AMERICAN METEOROLOGICAL SOCIETY

# The Maury Project

# Wind-Driven Ocean Circulation

## TEACHER'S GUIDE

## The Maury Project

This guide is one of a series produced by The Maury Project, an initiative of the American Meteorological Society and the United States Naval Academy. The Maury Project has created and trained a network of selected master teachers who provide peer training sessions in precollege physical oceanographic education. To support these teachers in their teacher training, The Maury Project develops and produces teacher's guides, slide sets, 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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## Forward

This guide has been prepared to introduce fundamental understandings about the guide topic.  This guide is organized as follows:

## Introduction

This is a narrative summary of background information to introduce the topic.

## Basic Understandings

Basic understandings are statements of principles, concepts, and information.  The basic understandings represent material to be mastered by the learner, and can be especially helpful in devising learning activities and in writing learning objectives and test items.  They are numbered so they can be keyed with activities, objectives and test items.

## Activities

These are related investigations.  Each activity typically provides learning objectives, directions useful for presenting and completing the activity and questions designed to reinforce the learning objectives.

## Information Sources

A brief list of references related to the guide topic is given for further reading.

*If we except the tides, and ... those that may be created by the wind, we may lay it down as a rule that all the currents of the ocean owe their origin to difference of specific gravity between sea water at one place and sea water at another; for wherever there is such a difference, whether it be owing to difference of temperature or to difference of saltiness, etc., it is a difference that disturbs equilibrium, and currents are the consequence.*

*Matthew Fontaine Maury*
*from The Physical Geography of the Sea. 1855.*

# Introduction: Wind-Driven Ocean Circulation

The lower atmospheric circulation and the upper oceanic circulation are closely linked, with the sun being the ultimate source of energy for both circulations. Unequal heating of the atmosphere produces atmospheric circulation and wind. The wind blowing over the surface of the water drives the ocean's major surface currents. These currents, along with the wind, transfer heat from tropical regions, where there is a surplus, 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 main features of the wind-driven surface circulation are the large, roughly circular current systems, called **gyres**, which are found in most ocean basins. Driven by the prevailing wind systems and deflected by continental boundaries and Earth's rotation, the gyres help to redistribute heat from low to high latitudes. Along the western margins of ocean basins, warm ocean currents, such as the Gulf Stream, transport heat poleward. The meanders of these fast moving currents give rise to large rotating warm and cold water rings which are similar to high and low pressure cells observed in the atmosphere. Along the eastern margins of the major ocean basins, currents, such as the California Current, transport cold water to the lower latitudes.

Related to the gyre circulation patterns are other surface circulation features. In the land-locked higher latitudes of the Northern Hemisphere, the prevailing winds drive smaller gyres which redistribute heat to the polar regions. In the higher latitudes of the Southern Hemisphere where there are no blocking continents, strong westerly winds drive the largest volume surface current in the world around Antarctica. Limited by land boundaries, the surface circulation in the northern Indian Ocean actually reverses itself, driven by the seasonally reversing monsoon winds.

Along with widespread horizontal currents at the surface of the world ocean, there are limited regions where vertical circulation is set in motion by persistent winds. In some coastal and equatorial regions, the wind transports warm surface water away from the coast or equator, to be replaced by water from below. This process, called **upwelling**, brings to the sunlit surface cool, nutrient-rich water which can lead to an increase in biological production.

Recent research is investigating the global connections between the wind-driven surface circulation and the density-driven deep circulation. This is a possible mechanism by which small changes in the surface circulation can influence not only the weather, but climate and climate change.

# Basic Understandings

## The Role of the Sun

1. The Sun is the ultimate source of energy that brings about the surface circulation of the ocean.

2. Because of astronomical and atmospheric factors, ocean surfaces in tropical regions receive more of the Sun's energy over the course of a year than do those at higher latitudes.

3. In tropical regions, the radiant energy received from the Sun exceeds the radiant energy lost from Earth to space. At higher latitudes, radiation loss from Earth is greater than the solar input.

4. The imbalance between radiant energy gains and losses at different latitudes results in a poleward flow of heat that is almost entirely accomplished by atmospheric and oceanic motions.

## The Role of the Atmosphere

1. Unequal heating of the atmosphere from underlying ocean and land surfaces produces atmospheric circulations and winds.

2. The frictional effects between the resulting winds and the ocean surface produce the broad-scale horizontal water movements of the ocean's surface, called surface currents, that tend to resemble the patterns of surface winds.

3. If the Earth were not rotating, the friction of wind blowing on the ocean surface would push a thin layer of the water in the same direction, but at a small percentage of the wind's speed. This layer, in turn, would push on the layer beneath and push it into motion. This would continue downward through successive layers, like pages in a book, each with a lower speed than that of the layer above.

## Ekman Circulation

1. Since the Earth does rotate, the shallow layer of surface water set in motion by the wind will be deflected to the right of the wind's direction in the Northern Hemisphere and to the left of the wind's path in the Southern Hemisphere. This deflection is called the **Coriolis effect**.

2. Except at the Equator, where there is no Coriolis effect, each layer of water put into motion by the layer above will be further turned in direction because of the Earth's rotation.

3. When viewed from above, the changes in current direction and decreased speed with increased depth form a spiral pattern called the **Ekman spiral**.

4. Although the motion of the surface water layer can be up to 45 degrees to the right or left of the wind, the Ekman spiral phenomenon can cause the direction of net transport of water in around the top 100 meters of the ocean to be at right angles to the wind direction. This is called the **Ekman transport**.

## Gyre Circulation

1. The surface circulation of most of the major ocean basins is dominated by large, roughly circular patterns, called **gyres**, centered at about 30 degrees latitude. As seen from above, they flow clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The locations are largely 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.

