AMERICAN METEOROLOGICAL SOCIETY



Project Ocean

Wind-Driven Ocean Circulation, Ekman Transport, and Coastal Upwelling

TEACHER'S GUIDE

Project Ocean

This guide is one of a series produced by Project Ocean, a U.S. Office of Naval Research-sponsored initiative of the American Meteorological Society (AMS), in recent partnerships with St. Mary's College of Maryland, Washington College, and the United States Naval Academy. Project Ocean is a continuation of past projects focused on creating and training a network of master teachers to provide peer training sessions in pre-college (K-12) physical oceanographic education. To support these teachers in their teacher training, Project Ocean develops and produces course modules and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

American Meteorological Society
Education Department
45 Beacon Street
Boston, MA 02108
amsedu@ametsoc.org

This material is based upon work previously supported by the National Science Foundation and the U.S. Office of Naval Research (under Awards N00014-20-1-2384 and N00014-23-1-2666).

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation or the U.S. Office of Naval Research.



AMS Peer Training Modules © 2025 by American Meteorological Society is licensed under CC BY-SA 4.0.

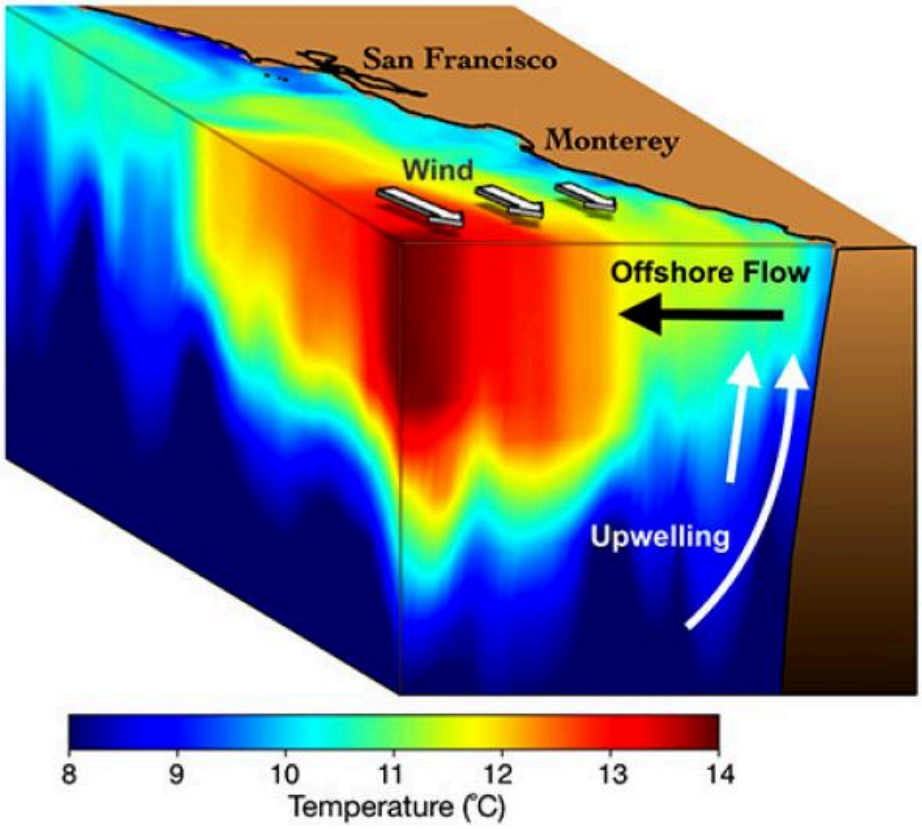


Figure i. Diagram of a scenario that creates upwelling along the California coast. [NOAA]

*"**We must take the current when it serves, or lose our ventures**."*

- William Shakespeare (1564 – 1616)

Module: Wind-Driven Ocean Circulation, Ekman Transport, and Coastal Upwelling
Audience/Grade Level: K-12 Educators

Learning Objectives

After completion of this module participants will be able to:

5. Open Ocean Surface Currents

- Identify the physical laws (e.g., conservation principles) and dominant forces used to describe ocean fluid motion.
- Describe how differential solar heating of Earth's surface drives atmospheric and oceanic circulation, and explain the role of the Sun and Earth's rotation in generating wind patterns and surface currents that transport heat from the tropics toward the poles.
- Describe how wind transfers momentum to the ocean surface and generates surface currents.
- Explain how wind-driven friction transfers momentum through successive layers of ocean surface layer.
- Explain the Coriolis effect, resulting from the Coriolis force, and describe how it influences the direction of surface water movement in the Northern and Southern Hemispheres.
- Describe the Ekman spiral and Ekman transport and their effects on surface water flow.
- Analyze the roles of divergence and convergence in driving upwelling and downwelling.
- Explain how coastal wind patterns influence productivity via upwelling and downwelling.
- Describe equatorial upwelling and its relation to the Coriolis effect and surface current divergence.

6. Open Ocean Surface Circulation

- Distinguish between cyclonic and anticyclonic rotation.

STANDARDS:

Project Ocean Fundamental Understandings:

Open Ocean Surface Currents (5.1-5.16)

Open Ocean Surface Circulation (6.5)

Applicable Ocean Literacy Principles:

1.C, 3.A, 3.B, 6.A, 6.B

Next Generation Science Standards:

Performance Expectations

- 3-ESS2-2. Obtain and combine information to describe climates in different regions of the world.
- 4-ESS2-2. Analyze and interpret data from maps to describe patterns of Earth's features.
- 5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.
- MS-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.
- MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

Disciplinary Core Ideas

- ESS2.A: Earth Materials and Systems
- ESS2.C: The Roles of Water in Earth's Surface Processes

Crosscutting Concepts

1. Patterns.
4. Systems and system models.
5. Energy and matter: Flows, cycles, and conservation.

Science and Engineering Practices

2. Developing and Using Models
4. Analyzing and Interpreting Data

Engage | Coastal Upwelling Areas

Fish and other types of seafood globally comprise about 6% of dietary protein for humans. Still, for over one-third of the world, fish accounts for up to 20% of the average per-capita intake of animal protein (FAO, 2014). **Figure 1** shows major **coastal upwelling** areas along the world's coasts. Within these areas are some of the most productive fisheries on Earth (NOAA, 2021). This is not a coincidence.

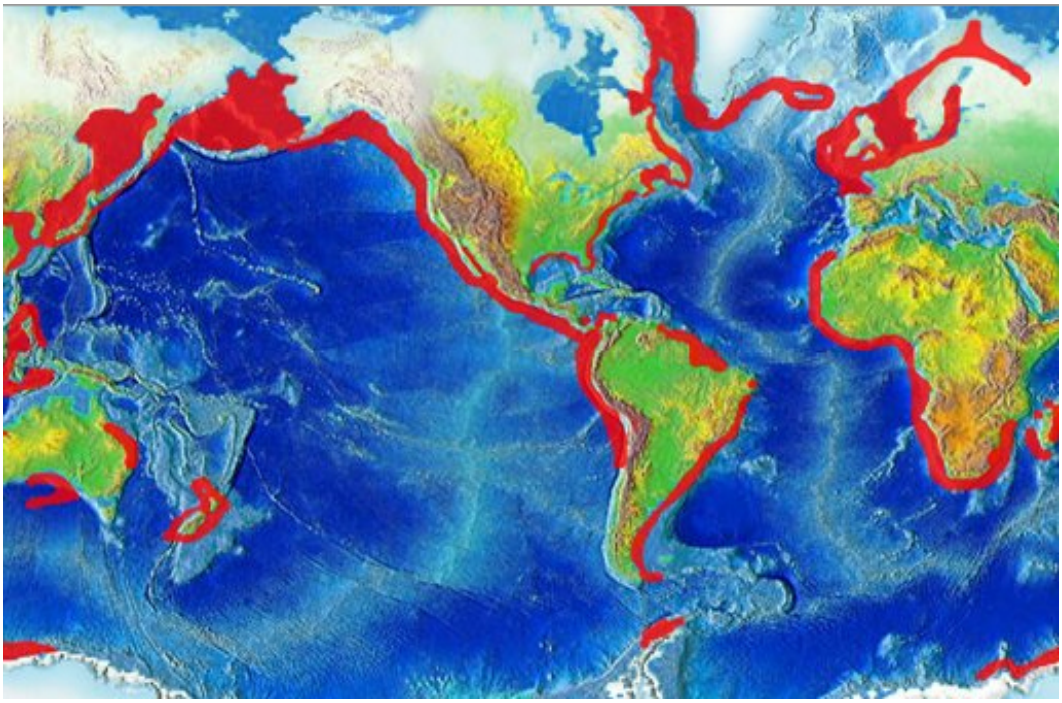


Figure 1. Major coastal upwelling areas along the world's coasts are shown in red. [NOAA]

Figure 2 illustrates an example of the conditions that cause cold, nutrient-rich water to upwell from below in a coastal area. The presence of these nutrients supports phytoplankton and zooplankton, which in turn attract fish.

