GEO/OC 103
Exploring the Deep…

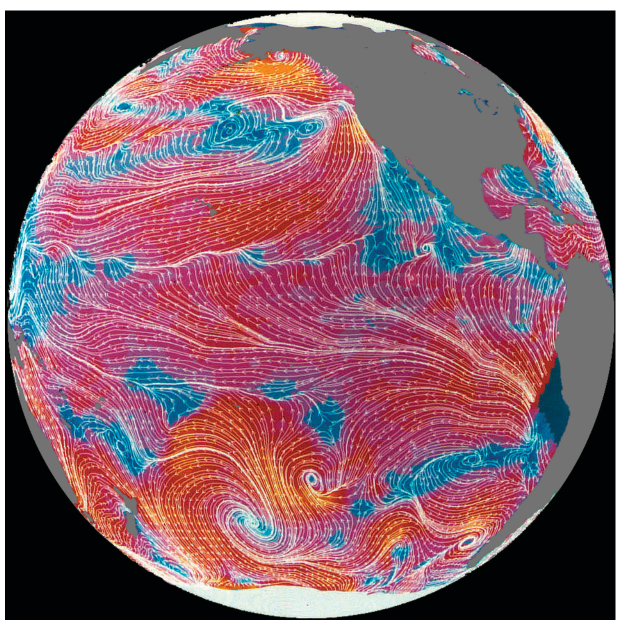
Lab 4

Unit 2
Ocean Currents

In this unit, you will

- ***Investigate the forces that drive surface currents in the world's oceans.***
- ***Identify major ocean gyres and their physical properties — temperature, speed, and direction.***
- ***Correlate current direction and speed with global winds.***
- ***Examine ocean salinity and temperature patterns and their relationship to deep-water density currents.***

NASA



NASA SEASAT satellite image showing average surface wind speed (colors) and direction (arrows) over the Pacific Ocean.

Warm-up 2.1

A puzzle at 70° N

"Common sense tells us that temperatures increase closer to Earth's equator and decrease closer to the poles. If this is true, the pictures below present a strange puzzle (Figure 1). They show two coastal areas at about the same latitude but on opposite sides of the North Atlantic Ocean. Nansen Fjörd, on the left, is on Greenland's eastern coast, while Tromsø, right, lies on the northwestern coast of Norway. These places are at roughly the same latitude, but their climates could hardly be more different.

Figure 1. A summer day at Nansen Fjörd, on the eastern coast of Greenland (left) and in Tromsø, on the northwestern coast of Norway (right). Both locations are near latitude 70° N.

1. Why do you think the temperatures at the same latitude in Greenland and Norway are so different?

Since the first seafarers began traveling the world's oceans thousands of years ago, navigators have known about currents — "rivers in the ocean" — that flow over long distances along predictable paths.

In 1855, Matthew Maury wrote about the Gulf Stream current, which flows off the east coast of Florida.

> *"There is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows; its banks and its bottom are of cold water, while its current is of warm; the Gulf of Mexico is its fountain, and its mouth is the Arctic Sea. It is the Gulf Stream. There is in the world no other such majestic flow of waters."*
>
> —Matthew Maury, *The Physical Geography of the Sea and Its Meteorology*

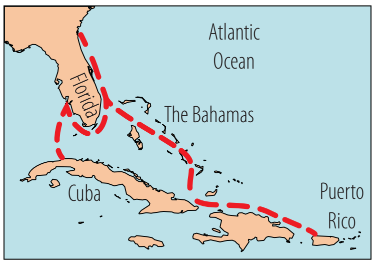


Figure 2. Ponce de León's route.

Maury was not the first person to notice the Gulf Stream. In March 1513, the Spanish explorer Juan Ponce de León left the island of Boriquien (Puerto Rico) in search of the island of Bimini and the legendary Fountain of Youth (Figure 2). Instead, he landed on what is now Florida. After sailing northward along Florida's east coast, he turned around and headed south. While sailing in this direction he discovered that even under full sail with a strong breeze at his back, his ship moved backward in the water! His solution was to maneuver his ship closer to shore and out of the current.

Two hundred fifty years later, Benjamin Franklin, then serving as Deputy Postmaster General, received complaints that ships delivering mail between Boston and England took as long as two months to make the return trip back to America. Merchant ships, which were heavier and took a less direct route than the mail ships, were making the trip back from England in just six weeks.

NOAA

Figure 3. Franklin and Folger's chart of the "gulph stream" current.

With help from his cousin Timothy Folger, a whaling captain, Franklin determined that the returning mail ships were sailing against a strong current that ran along the eastern seaboard and across the Atlantic to the British Isles. Whalers knew about the current, whose plankton-rich margins attract whales, and used or avoided the current as needed to speed their travels. Franklin and Folger offered their chart of the *gulph stream* (Figure 3) to the mail-ship captains, with the promise of cutting their return time in half, but they were largely ignored.

2. What are some factors that might cause ocean water to flow in currents like the Gulf Stream?

3. Explore the idea of what causes ocean currents by comparing how water behaves in a bathtub or small pond, compared to water in the ocean. In Table 1, make a list of differences between the conditions present or acting on a bathtub of water and those in an ocean, and explain how those different conditions might cause currents.

