Ocean Surface Currents

Introduction to Ocean Gyres

One of the primary goals of physical oceanography is to know the average movement of ocean water, everywhere around the globe. Besides knowing the average flow, it is also very useful to know how much this flow can change over a course of a day, over a year, over ten years, and longer. Ocean currents are organized flows that persist over some geographical region and over some time period such that water is transported from one part of the ocean to another part of the ocean. Currents also transport plankton, fish, heat, momentum, and chemicals such as salts, oxygen, and carbon dioxide. Currents are a significant component of the global biogeochemical and hydrological cycles. Knowledge of ocean currents is also extremely important for marine operations involving navigation, search and rescue at sea, and the dispersal of pollutants.

It is quite evident from observations of ocean flow that the wind moves water, and that the wind is one of the primary forces that drive ocean currents. In the early part of the 20th century, a Norwegian scientist, Fridtjof Nanson, noted that icebergs in the North Atlantic moved to the right of the wind. His student, V. Walfrid Ekman, demonstrated that the earth's rotation caused this effect and in particular, that the Coriolis force was responsible and in the Southern Hemisphere, it causes water to move to the left of the wind. One of the primary results of Ekman dynamics is that the net movement of water, forced by large-scale winds, are to the right (left) of the wind in the Northern (Southern) Hemisphere. This is a surprising result since one would guess that water moves in the direction of the wind, and a quick glance at wind and current data would also indicate this. For example, the Gulf Stream flows eastward, in the direction of the overlying westerly winds (winds flowing from west to east). However, the story is more complicated than this.

Winds accelerate (near-)surface fluid particles by imparting momentum to the fluid through surface stresses. At first, particles move in the direction of the wind. As time goes on, the earth's rotation deflects the particles to the right/left in the Northern/Southern hemispheres, respectively. The large-scale mass field adjusts so that there is an approximate geostrophic balance between the pressure gradient force and the Coriolis acceleration.

The Coriolis force varies over the globe as a function of latitude, being zero at the equator, a minimum at the S. Pole and a maximum at the N. Pole. In the late 1940s, Henry Stommel showed that this variation of the Coriolis force was responsible for the observed fact that western boundary currents, such as the Gulf Stream and the Kuroishio, are much narrower and faster than eastern boundary currents, such as the California Current and Canary Current. Both of these western boundary currents move significant amounts of warm waters northward and are important in transporting the excess heat the earth receives in the tropics towards the poles. Oceanic gyres are not symmetric due to faster currents on their western boundaries.

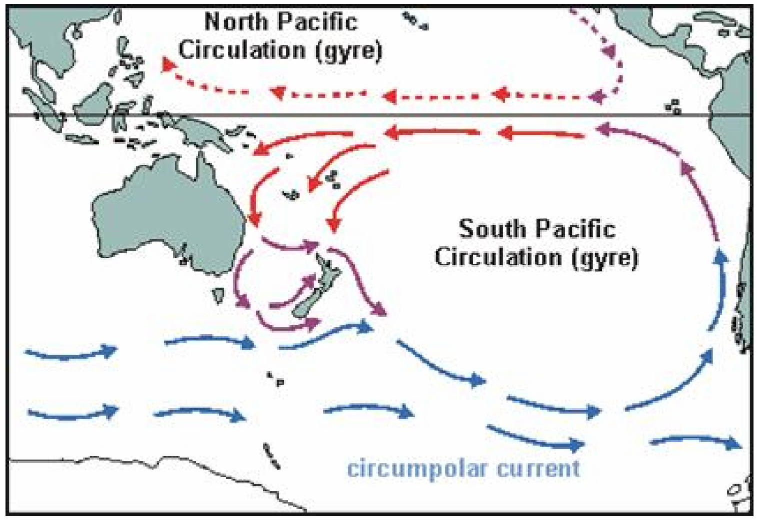

Figure 1: The westerly winds, that blow over most of the U.S., forces a net movement of water to the south, due to Ekman dynamics. The easterly winds, that blow over the (sub)tropical Atlantic, forces a net movement of water to the north, due to Ekman dynamics. There is a convergence of mass and a resulting high-pressure system, known as the subtropical gyre, is formed. The Coriolis acceleration sets up a clockwise gyre circulation around the high pressure. Be sure to correlate your schematic with wind patterns and with areas of low and high pressure known to exist in the atmosphere. In addition, illustrate the western-intensification of ocean currents.

