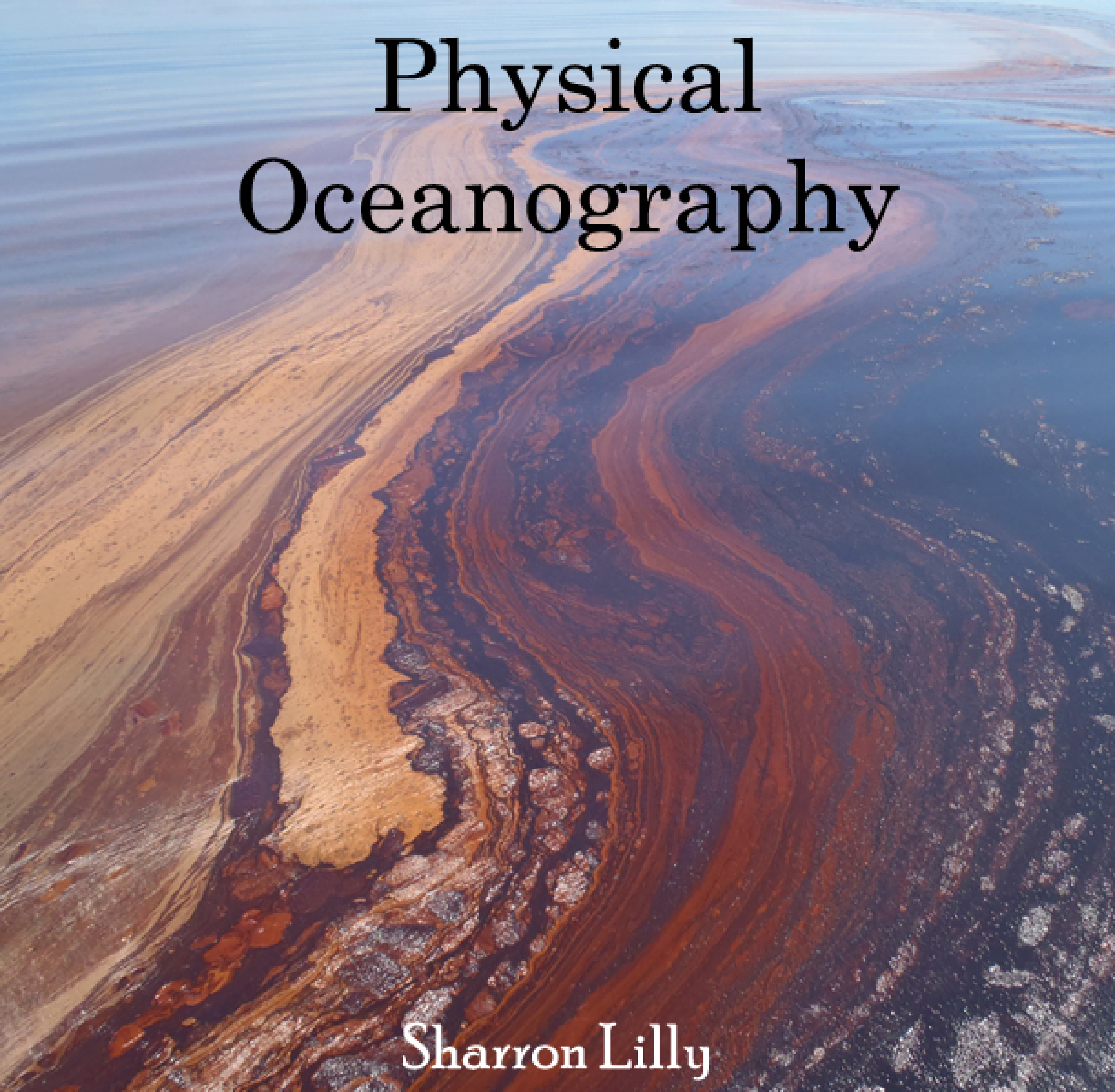
Physical Oceanography



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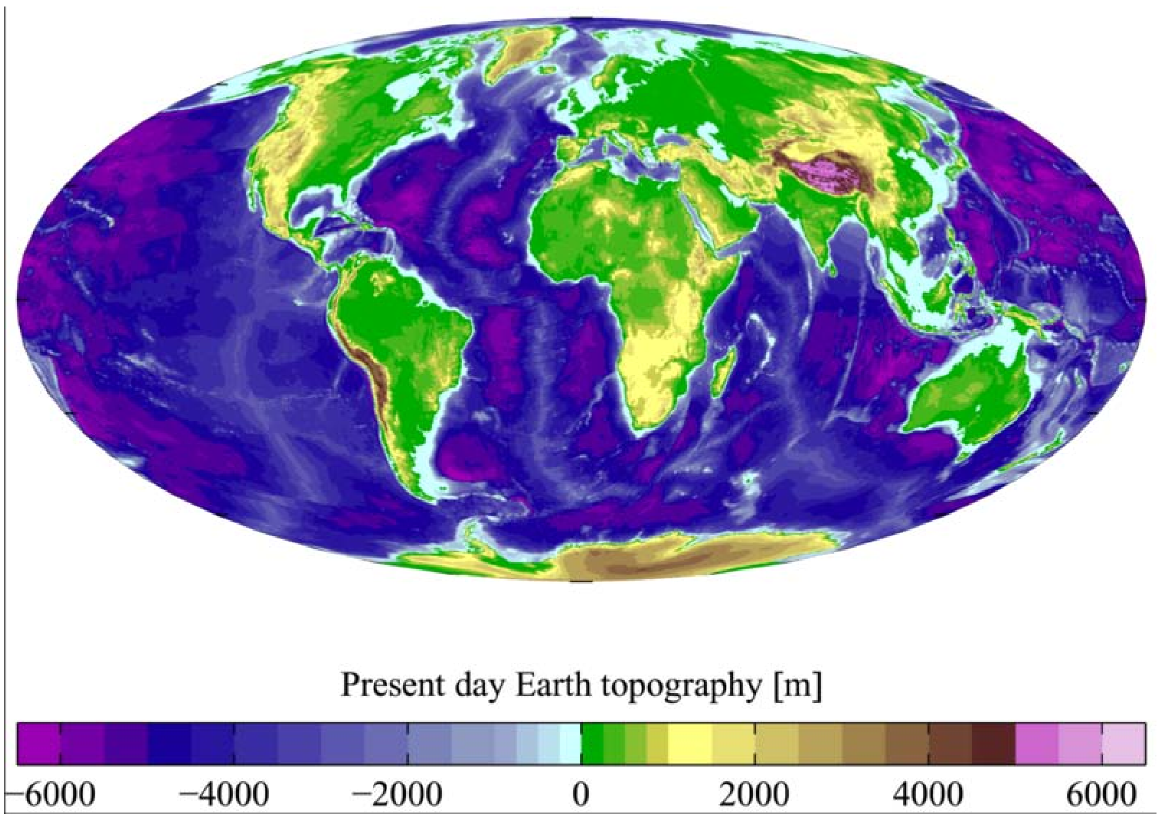
Physical Oceanography

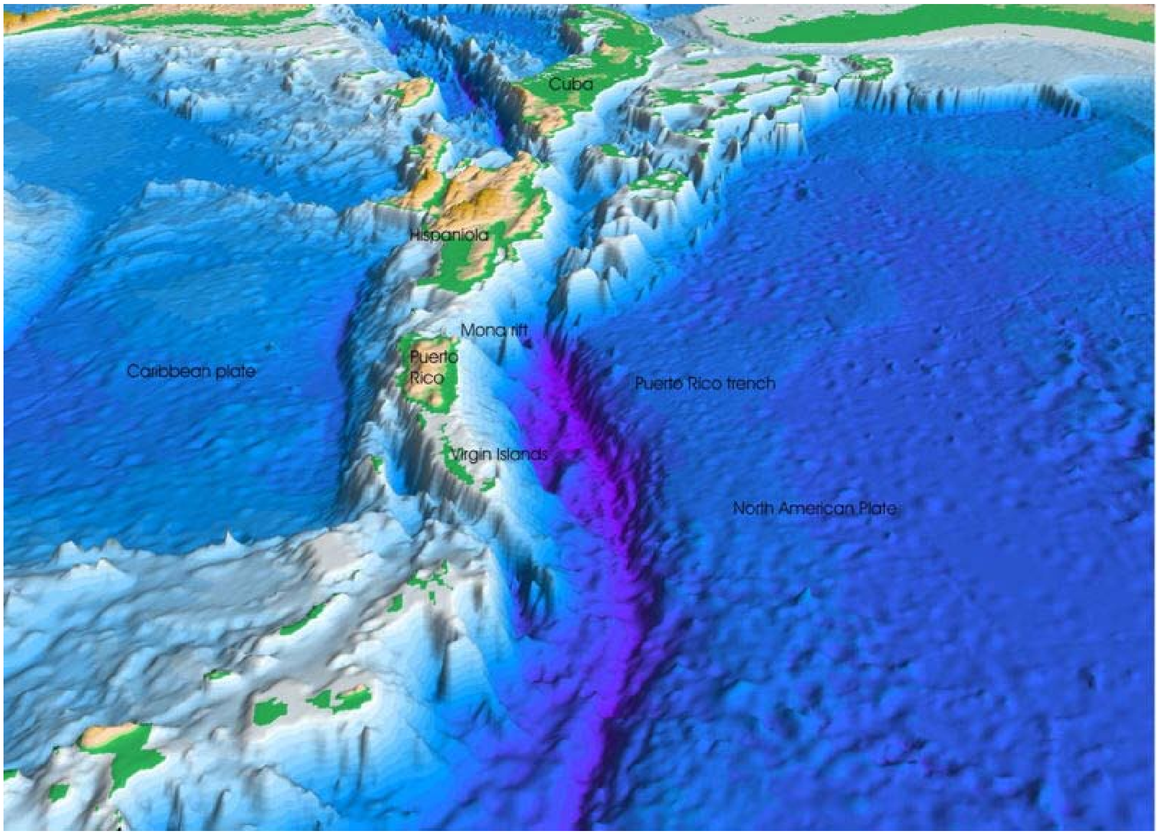


World ocean bathymetry.

Physical oceanography is the study of physical conditions and physical processes within the ocean, especially the motions and physical properties of ocean waters.

Physical oceanography is one of several sub-domains into which oceanography is divided. Others include biological, chemical and geological oceanographies.

The physical setting



Perspective view of the sea floor of the Atlantic Ocean and the Caribbean Sea. The purple sea floor at the center of the view is the Puerto Rico Trench.

The pioneering oceanographer Matthew Maury said in 1855 *"Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface."* The fundamental role of the oceans in shaping Earth is acknowledged by ecologists, geologists, meteorologists, climatologists, geographers and others interested in the physical world. An Earth without oceans would truly be unrecognizable.

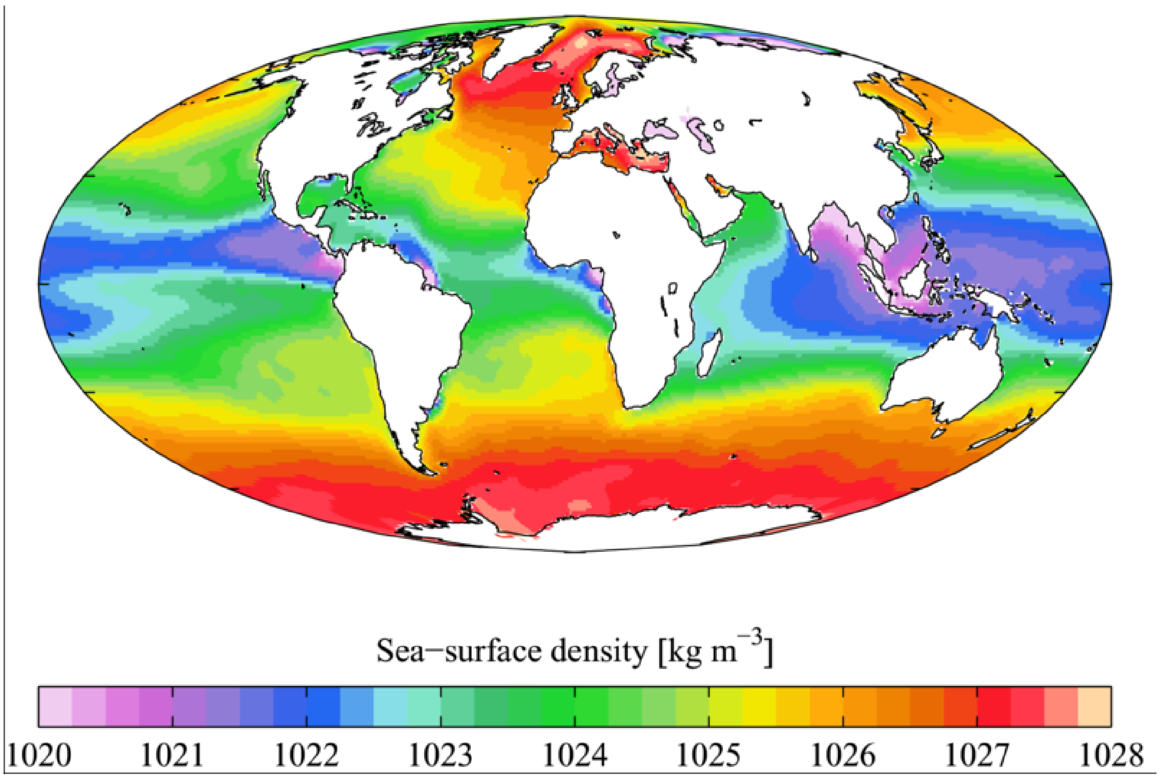
Roughly 97% of the planet's water is in its oceans, and the oceans are the source of the vast majority of water vapor that condenses in the atmosphere and falls as rain or snow on the continents. The tremendous heat capacity of the oceans moderates the planet's climate, and its absorption of various gases affects the composition of the atmosphere. The ocean's influence extends even to the composition of volcanic rocks through seafloor metamorphism, as well as to that of volcanic gases and magmas created at subduction zones.

The oceans are far deeper than the continents are tall; examination of the Earth's hypsographic curve shows that the average elevation of Earth's landmasses is only 840 metres (2,760 ft), while the ocean's average depth is 3,800 metres (12,500 ft). Though this apparent discrepancy is great, for both land and sea, the respective extremes such as mountains and trenches are rare.

Area, volume plus mean and maximum depths of oceans (excluding adjacent seas)

Body	**Area** ($10^6 km^2$)	**Volume** ($10^6 km^3$)	**Mean depth** (m)	**Maximum** (m)
Pacific Ocean	165.2	707.6	4282	-10911
Atlantic Ocean	82.4	323.6	3926	-8605
Indian Ocean	73.4	291.0	3963	-8047
Southern Ocean	20.3			-7235
Arctic Ocean	14.1		1038	
Caribbean Sea	2.8			-7686

Temperature, salinity and density



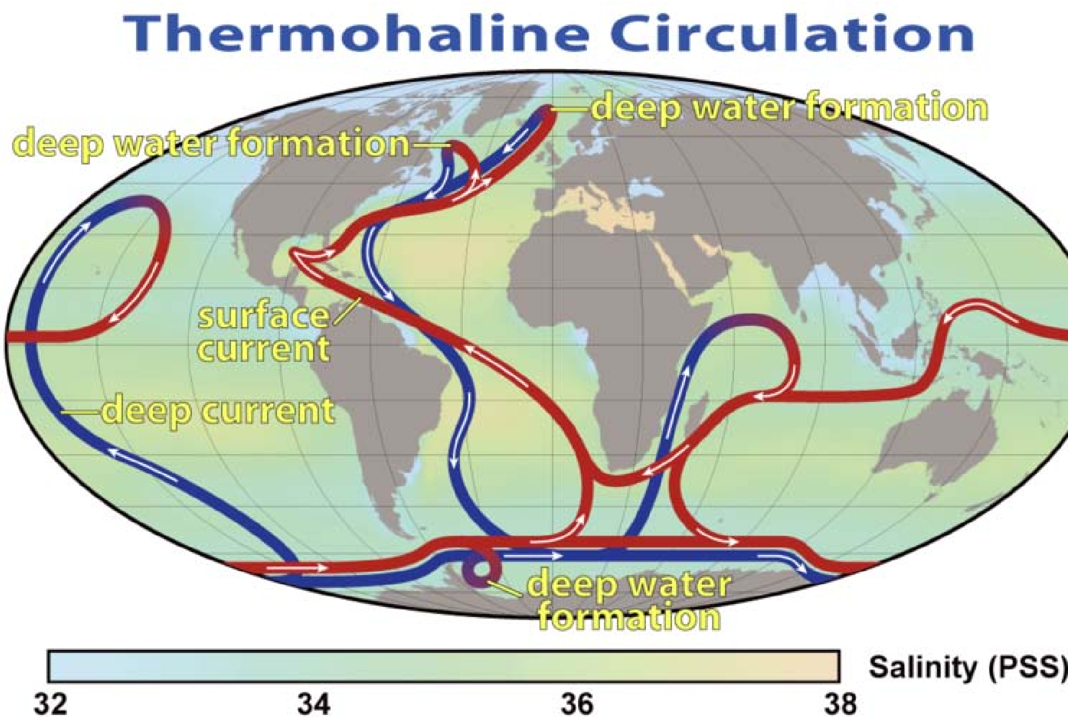
WOA surface density.

Because the vast majority of the world ocean's volume is deep water, the mean temperature of seawater is low; roughly 75% of the ocean's volume has a temperature from 0° – 5°C (Pinet 1996). The same percentage falls in a salinity range between 34–35 ppt (3.4–3.5%) (Pinet 1996). There is still quite a bit of variation, however. Surface temperatures can range from below freezing near the poles to 35°C in restricted tropical seas, while salinity can vary from 10 to 41 ppt (1.0–4.1%).

The vertical structure of the temperature can be divided into three basic layers, a surface mixed layer, where gradients are low, a thermocline where gradients are high, and a poorly stratified abyss.

In terms of temperature, the ocean's layers are highly latitude-dependent; the thermocline is pronounced in the tropics, but nonexistent in polar waters (Marshak 2001). The halocline usually lies near the surface, where evaporation raises salinity in the tropics, or meltwater dilutes it in polar regions. These variations of salinity and temperature with depth change the density of the seawater, creating the pycnocline.

Circulation



Density-driven thermohaline circulation

The ultimate energy source for the ocean circulation (and for the atmospheric circulation) is the sun. The amount of sunlight absorbed at the surface varies strongly with latitude, being greater at the equator than at the poles, and this engenders fluid motion in both the atmosphere and ocean that acts to redistribute heat from the equator towards the poles, thereby reducing the temperature gradients that would exist in the absence of fluid motion. Perhaps three quarters of this heat is carried in the atmosphere; the rest is carried in the ocean.

The atmosphere is heated from below, which leads to convection, the largest expression of which is the Hadley circulation. By contrast the ocean is heated from above, which tends to suppress convection. Instead ocean deep water is formed in polar regions where cold salty waters sink in fairly restricted areas. This is the beginning of the thermohaline circulation.

Oceanic currents are largely driven by the surface wind stress; hence the large-scale atmospheric circulation is important to understanding the ocean circulation. The Hadley circulation leads to Easterly winds in the tropics and Westerlies in mid-latitudes, which creates an anticyclonic wind stress curl over the subtropical ocean. This leads to slow equatorward flow throughout most of a subtropical ocean basin (the Sverdrup balance). The return flow occurs in an intense, narrow, poleward western boundary current. Like the atmosphere, the ocean is far wider than it is deep, and hence horizontal motion is in general much faster than vertical motion. In the southern hemisphere there is a continuous belt of ocean, and hence the mid-latitude westerlies force the strong Antarctic Circumpolar Current. In the northern hemisphere the land masses prevent this and the ocean circulation is broken into smaller gyres in the Atlantic and Pacific basins.

Coriolis effect

The Coriolis effect results in a deflection of fluid flows (to the right in the Northern Hemisphere and left in the Southern Hemisphere). Because the distance around the Earth decreases as one moves away from the equator, and because the Earth rotates in a counter clockwise direction as seen from the north pole, air and water masses are deflected to the east as they move from the equator to the poles, and to the west as they move from the poles to the equator. This has profound effects on the flow of the oceans. In particular it means the flow goes *around* high and low pressure systems, permitting them to persist for long periods of time. As a result, tiny variations in pressure can produce measurable currents. A slope of one part in one million in sea surface height, for example, will result in a current of 1 cm/s at mid-latitudes. The fact that the Coriolis effect is largest at the poles and weak at the equator results in sharp, relatively steady western boundary currents which are absent on eastern boundaries.

The Coriolis effect is also responsible for coastal upwelling as wind-driven currents tend to forced to the right of the winds in the Northern Hemisphere and to the left of the winds in the Southern Hemisphere. When winds blow either equatorward along an eastern ocean boundary or poleward along a western ocean boundary, water is driven away from the coasts (the so called Ekman transport), and denser water rises from below to replace it.

Ekman transport

Ekman Transport results in the net transport of surface water 90 degrees to the right of the wind in the Northern Hemisphere, and 90 degrees to the left of the wind in the Southern Hemisphere. As the wind blows across the surface of the ocean, it "grabs" onto a thin layer of the surface water. In turn, that thin sheet of water transfers motion energy to the thin layer of water under it, and so on. However, because of the Coriolis Effect, the direction of travel of the layers of water slowly move farther and farther to the right as they get deeper in the Northern Hemisphere, and to the left in the Southern Hemisphere.

In most cases, the very bottom layer of water affected by the wind is at a depth of 100 m – 150 m and is traveling about 180 degrees, completely opposite of the direction that the wind is blowing. Overall, the net transport of water would be 90 degrees from the original direction of the wind.

Langmuir circulation

Langmuir circulation results in the occurrence of thin, visible stripes, called windrows on the surface of the ocean parallel to the direction that the wind is blowing. If the wind is blowing with more than 3 m s^{-1}, it can create parallel windrows alternating upwelling and downwelling about 5–300 m apart. These windrows are created by adjacent ovular water cells (extending to about 6 m (20 ft) deep) alternating rotating clockwise and counterclockwise. In the convergence zones debris, foam and seaweed accumulates, while at the divergencezones plankton are caught and carried to the surface. If there are many plankton in the divergencezone fish are often attracted to feed on them.

Ocean–atmosphere interface

Hurricane Isabel east of the Bahamas on 15 September 2003

At the ocean-atmosphere interface, the ocean and atmosphere exchange fluxes of heat, moisture and momentum.

Heat

The important heat terms at the surface are the sensible heat flux, the latent heat flux, the incoming solar radiation and the balance of long-wave (infrared) radiation. In general, the tropical oceans will tend to show a net gain of heat, and the polar oceans a net loss, the result of a net transfer of energy polewards in the oceans.

The oceans' large heat capacity moderates the climate of areas adjacent to the oceans, leading to a maritime climate at such locations. This can be a result of heat storage in summer and release in winter; or of transport of heat from warmer locations: a particularly notable example of this is Western Europe, which is heated at least in part by the north atlantic drift.

Momentum

Surface winds tend to be of order meters per second; ocean currents of order centimeters per second. Hence from the point of view of the atmosphere, the ocean can be considered effectively stationary; from the point of view of the ocean, the atmosphere imposes a significant wind stress on its surface, and this forces large-scale currents in the ocean.

Through the wind stress, the wind generates ocean surface waves; the longer waves have a phase velocity tending towards the wind speed. Momentum of the surface winds is transferred into the energy flux by the ocean surface waves. The increased roughness of the ocean surface, by the presence of the waves, changes the wind near the surface.

