AMERICAN METEOROLOGICAL SOCIETY



Project Ocean

Wind-Driven Ocean Circulation, Geostrophic Flow, and Oceanic Gyres

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:

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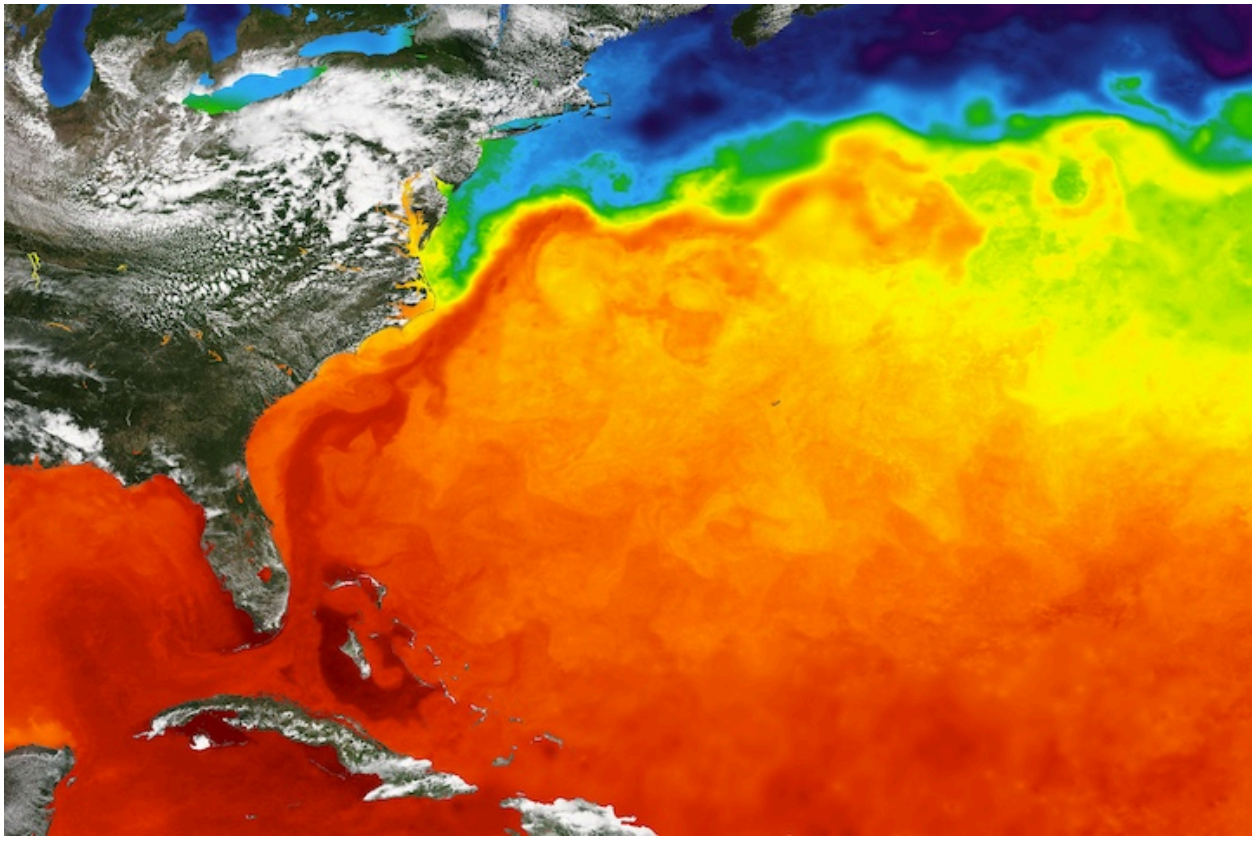


Figure i. Map of the Gulf Stream on 29 May 2024, shown as a ribbon of darker red hugging the southeastern Atlantic coast. [NASA].

"Big whirls have little whirls, That feed on their velocity; And little whirls have lesser whirls, And so on to viscosity."

- Lewis Fry Richardson (1881-1953)

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:

1. Ocean Basics: Size and Scale

- Identify and differentiate the five major ocean basins by geography and oceanographic criteria.
- Define the five major ocean basins and explain how the Antarctic Circumpolar Current distinguishes the placement of the Southern Ocean.

3. Open Ocean Water Column Structure

- Describe the relationship between temperature, salinity, pressure, and seawater density.
- Explain how pressure acts on a parcel of seawater, describe the concept of hydrostatic balance in the ocean, and analyze how pressure influences seawater density and temperature with increasing depth.
- Explain the Equation of State for Seawater and its significance.

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 the 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

- Describe the formation and characteristics of ocean gyres in different hemispheres.
- Explain how geostrophic balance shapes gyre circulation.
- Distinguish between western boundary currents and eastern boundary currents in terms of speed, depth, and direction.
- Distinguish between cyclonic and anticyclonic rotation.
- Define warm-core and cold-core eddies and describe their characteristics.
- Identify how monsoon winds affect surface currents in the northern Indian Ocean.
- Explain the formation of equatorial counter currents.
- Describe the Antarctic Circumpolar Current and its significance.
- Summarize the circulation in high-latitude oceans including the Beaufort Gyre and Labrador Current.

Standards

Project Ocean Fundamental Understandings:

Ocean Basics: Size and Scale (1.4)
Open Ocean Water Column Structure (3.2, 3.4, 3.5, 3.7, 3.10, 3.11, 3.14)
Open Ocean Surface Currents (5.1-5.16)
Open Ocean Surface Circulation (6.1-6.12)

Applicable Ocean Literacy Principles:

1.A, 1.C, 3.C, 3.D, 3.G, 6.A, 7.B

Next Generation Science Standards

Performance Expectations

3-PS2-1. Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.
3-PS2-2. Make observations and/or measurements of an object's motion to provide evidence that a pattern can be used to predict future motion.
3-ESS2-2. Obtain and combine information to describe climates in different regions of the world.
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

PS1.A: Structure and Properties of Matter
PS2.A: Forces and Motion
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 | The "Great Pacific Garbage Patch"

Humans use a lot of plastic. Many tons of plastics and other man-made debris are introduced into waterways and the ocean by humans. These materials are ubiquitous in the marine environment, and can be harmful to marine ecosystems in all regions of the ocean. They can cause entanglement and can be ingested by marine species, leading to choking, starvation, and other impairments (NOAA, 2021).

In the context of marine debris and plastics, you may have heard the term, **The Great Pacific Garbage Patch**, or something similar in the media. This term has drawn public attention to the issue of marine debris and plastics, but it is a bit misleading. It conjures up an image of a large continuous patch or even a floating island of marine plastic debris like bottles, plastic bags, and other litter that can be easily seen by the naked eye, satellite, or aerial photographs. This is not the case.

The Great Pacific Garbage Patch and other marine **"**garbage patches**"** are regions of the ocean where physical circulation collects **marine debris** in high concentrations (**Figure 1**). While some of this debris consists of larger items such as plastic bottles, fishing nets, and litter, most consist of **microplastics**, plastic pieces smaller than 5 mm that are not visible to the naked eye. So, instead of finding large islands or patches of plastics in the ocean, in reality, it is more likely that you would sail through an ocean garbage patch and not even notice it. But that does not mean ocean garbage patches do not exist or are not harmful to marine ecosystems.

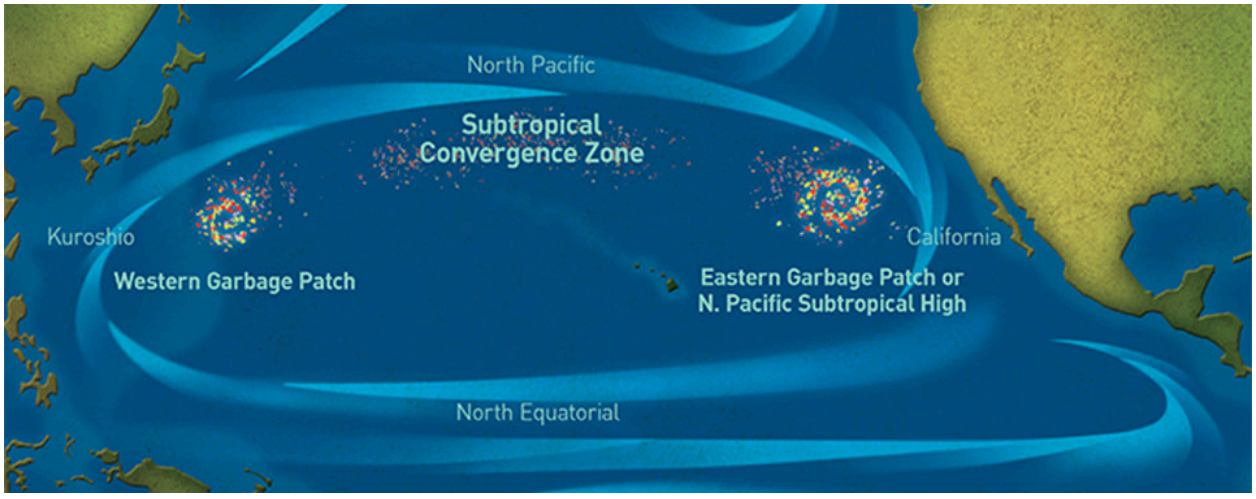


Figure 1. General location of the Eastern and Western Garbage Patches and regions of high marine debris concentration in various areas of the North Pacific. [NOAA NOS]

In the ocean, plastics are continuously acted upon by wind and wave action. They are mechanically broken down into smaller pieces, chemically degraded by sunlight, and

widely dispersed both over huge surface areas and mixed throughout the top portion of the **water column**. Large-scale **surface ocean circulation** in the form of rotating ocean currents called **gyres** gathers microplastics and other marine debris in specific locations in the ocean; these are garbage patches**.** There are five major oceanic gyres—one in the Indian Ocean, two in the Atlantic Ocean, and two in the Pacific Ocean. Garbage patches of different extents and concentrations can be found in each gyre.

