Slide 1

Ocean Circulation

Tom Garrison

Slide 2

Palm trees in Northern Ireland?

Slide 3

Circulation is at the HEART of Physical Oceanography

The palms grow in Ireland at 54°N, the same latitude as Ontario's Polar Bear Provincial Park, a sanctuary for migrating polar bears. Why the great difference in climate?

Look *west* from each location.

West of Polar Bear Park you find only frozen dirt.
West of these palm trees is the water of the Atlantic Ocean.

And the wind in each place blows from the west.

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The wind blowing from the west picks up heat. In the winter, Atlantic is relatively warm; the dirt is not. The palm trees grow with the aide of equatorial heat imported by moving sea water. A small but important example of the effects of ocean circulation!

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We'll discuss…

- The forces that drive currents.
- Geostrophic gyres, surface currents within gyres.
- Coriolis effect and ocean circulation.
- Characteristics of western and eastern boundary currents and transverse currents.
- El Niño, La Niña.
- The effects of surface currents on climate.
- Wind-induced vertical circulation.
- Thermohaline circulation.
- Water masses.
- Thermohaline circulation patterns.
- Methods of studying ocean currents.

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An Overview…

Ocean water circulates in currents.

There are two kinds of currents

- Surface currents
- Thermohaline currents

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Surface Currents affect the uppermost 10% of the world ocean. The movement of surface currents is powered by the warmth of the sun and by winds. Water in surface currents tends to flow horizontally, but it can also flow vertically in response to wind blowing near coasts or along the equator. Surface currents transfer heat from tropical to polar regions, influence weather and climate, distribute nutrients, and scatter organisms. They have contributed to the spread of humanity to remote islands, and they are important factors in maritime commerce.

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Circulation of the 90% of ocean water beneath the surface zone is driven by the force of gravity, as dense water sinks and less dense water rises. Since density is largely a function of temperature and salinity, the movement of deep water due to density differences is called thermohaline circulation. Currents near the seafloor flow as slow, river-like masses in a few places, but the greatest volumes of deep water creep through the ocean at an almost imperceptible pace.

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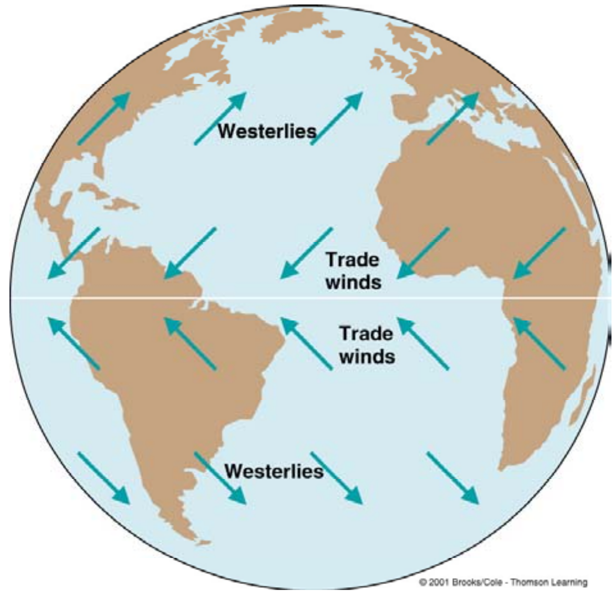
Surface Currents

About 10% of the water in the world ocean is involved in ***surface currents***, water flowing horizontally in the uppermost 400 meters (1,300 feet) of the ocean's surface, driven mainly by wind friction.

(right) Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents.

The prime movers are the powerful westerlies and the persistent trade winds (easterlies).



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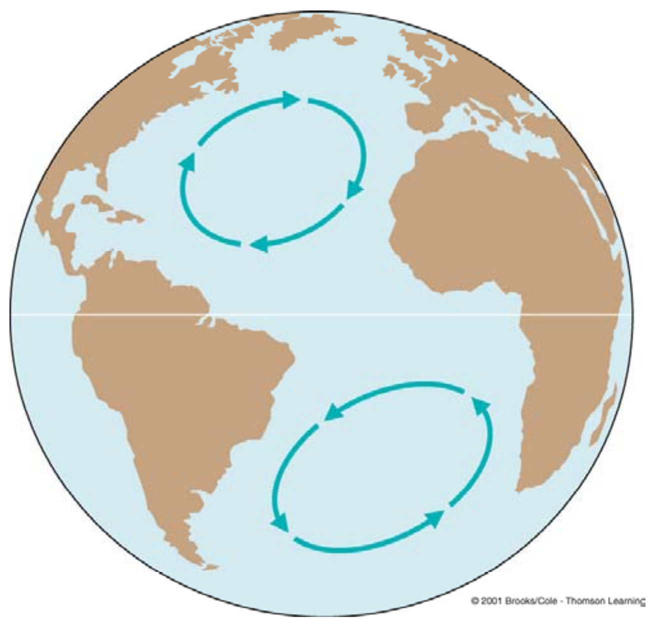
Continents and basin topography often block continuous flow and help to deflect the moving water into a circular pattern. This flow around the periphery of an ocean basin is called a ***gyre*** (gyros = a circle).

(right) A combination of four forces - surface winds, the sun's heat, the Coriolis effect, and gravity - circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.



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The North Atlantic gyre, a series of four interconnecting currents with different flow characteristics and temperatures.