Moisture

The ocean can gain moisture from rainfall, or lose it through evaporation. Evaporative loss leaves the ocean saltier; the Mediterranean and Persian Gulf for example have strong evaporative loss; the resulting plume of dense salty water may be traced through the Straits of Gibraltar into the Atlantic Ocean. At one time, it was believed that evaporation/precipitation was a major driver of ocean currents; it is now known to be only a very minor factor.

Planetary waves

Kelvin Waves

A Kelvin wave is any progressive wave that is channeled between two boundaries or opposing forces (usually between the Coriolis force and a coastline or the equator). There are two types, coastal and equatorial. Kelvin waves are gravity driven and non-dispersive, meaning that the phase speed of the wave at any one frequency will equal the group speed of the wave energy for all frequencies. This means that Kelvin waves can retain their shape and direction over long periods of time. They are usually created by a sudden shift in the wind, such as the change of the trade winds at the beginning of the El Niño-Southern Oscillation.

Coastal Kelvin waves follow shorelines and will always propagate in a counterclockwise direction in the Northern hemisphere (with the shoreline to the right of the direction of travel) and clockwise in the Southern hemisphere.

Equatorial Kelvin waves propagate to the east in the Northern hemisphere and to the west in the Southern hemisphere, using the equator as a guide.

Kelvin waves are known to have very high speeds, typically around 2–3 meters per second. They have wavelengths of thousands of kilometers and amplitudes in the tens of meters.

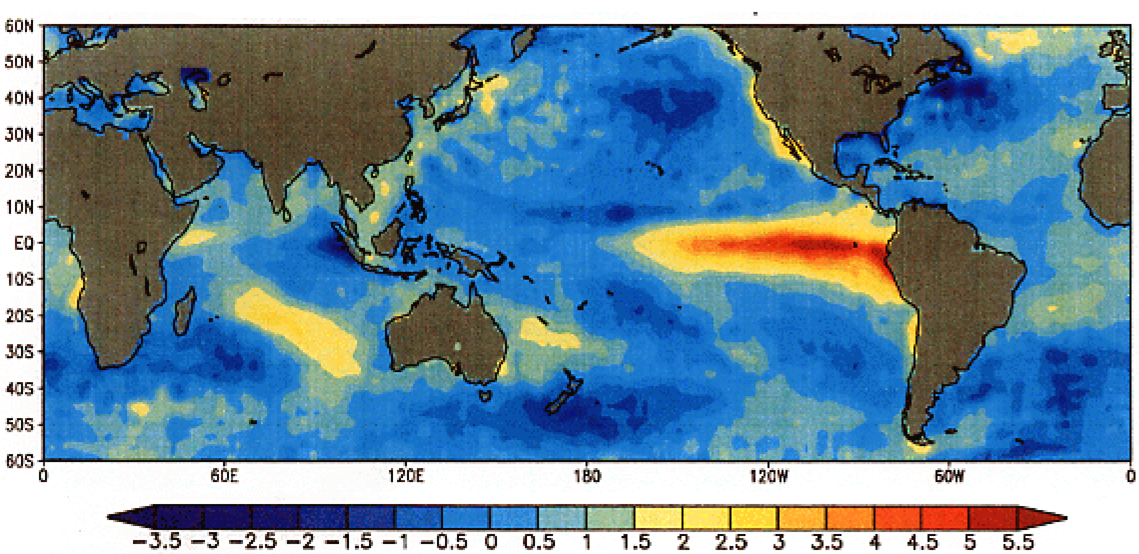
Rossby Waves

Rossby waves, or planetary waves are huge, slow waves generated in the troposphere by temperature differences between the ocean and the continents. Their major restoring force is the change in Coriolis force with latitude. Their wave amplitudes are usually in the tens of meters and very large wavelengths. They are usually found at low or mid latitudes

There are two types of Rossby waves, barotropic and baroclinic. Barotropic Rossby waves have the highest speeds and do not vary vertically. Baroclinic Rossby waves are much slower.

The special identifying feature of Rossby waves is that the phase velocity of each individual wave always has a westward component, but the group velocity can be in any direction. Usually the shorter Rossby waves have an eastward group velocity and the longer ones have a westward group velocity.

Climate variability



December 1997 chart of ocean surface temperature anomaly [°C] during the last strong El Niño

The interaction of ocean circulation, which serves as a type of heat pump, and biological effects such as the concentration of carbon dioxide can result in global climate changes on a time scale of decades. Known climate oscillations resulting from these interactions, include the Pacific decadal oscillation, North Atlantic oscillation, and Arctic oscillation. The oceanic process of thermohaline circulation is a significant component of heat redistribution across the globe, and changes in this circulation can have major impacts upon the climate.

La Niña–El Niño

Antarctic circumpolar wave

This is a coupled ocean/atmosphere wave that circles the Southern Ocean about every eight years. Since it is a wave-2 phenomenon (there are two peaks and two troughs in a latitude circle) at each fixed point in space a signal with a period of four years is seen. The wave moves eastward in the direction of the Antarctic Circumpolar Current.

Ocean currents

Among the most important ocean currents are the:

- Antarctic Circumpolar Current
- Deep ocean (density-driven)
- Western boundary currents
    - Gulf Stream
    - Kuroshio Current
    - Labrador Current
    - Oyashio Current
    - Agulhas Current
    - Brazil Current
    - East Australia Current
- Eastern Boundary currents
    - California Current
    - Canary Current
    - Peru Current
    - Benguela Current

Antarctic circumpolar

The ocean body surrounding the Antarctic is currently the only continuous body of water where there is a wide latitude band of open water. It interconnects the Atlantic, Pacific and Indian oceans, and provide an uninterrupted stretch for the prevailing westerly winds to significantly increase wave amplitudes. It is generally accepted that these prevailing winds are primarily responsible for the circumpolar current transport. This current is now thought to vary with time, possibly in an oscillatory manner.

Deep ocean

In the Norwegian Sea evaporative cooling is predominant, and the sinking water mass, the North Atlantic Deep Water (NADW), fills the basin and spills southwards through crevasses in the submarine sills that connect Greenland, Iceland and Britain. It then flows along the western boundary of the Atlantic with some part of the flow moving eastward along the equator and then poleward into the ocean basins. The NADW is entrained into the Circumpolar Current, and can be traced into the Indian and Pacific basins. Flow from the Arctic Ocean Basin into the Pacific, however, is blocked by the narrow shallows of the Bering Strait.

Western boundary

An idealised subtropical ocean basin forced by winds circling around a high pressure (anticyclonic) systems such as the Azores-Bermuda high develops a gyre circulation with slow steady flows towards the equator in the interior. As discussed by Henry Stommel, these flows are balanced in the region of the western boundary, where a thin fast polewards flow called a western boundary current develops. Flow in the real ocean is more complex, but the Gulf stream, Agulhas and Kuroshio are examples of such currents. They are narrow (approximately 100 km across) and fast (approximately 1.5 m/s).

Equatorwards western boundary currents occur in tropical and polar locations, e.g. the East Greenland and Labrador currents, in the Atlantic and the Oyashio. They are forced by winds circulation around low pressure (cyclonic)

Gulf stream

The Gulf Stream, together with its northern extension, North Atlantic Current, is a powerful, warm, and swift Atlantic ocean current that originates in the Gulf of Mexico, exits through the Strait of Florida, and follows the eastern coastlines of the United States and Newfoundland to the northeast before crossing the Atlantic Ocean.

Kuroshio

The Kuroshio Current is an ocean current found in the western Pacific Ocean off the east coast of Taiwan and flowing northeastward past Japan, where it merges with the easterly drift of the North Pacific Current. It is analogous to the Gulf Stream in the Atlantic Ocean, transporting warm, tropical water northward towards the polar region.

Heat flux

Heat storage

Heat storage and transfer in the ocean is very uneven.

Sea level change

Tide gauges and satellite altimetry suggest an increase in sea level of 1.5–3 mm/yr over the past 100 years.

The IPCC predicts that by 2100, global warming will lead to a sea level rise of 110 to 880 mm.

Rapid variations

Tides

The **Bay of Fundy** is a bay located on the Atlantic coast of North America, on the northeast end of the Gulf of Maine between the provinces of New Brunswick and Nova Scotia.

The rise and fall of the oceans due to tidal effects is a key influence upon the coastal areas. Ocean tides on the planet Earth are created by the gravitational effects of the Sun and Moon. The tides produced by these two bodies are roughly comparable in magnitude, but the orbital motion of the Moon results in tidal patterns that vary over the course of a month.

The ebb and flow of the tides produce a cyclical current along the coast, and the strength of this current can be quite dramatic along narrow estuaries. Incoming tides can also produce a tidal bore along a river or narrow bay as the water flow against the current results in a wave on the surface.

Tide and Current (Wyban 1992) clearly illustrates the impact of these natural cycles on the lifestyle and livelihood of Native Hawaiians tending coastal fishponds. *Aia ke ola ka hana* meaning . . . *Life is in labor*.

Tidal resonance occurs in the Bay of Fundy since the time it takes for a large wave to travel from the mouth of the bay to the opposite end, then reflect and travel back to the mouth of the bay coincides with the timing between this repeating wave that is also reinforced by the tidal rhythm producing the world's highest tides.

As the surface tide oscillates over topography, such as submerged seamounts or ridges, it generates internal waves at the tidal frequency, which are known as internal tides.

Tsunamis

A series of surface waves can be generated due to large-scale displacement of the ocean water. These can be caused by sub-marine landslides, seafloor deformations due to earthquakes, or the impact of a large meteorite.

The waves can travel with a velocity of up to several hundred km/hour across the ocean surface, but in mid-ocean they are barely detectable with wavelengths spanning hundreds of kilometers.

Tsunamis, originally called tidal waves, were renamed because they are not related to the tides. They are regarded as shallow-water waves, or waves in water with a depth less than 1/20 their wavelength. Tsunamis have very large periods, high speeds, and great wave heights.

The primary impact of these waves is along the coastal shoreline, as large amounts of ocean water are cyclically propelled inland and then drawn out to sea. This can result in significant modifications to the coastline regions where the waves strike with sufficient energy.

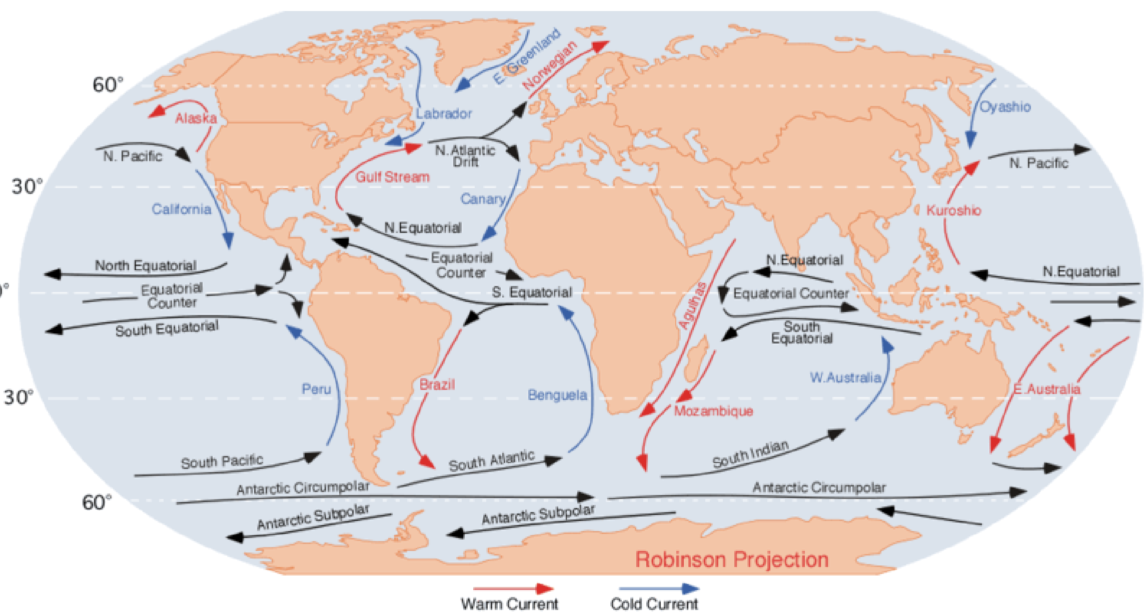
The tsunami that occurred in Lituya Bay, Alaska on July 9, 1958 was 520 m (1,710 ft) high and is the biggest tsunami ever measured, almost 90 m (300 ft) taller than the Sears Tower in Chicago and about 110 m (360 ft) taller than the World Trade Center in New York.

Surface waves

The wind generates ocean surface waves, which have a large impact on offshore structures, ships, coastal erosion and sedimentation, as well as harbours. After their generation by the wind, ocean surface waves can travel (as swell) over long distances.

Chapter- 2

Ocean Current

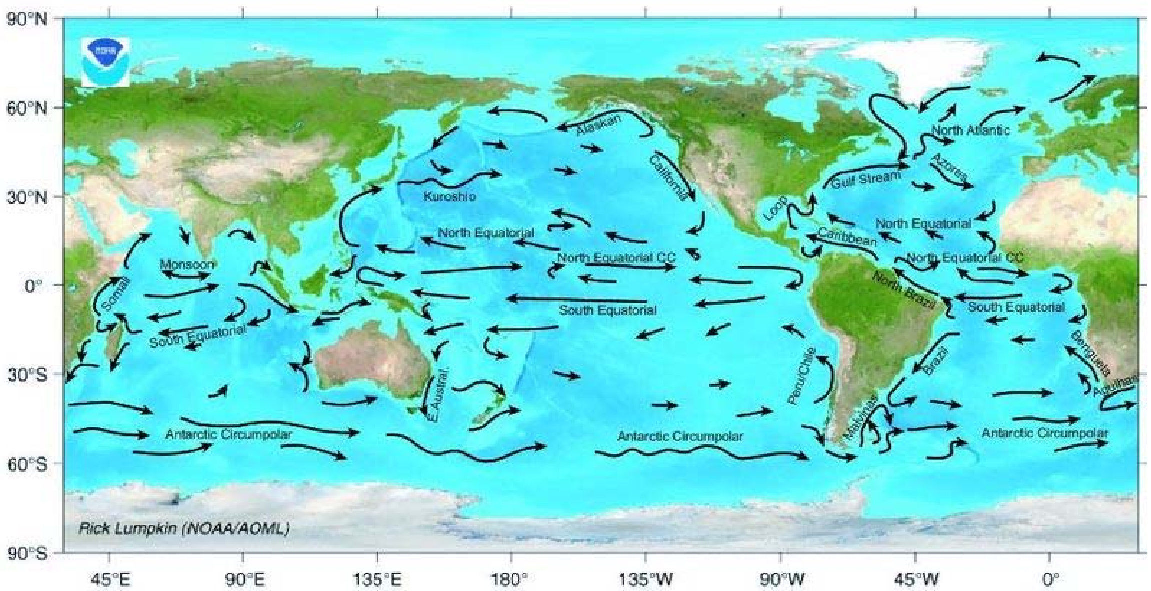


The ocean currents.

An **ocean current** is a continuous, directed movement of ocean water generated by the forces acting upon this mean flow, such as breaking waves, wind, Coriolis force, temperature and salinity differences and tides caused by the gravitational pull of the Moon and the Sun. Depth contours, shoreline configurations and interaction with other currents influence a current's direction and strength.

Ocean currents can flow for great distances, and together they create the great flow of the global conveyor belt which plays a dominant part in determining the climate of many of the Earth’s regions. Perhaps the most striking example is the Gulf Stream, which makes northwest Europe much more temperate than any other region at the same latitude. Another example is the Hawaiian Islands, where the climate is cooler (sub-tropical) than the tropical latitudes in which they are located, due to the effect of the California Current.

Function



Major ocean surface currents, (Source: NOAA).

Device to record ocean currents.

Surface ocean currents are generally wind driven and develop their typical clockwise spirals in the northern hemisphere and counter-clockwise rotation in the southern hemisphere because of the imposed wind stresses. In wind driven currents, the Ekman spiral effect results in the currents flowing at an angle to the driving winds. The areas of surface ocean currents move somewhat with the seasons; this is most notable in equatorial currents.

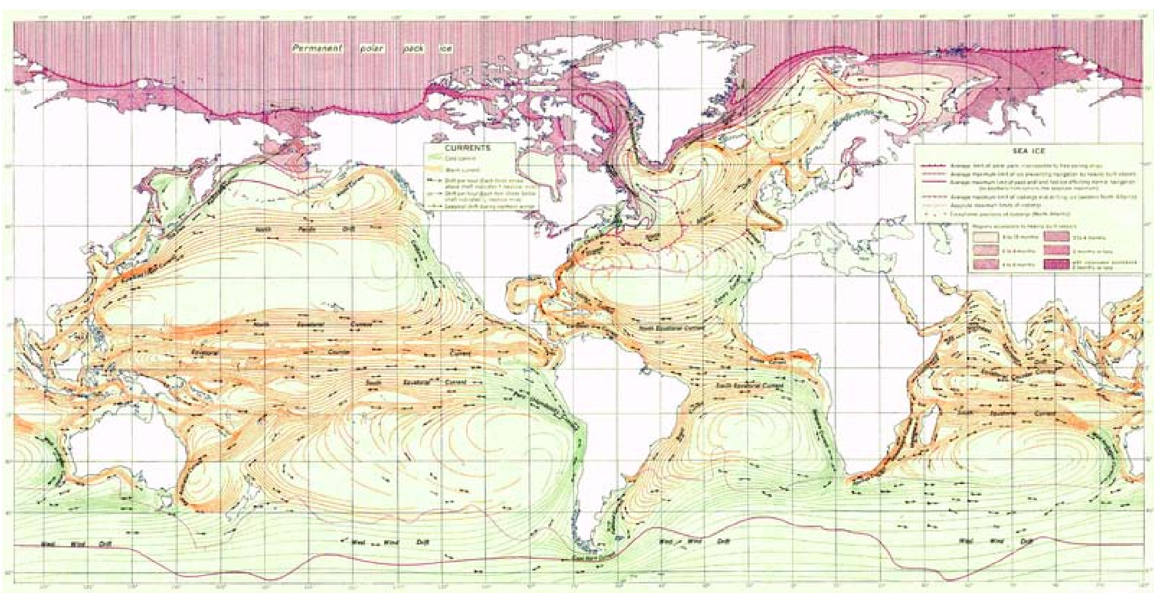
Ocean basins generally have a non-symmetric surface current, in that the eastern equatorward-flowing branch is broad and diffuse whereas the western poleward-flowing branch is very narrow. These western boundary currents (of which the gulf stream is an example) are a consequence of basic fluid dynamics.

Deep ocean currents are driven by density and temperature gradients. Thermohaline circulation, also known as the ocean's conveyor belt, refers to the deep ocean density-driven ocean basin currents. These currents, which flow under the surface of the ocean and are thus hidden from immediate detection, are called submarine rivers. These are currently being researched using a fleet of underwater robots called Argo. Upwelling and downwelling areas in the oceans are areas where significant vertical movement of ocean water is observed.

Surface currents make up about 10% of all the water in the ocean. Surface currents are generally restricted to the upper 400 m (1,300 ft) of the ocean. The movement of deep water in the ocean basins is by density driven forces and gravity. The density difference is a function of different temperatures and salinity. Deep waters sink into the deep ocean basins at high latitudes where the temperatures are cold enough to cause the density to increase.

Ocean currents are measured in Sverdrup (Sv), where 1Sv is equivalent to a volume flow rate of 1,000,000 m^3 (35,000,000 cu ft) per second.

Importance

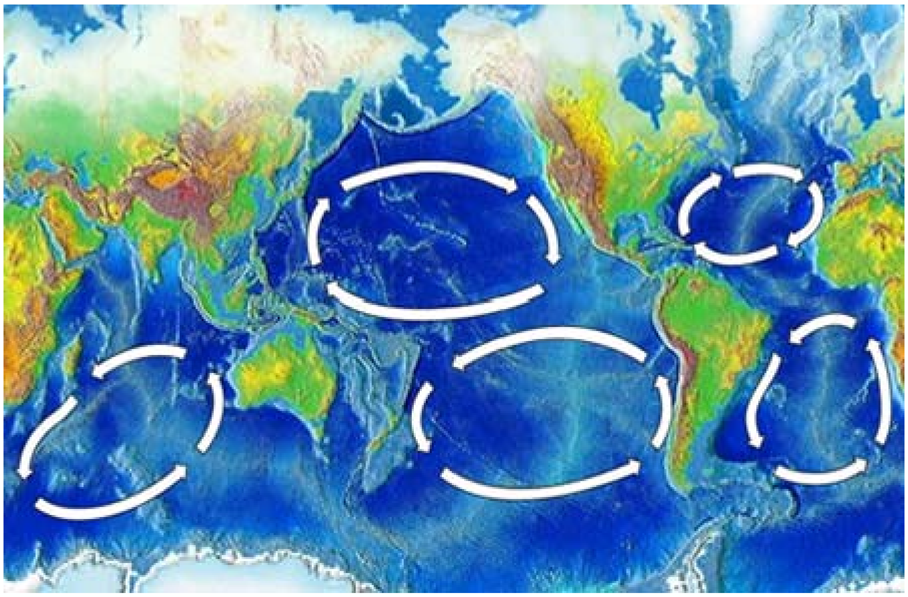


A 1943 map of the world's ocean currents.

Knowledge of surface ocean currents is essential in reducing costs of shipping, since they reduce fuel costs. In the sail-ship era knowledge was even more essential. A good example of this is the Agulhas current, which long prevented Portuguese sailors from reaching India. Even today, the round-the-world sailing competitors employ surface currents to their benefit. Ocean currents are also very important in the dispersal of many life forms. An example is the life-cycle of the eel.

Ocean currents are important in the study of marine debris, and vice versa. These currents also affect temperatures throughout the world. For example, the current that brings warm water up the north Atlantic to northwest Europe stops ice from forming by the shores, which would block ships from entering and exiting ports.

Ocean gyre



The five major ocean gyres

A **gyre** in oceanography is any large system of rotating ocean currents, particularly those involved with large wind movements. Gyres are caused by the Coriolis Effect; planetary vorticity along with horizontal and vertical friction, which determine the circulation patterns from the wind curl (torque). The term *gyre* can be used to refer to any type of vortex in the air or the sea, even one that is man-made, but it is most commonly used in oceanography, to refer to the major ocean systems.