But while the general locations of these garbage patches are known, it is difficult to estimate their size. Their borders and contents constantly change as winds and **surface ocean currents** shift in response. So, to understand marine debris and garbage patches, one must understand the relationship between winds, surface ocean currents, and the large, basin-scale surface circulation. However, understanding marine debris is not the only reason for learning about wind-driven surface ocean circulation. The surface ocean continuously exchanges heat with the atmosphere. Surface ocean circulation, along with atmospheric circulation, transfers heat away from the tropics towards the poles, thereby regulating Earth's climate. The horizontal movement of surface waters can lead to vertical movement of waters in the ocean water column, which is essential in influencing **biological productivity** and material exchange between the atmosphere and deeper ocean waters.

Group Review and Discussion:

1) *What are microplastics, and why are they harmful?*
2) *Explain how the Great Pacific Garbage Patch relates to microplastics.*
3) *How do ocean gyres create "garbage patches" in the ocean?*

Explore | Global Winds and Ocean Currents

What drives ocean surface currents? Lower atmospheric winds blowing across the ocean surface transfer momentum to the upper ocean and drive surface currents. These currents, along with the wind, transfer heat from tropical regions, where there is a surplus of solar heating, to polar regions, where there is a deficit. The ocean, in turn, releases energy to the atmosphere, which helps maintain the general atmospheric circulation. The surface circulation of most of the major ocean basins is dominated by large, roughly circular patterns called gyres.

The locations of major oceanic gyres are significantly influenced by the pattern of prevailing winds near Earth's surface. **Figure 2** illustrates the major planetary-scale wind belts. Examine these features, particularly noting the locations of the subtropical anticyclones, trade winds, westerlies, polar easterlies, and the wind flow associated with

these features. **Subtropical anticyclones** are prominent features of the planetary-scale circulation centered over subtropical latitudes (on average, near 30°N and 30°S) in the North and South Atlantic, the North and South Pacific, and the Indian Ocean. These high-pressure areas extend from the ocean surface up to the tropopause and exert a significant influence on weather and climate over vast regions of the ocean and continents. The **trade winds** extend from the equatorward flank of the subtropical anticyclones, with winds from both hemispheres coming together to form the **Intertropical Convergence Zone (ITCZ)**. The **midlatitude westerlies** extend from the poleward flank. Surface westerlies flow into areas of low pressure (**subpolar lows**), found primarily over subpolar ocean basins. These low pressure cells in the Northern Hemisphere mark the convergence of midlatitude southwesterlies with polar northeasterly winds. In contrast, in the Southern Hemisphere, midlatitude northwesterlies and polar southeasterlies converge along a nearly continuous belt of low pressure surrounding the Antarctic continent.

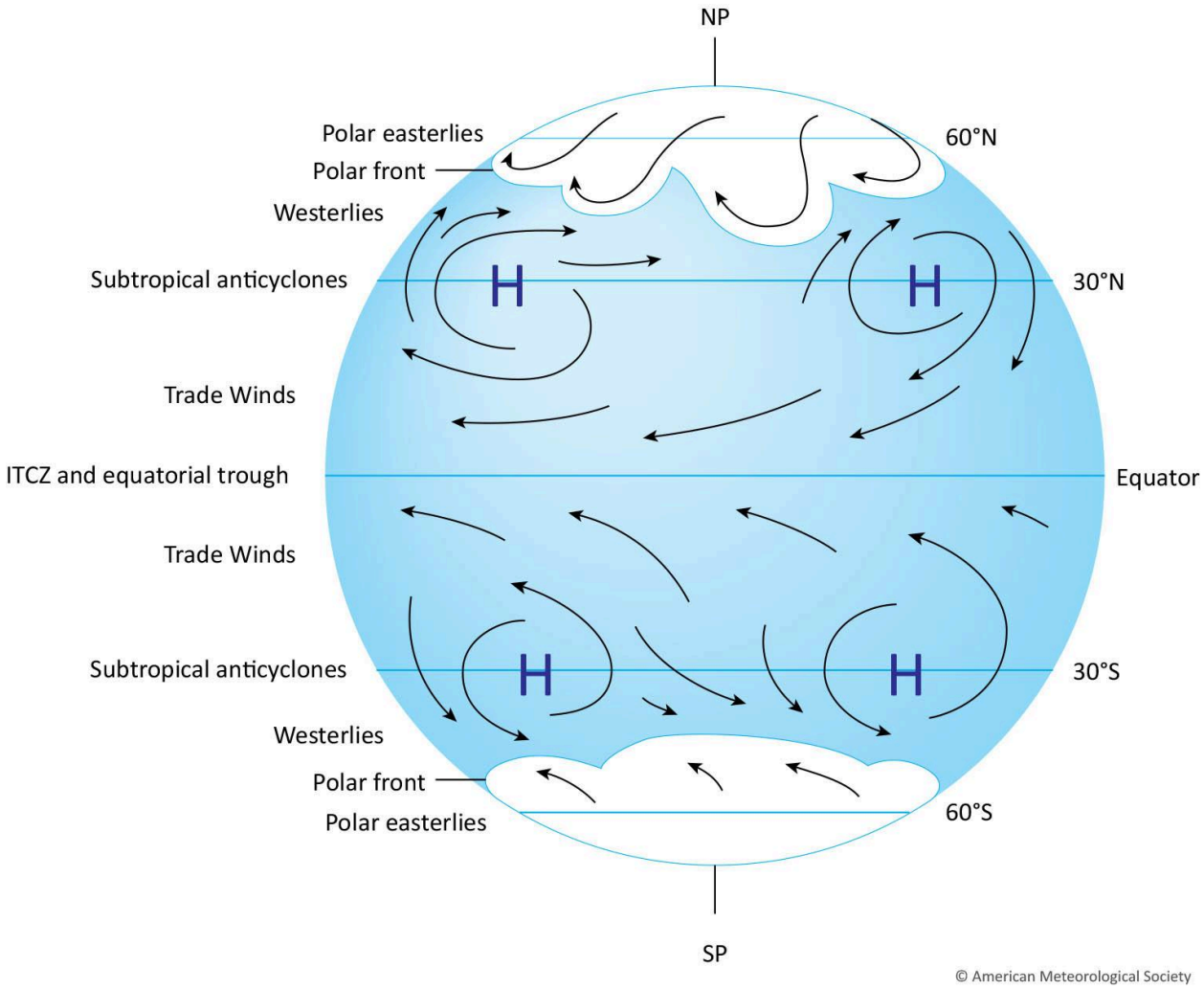


Figure 2. Schematic representation of the planetary-scale surface circulation of the atmosphere. [Segar, Kish, and Mills, 2018]

To learn how prevailing surface winds help generate gyres and other surface ocean currents, go to Global winds and currents | Middle school Earth and space science | Khan Academy. Watch the video until the 3:30 mark.

Group Review and Discussion:

1) *Explain how the Sun's uneven heating of Earth's surface contributes to general bands of low and high atmospheric pressure.*
2) *Why do the prevailing winds curve while flowing from high to low pressure regions?*
3) *How do the prevailing winds induce ocean surface currents? What forms when the ocean surface currents connect?*

4) *Do the subtropical gyres rotate clockwise or counterclockwise? How does the rotation differ between the Northern and Southern hemispheres?*
5) *How are gyres key to oceanic heat transport?*

Group Demonstration: Global Winds and Ocean Currents

Explain | Wind-Driven Ocean Circulation

Background: Global Wind-driven Surface Ocean Circulation

The dominant forces that determine the acceleration and advection of surface ocean waters are:

- **gravity** (includes buoyancy differences)
- horizontal pressure gradients which constitute the **pressure gradient Force (PGF)**
- fluid **friction and viscous forces**
- **Coriolis force** (sometimes called the **Coriolis Effect**); technically, the Coriolis Force is the apparent force that arises due to Earth's rotation, and the Coriolis Effect is the observable effect of that force, meaning the apparent deflection of a fluid in motion on Earth's surface

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). Surface currents in the ocean flow in the same general direction as the prevailing global wind patterns.

The surface circulation in most major ocean basins is dominated by large, roughly circular circulation patterns called **gyres**, centered at about 30° latitude. As seen from above, they flow clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The locations of major oceanic gyres are primarily determined by the locations of the Earth's major wind belts, the blocking effects of the continents, and the effects of the Earth's rotation.

