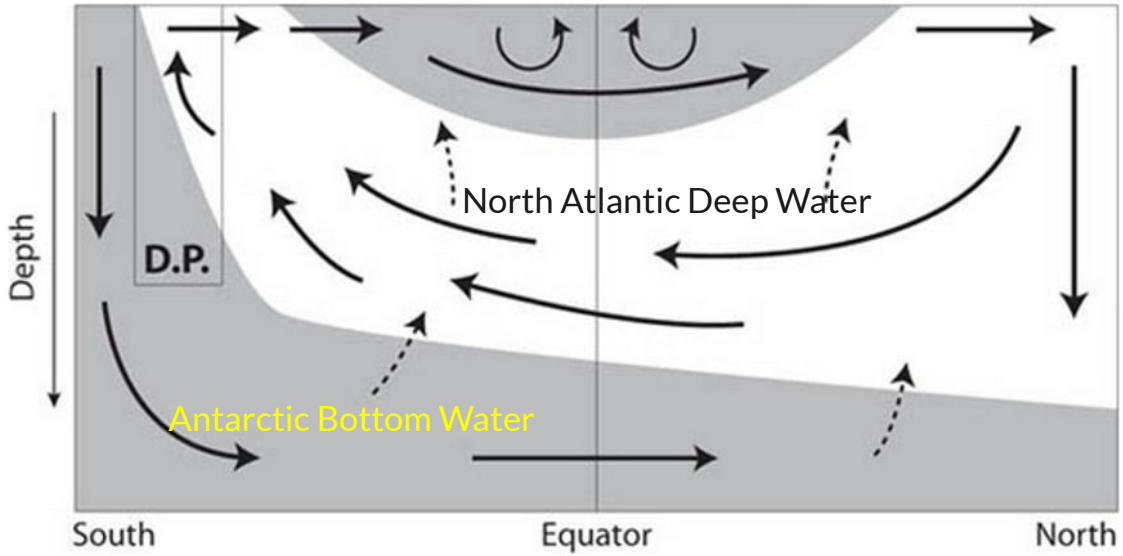
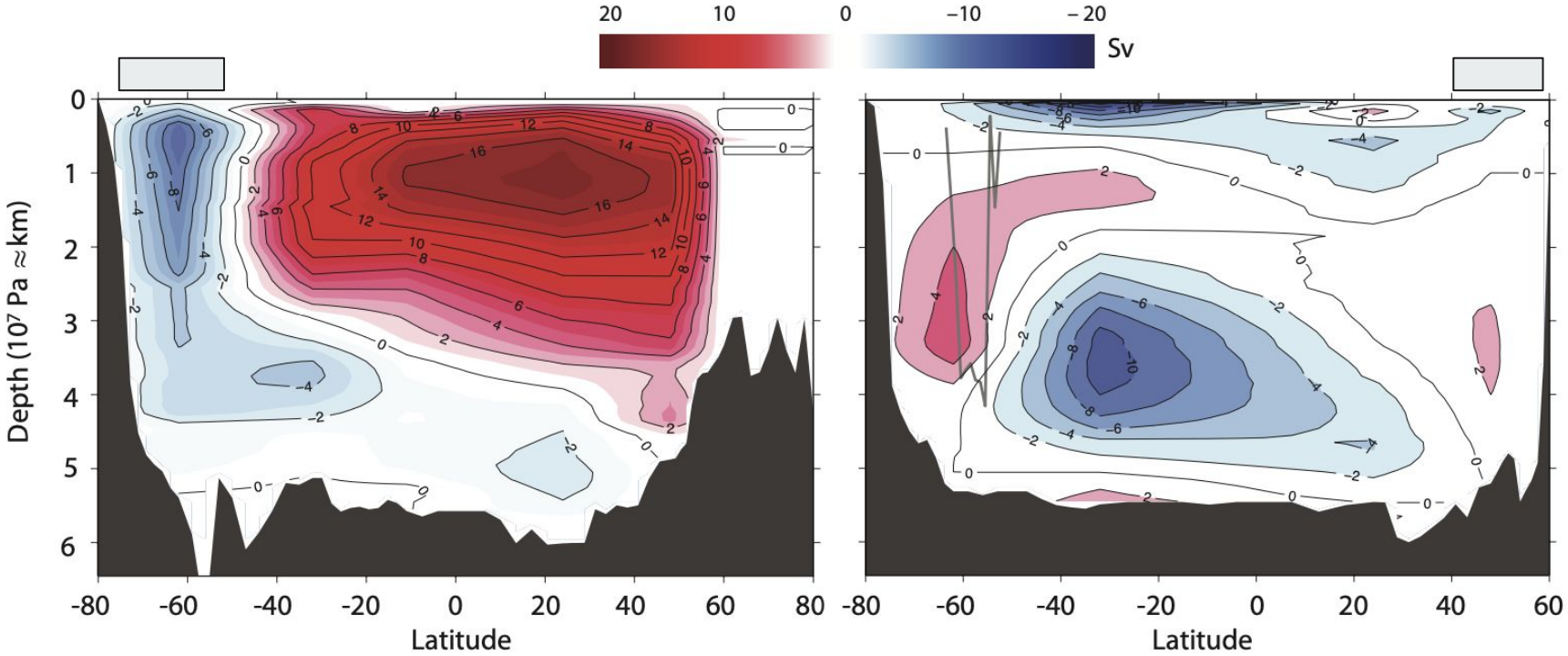


Figure 4.8. Schematic of the meridional overturning circulation, most applicable to the Atlantic Ocean (D.P. indicates the Drake Passage, the narrowest part of the ACC). The arrows indicate water flow, and dashed lines signify water crossing constant-density surfaces, made possible by mixing. The upper 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.

Meridional Overturning Circulation



Residual streamlines for overturning circulation. From Atmospheric and Oceanic Fluid Dynamics by Vallis