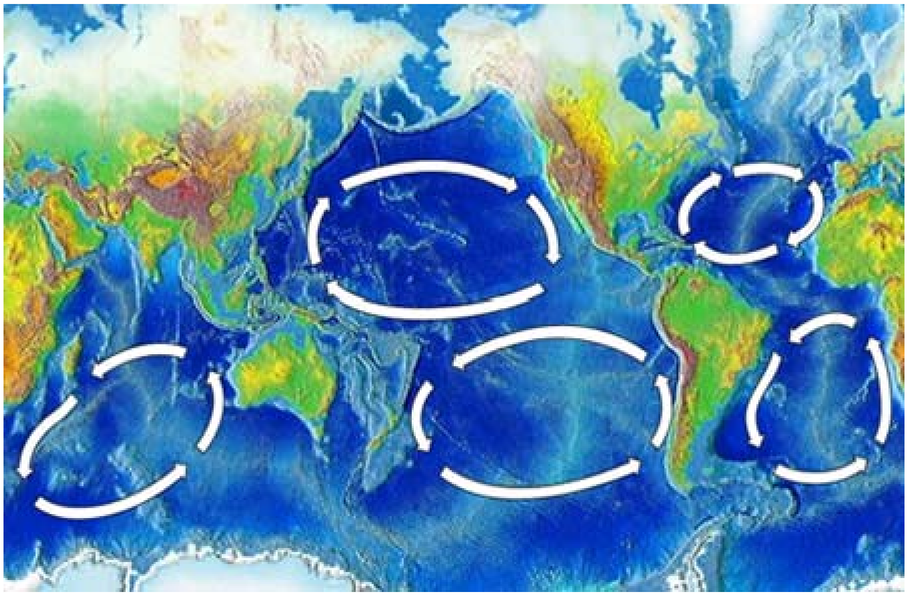
Major gyres

The following are the five most notable gyres:

- North Atlantic Gyre
- South Atlantic Gyre
- Indian Ocean Gyre
- North Pacific Gyre
- South Pacific Gyre

Description of above five most notable gyres: -

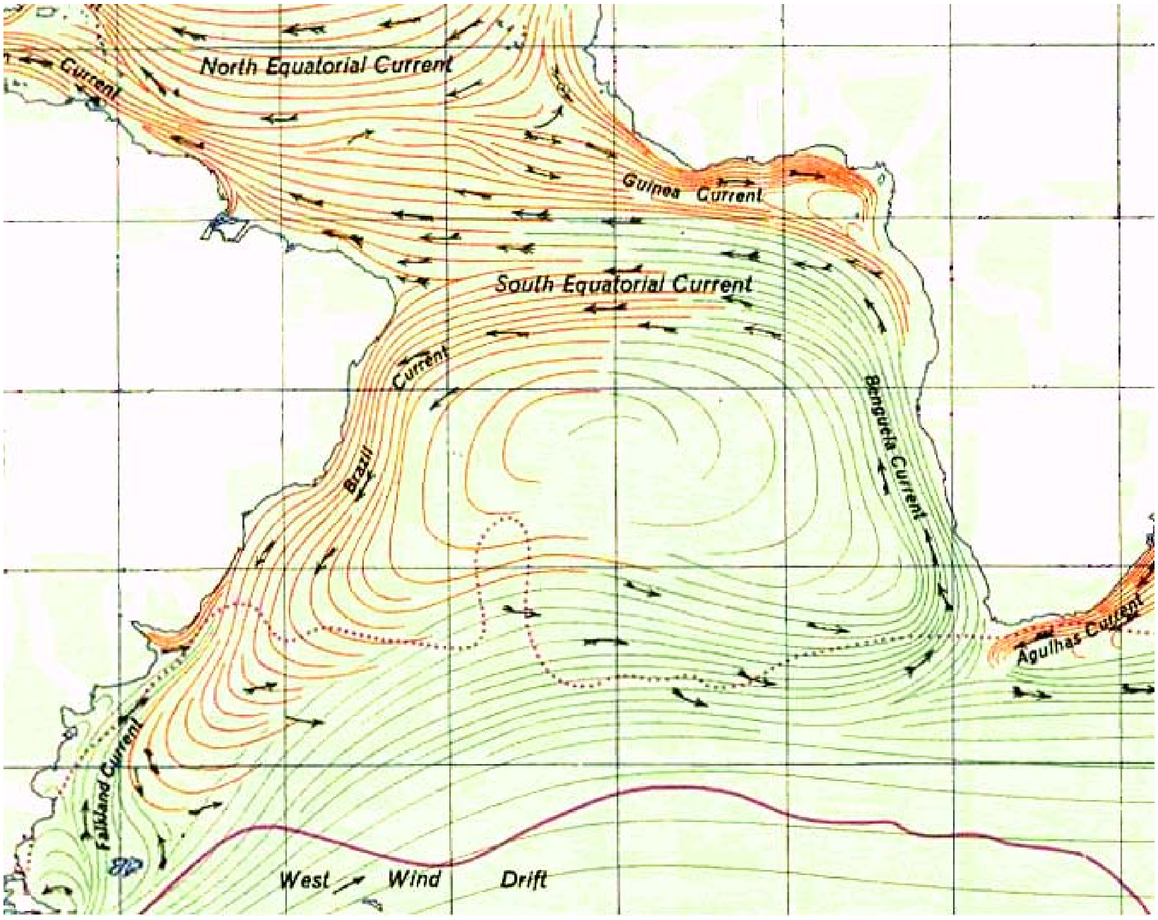
North Atlantic Gyre



The five major oceanic gyres.

The **North Atlantic Gyre**, located in the Atlantic Ocean, is one of the five major oceanic gyres, and contains the Sargasso Sea. This gyre is similar to the North Pacific Gyre by way that this gyre traps man-made ocean debris in the North Atlantic Garbage Patch, similar to the Great Pacific Garbage Patch in the North Pacific.

South Atlantic Gyre



The South Atlantic Gyre.

The **South Atlantic Gyre** is the southern branch of the subtropical gyre in the south Atlantic. This gyre is heavily influenced by northwesterly winds that drive a broad eastward drift, which makes it difficult to distinguish between the northern boundary of the subtropical gyre and the southern boundary of the Antarctic Circumpolar Current.

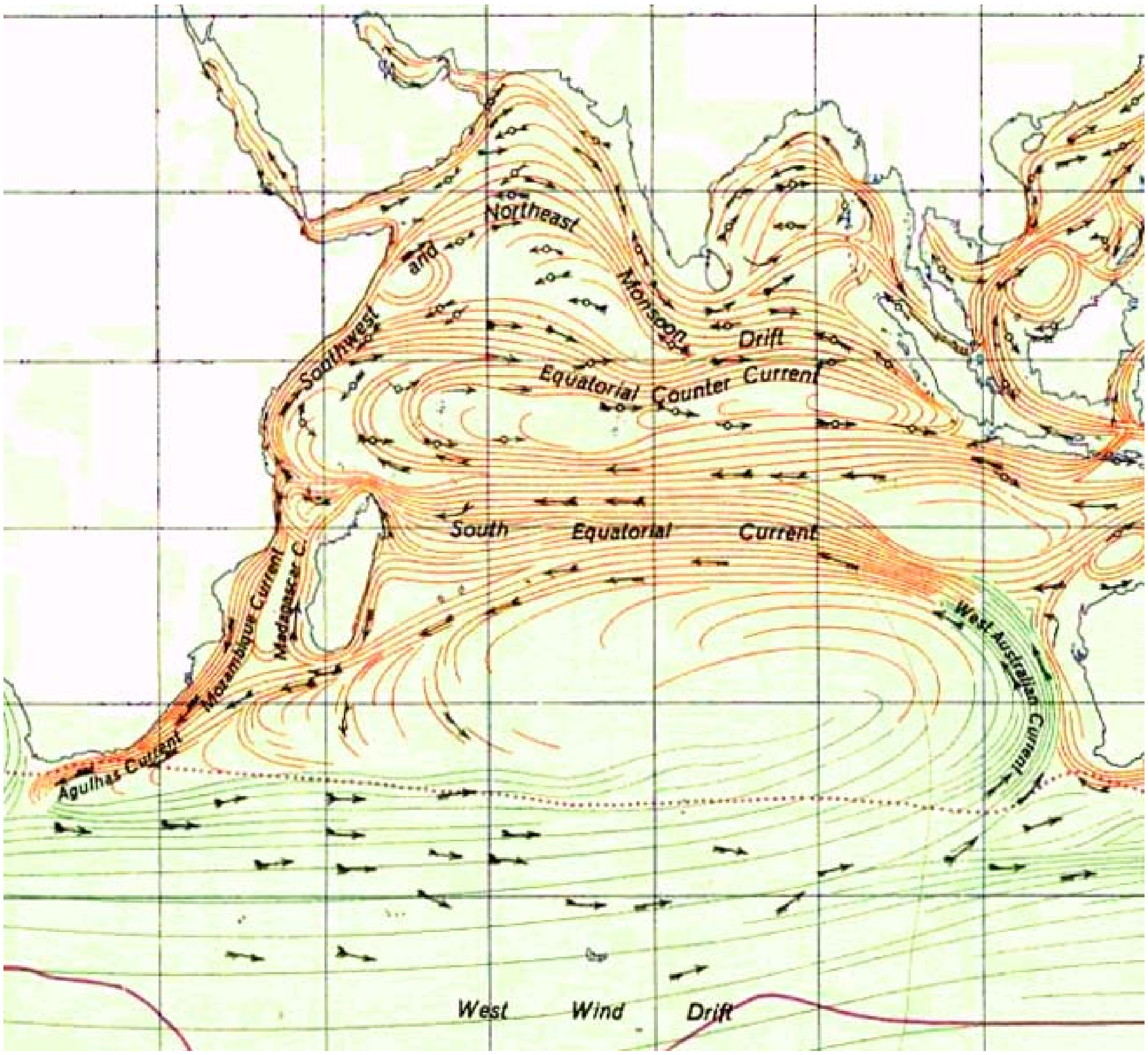
Southern boundary

South of this gyre is the Antarctic Circumpolar Current. This current flows from West to East around Antarctica. Another name for this current is the West Wind Drift. This current allows Antarctica to maintain its huge ice sheet by keeping warm ocean waters away. At approximately 125Sv, this current is the largest ocean current.

Northern boundary

North of this gyre is the Brazil Current. This current flows south along the south Brazilian coast to the mouth of Rio de la plata. Its a western boundary current, as is the Gulf Stream, but it is considerably weaker.

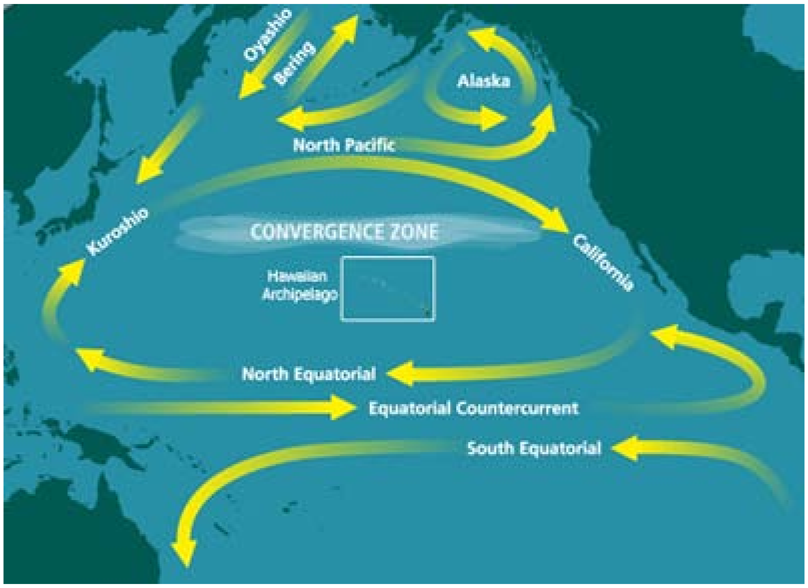
Indian Ocean Gyre



The Indian Ocean Gyre.

The **Indian Ocean Gyre**, located in the Indian Ocean, is one of the five major oceanic gyres.

North Pacific Gyre



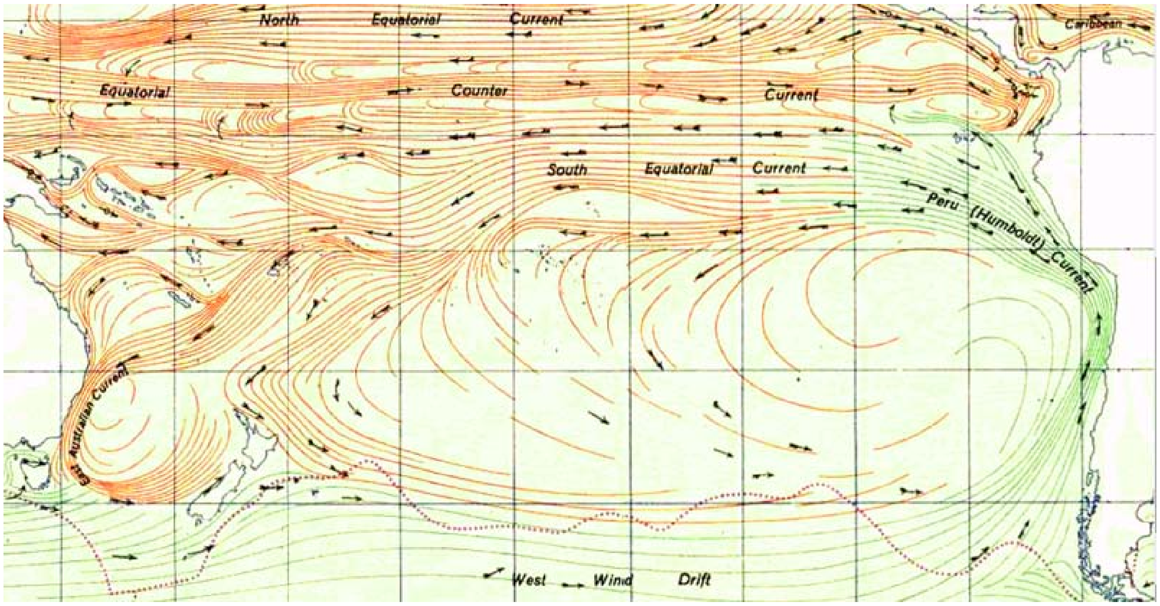
The main ocean currents involved with the North Pacific Gyre

The **North Pacific Gyre**, located in the northern Pacific Ocean, is one of the five major oceanic gyres. This gyre comprises most of the northern Pacific Ocean. It is the largest ecosystem on our planet. It is located between the equator and 50º N latitude and occupies an area of approximately 20 million square kilometers. The gyre has a clockwise circular pattern and comprises four prevailing ocean currents: the North Pacific Current to the north, the California Current to the east, the North Equatorial Current to the south, and the Kuroshio Current to the west. It is the site of an unusually intense collection of man-made marine debris, known as the Great Pacific Garbage Patch.

South Pacific Gyre

The **South Pacific Gyre** is the Earth's biggest system of ocean currents, located south of the equator between South America and Australia. It is mostly inactive and contains little marine life.

Sediment



The South Pacific Gyre.

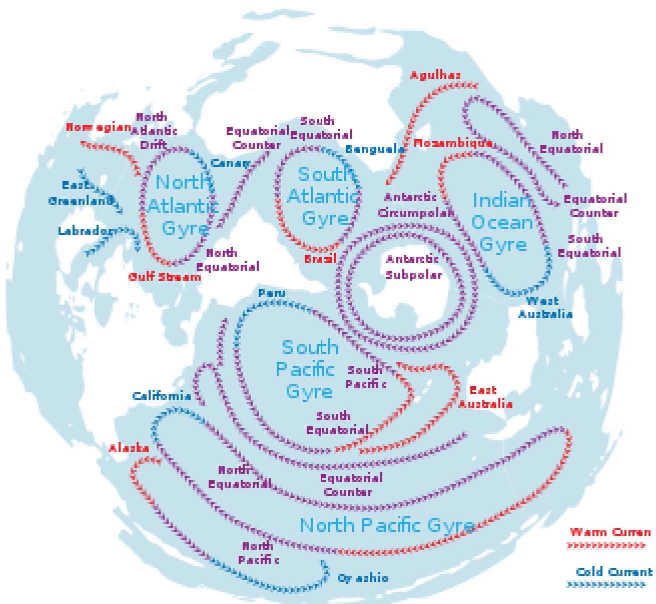
The gyre's sediment accumulates very slowly, approximately 0.1 to 1 m (0.3 to 3.3 ft) every million years. Its ecosystem has very little living matter and contains low amounts of life and has low growth and reproduction rates. At all depths in the gyre's sediment, mean cell abundances and net rates of respiration are several orders of magnitude lower than those of other subseafloor communities at the same depths. Because of the low respiration rates and thin consistency of the sediment in the area, most of the spaces between the sediment columns contain oxygen. This results in the sedimentary community of the SPG generally requiring oxygen to function, unlike previously explored subseafloor communities. Though per-cell, the respiration rates of this community are a couple orders of magnitude higher than in most subseafloor ecosystems living without oxygen, they may soon be decreasing to the approximate rates of the South Pacific Gyre. Sediment from the South Pacific Gyre contains far fewer living cells than other areas. Sediment cores from this area contained a minimum of 1,000 living cells per cubic centimeter, while sediments from closer to the shore can have 1 billion living cells per cubic centimeter, and even areas as far out as the SPG can have 1 million. Little organic matter settles in the sediment of the South Pacific Gyre because the currents around it move so slowly, so the water is very clear.

Water Color

Satellite observations by researchers have shown that some areas in the gyre are greener than the surrounding clear blue water. Their theory is that these green patches are a result of the accumulated waste of marine life. From satellite images, this disintegrated material often looks like living phytoplankton, but the assumed theory that the greener the ocean water, the more phytoplankton it contains, is not always true. The South Pacific Gyre is an example of this, because it contains these patches of green water, but has very little organism growth.

Other gyres

Tropical gyres



All of the world's larger gyres

Tropical gyres are less unified and tend to be mostly east-west with minor north-south extent.

- Atlantic Equatorial Current System (two counter-rotating circulations)
- Pacific Equatorial Current System
- Indian Monsoon Gyres (two counter-rotating circulations in northern Indian Ocean)

Subtropical gyres

The center of a subtropical gyre is a high pressure zone. Circulation around the high pressure is clockwise in the northern hemisphere and anticlockwise in the southern hemisphere, due to the Coriolis effect. The high pressure in the center is due to the westerly winds on the northern side of the gyre and easterly trade winds on the southern side of the gyre. These cause frictional surface currents towards the latitude at the center of the gyre. The build-up of water in the center of the gyre creates equatorward flow in the upper 1,000 to 2,000 m (3,300 to 6,600 ft) of the ocean, through rather complex dynamics. This equatorward flow is returned poleward in an intensified western boundary current.

The intensified western boundary current of the North Atlantic Gyre is the Gulf Stream, in the North Pacific it's the Kuroshio Current, in the South Atlantic it's the Brazil Current, in the South Pacific it's the East Australian Current, and in the Indian Ocean it's the Agulhas Current.

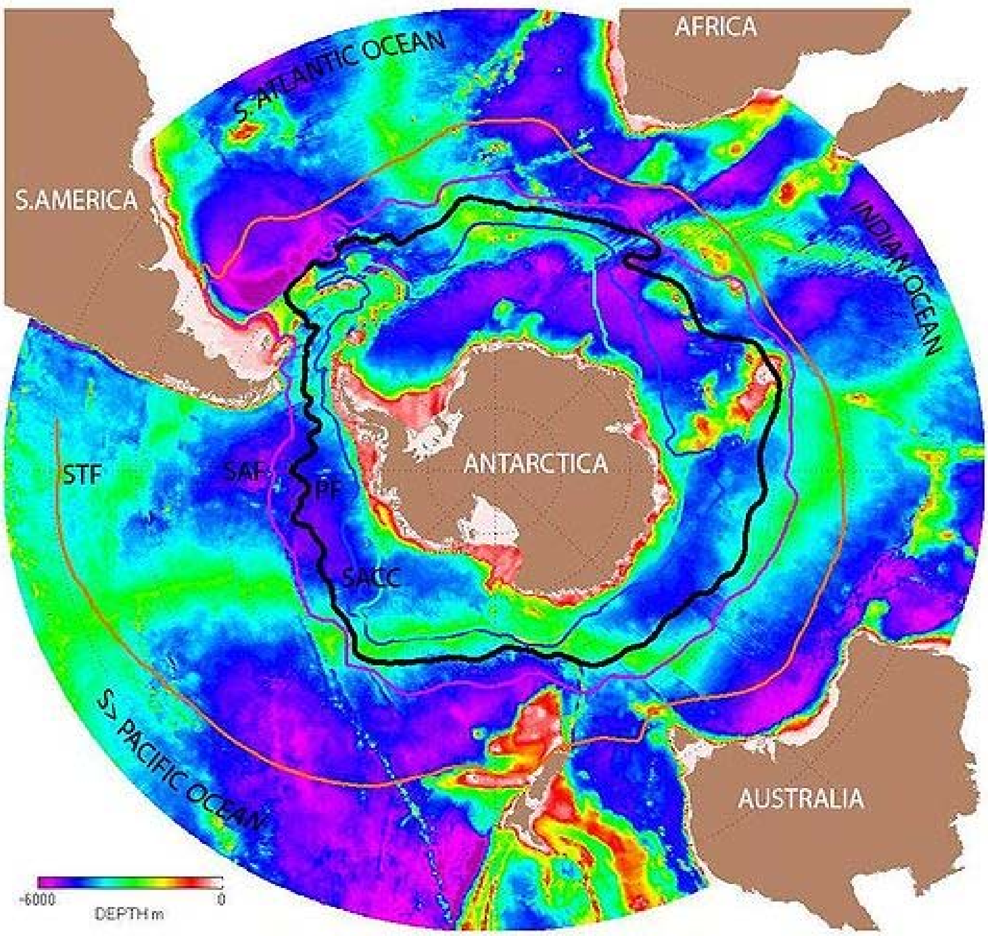
Subpolar gyres

Subpolar gyres form at high latitudes (around 60°). Circulation of surface wind and ocean water is anticlockwise in the Northern Hemisphere, around a low-pressure area, such as the persistent Aleutian Low and the Icelandic Low. Surface currents generally move outward from the center of the system. This drives the Ekman transport, which creates an upwelling of nutrient-rich water from the lower depths.

Subpolar circulation in the southern hemisphere is dominated by the Antarctic Circumpolar Current, due to the lack of large landmasses breaking up the Southern Ocean. There are minor gyres in the Weddell Sea and the Ross Sea, the Weddell Gyre and Ross Gyre, which circulate in a clockwise direction.

Chapter- 3

Antarctic Circumpolar Current



ANTARCTIC CIRCUMPOLAR CURRENT
SEAWATER DENSITY FRONTS (FROM ORSI et al, 1995),
AND *BATHYMETRY* OF THE SOUTHERN OCEAN (UP TO LATITUDE 25 S)

The Antarctic Circumpolar Current (ACC) is the strongest current system in the world oceans, the one that links the Atlantic, Indian and Pacific basins.

The **Antarctic Circumpolar Current** (**ACC**) is an ocean current that flows from west to east around Antarctica. An alternative name for the ACC is the **West Wind Drift**. The ACC is the dominant circulation feature of the Southern Ocean and, at approximately 125 Sverdrups, the largest ocean current. It keeps warm ocean waters away from Antarctica, enabling that continent to maintain its huge ice sheet.

The ACC has been known to sailors for centuries; it greatly speeds up any voyages from west to east, but makes sailing extremely difficult from east to west; though this is mostly due to the prevailing westerly winds. The circumstances preceding the Mutiny on the Bounty and Jack London's story "Make Westing" poignantly illustrated the difficulty it caused for mariners seeking to round Cape Horn on the clipper ship route between New York and California. The clipper route, which is the fastest sailing route around the world, follows the ACC around three continental capes - Cape of Good Hope (Africa), Southeast Cape (Australia) and Cape Horn (South America).

The current creates two Antarctic gyres.

Structure

The ACC connects the Atlantic, Pacific and Indian Ocean basins, and as such serves as a principal pathway of exchange between these basins. The current is strongly constrained by landform and bathymetric features. Starting at South America, it flows through the Drake Passage between South America and the Antarctic Peninsula and then is split by the Scotia Arc to the east, with a shallow warm branch flowing to the north in the Falkland Current and a deeper branch passing through the Arc more to the east before also turning to the north. Passing through the Indian Ocean, the current is split by the Kerguelen Plateau in the Indian Ocean, and then moving northward again. Deflection is also seen as it passes over the mid-ocean ridge in the Southeast Pacific.

