Ocean Circulation

I. General Considerations

A. Ocean currents are classified as being wind driven or thermohaline.
   - Wind Driven currents are caused by friction between the air and the surface of the water.
   - Primarily horizontal, and primarily in the upper 100 meters
   - Thermohaline currents are caused by the sinking of high density water from the surface (thermo for temperature, haline for salt)

B. Review: The ocean has several layers
   - Surface Mixed Layer, warm, less dense which “floats”, and is usually between about 50 – 200 m thick, and of constant density
   - Clines lie below the SML, and can be thermo-, pycno-, or halo-
   - The pycnocline acts as a barrier to mixing, so the surface mixed layer remains essentially isolated from deeper water
   - Intermediate Water is below the SML, extending to 1500 m
   - Deep Water is from 1500-4000 m, and doesn’t touch the bottom
   - Bottom Water is the water below 4000 m

Horizontal Circulation
   - Develops from friction between the wind and the sea surface
   - Only a small percentage of the energy is converted to currents, probably on the order of 1-3%.
   - Therefore, a steady 60 km/h wind could generate surface current with a speed of 1-2 km/h
   - This is mostly because water is 8000x more dense!

A. Boundary Currents
   - Equatorial currents are formed by the strong band of Trade Winds
   - At the equator, the coriolis force is zero, so the trade winds push the water from east to west, with no deflection
   - When they hit the continents (boundaries), they are forced to turn…the turn Northward (to the right) in the N Hemisphere because of the Coriolis Force
   - These become the Western Boundary Currents
   - At 30-60° Latitude, the Westerlies pick up (west to east!)
   - The water turns to the right (Coriolis), forming the Eastern Boundary Currents
- Taken together, they form a gyre
- The center of the gyre sits at about 30°, so it is called a Subtropical Gyre
- At higher latitudes, the Polar Easterlies form Subpolar Gyres, which rotate in the opposite direction

C. Ekman Transport
- Wind drags at the surface layer of the ocean (or lake, etc.)
- Coriolis turns it to the right (N. Hemisphere), about 45°
- The layer above drags a layer beneath it, with less force, again at 45°
- This continues down the water column until you run out of energy
- If you add up all of the layers, the net movement is 90° to the right…however, in reality, the currents usually turn less than 45°, and the net movement is usually less than 90°
- The entire layer that moves (the net movement) is called the Ekman Layer, and is dependent on the strength of the wind and the latitude, but on average doesn’t extend below 100 m
- The net movement of water is called Ekman Transport
- In shallow water (<100 m), friction against the bottom boundary dominates, and the water moves more or less in the same direction as the wind

D. Geostrophic Transport
- Ekman transport pushes water towards the center of the gyre, because the Coriolis force is constantly pushing the water 90°, or towards the center
- In the North Atlantic, this literally forms a “hill” which can be 2 meters higher than the edge of the gyre
- Gravity pulls water down the hill, but coriolis forces are trying to turn them to the right
- When gravity balances the coriolis force, you get a slope that pushes the current along…this is called a geostrophic current (geostrophic means “earth turning”)
- Geostrophic currents get their energy from the balance between gravity and coriolis forces…there is no wind energy involved (at least not directly)

E. Westward Intensification
- As we mentioned, the gyres have a “hill” of water which is formed by convergence of the Ekman Transport
- In addition to the coriolis force, there is also something called vorticity, which is the tendency to spin…if we were standing on the North Pole, we would spin around the axis once every 24 hours. On the equator, we don’t spin at all
Because of this, water moving from North to South has extra “spin”, or vorticity, and turns to the right more easily (from Coriolis) than water moving from the South to the North.

- We get broad, weak currents on the east side of the gyres, because the turn easily and early.
- On the west side, the currents resist turning, and get very deep and fast (think of the Gulf Stream).
- On average, western boundary currents are 10x faster, much deeper, and about 1/20 as wide as eastern boundary currents….this is called **westward intensification**

F. Dynamic Topography
- If we measure T-S, we can calculate density.
- Low density water sits higher…it “floats”
- If we assume there’s a layer at depth with no movement (typically greater than 100 m), we can measure the height above that layer…from that we can calculate the geostrophic balance.
- This is how the satellites measure currents.