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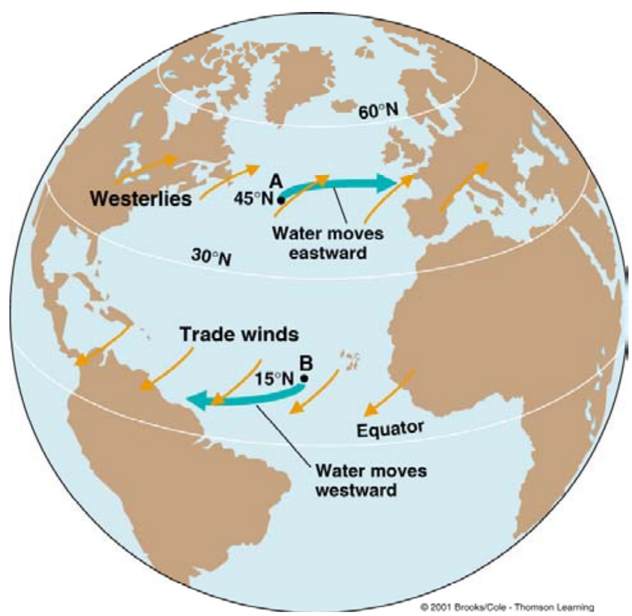
Surface water blown by the winds at point “A” will veer to the right of its initial path and continue eastward.

Water at point “B” veers right and continues westward.



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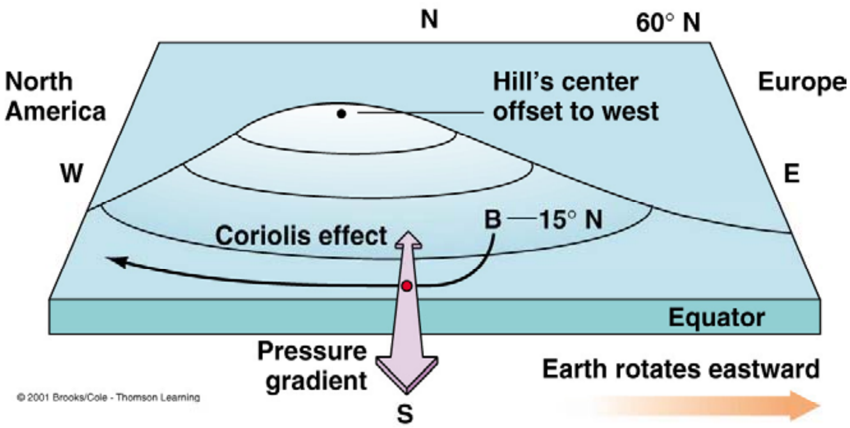

The surface of the North Atlantic is raised through wind motion and Ekman transport to form a low hill. The eastward rotation of Earth offsets the center of the hill to the west. Water from point B turns westward and flows along the side of this hill. The westward-moving water is balanced between the Coriolis effect (which would turn the water to the right) and flow down the pressure gradient, driven by gravity (which would turn it to the left). Thus, water in a gyre moves along the outside edge of an ocean basin. Note that the measured position of the hill is offset to the west. The gradually sloping hill is only 2 meters (6.5 feet) high and would not be apparent to anyone crossing the ocean.

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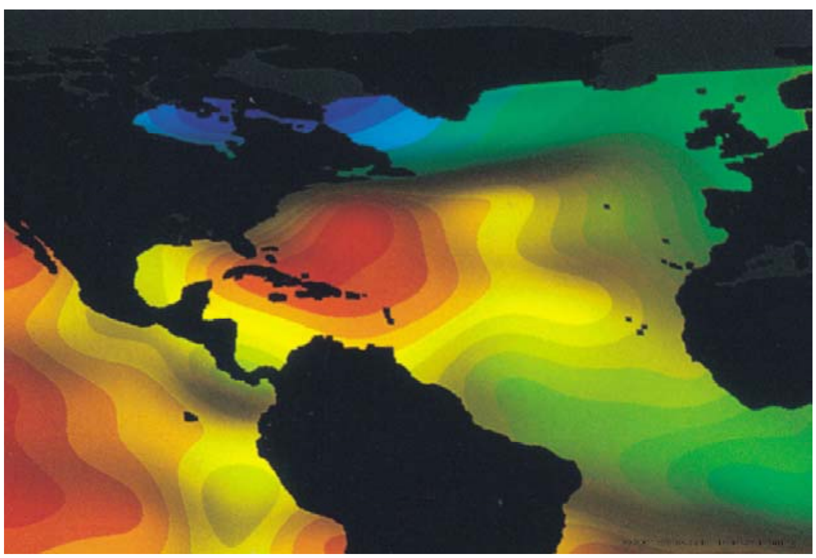

The average height of the surface of the North Atlantic is shown in color in this image derived from data taken in 1992 by the *TOPEX/Poseidon* satellite. Red indicates the highest surface, green and blue the lowest.

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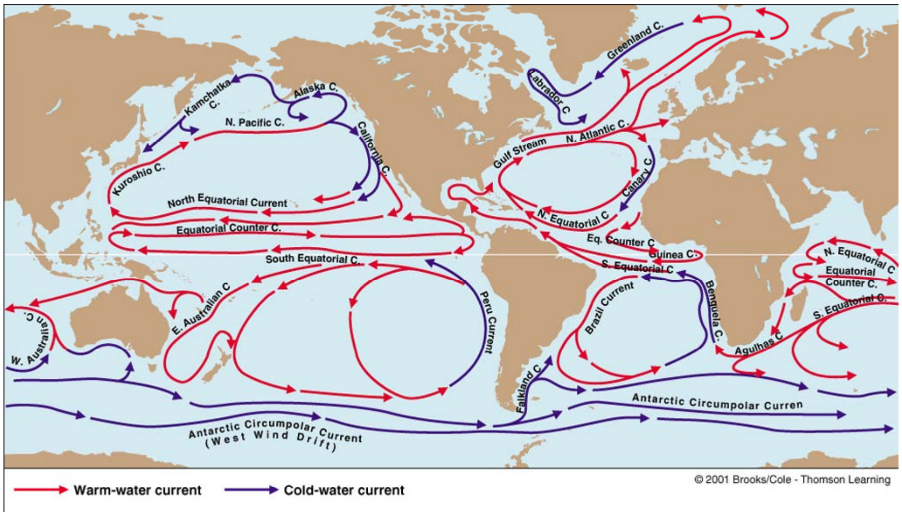

A chart showing the names and usual direction of the world ocean's major surface currents.