Table 1 — Comparing bathtub water with ocean water

Condition	Bathtub conditions	Ocean conditions	Why this characteristic might cause currents to form
bottom and surface features			
wind			
volume of water			
salinity			
uniformity of temperature			
Coriolis effect (see note at left)			

4. Which of the conditions above do you think are the most important in the formation of ocean currents? Explain.

Coriolis effect

As a fluid like air or water moves over Earth's surface, the planet rotates under it. Relative to the solid Earth, the flow appears to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. In this way, the Coriolis effect influences the rotation of large-scale weather and ocean-current systems. The Coriolis effect does not influence water in sinks or toilets because the distances involved are very small.

To learn more about the Coriolis effect, point your Web browser to:

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/crls.rxml

NASA/SeaWiFs

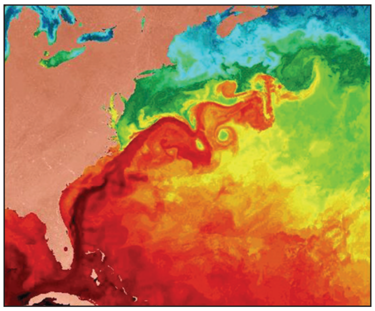


Figure 4. Satellite image of sea-surface temperatures associated with the Gulf Stream off the east coast of North America. Reds and oranges represent warm water, greens and blues cooler water. The warmest water appears dark brown or almost black in this image.

Early nautical charts depicting the Gulf Stream current were useful, but were not entirely accurate. They often assumed that the Gulf Stream began in the Gulf of Mexico when, in fact, it flows westward from the equatorial Atlantic Ocean, turns northward and flows along the East Coast from Florida to the Saint Lawrence Seaway, and then across the Atlantic toward Great Britain (Figure 4).

5. Maury and Franklin both described the Gulf Stream as a warm surface current—that is, its water is warmer than the surrounding ocean. Do you think the ocean also has cold surface currents? Explain your reasoning.

Despite Maury's assertion that "There is in the world no other such majestic flow of waters," the Gulf Stream is not unique. Surface currents have existed in the world's oceans throughout Earth's history, and have influenced life on our planet in important ways.

6. Describe four ways that surface currents might affect you (or another person), either at sea or on land.

   a.

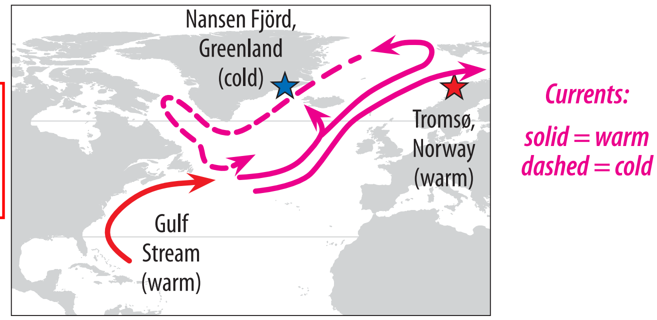
   b.

   c.

   d.

7. Recall the puzzle posed in Question 1 about the extreme climate differences between the coasts of Greenland and Norway. Map 1 shows the location of the Gulf Stream current. On the map, see the locations of other currents

Map 1 — Location of Gulf Stream current



In this unit, you will investigate the forces that drive surface currents and how these currents influence ocean processes and life on Earth.

Reading 2.3

Current basics

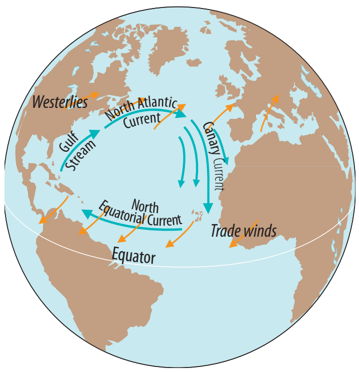


Figure 1. Global winds (orange) and their corresponding surface currents (blue) in the North Atlantic Ocean.

Ocean waters are continuously moving, circling the ocean basins in powerful currents hundreds of kilometers wide, and in swirls and eddies as small as a centimeter across. The primary forces driving the large-scale motions are the sun's energy and Earth's rotation. Energy from the sun warms Earth's surface and atmosphere, generating winds that initiate the horizontal movement of surface water (Figure 1 at left). Vertical movement between the surface and the ocean depths is tied to variations in temperature and salinity, which together alter the **density** of seawater and trigger sinking or rising of water masses. Together, the horizontal and vertical motions of water link the world's oceans in a complex system of surface and subsurface currents often referred to as the **Global Conveyor Belt** (Figure 2). This circulation system plays a vital role in transporting and distributing heat, nutrients, and dissolved gases that support life around the globe.