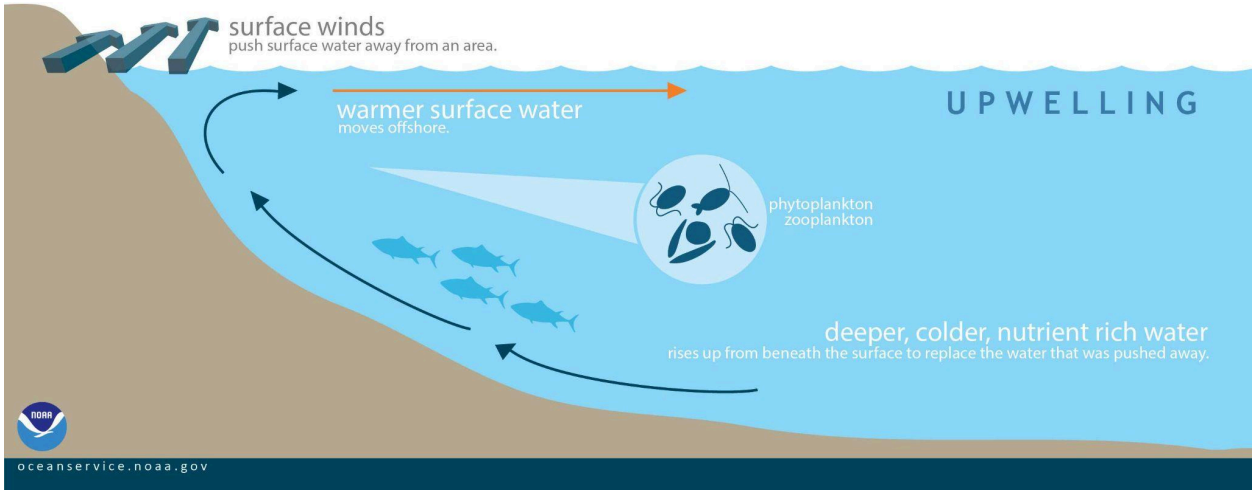


Figure 2. Displaced surface waters are replaced by nutrient-rich colder water from below. [NOAA]

Group Review and Discussion:

1.) *Describe some regions of upwelling. How do these regions connect to your prior knowledge of where major fisheries are located?*
2.) *Drawing from the example of coastal upwelling, what appears to be the relationship between surface wind direction and the prevailing surface ocean current?*
3.) *Why do you think an increased population of phytoplankton and zooplankton attract fish to an area?*

Explore | Primary Production, Nutrient Cycling, and Coastal Upwelling

Surface waters generally display higher rates of **primary production** through **photosynthesis** compared to deeper waters because of the greater availability of light energy. Photosynthetic organisms like **phytoplankton** form the basis of the **marine food web**, providing energy and essential nutrients to organisms at higher **trophic levels**, including **zooplankton** and fish. In addition to light, phytoplankton need carbon dioxide from the atmosphere and nutrients such as nitrogen and phosphorus to grow and reproduce. Nutrient concentrations are typically higher in coastal surface waters than in the deep ocean, leading to increased rates of primary production.

While our focus here is on surface versus deeper waters, it is also important to recognize that coastal waters are typically more biologically productive than those of the open ocean. While some open ocean areas have high nutrient levels, phytoplankton growth is limited by the scarcity of iron and other nutrients. Due to ocean stratification, nutrients and phytoplankton growth are limited in other regions.

Stratification, which is explored in another Project Ocean module, refers to the layering of water masses based on their density, with denser water at depth. In stratified ocean waters, as primary production increases, nutrients become depleted in surface waters. Without nutrients, photosynthetic organisms cannot grow and reproduce, causing them to die and sink through the water column as **particulate organic matter**. This downward transport of organic matter from the ocean's surface to deeper waters is a key component of the marine biological pump (**Figure 3**). Particulate organic matter serves as an energy source for **decomposers** like **bacteria**, which break it down and remineralize nutrients back into the water column. However, most of these nutrients are remineralized into **intermediate waters** below the photic zone, where stratification prevents their return to the surface, making them biologically unavailable to photosynthetic organisms.

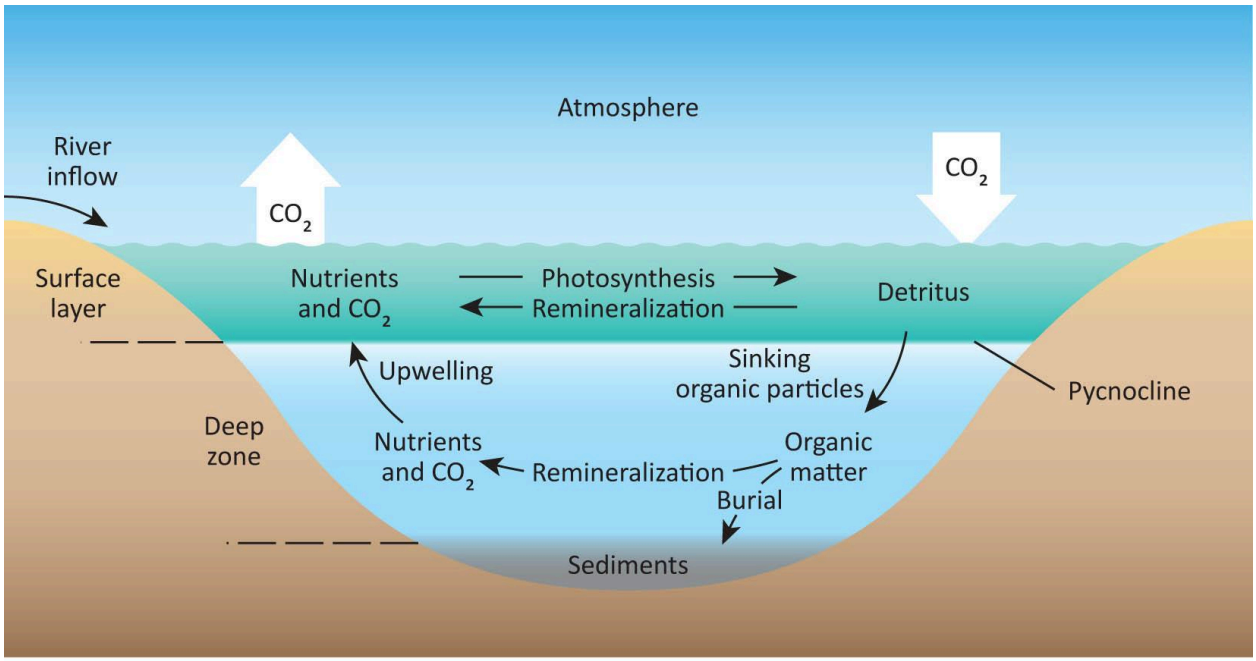


Figure 3. Biological processes that control the distribution of carbon in the ocean constitute the biological pump. [Segar, Kish, and Mills, 2018]

Coastal upwelling occurs when sustained winds blow across the ocean surface parallel to a coastline, resulting in the mass transport of nutrient-depleted, warm surface waters away from the coast. As these warm surface waters move away, they are replaced by colder, nutrient-rich **intermediate waters** from below that rise, or upwell, to the surface. This process continually refreshes surface waters with nutrients, stimulating primary production and biological production up the food web. More biological production means more energy and nutrients are available for organisms like fish, making the fishery more productive.

Depending on your perspective and background, this may all sound pretty straightforward or it may seem quite complicated. Coastal upwelling is actually a bit more complicated than described above. To understand coastal upwelling, one must understand the basics of wind-driven surface ocean circulation. Humans have a vested interest in understanding processes that drive ecological systems like fisheries. Although ecological fisheries systems are often viewed from a biological perspective, it is essential to understand the physics that govern these ecological systems. So, let's dive into learning the basics of wind-driven ocean circulation and coastal upwelling!