Geostrophic Flow and Geostrophic Balance

Wind-driven global surface circulation sets up an Ekman Spiral leading to **Ekman Mass Transport**, where the net water transport in the top 100 m of the ocean is 90 degrees (to the right in the Northern Hemisphere and to the left in the Southern Hemisphere) from the prevailing wind direction (**Figure 3**).

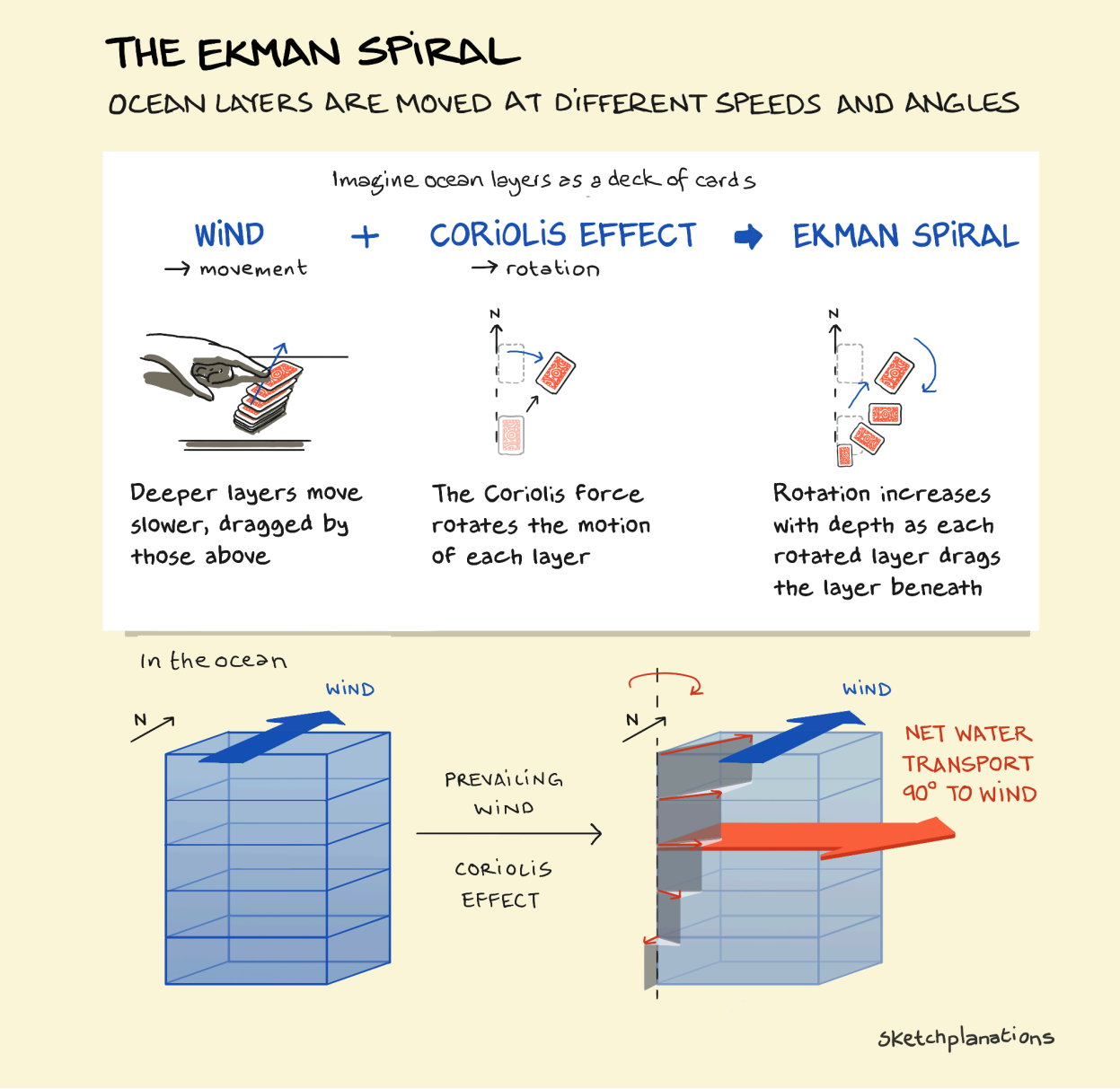


Figure 3. The Ekman spiral describes how the horizontal wind sets surface waters in motion. Viewed from above in the Northern Hemisphere, the surface layer of water moves at 45° to the right of the wind direction. The net transport of water through the entire wind-driven column (the Ekman transport) 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. [Sketchplanations]

Ekman Transport drives **convergence** and the piling-up (bulge) of water at 30°N and 30°S latitude producing a broad mound of water as high as one meter at the center of a gyre. This creates a horizontal pressure gradient with a PGF directed off the mound. The Coriolis force will act on the resultant currents moving off the mound until it balances the PGF, achieving **geostrophic balance**. Water then flows parallel to pressure contours (geostrophic flow), circling the mound.

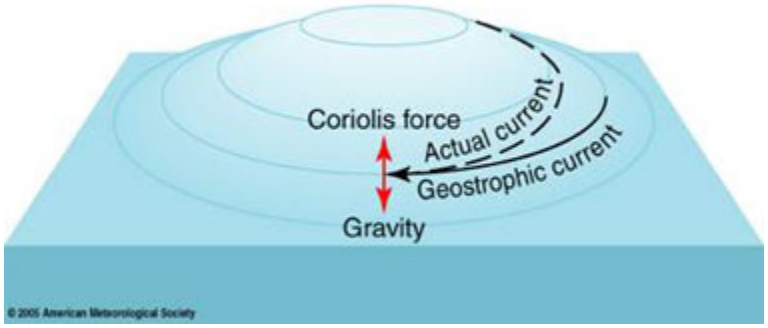


Figure 4. Ekman transport causes surface waters to converge toward the central region of a subtropical gyre from all sides, producing a broad mound of water. A balance develops between the Coriolis force and the force arising from the horizontal water pressure gradient such that surface currents flow parallel to the contours of elevation of sea level. This current is known as geostrophic flow. [AMS]

In the Northern Hemisphere, water flowing down the sloping mound of the gyres is deflected to the right due to the Coriolis effect, reinforcing the clockwise circulation of the gyres. In the Southern Hemisphere, water flowing down the sloping mound of the gyres is deflected to the left due to the Coriolis effect, reinforcing the counterclockwise circulation of the gyres.

View the AMS Water Mound video. It starts with the June 2008 monthly-averaged wind field. Black arrows approximate the wind pattern over the North Atlantic Ocean basin and blue arrows represent the Ekman transport. The contour lines delineate the resulting mound of water produced by the Ekman transport, with the innermost contour enclosing the highest sea surface. The color-coded ocean surface shows the sea-surface height observed at that time.

Western Intensification and Western Boundary Currents

An added effect of the Earth's eastward rotation is the westward displacement of the gyre mounds within their ocean basin. Easterly trade winds converge at the equator, piling up water at low latitudes along the western edges of ocean gyres. Currents flow 'downhill'/poleward along the western edge in a narrow band until they are pushed back across the ocean by westerly winds in the midlatitudes. The narrow band of strong poleward flow along the western edge of the gyre is balanced by a broad area of slower equatorward flow along the eastern edge. Fluid **vorticity** (an internal measure of spin) must be conserved as a parcel moves around an ocean gyre. A combination of the steeper ocean-surface slopes on the western sides of the gyres, **frictional drag** along the coast, changes in the Coriolis effect with latitude, and torque from **wind stress** help produce higher water speeds in the western regions of the gyre. These **western**

boundary currents are narrow (< 100 km), deep (up to 1000 m) bands of strong poleward flow of warmer waters from the Tropics towards the mid-latitudes along the western edge of the gyre. Western boundary currents are balanced by wider (up to 1000 km), shallower (< 500 m) areas of slower equatorward flow of cooler waters from mid-latitudes back to the Tropics along the eastern edge of the gyre (**Figure 5**).