- There are six great current circuits in the world ocean, two in the Northern Hemisphere and four in the Southern Hemisphere

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The 6 surface current gyres

These are easy to see:

- North Atlantic
- South Atlantic
- North Pacific
- South Pacific

These are a bit hidden:

- Indian Ocean
- West Wind Drift (Antarctic Circumpolar Current)

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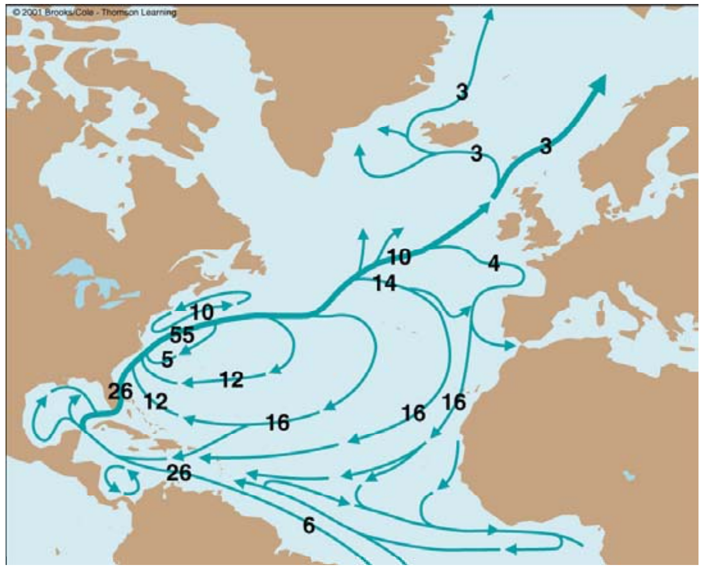
The general surface circulation of the North Atlantic.

The unit used to express volume in transport in ocean currents is the sverdrup (sv), named in honor of Harald Sverdrup, one of this century's pioneering oceanographers.

The numbers indicate flow rates in sverdrups (1 sv = 1 million cubic meters of water per second).



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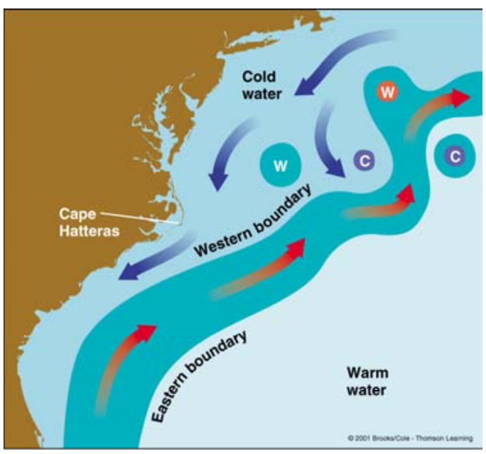

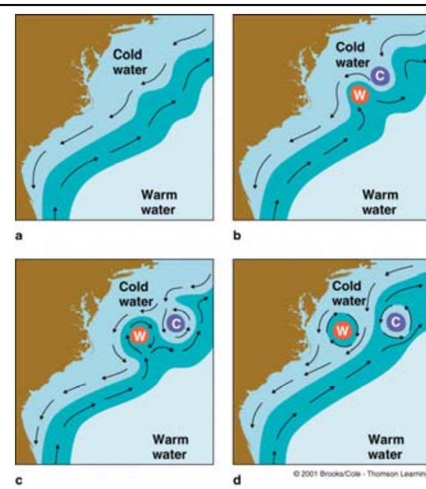

Eddy formation

The western boundary of the Gulf Stream is usually distinct, marked by abrupt changes in water temperature, speed, and direction.

(a) Meanders (eddies) form at this boundary as the Gulf Stream leaves the U.S. coast at Cape Hatteras. The meanders can pinch off (b) and eventually become isolated cells of warm water between the Gulf Stream and the coast (c). Likewise, cold cells can pinch off and become entrained in the Gulf Stream itself (d). (C = cold water, W = warm water; blue = cold, red = warm.)

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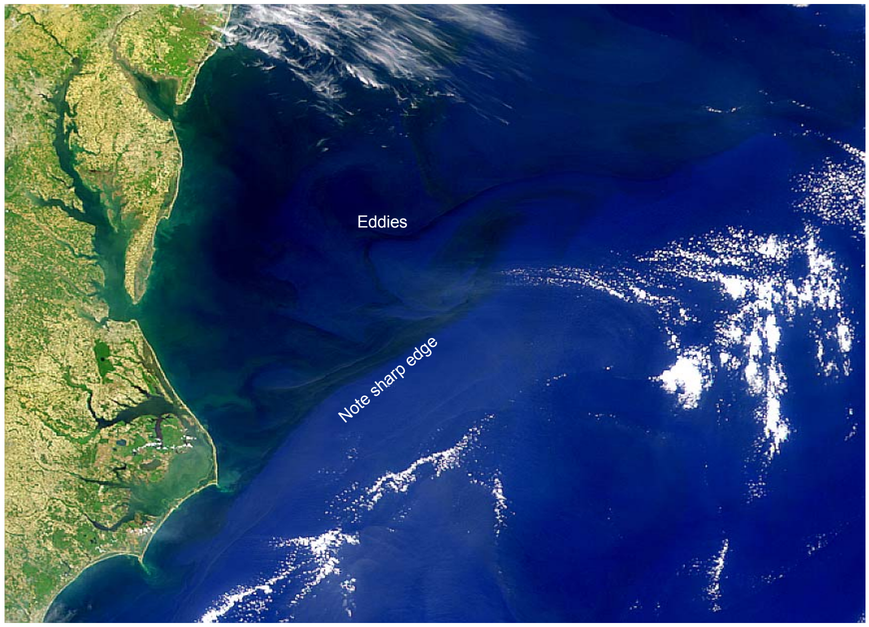
The Gulf Stream off Cape Hatteras