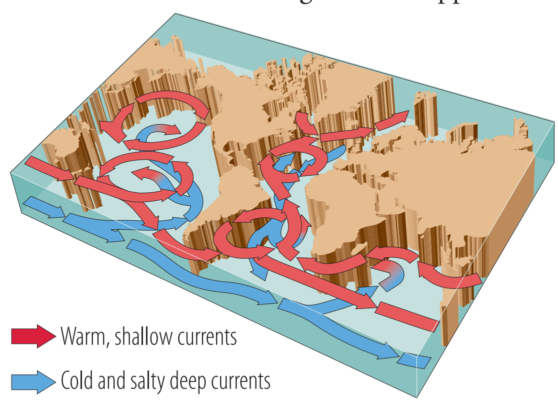


Figure 2. A highly simplified diagram of the Global Conveyor Belt.

density — the mass per unit volume of a substance or object.

$$\text{density (kg/m}^3) = \frac{\text{mass (kg)}}{\text{volume (m}^3)}$$

Structure of the ocean waters

The oceans contain numerous **water masses**, which can be recognized as different by their physical and chemical characteristics such as salinity, temperature, and density. The density of seawater depends on its temperature and salinity, as well as the amount of pressure exerted on it. Water expands as it warms, increasing its volume and decreasing its density. As water cools, its volume decreases and its density increases. Salinity, the amount of dissolved solids (like salts) in the water, alters density because the dissolved solids increase the mass of the water without increasing its volume. So, as salinity increases, the density of the water increases. Finally, when the pressure exerted on water increases, its density also increases.

1. Rank the following types of ocean water from highest density (1) to lowest density (3).
   a. Warm, salty water ______
   b. Cold, salty water ______
   c. Warm, fresh water ______

Changing density

The density of water changes as its temperature or salinity (or both) change.

- If the temperature decreases and/or the salinity increases, the water becomes more dense.
- If the temperature increases and/or the salinity decreases, the water becomes less dense.

photosynthesis — the process by which chlorophyll-containing plants convert sunlight and carbon dioxide to carbohydrates (food) and oxygen (O_2).

Thermocline

The thermocline is a layer of the ocean in which the temperature decreases rapidly with depth. Above the thermocline, the temperature is fairly uniform due to the mixing processes of currents and wave action. In the deep ocean below the thermocline, the temperature is cold and stable.

The characteristics of a water mass typically develop at the ocean surface due to interactions with the atmosphere. Evaporation can increase salinity as fresh water is removed from the ocean and the salts are left behind. Precipitation has the opposite effect, decreasing salinity levels as fresh water is added to the ocean. Processes like **photosynthesis** and the exchange of energy and matter between the ocean surface and the atmosphere can affect the amounts of oxygen and other dissolved gases in the water.

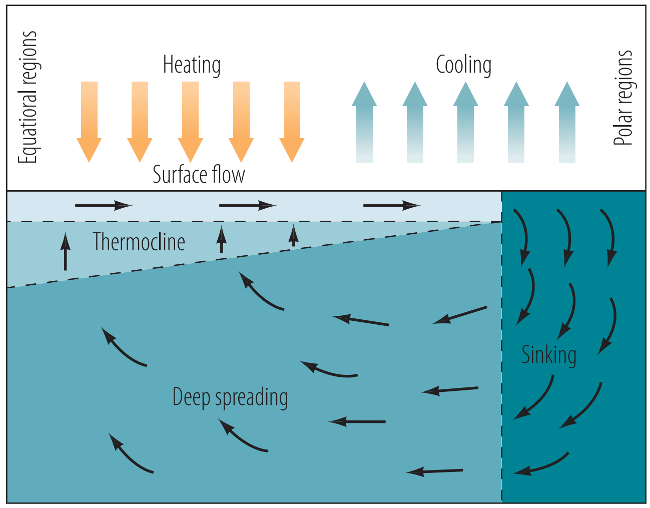


Figure 3. Schematic cross section of ocean from equator to pole.

In addition, water temperature (and thus density) changes rapidly as surface currents transport water masses from the equator to the poles and vice versa. Although the sun's energy is very efficient at warming the upper 100 meters of the ocean, very little solar energy penetrates to deeper waters. Therefore, water temperature decreases rapidly between 100 and 800 m depth. This region of decreasing temperature is called the **thermocline**, and marks the boundary between surface-water circulation and deep-water circulation (Figures 3 and 4).