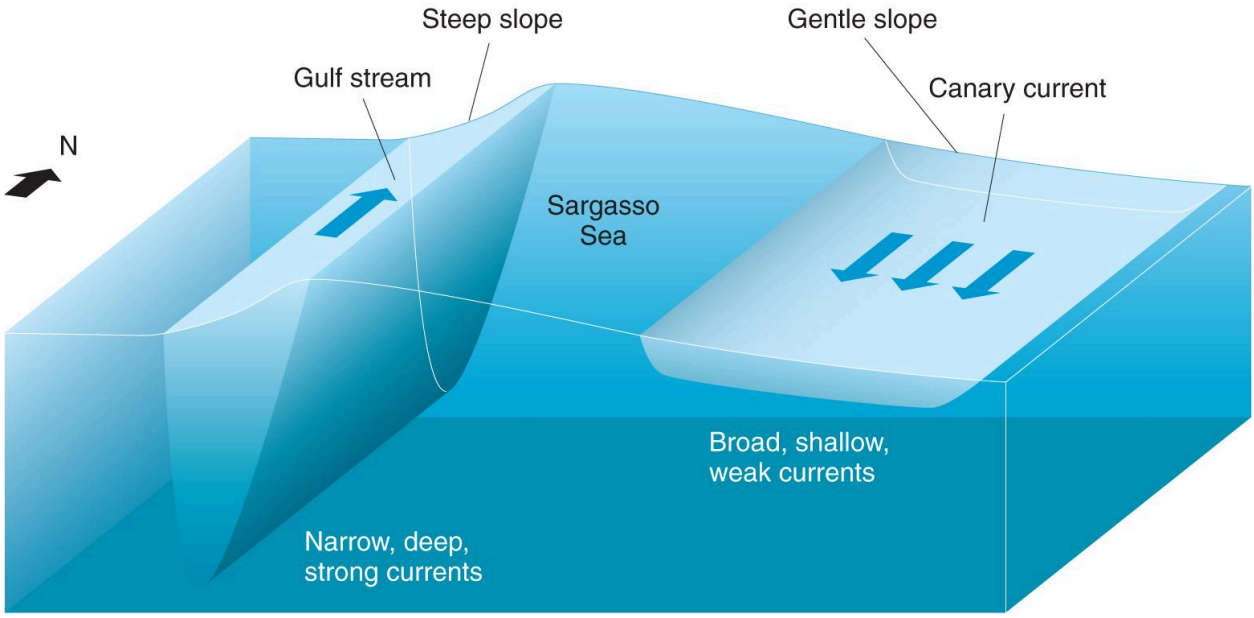


Figure 5. Surface ocean currents are faster, narrower, and deeper on the western side of an ocean basin. These are known as western boundary currents. Note that the vertical scale is greatly exaggerated. [Segar, Kish, and Mills, 2018]

Gyres play a significant role in transporting heat away from the Tropics towards the poles. **Geostrophic currents** around oceanic gyres and **western intensification** set up a general circulation that moves warmer surface waters from the tropics poleward along **western boundaries** in strong, deep, and narrow surface currents like the **Gulf Stream**. Cooler surface waters from mid-latitudes are, in turn, moved back towards the equator along **eastern boundaries** in weaker, shallower, and broader surface currents like the **Canary Current**. The same large-scale surface ocean gyre circulation focuses microplastics and other marine debris into “garbage patches” at specific locations in the ocean.

Warm- and Cold-Core Eddies

The formation of large rotating warm and cold-water rings also distinguishes the fast-moving western boundary currents. Along fast-moving western boundary currents, such as the Gulf Stream, **meanders** in the current due to friction along boundaries can pinch off large, rotating rings of warm or cold water with rotational current directions distinct from the direction of the primary current (**Figure 6**). These are called **mesoscale eddies**. A counterclockwise direction of rotation in the Northern Hemisphere is described as **cyclonic,** whereas a clockwise direction of rotation is **anticyclonic**. In the Southern Hemisphere, a counterclockwise direction of rotation is anticyclonic, and a clockwise direction of rotation is cyclonic.

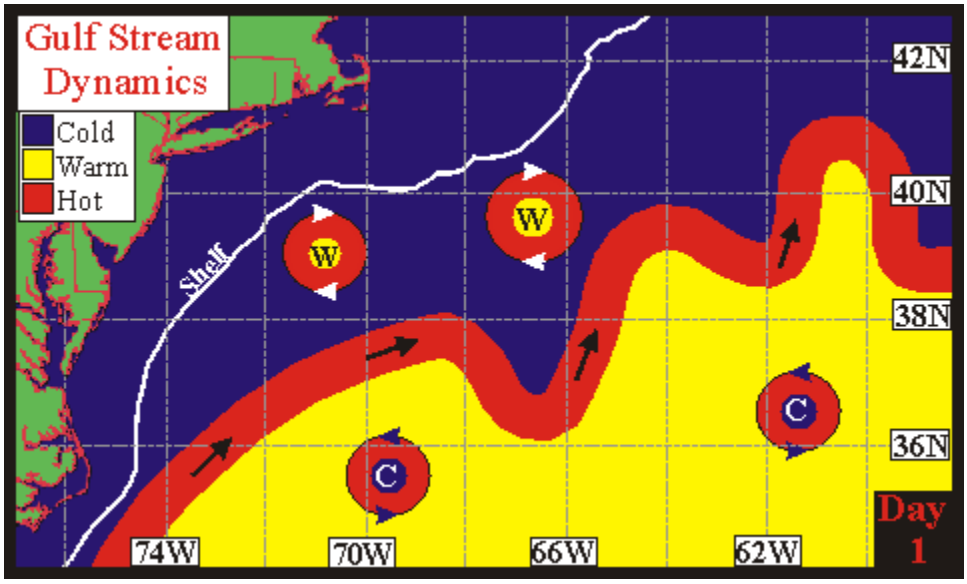


Figure 6. Diagram of the Gulf Stream and associated warm- and cold-cold eddies. [Naval Postgraduate School; extracted from Univ. of Wisconsin-Madison Space Science and Engineering Center website]

Mesoscale **warm-core eddies** formed along western boundaries that are anticyclonic in rotation tend to trap warmer surface waters at their center and have a slightly elevated sea surface height. Mesoscale **cold-core eddies** formed along western boundaries that are cyclonic in rotation tend to have cooler waters at their center and a somewhat depressed sea surface height. Warm- and cold-core mesoscale eddies can reach sizes of up to 400 km in diameter, have rotational speeds of over 0.5 m/sec, and can extend to the seafloor. At their core, they also carry the characteristics of the water from which they were sourced, including marine organisms. Large mesoscale eddies can persist for months to years.

Removed from western boundaries, under special conditions, atmospheric circulation can sometimes set up ocean circulation and Ekman transport, which leads to the convergence or divergence of waters on a smaller scale resulting in short-lived *rotational eddies* a few kilometers in diameter. Anticyclonic rotational eddies stack nutrient-depleted warmer surface waters at their center, resulting in a higher sea surface height and net downwelling of warmer waters at the core. These warm-core rotational eddies are typically less productive. Cyclonic rotational eddies move nutrient-depleted warmer surface waters away from their center, resulting in a lower sea surface height and net upwelling of cooler, nutrient-rich intermediate waters at the core. These cold-core rotational eddies are areas of higher biological productivity.

General Circulation in the Atlantic Ocean Basin

Examine the features of **Figure 7**, in particular noting the location of the major gyres and warm (red) and cold (blue) currents near coastal areas of the continents. Also examine the general flow in equatorial regions and also how the flow in the Southern Ocean differs from the other ocean basins.

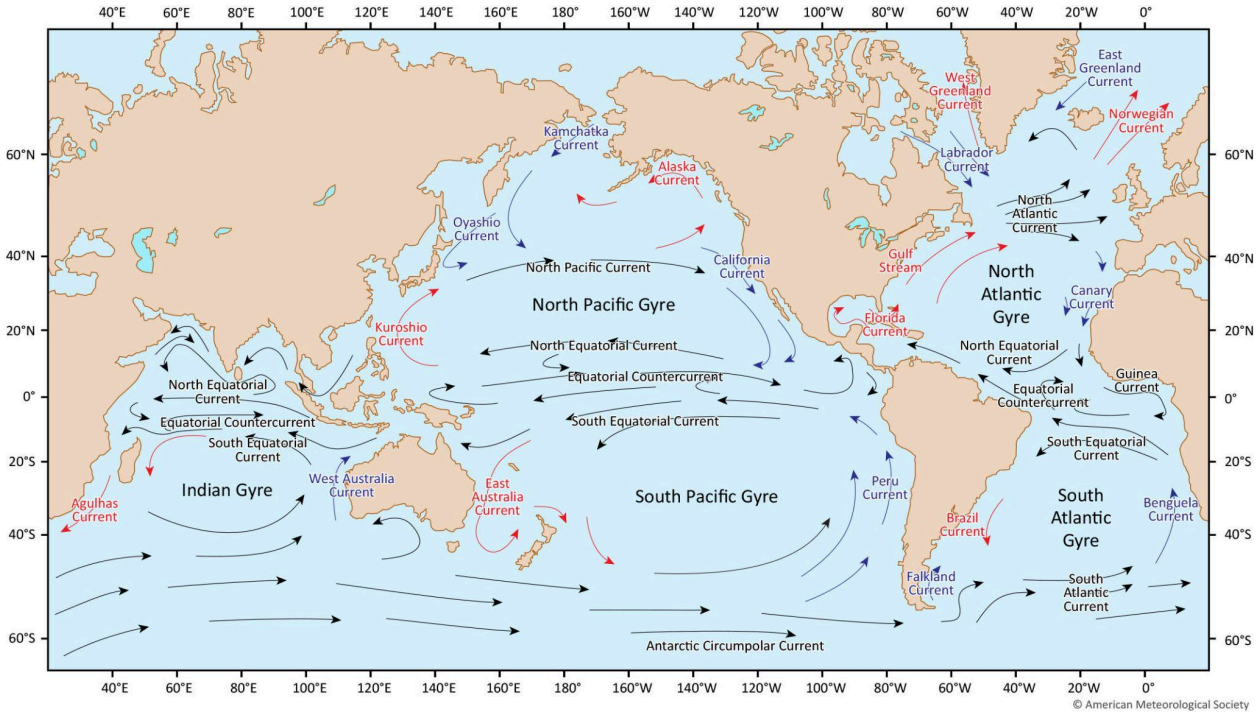


Figure 7. Long-term average pattern of wind-driven ocean-surface currents. Gyres in the ocean basin are driven by the planetary-scale atmospheric circulation. [Segar, Kish, and Mills, 2018]