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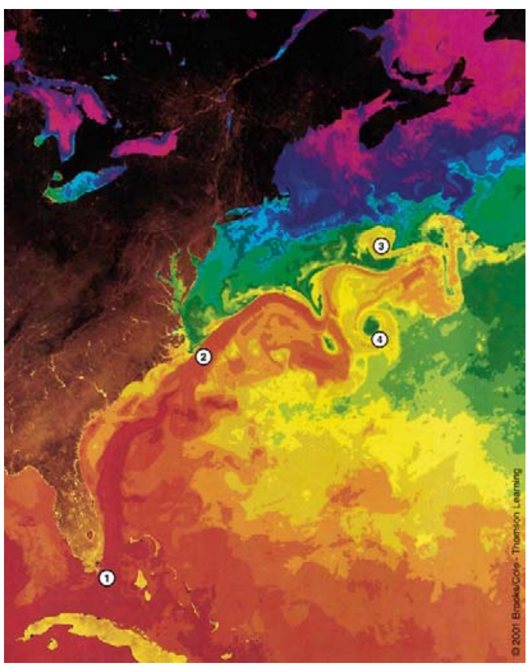

The Gulf Stream viewed from space.

The image is a composite of temperature data returned from NOAA polar-orbiting meteorological satellites during the first week of April 1984. The composite image is printed with an artificial color scale: Reds and oranges are a warm 24 - 28ºC (76 – 84ºF); yellows and greens are 17 - 23ºC (63 - 74ºF); blues are 10 - 16ºC (50 - 61ºF); and purples are a cold 2 - 9ºC (36 - 48ºF). The Gulf Stream appears like a red (warm) river as it moves from the southern tip of Florida (1) north along the east coast. Moving offshore at Cape Hatteras (2), it begins to meander, with some meanders pinching off to form warm-core (3) and cold-core (4) eddies. As it moves northeastward, the water cools dramatically, releasing heat to the atmosphere and mixing with the cooler surrounding waters. By the time it reaches the middle of the North Atlantic, it has cooled so much that its surface temperature can no longer be distinguished from that of the surrounding waters.

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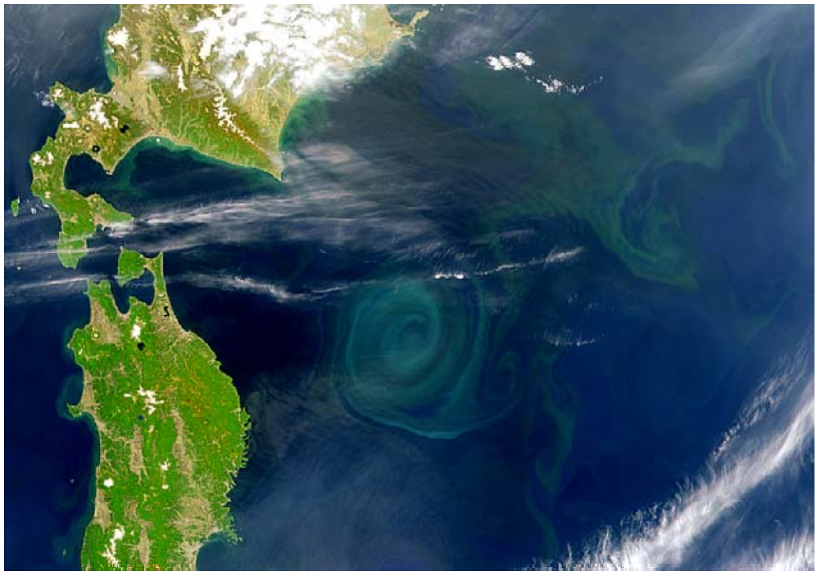
Circulation eddy off Japan

This is in natural color; the greenish swirls are blooms of coccolithophores.



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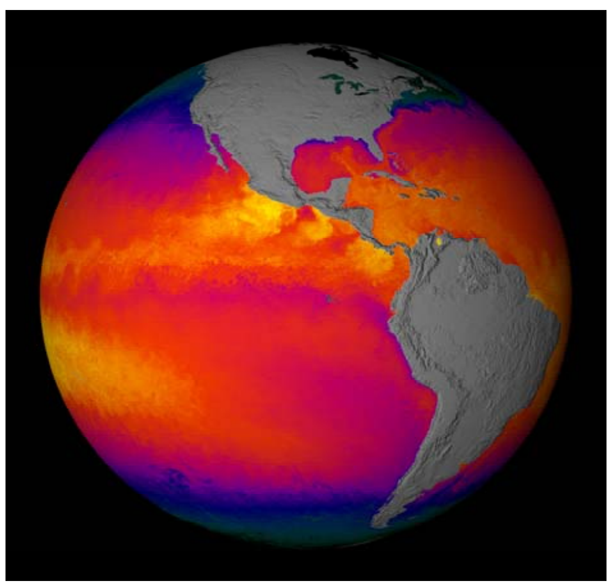
Worldwide heat flow in currents



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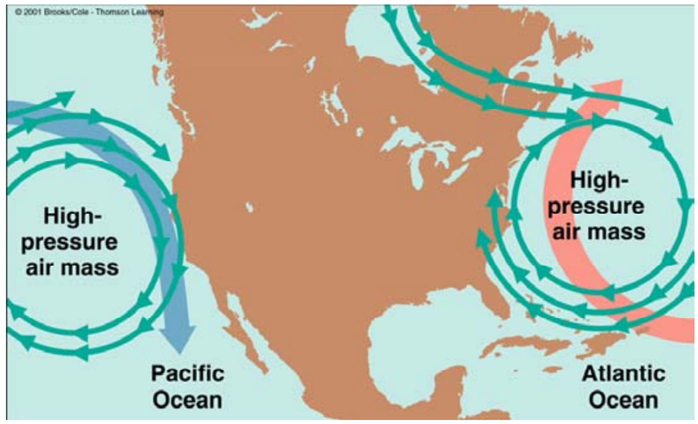
Effects Of Surface Currents On Climate



General summer air circulation patterns of the east and west coasts of the United States. Warm ocean currents are shown in red, cold currents in blue. Air is chilled as it approaches the west coast and warmed as it approaches the east coast.