The current consists of a number of fronts. The northern boundary of the ACC is defined by the Subtropical Front. This marks the boundary between warm, salty subtropical waters (generally with a salinity of greater than 34.9 parts per thousand) and fresher, cooler subpolar waters. Moving southward we find the Subantarctic Front, along which much of the ACC transport is carried, which is defined as the latitude at which a subsurface salinity minimum or a thick layer of unstratified Subantarctic Mode Water first appears. Still further south lies the Polar Front, which is marked by a transition to very cold, relatively fresh, Antarctic Surface Water at the surface. Further south still is the Southern Boundary front, which is determined as the point where very dense abyssal waters upwell to within a few hundred meters of the surface. The bulk of the transport is carried in the middle two fronts. The total transport of the ACC at Drake Passage is estimated to be around 135 Sverdrups (135,000,000 m^3/s), or about 135 times the transport of all the world's rivers combined. There is a relatively small addition of flow in the Indian Ocean, with the transport south of Tasmania reaching around 147 Sv, at which point the current is probably the largest on the planet.

Dynamics

The Circumpolar Current is driven by the strong westerly winds which are found in the latitudes of the Southern Ocean.

In latitudes where there are continents, winds blowing on light surface water can simply pile up light water against these continents. But in the Southern Ocean, the momentum imparted to the surface waters cannot be balanced in this way. Different theories of the Circumpolar Current balance the momentum imparted by the winds in different ways. The increasing eastward momentum imparted by the winds causes water parcels to drift outwards from the axis of the Earth's rotation (in other words, northward) as a result of the Coriolis force. This northward transport is balanced by a southward, pressure-driven flow below the depths of the major ridge systems. Some theories connect these flows directly, implying that there is significant upwelling of dense deep waters within the Southern Ocean, transformation of these waters into light surface waters, and a transformation of waters in the opposite direction to the north. Such theories link the magnitude of the Circumpolar Current with the global thermohaline circulation, particularly the properties of the North Atlantic.

Alternatively, ocean eddies, the oceanic equivalent of atmospheric storms, or the large scale meanders of the Circumpolar Current may directly transport momentum downwards in the water column. This is because such flows can produce a net southward flow in the troughs and a net northward flow over the ridges without requiring any transformation of density. In practice both the thermohaline and the eddy/meander mechanisms are likely to be important.

The current flows at a rate of about four km per hour. Recent studies have indicated that the Antarctic Circumpolar Current varies with time. Evidence of this is the Antarctic Circumpolar Wave, a periodic oscillation that affects the climate of much of the southern hemisphere. There is also the Antarctic oscillation, which involves changes in the location and strength of Antarctic winds. Trends in the Antarctic Oscillation have been hypothesized to account for an increase in the transport of the Circumpolar Current over the past two decades.

Formation

Published estimates of the onset of the Antarctic Circumpolar Current vary, but it is commonly considered to have started at the Eocene/Oligocene boundary. The isolation of Antarctica and formation of the ACC occurred with the openings of the Tasmanian Seaway and the Drake Passage. The Tasmanian Seaway separates East Antarctica and Australia, and is reported to have opened to water circulation 33.5 Ma. The timing of the opening of the Drake Passage, between South America and the Antarctic Peninsula, is more disputed. Tectonic and sediment evidence show that it could have been open as early as pre 34 Ma, estimates of the opening of the Drake passage are between 20 and 40 Ma. The isolation of Antarctica by the current is credited by many researchers with causing the glaciation of Antarctica and global cooling in the Miocene Period. Oceanic models have shown that the opening of these two passages limited polar heat convergence and caused a cooling of sea surface temperatures by several degrees, other models have shown that CO_2 levels also played a significant role in the glaciation of Antarctica .

Phytoplankton

Antarctic sea ice cycles seasonally, in February-March the amount of sea ice is lowest, and in August-September the sea ice is at its greatest extent. Ice levels have been monitored by satellite since 1973. Upwelling of deep water under the sea ice brings substantial amounts of nutrients. As the ice melts, the melt water provides stability and the critical depth is well below the mixing depth, which allows for a positive net primary production. As the sea ice recedes epontic algae dominate the first phase of the bloom, and a strong bloom dominate by diatoms follows the ice melt south .

Another phytoplankton bloom occurs more to the north near the antarctic convergence, here nutrients are present from thermohaline circulation. Phytoplankton blooms are dominated by diatoms and grazed by copepods in the open ocean, and by krill closer to the continent. Diatom production continues through the summer, and populations of krill are sustained, bringing large stocks of whales, seals, and fish to the area .

Phytoplankton blooms are believed to be limited by irradiance in the austral (southern hemisphere) spring, and by biologically available iron in the summer. Much of the biology in the area occurs along the major fronts of the current, the Subtropical, SubAntarctic, and the Antarctic Polar fronts, these are areas associated with well defined temperature changes. Size and distribution of phytoplankton are also related to fronts. Microphytoplankton (>20μm) are found at fronts and at sea ice boundaries, while nanophytoplankton (<20μm) are found between fronts.

Studies of phytoplankton stocks in the southern sea have shown that the Antarctic Circumpolar Current is dominated by diatoms, while the Weddell Sea has abundant coccolithophorids and silicoflagellates. Surveys of the SW Indian Ocean have shown phytoplankton group variation based on their location relative to the Polar Front, with diatoms dominating South of the front, and dinoflagellates and flagellates in higher populations North of the front .

Some research has been done on Antarctic phytoplankton as a carbon sink. Areas of open water left from ice melt are good areas for phytoplankton blooms. The phytoplankton takes carbon from the atmosphere during photosynthesis. As the blooms die and sink, the carbon can be stored in sediments for thousands of years. This natural carbon sink is estimated to remove 3.5 million tonnes from the ocean each year. 3.5 million tonnes of carbon taken from the ocean and atmosphere is equivalent to 12.8 million tonnes of carbon dioxide.

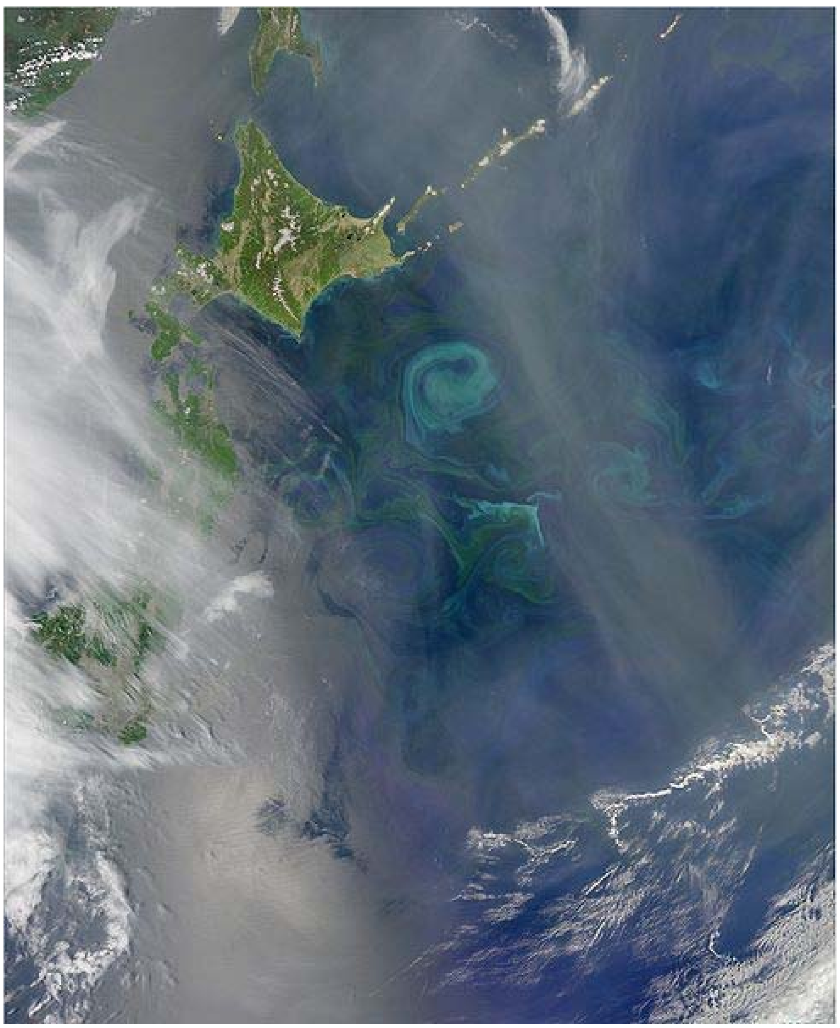
Studies

An expedition in May 2008 by 19 scientists studied the geology and biology of eight Macquarie Ridge sea mounts, as well as the Antarctic Circumpolar Current to investigate the effects of climate change of the southern Ocean. The circumpolar current merges the waters of the Atlantic, Indian, and Pacific Oceans and carries up to 150 times the volume of water flowing in all of the world's rivers. After studying the circumpolar current it is clear that it strongly influences regional and global climate as well as underwater biodiversity.

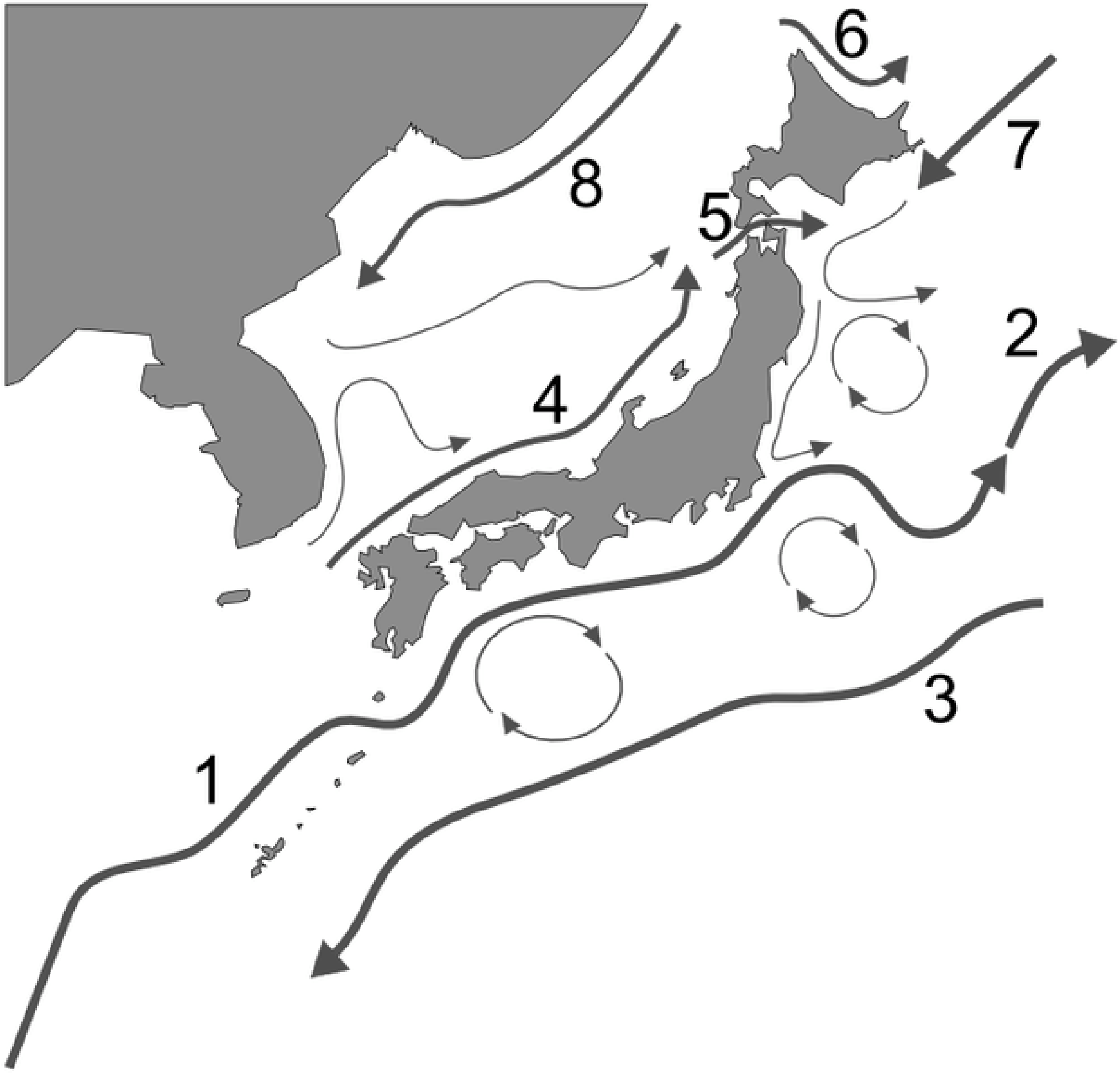
Chapter- 4

Western Boundary Currents

Kuroshio Current



The Oyashio Current colliding with the Kuroshio Current near Hokkaido. When two currents collide, they create eddies. Phytoplankton growing in the surface waters become concentrated along the boundaries of these eddies, tracing out the motions of the water.



The ocean currents surrounding the Japanese Archipelago: **1. Kuroshio** 2.Kuroshio extension 3. Kuroshio countercurrent 4. The Tsushima Current 5. The Tsugaru Current 6. The Sōya Current 7. Oyashio 8. The Liman Current

Physical properties

The **Kuroshio** is a strong western boundary current in the western north Pacific Ocean. It begins off the east coast of Taiwan and flows northeastward past Japan, where it merges with the easterly drift of the North Pacific Current. It is analogous to the Gulf Stream in the Atlantic Ocean, transporting warm, tropical water northward towards the polar region. It is also sometimes known as the *Black Stream* — the English translation of *kuroshio*, and an allusion to the deep blue of its water—and also as the "Japan Current" (日本海流 *Nihon Kairyū* ?).

The path of Kuroshio south of Japan is reported every day. Its counterparts are the North Pacific Current to the north, the California Current to the east, and the North Equatorial Current to the south. The warm waters of the Kuroshio Current sustain the coral reefs of Japan, the northernmost coral reefs in the world. The branch into the Sea of Japan is called **Tsushima Current** (対馬海流 *Tsushima Kairyū* ?). The Japan Current is also responsible for the mild weather experienced around Alaska's southern coast and in British Columbia.

Biological properties

Distribution

Western boundary currents transport organisms long distances rapidly and a variety of commercially important marine organisms migrate in these currents in the course of completing their life histories . Subtropical gyres occupy a large fraction of the world's ocean and are more productive than originally thought. In addition, their fixation of carbon dioxide is an important factor in the global budget for carbon dioxide in the atmosphere.

Satellite images of the **Kuroshio Current** illustrates how the current path meanders and forms isolated rings or eddies on the order of 100–300 km. Eddies retain their unique form for several months and have their own biological characteristics that depend on where they form. If the eddies are formed between the current and coastline of Japan, they may impinge on the continental shelf and their high kinetic energy has the effect of drawing large volumes of water off the shelf on one side of the ring, while adding water to the other side. Eddies size and strength decline with distance from major ocean currents. The amount of energy decreases from the rings associated with the major currents and down to eddies remote from those currents. Cyclonic eddies have the potential to cause upwelling that would affect the global primary-production budget . Upwelling brings cold, nutrient rich water to the surface resulting in an increase in productivity. The biological consequences for young fish populations that inhabit the shelf are quite large.

Production

Impact of eddies

The Kuroshio is a warm current (24°C annual average sea surface temperature), about 100 km wide and produces frequent small to meso-scale eddies. The Kuroshio Current is ranked as a moderately high productivity ecosystem (150-300 $gCm^{-2}y^{-1}$) based on SeaWiFs global primary productivity estimates. The coastal areas are highly productive and the maximum chlorophyll value is found around 100 meters depth .

There are indications that eddies contribute to the preservation and survival of fish larvae transported by the Kuroshio . Plankton biomass fluctuates yearly and is typically highest in the eddy area of the Kuroshio's edge. Warm-core rings are not known for having high productivity. However, the biology of the warm-core rings from the Kuroshio Current show results of productivity equally distributed throughout for a couple of reasons. One is upwelling at the periphery and two, the convective mixing caused by the cooling of surface water as the ring moves north of the current. The thermostad is the deep mixed layer that has discrete boundaries and uniform temperature. Within this layer, nutrient-rich water is brought to the surface, which generates a burst of primary production. Given that the water in the core of a ring has a different temperature regime than the shelf waters, there are times when a warm-core ring is undergoing its spring bloom while the surrounding shelf waters are not.

There are many complex interactions with the warm-core ring and thus lifetime productivity is not very different from the surrounding shelf water. A study in 1998 found that the primary productivity within a warm-core ring was almost the same as in the cold jet outside it, with evidence of upwelling of nutrients within the ring. In addition, there was discovery of dense populations of phytoplankton at the nutricline within a ring, presumably supported by upward mixing of nutrients. Furthermore, there have been acoustic studies in the warm-core ring, which showed intense sound scattering from zooplankton and fish populations within the ring and very sparse acoustic signals outside of it.

Copepods have been used as indicator-species of water masses. It has been suggested that copepods have been transported from the Kuroshio Current into southwest Taiwan through the Luzon Strait . The Kuroshio intrusion through the Luzon Strait and further into the South China Sea may also explain why copepods show a very high diversity in adjacent waters of the intrusion areas. The Kuroshio Current intrusion has a major influence on *C. sinicus* and *E. concinna*, which are two copepod species with higher index values for winter and originate from the East China Sea. During the SW monsoon, the South China Sea Surface Current moves northwards during the summer towards the Kuroshio Current. As a result of this water circulation, the zooplankton communities in the boundary waters are unique and diverse.

Fish

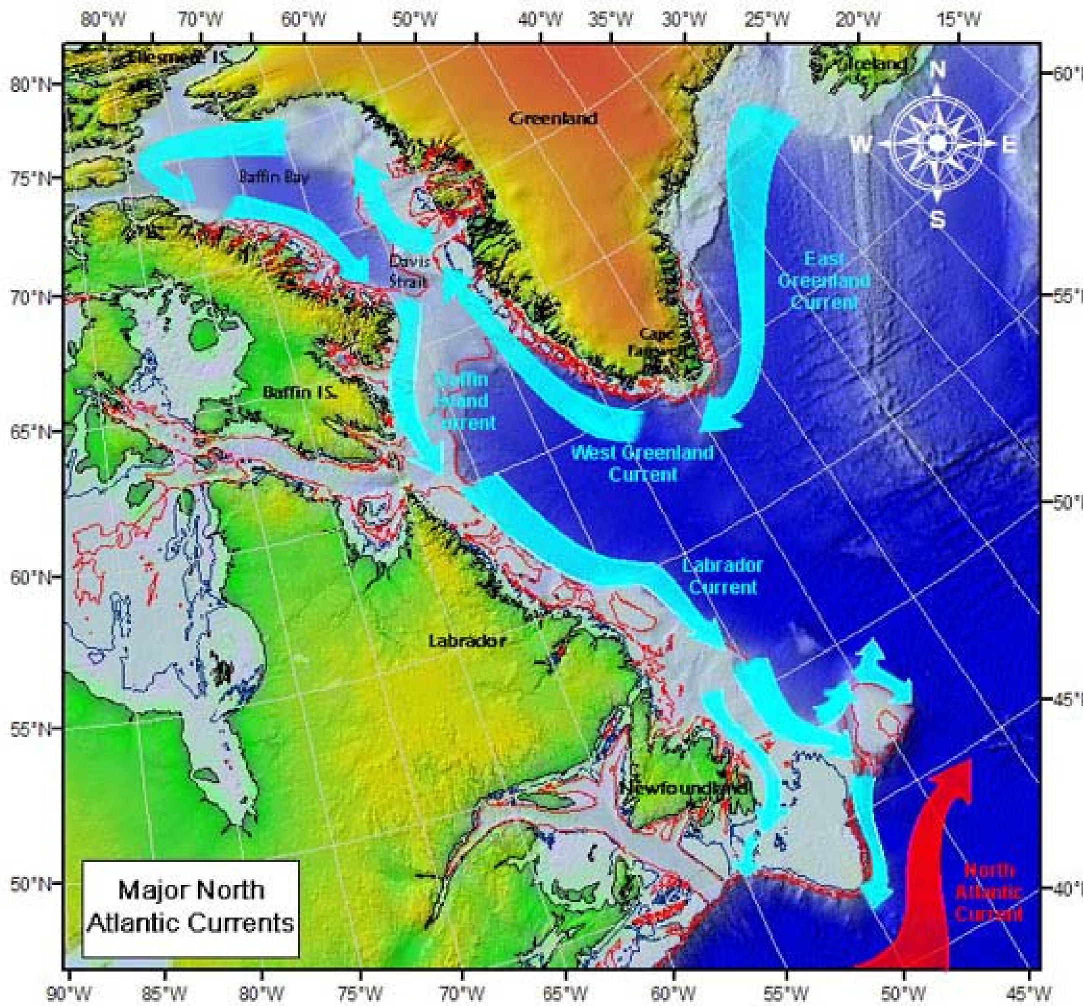
The biomass of fish stocks depends on the biomass of lower trophic levels, primary production and on oceanic and atmospheric conditions . In the Kuroshio-Oyashio region, the fish catches depend on oceanographic conditions, such as the Oyashio's southward intrusion and the Kuroshio's large meander south of Honshu. The Oyashio Current contains subarctic water that is much colder and fresher than the resident water east of Honshu. Thus, the Oyashio intrusion affects recruitment, biomass, and catch of species such as Pollock, sardine, and anchovy. When the Oyashio is well developed and protrudes southward, the cold waters are favorable for sardine production. The Kuroshio large meander development correlates with sardine recruitment and catch due to the proximity of the Kuroshio meander to the southern spawning grounds of sardine.

Squid

The Japanese squid *Todarodes Pacificus* has three stocks that breed at different seasons: winter, summer, and autumn. The winter spawning group is associated with the Kuroshio Current. After spawning in the period of January to April in the East China Sea, the larvae and juveniles travel north with the Kuroshio Current. They are turned inshore and are caught between the islands of Honshu and Hokkaido during the summer. The summer spawning is in another part of the East China Sea, from which the larvae are entrained into the Tsushima current that flows north between the islands of Japan and the mainland. Afterward, the current meets a southward flowing cold coastal current, the Liman Current, and the summer-spawned squid are fished along the boundary between the two. This illustrates the use of these western boundary currents as a rapid transport that enable the eggs and larvae to develop during winter in warm water, while the adults travel north with minimum energy expenditure to exploit the rich feeding grounds further north. Studies have reported that annual catches in Japan have gradually increased since the late 1980s and it has been proposed that changing environmental conditions have caused the autumn and winter spawning areas in the Tsushima Strait and near the Goto Islands to overlap . In addition, winter spawning sites over the continental shelf and slope in the East China Sea are expanding.

Labrador Current

Photo of edies in the Labrador Current



Map of Labrador Current

The **Labrador Current** is a cold current in the North Atlantic Ocean which flows from the Arctic Ocean south along the coast of Labrador and passes around Newfoundland, continuing south along the east coast of Nova Scotia. It is a continuation of the West Greenland Current and the Baffin Island Current.

It meets the warm Gulf Stream at the Grand Banks southeast of Newfoundland and again north of the Outer Banks of North Carolina. The combination of these two currents produces heavy fogs and also created one of the richest fishing grounds in the world.