Understanding the physics of wind-driven surface ocean currents and circulation leads to a better grasp of surface ocean circulation across the five major basins of the global

ocean (**Figure 7**). In the Atlantic Ocean basin, general surface ocean circulation includes a clockwise **North Atlantic Gyre,** characterized by a northward warm **Gulf Stream** in the west, an eastward **North Atlantic Current** in the north, a southward cold **Canary Current** in the east, and a westward **North Equatorial Current** in the south) and a counterclockwise **South Atlantic Gyre,** which consists of a southward warm **Brazil Current** in the west, an eastward **South Atlantic Current** in the south, a northward cold **Benguela Current** in the east, and a westward **South Equatorial Current** in the north. Smaller counterclockwise **subpolar gyres** transport cold water currents south to the **western Atlantic,** around the tip of Greenland to the **Labrador Sea**. The **Labrador Current** carries icebergs from Greenland into the **North Atlantic** shipping channels.

General Circulation in the Pacific Ocean Basin

In the Pacific Ocean basin, general surface ocean circulation consists of a clockwise **North Pacific Gyre**, which includes the northward warm **Kuroshio Current** in the west, the eastward **North Pacific Current** in the north, the southward cold **California Current** in the east, and the westward **North Equatorial Current** in the south. It also includes a counterclockwise ***South Pacific Gyre***, which has the southward warm **East Australia Current** in the west, the eastward **South Pacific Current** in the south, the northward cold **Peru Current** in the east, and the westward **South Equatorial Current** in the north. The tropical regions of the ocean *basins* are **stratified** and characterized by a thin, permanent shallow layer of warm water over deeper, colder water.

The convergence of the trade winds near the equator drives an east-west flow in the shallow ocean surface layer across the expansive open waters of the Tropical Pacific. Under normal conditions, this flow causes warmer surface waters to accumulate along the western margin of the Pacific Ocean basin. This accumulation creates a horizontal pressure gradient, which supports a weaker west-east countercurrent just north of the equator.

The general east-west movement of warm, equatorial surface waters also leads to a deepening of the **thermocline** from east to west. As a result, **equatorial upwelling** brings colder waters to the surface in the eastern Pacific, maintaining a significant east-west temperature gradient. This gradient drives a pattern of zonal atmospheric circulation and convection in the tropics known as the **Walker Circulation**.

Fluctuations in the temperature gradient across the Tropical Pacific influence the Walker Circulation, which, in turn, affects ocean currents. These interactions can create feedback loops, potentially leading to instability in the atmosphere-ocean system—a phenomenon referred to as the **El Niño-Southern Oscillation (ENSO)**. Due to the vast

size of the Tropical Pacific, shifts in heat distribution between the ocean and atmosphere associated with ENSO can impact regional and global weather patterns. Additionally, the western margin of the Pacific is influenced by the seasonal shift in prevailing winds and precipitation patterns linked to the Southeast Asian Monsoon.

General Circulation in the Indian Ocean Basin

In the Indian Ocean Basin, the general circulation is dominated by a single, counterclockwise **Indian Gyre,** which includes the southward, warm **Agulhas and East Madagascar Currents** in the west; the eastward **South Indian Current** in the south; the northward, cold **West Australian Current** in the east; and the westward **South Equatorial Current**. The Indian Ocean extends only to 20°N and is bounded to the north by the Asian continent. As a result, circulation in the northern Indian Ocean basin, as well as in sub-basins like the **Arabian Sea** and the **Bay of Bengal,** is significantly influenced by land. In the summer, the land masses north of the Indian Ocean are much hotter than the cooler surface waters of the northern Indian Ocean. This creates a pattern of convective circulation where low pressure is centered on the Asian (sub-)continent, and high pressure is centered over the northern Indian Ocean. During the winter, the surface waters in the north Indian Ocean are warmer than the land surfaces of the Asian (sub-)continent, resulting in a pattern of convective circulation where high pressure is focused on the Asian (sub-)continent and low pressure is over the northern Indian Ocean. This monsoonal reversal in wind direction and precipitation leads to dramatic seasonal reversals in surface current directions in the north Indian Ocean.

General Circulation in the Arctic Ocean Basin

Surface ocean circulation in the Arctic Ocean features a single clockwise gyre, the **Beaufort Gyre**, situated in the **Beaufort Sea**, and a Transpolar Current that runs from the Beaufort Sea to the North Atlantic Ocean (**Figure 8**).

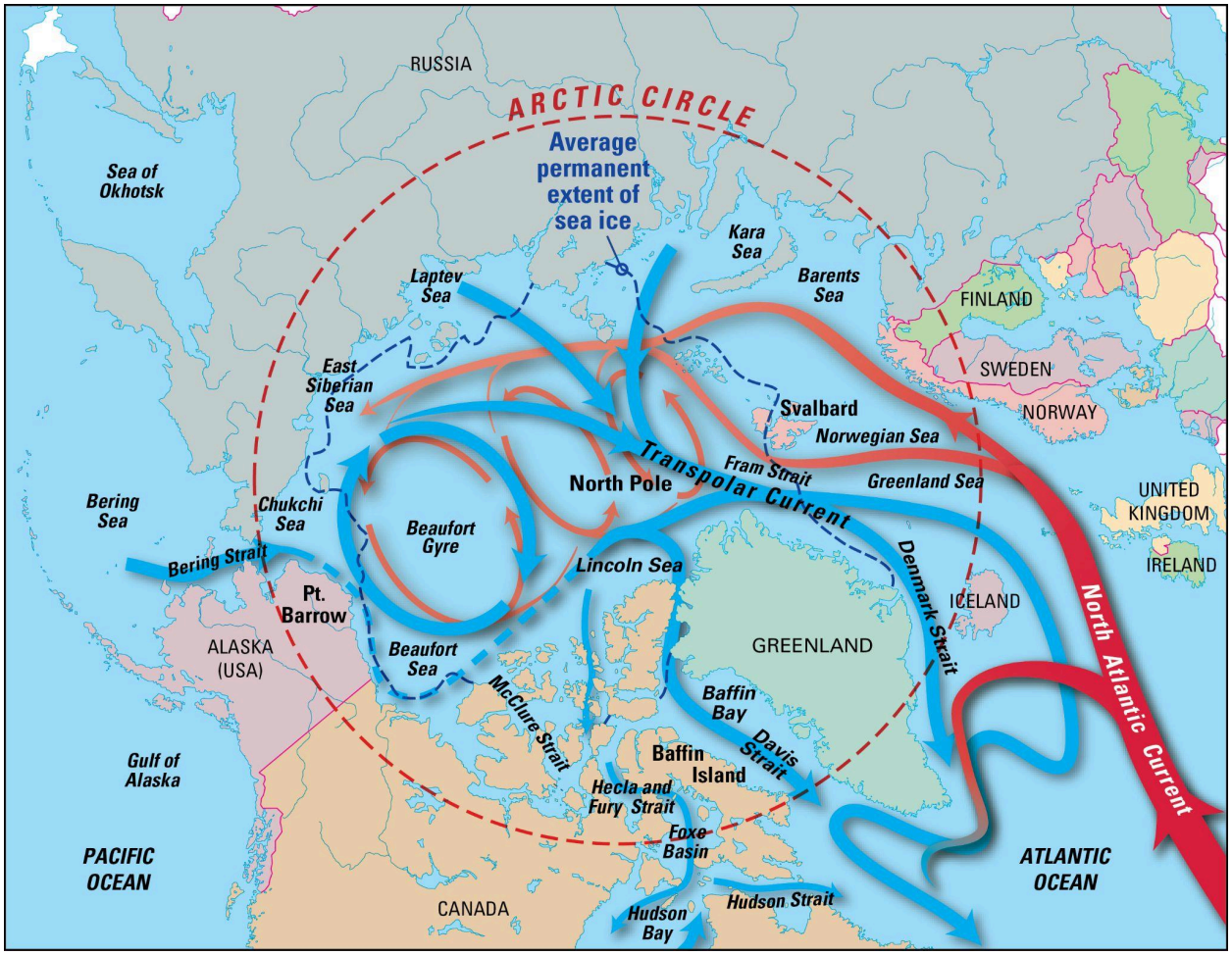


Figure 8. Circulation in the Arctic Ocean. [Courtesy of Jack Cook/Woods Hole Oceanographic Institution, Used with Permission]