2. Due to Ekman transport, water at and near the surface is moved towards the middle of the gyres from all sides, producing a broad mound of water as high as one meter at the gyres' centers.

3. In the Northern Hemisphere, water flowing down the sloping mound of the gyres is deflected to the right, due to the Coriolis effect. This reinforces the clockwise circulation of the gyres. In the Southern Hemisphere, the left turning helps to maintain the counterclockwise pattern of the gyres.

4. An added effect of the Earth's eastward rotation is the westward displacement of the ocean gyre mounds within their ocean basin. The resulting steeper ocean-surface slopes on the western sides of the gyres help produce higher water speeds in those regions. These **western boundary currents** that flow poleward include the fastest currents of the ocean. They play a major role in transporting heat from the tropics towards the poles.

5. The fast moving western boundary currents are also distinguished by the formation of large rotating warm and cold water rings that form as meanders in the current become pinched off to form eddies. These eddies, which may reach a size of 200 miles (325 km), a rotation speed of over 1 knot (0.5 m/sec), and extend to the seafloor, have similarities with high and low pressure cells observed in the atmosphere.

## Surface Circulation Features

1. In the northern Indian Ocean which extends to only 20 degrees North Latitude, the surface circulation is dominated by the monsoon wind systems and undergoes dramatic seasonal reversals in direction.

2. In tropical latitudes, warm surface water is piled up in the western margin of the ocean basins by the steady trade winds and westward flowing equatorial currents. The resulting downhill flows of water in an easterly direction are called equatorial counter currents.

3. Around the Antarctic, where there are no blocking continents, flows the largest volume surface current, the Antarctic Circumpolar Current. It is also known as the West Wind Drift, after the strong winds driving it.

4. In the high latitudes of the Northern Hemisphere, where current flow is driven by cyclonic wind systems and modified by land masses, smaller counterclockwise subpolar gyres form, bringing cold water currents south to the western basins. One of these, the Labrador Current, carries icebergs, like the one instrumental in the sinking of the Titanic, into the North Atlantic shipping channels.

5. Farthest north, the Arctic Sea, which is almost surrounded by land and covered by ice, has a clockwise gyre.

## Upwelling

1. There are regions where the winds and surface currents cause surface water to move away from the area and to be replaced by the vertical movement of colder water from below. Such occurrences are called **upwelling**.

2. In coastal regions, upwelling can result from water being moved by Ekman transport away from the coast by winds along the shore.

3. The Coriolis effect, acting on the westward flowing equatorial currents, moves water away from the equator, to be replaced by equatorial upwelling.

4. By replacing warm surface water with cooler nutrient-rich water from below, upwelling increases the concentration of nutrients in sunlit water that can lead to an increase in biological productivity.

## Whole Ocean Circulation

1. On a global scale, the connections between wind-driven surface currents, density-driven deep circulation, and the atmosphere are being investigated.

2. This research into whole-ocean circulation may help to identify the mechanisms by which small changes in surface circulation can influence not only the weather, but climate and climate change as well.

# Activity: Predicting the Patterns and Characteristics of Surface Ocean Currents

## Introduction

When viewed from space, the surface currents of the major ocean basins can be seen to follow the prevailing wind systems that drive them. Contained by continental boundaries and deflected by the Earth's rotation, these surface currents flow in large, roughly circular patterns called gyres. The **gyres** play an important role in redistributing heat from the low to the high latitudes, thus influencing ocean temperature, weather, and climate. The following activity investigates gyres by first looking at single surface currents and then building to a global perspective of ocean gyre circulation.

## Materials

A set of ***Current Cards***, ***Global Ocean Basin Chart***, and ***Global Ocean Surface Current Chart***.

## Objectives

After completing this investigation, you should be able to:

* Describe the typical gyre circulation pattern found in each of the major ocean basins.

* Describe the relative speeds, temperatures, and directions of the currents comprising a typical gyre.

Method

1. Cut out the entire set of current cards. Sort them into four groups by Northern or Southern Hemisphere and Atlantic or Pacific Ocean basin. For example, all four Northern Hemisphere Atlantic cards should be together in one group and all Southern Hemisphere Atlantic in another group.

2. Randomly choose one of these four groups. From the selected group, choose <u>two</u> current cards and examine the front of the cards. On the ***Global Ocean Basin Chart***, pencil in these two currents. Flip the cards over and examine the information on the back, comparing and contrasting them to identify any relationships between current characteristics, such as direction of flow and temperature. On the chart, write the temperature information from the back of the card next to the currents.

3. Use these relationships, and the limited information contained on the two current cards, to predict the location and characteristics of the other two currents in the same ocean basin and hemisphere. On the ***Global Ocean Basin Chart***, pencil in lightly your predictions of these two currents and their temperatures. Check your predictions by examining the remaining two cards. If your predictions were not correct, try to determine why they were not right and draw in the currents as shown on the cards.

4. Once all of the first group of cards have been examined, select the next group of cards from the other ocean basin in the same hemisphere. From this group, select only <u>one</u> card. Examine both sides of the card and on the chart, pencil in this current with its temperature. Use what you have leaned so far to predict the location and characteristics of the other three currents in this ocean basin and hemisphere. On the chart, pencil in lightly these three currents and their temperatures as you predict them. Check your predictions by examining the remaining cards and make any changes on your chart.

5. Now select, in turn, each of the two groups of cards from the opposite hemisphere. Follow the same procedure above, selecting two cards from the first group and <u>one</u> card from the second group, to make your predictions. Again pencil in your predictions lightly and make any corrections on your chart after you have looked at the cards.

6. Use what you have learned about global surface circulation from this activity to predict the circulation pattern of the Southern Hemisphere Indian Ocean. On the ***Global Ocean Basin Chart***, pencil in your predicted currents with their temperatures.