G. Equatorial Counter Currents
- Because of the trade winds, water is constantly piling up on one side of the ocean…at the equator, there’s no coriolis force, so it doesn’t turn easily.
- To counteract that, there’s a “replacement” of water from west to east at depth…these form the **Equatorial Counter Currents**

**Vertical Circulation**
- this is the transport of water from the thin, wind-driven surface layer to depths.
- It is dominated by changes in density, and is called thermohaline circulation.

A. Wind-Induced
- A special case of vertical circulation is related to wind stress…it is **upwelling** and **downwelling**
- upwelling from depth occurs when there is not enough surface water to replace the surface flow away from an area (Ekman transport).
- This can occur anywhere there are differences in speeds, or where there is a boundary.
- Coastal upwelling is the most common example.
- There is also a general, slow upwelling throughout the world’s oceans.
- When you have weak but steady winds blowing for long periods, you can also get **Langmuir Circulation**, which is basically a series of convection cells.
H. Thermohaline Circulation

- This forms the deep water of the ocean basins
- There are 2 sources:
  1. North Atlantic Deep Water (cold, salty water sinks)
  2. Antarctic Bottom Water (not as salty, but VERY cold)
- For every liter of water that sinks, another liter must rise to the surface somewhere because of displacement
- Water in general moves from the North Atlantic, around Antarctica, and then into the Indian Ocean and Pacific
  1. Oxygen decreases and nutrients increase along the way
  2. Salinity in the surface increases from the Pacific to the Atlantic, as the water ages and more evaporates
  3. In the “conveyor belt” view of the oceans, water moves through the Atlantic at depth, and returns to the Atlantic in the surface waters

- In addition to the deep water formation, there is some (less important) formation at the convergence zones, which form the intermediate waters (Antarctic Polar Front produces Antarctic Intermediate Water, Arctic Convergence form the North Atlantic Intermediate Water)

II. Regional Circulation

Antarctic Circulation

- Antarctic Circumpolar Current goes around the whole globe!
- It isn’t very fast, but it is the biggest current…130 Sv
- One Sv is 1x10^6 m^3/s!
- It’s driven by the Westerly Winds, and is so called the West Wind Drift
- The East Wind Drift flows the opposite direction, and is forced by the Polar Easterlies…it hugs the Antarctic continent
- At about 60°S, there is the Antarctic Divergence
- At about 50° S, there is the Antarctic Polar Front

Atlantic Circulation

- Circulation is dominated by the subtropical gyres
- The Gulf Stream is an intense, Western Boundary Current—it’s the fastest current in the ocean! It makes Europe warmer than it should be, and also forms Warm/Cold Core Rings (p. 244-245)

Pacific Circulation

- Similar to the Atlantic, with Gyres, etc. The Gulf Stream is replaced by the Kuroshio Current
- Deep water circulation is also similar, but there is an additional source of density-driven circulation (heat) from the East Pacific Rise
- The Bering Strait (fairly shallow) keeps the deep water from getting into the basin, so it is much more weakly stratified than the Atlantic Ocean

**Indian Ocean**

- Surface circulation is dominated by the **monsoons**
- NE monsoons in the winter are caused by the high pressure cell over the Asian continent
- In the summer, the High Pressure is replaced by Low Pressure, and the winds reverse…these are the SW monsoons
- Primary deep water is from the Red Sea, with high salinity and very low oxygen

**III. Summary**

Denser water masses sink below lighter ones
A water mass seeks its appropriate density level and then spreads laterally
When one water mass sinks, an equal mass must rise somewhere else!
When water masses run into each other (convergence), the less dense water “floats” on top of the more dense water
Ultimately, all water masses gain their particular characteristics (T, S, oxygen, nutrients) because of interaction with the surface during their development, and the following:
Different inputs of fresh water
Different patterns of precipitation and evaporation
Different temperature regimes at the surface

Once water masses sink, their T, S are modified primarily by mixing with other water masses. In the deep ocean, there is little energy to mix the layers (there’s no wind!) so this is very low.
This gives each water mass a distinct “fingerprint”
It takes about 1000 years for water to reach the surface once it gets to the bottom!