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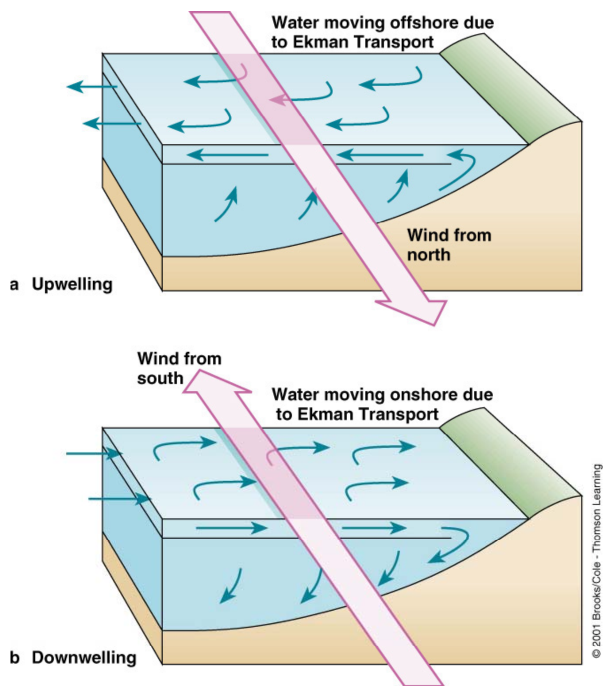
Coastal upwelling and downwelling.

Upward movement of water is known as ***upwelling***; the process brings deep, cold, usually nutrient-laden water toward the surface.

Downward movement is called ***downwelling***.

(a) In the Northern Hemisphere, coastal upwelling can be caused by winds from the north blowing along the west coast of a continent. Water moved offshore by Ekman transport is replaced by cold, deep, nutrient-laden water.

(b) A prolonged southerly wind along a Northern Hemisphere west coast can result in downwelling.



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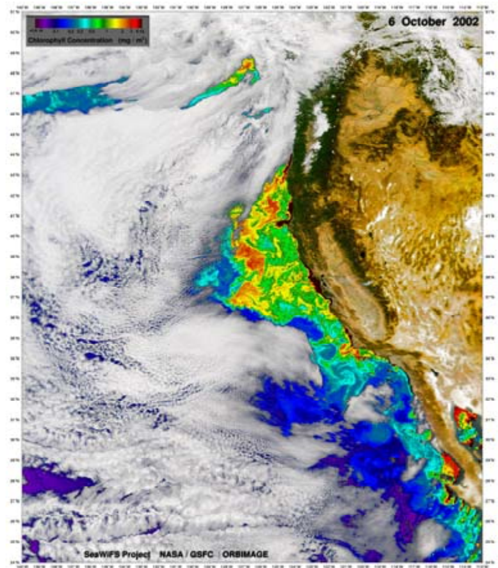
Upwelling off the California coast

Nutrients stimulate biological productivity, shown in colors.



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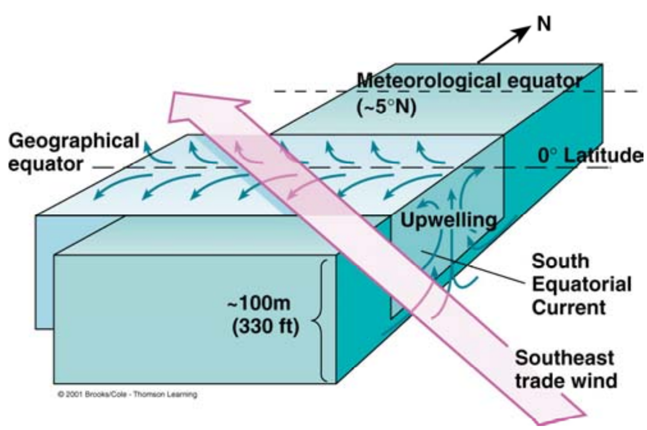
Upwelling And Downwelling



Equatorial upwelling. The South Equatorial Current, especially in the Pacific, straddles the geographical equator. Water north of the equator veers to the right (northward), and water to the south veers to the left (southward). Surface water therefore diverges, causing upwelling. Most of the upwelled water comes from the area above the equatorial undercurrent, at depths of 100 meters or less.

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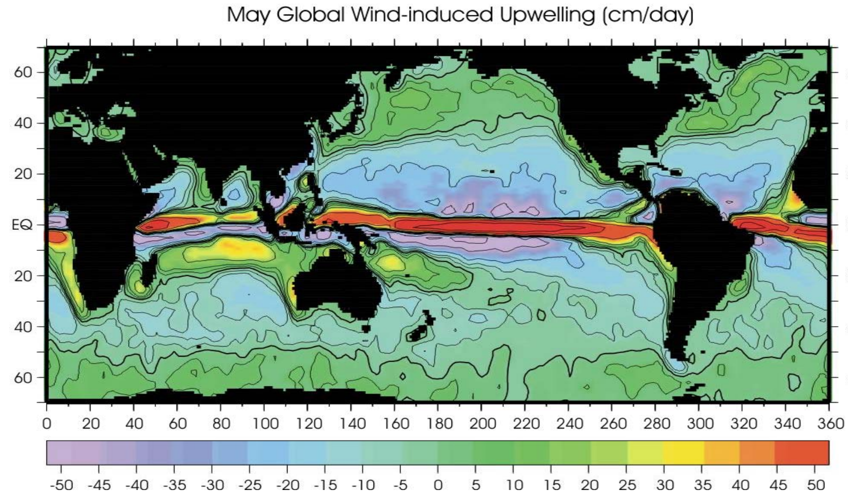

Global upwelling for May, 2003.