For an overview of surface wind stress, Ekman Transport, upwelling and downwelling, and implications for fisheries go to Surface currents, the Ekman spiral, and Ekman transport. Watch the full 4-minute video.

Ocean Upwelling and Downwelling (5-min video) also provides a helpful explanation.

Group Review and Discussion:

1.) *Why do surface waters generally have the highest rates of primary production?*
2.) *Why are phytoplankton so important for the marine food web?*
3.) *How do nutrients in surface waters become depleted, and why is coastal upwelling critical for replacing them?*
4.) *How does surface wind direction impact surface ocean current direction and the potential for upwelling or downwelling.*
5.) *How do upwelling and downwelling change the clarity of surface waters?*

Explain | Wind-Driven Ocean Circulation and Coastal Upwelling

The Physics Behind Understanding Ocean Dynamics

Physical oceanographers are physicists. To mathematically describe fluid motion in the oceans, Physical Oceanographers assume some fundamental governing laws of physics: **Conservation of Mass** (water and salt); **Conservation of Energy**; **Conservation of Momentum**, and; **Conservation of Angular Momentum**. Conservation of Mass leads to the **(volume) Continuity Equation**. Conservation of Energy leads to ocean heat balance and the **Wave Equations**; Conservation of Mass and Momentum leads to the **Equations of Motion**; and Conservation of Angular Momentum leads to the **Conservation of Fluid Vorticity**.

The dominant forces Physical Oceanographers use for determining ocean dynamics and circulation are: **Gravity** (includes buoyancy differences); horizontal pressure

gradients which generate the **pressure gradient Force (PGF)**; **fluid friction and viscous forces***;* and the **Coriolis force***.* The equations of motion that determine the **acceleration** and **advection** of a unit **parcel** of seawater represent these forces.

The 3-Cell Model of Atmospheric Circulation

The Sun is the source of energy that drives atmospheric circulation and ultimately the surface circulation of the oceans on Earth. Over the course of a year, geometric and atmospheric factors lead to a surplus of net radiative energy reaching the surface of the Earth in the tropics and a deficit of net radiative energy reaching the surface of the Earth at the poles. The imbalance between net radiative energy gains and losses reaching the surface of the Earth at different latitudes results in net heat transport via atmospheric circulation by **convection** and ocean circulation by **advection** from the tropic regions poleward towards the poles. Unequal heating of the atmosphere from underlying ocean and land surfaces would set up a two-cell atmospheric pattern of convection and winds on a non-rotating Earth. But, on a rotating Earth, the Coriolis force produces general atmospheric circulation and global wind patterns that are described better by a **3-cell model for atmospheric circulation** (**Figure 4**). It is these wind patterns that drive *surface ocean currents.*

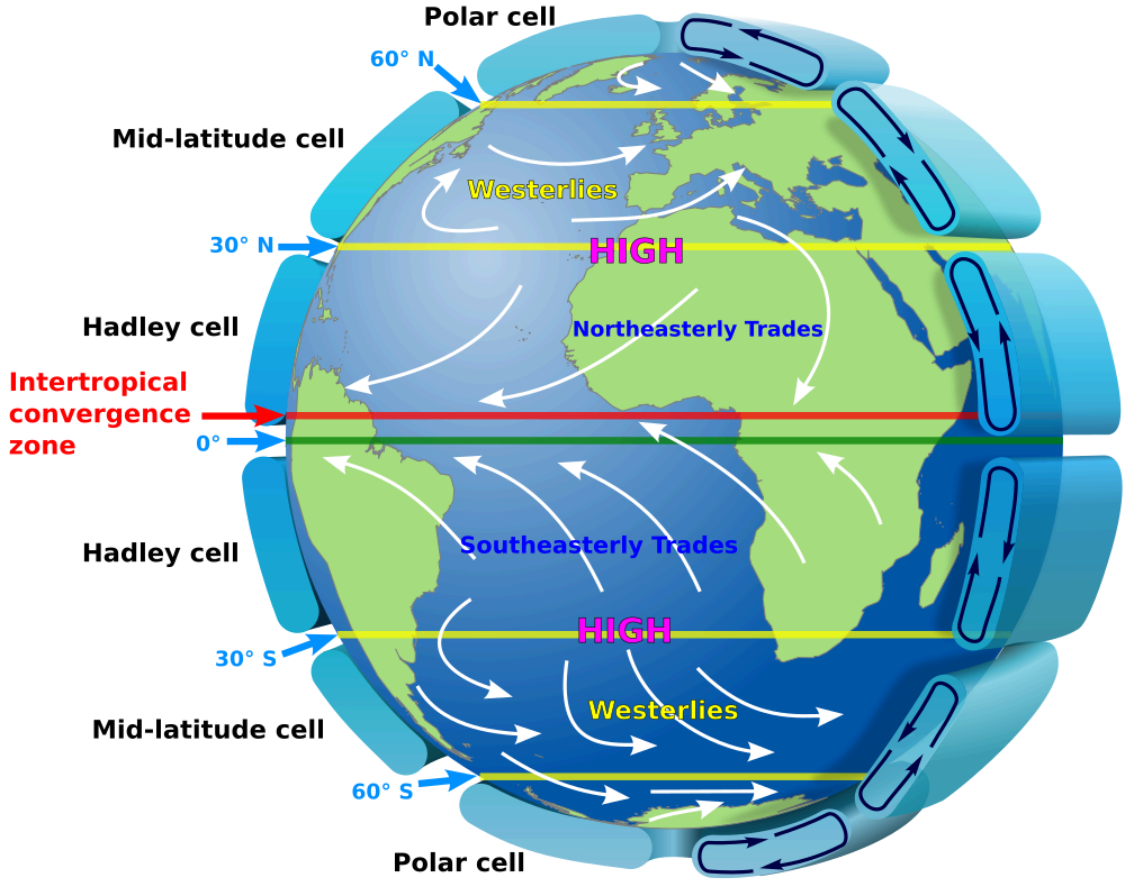


Figure 4. Model for atmospheric circulation. [By Kaidor - Own work based on File:NASA depiction of earth global atmospheric circulation.jpg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=23902538]

Wind-Driven Surface Ocean Currents

Wind blowing across the sea surface transfers energy from the atmosphere to the surface ocean via friction. This can create waves and impart momentum to move water (currents). **Wind stress (τ)**, or tangential pressure, is the magnitude and direction of the **shear stress** that is exerted by the atmospheric winds on the ocean surface. Shear stress from winds on the ocean surface generates **turbulence,** which transfers horizontal momentum vertically into the topmost layer of the ocean (**turbulent drag**). Some kinetic energy is lost to friction. Friction and viscous forces between the uppermost ocean layer and the layer of water below it again generate turbulence, which transfers horizontal momentum downward through the water column. This energy and momentum transfer continues downward through subsequent layers of the surface ocean with kinetic energy being lost to friction at each step. This is why surface currents do not extend past a maximum of ~1000 m. Still, the generation of turbulence in the ocean surface mixed layer enhances the downward transfer of horizontal momentum

through the water column as well as the transfer of heat, the exchange of gases with the atmosphere, and chemical diffusion. To summarize, the wind blowing across the sea surface transfers energy from the atmosphere to the surface ocean via friction, imparting momentum to move surface water within the uppermost part of the ocean in the general direction of the wind.

However, on a rotating Earth, the Coriolis Force deflects surface currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (deflection varies by latitude). The Coriolis force is an apparent force acting on a mass of water that is perpendicular to the direction of motion and to the axis of Earth's rotation. Coriolis forcing is zero at the equator and increases poleward. The Coriolis force acts upon each moving 'layer' of the surface ocean. Also, wind-driven movement of surface waters sets up differences in sea surface heights (only a few cm over long distances) that establish horizontal pressure gradients. The PGF is the restorative force acting to reestablish an equilibrium (even) sea surface that moves water from areas of high to low pressure. Furthermore, wind-driven currents can be blocked or deflected by the coast or affected by friction with the seafloor in shallow coastal areas.

The Ekman Layer, Ekman Spiral, and Ekman Mass Transport

On larger spatial scales, sustained winds over surface waters with a uniform density to a depth greater than the depth of maximum frictional influence can set up an **Ekman Spiral**, leading to **Ekman (mass) Transport** (**Figure 5**)**.**

The Ekman Spiral is a theoretical solution to the horizontal equations of motion for a wind blowing across a flat ocean surface with no horizontal pressure gradient, no acceleration, and no internal molecular friction. Here, internal friction refers to viscosity at the molecular level, which is assumed to be negligible in the model. In contrast, turbulent friction, arising from momentum transfer due to turbulent eddies, is essential to the development of the Ekman Layer. In other words, the Ekman Spiral is a theoretical model that considers only certain forces for simplicity and practicality. This functional and important model enables us to visualize key aspects of ocean circulation.