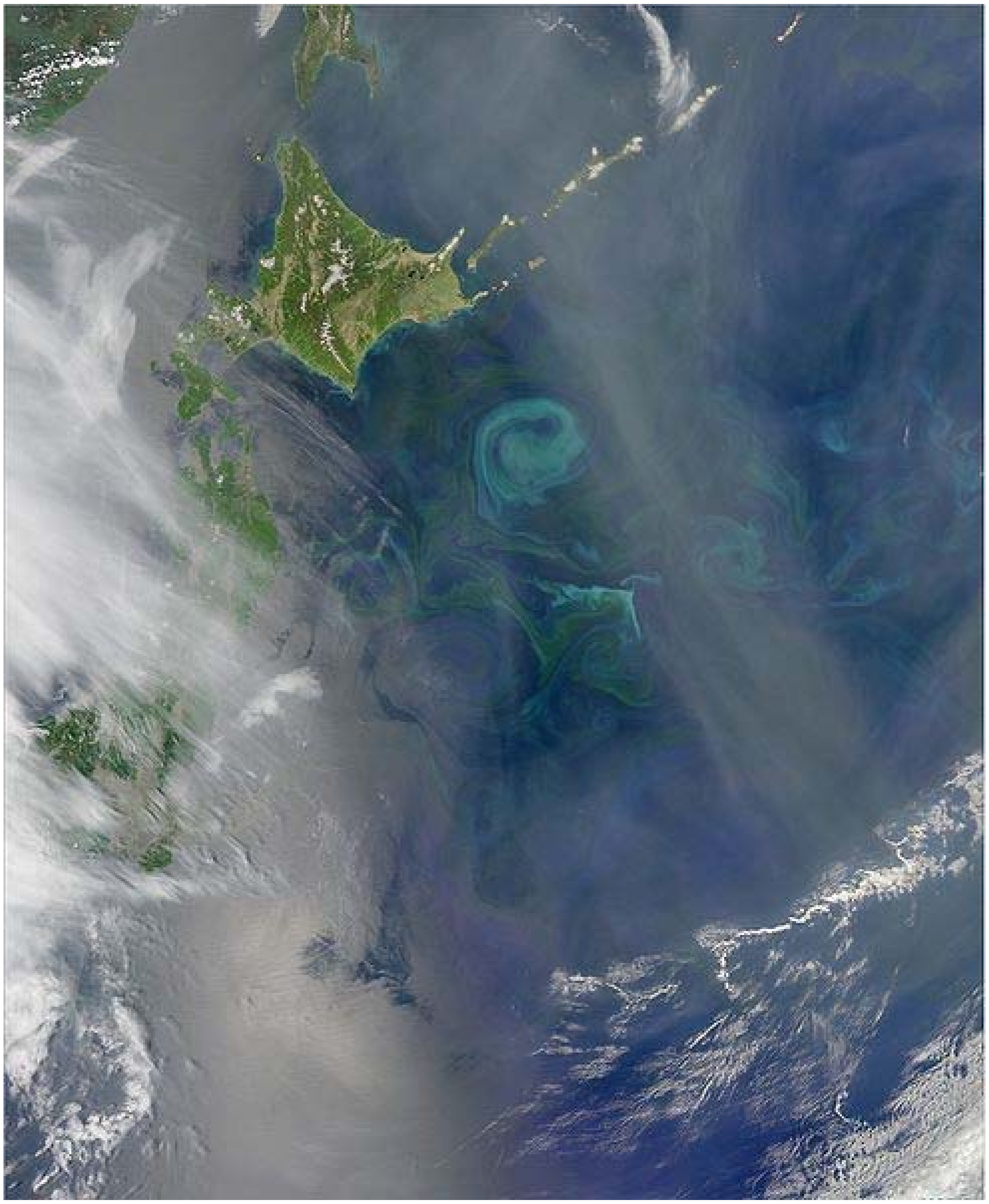
In spring and early summer, this current transports icebergs from the glaciers of Greenland southwards into the trans-Atlantic shipping lanes.

The waters of the Labrador Current have a cooling effect on the Canadian Atlantic provinces and coastal New England, but rarely have a significant effect on waters south of Cape Cod. This can most clearly be seen in the fact that the northern limit of tree growth can be as much as *fifteen degrees* farther south than in Siberia, Europe or western Canada.

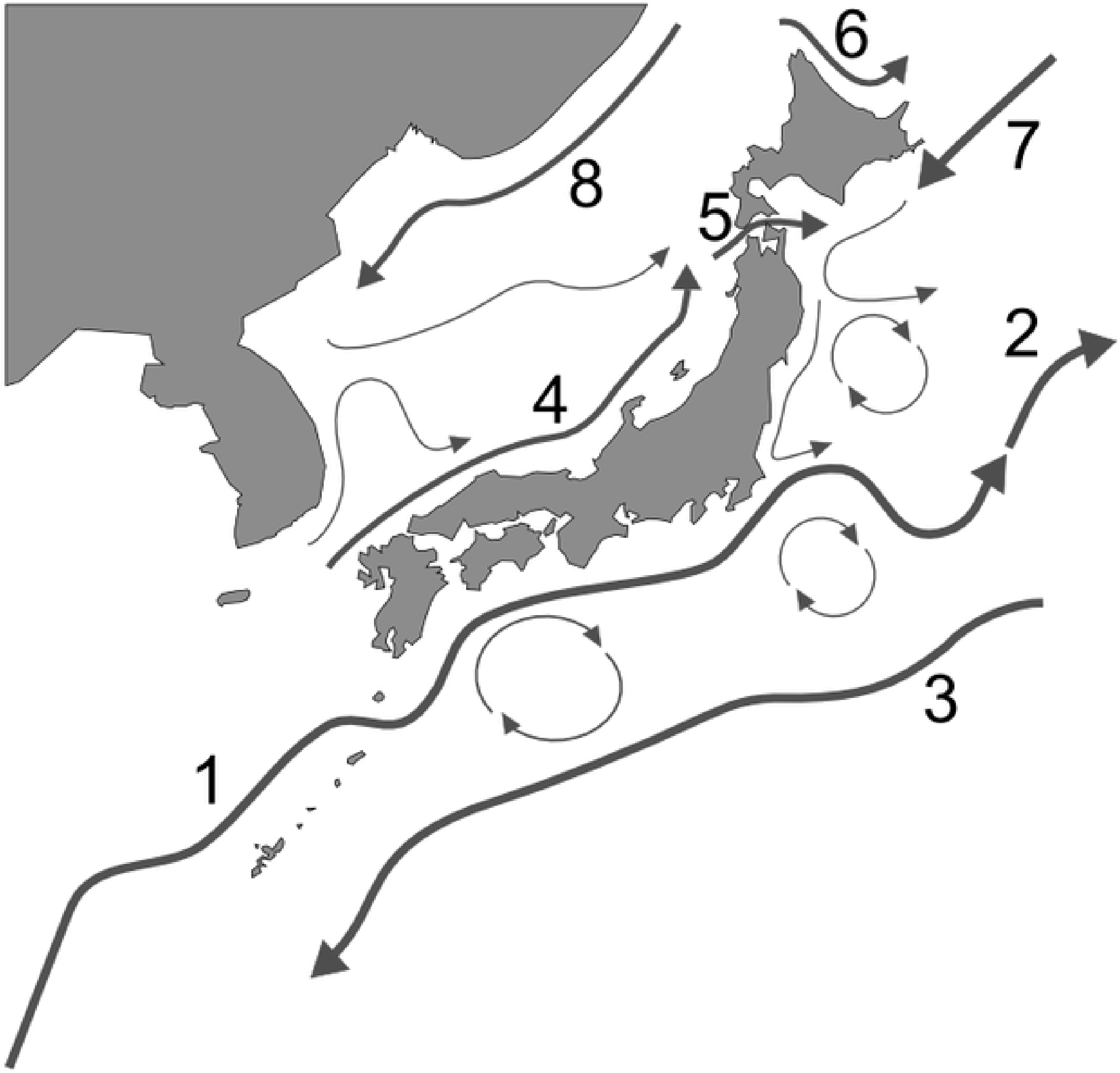
The transport of the Labrador Current is believed to contain a large barotropic component. Early estimates indicated that the current may be 30% stronger than geostrophic calculations indicated as a result of a significant barotropic flow component (Hayes and Robe, 1978). Greenberg and Petrie (1988) calculated a total transport of 7.6 Sverdrup. (One Sverdrup (Sv) is equal to 10^6 cubic meters per second.) The geostrophic transport was calculated to be just 4.1 Sv (based on IIP sections). With a 30% increase (due to barotropic flow) the transport is only 5.3 Sv so, the high transport values are thought to largely from the inclusion of deep currents indicated by a deep water mooring. Speeds for the Labrador Current are about 0.3–0.5 m/s along the shelf edge (Greenbergand Petrie, Reynaud et al., 1985. Current speeds of 0.3–0.5 m/s were found by Reynaud et al. (1995) for the Labrador Current. Including the barotropic component, they estimate a value of 3 Sv for the continental shelf branch of the Labrador Current and 16 Sv transport for the slope branch of the Labrador Current. The inshore branch of the Labrador Current is approximately 100 km wide and 150 m deep and it passes through Avalon Channel and the splitting of the Labrador Current around Flemish Cap can be seen in the tracks of satellite tracked drifters (Petrie and Isenor). Within the Flemish Pass, Petrie and Isenor (1985) report that the width of the Labrador Current is reduced to 50 km with a speed of 0.25 m/s which they believe is actually 0.30 m/s.

The Labrador Current has a tendency to sometimes go farther south and/or east than normal. This can make it very hazardous to ships as it can carry icebergs into an area of the Atlantic where they are not usually found. The current has been known to transport icebergs as far south as Bermuda and as far east as the Azores. The International Ice Patrol was set up to track icebergs, including those found in areas of the ocean where they are rarely located. .

Oyashio Current



The Oyashio Current colliding with the Kuroshio Current near Hokkaido. When two currents collide, they create eddies. Phytoplankton growing in the surface waters become concentrated along the boundaries of these eddies, tracing out the motions of the water.



The ocean currents surrounding the Japanese Archipelago: 1.Kuroshio 2. Kuroshio extension 3. Kuroshio countercurrent 4. The Tsushima Current 5. The Tsugaru Current 6. The Sōya Current 7. **Oyashio** 8. The Liman Current

Oyashio (親潮?), also known as **Oya Siwo**, **Okhotsk** or the **Kurile** current, is a cold subarctic ocean current that flows south and circulates counterclockwise in the western North Pacific Ocean. It collides with the Kuroshio Current off the eastern shore of Japan to form the North Pacific Current (or Drift). This cold current flows through Bering Strait in the southern direction and transports cold water of the Arctic Sea into the Pacific ocean. The waters of the Oyashio Current originate in the Arctic Ocean and flow southward via the Bering Sea. The current has an important impact on the climate of the Russian Far East, mainly in Kamchatka and Chukotka, where the northern limit of tree growth is moved up to ten degrees south of the latitude it can reach in inland Siberia. The waters of the Oyashio Current form probably the richest fishery in the world owing to the extremely high nutrient content of the cold water and the very high tides (up to ten metres) in some areas - which further enhances the availability of nutrients. However, the

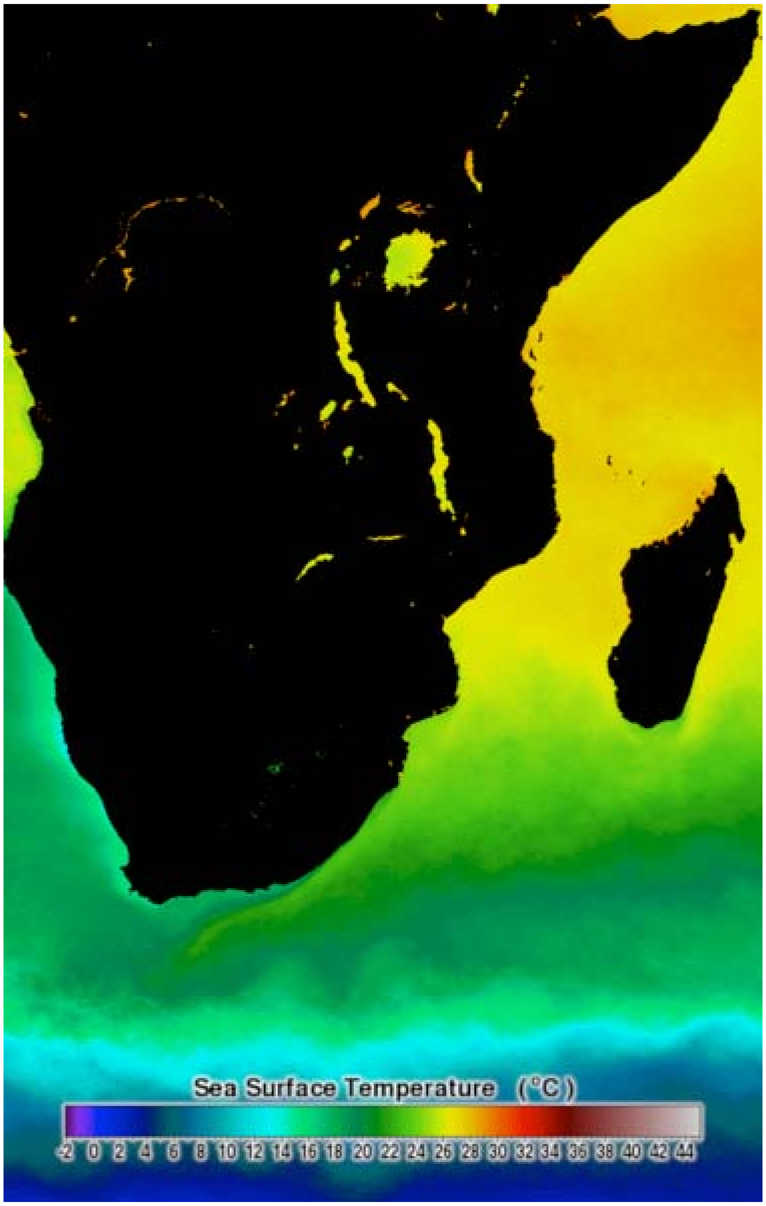
Oyashio Current also causes Vladivostok to be the most equatorward port to seasonally freeze and require icebreaking ships to remain open in winter. Nonetheless, this has relatively little effect on the fish yield through the Sea of Okhotsk because the large tides mean freezing does not occur so easily.

Another important feature of the Oyashio Current is that during glacial periods, when lower sea level causes the formation of the Bering land bridge, the current cannot flow and in the regions the Oyashio affects today, the level of cooling with the onset of glacial conditions (after an interglacial) is much less than in other areas of the Earth at similar latitudes. This allowed Tōhoku and Hokkaidō, which were the only areas of East Asia that receive enough snowfall to potentially form glaciers, to remain unglaciated except at high elevations during periods when Europe and North America were largely glaciated. This lack of glaciation explains why, despite its present climate being much colder than most of Europe, East Asia has retained 96 percent of Pliocene tree genera, whereas Europe has retained only 27%.

Agulhas Current

The **Agulhas Current** is the Western Boundary Current of the southwest Indian Ocean. It flows down the east coast of Africa from 27°S to 40°S. It is narrow, swift and strong. It is even suggested that the Agulhas is the largest western boundary current in the world ocean, as comparable western boundary currents transport less, ranging from the Brazil Current, 16.2 Sverdrups), to the Kuroshio, 42 Sverdrups.

Physical properties



Mean sea surface temperature map of the Agulhas Current for 2009. Note the separation of the current from the African coast as a warm tongue of water south of Cape Agulhas, as it retroflects into the Indian Ocean.

The sources of the Agulhas Current are the East Madagascar Current (25 Sverdrups), the Mozambique Current (5 Sverdrups) and a reticulated part of the Agulhas Current itself (35 Sverdrups). The net transport of the Agulhas Current is estimated as 100 Sv. The flow of the Agulhas Current is directed by the topography. The current follows the continental shelf from Maputo to the tip of the Agulhas Bank (Cape Agulhas). Here the momentum of the current overcomes the vorticity balance holding the current to the topography and the current leaves the shelf.

Retroflection

In the southeast Atlantic Ocean the current retroflects (turns back on itself) in the Agulhas Retroflection due to shear interactions with the strong Antarctic Circumpolar Current. This water becomes the Agulhas Return Current, rejoining the Indian Ocean Gyre. It is estimated that up to 85 Sv (Sverdrups) of the net transport is returned to the Indian Ocean through the retroflection. The remaining water is transported into the South Atlantic Gyre in the Agulhas Leakage. Along with direct branch currents, this leakage takes place in surface water filaments, and Agulhas Eddies.

Agulhas leakage

It is estimated that as much as 15 Sv of Indian Ocean water is leaked directly into the South Atlantic. 10 Sv of this is relatively warm, salty thermocline water, with the remaining 5 Sv being cold, low salinity Antarctic Intermediate Water. Since Indian Ocean water is significantly warmer (24-26°C) and saltier than South Atlantic water, the Agulhas Leakage is a significant source of salt and heat for the South Atlantic Gyre. This heat flux is believed to contribute to the high rate of evaporation in the South Atlantic, a key mechanism in the Meridional Overturning Circulation. It should be noted that a small amount of the Agulhas Leakage joins the North Brazil Current, carrying Indian Ocean water into the North Atlantic Subtropical Gyre .

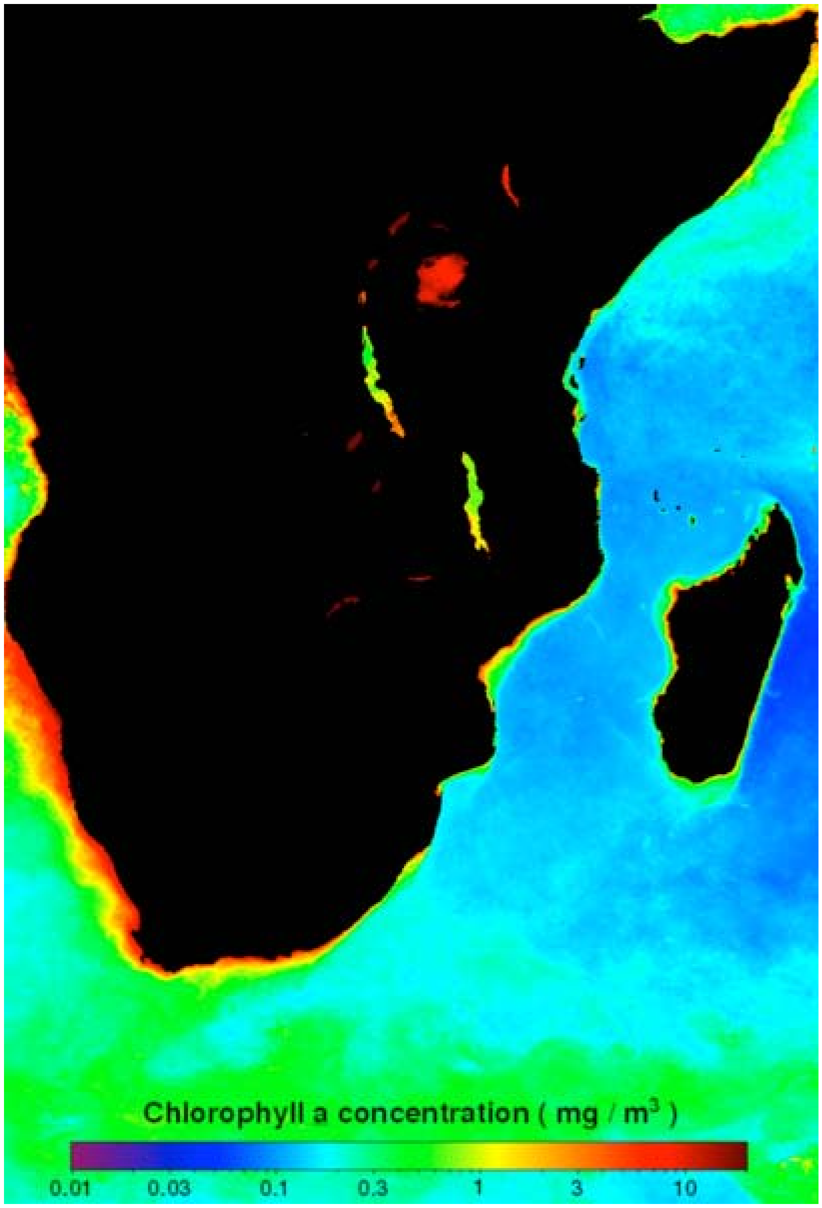
Filaments

Surface water filaments are estimated to account for up to 13% of the total salt transport from the Agulhas Current into the Benguela Current and South Atlantic Gyre. Due to surface dissipation, these filaments are not believed to significantly contribute to inter-basin heat flux.

Eddies

Where the Agulhas turns back on itself the loop of the retroflection pinches off periodically, releasing an eddy into the South Atlantic Gyre. This "Agulhas Ring" enters the flow of the Benguela Current or is advected northwestward across the South Atlantic where it joins the South Equatorial Current, where they dissipate into the larger background currents. These anticyclonic warm core rings are estimated to have a transport of 3-9 Sv each, in total injecting salt at a rate of $2.5.10^6$ kg/s and heat at a rate of 0.045 PW .

Biological properties



Mean chlorophyl-a concentration map of the Agulhas Current for 2009. Note the high productivity water in the Agulhas Retroflection.

Primary production

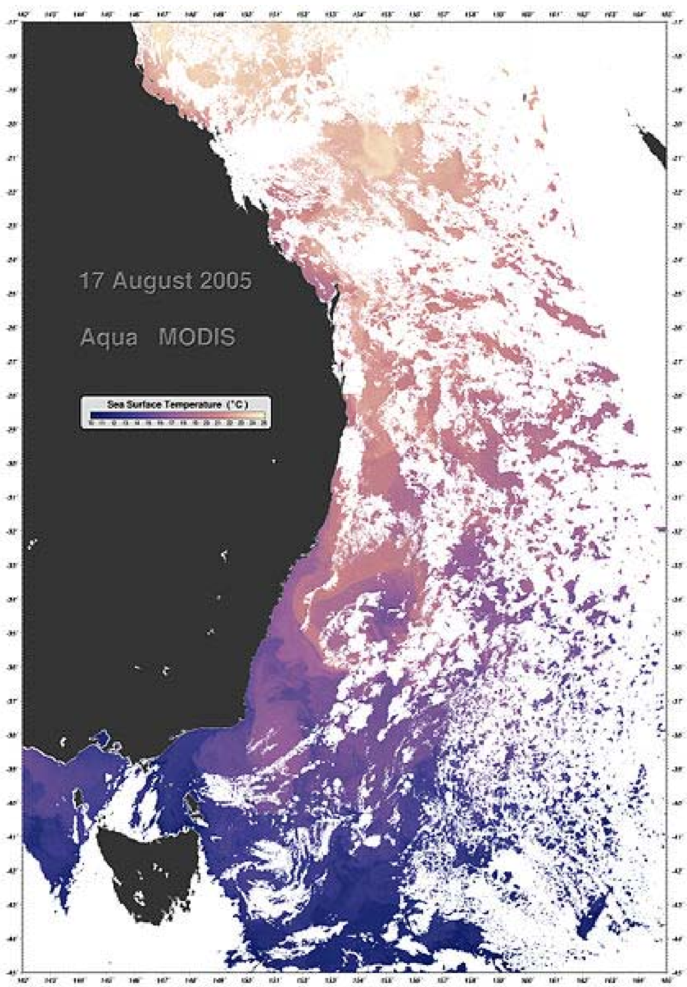
The Agulhas acts as an oceanic convergence zone. Due to mass continuity this drives surface waters down, resulting in the upwelling of cold, nutrient rich water south of the current. Additionally, the convergence tends to increase the concentration of plankton in and around the Agulhas. Both of these factors result in the area being one of enhanced primary productivity as compared to the surrounding waters. This is especially notable in the Agulhas Retroflection waters, where chl-a concentrations tend to be significantly higher than the surrounding South Indian Ocean and South Atlantic Ocean waters.

Impact of rings

Warm core rings are known to have lower primary productivity than surrounding cold waters. Agulhas Rings are no exception, and have been observed to carry waters with low chlorophyll-a concentration water into the South Atlantic. It can also be noted that the size of phytoplankton in Agulhas Rings tends to be smaller than in the surrounding water (around 20 µm in diameter).

Agulhas Rings have also bee observed as removing larval and juvenile fish from the continental shelf. This removal of young fish can result in a reduced Anchovy catch in the Benguela system if a ring passes through the fishery.