Image courtesy of Dr. William Hsieh, University of British Columbia.

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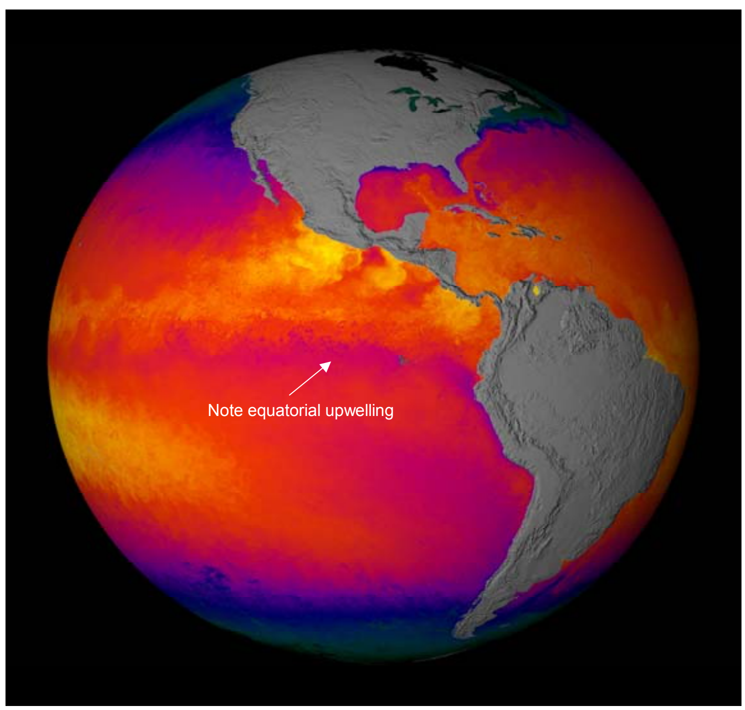

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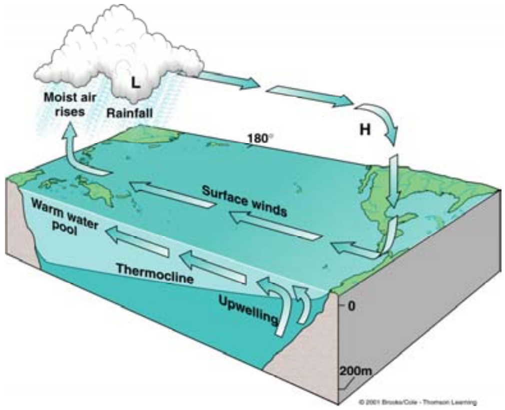
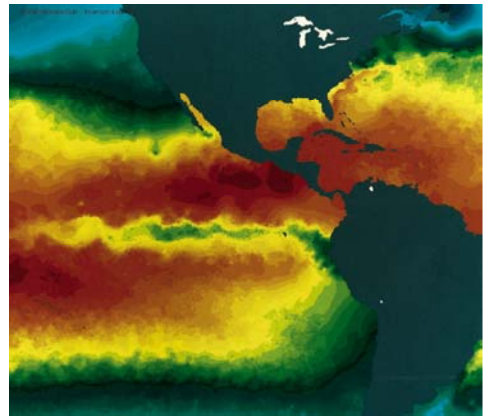
El Niño And La Niña





A non- El Niño year.

(above-left) Normally the air and surface water flow westward, the thermocline rises, and upwelling of cold water occurs along the west coast of Central and South America.

(above-right) This map from satellite data shows the temperature of the equatorial Pacific on 31 May 1988. The warmest water is indicated by the dark red, and progressively cooler water by yellow and green. Note the coastal upwelling along the coast at the lower right of the map, and the tongue of recently upwelled water extending westward along the equator from the South American coast. An El Niño year.

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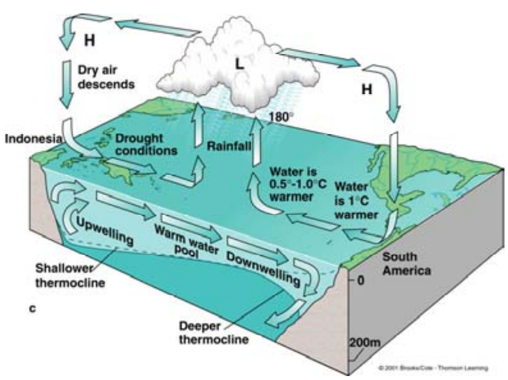

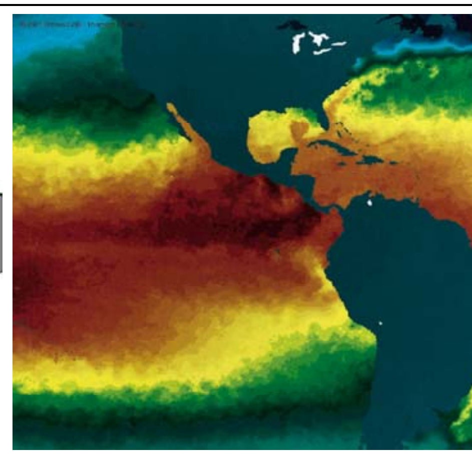

(above-left) When the Southern Oscillation develops, the trade winds diminish and then reverse, leading to an eastward movement of warm water along the equator. The surface waters of the central and eastern Pacific become warmer, and storms over land may increase.

(above-right) Sea-surface temperatures on 13 May 1992, a time of El Niño conditions. The thermocline was deeper than normal, and equatorial upwelling was suppressed. Note the absence of coastal upwelling along the coast and the lack of a tongue of recently upwelled water extending westward along the equator.