The Arctic Ocean basin is distinctive compared to other ocean basins. It is primarily located north of 60°N and receives less net annual solar radiation than basins at lower latitudes. This ocean basin is surrounded mainly by land, leading to limited exchange with lower-latitude ocean basins. A section of the Arctic Ocean is covered by **sea ice** year-round. Sea ice is essentially frozen seawater. It can be seasonal, forming in winter and completely melting in summer, or it may develop into multiyear sea ice that lasts from year to year. A significant portion of Arctic sea ice is multiyear sea ice, which is fresher than the surrounding seawater from which it originated due to the rejection of salts as brines during freezing, **a process known as brine rejection**. In addition, four major river systems and numerous smaller rivers contribute freshwater to the basin. These freshwater inputs, along with freshwater from the melting of multiyear sea ice and land ice from the nearby **Greenland Ice Sheet** into the semi-enclosed Arctic Ocean basin, make the surface waters of the Arctic Ocean considerably fresher than those of other major ocean basins. This affects water column stratification and structure, establishing a two-layer surface circulation in the Arctic Ocean basin. Generally, cold,

relatively fresh water from the North Pacific Ocean flows into the Arctic Ocean through the Bering Strait. It mixes with the relatively fresh waters of the Arctic Ocean and is drawn into the clockwise Beaufort Gyre. Colder, fresher surface water exits into the North Atlantic Ocean via the Transpolar Current through three gateways: the Fram Strait, the Davis Strait, and the Hudson Strait. Warmer, saltier, dense waters from the North Atlantic Ocean enter the Arctic Ocean through the Fram Strait via the North Atlantic Current and circulate beneath the colder, fresher surface water layers of the Arctic Ocean.

General Circulation in the Southern Ocean Basin

In the Southern Ocean basin around the continent of Antarctica, where there are no blocking continents, general surface ocean circulation is dominated by the largest volume surface current in the Global Ocean, the **Antarctic Circumpolar Current (ACC)**. It is also known as the *West Wind Drift*, after the strong westerly winds driving it. South of the southernmost bound of the ACC, polar easterlies drive a weaker *East Wind Drift* around Antarctica. Small gyres exist in the Ross and Weddell Seas. Circulation around the Antarctic is influenced by sea ice formation and wind-forcing off the **Antarctic Ice Sheet(s)** and their standing **ice shelves**. These ice sheets are the largest masses of standing land ice on Earth and contain about 70% of the freshwater on Earth.

Group Review and Discussion:

1) *How does Ekman Mass Transport relate to the prevailing surface winds?*
2) *Explain the concept of geostrophic balance within a subtropical ocean gyre.*
3) *What forces create a western boundary current?*
4) *Describe the features of warm-core and cold-core eddies.*
5) *Describe common features of major currents in the Atlantic, Pacific, and Indian Ocean basins.*
6) *What are the major currents near the equator, and how do they relate to ENSO?*
7) *How do currents with the Arctic and Southern Ocean basins differ from the other major ocean basins?*

Elaborate | Understanding Meanders and Warm- and Cold-Core Rings

Fast-moving western boundary currents can be identified by the formation of large, rotating rings of warm or cold water with rotational current directions distinct from the direction of the main current. This activity utilizes “AMS Pressure Blocks” to investigate how meanders in fast-moving western boundary currents can form warm- and cold-core mesoscale eddies. If you don’t have access to a set of physical

pressure blocks, this section can still be completed using the diagrams provided, along with some specifications on the simulated blocks.

Simulated blocks:
Whether red or blue, the blocks have the following common characteristics:

- Each block has the same weight regardless of the volume each occupies
- Each block has the same size square base
- Each block exerts the same downward pressure on the surface beneath them (because the equivalent weight acts on the same size base)

The red block represents warm, less dense water, while the blue block represents cold, denser water. Because water expands when heated, a warm air mass takes up more space than a cold air mass. Although their weight and pressure are the same, the blue block or a cold air mass is denser than the red block or a warm air mass and thus takes up less vertical space.

This activity will help you describe how meanders in fast-moving western boundary currents can form warm- and cold-core mesoscale eddies. It will also help you understand the sea surface slopes associated with mesoscale eddies and ocean surface currents.

Figure 9 illustrates the northern branch of the Gulf Stream, a warm, fast-moving western boundary current that carries surface waters from the Tropical Atlantic toward the North Atlantic along the east coast of the United States. This image was derived from infrared measurements taken by the NASA Moderate-resolution Imaging Spectroradiometer (MODIS) satellite on a nearly cloud-free day. The coldest waters are depicted in purple, with blue, green, yellow, and red representing progressively warmer temperatures. Temperatures range from approximately 7 to 22°C, with the warm Gulf Stream waters appearing dark red. Clockwise-rotating warm-core mesoscale eddies are visible north of the Gulf Stream's core, while counterclockwise-rotating cold-core mesoscale eddies can be observed south of the Gulf Stream.

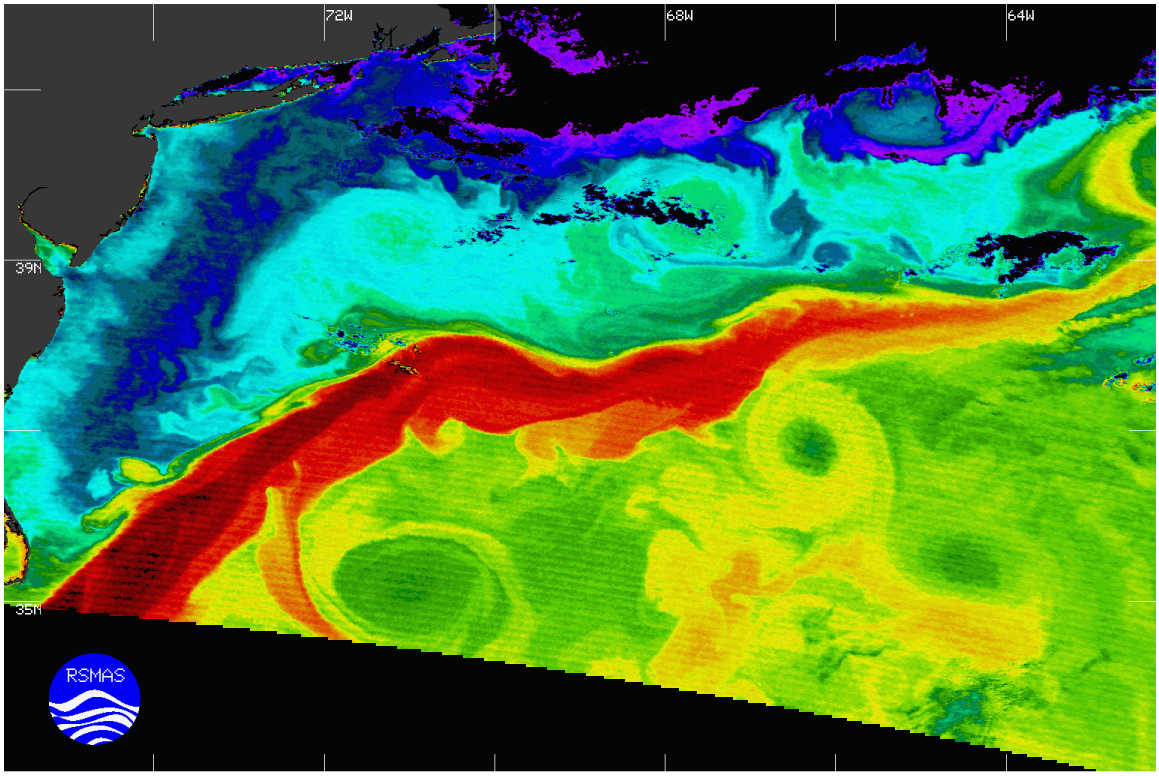


Figure 9. Infrared satellite images showing ocean temperatures in the vicinity of the Gulf Stream. [NASA]

The Gulf Stream separates warmer waters from the mid-latitudes of the central Atlantic from colder waters of the North Atlantic. It is clear from the satellite image that the Gulf Stream does not follow a straight-line path. Instead, it follows a winding path that is determined by local water conditions and bathymetry. These bends or turns in its path are called meanders. Occasionally, a meander will pinch off the main Gulf Stream flow to form rotating rings. If the meander pinches off to the north of the Gulf Stream, it traps warmer waters from south of the Gulf Stream at the center of the ring. If the meander pinches off to the south of the Gulf Stream, it traps colder waters from north of the Gulf Stream at the center of the ring. These warm-core and cold-core rings are mesoscale eddies.

To model the ocean surface along the northern branch of the ***Gulf Stream***, arrange (or visualize, using **Figure 10**) four of the blue ***AMS Pressure Blocks*** side-to-side (on their square bases) in a straight line on a table or desk top in front of you from your left to right. Arrange (or visualize) four of the red AMS Pressure Blocks side-to-side (on their square bases) in a straight line below the blue blocks so they are parallel to, aligned with, and touching the blue blocks. You should now have two parallel lines of blocks in front of you. In this activity, the blue blocks represent colder, more dense waters to the north of the Gulf Stream, as depicted in **Figure 9,** and the red blocks represent warmer, less dense waters to the south of the Gulf Stream.