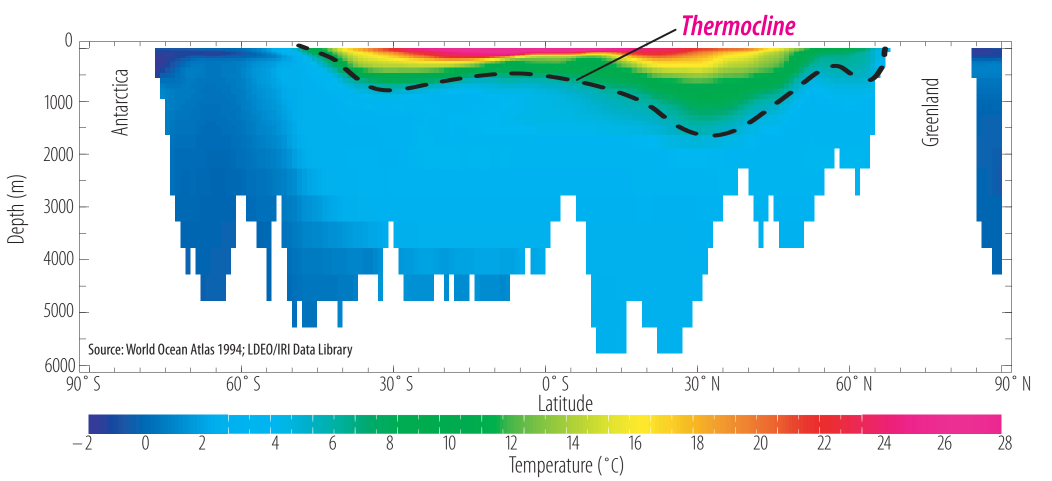


Figure 4. South-north temperature profile of the Atlantic Ocean at 32.5° W longitude. White represents the ocean floor and continents.

2. The water temperature at the base of the thermocline is around 5 °C. Using this information, sketch and label the approximate location of the base of the thermocline in Figure 4.

A similar zone, in which salinity changes rapidly with depth, is called the **halocline** (Figure 5). However, the halocline is not as well defined as the thermocline and in some places does not exist.

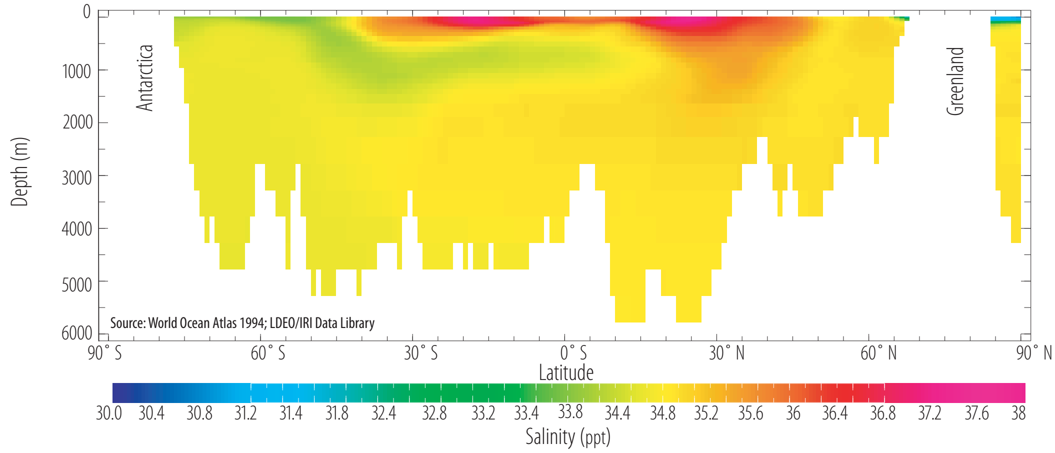


Figure 5. South-north salinity profile of the Atlantic Ocean at 32.5° W longitude. White represents the ocean floor and continents.

Once formed, water masses tend to retain their original characteristics because they mix very slowly with the surrounding water — except in places where the thermocline is very weak. Their distinctive characteristics make it possible to identify their place of origin and track their movements. In fact, it is by tracking differences in the physical properties of water masses that scientists have been able to begin mapping the Global Conveyor Belt.

Wind-driven currents

Winds are created by the uneven heating of Earth's surface by the sun, due primarily to Earth's nearly spherical shape (Figure 6). Surface temperature variations create temperature and pressure differences in the layer of air near the surface. To equalize these differences, air moves from regions of high pressure to regions of low pressure, creating wind.

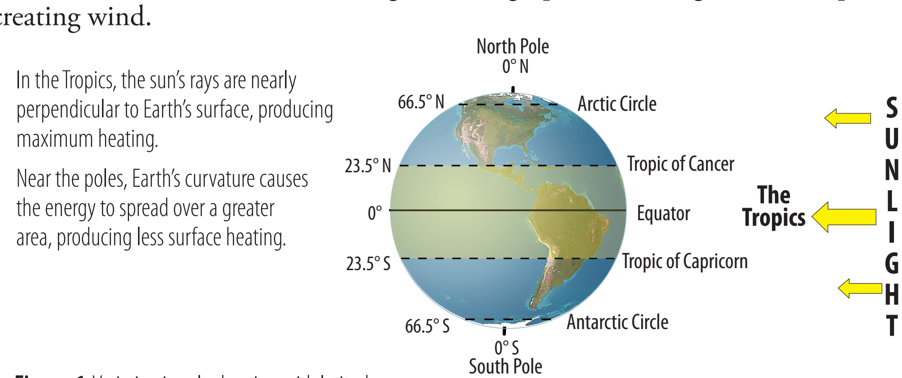


Figure 6. Variation in solar heating with latitude.

Spreading light

When the sun is directly overhead at the equator, the same amount of sunlight that falls on one square meter at the equator would be spread over two square meters in Anchorage, Alaska.