Another way to get pressure differences in a fluid is through density differences in the fluid. The density of ocean water is primarily determined by its temperature, salinity, and the pressure of the surrounding water. Typical variations in salinity and temperature lead to density differences that are two to three orders-of-magnitude smaller than the wind-driven air-water density differences. When water is sufficiently cooled, at polar latitudes, by cold atmospheric air, it gets denser and sinks. The vertical sinking motion causes horizontal water motion as surface waters replace the sinking water. This is one example of what oceanographers call thermohaline flow. The large-scale flow pattern that results from the sinking of water in the Nordic and Greenlans Seas and around Antarctica is called the oceanic conveyor belt (figure 2a).

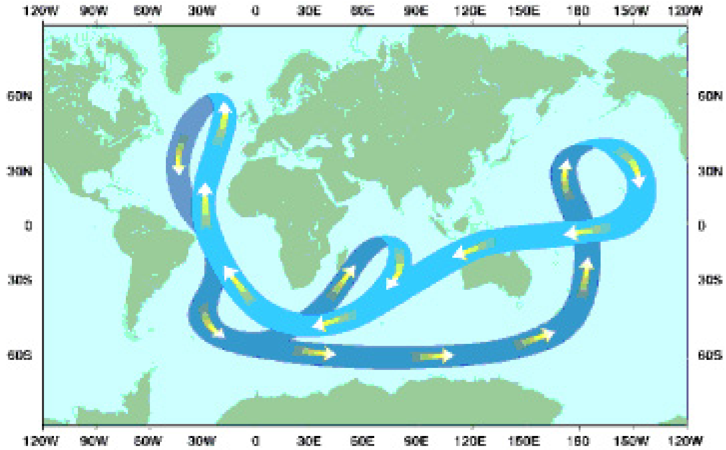

Figure 2a

Another example of thermohaline flow occurs in the Mediterranean Sea in summer when water gets heavier due to strong evaporation that transports fresh water into the atmosphere, feeding the hydrological cycle, and leaves salts behind that make the water denser and it sinks. This salty water, produced in the Mediterranean Sea, can be found in the Atlantic Ocean at depths of 1000 to 1500 m (figure 2b).

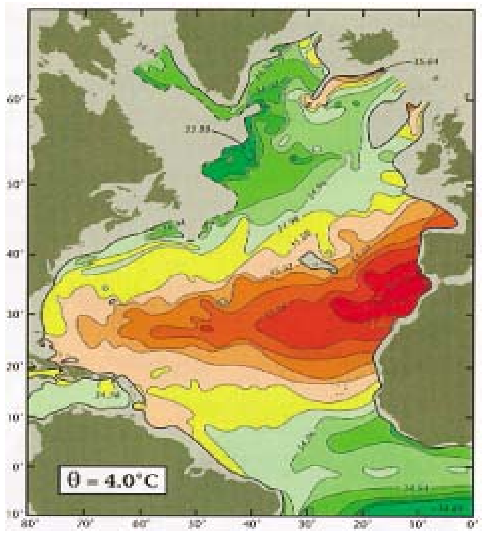

Figure 2b

Figure 2: (a) A cartoon of the global thermohaline circulation. Most of the poleward transport of warm waters occur along the western boundaries and the sinking of dense surface waters occur in relatively small regions. The upwelling of water occurs basin-wide and is most pronounced in regions with divergent Ekman transport. (b) The distribution of salinity on the four degree (Centigrade) potential temperature surface illustrates the Mediterranean salt tongue. High salinity water, formed by evaporation in the Mediterranean Sea, spills over the sill at Gibraltar, mixes with North Atlantic water, and spreads out thousand km across the basin.

The other major driving mechanism for ocean flow is due to tides primarily generated by the moon and sun. In the study of open ocean currents, this part of the flow is usually considered noise. In coastal areas, tidal flow is usually the dominant flow component, and its prediction is important for navigating shipping channels in and out of major ports.

Ocean Surface Currents – Glossary

Physical Oceanography, like all sciences, has its own jargon or special terms. This glossary contains short definitions of the oceanographic jargon used to describe ocean surface currents on this web-site and in the cited books and papers.