East Australian Current



Thermal profile of the East Australian Current

The **East Australian Current** (EAC) is an ocean current that moves warm water in a clockwise fashion down the east coast of Australia. It is the largest ocean current close to the shores of Australia. Its source is the tropical Coral Sea off the north-east coast of Australia. It can reach speeds of up to 7 knots in some of the shallower waters along the Australian continental shelf, but is generally measured at 2 or 3 knots. The EAC results in a current vortex in the Tasman Sea between Australia and New Zealand. The EAC also acts to transport tropical marine fauna to habitats in sub-tropical regions along the south east Australian coast.

Chapter- 5

Eastern Boundary Currents

California Current

The **California Current** is a Pacific Ocean current that moves south along the western coast of North America, beginning off southern British Columbia, and ending off southern Baja California. There are five major coastal currents affiliated with upwelling zones. These are the California Current (located off the coast of Oregon and California), the Humboldt Current (located off the coast of Chile and Peru), the Canary Current (located off the coast of northwest Africa), the Benguela Current (located off the coast of southwest Africa), and the Somali Current (located in the western Indian Ocean) (Mann and Lazier, 2006). The five major coastal currents are parts of the global ocean gyre system and as such, these currents are driven by wind and deflected by landmasses. Each of the major ocean basins has both a western boundary current and an eastern boundary current. The western boundary currents tend to be deep and fast and the eastern boundary currents are mainly shallow, broad, and less-defined (Mann and Lazier, 2006). The California Current is an Eastern boundary current and is part of the North Pacific Gyre, a large swirling current that occupies the northern basin of the Pacific. The movement of northern waters southward makes the coastal waters cooler than the coastal areas of comparable latitude on the east coast of the United States. Additionally, extensive upwelling of colder sub-surface waters occurs, caused by the prevailing northeasterly winds acting through the Ekman Effect. The winds drive surface water to the right of the wind flow, that is offshore, which draws water up from below to replace it. The upwelling further cools the already cool California Current. This is the mechanism that produces California's characteristic coastal fog and the negative temperature anomaly we measure in California's coastal waters during summer (Mann and Lazier, 2006). This translates into cold coastal waters during the summer, stretching from Oregon to Baja California. Note, this does not include the coastal water surrounding San Diego. There is a warm water anomaly off San Diego (Mann and Lazier, 2006).

The cold water is highly productive due to the upwelling, which brings to the surface nutrient-rich sediments, supporting large populations of whales, seabirds and important fisheries. Winds of the appropriate direction and strength to induce upwelling are more prevalent in the presence of Eastern boundary currents, such as the California Current (Mann and Lazier, 2006). Phytoplankton production is dramatically increased in these areas because the nutrient-rich water lying below the pycnocline is relatively close to the surface and is thus easily upwelled (Mann and Lazier, 2006). A narrower, weaker counter current, the Davidson Current, occasionally moves somewhat warmer water northwards during the winter months. During El Niño events, the California Current is disrupted, leading to declines in phytoplankton, resulting in cascading effects up the food chain, such as declines in fisheries, seabird breeding failures and marine mammal mortality (Schwing et al., 2003). In 2005, a failure in the otherwise predictable upwelling events, unassociated with El Niño, caused a collapse in krill in the current, leading to similar effects (Schwing et al., 2003).

Bakun (1973) calculated a 20-year average of the monthly mean Ekman transport for different regions off the California coast. His 'Bakun upwelling index' ranges from 300 meters-cubed/second (in the offshore direction) to -212 meters-cubed/second (toward the coast, or onshore direction) (Mann and Lazier,2006). Bakun's index showed there is year-round upwelling off Southern California's coast, but it is strongest in the summer months. Bakun's work also shows that off the coast of Oregon and Washington, there is forceful downwelling in the winter months, and upwelling in the region is restricted to the months of April through September (Mann and Lazier, 2006).

Primary Production in the California Current

Primary production is a topic of interest among those who study the California Current. In their study, Hayward and Venrick (1982) found great variability in both biomass and the productivity of phytoplankton in the California Current. The differences observed by Hayward and Venrick in carbon-fixation rates (0.2-2.0 grams Carbon/(meter-squared x day)) show the heterogeneous nature of the California Current, with its combination of advected and upwelled water. Several studies have investigated the carbon flow from primary production to the pelagic fish stocks which depend on the California Current. Lasker (1988) described powerful 'jets and squirts' off northern and central California. These 'jets and squirts' move large quantities of cold, nutrient rich water offshore. This water then gets carried by the southward bound California Current and adds significant primary production to the sardine population (Mann and Lazier, 2006).

Physical Properties of the California Current

The Southern California Bight is a sub-region of the California Current and has unique physical properties. Upwelling is fairly weak in the California Bight and Smith and Eppley (1982) stated that the 16-year average for primary production was 0.402 grams Carbon/(meter-squared x day),or approximately 150 grams Carbon/(meter-squared x year). Further, Smith and Eppley (1982) found that the highest daily rates of temperature decrease were correlated with the maximum amount of upwelling (Mann and Lazier, 2006). Digiacomo and Holt (2001) used satellite images to study the mesoscale and sub-mesoscale eddies in the Southern California Bight. Their work showed that all eddies were less than 50 km in diameter and 70 % of all eddies measured less than 10 km (Mann and Lazier, 2006). The eddies appeared to be caused mostly by topography (particularly islands), wind, and instabilities in the current. The location of these eddies was mainly between the California Current (flowing toward the equator) and the coastline (Mann and Lazier, 2006). The majority of these eddies were cyclonic and had the ability to induce the upwelling of nutrient-rich water. Small scale topographic features such as headlands have been shown to cause substantial effects on the population dynamics of benthic invertebrates, such a change in the settlement patterns of crabs and sea urchin (Mann and Lazier, 2006).

Fish Production and Growth in the California Current

The California Current produces an abundance of sardines, anchovies, hake, jack mackerel, and mackerel (Mann and Lazier, 2006). An abundance of these fish species is a common feature of eastern boundary currents. Sardines in particular were heavily fished from 1916 - 1967. This lead to the California state legislature to impose a suspension on sardine fishing in 1967 (Mann and Lazier, 2006). The largest stocks of both sardine and anchovy spawn in the Southern California Bight. Sardines in the California Current are divisible into four stocks and anchovies in this current have several subpopulations as well (Mann and Lazier, 2006). The largest stocks of both sardines and anchovies spawn in the Southern California Bight. The California Bight is a region of relatively weak upwelling (and thus weak phytoplankton production)compared to the greater California Current. From these observations, we see that fish often choose to spawn in areas where Ekman transport will not carry their eggs too far offshore. Many fish species avoid spawning in areas of strong upwelling. Although upwelling and the subsequent high biological productivity produces optimal conditions for the growth of juvenile and adult sardines, the absence of strong upwelling in late winter and early spring (such as that found in the California Bight) is what creates optimum conditions for the survival of fish larvae (Mann and Lazier, 2006). Once anchovy and sardine larvae have spent a significant amount of time in waters free of strong upwelling and mixing (i.e. The California Bight), they migrate (as juveniles) toward areas of great upwelling (i.e. The California Current proper). There the juveniles can take advantage of the high biological productivity and maximize their growth rate.

Canary Current

The **Canary Current** is a wind driven surface current that is part of the North Atlantic Gyre. This eastern Boundary current branches south from the North Atlantic Current and flows southwest about as far as Senegal where it turns west and later joins the Atlantic North Equatorial Current. The current is named after the Canary Islands. The archipelago partially blocks the flow of the Canary Current (Gyory, 2007).

This wide and slow moving current is thought to have been exploited in the early Phoenician navigation and settlement along the coast of western Morocco. The ancient Phoenicians not only exploited numerous fisheries within this current zone, but also established a factory at Iles Purpuraires off of present day Essaouira for extracting a Tyrian purple dye from a marine gastropod murex species (Hogan, 2007).

Upwelling

A prominent feature of Eastern Boundary Currents is the presence of upwelling. Ekman drift causes offshore transport of surface waters, which are then replaced with deep water from below. Deep waters are cold and Nutrient-rich and have a key role in stimulating Primary productivity. Upwelling has led to the enhancement of coastal fisheries in western Morocco (Hance, 1975).

Major upwelling occurs between 23 and 25 degrees northern latitude (Canary Current, 2002). Upwelling occurs year-round at Cap Blanc (Ras Nouadhibou) and northward. South of Cap Blanc, upwelling is limited to winter and spring due to the northward migration of the Azores high during summer, which is responsible for driving equatorward winds. Minas et al (1982) showed that at the latitude of Cap Blanc, a front exists that separates North Atlantic Central Water (NACW) and South Atlantic Central Water (SACW). SACW, to the south of Cap Blanc, is richer in nutrients than NACW. A poleward subsurface counter-current is responsible for bringing SACW to the Cap Blanc region resulting in maximal primary production. Primary production to the north is limited by nutrient availability in NACW. Primary production to the south of Cap Blanc is limited by the occurrence of upwelling events.

Upwelling and primary production

Huntsman and Barber (1977) hypothesized that high productivity results from alternating upwelling events and relatively calm periods. Upwelling is necessary to bring the nutrients to the surface but if the event is sustained for a long period of time, it is tough for phytoplankton to remain in the euphotic zone. Calm periods allow for stratification to develop, which means that phytoplankton can grow and multiply while held in the shallow mixed layer. In other words, there is a miniature spring bloom during each calm period (Mann & Lazier, 1996).

Upwelling and zooplankton

Upwelling and primary production follow the onset of a strong wind within a few days (Mann & Lazier, 1996). Zooplankton, such as copepods, take longer to respond to the abundance of food available because they have life cycles of weeks rather than days. Zooplankton in the Canary Current reach their peak density in autumn when upwelling intensity decreases. The decrease in upwelling allows the zooplankton to stay over the shelf where their food supply exists. Due to the rapid response of phytoplankton to upwelled nutrients, zooplankton are seldom food-limited.

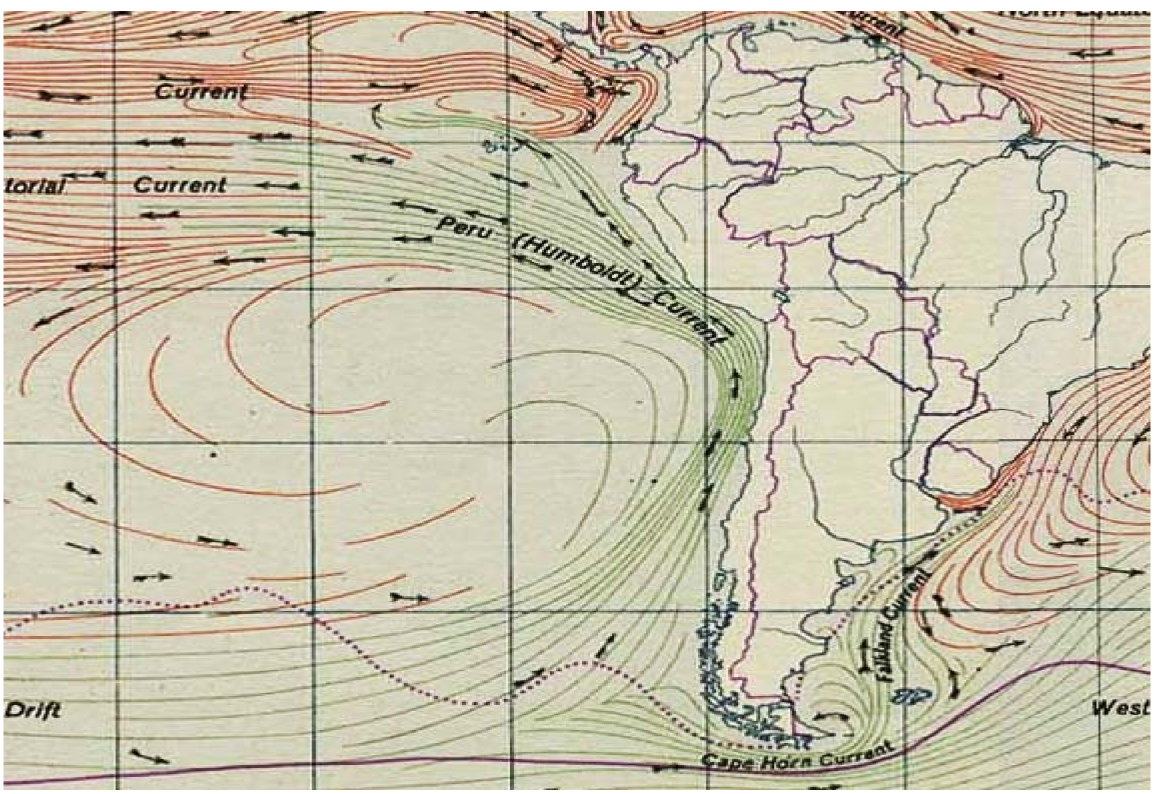
Upwelling and fish

Four types of fish comprise 75% of total catch in the Cap Blanc region (Mann & Lazier, 1996). Clupeids (*Sardina pilchardus*, the sardine, and *Sardinella aurita*) were the most abundant. *S. pilchards* dominate in the cooler northern waters while *S. aurita* are dominate in warmer southern waters. Next most abundant were Jack mackerel (*Trachurus* spp.) and Redfish (Sparidae). Ansa-Emmin (1982) found that in 1974, the total fish landings reached 2.68 million tons. Nearly 1 million tons were Clupeidae with .67 million tons being sardines.

Nutrient recycling

Phytoplankton over the shelf area face two fates: They sink to the bottom or are consumed by zooplankton. If they settle to the bottom, phytoplankton release ammonia during their decomposition, which returns nitrogen to the waters. Consequently, the phytoplankton remains could be consumed by benthic dwellers, which also excrete ammonia. If consumed by zooplankton, nitrogen from the phytoplankton will be returned to the environment via excreted ammonia or fecal pellets, which settle to the bottom. Regardless of the mechanism, a high proportion of phytoplankton nitrogen ends up being released in the shoreward-moving lower layer of the water column (Mann & Lazier, 1996). This water will later be upwelled and can stimulate further primary production. Barber and Smith (1981) estimated that on the shelf off Cap Blanc, regenerated nitrogen accounted for 72% of total nitrogen.

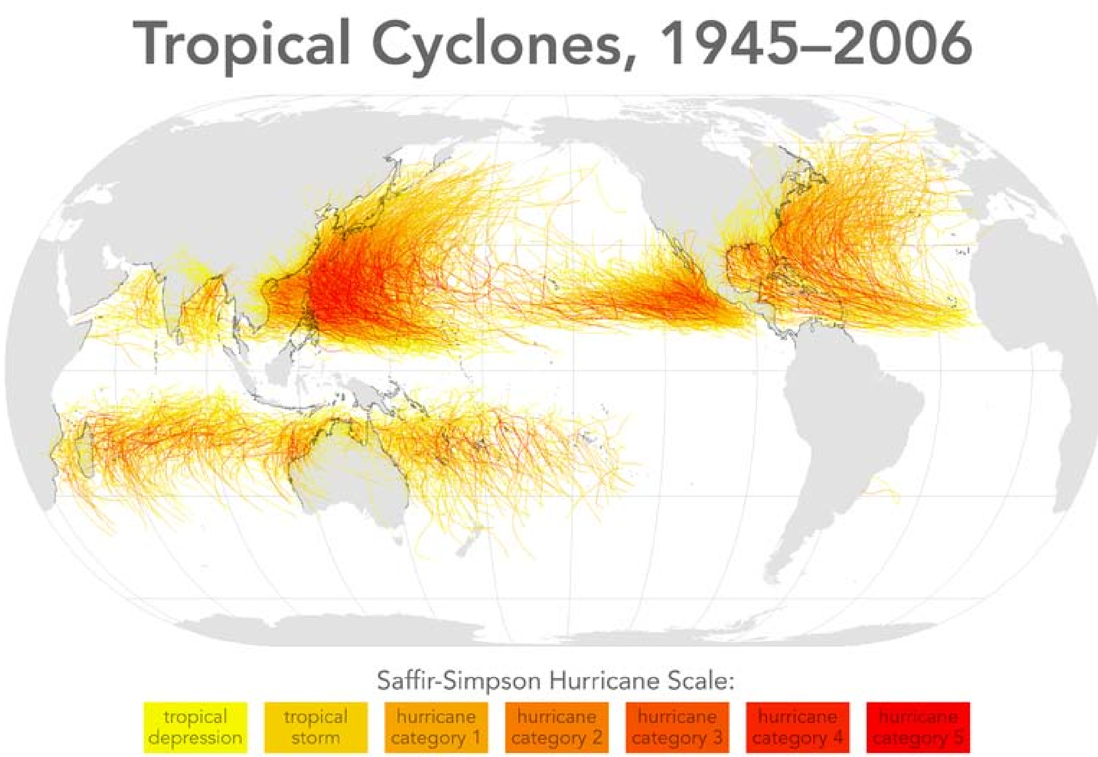
Humboldt Current



Humboldt Current

The **Humboldt Current** is a cold, low-salinity ocean current that flows north-westward along the west coast of South America from the southern tip of Chile to northern Peru. It is an eastern boundary current flowing in the direction of the equator, and can extend 1,000 kilometers offshore. The Humboldt Current Large Marine Ecosystem (**LME**), named after the Prussian naturalist Alexander von Humboldt, is one of the major upwelling systems of the world, supporting an extraordinary abundance of marine life. Upwelling occurs off Peru year-round but off Chile only during the spring and summer, because of the displacement of the subtropical center of high pressure during the summer.

The Humboldt Current LME is considered a Class I, highly productive (>300 gC/m2-yr), ecosystem. It is the most productive marine ecosystem in the world, as well as the largest upwelling system. The Humboldt's high rates of primary and secondary productivity support the world's largest fisheries. Approximately 18-20% of the world's fish catch comes from the Humboldt Current LME. The species are mostly pelagic: sardines, anchovies and jack mackerel. The LME's high productivity supports other important fishery resources as well as marine mammals. The cold, nutrient-rich water brought to the surface by upwelling drives the system's extraordinary productivity.

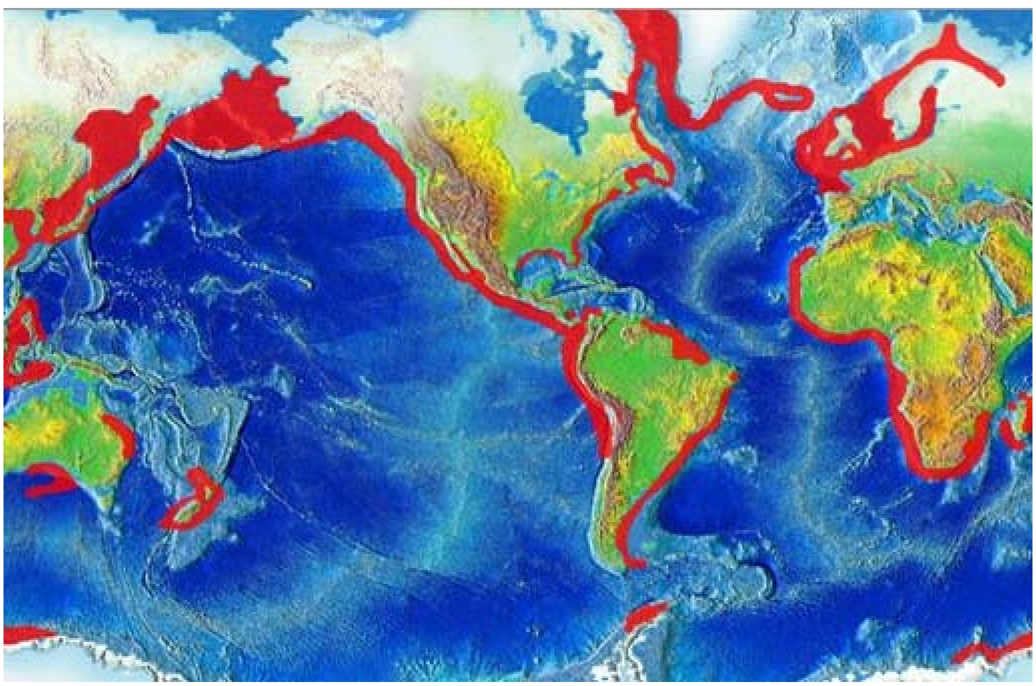


The presence of the Humboldt Current and its associated wind shear prevents the formation of tropical cyclones in the area (The same effect occurs in the South Atlantic with the Benguela Current).
(Worldwide tropical cyclone tracks, 1945–2006.)

Periodically, the upwelling that drives the system's productivity is disrupted by the El Niño-Southern Oscillation (ENSO) event. When this occurs, fish abundance and distribution are significantly affected, often leading to stock crashes and cascading social and economic impacts. These events have led to sequential changes, where sardines and anchovies have replaced each other periodically as the dominant species in the ecosystem. These species changes can have negative consequences for the fishing industry and the economies of the countries that fish the system.

The Humboldt has a considerable cooling influence on the climate of Chile, the climate of Peru and the climate of Ecuador. It is also largely responsible for the aridity that prevails in northern Chile and coastal areas of Peru and southern Ecuador. Marine air is cooled by the current and thus is not conducive to generating precipitation (although clouds and fog are produced).

Benguela Current



The red areas show major upwelling areas. The Benguela Current is on the southwest coast of Africa.

The **Benguela Current** is the broad, northward flowing ocean current that forms the eastern portion of the South Atlantic Ocean gyre. The current extends from roughly Cape Point in the south, to the position of the Angola-Benguela Front in the north, at around 16°S. The current is driven by the prevailing South Easterly Trade winds. Inshore of the

Benguela Current proper, the south easterly winds drive coastal upwelling, forming the Benguela Upwelling System. The cold, nutrient rich waters that upwell from around 200-300 m depth in turn fuel high rates of phytoplankton growth, and sustain the productive Benguela ecosystem.

Boundaries

Source waters for the Benguela include Indian and South Atlantic subtropical thermocline water; saline, low-oxygen tropical Atlantic water; and cooler, fresher deep water. The Benguela current is 200 to 300 km wide and widens further as it flows north and northwest. Its western, seaward edge is ill-defined, with many temporary and seasonal eddies and meanders. There is however a well defined thermal front between the waters associated with the Benguela Upwelling System and those of the south east Atlantic.

Where the icy Benguela and the warm, south-flowing Agulhas current mix, there is a richly productive marine ecosystem off the Cape of Good Hope but storms and turbulence above.

Upwelling and Primary Production

Northward winds along the coast result in Ekman transport offshore and upwelling of nutrient rich deep water to the euphotic zone. The intensity of the upwelling event is determined by wind strength. Variations in wind strength cause pulses of upwelling, which propagate to the south along the coast with speeds of 5 to 8 m/s. The pulses are similar to a Kelvin wave, except on a scale of 30 to 60 km instead of 1000 km, and can propagate around the cape depending on wind systems.

Pulses of upwelling induce biological production. In the Benguela system, phytoplankton growth requires a period of upwelling followed by a period of stratification and relatively calm waters. The phytoplankton bloom usually lags the upwelling event by 1 to 4 days and blooms for 4 to 10 days. In order for zooplankton to have a continuous food supply, the phytoplankton blooms must not occur too far apart. Pulses of upwelling in the Benguela system regularly have a duration of 10 days, an optimal period for biological production. It is estimated that the annual new production in the Benguela system is 4.7 × 10^13 gC/y, making the Benguela system 30 to 65 times more productive per unit area than the global ocean average.

While upwelling promotes abundant primary and secondary production in the upper parts of the water column and near the coast, deeper waters with limited oxygen exchange create hypoxic areas called oxygen minimum zones at the coastal shelf and upper coastal slope. The Benguela oxygen minimum zone starts around a depth of 100 m and is a few hundred meters thick. Bacteria that use sulpher rather than oxygen reside in the oxygen minimum zone.