Low pressure belts form where warm air rises, near the equator and around 60° latitude (Figure 7 on the following page); high pressure belts are found where cool air sinks, near the poles and around 30° latitude. Air moving from high pressure toward low pressure creates six global wind belts encircling Earth. These belts shift slightly north and south with the seasons, but they are otherwise permanent features. Strong prevailing winds and solar warming produce ocean surface currents that extend to depths ranging from 45–400 m under typical conditions. This surface layer of currents is called the **Ekman layer**, or the **wind-blown layer**.

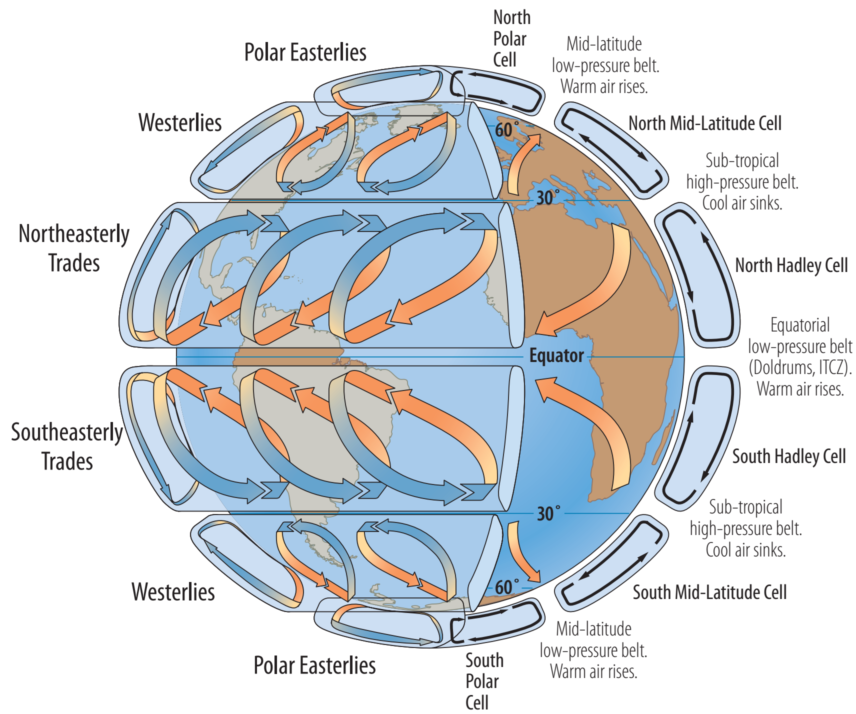


Figure 7. Global wind belts.

Traditional wind names

The global wind belts in Figure 6 are named, by tradition, according to the direction they are *blowing from*. In these materials we name both winds and ocean currents according to the direction they are *blowing toward*. For example, in the Northern Hemisphere, we would describe the direction of the Westerlies as *northeast* (or *NE*).

The Coriolis effect and Ekman transport

Over short distances, winds and the ocean surface currents they generate follow straight paths, but over greater distances they curve due to Earth's rotation. This phenomenon is called the *Coriolis effect*. In the Northern Hemisphere, the Coriolis effect causes winds and ocean currents to veer to the right; in the Southern Hemisphere, the winds and ocean currents curve to the left.

As you learned in Investigation 2.2, Ekman transport is an offset between a current direction and its associated wind. It is useful to think of the Ekman layer as containing many thinner layers of water flowing over one another (Figure 8). In the Northern Hemisphere Ekman transport is deflected to the right and in the Southern Hemisphere Ekman transport is deflected to the left. This phenomenon is caused by the Coriolis effect and the slowing and deflection of water due to friction between successively deeper layers of water. It is theoretically possible for water to actually flow in a direction opposite to the surface current, but this has never been observed. The overall motion of the Ekman layer, referred to as *Ekman transport*, is at an angle of about 90° to the wind direction.

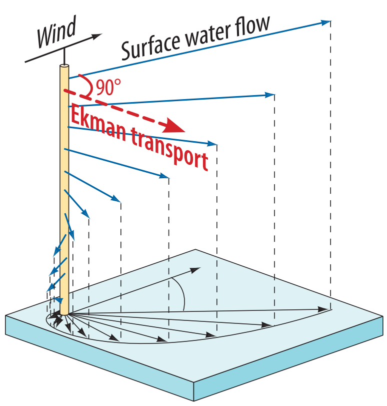
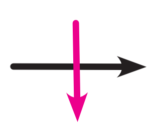


Figure 8. The Ekman spiral. The red arrow represents the net effect, called Ekman transport. Clockwise Northern Hemisphere deflection is shown here. (Southern Hemisphere deflection is counterclockwise.)

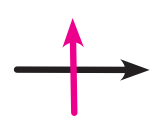
Note: The water does not spiral downward like a whirlpool.

3. If the arrows below represent the prevailing winds somewhere over the ocean in the Northern and Southern Hemispheres, see pink arrow to indicate which direction Ekman transport would cause water to flow.

   a. Northern

   b. Southern

Wind-driven upwelling and downwelling

In nearshore environments, it is common to have winds blowing parallel to shore over the ocean (Figure 9). Ekman transport moves surface water offshore and pulls deep, cold, nutrient-rich water to the surface. This process, known as **wind-driven upwelling**, is restricted mainly to the west coast of continents, and is responsible for the high productivity of nearshore waters.