A true Ekman Spiral only exists in what is called the **Ekman Layer**, an integrated layer of the ocean where PGF, Coriolis, and turbulent drag are in balance. Due to surface wave action and changes in **eddy viscosity** with depth, it is rare to find a true Ekman Layer in the ocean. Where they can be observed, they only extend to depths of 10s of meters. Still, the theoretical Ekman Spiral allows for a mathematical and theoretical construct to explain Ekman Mass Transport, the mass transport of surface waters in a

direction nearly 90° to the wind, of sustained wind forcing that can be observed in some areas of the ocean under certain conditions.

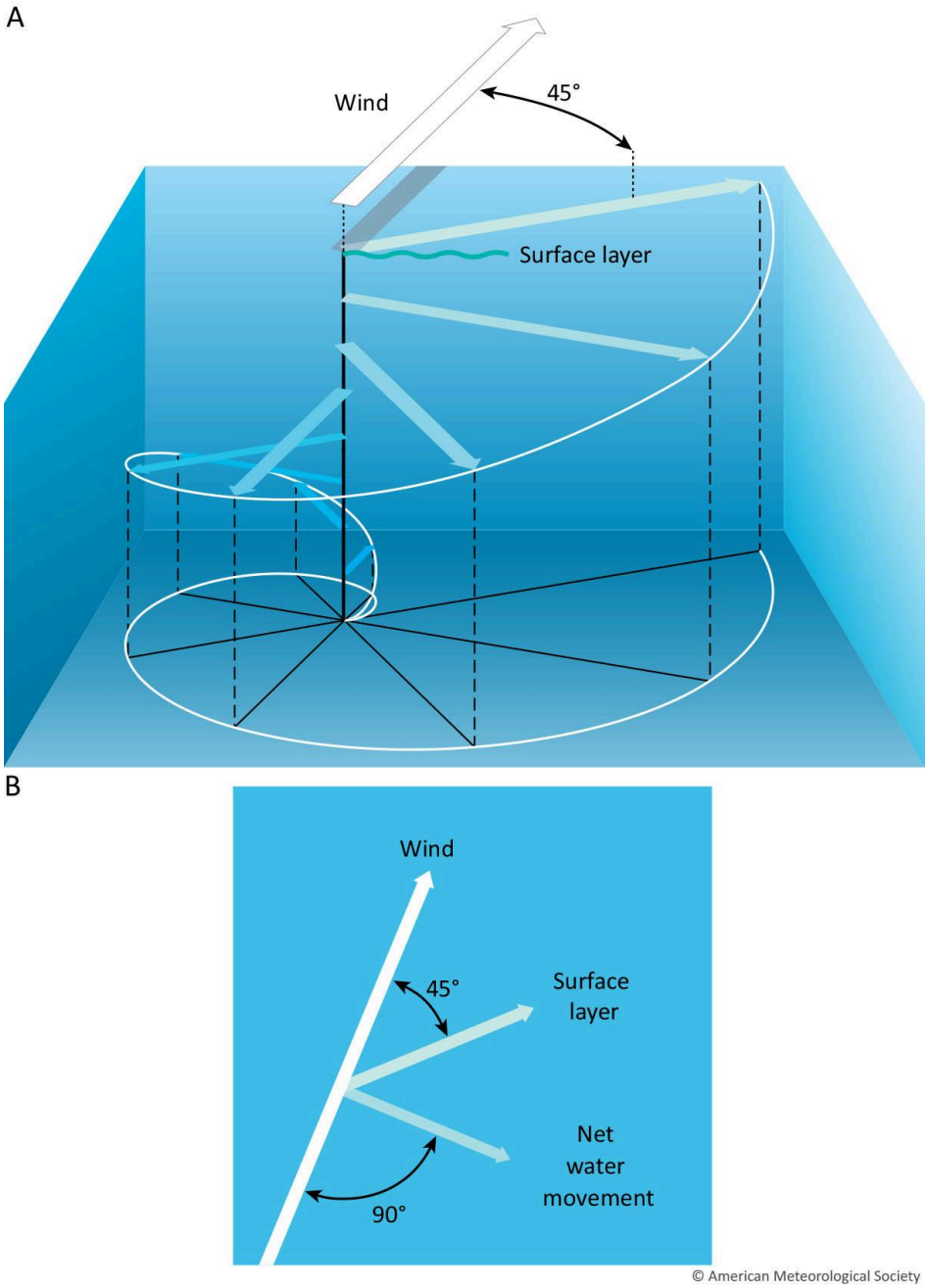


Figure 5. The Ekman spiral describes how the horizontal wind sets surface waters in motion. (A) As represented by horizontal vectors, the speed and direction of water motion change with increasing depth. (B) Viewed from above in the Northern Hemisphere, the surface layer of water moves at 45° to the right of the wind direction. The net transport of water through the entire wind-driven column (the Ekman transport) is 90° to the right of the wind. Because of the reversal of the Coriolis deflection in the Southern Hemisphere, Ekman transport is 90° to the left of the wind south of the equator. [Moran, 2011]

Briefly, wind blowing across an ocean surface imparts turbulent drag (wind stress, $\boldsymbol{\tau}$), which transfers momentum from the wind to the uppermost ocean surface layer and thereby moves water in the surface layer in the direction of the wind. The Coriolis force deflects surface flow 45º to the right (left in the Southern Hemisphere) of the original wind vector. Energy/momentum is lost, so the amplitude of the current is less than the amplitude of the original wind vector. The uppermost ocean surface layer moves across a deeper ocean layer directly below it. Turbulent drag force transfers momentum from the uppermost ocean surface layer to the ocean layer below it and moves water in the direction of the uppermost ocean surface layer. The Coriolis force deflects layer flow 45º to the right (left in the S. Hemisphere) of the surface layer vector. Again, energy/momentum is lost, so the amplitude of the current in the next deeper ocean layer is less than the amplitude of the surface ocean layer flow. The process continues downward through successive layers, like pages in a book, each with a lower speed than that of the layer above, until ocean layer velocities at depth approach zero. When the Ekman Spiral is integrated over the depth of the Ekman Layer, the net (mass) water movement (Ekman Transport) is 90º to the right (left in the S. Hemisphere) of the original wind vector.

Coastal Upwelling

There are regions of the ocean where the winds and surface currents set up Ekman Mass Transport that results in the net transport of surface waters en masse away from or towards a boundary. In the context of the coast, the movement of surface water away from the coast results in surface divergence and the movement of water towards the coast results in surface convergence. The divergence of surface waters away from a coast results in a depressed sea surface height along the coastline that establishes an onshore horizontal pressure gradient. The PGF and volume continuity act to reestablish an equilibrium (even) sea surface by upwelling colder, nutrient-rich intermediate waters from below the Ekman Layer to the surface, which spread outward along the coast. A convergence of surface waters along a coast sets up an elevated sea surface height on the coast that establishes an offshore horizontal pressure gradient. The PGF and volume continuity act to reestablish an equilibrium (even) sea surface by downwelling warmer, nutrient-poor surface waters along the coast, which sink and spread outward from the coast at intermediate depths below the Ekman Layer.

In coastal regions, Ekman Mass Transport of surface waters towards or away from the coast can be caused by sustained winds blowing more or less parallel to the shore (**Figures 6 and 7**). At coastal upwelling centers, the prevailing wind direction relative to the coast sets up Ekman Mass Transport leading to the divergence of warmer, nutrient-poor surface waters away from the coast. These waters are replaced by colder,

nutrient-rich waters upwelled from below. Coastal upwelling regions are among the most productive fisheries in the world. In contrast, when the prevailing wind leads to Ekman Mass Transport toward the coast, there is convergence, stacking, and downwelling of warm, nutrient-poor surface water. These areas tend to be low-productivity regions.