7. The ***Global Ocean Surface Current Chart*** depicts most of the world's major ocean currents, including those shown on the activity cards. Use this chart to check your predictions about the South Indian Ocean.

## Questions

Now use the current cards, the ***Global Ocean Surface Current Chart***, and what you have learned about this activity to answer the following questions about wind-driven circulation:

1. The Trade Winds that prevail between the equator and a latitude of 30 degrees have strong east to west components. Ocean currents under the Trade Winds flow generally in the (<u>***same***</u>) (<u>***opposite***</u>) direction.

2. The Prevailing Westerlies found between a latitude of 30 and 60 degrees are winds that have a strong west to east component. Ocean currents under the Prevailing Westerlies flow generally in the (<u>***same***</u>) (***opposite***) direction.

3. The ocean currents driven by these prevailing wind systems are deflected by continental boundaries to help form the gyres. The one latitude where blocking continental boundaries are lacking is (***0***) (***30 N***) (***30 S***) (***60 N***) (***60 S***).

4. The ocean gyres in the major ocean basins form large, roughly circular, closed currents which are centered at a latitude of approximately (***0***) (***30***) (***60***) degrees.

5. As seen from space, the gyre circulation patterns in the Northern Hemisphere show a (***clockwise***) (***counterclockwise***) flow. In the Southern Hemisphere, these gyre circulations are (***clockwise***) (***counterclockwise***).

6. Near Perth, located on the west coast of Australia, the ocean gyre current flows from the direction of the (***Equator***) (***South Pole***).

7. In ocean gyres, regardless of hemisphere, warm water is transported poleward in the (***eastern***) (***western***) region of each ocean basin. The cold currents from the higher latitudes are found in the (***eastern***) (***western***) region of each ocean basin.

8. Near Peru, located on the west coast of South America, the ocean gyre current is (***warm***) (***cold***).

9. In ocean gyres, regardless of hemisphere, the faster currents are found in the (***eastern***) (***western***) region of each ocean basin. The slower currents are found in the (***eastern***) (***western***) region of each ocean basin.

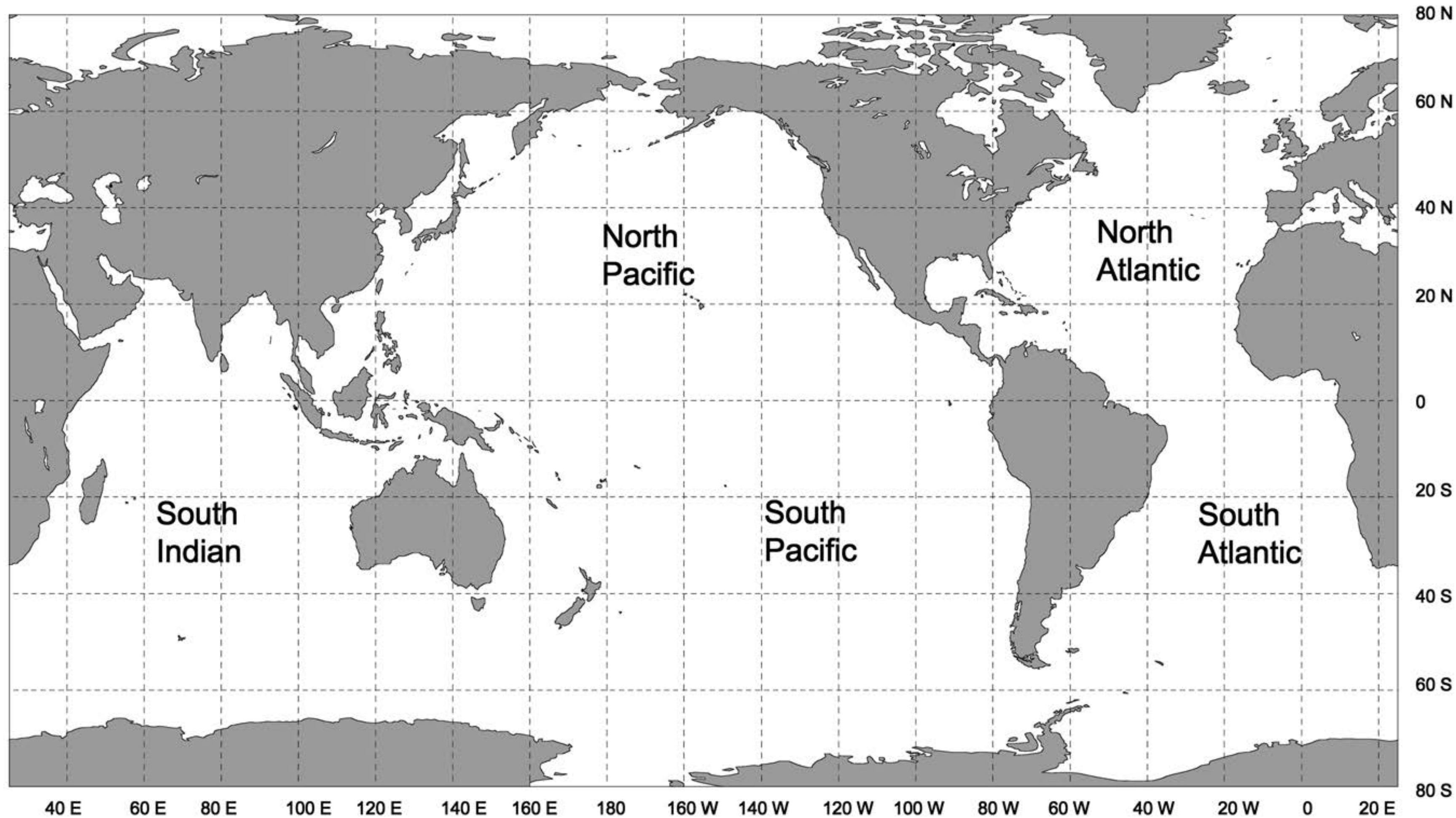
10. Near Tokyo, Japan, the ocean gyre surface current is (***fast***) (***slow***).