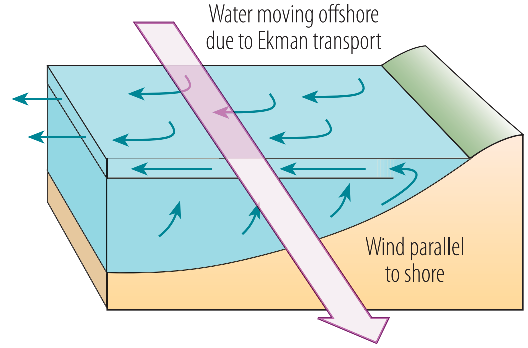


Figure 9. Factors that produce coastal upwelling.

Upwelling occurs in the open ocean near the equator in a similar manner (Figure 10). On both sides of the equator, surface currents moving westward are deflected slightly poleward and are replaced by nutrient-rich, cold water from great depths.

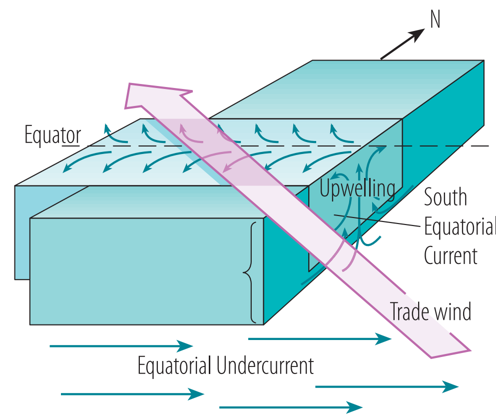


Figure 10. Factors that produce equatorial upwelling.

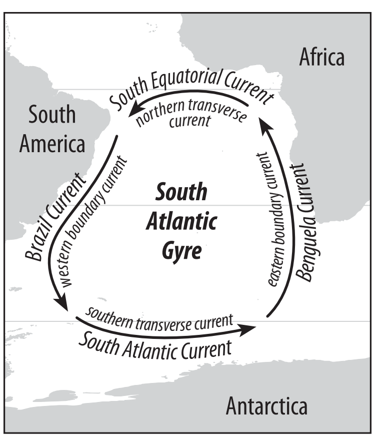


Figure 11. The four boundary currents that form a gyre.

The mechanical action of wind on the currents promotes mixing of the Ekman layer, which tends to deepen the thermocline and promote the upwelling of nutrients. The thermocline, which separates less dense, warm surface water from the more dense, cold water below, is most pronounced at low latitudes and prevents nutrient-rich deep waters from rising to the surface. In contrast, upwelling occurs more readily in high-latitude regions near the poles. These regions receive little sunlight and are not warmed by solar energy. Without a distinct thermocline, upwelling easily brings nutrients toward the surface and promotes mixing.

Surface currents

Gyres play a major role in redistributing the sun's heat energy around the globe. Each gyre consists of four interconnected, yet distinct currents (Figure 11). A pair of boundary currents flows north or south, parallel to the bordering landmasses.

Western boundary currents carry warm equatorial water poleward, while eastern boundary currents carry cooler temperate and polar water toward the equator. These currents interact with the air near the surface to moderate the climate of coastal regions. Within a gyre, boundary currents are connected by transverse currents. Transverse currents move east or west across the gyre's northern and southern edges.

The speed of a current within a gyre is related to the prevailing winds and the location of landmasses. Western boundary currents are narrow but move huge masses of water quickly as the westward-blowing trade winds push water against the eastern edges of continental landmasses (Figure 12).

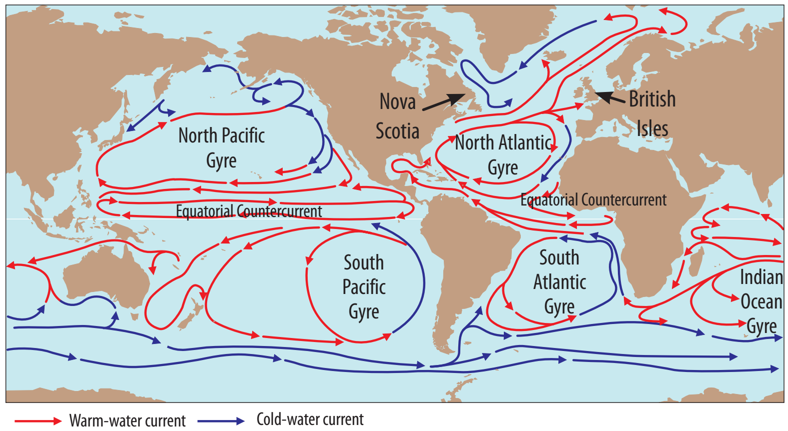


Figure 12. Major ocean surface currents and gyres.

