3. Ocean circulation and transport

Like the atmosphere, the ocean has a time-averaged, planetary-scale circulation pattern but with important transient eddy motions superimposed upon the slow, general circulation. The general circulation is typically described in terms of a primarily wind-driven system of gyres (quasi-circular, basin-scale circulations as viewed from above), and an overturning circulation commonly called the thermohaline circulation. The latter is the circulation that “ventilates” the deep ocean and eventually returns deep waters to the surface. Its driving forces are more complicated than those of the “wind-driven” circulation, and will be discussed in the papers since the thermohaline circulation is of direct importance to paleoclimate.

Wind-driven gyres

The gyre circulations are depicted schematically in Fig. 1. Associated with these circulations are a number of currents whose names are given in the figure, including notably the Gulf Stream. The gyres are driven directly by the drag of surface winds, with midlatitude westerlies and tropical easterlies giving rise to the main gyres. They extend about halfway down to the bottom, although their depth is variable. The western boundary currents (e.g., the Gulf Stream) are concentrated into intense, narrow currents, while the return flow is gradually spread out over most of the rest of each basin. Dead waters at the center of circulation (e.g., the Sargasso Sea in the N. Atlantic) thus lie well to the west of the center of each basin. Typical current velocities are up to several m/s at the peak of the Gulf Stream, much less in most other places.

The gyre currents are geostrophically balanced, as were the atmospheric jets; the sea surface is, for example, about a meter or two higher (relative to the geoid) in the center of the anti-cyclonic, mid-latitude gyres than on the coasts, which provides the higher pressure necessary to balance the Coriolis force that pushes water toward the center of these gyres. Since the gyres decay with depth, the thermal wind balance (which also applies in the ocean!) implies that the water inside the anticyclonic gyres must be warmer than the water near the coast; this is indeed the case, with water temperatures (especially at depths of a few hundred meters) increasing by up to 10°C from the west flank of the Gulf Stream to the east flank, for example.

Other interesting currents also occur. The west wind drift is an important current that encircles Antarctica, the only place where a current can proceed uninhibited around the globe. This current cannot have existed prior to the opening of the Drake passage between S. America and Antarctica. Equatorial countercurrents flow opposite to the main gyres, in an eastward direction very close to the equator; these are essentially driven away from the western margin by the same high equatorial pressure there that drives the strong western boundary currents, and flow very close to the equator because of the disappearance of the Coriolis force there.

Conservation laws and driving forces
In the atmosphere, the most fundamental conservation law for understanding the main winds was that of angular momentum. The jet stream, for example, results from transporting equatorial air, at constant angular momentum about earth’s rotation axis, to a higher latitude where it must orbit the axis more rapidly since it is closer to that axis. In the ocean, the most important conservation law is that of potential vorticity, which may be crudely defined as the angular momentum per unit mass of a fluid about the local, vertical axis (as opposed to Earth’s axis). This is more relevant in the ocean because (except for the west wind drift) currents must deflect in circles around the ocean basins rather than flowing all the way around the earth as the winds can.

Note that angular momentum can be changed by exerting torque, which is exactly what winds in the subtropics do to the ocean, since the wind direction changes from easterly to westerly as you head away from the equator. The only way water can lose the angular momentum it picks up in that part of the ocean is through friction, which can only happen with the correct sign at the western boundary. This is ultimately the reason for the intense western boundary currents. Other variations in current can be explained by depth variations (recall that if the water gets shallower, it must rotate more slowly—and it is always rotating due to the Earth’s rotation—to conserve angular momentum, just like a figure skater who crouches down while spinning). We will examine this phenomenon more closely when we look at the turning of atmospheric flows over mountains, which involves basically the same physics.

**Upwelling and Ekman pumping**

Anyone who studies life in the ocean or lives from catching fish knows that upwelling waters bring nutrients to the surface that are critical to sustaining the base of the food chain. Key regions of upwelling are many eastern ocean boundaries and other coastal regions, and central and western equatorial regions. The reason for upwelling in certain places is related to a phenomenon called *Ekman pumping*, which is a direct result of the Coriolis force.

When wind exerts a drag force on the water, the water will initially move in the direction of the drag (i.e., the wind direction). But within a very short time it will begin turning to the right (in the northern hemisphere) due to the Coriolis force. When things settle down, the surface water will be moving in an “Ekman” flow at right angles to the exerted force and will stay that way as long as the wind stays steady. Note, this implies surface flow toward the center of the great gyres, rather than what we see! Well, the initial inward flow quickly builds up the mound of water mentioned earlier, which sets up back pressure, balancing a geostrophic flow that ends up looking a lot more like the wind itself except smoothed out. Note that the wind and water must move in similar directions in order for the wind to perform work on the ocean, imparting the energy needed to maintain the ocean circulation against losses from internal friction, and indeed they do.