A

Advection vs Convection

Historically, these terms were used interchangeably and denote the macroscopic transport (or movement) of a fluid and its properties (temperature, salinity, oxygen, etc.) by the fluid's organized velocity field. Common usage now is that **Advection** is the horizontal transport of a fluid and its properties and **convection** is the vertical transport of a fluid and its properties. In many important ocean and atmospheric phenomena, convection is driven by density differences in the fluid, e.g. the sinking of cold, dense water in polar regions of the world's oceans; and the rising of warm, less-dense air during the formation of cumulonimbus clouds and hurricanes. Thermal convection, or **conduction**, is one of the three primary processes, that redistributes heat in a fluid. The other two are radiative (wave process) and diffusive, that due to the random motion of the fluid. In ocean and atmospheric fluids, diffusion is dominated by turbulent process, that are faster and more efficient than molecular processes.

Altimeters are instruments for measuring elevation. Space-borne altimeters aboard the TOPEX/Poseidon satellite are used to measure sea surface height, relative to an assumed geoid. Sea surface height estimates derived from the Topex-Posiedon mission, from 1,336 km away in space, have a random error of 2-3 cms. Unfortunately for oceanographers, uncertainties in the geoid are large and the resulting bias error swamps the oceanographic signal. Nevertheless, sea surface height anomaly (SSHA) maps, constructed by removing a long-term mean that is a function of longitude and latitude, are good indicators of ocean variability. See http://topex-www.jpl.nasa.gov/overview/overview.html for an overview of satellite measurements of sea surface height.

Advanced Very-High Resolution Radiometers (AVHRR) are sensors aboard the NOAA polar orbiting satellites that measure energy at different frequencies in the visible and infra-red bands. These "skin" (upper few mm of the ocean near-surface) measurements are calibrated with in-situ ocean temperature measurements, mostly from the oceanic mixed-layer, to produce estimates of sea surface temperature. There are Local Area Coverage (LAC) and Global Area Coverage (GAC) data with 1 km and 4 km, horizontal resolution, respectively.

B

Barotropic vs Baroclinic

Barotropic is the depth-independent part of the flow. In classic wind-driven ocean circulation theory, it is the flow that results from, or is in balance with, a sea surface slope. The barotropic component of a flow has also been defined as the depth-averaged flow and the flow at the zero-crossing depth of the first baroclinic mode. **Barotropic Instability** is the process in which mesoscale turbulence uses the kinetic energy of the mean flow to grow. This process occurs in regions of strong ocean currents like western boundaries and along the Equator. **Baroclinic** is the depth-dependent part of the flow. It is the component of the flow that results from the density distribution of the fluid. It is the component of flow that acts to cancel the sea surface flow. (ADD GS temperature transect figure). **Baroclinic Instability** is the process in which mesoscale turbulence uses the available potential energy contained in stratified fluids. This process occurs in regions with large vertical gradients in buoyancy due to temperature and salinity differences.

Bottom water is the water found at the deepest depths of the ocean. **Antarctic Bottom Water** (AABW), formed by deep convection primarily in the Weddell Sea, is characterized by an average temperature of -0.4 C and a salinity of 34.66. North Atlantic Deep Water (NADW) is the major source of deep water for the Atlantic Ocean and is formed by winter-time convection in the Norwegian, Greenland, and Labrador Seas.

Brackish water is water that is not fresh, but is not salty like ocean water. It is often characterized by a dirty color, small amounts of salts, and is heavily influenced by the tides.

Brine is water containing relatively large amounts of salts. Brine water is created in areas of strong evaporation, like the Dead Sea, and in polar regions, when salt is ejected from water during freezing.

C

Cold-core vs Warm-core Rings

Rings are oceanic vortices formed when a current with a large meander wraps around on itself and detaches. **Cold-core rings** are large eddies that have a core of cold water. Cold-core rings are found south of the Gulf Stream). **Warm-core rings** are large eddies that have a core of warm water (Warm-core rings are found north of the Gulf Stream).

Cold surface currents come from polar and temperate latitudes, and they tend to flow towards the equator. Like warm surface currents, they are driven mainly by atmospheric forces and are influenced by the earth's rotation. The E. Greenland Current, Labrador Current, Malvinas Current, and Benguela Current are important cold surface currents in the Atlantic Ocean.

Convergence vs Divergence

Mathematically, divergence is the net gain or loss of fluid per unit volume per unit time and is given by the dot product of the gradient operator and the velocity vector of the fluid. An incompressible fluid, which is an excellent approximation for the study of ocean currents, has zero divergence. Common usage for the surface of the ocean is that **Convergence** is the accumulation of water particles, and water sinks or is down-welled. Weed lines, that are great for fishing, can be, and oceanic surface drifters are, usually found in convergence zones. **Divergence** of surface waters is indicated by surface drifters leaving an area. Upwelled water, that is usually colder and nutrient-rich, from below replaces the diverging surface flow.