The Coriolis effect and resulting Ekman transport occurring at 90° from the wind direction further enhance the speed of western boundary currents, a phenomenon called **western intensification**. Although most of the water at the equator moves westward then poleward, the low-intensity winds and lack of Coriolis effect at the equator allow for some of the water at the surface to flow eastward in equatorial countercurrents.

Figure 13 shows the currents of the North Pacific Gyre. Use what you have learned about surface currents to answer the following questions.

Kuroshio = kuhr-oh-SHEE-oh

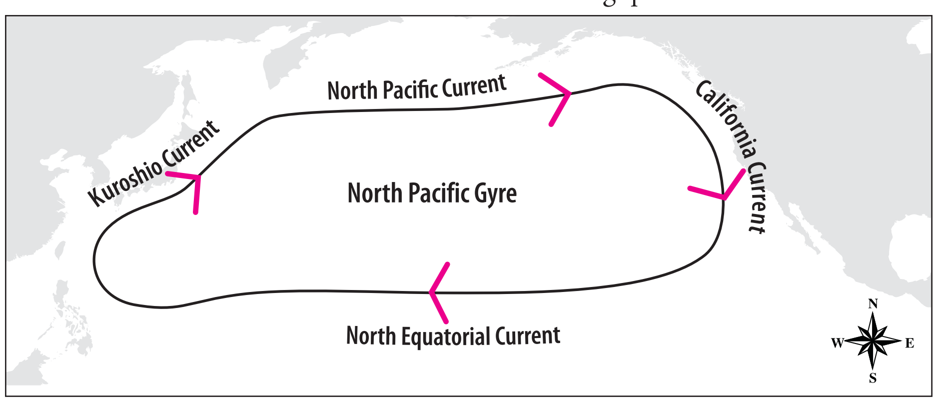


Figure 13. The North Pacific Gyre.

4. Already indicated above for you. Happy birthday!

5. Complete Table 1 on the following page with information about the surface currents of the North Pacific Gyre. For **Heat exchange type**, indicate whether the current is gaining heat (warming) or losing heat (cooling) as it flows.

Table 1 — Boundary currents of the North Pacific Gyre

Type of current	Name	Heat exchange type *cooling / warming*
Eastern Boundary		
Western Boundary		
Northern Transverse		
Southern Transverse		

Density-driven currents

In addition to wind-driven horizontal surface currents, ocean circulation has a vertical component that is driven by differences in water density. When surface water cools or becomes more saline due to evaporation or other processes, its density increases and it sinks either to the bottom of the ocean or to a depth where its density equals that of the surrounding water. This density-driven circulation pattern is referred to as **thermohaline circulation**, and the currents it produces are called **density currents**. The cold water eventually returns to the surface to be reheated and returned to the poles by surface currents, or to mix with other water masses and return to the depths. Thermohaline currents move very slowly—about 1 centimeter per second—10 to 20 times slower than surface currents.

saline—salty [Latin *sal* = salt].

thermohaline—combined effects of temperature [Greek *thermo* = heat] and salinity [Greek *hal* = salt].

Salinity

The average salinity of seawater is 34.7 ppt or **parts per thousand** (also symbolized ‰). That means that a liter of ocean water (a little more than a quart) contains 34.7 grams (~2.5 tablespoons) of various salts.

To learn more about the composition of seawater, click the Media Viewer button and choose **Seawater**.

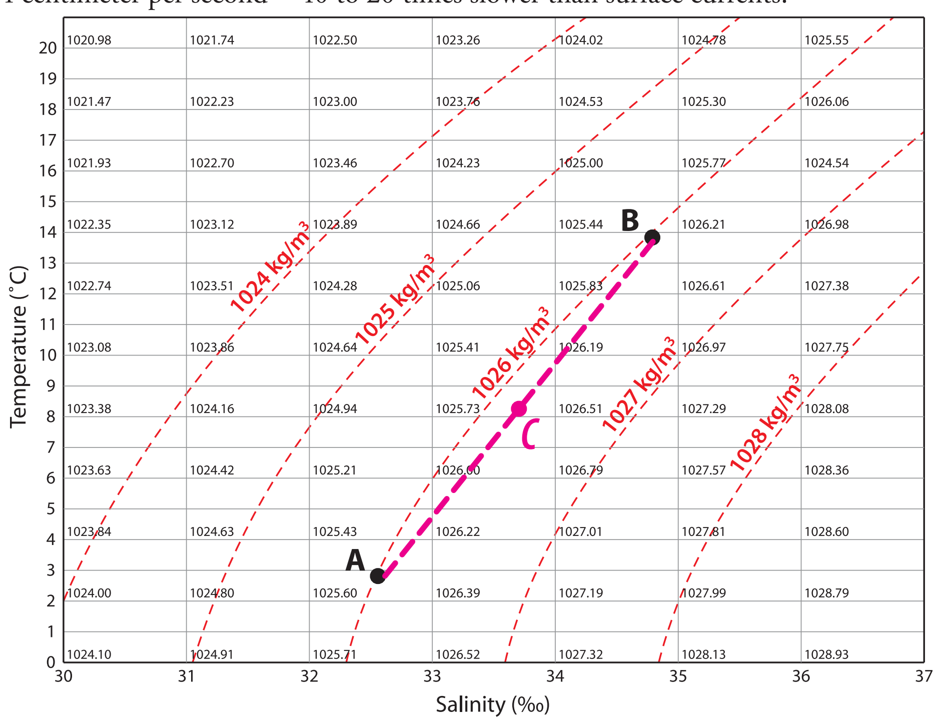


Figure 14. Ocean water Temperature-Salinity-Density chart showing the relationship between temperature, salinity, and density of ocean water. The dashed lines are lines of constant density.