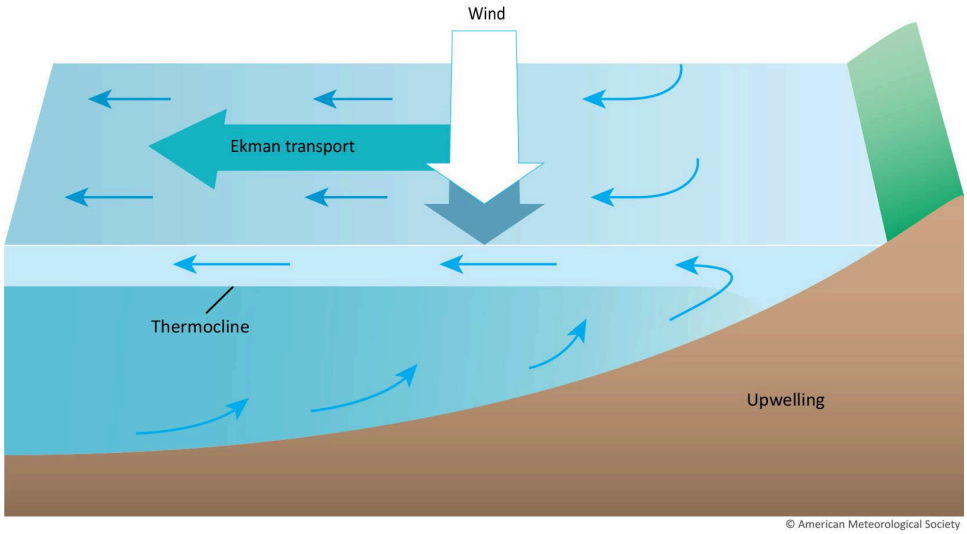


Figure 6. Where Ekman transport moves surface waters away from the coast, surface waters are replaced by water that wells up from below in the process known as upwelling. [Segar, Kish, and Mills, 2018]

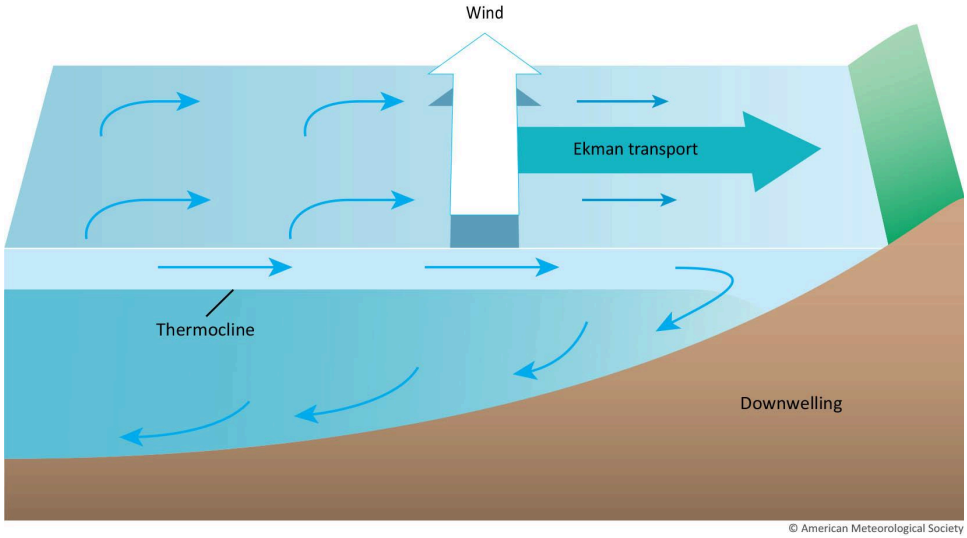


Figure 7. Where Ekman transport moves surface waters toward the coast, the water piles up and sinks in the process known as downwelling. [Segar, Kish, and Mills, 2018]

Equatorial Upwelling

Coriolis forcing is zero at the equator, and equatorial trade winds normally blow east-to-west in both the Northern and Southern Hemispheres, driving east-to-west equatorial surface currents. North of the equator, surface currents are deflected to the

right by the Coriolis Force, which sets up Ekman Mass Transport within the Ekman Layer 90° to the right, away from the equator. South of the equator, surface currents are deflected to the left by the Coriolis Force, setting up Ekman Mass Transport within the Ekman Layer 90° to the left, away from the equator. This leads to a divergence of surface waters along the equator and a depressed sea surface height that establishes a horizontal pressure gradient towards the equator. The PGF and volume continuity act to reestablish an equilibrium sea surface by upwelling colder, nutrient-rich intermediate waters from below the Ekman Layer to the surface that spreads outward along the equator. This process is known as equatorial upwelling (**Figure 8**).

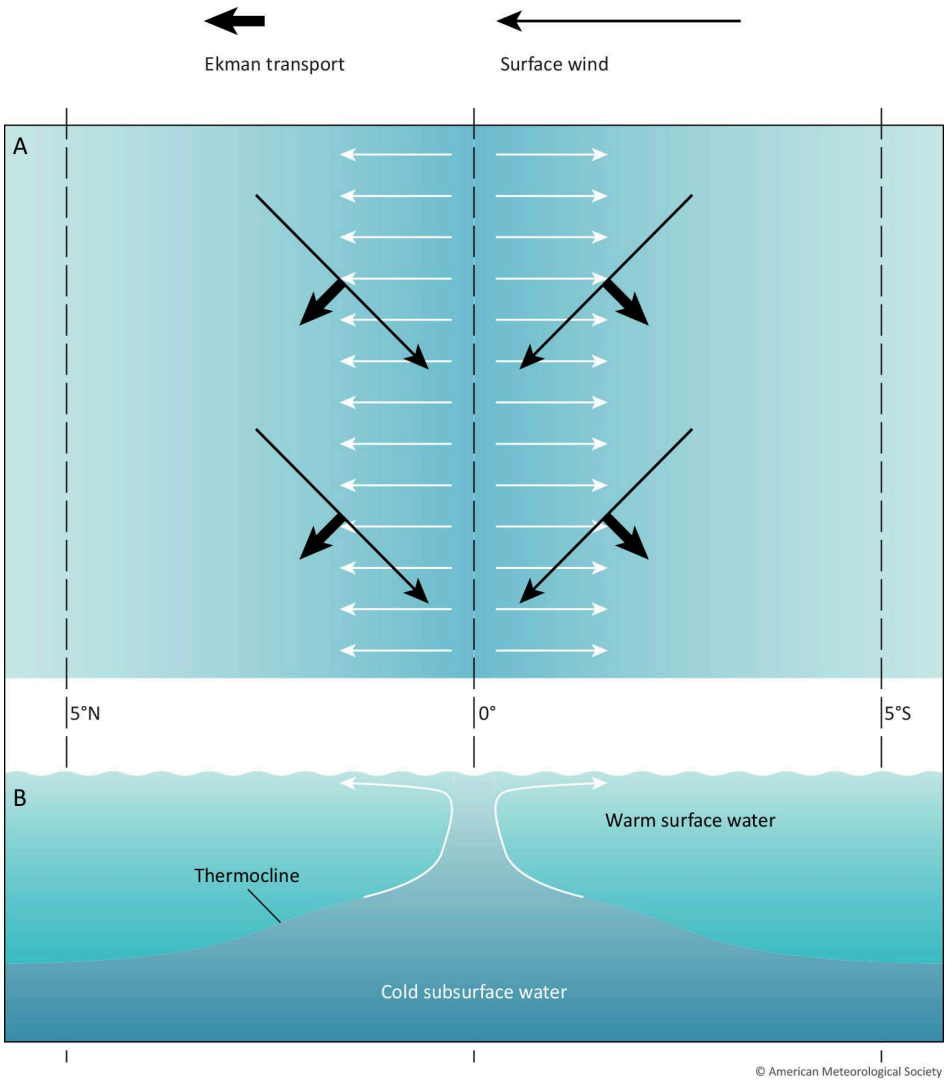


Figure 8. Equatorial upwelling. (A) In this plan view of the ocean from 5°N–5°S, the trade winds of the two hemispheres are shown to converge near the equator. The consequent Ekman transport away from the equator gives rise to upwelling as shown in (B) a vertical cross-section from 5°N–5°S. The white arrows represent the flow of the cold water welling up from below. The dashed lines in (A) delineate 5°N and 5°S latitude. [Segar, Kish, and Mills, 2018]

Under certain circumstances, anticyclonic (clockwise in NH) wind forcing and the Coriolis force can drive Ekman Mass Transport to the right of the applied stress towards the center of rotation, leading to a convergence (bulging) of surface waters. This sets up a horizontal pressure gradient away from the center of rotation. The PGF and volume continuity drive downwelling of warmer, nutrient-poor surface waters at the center.