Currents are the coherent horizontal movement of water. **Density currents** are driven by gravity. Density differences in a fluid in a gravitational field leads to pressure differences that drive flows. Examples of density currents are turbidity currents or the thermohaline circulation.

Geostrophic currents are controlled by a balance between a pressure gradient force and the Coriolis deflection. Geostrophic currents flow along isobars, in contrast, to our everday experience of fluids flowing from high pressure to low pressure. Large-scale mid-latitude ocean (and atmospheric) flow are in approximate geostrophic balance. The other significant component of large-scale ocean circulation flow is wind-driven and is known as Ekman (see below) flow.

D

Diffusion is either characterized as molecular or turbulent. Molecular diffusion results from the random motion of molecules and it leads to a homogenization of fluid properties if given enough time. Turbulent diffusion involves motion that results from the random motion of small-scale coherent features. These features, usually not resolved by measurements, are efficient stirrers and lead to ocean and atmospheric mixing rates that are much larger than those from molecular diffusion. The modeling of turbulent diffusion is one of the outstanding problems in applied physics.

Downwelling regions are due to the convergence of surface waters and are areas where water sinks. Less dense particles, that can not sink, will convergence on the surface, forming weed- and debris lines.

E

Eddies is a term that has been used to denote all time-varying mesoscale ocean phenomena such as planetary waves and oceanic vortices. Some authors reserve the use of this term for closed circulation features like Gulf Stream and rings and other mesoscale vortices.

Ekman flow is named after the pioneering work of the Swedish Oceanographer, V.W. Ekman, who laid the foundation for dynamical theories of wind-driven ocean circulation while under the guidance of Vilhelm Bjerknes and Fridtjof Nansen from Norway. He derived the steady-state solution for the problem of a constant wind blowing on an infinite slab of water. This solution, known as the **Ekman spiral** (add figure), has a flow that begins 45 degrees to the right (left) of the wind in the N. (S.) Hemisphere and rotates (counter-) clockwise with depth. **Ekman transport** is the total average flow, integrated over depth, and is 90 degrees to the right (left) of the wind in the N. (S.) Hemisphere. It is the convergence and divergence of Ekman transport and the resulting flow that set up the large-scale ocean gyres.

F

G

The **geostrophic balance** is a balance between the horizontal pressure gradient force and the Coriolis acceleration. The geostrophic balance is the dominant force balance for large-scale ocean and atmospheric flows. This balance leads to the counter-intuitive result that water (and air) flow along lines of constant pressure and not from high to low pressure.

Gyres are "circular", large-scale, ocean flow patterns that result from wind forcing, buoyancy forcing, and the Coriolis acceleration. Since the Coriolis acceleration changes with latitude, gyre circulations are not symmetric and the flow on the western boundaries is stronger. Subtropical gyres are found in all the world's oceans at mid-latitudes and they have a clock-wise circulation in the northern hemisphere and counter clock-wise circulation in the southern hemisphere. Subpolar gyres have the opposite circulation and are found poleward of subtropical gyres. Recirculation gyres are flows associated with major ocean currents and consists of water that recirculates in a closed pattern around most of the ocean basin. Large-scale recirculation gyres are associated with fast western boundary currents (Worthington Fig). Mesoscale recirculations are associated with meandering currents.

H

Hydrostatic pressure is the pressure at some point in a fluid that results from the weight of the fluid above. The **hydrostatic balance** for a fluid column of height H, at rest, is,

$$P = md * g * H,$$

where P is pressure, g is the magnitude of the gravitational acceleration and md is the mean density of the fluid volume. This is an excellent approximation for mesoscale and large-scale ocean flows. Nonhydrostatic flows contain significant vertical velocities that vary in space and time.

I

Intermediate water is the water found at great depths in the world's oceans. It lies above the deepest bottom waters and is the result of sinking water that does not have sufficient density to make it all the way to the bottom. Examples include Antarctic Intermediate water (AAIW) with a salinity of 34.2 and temperatures between 2 and 4 C. AAIW is a subpolar mode water found above NADW in the tropical Atlantic and S. Atlantic. AAIW mixes with AABW near its formation site and mixes with salty, S > 36.5, Meditterian waters at depths between 1500 and 2000 m near its northern extent. Meditterian water is an intermediate water mass formed by strong evaporation in the Meditterian Sea. Water with salinities greater than 38.0 flow down the still at Gibraltar to depths greater than 1000 m and mixes.