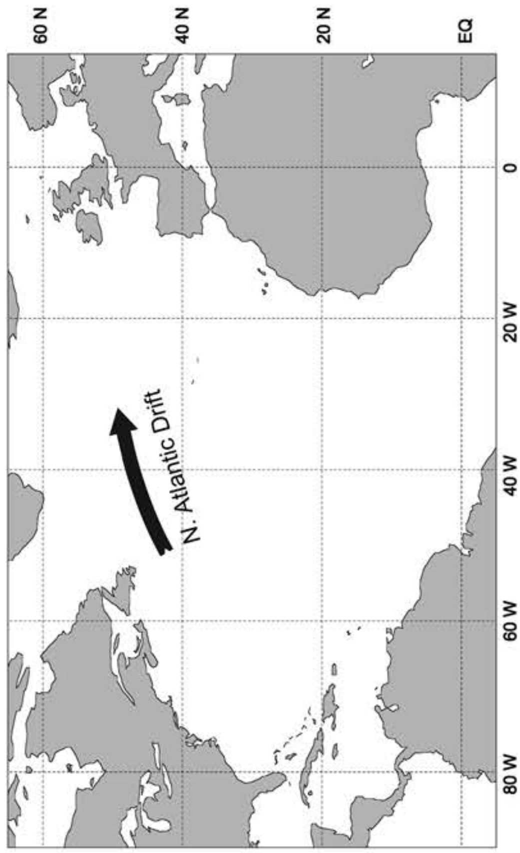
11. Locate the North Indian Ocean on the Global Ocean Surface Current Chart. There is no permanent gyre there since the ocean basin does not extend into the latitudes of the current-driving Prevailing Westerlies. Another contributing factor is the seasonal reversing of the surface currents due to the influence of the (***steady trade winds***) (***seasonally reversing monsoon winds***).

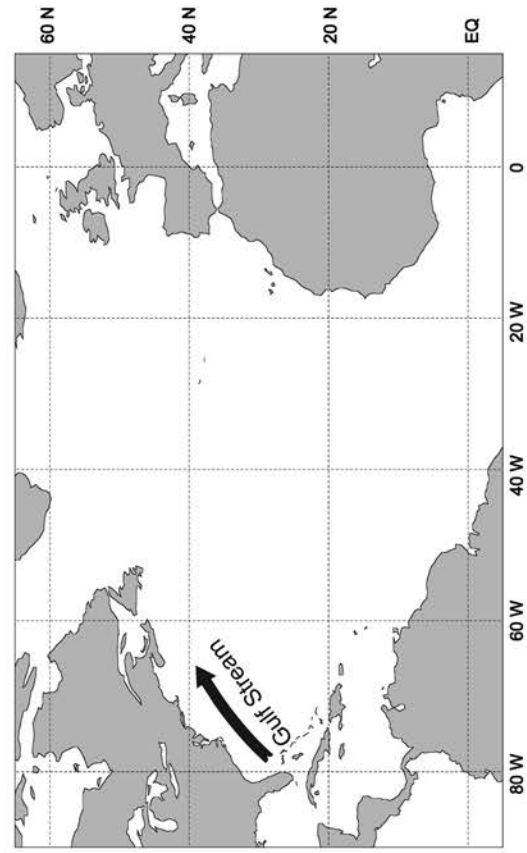
12. In the Southern Hemisphere, the strong Prevailing Westerly winds and the lack of blocking land in the southern region of all the major ocean basins contribute to the formation of a circumpolar current around Antarctica called the West Wind Drift. According to the information on the activity card, these factors help make this current the (***fastest***) (***largest volume***) in the world ocean.

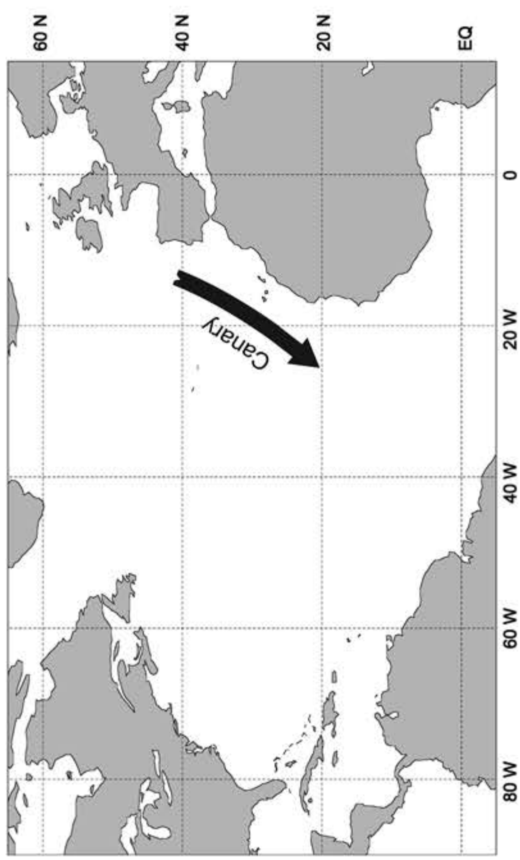
13. The surface circulation of the ocean is primarily a consequence of the interaction between the Sun, the atmosphere and the ocean. From what you have learned in this activity, explain why.