The most abundant fishes in the Benguela system are *Sardinops* and *Engraulis*. *Sardinops ocelata* (pilchard) was intensely fished beginning in the 1950s and peaking in 1968 with landings over 1.3 million tons. Since then, the *Sardinops* fishery has declined and the *Engraulis capensis* (anchovy) fishery has taken over.

Benguela Niño

Similar to the Pacific El Niño, a thick slab of warm, nutrient poor water enters the northern part of the Benguela upwelling system off the Namibia coast about once per decade. During the Benguela Niño, warm, salty waters from the Angola Current move southward, from 15°S to as far as 25°S. This slab of warm salty water extends to 150 km offshore and to 50 m depth. Heavy rains, changes in fish abundance, and temporal proximity to the Pacific El Niño have been observed; however, the causes and effects of the Benguela Niño are not well understood. One research team has shown that the Benguela Niño is caused by winds in the west-central equatorial Atlantic Ocean that propagate as subsurface sea temperature anomalies to the African coast.

Chapter- 6

Kelvin Wave and Rossby Wave

Kelvin wave

A **Kelvin wave** is a wave in the ocean or atmosphere that balances the Earth's Coriolis force against a topographic boundary such as a coastline, or a waveguide such as the equator. A feature of a Kelvin wave is that it is non-dispersive, i.e., the phase speed of the wave crests is equal to the group speed of the wave energy for all frequencies. This means that it retains its shape in the alongshore direction over time.

A Kelvin wave (fluid dynamics) is also a long scale perturbation mode of a vortex in superfluid dynamics; in terms of the meteorological or oceanographical derivation, one may assume that the meridional velocity component vanishes (i.e. there is no flow in the north–south direction, thus making the momentum and continuity equations much simpler).

Coastal Kelvin wave

In a stratified ocean of mean depth H, free waves propagate along coastal boundaries (and hence become trapped in the vicinity of the coast itself) in the form of internal Kelvin waves on a scale of about 30 km. These waves are called coastal Kelvin waves, and have propagation speeds of approximately 2 m/s in the ocean. Utilizing the assumption that the cross-shore velocity v is zero at the coast, $v = 0$, one may solve a frequency relation for the phase speed of coastal Kelvin waves, which are among the class of waves called boundary waves, edge waves, trapped waves, or surface waves (similar to the Lamb waves). The (linearised) primitive equations then become the following:

- the continuity equation (accounting for the effects of horizontal convergence and divergence):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{-1}{H}\frac{\partial \eta}{\partial t}$$

- the u-momentum equation (zonal wind component):

$$\frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} + fv$$

- the *v*-momentum equation (meridional wind component):

$$\frac{\partial v}{\partial t} = -g\frac{\partial \eta}{\partial y} - fu.$$

If one assumes that the Coriolis coefficient *f* is constant along the right boundary conditions and the zonal wind speed is set equal to zero, then the primitive equations become the following:

- the continuity equation:

$$\frac{\partial v}{\partial y} = \frac{-1}{H}\frac{\partial \eta}{\partial t}$$

- the *u*-momentum equation:

$$g\frac{\partial \eta}{\partial x} = fv$$

- the *v*-momentum equation:

$$\frac{\partial v}{\partial t} = -g\frac{\partial \eta}{\partial y}.$$

The solution to these equations yields the following phase speed: $c^2 = gH$, which is the same speed as for shallow-water gravity waves without the effect of Earth's rotation. It is important to note that for an observer traveling with the wave, the coastal boundary (maximum amplitude) is always to the right in the northern hemisphere and to the left in the southern hemisphere (i.e. these waves move equatorward/southward – negative phase speed – on a western boundary and poleward/northward – positive phase speed – on an eastern boundary; the waves move cyclonically around an ocean basin).

Equatorial Kelvin wave

The equatorial zone essentially acts as a waveguide, causing disturbances to be trapped in the vicinity of the equator, and the equatorial Kelvin wave illustrates this fact because the equator acts analogously to a topographic boundary for both the Northern and Southern Hemispheres, making this wave very similar to the coastally-trapped Kelvin wave. The primitive equations are identical to those used to develop the coastal Kelvin wave phase speed solution (U-momentum, V-momentum, and continuity equations) and the motion is unidirectional and parallel to the equator. Because these waves are equatorial, the Coriolis parameter vanishes at 0 degrees; therefore, it is necessary to use the equatorial beta plane approximation that states:

$$f = \beta y,$$

where β is the variation of the Coriolis parameter with latitude. This equatorial Beta plane assumption requires a geostrophic balance between the eastward velocity and the north-south pressure gradient. The phase speed is identical to that of coastal Kelvin waves, indicating that the equatorial Kelvin waves propagate toward the east without dispersion (as if the earth were a non-rotating planet). For the first baroclinic mode in the ocean, a typical phase speed would be about 2.8 m/s, causing an equatorial Kelvin wave to take 2 months to cross the Pacific Ocean between New Guinea and South America; for higher ocean and atmospheric modes, the phase speeds are comparable to fluid flow speeds.

When the motion at the equator is to the east, any deviation toward the north is brought back toward the equator because the Coriolis force acts to the right of the direction of motion in the Northern Hemisphere, and any deviation to the south is brought back toward the equator because the Coriolis force acts to the left of the direction of motion in the Southern Hemisphere. Note that for motion toward the west, the Coriolis force would not restore a northward or southward deviation back toward the equator; thus, equatorial Kelvin waves are only possible for eastward motion (as noted above). Both atmospheric and oceanic equatorial Kelvin waves play an important role in the dynamics of El Nino-Southern Oscillation, by transmitting changes in conditions in the Western Pacific to the Eastern Pacific.

There have been studies that connect equatorial Kelvin waves to coastal Kelvin waves. Moore (1968) found that as an equatorial Kelvin wave strikes an "eastern boundary," part of the energy is reflected in the form of planetary and gravity waves; and the remainder of the energy is carried poleward along the eastern boundary as coastal Kelvin waves. This process indicates that some energy may be lost from the equatorial region and transported to the poleward region.

Equatorial Kelvin waves are often associated with anomalies in surface wind stress. For example, positive (eastward) anomalies in wind stress in the central Pacific excite positive anomalies in 20°C isotherm depth which propagate to the east as equatorial Kelvin waves.

Rossby wave

Atmospheric Rossby waves are giant meanders in high-altitude winds that are a major influence on weather. They are not to be confused with **oceanic Rossby waves**, which move along the thermocline: that is, the boundary between the warm upper layer of the ocean and the cold deeper part of the ocean.

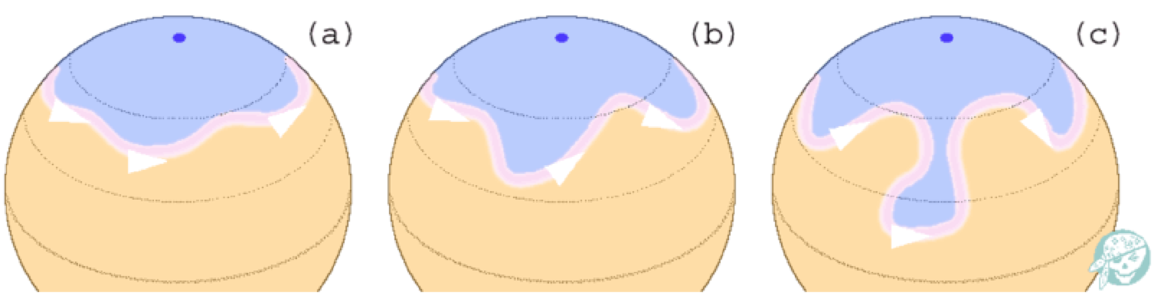
Rossby waves are a subset of inertial waves.

Atmospheric waves

The emergence of atmospheric Rossby waves is due to shear in rotating fluids, so that the Coriolis force changes along the sheared coordinate. In planetary atmospheres, they are due to the variation in the Coriolis effect with latitude. The waves were first identified in the Earth's atmosphere in 1939 by Carl-Gustaf Arvid Rossby who went on to explain their motion.

The special identifying feature of the Rossby wave is its phase velocity (that of the wave crests) always has a westward component. However, the wave's group velocity (associated with the energy flux) can be in any direction. In general: shorter waves have an eastward group velocity and long waves a westward group velocity.

The terms "barotropic" and "baroclinic" Rossby waves are used to distinguish their vertical structure. Barotropic Rossby waves do not vary in the vertical, and have the fastest propagation speeds. The baroclinic wave modes are slower, with speeds of only a few centimetres per second or less.



Meanders of the northern hemisphere's jet stream developing (a, b) and finally detaching a "drop" of cold air (c). Orange: warmer masses of air; pink: jet stream.

Most work on Rossby waves has been done on those in Earth's atmosphere. Rossby waves in the Earth's atmosphere are easy to observe as (usually 4-6) large-scale meanders of the jet stream. When these loops become very pronounced, they detach the masses of cold, or warm, air that become cyclones and anticyclones and are responsible for day-to-day weather patterns at mid-latitudes.

Free Barotropic Rossby Waves under a zonal flow with linearized vorticity equation

Let us start with perturbing a flow that with only a time and spatially invariant zonal flow U with no meridional component.

$$u = U + u'(t, x, y)$$
$$v = v'(t, x, y)$$

We assume the perturbation to be much smaller than the mean zonal flow.

$$U \gg u', v'$$

Relative Vorticity η, U and V can be written in the form stream function (ψ) (assuming non-divergent flow which stream function completely describes the flow):

$$u = \frac{\partial \psi}{\partial y}$$
$$v = -\frac{\partial \psi}{\partial x}$$
$$\eta = \nabla \times (u\hat{\boldsymbol{\imath}} + v\hat{\boldsymbol{\jmath}}) = \nabla^2 \psi$$

Considering a parcel of air that has no relative vorticity before perturbation (uniform U has no vorticity) but with planetary vorticity f as a function of the latitude, perturbation will lead to a slight change of latitude, so the perturbed relative vorticity must change in order to conserve potential vorticity. Also we make the approximation that $U >> u'$, so the perturbation flow does not advect relative vorticity.

$$\frac{d(\eta + f)}{dt} = 0 = \frac{\partial \eta}{\partial t} + U\frac{\partial \eta}{\partial x} + \beta v'$$

which $\beta = \frac{\partial f}{\partial y}$, and plug in the definition of stream function to obtain:

$$0 = \frac{\partial \nabla^2 \psi}{\partial t} + U\frac{\partial \nabla^2 \psi}{\partial x} + \beta\frac{\partial \psi}{\partial x}$$

Guess a traveling wave solution with wave numbers k and l, and frequency omega:

$$\psi = \psi_0 e^{i(kx + ly - \omega t)}$$

We obtain the dispersion relation of:

$$\omega = Uk - \beta \frac{k}{k^2 + l^2}$$

The zonal phase speed and group speed are given by

$$c \equiv \frac{\omega}{k} = U - \frac{\beta}{(k^2 + l^2)},$$
$$c_g \equiv \frac{\partial \omega}{\partial k} = U - \frac{\beta(l^2 - k^2)}{(k^2 + l^2)^2},$$

where c is the phase speed, c_g is the group speed, u is the mean westerly flow, β is the Rossby parameter, and k is the zonal wave number. The above proves that phase speed is always westward relative to mean flow, but group speed can travel both ways depending on the wave number; large zonal wave number waves (short waves) leads the mean flow, and small zonal wave number waves (long wave) retrogrades. The meaning of large and small only depends on the value of l, if $l = k$, then the group speed is the same as the mean zonal flow.

Meaning of Beta

The Rossby parameter is defined:

$$\beta = \frac{\partial f}{\partial y} = \frac{1}{a} \frac{d}{d\phi}(2\omega \sin \phi) = \frac{2\omega \cos \phi}{a}$$

φ is the latitude, ω is the angular speed of the Earth's rotation, and a is the mean radius of the Earth.

If $\beta = 0$, there will be no Rossby Waves; Rossby Waves owe their origin to the gradient of the tangential speed of the planetary rotation (planetary vorticity). A "cylinder" planet has no Rossby Waves. It also means that near the equator on Earth where $f = 0$ but $\beta > 0$ except at the poles, one can still have Rossby Waves (Equatorial Rossby wave).

Oceanic waves

Oceanic Rossby waves are thought to communicate climatic changes due to variability in forcing, due to both the wind and buoyancy. Both barotropic and baroclinic waves cause variations of the sea surface height, although the length of the waves made them difficult to detect until the advent of satellite altimetry. Observations by the NASA/CNES TOPEX/Poseidon satellite confirmed the existence of oceanic Rossby waves.

Baroclinic waves also generate significant displacements of the oceanic thermocline, often of tens of meters. Satellite observations have revealed the stately progression of

Rossby waves across all the ocean basins, particularly at low- and mid-latitudes. These waves can take months or even years to cross a basin like the Pacific.

Rossby waves have been suggested as an important mechanism to account for the heating of Europa's ocean.

Rossby-gravity waves

Rossby-gravity waves are equatorially-trapped waves (much like Kelvin waves), meaning that they rapidly decay as their distance increases away from the equator (along as the Brunt–Vaisala frequency does not remain constant). These waves have the same trapping scale as Kelvin waves, more commonly known as the equatorial Rossby deformation radius. They always carry energy eastward, but, oddly, their 'crests' and 'troughs' may propagate westward if their periods are long enough. The eastward speed of propagation of these waves can be derived for an inviscid slowly moving layer of fluid of uniform depth H . Because the Coriolis parameter ($f = 2\Omega \sin(\theta)$ where Ω is the angular velocity of the earth, 7.2921×10^{-5} rad/s, and θ is latitude) vanishes at 0 degrees latitude (equator), the "equatorial beta plane" approximation must be made. This approximation states that "f" is approximately equal to βy, where "y" is the distance from the equator and "β" is the variation of the coriolis parameter with latitude, $\frac{\partial f}{\partial y} = \beta$. With the inclusion of this approximation, the primitive equations become (neglecting friction):

- the continuity equation (accounting for the effects of horizontal convergence and divergence and written with geopotential height):

$$\frac{\partial \phi}{\partial t} + c^2 \left(\frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} \right) = 0$$

- the U-momentum equation (zonal wind component):

$$\frac{\partial u}{\partial t} - v\beta y = -\frac{\partial \phi}{\partial x}$$

- the V-momentum equation (meridional wind component):

$$\frac{\partial v}{\partial t} + u\beta y = -\frac{\partial \phi}{\partial y}.$$

These three equations can be separated and solved using solutions in the form of zonally-propagating waves, which are analogous to exponential solutions with a dependence on *x* and *t* and the inclusion of structure functions that vary in the *y*-direction:

$$\{u, v, \phi\} = \{\hat{u}(y), \hat{v}(y), \hat{\phi}(y)\} e^{i(kx-\omega t)}.$$

Once the frequency relation is formulated in terms of ω, the angular frequency, the problem can be solved with 3 distinct solutions. These three solutions correspond to the equatorially-trapped gravity wave, the equatorially-trapped Rossby wave and the mixed Rossby-gravity wave (which has some of the characteristics of the former two) . It is important to note that equatorial gravity waves can be either westward- or eastward-propagating and correspond to n=1 (same as for the equatorially-trapped Rossby wave) on a dispersion relation diagram ("w-k" diagram). At $n = 0$ on a dispersion relation diagram, the mixed Rossby-gravity waves can be found where for large, positive zonal wave numbers ($+k$), the solution behaves like a gravity wave; but for large, negative zonal wave numbers ($-k$), the solution appears to be a Rossby wave (hence the term Rossby-gravity waves). As mentioned earlier, the group velocity (or energy packet/dispersion) is always directed toward the east with a maximum for short waves (gravity waves).

Vertically-propagating Rossby-gravity waves

As previously stated, the mixed Rossby-gravity waves are equatorially-trapped waves unless the buoyancy frequency remains constant, introducing an additional vertical wave number to complement the zonal wave number and angular frequency. If this Brunt–Vaisala frequency does not change, then these waves become vertically-propagating solutions. On a typical "*m*,*k*" dispersion diagram, the group velocity (energy) would be directed at right angles to the $n = 0$ (mixed Rossby-gravity waves) and $n = 1$ (gravity or Rossby waves) curves and would increase in the direction of increasing angular frequency. Typical group velocities for each component are the following: 1 cm/s for gravity waves and 2 mm/s for planetary (Rossby) waves.

These vertically-propagating mixed Rossby-gravity waves were first observed in the stratosphere as westward-propagating mixed waves by M. Yanai. They had the following characteristics: 4–5 days, horizontal wavenumbers of 4 (four waves circling the earth, corresponding to wavelengths of 10,000 km), vertical wavelengths of 4–8 km, and upward group velocity. Similarly, westward-propagating mixed waves were also found in the Atlantic Ocean by Weisberg et al. (1979) with periods of 31 days, horizontal wavelengths of 1200 km, vertical wavelengths of 1 km, and downward group velocity. Also, the vertically-propagating gravity wave component was found in the stratosphere with periods of 35 hours, horizontal wavelengths of 2400 km, and vertical wavelengths of 5 km.

Chapter- 7

Tsunami

Tsunami striking Thailand on December 26, 2004

A **tsunami** or **tidal wave** is a series of water waves (called a **tsunami wave train**) caused by the displacement of a large volume of a body of water, usually an ocean, but can occur in large lakes. Tsunamis are a frequent occurrence in Japan; approximately 195 events have been recorded. Due to the immense volumes of water and energy involved, tsunamis can devastate coastal regions.

Earthquakes, volcanic eruptions and other underwater explosions (including detonations of underwater nuclear devices), landslides and other mass movements, meteorite ocean impacts or similar impact events, and other disturbances above or below water all have the potential to generate a tsunami.

The Greek historian Thucydides was the first to relate tsunami to submarine earthquakes, but understanding of tsunami's nature remained slim until the 20th century and is the subject of ongoing research. Many early geological, geographical, and oceanographic texts refer to tsunamis as "**seismic sea waves**."

Some meteorological conditions, such as deep depressions that cause tropical cyclones, can generate a storm surge, called a meteotsunami, which can raise tides several metres above normal levels. The displacement comes from low atmospheric pressure within the centre of the depression. As these storm surges reach shore, they may resemble (though are not) tsunamis, inundating vast areas of land. Such a storm surge inundated Burma in May 2008.

Etymology

The term ***tsunami*** comes from the Japanese, meaning "**harbor**" (*tsu*, 津) and "**wave**" (*nami*, 波). (For the plural, one can either follow ordinary English practice and add an *s*, or use an invariable plural as in the Japanese.)

Tsunami are sometimes referred to as **tidal waves**. In recent years, this term has fallen out of favor, especially in the scientific community, because tsunami actually have nothing to do with tides. The once-popular term derives from their most common appearance, which is that of an extraordinarily high tidal bore. Tsunami and tides both produce waves of water that move inland, but in the case of tsunami the inland movement of water is much greater and lasts for a longer period, giving the impression of an incredibly high tide. Although the meanings of "tidal" include "resembling" or "having the form or character of" the tides, and the term *tsunami* is no more accurate because tsunami are not limited to harbours, use of the term *tidal wave* is discouraged by geologists and oceanographers.

There are only a few other languages that have a native word for this disastrous wave. In the Tamil language, the word is *aazhi peralai*. In the Acehnese language, it is *ië beuna* or *alôn buluëk* (Depending on the dialect. Note that in the fellow Austronesian language of Tagalog, a major language in the Philippines, *alon* means "wave".) On Simeulue island, off the western coast of Sumatra in Indonesia, in the Defayan language the word is *smong*, while in the Sigulai language it is *emong*.

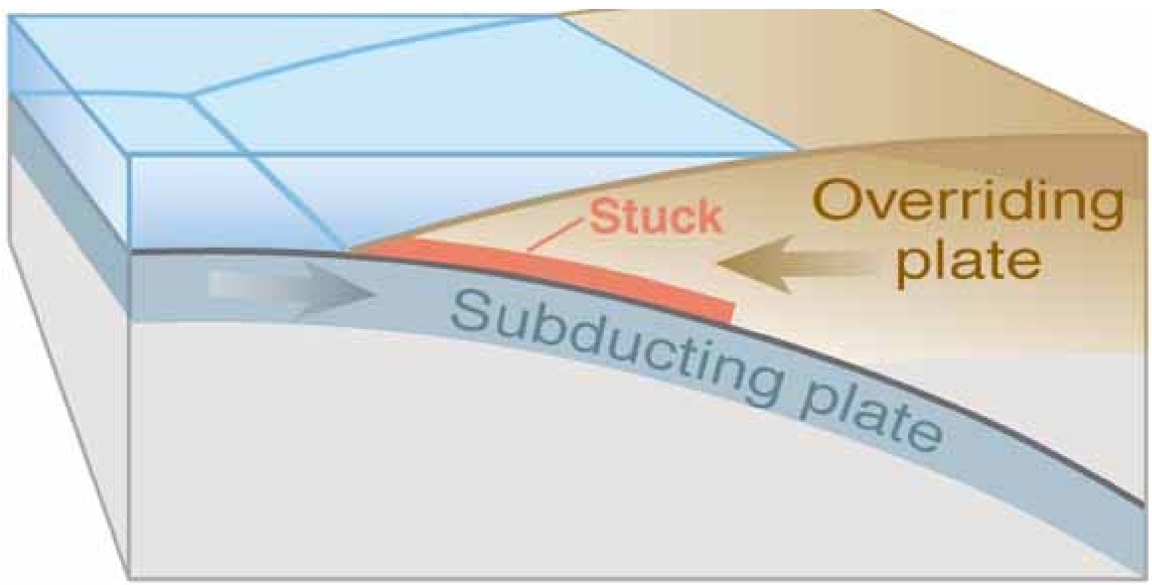
Generation mechanisms

The principal generation mechanism (or cause) of a tsunami is the displacement of a substantial volume of water or perturbation of the sea. This displacement of water is usually attributed to either earthquakes, landslides, volcanic eruptions, or more rarely by meteorites and nuclear tests. The waves formed in this way are then sustained by gravity.

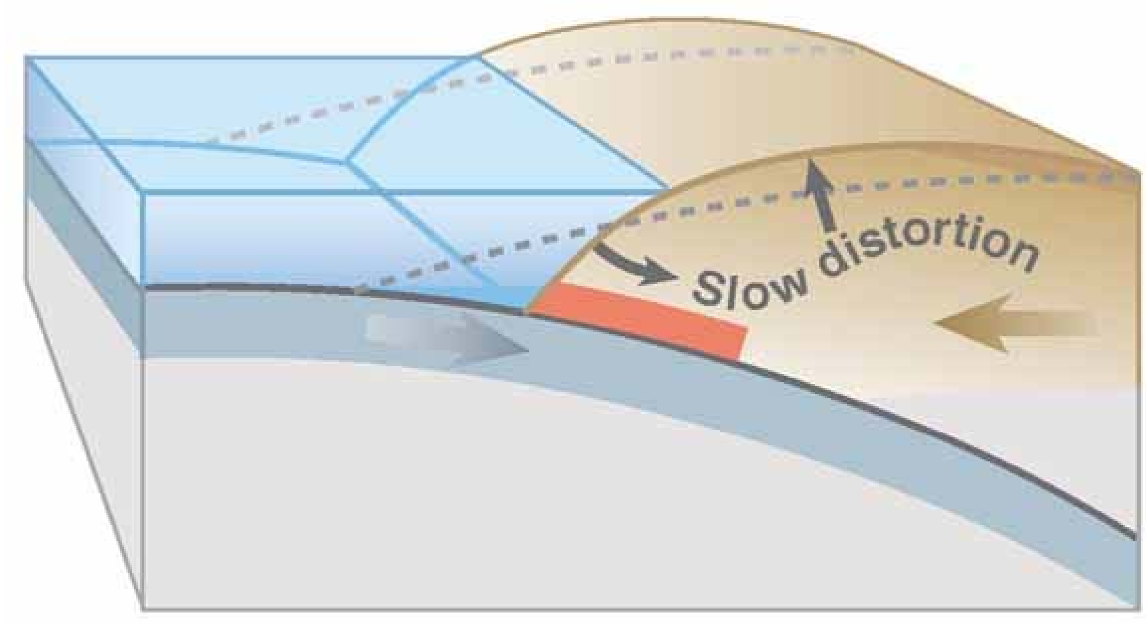
It is important to note that tides do not play any part in the generation of tsunamis, hence referring to tsunamis as 'tidal waves' is inaccurate.