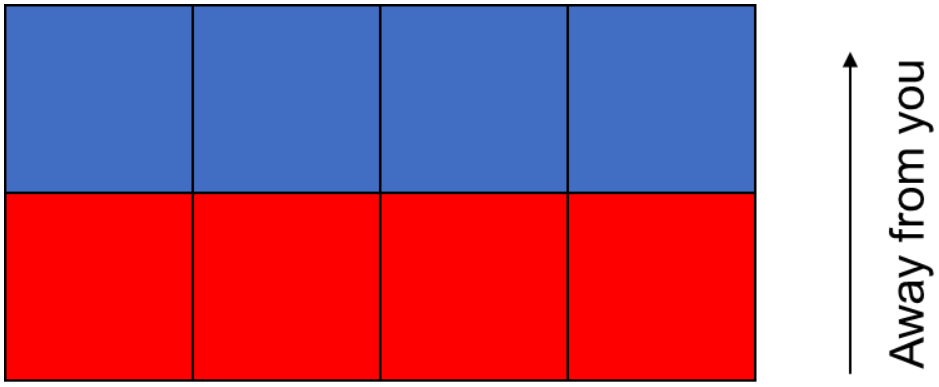


Figure 10. Initial arrangement of AMS Pressure Blocks to model the northern branch of the Gulf Stream.

1. According to the AMS Pressure Block model of the northern branch of the Gulf Stream, the surface of the warmer, less dense water to the south would be _____ than the surface of the colder, more dense water to the north.
   a. higher
   b. lower

To simulate a northward meander in the northern branch of the Gulf Stream, place (or visualize, using the figure below) the extra red block directly below one of the middle blocks in the line of red blocks on the table or desk top in front of you. Gently push the red block away from you towards the lines of blocks until it is in line with the other three red blocks in your initial setup. The resulting pattern of red and blue blocks represents a meander to the north of the northern branch of the Gulf Stream (**Figure 11**). Looking at the red and blue blocks the resulting alignment leads to a surface slope downward off the meander (from red to blue). This represents a horizontal pressure gradient that moves water off the center of the meander. In the Northern Hemisphere, the Coriolis effect deflects this motion to the right as water tries to flow downhill.

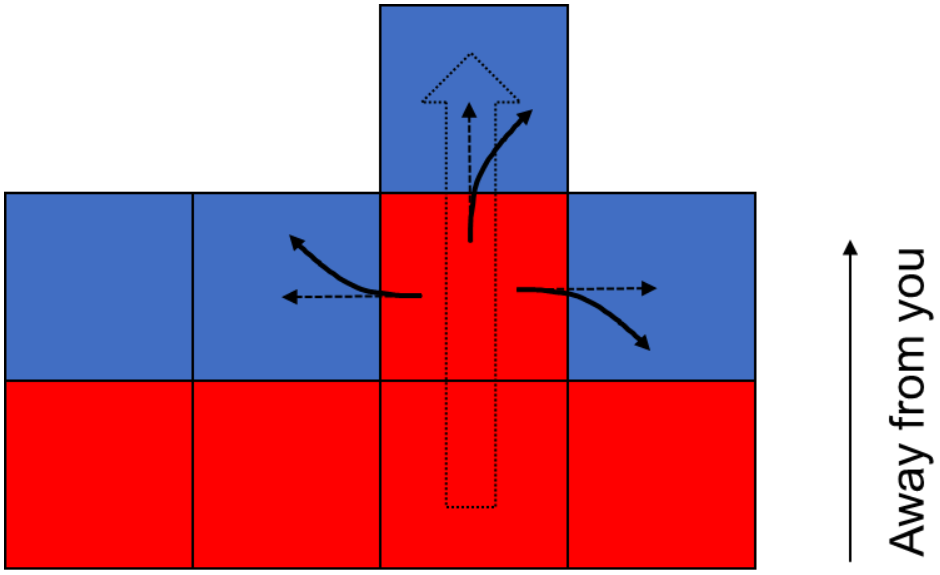


Figure 11. Arrangement of AMS Pressure Blocks to model a northward meander in the northern branch of the Gulf Stream. The solid black lines show the direction of surface flow off the meander as a result of the horizontal pressure gradient (dashed lines) and the Coriolis force.

2. According to the AMS Pressure Block model of a northward meander in the northern branch of the Gulf Stream, surface flow off the meander (as viewed from above) would be in a general _____ direction.
   a. clockwise
   b. counterclockwise

To simulate a northward meander in the northern branch of the Gulf Stream pinching off to form a ring, gently slide (or visualize, using the figure below) the displaced red block and the three blue blocks around it away from you until they are at least one block width away from the line of red blocks. Add a fourth blue block directly below the displaced red block. The resulting pattern shows a red block with blue blocks surrounding it on all sides. This represents a warm core ring that results from the pinching off of a meander to the north of the northern branch of the Gulf Stream (**Figure 12**). This is a warm-core mesoscale eddy. The alignment of red and blue blocks in the ring results in a surface slope downward off the ring (from red to blue). This represents a horizontal pressure gradient that moves water off the center of the ring. In the Northern Hemisphere, the Coriolis effect deflects this motion to the right as water tries to flow downhill.

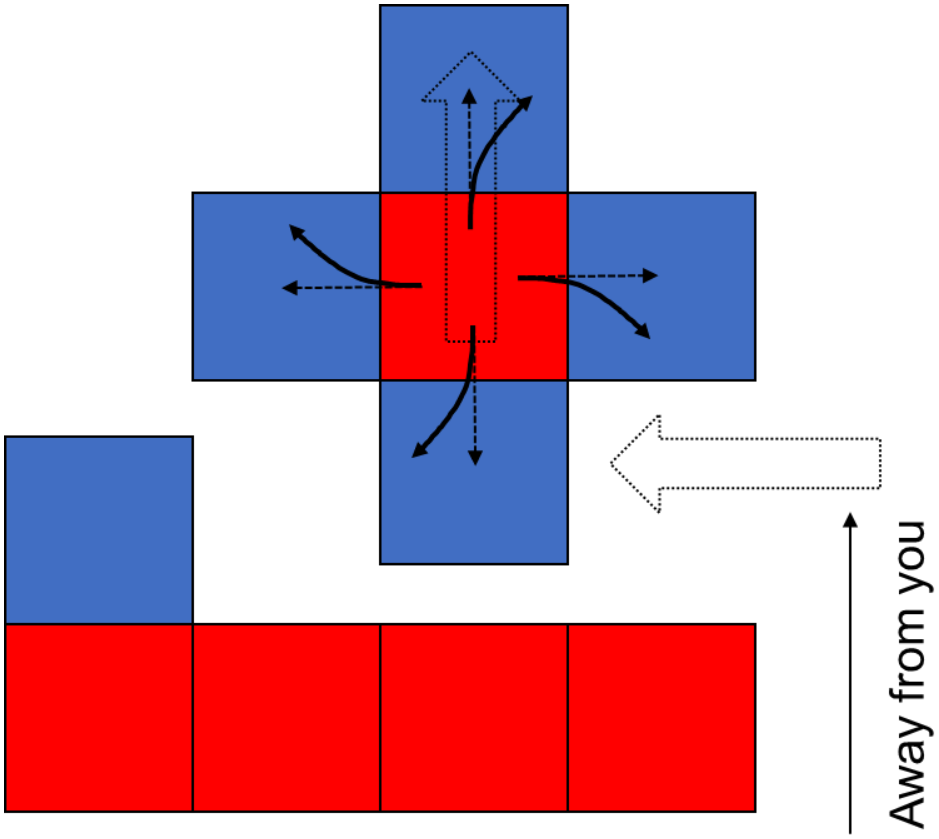


Figure 12. Arrangement of AMS Pressure Blocks to model a warm-core mesoscale eddy that forms from the pinching off of a northward meander in the northern branch of the Gulf Stream. The solid black lines show the direction of surface flow off the center of the ring as a result of the horizontal pressure gradient (dashed lines) and the Coriolis force.

3. According to the AMS Pressure Block model of a warm-core mesoscale eddy that forms a northward meander in the northern branch of the Gulf Stream, the surface flow of the warm-core mesoscale eddy (as viewed from above) would be in a _____ direction.
   a. clockwise
   b. counterclockwise

Return your AMS Pressure Blocks to their initial alignment modeling the ocean surface along the northern branch of the Gulf Stream (Figure 9). As a review, in this activity, the blue blocks represent colder, more dense waters to the north of the Gulf Stream, and the red blocks represent warmer, less dense waters to the south of the Gulf Stream.

To simulate a southward meander in the northern branch of the Gulf Stream, place (or visualize) the extra blue block directly above one of the middle blocks in the line of blue blocks on the table or desktop in front of you. Gently push the blue block towards you towards the lines of blocks until it is in line with the other three blue blocks in your initial

setup. The resulting pattern of red and blue blocks represents a meander to the south of the northern branch of the Gulf Stream (**Figure 13**). Looking at the red and blue blocks, the resulting alignment leads to a surface slope downward onto the meander (from red to blue). This represents a horizontal pressure gradient that moves water towards the center of the meander. In the Northern Hemisphere, the Coriolis effect deflects this motion to the right as water tries to flow downhill.