6. Examine Figure 14. What happens to the density of the water as the temperature decreases? (Follow one of the vertical lines of constant salinity downward, and note what happens to the density values.)

7. Use Figure 14 (on the previous page) to determine what happens to the density of ocean water as the salinity increases? (Follow one of the horizontal lines of constant temperature from left to right, and note what happens to the density values.)

Deep currents are generated by relatively small density variations. In fact, the density of seawater must be determined to several decimal places to detect significant differences. The points labeled A and B on Figure 14 represent the salinity and temperature values for two water masses.

8. Use Figure 14 to determine the temperature, salinity, and density of water masses A and B and record them in Table 2.

Table 2 — Mixing of water masses A and B

Point	Temperature *°C*	Salinity *ppt*	Density *kg/m³*
A			
B			
C			

When two water masses of the same density meet, they tend to mix. The temperature and salinity of the new water mass lie somewhere between those of the two original water masses. Imagine mixing equal parts of the two water masses. The temperature and salinity of the new water mass would lie at the midpoint of a straight line connecting point A to point B.

9. Draw a straight line connecting points A and B on Figure 14. Plot the midpoint of the line and label it C.

10. Would the density of the new water mass C be higher or lower than the densities of the two original water masses, A and B?

11. Record the temperature and salinity of point C in Table 2. Use the curved equal-density lines to estimate the density of water mass C and record it in Table 2.

12. Would the new water mass remain at the surface or sink? Explain.

Stability and instability of water masses

When the density of a water column increases with depth, the water column is **stable** and mixing does not occur. Conversely, when the density of a water column decreases with depth, it is **unstable**. As the dense water sinks, it produces turbulence and mixes with the layers beneath it. Instability is caused by an increase in the density of surface water due to a decrease in temperature, an increase in salinity, or both.

High evaporation rates can increase the salinity of the surface water; and low air temperatures can cool the surface water, causing it to become unstable and sink. When sea ice forms near the poles, most of the salt remains in the liquid water, increasing its density and producing instability.

There is also a seasonal aspect to ocean stability. During spring and summer, stability increases as the ocean surface warms. In fall and winter, stability decreases as the ocean surface cools.

Areas of instability can produce complex patterns of stratification and thermohaline and surface circulation in the ocean.

As sea ice forms along the coast of Antarctica, surface water cools and becomes more salty. This process is called brine rejection. This salty water sinks and flows northward along the ocean floor, forming the Antarctic Bottom Water mass (AABW). As winds blow the Antarctic Surface Water (AASW) eastward, the Coriolis effect deflects it toward the north. This causes upwelling of warmer, salty water, the Northern Atlantic Deep Water (NADW). This water mass mixes with the AASW to form the Antarctic Intermediate Water mass (AAIW). Because the AAIW is denser than the surface water (the Subantarctic Water mass or SAAW), it sinks below the SAAW at the Antarctic convergence.

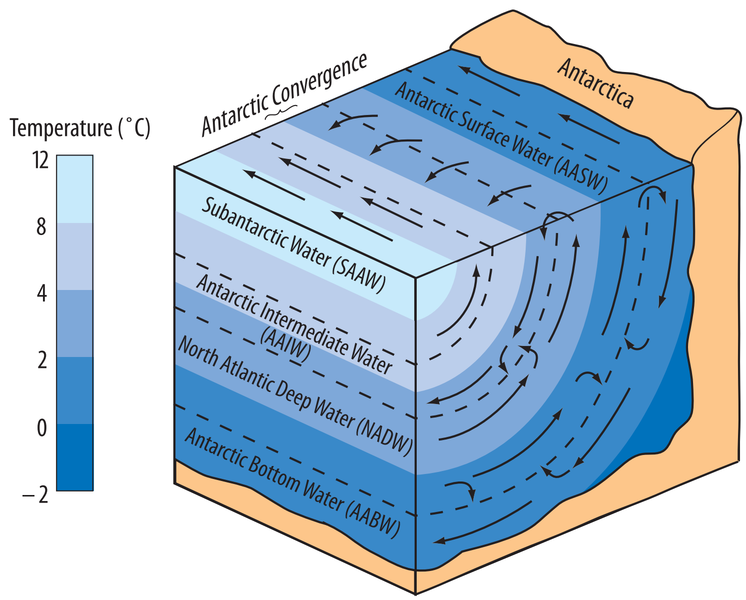


Figure 15. Thermohaline and surface currents off the coast of Antarctica. Colors represent water temperature, and dashed lines represent the boundaries between water masses.

13. Is the water column shown in Figure 15 stable or unstable? Explain.