Cyclonic (counterclockwise in NH) wind forcing and the Coriolis force can drive Ekman Mass Transport to the right of the applied stress away from the center of rotation, leading to a divergence (depression) of surface waters. This sets up a horizontal pressure gradient towards the center of rotation. The PGF and volume continuity drive upwelling of colder, nutrient-rich intermediate waters at the center.

In general, as ocean surface waters move horizontally, they can stack up against boundaries with other water masses or land. This creates ocean surfaces with differential geopotential heights relative to a reference geopotential surface, thereby establishing a horizontal pressure gradient. Differences in water temperature and salinity can also affect density, setting up horizontal pressure gradients, but in surface waters the horizontal pressure gradient is mostly a function of relative sea level. The PGF is the force due to a pressure difference across a horizontal distance. This moves surface waters horizontally from regions of higher pressure to lower pressure.

Group Review and Discussion:

1.) *What are the dominant forces Physical Oceanographers use for determining ocean dynamics and circulation?*
2.) *What is the primary source of energy that drives atmospheric circulation and, ultimately, the surface circulation of the oceans on Earth? Explain your answer.*
3.) *How do surface winds impart energy to the uppermost layer of the ocean?*
4.) *Describe how Ekman Transport varies between the Northern and Southern Hemispheres.*
5.) *Describe scenarios where wind flowing parallel to the coastline leads to upwelling and downwelling.*
6.) *How does Ekman Transport near (but not immediately at) the equator lead to equatorial upwelling?*

Elaborate | Upwelling and Downwelling

In some near-shore areas of the ocean, the coastal orientation, prevailing wind, and rotation of the Earth combine to influence vertical ocean circulation. In these regions, the wind sometimes transports water in about the upper 10 to 100 meters, away

from a coast, to be replaced by cooler water from below. This process, called coastal upwelling, brings nutrient-rich water to the sunlit surface, which can spur biological production. At other times, the wind moves near-surface water towards a coast, causing warm surface waters to pile up and sink. This process, called coastal downwelling, thickens the layer of nutrient-deficient water, resulting in reduced biological production. This activity investigates coastal upwelling and downwelling by looking at the combinations of coastline orientation, persistent wind direction, and Earth rotation that produce them.

Materials:

- ***Model Ocean Basin and Coastal Physics Spin Wheel (at end of module)***
- ***Scissors***
- ***Paper Brads***
- ***Red and Blue pencils***

Activity - Coastal:

Use the scissors to separate the top and bottom ***Model Ocean Basin and Coastal Physics Spin Wheel*** diagrams along the dashed line and cut out the blocks from the top diagram as indicated. Use the pencils to color the arrows in the bottom diagram marked “W” (for warm) red, and those marked “C” (for cool) blue.

The top block diagram represents the ocean surface with a vertical cross-section through a model **ocean basin**. If desired, this can be better seen by folding the diagram along the intersection of the ocean surface and the vertical cross-section and placing it so the vertical cross-section is hanging off the edge of a table.

1. To orient ourselves, answer the following question by *choosing the best response(s)*:

   According to the cardinal direction arrows in the upper left-hand corner of the top ***Model Ocean Basin*** diagram, the *west boundary* of any ocean basin is the land’s _____ coast, and the *east boundary* of any ocean basin is the land’s _____ coast.

   a. eastern … eastern
   b. eastern … western
   c. western … eastern
   d. western … western

Use a pencil point to poke a small hole through the centers (each marked) of the two diagrams. Lay the top diagram (*Model Ocean Basin*) directly over the bottom diagram (*Coastal Physics Spin Wheel*) so the center points of the two coincide. To hold the two together, place a paper brad pin down through the holes at the center of the diagrams.

While holding the top diagram stationary, twist the bottom diagram through all 4 positions to determine that since there are 2 different hemispheres, each with 2 different wind directions and 2 different coasts possible, the total number of different combinations of wind directions, coasts, and hemispheres is 8.

2. On Earth, away from the equator, surface water set in motion by the wind will be deflected by Earth's rotation. This deflection is called the Coriolis effect. Sustained wind blowing parallel to the coast drives surface currents that are deflected to the right by the Coriolis Force, which can set up Ekman (Mass) Transport within the Ekman Layer. Turn the *Coastal Physics Spin Wheel* until a Northern Hemisphere combination appears, that is, an "N" appears in the upper right window of the Model Ocean Basin. Compare the wind direction and the direction of the near-surface flow. If desired, this can be better seen by orienting yourself so that you are on the tail of the wind arrow facing its head. In the Northern Hemisphere, the near-surface flow is about 90 degrees to the _____ of the wind direction.
   a. right
   b. left

3. Now rotate the *Coastal Physics Spin Wheel* until the other "N" appears in the window of the *Model Ocean Basin*. In the Northern Hemisphere, if the prevailing wind direction is reversed, the near-surface flow is about 90 degrees to the _____ of the wind direction.
   a. right
   b. left

4. Repeat the last two steps, but this time for the Southern Hemisphere. In the Southern Hemisphere, the near-surface flow is about 90 degrees to the _____ of the wind direction.
   a. right
   b. left

5. In the Southern Hemisphere, if the prevailing wind direction is reversed, the near-surface flow is about 90 degrees to the _____ of the wind direction.
   a. right
   b. left

6. When wind transports near-surface water away from a coast this leads to a divergence at the coast and a depressed sea surface that sets up a horizontal pressure gradient towards the coast. Warmer near-surface waters that moved away from the coast are replaced by cooler intermediate water from below in a process

called upwelling. Rotate the *Coastal Physics Spin Wheel* to a position showing the wind blowing from north to south in the Southern Hemisphere.

This combination will produce upwelling along the land's _____ coast.

a. eastern
b. western

7. When wind transports near-surface water towards a coast, this leads to convergence at the coast and an elevated sea surface that sets up a horizontal pressure gradient away from the coast. Warmer, nutrient-poor surface waters along the coast sink and spread outward from the coast at intermediate depths in a process called downwelling. Rotate the *Coastal Physics Spin Wheel* to a position showing the wind blowing from south to north in the Northern Hemisphere.

   This combination will produce downwelling along the land's _____ coast.

   a. eastern
   b. western

The coastal upwelling of colder, nutrient-rich intermediate water stimulates the growth of marine phytoplankton and other photosynthetic organisms leading to higher biological productivity, which supports fisheries. Coastal regions with downwelling regions of warmer, nutrient-poor surface waters are areas of lower biological productivity.

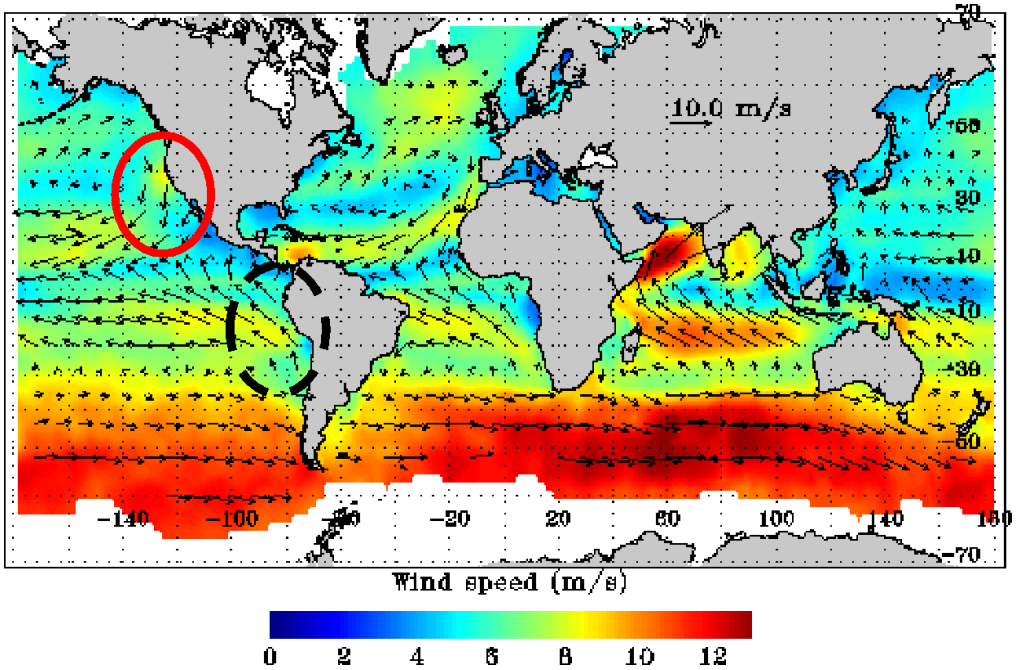


Figure 9. Average global wind speed and direction in July. The black dashed circle indicates the western coast of Peru in the eastern Pacific Ocean in the Southern