One way to analyze ocean data is to the plot the value of temperature, for example, as a function of either longitude, latitude, depth, distance from coast, or along your transect. Oceanographers then connect all locations where temperature is constant, say ten degrees, by drawing a line or surface through these points.

> **Isobars** is a contour (or line) of constant pressure.
> **Isohalines** is a contour (or line) of constant salinity.
> **Isopycnal** is a contour (or surface) of constant density.

Isotherm is a contour (or surface) of constant temperature.

J

K

L

M

Meanders are large-amplitude wave-like features evident in ocean currents. They can either propagate in the direction of the current (small meanders), remain stationary, or propagate against the direction of the current (meanders with long wavelengths). In strong currents, like the Gulf Stream, meanders can grow and pinch off and form either cold-core or warm-core rings.

Measurements of ocean current are collected by a variety of methods. One popular way to measure ocean currents is to determine the water's velocity at one fixed place in the ocean. This type of measurement is called Eulerian, in honor of the Swiss mathematician Leonhard Euler. This is typically accomplished by the use of a electro-mechanical current meter (which measures the velocity at a single depth) or Acoustic Doppler Current Profiler (ADCP) (which can provide a profile of velocity with depth). Current meters are usually on a mounted on a wire of a mooring, which is deployed from a ship, and ADCPs can be mounted on a mooring, the bottom, or the underside of a vessel. Both will provide a time series of the velocity of the ocean's water at a single geographic location. Current measurements are also obtained using radar-based measurements.
Another direct way to measure ocean currents is by tagging a water material with either floats or dyes. This viewpoint of following a tagged water parcel is called Lagrangian, named in honor of Joseph Louis Lagrange, a French mathematician. (Near-)surface ocean currents are measured by so-called drifters, which is a buoy which rides at the ocean surface and is usually drogued at some depth to negate the direct effects of wind on the buoy itself. Tracking this drifter (by satellite, radar, radio, sound, etc.) will give a description of the ocean current. Other examples of this type of measurement are SOFAR, RAFOS, and (P)ALACE, floats.
Other measurements techniques including using ship-drift estimates and indirect methods based on the thermal wind relationship.

N

O

P

Q

R

S

Sargasso Sea is the area of the N. Atlantic ocean enclosed by the subtropical gyre circulation. The Sargasso Sea is east of the U.S. and south of the Gulf Stream. It is relatively warm, salty and is populated by many oceanic eddies.

Scales are the characteristic size of organized fluid flows. A spatial scale of an oceanic vortex (eddy, ring) is its radius. A temporal scale of a vortex is its rotational period. A spatial scale of a wave is its wavelength. A time scale of a wave is its period. Scales for vertical motion is usually determined by either the depth of the Ekman layer, depth of the main thermocline, or the bottom depth. Horizontal scales for currents are given by the width of the current or by its wavelength, i.e., the distance between successive meander crests (or troughs). The scale of turbulent fluid flow is usually given by the e-folding scale (distance or time in that the autocorrelation function of the pressure/velocity field decreases by 1/e (37%) of its initial value), where the autocorrelation function becomes zero (zero-crossing scale) or the integral time scale calculated by integrating the autocovariance function.

Mesoscale (or synoptic) flow is the oceanographic equivalent of atmospheric weather. Time scales are on the order of a week to months. Space scales are on the order of tens of km to hundreds of km.

Large-scale flow is the oceanographic equivalent of atmospheric climatology. Time scales are on the order of one year to many years. Space scales are on the order of the size of ocean basins and range from many hundreds to a few thousand of km.

Sverdrup (Sv) is the basic unit of volume transport used in physical oceanography and is equal to one million cubic meters of water flowing per second. This unit is named after author and Scripps Director Harald Sverdrup. One Sv is about the average amount of water that flows in all of the world's rivers. During spring thaw, runoff from melting snow and rain from strong seasonal storms increases the amount of river flow to 2 Sv. In comparison, the transport of the Fl current is about 30 Sv and the peak flow of the Gulf Stream has a transport of approximately 150 Sv.