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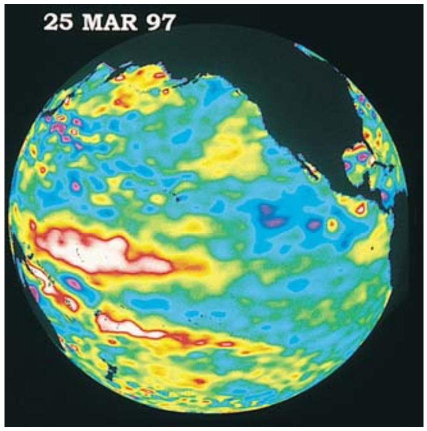

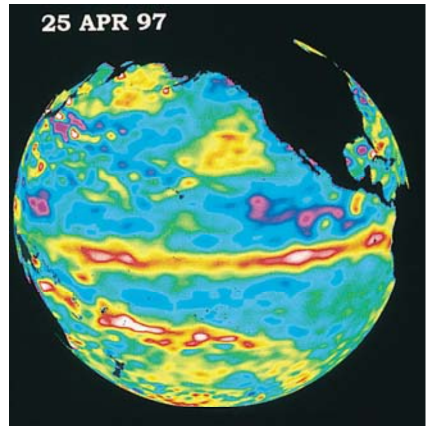

Development of the 1997-98 El Niño, observed by the *TOPEX/Poseidon* satellite.

(March 1997) The slackening of the trade winds and westerly wind bursts allow warm water to move away from its usual location in the western Pacific Ocean. Red and white colors indicate sea level above average height.

(April 1997) About a month after it began to move, the leading edge of the warm water reaches South America.

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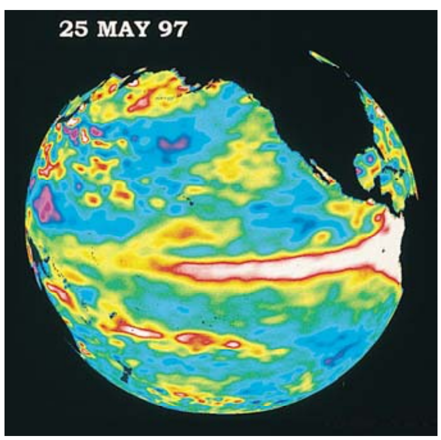

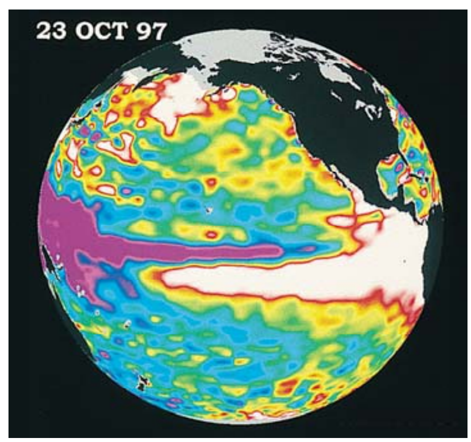

(May 1997) Warm water piles up against the South American continent. The white area of sea level is 13 - 30 centimeters (5 - 12 inches) above normal height, and 1.6 - 3°C (3 - 5°F) warmer.

(October 1997) By October, sea level is up to 30 centimeters (12 inches) lower than normal near Australia. The bulge of warm water has spread northward along the coast of North America from the equator to Alaska. Fisheries in Peru are severely affected - the warm water prevents upwelling of cold, nutrient - rich water necessary for the support of large fish populations.

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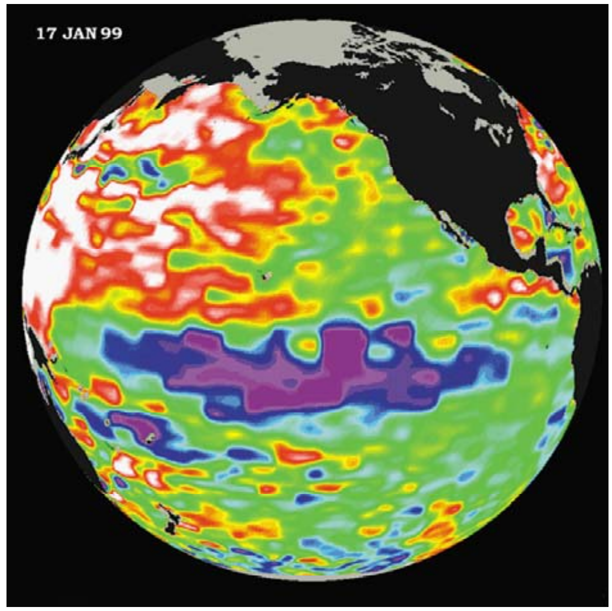
Normal circulation sometimes returns with surprising vigor after an El Niño event, producing strong currents, powerful upwelling, and chilly and stormy conditions along the South American coast.

This image was prepared from data for 17 January 1999.

Note the mass of cold surface water and relatively low sea level (purple).

Such cold water tends to deflect winds around it, changing the course of weather systems locally and the nature of weather patterns globally.



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We now turn to **THERMOHALINE CIRCULATION**

Remember, the circulation of the 90% of ocean water beneath the surface zone is driven by the force of gravity, as dense water sinks and less dense water rises. Since density is largely a function of *temperature* and *salinity*, the movement of deep water due to density is termed "thermohaline."