If wind is parallel to a coast with the coast on the left (in the northern hemisphere), the Ekman flow will be away from the coast. This will require upwelling to replace the
water lost. Since friction is important near coasts, this---rather than a mound of water as occurred for the gyres---ends up pushing back against the Coriolis force, so the upwelling and offshore flow continue permanently. The required winds are common off the west coast of the US, leading to cold water (but rich in plankton) off the west coast compared to the east coast. The tropical easterlies produce a similar effect at the equator, where the change in sign of the Coriolis force but similar wind direction on both sides produces a similar effect as having a coast there. During El Nino, the trade winds fail, causing the upwelling to cease and the fish to depart for other waters, much to the dismay of local fishermen (as if all the bad weather they get weren’t bad enough).

The Ekman drift currents are typically only a few hundred meters deep or less. The upwelling necessary to balance them near coasts may extend quite a bit deeper though.

The abyssal circulation

In the lower half of the ocean, the abyssal circulations are quite different from those at the surface (Fig. 2). One common characteristic is the apparent dominance of strong western boundary currents. The abyssal circulations are still poorly measured and understood.

The thermohaline circulation

The gyre circulations (and transient eddies) do effectively mix the hemispheric ocean basins horizontally on time scales of months to decades (depending on depth). However, like the atmospheric jets, they do not bring fluid to or from the surface. This is accomplished in the ocean, just as in the atmosphere, by convection. Also, just as in the atmosphere, there are basically two kinds of ocean convection: shallow convection that mixes a layer near the surface, and deep convection that mixes the entire ocean but at a much slower rate. The deep convection of the ocean is loosely referred to as the thermohaline circulation, although we will find that precisely defining this circulation is problematic.

In today’s ocean, shallow convection proceeds down to about half a kilometer or so (the oceans themselves are ~4 km deep). Most occurs in winter during surface cooling, but convection is also strongly affected by winds. In equatorial regions with high rainfall and weak winds, the convection may usually only reach a few meters down. Convection is regulated by the ability of winds to overcome stable stratification of density, which depends on temperature and salinity (warmer and/or fresher water is lighter). On average, surface water is warmest and freshest (see Fig. 3), so it takes wind to mix this lighter water down and it can only get so far. The base of the mixing is called the thermocline.

Most oceanic deep convection currently occurs near the poles, though some has recently been observed near Japan. The deepest occurs in the shallow seas off of Antarctica, generating “Antarctic Bottom Water” (AABM). In the North Atlantic, “North Atlantic Deep Water” is formed that is not quite as dense and flows out to fill much of the ocean
(Fig. 4). Other water masses can also be identified. The deep waters currently form from brine ejected from seasonal sea ice formation, which is sufficiently cold and salty to sink to great depths. This sinking must be balanced by a slow, horizontally-averaged rising of water in the rest of the ocean. It takes several thousand years for sufficient deep water to form to completely refill the oceans; this number is uncertain due to the difficulty of observing deep water formation rates. As the water rises, it warms; the energy source for this is still not fully understood (this is the subject of Wunsch’s papers) but is central to the long-term behavior of the thermohaline circulation.

Due to the nature of the circulation, as apparent in Fig. 4, the properties of abyssal waters are determined proximately by those of the surface at (in today’s climate) high latitudes. Thus, benthic warming in past climates is thought to indicate high-latitude warming, and similarly for other constituents.

The thermohaline circulation is thought to be inherently bimodal, owing to an instability discovered by Henry Stommel. In the subtropics and midlatitudes, net evaporation causes a salt source to occur near the surface. Simple model results show that if high latitude waters became temporarily lighter, and surface waters began flowing more equatorward, the resulting flux of these salty anomalies toward low latitudes might be sufficient to switch the sign of the surface density gradient, causing deep convection to move to lower latitudes, drawing more southward flow and reinforcing the source of dense salty water. The new equilibrium could persist even if the original forcing of the system were restored (this instability is summarized well in Saltzman). It is not known whether more realistic models have the same instability, but many GCM’s do show that thermohaline circulations are easily altered.
Figure 1

Figure 2

10.2 Average ocean surface circulation.

10.26 Deep circulation below 2,000 m. The regions where three short arrows converge (near Greenland and the Antarctic) are the input locales for sinking deep waters. In addition, there is a sinking of water at the Antarctic Divergence. (After Stommel, 1958, see Further Readings)
**Figure 3**

Vertical profiles of temperature (T, °C), salinity (S, %), and potential density ($\rho_l$, kg m$^{-3}$) at Ocean Station P, 50°N, 145°W, on June 23, 1970 showing the mixed layer in the top 50 m. The hatched area shows the change since May 19, 1970 and indicates the springtime warming and thinning of the mixed layer. [From Denman and Miyake (1973). Reprinted with permission from the American Meteorological Society.]

**Figure 4**

Deep-water flow in the Atlantic Ocean inferred from temperature, salinity, and oxygen measurements. [Adapted from Dietrich et al. (1980). Reprinted with permission from Wiley and Sons, Inc.]