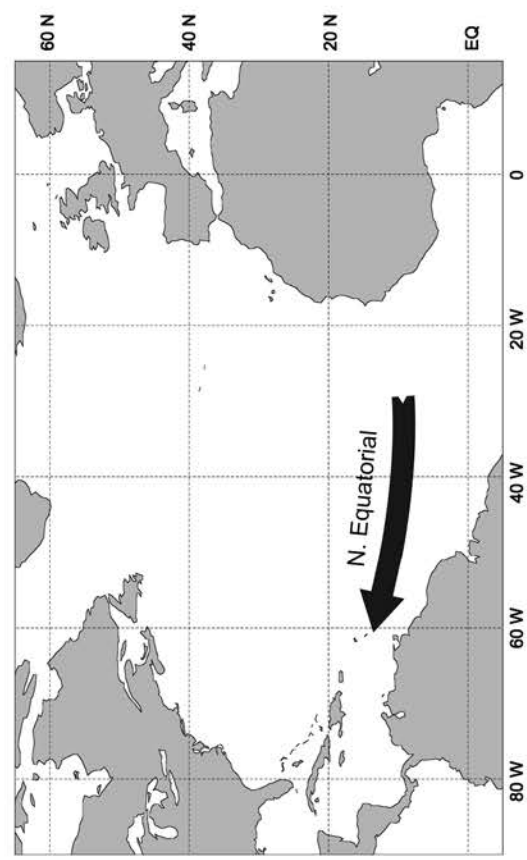
# Global Ocean Basin Chart




N. Atlantic Drift
60 N
40 N
20 N
EQ
0
20 W
40 W
60 W
80 W


Gulf Stream
60 N
40 N
20 N
EQ
0
20 W
40 W
60 W
80 W


Canary
60 N
40 N
20 N
EQ
0
20 W
40 W
60 W
80 W

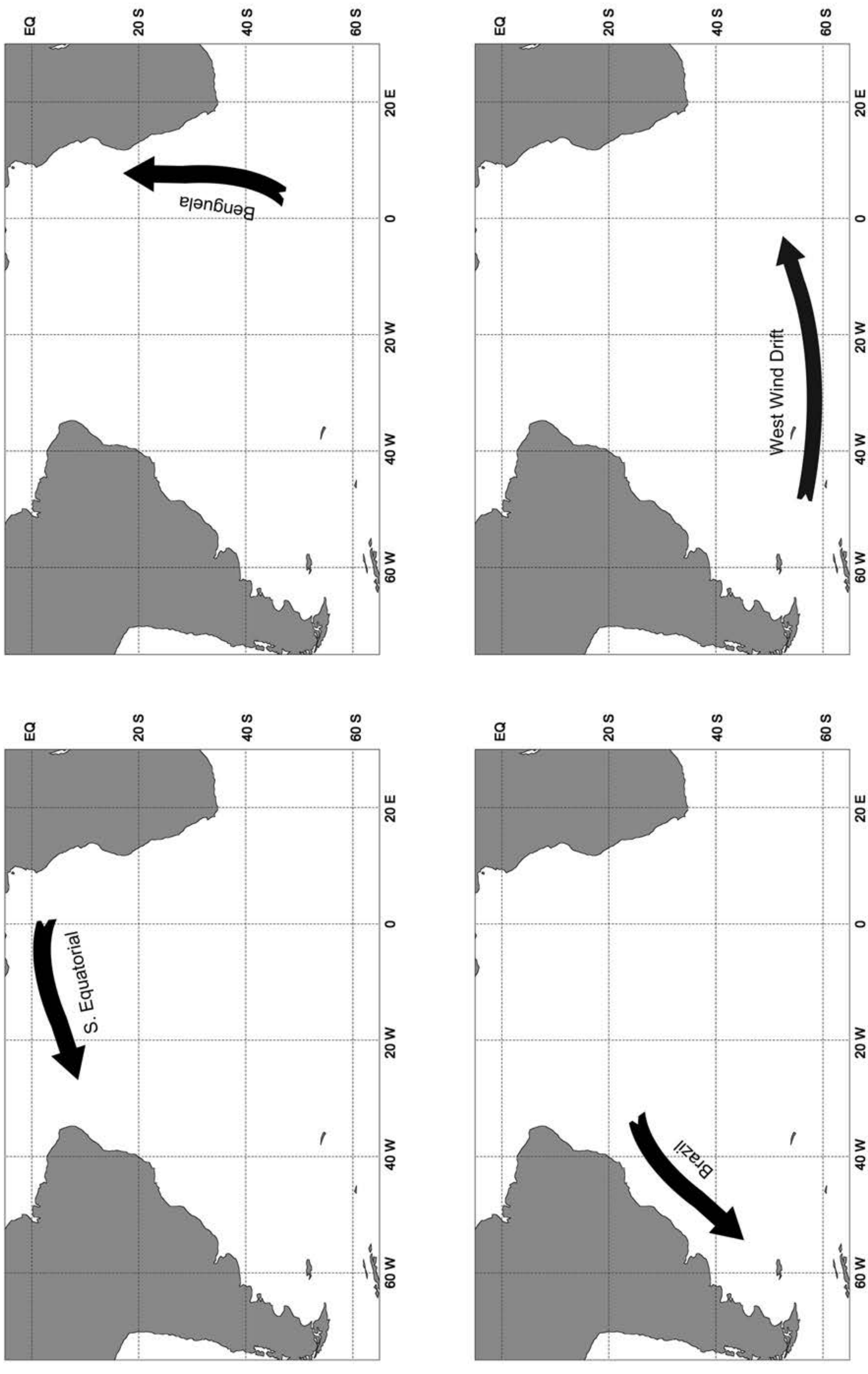

N. Equatorial
60 N
40 N
20 N
EQ
0
20 W
40 W
60 W
80 W

| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Northern |
| Location: | Northern Basin |
| Flows: | From Canada to Europe |
| Temperature: | Cooling |
| Character: | Slow, Shallow & Wide |

| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Northern |
| Location: | Eastern Basin |
| Flows: | From pole towards equator |
| Temperature: | Cold |
| Character: | Slow, Shallow & Wide |

| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Northern |
| Location: | Western Basin |
| Flows: | From equator towards pole |
| Temperature: | Warm |
| Character: | Fast, Deep & Narrow |

| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Northern |
| Location: | North of Equator |
| Flows: | From Africa to South America |
| Temperature: | Warming |
| Character: | Slow, Shallow & Wide |