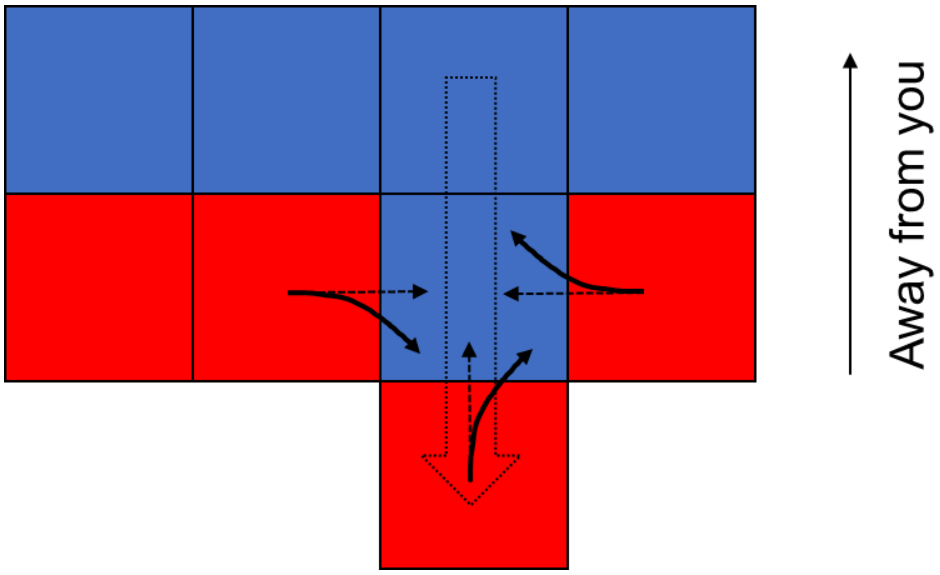


Figure 13. Arrangement of AMS Pressure Blocks to model a southward meander in the northern branch of the Gulf Stream. The solid black lines show the direction of surface flow onto the meander as a result of the horizontal pressure gradient (dashed lines) and the Coriolis force.

4. According to the AMS Pressure Block model of a southward meander in the northern branch of the Gulf Stream, surface flow off the meander (as viewed from above) would be in a general _____ direction.
   a. clockwise
   b. counterclockwise

To simulate a southward meander in the northern branch of the Gulf Stream pinching off to form a ring, gently slide (or visualize, using the figure below) the displaced blue block and the three red blocks around it towards you until they are at least one block width away from the line of red blocks. Add a fourth red block directly above the displaced blue block. The resulting pattern shows a blue block with red blocks surrounding it on all sides. This represents a cold core ring that results from the pinching off of a meander to the south of the northern branch of the Gulf Stream (**Figure 14**). This is a cold-core mesoscale eddy. The alignment of red and blue blocks in the ring results in a surface slope downward onto the ring (from red to blue). This represents a horizontal pressure gradient that moves water onto the center of the ring. In the Northern Hemisphere, the

Coriolis force deflects this motion to the right as water tries to flow downhill.

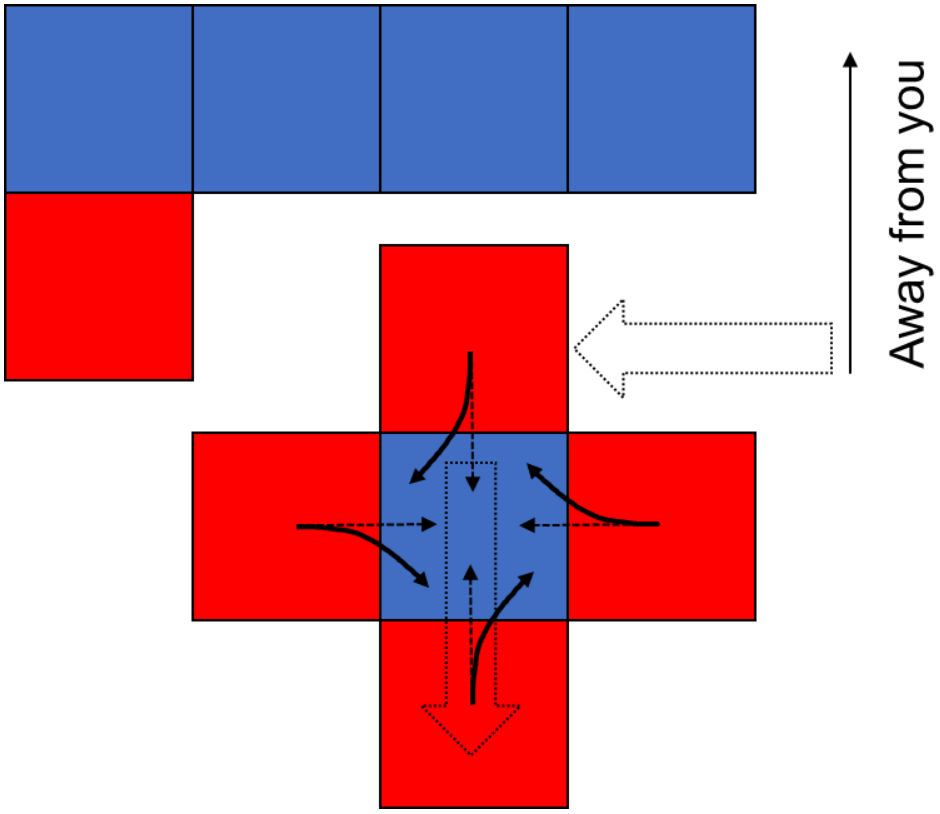


Figure 14. Arrangement of AMS Pressure Blocks to model a cold-core mesoscale eddy that forms from the pinching off of a southward meander in the northern branch of the Gulf Stream. The solid black lines show the direction of surface flow towards the center of the ring as a result of the horizontal pressure gradient (dashed lines) and the Coriolis force.

5. According to the AMS Pressure Block model of a cold-core mesoscale eddy that forms form a southward meander in the northern branch of the Gulf Stream, surface flow of the cold-core mesoscale eddy (as viewed from above) would be in a _____ direction.
   a. clockwise
   b. counterclockwise

Group Review and Discussion:

1) *Explain how AMS Pressure Blocks can be used to model warm- and cold-core mesoscale eddies near western boundary currents in the Southern Hemisphere.*
2) *Warm- and cold-core mesoscale eddies can reach sizes of up to up to 400 km in diameter, have rotational speeds of over 0.5 m/sec and can extend to the seafloor. Large mesoscale eddies can persist for months to years. At their core,*

they also carry the characteristics of the water from which they were sourced, including marine organisms. Explain why this can influence biological processes near western boundary currents.

Evaluate | Wind-driven ocean circulation

6. Ocean “garbage patches” are mostly comprised of _____.
   a. microplastics
   b. water bottles and other larger containers

7. The most publicized example of an ocean garbage patch is associated with the _____.
   a. Antarctic Circumpolar Current
   b. North Atlantic Gyre
   c. North Pacific Gyre
   d. South Pacific Gyres

8. In the Northern Hemisphere, Ekman Mass Transport is _____ of the prevailing surface wind direction.
   a. 45 degrees to the left
   b. 45 degrees to the right
   c. 90 degrees to the left
   d. 90 degrees to the right

9. Geographic balance is between which two forces?
   a. Coriolis Effect and friction
   b. Coriolis Effect and pressure gradient force
   c. Pressure gradient force and friction
   d. Pressure gradient force and centripetal force

10. Which factor is responsible for the formation of the faster boundary currents on the western side of a subtropical ocean gyre?
    a. increase in the Coriolis effect with latitude
    b. frictional drag along the coast
    c. steeper ocean-surface slope
    d. torque from wind stress
    e. All of the above are correct.

11. Warm-core mesoscale eddies connected to a western boundary current rotate in a _____ direction.
    a. clockwise
    b. counterclockwise

12. Cold-core mesoscale eddies connected to a western boundary current rotate in a _____ direction.
    a. clockwise
    b. counterclockwise

13. The Antarctic Circumpolar Current is a _____.
    a. series of wind-driven surface currents
    b. single, defined current

14. California Current is cold because it flows from higher latitudes on the _____ side of the North Pacific subtropical gyre.
    a. eastern
    b. western

15. The North Atlantic Current, which is responsible for a more temperate climate in the United Kingdom, is an extension of the _____.
    a. Canary Current
    b. East Greenland Current
    c. Gulf Stream
    d. Kurushio Current

Extend | Personal Reflection

Did you have any misconceptions before beginning the module? What were they, and how might you explain the scientific reasoning to your students?

How could you use the information and data in this module to cover your school's learning objectives or standards?

How would you scaffold the content in this module for your grade level?

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.

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National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: What is the Great Pacific Garbage Patch? Accessed 23 April 2021, https://oceanservice.noaa.gov/facts/garbagepatch.html.

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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.

Woods Hole oceanographic Institution (WHOI), 2006: Polar Discovery. Accessed 14 November 2016, http://polardiscovery.whoi.edu/arctic/circulation.html.

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