T

Thermohaline circulation is the flow of water induced by differences in temperature (thermo-) and salinity (haline). These differences in water properties leads to density differences. **Deep water** forms when sea water entering polar regions cools and freezes. This process leaves colder, saltier and denser water that can sink to great depths and flow into the ocean basins. Surface water must replace the sinking water leading to a large-scale poleward surface flow in the North Atlantic. **A global "conveyor belt"** is a simple model of the large-scale thermohaline circulation. Deep-water forms in the North Atlantic, sinks, moves south, circulates around Antarctica, and finally enters the Indian, Pacific, and Atlantic basins. This water is upwelled and returned in a surface circulation (ADD figure). It can take a thousand years for water from the North Atlantic to find its way into the surface waters of the North Pacific.
A **tracer** as the name implies, is anything that allows us to follow or 'trace' a process. For example, tracers can be used to follow a water mass as it flows from the ocean surface into the

interior. Almost any property we can measure in the ocean can be considered a tracer as its distribution is due to some oceanographic process. For example, dye injected into water at the surface can be seen spreading through the water column and can be considered a tracer. Tracers can be classified into different types: 1) stable, conservative tracers, for example, salinity or potential temperature. A **conservative** tracer is one that can only be altered by mixing in the ocean interior. Potential temperature and salinity can be used to identify water masses for this reason. These properties are set by processes occurring in the ocean boundary, so once a water mass is isolated from the atmosphere below the mixed layer, it can be identified by its temperature and salinity. Another type of tracer includes: 2) stable, non-conservative, which can be altered by physical, chemical or biological processes occurring within the ocean. An example of this type of tracer is O2 or CO2. Dissolved oxygen is produced by phytoplankton photosynthesis and is consumed throughout the water column by respiration and bacterial oxidation of decaying material Two other classifications of tracers include: 3) radioactive, conservative (e.g. 222Rn) and 4) radioactive, non-conservative (eg.14CO2).

Transport is the amount of water flowing per unit time. Transport values are either given as a volume transport, UA, where U is the average velocity perpendicular to the plane with surface area A. Its units are m^3/s. Since most ocean currents involve volume transports of millions to hundred millions m^3/s of water, physical oceanographers use units of Sverdrup, 1 Sv = 1,000,000 m^3/s. Mass transport is calculated as mdUA, where md is the mean density and has units of kg^3/s. The Florida Current is bounded by the Florida Coast to its west and the Bahama Islands to its east. If you were to measure all the water flowing between Miami, FL and the Bahamas, from top to bottom, the mean volume transport would probably be around 30 Sv. That is, on the average, 30,000,000 m^3 of water is flowing, every second, between Miami and the Bahamas.

U

Upwelling brings cold, nutrient-rich water from the depths up to the surface. Earth's rotation and strong seasonal winds push surface water away from some western coasts, so water rises on the western edges of continents to replace it. Marine life thrives in these nutrient-rich waters. **Coastal upwelling** is usually induced by Ekman transport (see below). Large-scale **equatorial upwelling** results at the equator due to the divergence of the Ekman transports at the Equator. The trade winds predominantly blow from east-to-west in the tropics. In the N. Hemisphere, this leads to an Ekman transport poleward to the north and in the S. Hemisphere, poleward to the south. Deeper, colder and more nutrient rich waters replace the poleward moving surface waters.

V

W

Warm surface currents invariably flow from the tropics to the higher latitudes, driven mainly by atmospheric winds, as well as the earth's rotation. **Subtropical western boundary currents**, such as the Gulf Stream and Kuroshio, are warm, fast surface currents that transport a lot of water and heat of tropical origin to subpolar regions. This process is extremely important for maintaining the earth's heat balance.

Water masses are fairly large volumes of water with similar, nearly homogeneous, physical and chemical properties (temperature, salinity, oxygen, silicon, etc.). These properties are either acquired at the ocean surface in regions of strong atmospheric forcing or are the result of homogenization by oceanic mixing. Major examples include North Atlantic Deep Water (NADW), Antarctica Bottom Water (AABW) and the central or common waters of the Pacific and Indian Ocean. Tracking water masses from their formation regions to where you observe them is one way oceanographers learn about ocean circulation and mixing.

Wind-driven circulation is the large-scale oceanic circulation that results from the actions of the wind. There are two-components, a directly-driven Ekman component and an indirect component, due to the divergences and convergences of the Ekman transport that either leads to water piling up, creating a high pressure system in the ocean or to a low pressure system where surface waters diverge. The indirect component is in geostrophic balance with these pressure systems and the indirect flow is much larger than the directly driven flow

X

Y

Z