Hemisphere, and the red solid circle indicates the western coast of California in the eastern Pacific Ocean in the Northern Hemisphere [SEOS]

8. Looking at **Figure 9**, rotate the *Coastal Physics Spin Wheel* to simulate the prevailing wind direction along the western coast of Peru in the eastern Pacific Ocean in the Southern Hemisphere in July. In July, _____ should occur along the western coast of Peru in the eastern Pacific Ocean in the Southern Hemisphere.
   a. upwelling
   b. downwelling

9. Looking at **Figure 9**, rotate the *Coastal Physics Spin Wheel* to simulate the prevailing wind direction along the western coast of California in the eastern Pacific Ocean in the Northern Hemisphere. In July, _____ should occur along the western coast of California in the eastern Pacific Ocean in the Northern Hemisphere.
   a. upwelling
   b. downwelling

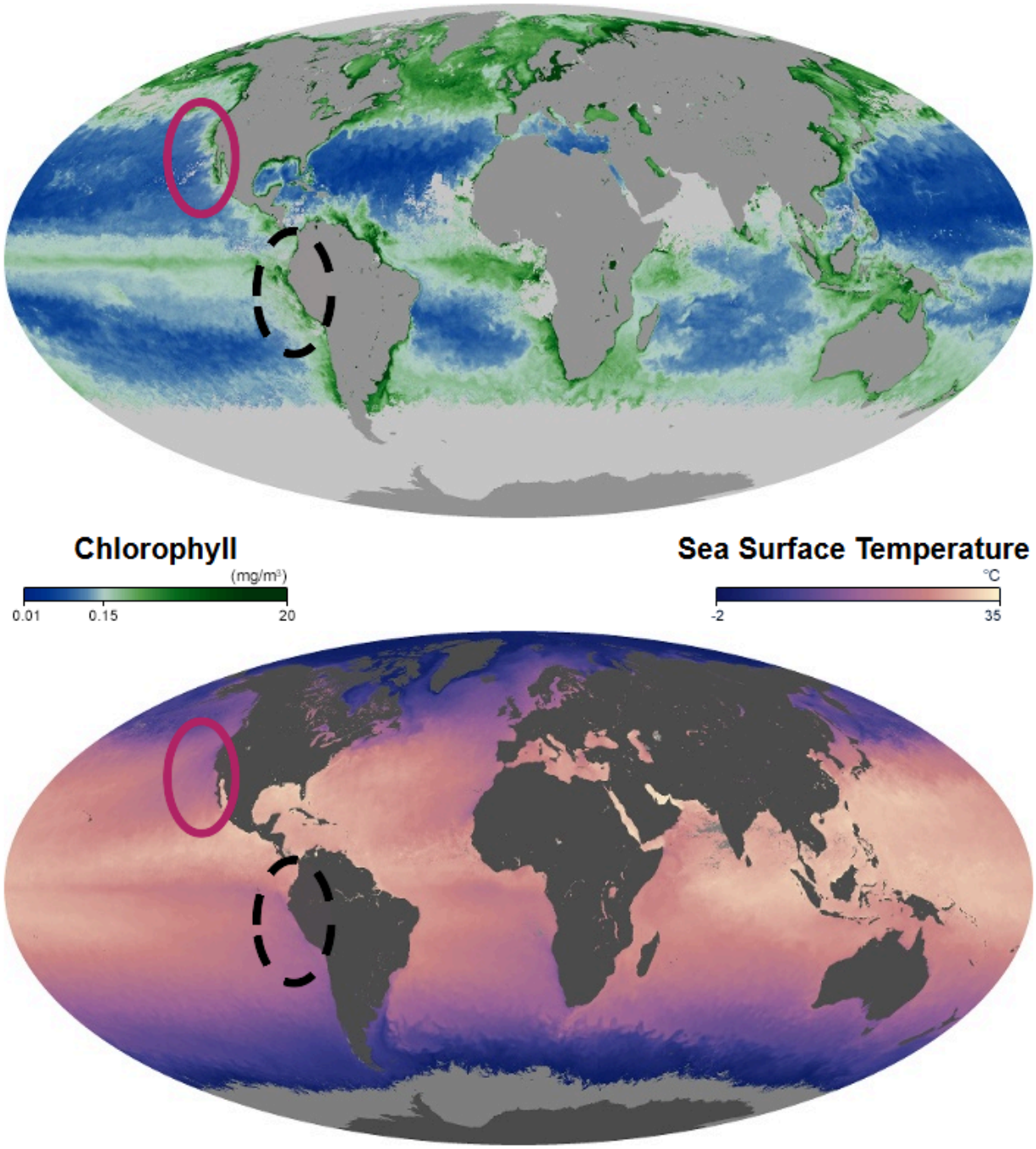


Figure 10. Global mean surface ocean chlorophyll concentrations (upper) and sea surface temperature (lower) for the month of July 2024. The black dashed circle indicates the western coast of Peru in the eastern Pacific Ocean in the Southern Hemisphere, and the red solid circle indicates the western coast of California in the eastern Pacific Ocean in the Northern Hemisphere. [NASA Ocean Observatory, 2024: Chlorophyll & Sea Surface Temperature].

Looking at **Figure 10**, answer the following questions:

10. In July 2024, surface water chlorophyll concentrations along the coast of California in the eastern Pacific Ocean in the Northern Hemisphere and along the coast of Peru in the eastern Pacific Ocean in the Southern Hemisphere were generally _____ than over ocean waters to the west.
    a. higher
    b. lower

11. In July 2024, sea surface temperatures along the coasts of California and Peru were generally _____ than over open ocean waters to the west.
    a. higher
    b. lower

Group Review and Discussion:

1.) *In July 2024, the equatorial region of the tropical Pacific appears to have elevated surface ocean chlorophyll concentrations and lower sea surface temperatures than higher latitude waters around the equator (**Figure 10**). Use **Figure 9** to explain the likely reason.*
2.) *Looking at **Figures 9 and 10**, identify regions of potential coastal upwelling and downwelling other than the west coast of Peru and the west coast of California.*

Evaluate | Ekman Transport and Coastal Upwelling

12. Coastal upwelling _____ primary production in ocean surface waters.
    a. stimulates
    b. suppresses
    c. has no effect on

13. Due to Ekman Transport, a surface wind blowing from north to south along the U.S. West Coast, leads to transport of surface waters toward the _____.
    a. north
    b. south
    c. east
    d. west