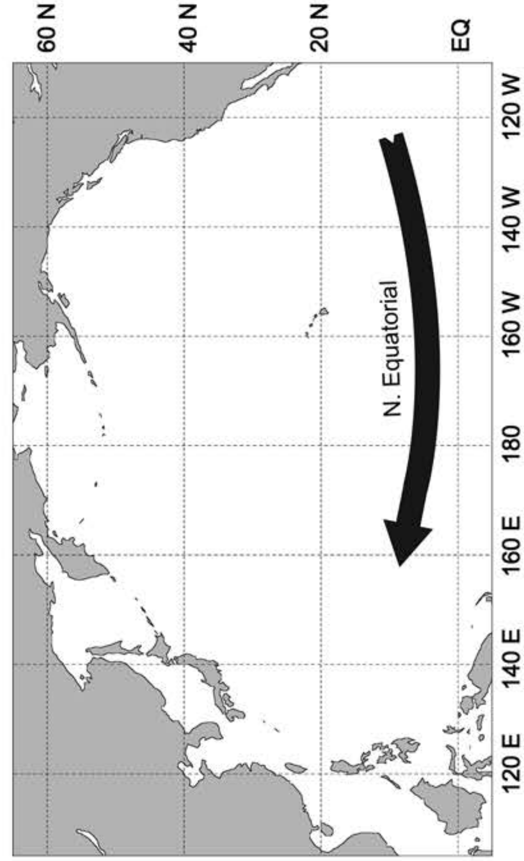

S. Equatorial
Benguela
Brazil
West Wind Drift
EQ
20 S
40 S
60 S
60 W
40 W
20 W
0
20 E

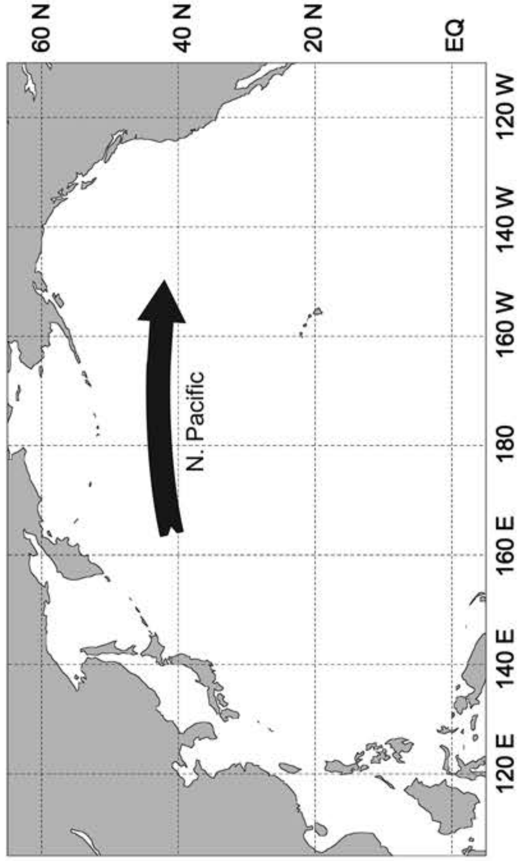
| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Southern |
| Location: | Eastern Basin |
| Flows: | From pole towards equator |
| Temperature: | Cold |
| Character: | Slow, Shallow & Wide |

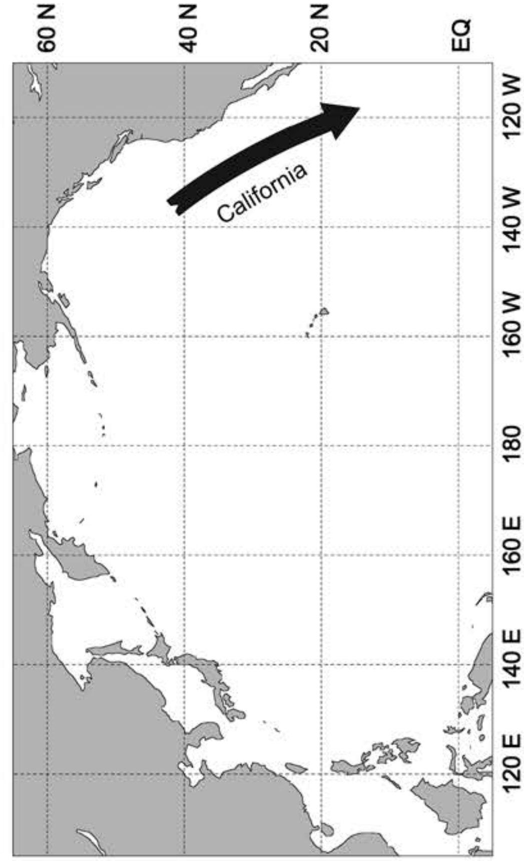
| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Southern |
| Location: | South of Equator |
| Flows: | From Africa to South America |
| Temperature: | Warming |
| Character: | Slow, Shallow & Wide |