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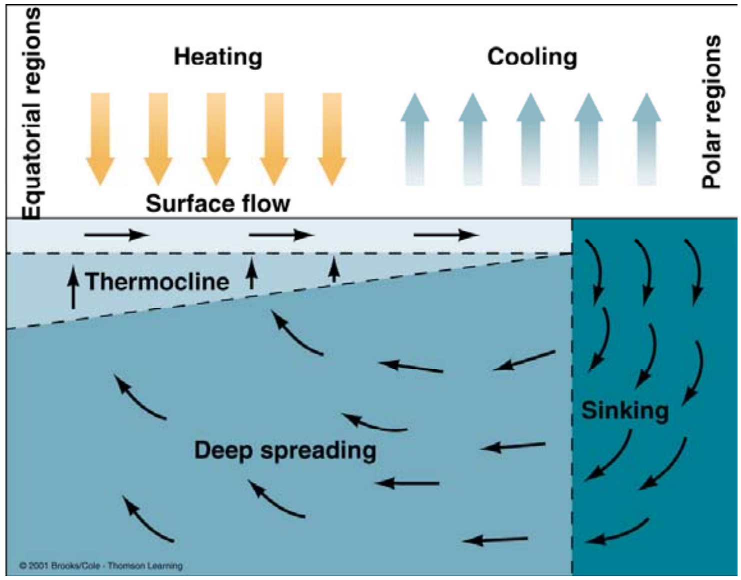

The classical model of a pure thermohaline circulation, caused by heating in lower latitudes and cooling in higher latitudes. The thermocline at middle and low latitudes is "held up" by the slow upward movement of cold water.

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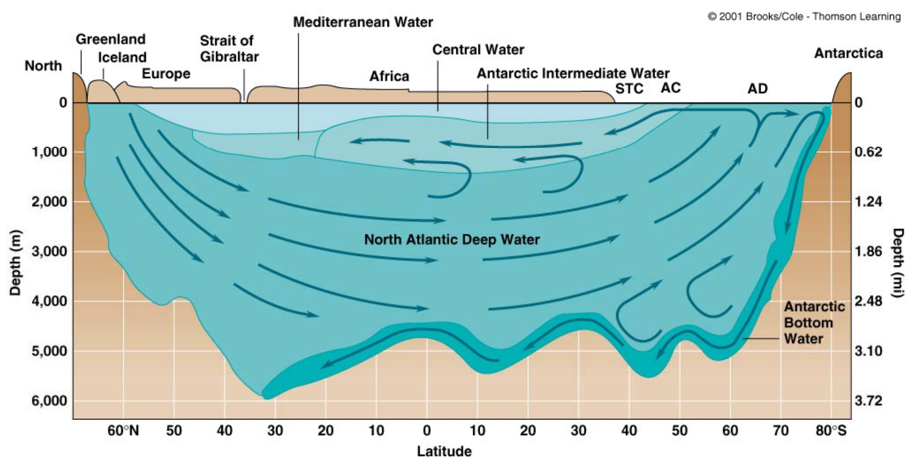

The water layers and deep circulation of the Atlantic Ocean. Arrows indicate the direction of water movement. STC indicates the position of the Subtropical Convergence, AC the Antarctic Convergence, and AD the Antarctic Divergence. The surface layer is too thin to show clearly at this scale. The vertical scale is greatly exaggerated.

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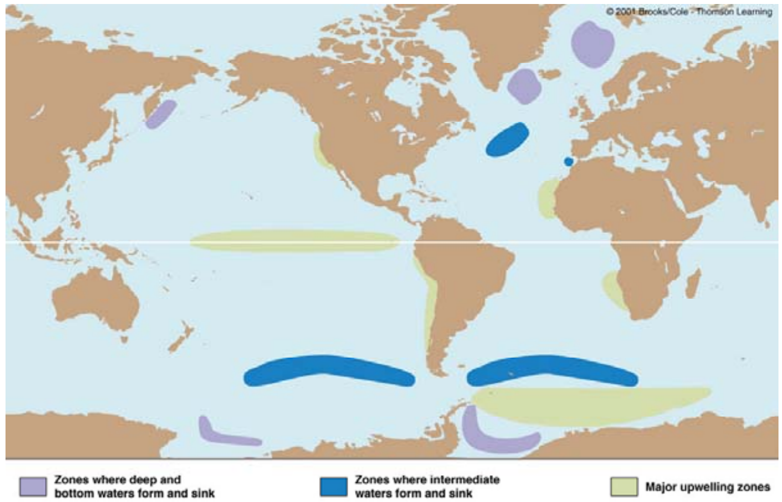
Thermohaline Circulation



(above) Places where most surface water sinks and where most deep or intermediate water rises.

- The movement of water due to differences in density is called ***thermohaline circulation.***

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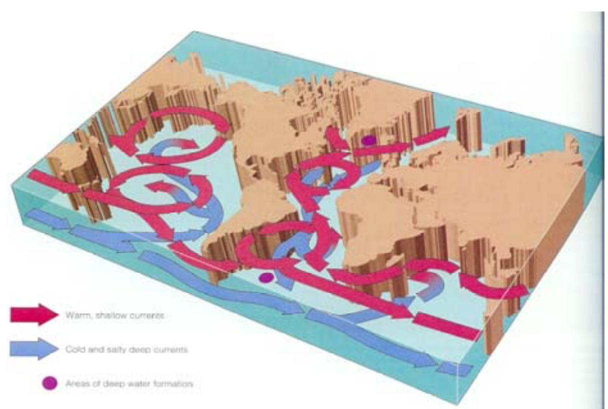
The Global Heat Conveyor



Remember those Irish palm trees!

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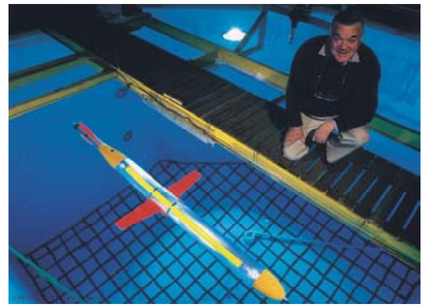
Studying Currents



Methods for measuring currents.

(left) A rubber duck of the kind lost overboard in large numbers in 1992 in an unintentional drift experiment.
(center) A Sofar float being launched from the Woods Hole Oceanographic Institution's research ship Oceanus. The probe will drop to a depth of 3,500 meters (11,500 feet) and produce a low-frequency tone once each day for tracking.
(right) A Slocum glider - a probe that uses energy from gravity, buoyancy, heat, and batteries to power long-range exploration of water masses.

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Yes, the water near those palm trees even *feels* warm!