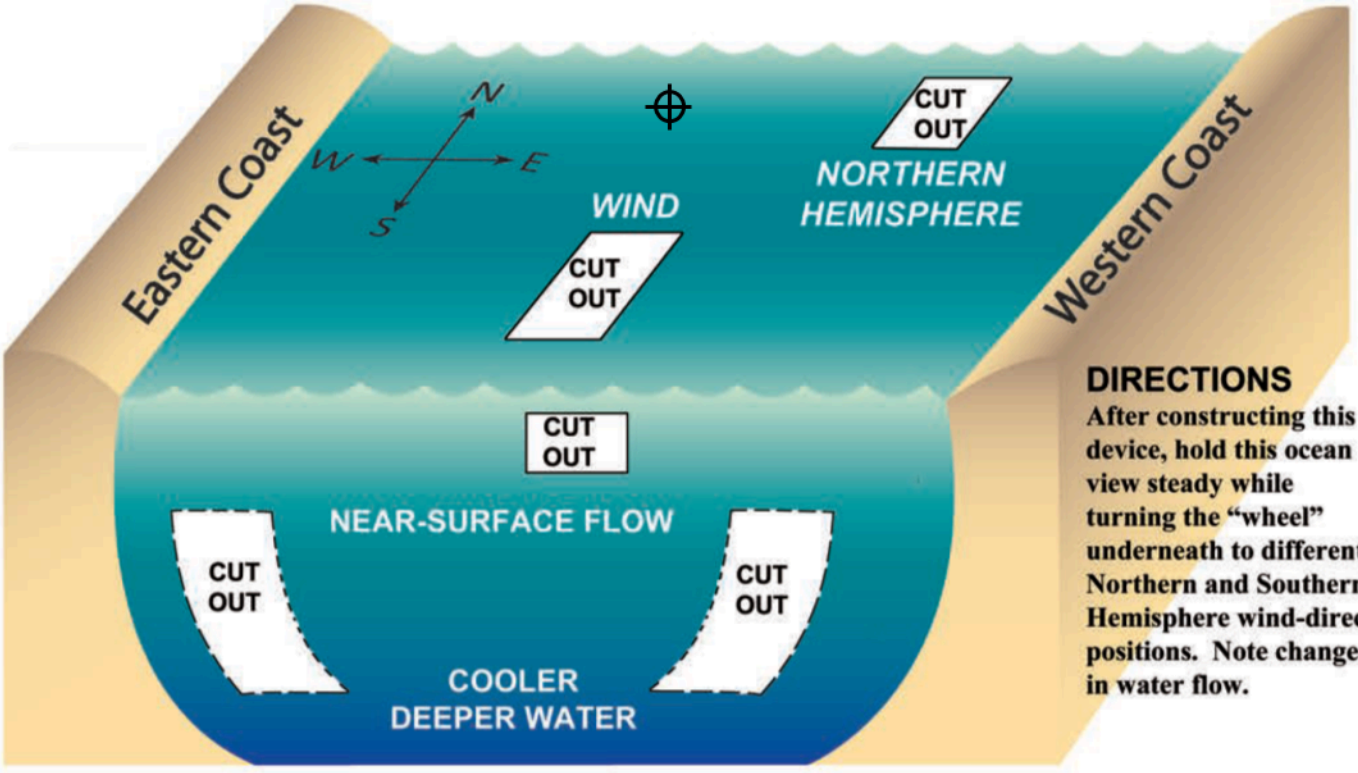
14. A surface wind blowing from north to south along the U.S. East Coast leads to _____ of surface waters.
    a. downwelling
    b. upwelling

15. Ekman Transport associated with east-to-west Trade Winds leads to equatorial _____.
    a. convergence and downwelling
    b. convergence and upwelling
    c. divergence and downwelling
    d. divergence and upwelling

Extend **| Exploring Wind-Driven Currents**

The NOAA Ocean motion: Wind-driven currents. National Education: Hands-on Activities website can be used for an in-class or workshop demonstration.

MODEL OCEAN BASIN

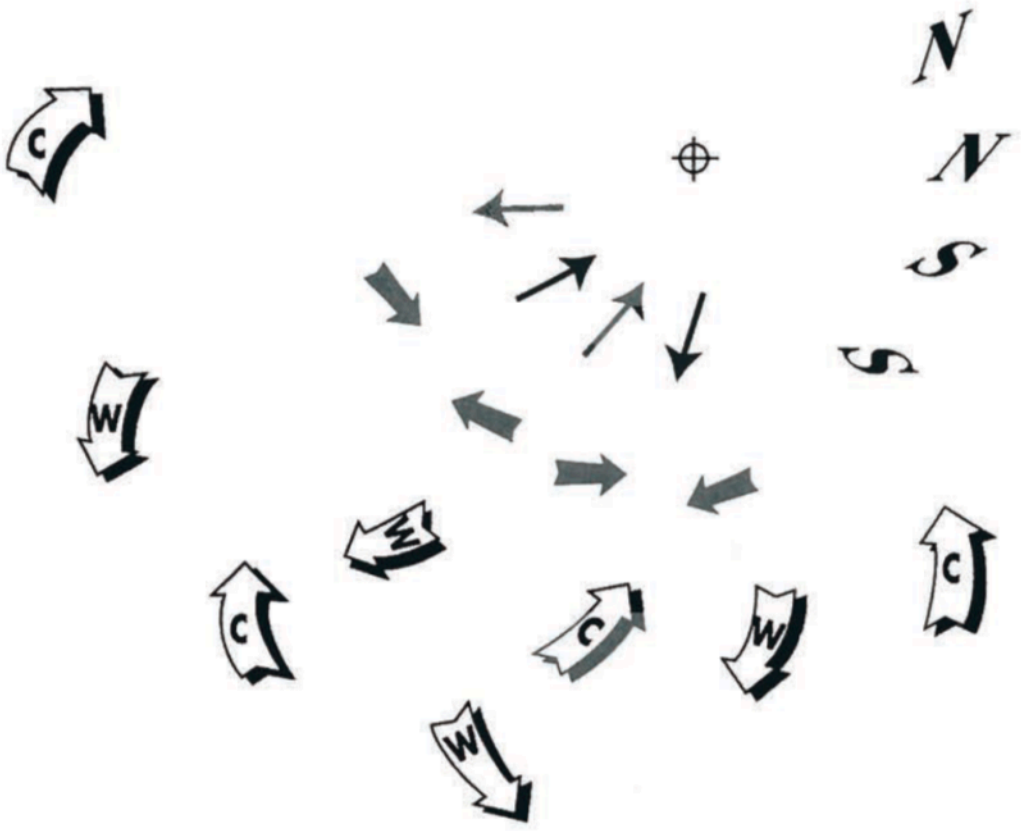


DIRECTIONS

After constructing this device, hold this ocean view steady while turning the "wheel" underneath to different Northern and Southern Hemisphere wind-direction positions. Note changes in water flow.

CUT HERE

COASTAL PHYSICS SPIN WHEEL



Additional Resources

General Information:

National Aeronautics and Space Administration (NASA), 2021: Ocean Motion and Surface Currents. Accessed 05 July 2021, http://oceanmotion.org/index.htm.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: Currents Tutorial. Accessed 05 July 2021, https://oceanservice.noaa.gov/education/tutorial_currents/.

Demos:

National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center Scientific Visualization Studio, 2011: Perpetual Ocean. Accessed 28 May 2021, https://svs.gsfc.nasa.gov/3827.

References

The Food and Agriculture Organization of the United Nations (FAO), 2014: The State of World Fisheries and Aquaculture 2014 (SOFIA). Rome, Italy, 243 pp.

Knauss, J. A., 1997: Introduction to Physical Oceanography, 2nd Edition. Prentice Hall, Inc., 309 pp.

Moran, J.M., 2011: Ocean Studies: Introduction to Oceanography 3rd Ed. American Meteorological Society, 522 pp.

National Aeronautics and Space Administration (NASA), 2021: Ocean Motion and Surface Currents, Wind Driven Surface Currents: Upwelling and Downwelling. Accessed 05 July 2021, http://oceanmotion.org/html/background/upwelling-and-downwelling.htm.

National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center Scientific Visualization Studio, 2011: Perpetual Ocean. Accessed 28 May 2021, https://svs.gsfc.nasa.gov/3827.

National Oceanic and Atmospheric Administration (NOAA), 2021: Science on a Sphere. Accessed 15 May 2021, https://sos.noaa.gov/datasets/ocean-circulation-labeled-currents/.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: Ekman spiral. Accessed 05 July 2021, https://oceanservice.noaa.gov/education/tutorial_currents/media/supp_cur04e.html.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: The Coriolis Effect. Accessed 15 May 2021, https://oceanservice.noaa.gov/education/tutorial_currents/04currents1.html.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: Upwelling - Currents Tutorial. Accessed 21 May 2021, https://oceanservice.noaa.gov/education/tutorial_currents/03coastal4.html.

NASA Ocean Observatory, 2021: Chlorophyll & Sea Surface Temperature. Accessed 05 July 2021, https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA/MYD28M.

National Research Council. 2008: Earth Observations from Space: The First 50 Years of Scientific Achievements. Washington, DC: The National Academies Press, 142 pp., https://doi.org/10.17226/11991.

Science Education through Earth Observation for High Schools (SEOS), 2021: Prevailing Winds. Accessed 05 July 2021, https://seos-project.eu/oceancurrents/oceancurrents-c02-p02.html.

Segar, D.A., S.W. Kish, and E.W. Mills., 2018: Ocean Studies: Introduction to Oceanography 4th Ed. American Meteorological Society, 774 pp.

Stewart, R. H., 2005: Introduction to Physical Oceanography. Accessed 24 September 2014, https://drive.google.com/file/d/1NVpCNP8iq2HXPOCvyFJSUKvMW88PG7iv/view.

Talley, L. D., G. L. Pickard, W. J. Emory, and J. H. Swift, 2011: Descriptive Physical Oceanography: An Introduction, 6th Edition. Elsevier, 555 pp.

Acknowledgements

During the preparation of this work the author(s) used ChatGPT-4o in order to copyedit text and understand some of the key concepts. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.