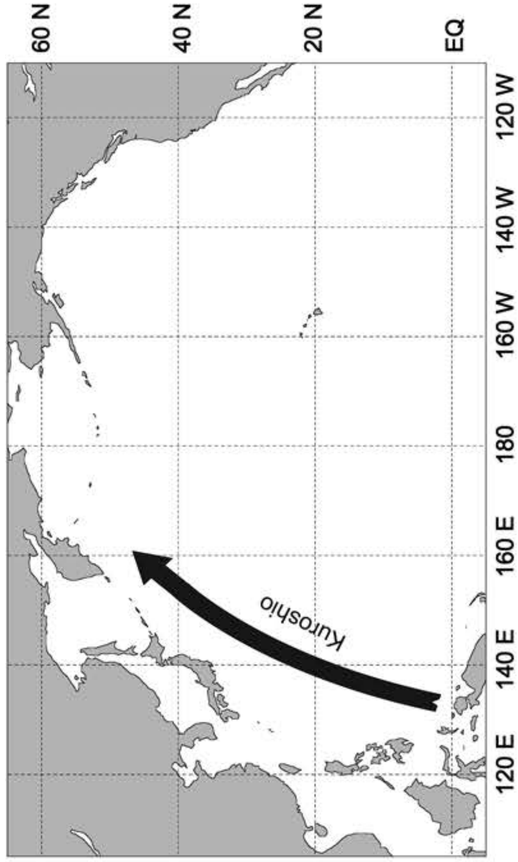
| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Southern |
| Location: | Southern Basin |
| Flows: | West to east around Antartica |
| Temperature: | Cooling |
| Character: | Slow, Largest Volume Current |

| | |
|---|---|
| Ocean: | Atlantic |
| Hemisphere: | Southern |
| Location: | Western Basin |
| Flows: | From equator towards pole |
| Temperature: | Warm |
| Character: | Fast, Deep & Narrow |


N. Equatorial
60 N
40 N
20 N
EQ
120 E
140 E
160 E
180
160 W
140 W
120 W


N. Pacific
60 N
40 N
20 N
EQ
120 E
140 E
160 E
180
160 W
140 W
120 W


California
60 N
40 N
20 N
EQ
120 E
140 E
160 E
180
160 W
140 W
120 W

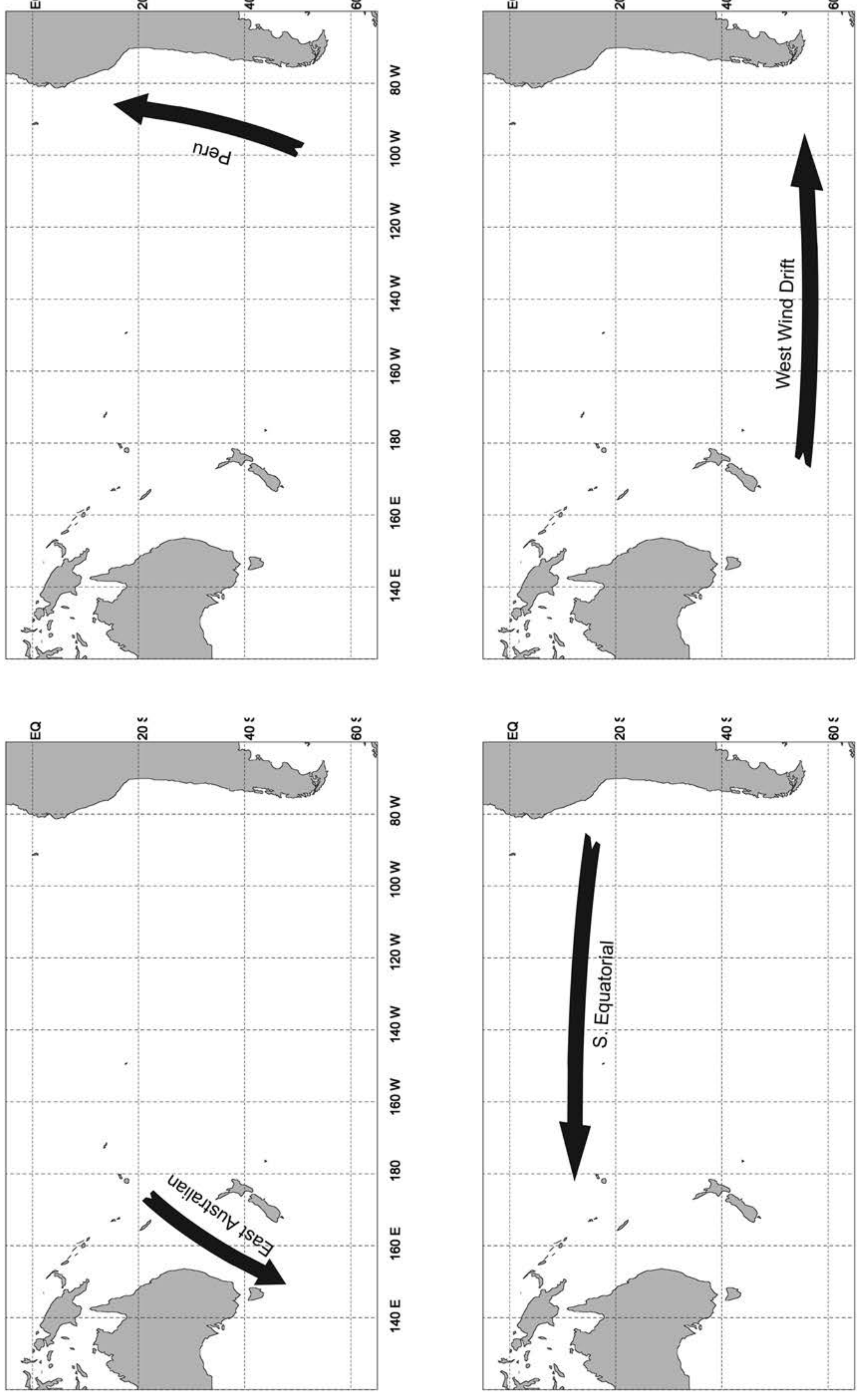

Kuroshio
60 N
40 N
20 N
EQ
120 E
140 E
160 E
180
160 W
140 W
120 W

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Northern |
| Location: | Western Basin |
| Flows: | From equator towards pole |
| Temperature: | Warm |
| Character: | Fast, Deep & Narrow |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Northern |
| Location: | Northern Basin |
| Flows: | From Asia to North America |
| Temperature: | Cooling |
| Character: | Slow, Shallow & Wide |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Northern |
| Location: | Eastern Basin |
| Flows: | From pole towards equator |
| Temperature: | Cold |
| Character: | Slow, Shallow & Wide |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Northern |
| Location: | North of Equator |
| Flows: | From Central America to S.E. Asia |
| Temperature: | Warming |
| Character: | Slow, Shallow & Wide |


Peru
East Australian
S. Equatorial
West Wind Drift
EQ
20 S
40 S
60 S
140 E
160 E
180
160 W
140 W
120 W
100 W
80 W

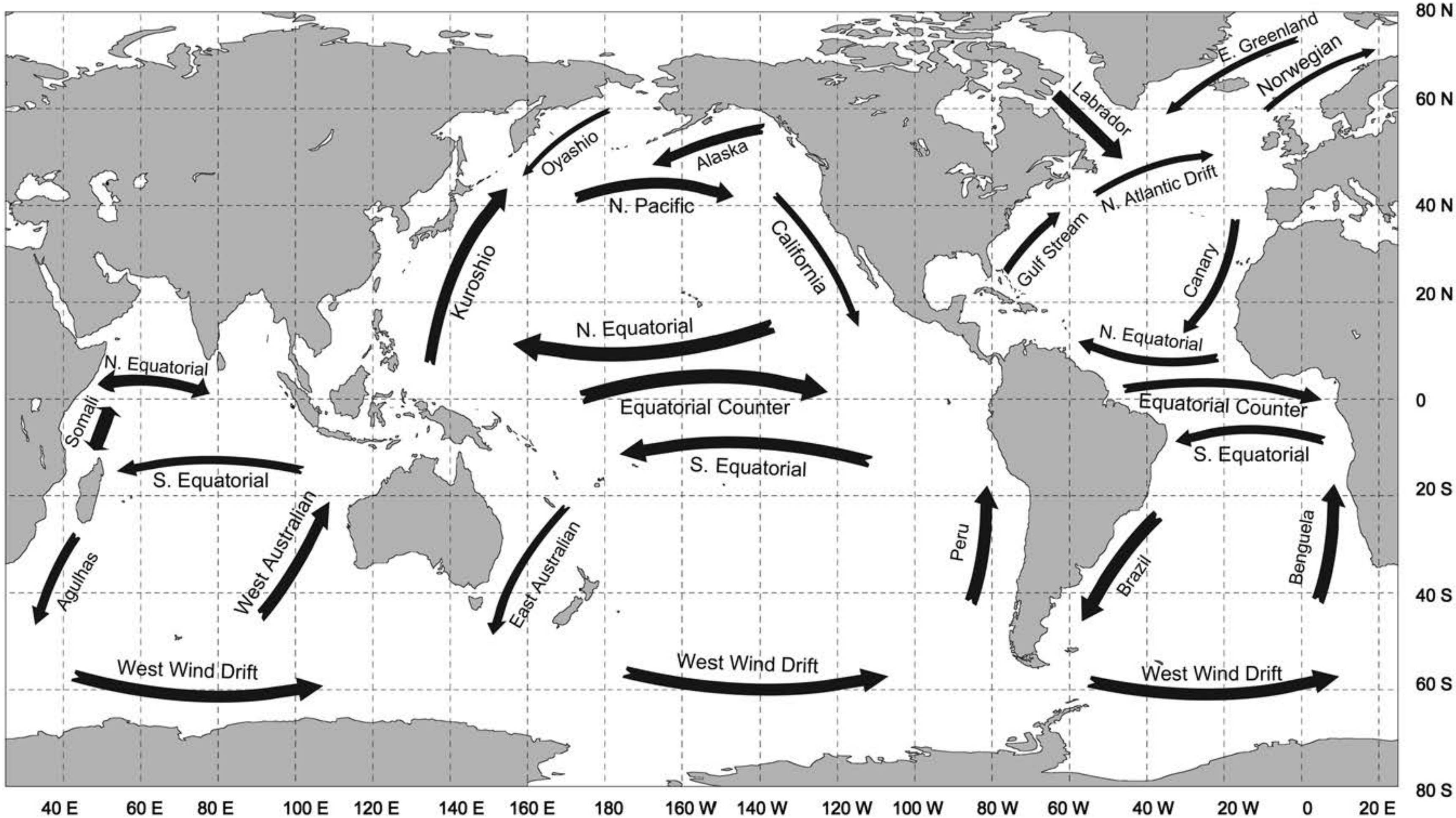
| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Southern |
| Location: | Eastern Basin |
| Flows: | From pole towards equator |
| Temperature: | Cold |
| Character: | Slow, Shallow & Wide |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Southern |
| Location: | Western Basin |
| Flows: | From equator towards pole |
| Temperature: | Warm |
| Character: | Fast, Deep & Narrow |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Southern |
| Location: | Southern Basin |
| Flows: | West to east around Antartica |
| Temperature: | Cooling |
| Character: | Slow, Largest Volume Current |

| | |
|---|---|
| Ocean: | Pacific |
| Hemisphere: | Southern |
| Location: | South of Equator |
| Flows: | From South America to Australia |
| Temperature: | Warming |
| Character: | Slow, Shallow & Wide |

# Global Ocean Surface Current Chart



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