Seismicity generated tsunamis

Tsunamis can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. Tectonic earthquakes are a particular kind of earthquake that are associated with the earth's crustal deformation; when these earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position. More specifically, a tsunami can be generated when thrust faults associated with convergent or destructive plate boundaries move abruptly, resulting in water displacement, due to the vertical component of movement involved. Movement on normal faults will also cause displacement of the seabed, but the size of the largest of such events is normally too small to give rise to a significant tsunami.



Drawing of tectonic plate boundary before earthquake.



Overriding plate bulges under strain, causing tectonic uplift.

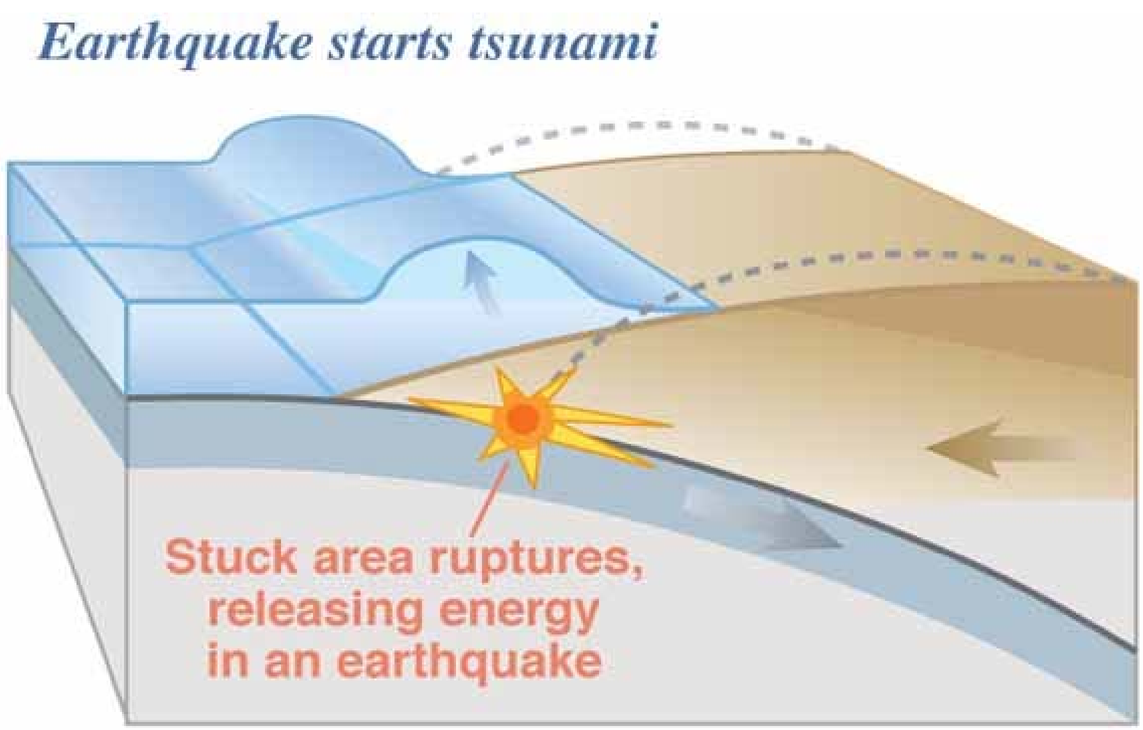
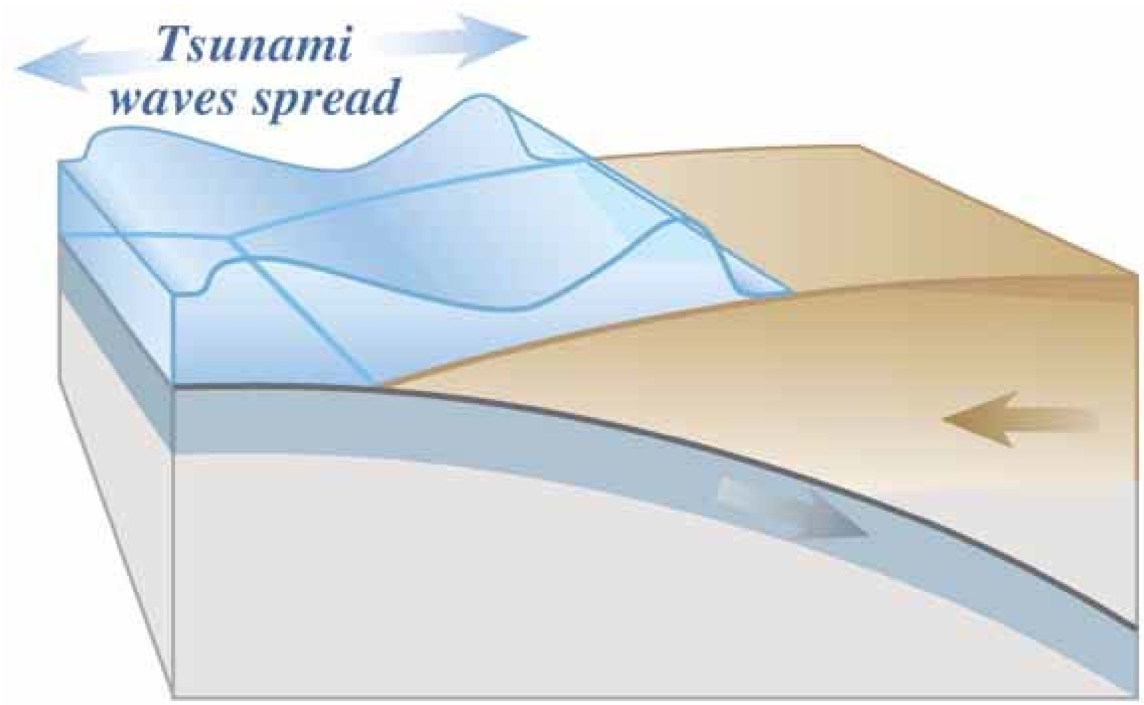


Plate slips, causing subsidence and releasing energy into water.



The energy released produces tsunami waves.

Tsunamis have a small amplitude (wave height) offshore, and a very long wavelength (often hundreds of kilometers long), which is why they generally pass unnoticed at sea, forming only a slight swell usually about 300 millimetres (12 in) above the normal sea surface. They grow in height when they reach shallower water, in a wave shoaling process described below. A tsunami can occur in any tidal state and even at low tide can still inundate coastal areas.

On April 1, 1946, a magnitude-7.8 (Richter Scale) earthquake occurred near the Aleutian Islands, Alaska. It generated a tsunami which inundated Hilo on the island of Hawai'i with a 14 metres (46 ft) high surge. The area where the earthquake occurred is where the Pacific Ocean floor is subducting (or being pushed downwards) under Alaska.

Examples of tsunami at locations away from convergent boundaries include Storegga about 8,000 years ago, Grand Banks 1929, Papua New Guinea 1998 (Tappin, 2001). The Grand Banks and Papua New Guinea tsunamis came from earthquakes which destabilized sediments, causing them to flow into the ocean and generate a tsunami. They dissipated before traveling transoceanic distances.

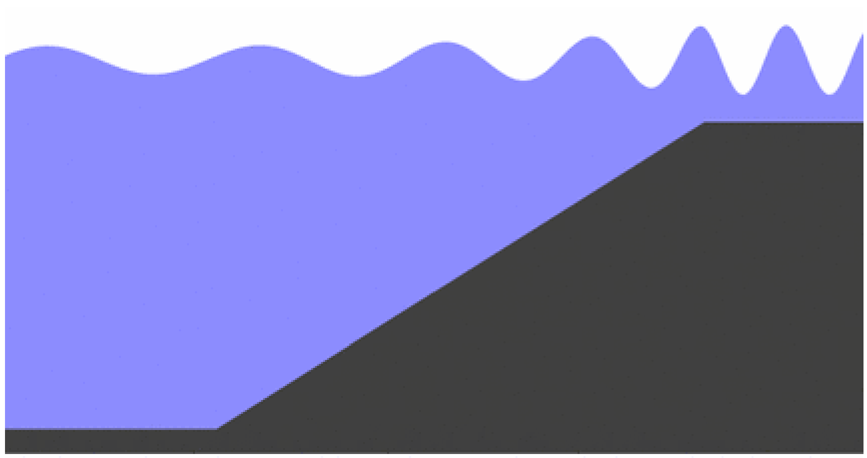
The cause of the Storegga sediment failure is unknown. Possibilities include an overloading of the sediments, an earthquake or a release of gas hydrates (methane etc.)

The 1960 Valdivia earthquake (M_w 9.5) (19:11 hrs UTC), 1964 Alaska earthquake (M_w 9.2), and 2004 Indian Ocean earthquake (M_w 9.2) (00:58:53 UTC) are recent examples of powerful megathrust earthquakes that generated tsunamis (known as teletsunamis) that can cross entire oceans. Smaller (M_w 4.2) earthquakes in Japan can trigger tsunamis (called **local** and **regional tsunamis**) that can only devastate nearby coasts, but can do so in only a few minutes.

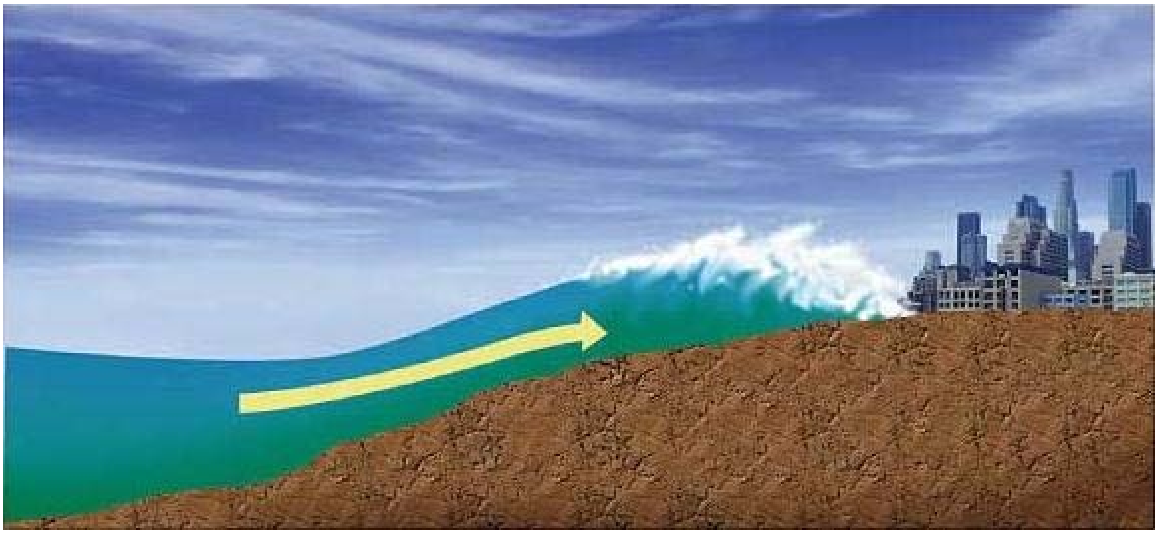
In the 1950s, it was discovered that larger tsunamis than had previously been believed possible could be caused by giant landslides. These phenomena rapidly displace large water volumes, as energy from falling debris or expansion transfers to the water at a rate faster than the water can absorb. Their existence was confirmed in 1958, when a giant landslide in Lituya Bay, Alaska, caused the highest wave ever recorded, which had a height of 524 metres (over 1700 feet). The wave didn't travel far, as it struck land almost immediately. Two people fishing in the bay were killed, but another boat amazingly managed to ride the wave. Scientists named these waves megatsunami.

Scientists discovered that extremely large landslides from volcanic island collapses can generate megatsunami, that can travel trans-oceanic distances.

Characteristics



When the wave enters shallow water, it slows down and its amplitude (height) increases.



The wave further slows and amplifies as it hits land. Only the largest waves crest.

While everyday wind waves have a wavelength (from crest to crest) of about 100 metres (330 ft) and a height of roughly 2 metres (6.6 ft), a tsunami in the deep ocean has a wavelength of about 200 kilometres (120 mi). Such a wave travels at well over 800 kilometres per hour (500 mph), but due to the enormous wavelength the wave oscillation at any given point takes 20 or 30 minutes to complete a cycle and has an amplitude of only about 1 metre (3.3 ft). This makes tsunamis difficult to detect over deep water. Ships rarely notice their passage.

As the tsunami approaches the coast and the waters become shallow, wave shoaling compresses the wave and its velocity slows below 80 kilometres per hour (50 mph). Its wavelength diminishes to less than 20 kilometres (12 mi) and its amplitude grows enormously, producing a distinctly visible wave. Since the wave still has such a long wavelength, the tsunami may take minutes to reach full height. Except for the very largest tsunamis, the approaching wave does not break (like a surf break), but rather appears like a fast moving tidal bore. Open bays and coastlines adjacent to very deep water may shape the tsunami further into a step-like wave with a steep-breaking front.

When the tsunami's wave peak reaches the shore, the resulting temporary rise in sea level is termed 'run up'. Run up is measured in metres above a reference sea level. A large tsunami may feature multiple waves arriving over a period of hours, with significant time between the wave crests. The first wave to reach the shore may not have the highest run up.

About 80% of tsunamis occur in the Pacific Ocean, but are possible wherever there are large bodies of water, including lakes. They are caused by earthquakes, landslides, volcanic explosions, and bolides.

Drawback

If the first part of a tsunami to reach land is a trough—called a **drawback**—rather than a wave crest, the water along the shoreline recedes dramatically, exposing normally submerged areas.

A drawback occurs because the water propagates outwards with the trough of the wave at its front. Drawback begins before the wave arrives at an interval equal to half of the wave's period. Drawback can exceed hundreds of metres, and people unaware of the danger sometimes remain near the shore to satisfy their curiosity or to collect fish from the exposed seabed. During the Indian Ocean tsunami, the sea withdrew and many people went onto the exposed sea bed to investigate. Photos show people walking on the normally submerged areas with the advancing wave in the background. Few survived.

Scales of intensity and magnitude

As with earthquakes, several attempts have been made to set up scales of tsunami intensity or magnitude to allow comparison between different events.

Intensity scales

The first scales used routinely to measure the intensity of tsunami were the *Sieberg-Ambraseys scale*, used in the Mediterranean Sea and the *Imamura-Iida intensity scale*, used in the Pacific Ocean. The latter scale was modified by Soloviev, who calculated the Tsunami intensity I according to the formula

$$I = \frac{1}{2} + \log_2 H_{av}$$

where H_{av} is the average wave height along the nearest coast. This scale, known as the *Soloviev-Imamura tsunami intensity scale*, is used in the global tsunami catalogues compiled by the NGDC/NOAA and the Novosibirsk Tsunami Laboratory as the main parameter for the size of the tsunami.

Magnitude scales

The first scale that genuinely calculated a magnitude for a tsunami, rather than an intensity at a particular location was the ML scale proposed by Murty & Loomis based on the potential energy. Difficulties in calculating the potential energy of the tsunami mean that this scale is rarely used. Abe introduced the *tsunami magnitude scale* M_t, calculated from,

$$M_t = a \log h + b \log R = D$$

where h is the maximum tsunami-wave amplitude (in m) measured by a tide gauge at a distance R from the epicenter, a, b & D are constants used to make the M_t scale match as closely as possible with the moment magnitude scale.

Warnings and predictions

One of the deep water buoys used in the DART tsunami warning system

Drawbacks can serve as a brief warning. People who observe drawback (many survivors report an accompanying sucking sound), can survive only if they immediately run for high ground or seek the upper floors of nearby buildings. In 2004, ten-year old Tilly Smith of Surrey, England, was on Maikhao beach in Phuket, Thailand with her parents and sister, and having learned about tsunamis recently in school, told her family that a tsunami might be imminent. Her parents warned others minutes before the wave arrived, saving dozens of lives. She credited her geography teacher, Andrew Kearney.

In the 2004 Indian Ocean tsunami drawback was not reported on the African coast or any other eastern coasts it reached. This was because the wave moved downwards on the eastern side of the fault line and upwards on the western side. The western pulse hit coastal Africa and other western areas.

A tsunami cannot be precisely predicted, even if the magnitude and location of an earthquake is known. Geologists, oceanographers, and seismologists analyse each earthquake and based on many factors may or may not issue a tsunami warning. However, there are some warning signs of an impending tsunami, and automated systems can provide warnings immediately after an earthquake in time to save lives. One of the most successful systems uses bottom pressure sensors that are attached to buoys. The sensors constantly monitor the pressure of the overlying water column. This is deduced through the calculation:

$$P = \rho g h$$

where
P = the overlying pressure in newtons per metre square,
ρ = the density of the seawater= 1.1 x 10^3 kg/m^3,
g = the acceleration due to gravity= 9.8 m/s^2 and
h = the height of the water column in metres.

Hence for a water column of 5,000 m depth the overlying pressure is equal to

$$P = \rho g h = \left(1.1 \times 10^3 \ \frac{\text{kg}}{\text{m}^3}\right)\left(9.8 \ \frac{\text{m}}{\text{s}^2}\right)\left(5.0 \times 10^3 \ \text{m}\right) = 5.4 \times 10^7 \ \frac{\text{N}}{\text{m}^2} = 54 \ \text{MPa}$$

or about 5500 tonnes-force per square metre.

Regions with a high tsunami risk typically use tsunami warning systems to warn the population before the wave reaches land. On the west coast of the United States, which is prone to Pacific Ocean tsunami, warning signs indicate evacuation routes. In Japan, the community is well-educated about earthquakes and tsunamis, and along the Japanese shorelines the tsunami warning signs are reminders of the natural hazards together with a network of warning sirens, typically at the top of the cliff of surroundings hills.

The Pacific Tsunami Warning System is based in Honolulu, Hawaiʻi. It monitors Pacific Ocean seismic activity. A sufficiently large earthquake magnitude and other information triggers a tsunami warning. While the subduction zones around the Pacific are seismically active, not all earthquakes generate tsunami. Computers assist in analysing the tsunami risk of every earthquake that occurs in the Pacific Ocean and the adjoining land masses.

Tsunami hazard sign at Bamfield, British Columbia

A tsunami warning sign on a seawall in Kamakura, Japan, 2004.

The monument to the victims of tsunami at Laupahoehoe, Hawaii

Tsunami memorial in Kanyakumari beach

A seawall at Tsu, Japan

Tsunami Evacuation Route signage along U.S. Route 101, in Washington

As a direct result of the Indian Ocean tsunami, a re-appraisal of the tsunami threat for all coastal areas is being undertaken by national governments and the United Nations Disaster Mitigation Committee. A tsunami warning system is being installed in the Indian Ocean.

Computer models can predict tsunami arrival, usually within minutes of the arrival time. Bottom pressure sensors relay information in real time. Based on these pressure readings and other seismic information and the seafloor's shape (bathymetry) and coastal topography, the models estimate the amplitude and surge height of the approaching tsunami. All Pacific Rim countries collaborate in the Tsunami Warning System and most regularly practice evacuation and other procedures. In Japan, such preparation is mandatory for government, local authorities, emergency services and the population.

Some zoologists hypothesise that some animal species have an ability to sense subsonic Rayleigh waves from an earthquake or a tsunami. If correct, monitoring their behavior could provide advance warning of earthquakes, tsunami etc. However, the evidence is controversial and is not widely accepted. There are unsubstantiated claims about the Lisbon quake that some animals escaped to higher ground, while many other animals in the same areas drowned. The phenomenon was also noted by media sources in Sri Lanka in the 2004 Indian Ocean earthquake. It is possible that certain animals (e.g., elephants) may have heard the sounds of the tsunami as it approached the coast. The elephants' reaction was to move away from the approaching noise. By contrast, some humans went to the shore to investigate and many drowned as a result.

It is not possible to prevent a tsunami. However, in some tsunami-prone countries some earthquake engineering measures have been taken to reduce the damage caused on shore. Japan built many tsunami walls of up to 4.5 metres (15 ft) to protect populated coastal areas. Other localities have built floodgates and channels to redirect the water from incoming tsunami. However, their effectiveness has been questioned, as tsunami often overtop the barriers. For instance, the Okushiri, Hokkaidō tsunami which struck Okushiri Island of Hokkaidō within two to five minutes of the earthquake on July 12, 1993 created waves as much as 30 metres (100 ft) tall—as high as a 10-story building. The port town of Aonae was completely surrounded by a tsunami wall, but the waves washed right over the wall and destroyed all the wood-framed structures in the area. The wall may have succeeded in slowing down and moderating the height of the tsunami, but it did not prevent major destruction and loss of life.

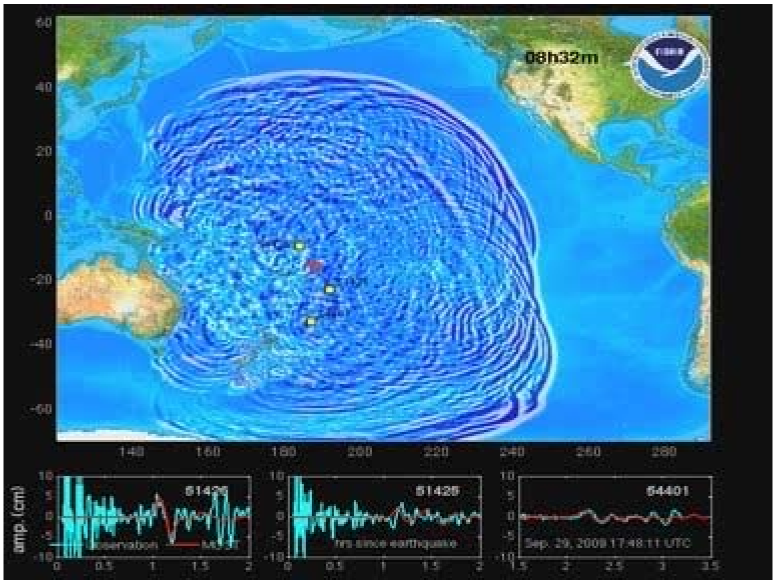
Natural factors such as shoreline tree cover can mitigate tsunami effects. Some locations in the path of the 2004 Indian Ocean tsunami escaped almost unscathed because trees such as coconut palms and mangroves absorbed the tsunami's energy. In one striking example, the village of Naluvedapathy in India's Tamil Nadu region suffered only minimal damage and few deaths because the wave broke against a forest of 80,244 trees planted along the shoreline in 2002 in a bid to enter the Guinness Book of Records. Environmentalists have suggested tree planting along tsunami-prone seacoasts. Trees require years to grow to a useful size, but such plantations could offer a much cheaper and longer-lasting means of tsunami mitigation than artificial barriers.

Mitigation

Natural barriers

A report published by the United Nations Environment Programme (UNEP) suggests that the tsunami of 26th December 2004 caused less damage in the areas where natural barriers were present, such as mangroves, coral reefs or coastal vegetation. A Japanese study of this tsunami in Sri Lanka used satellite imagery modelling to establish the parameters of coastal resistance as a function of different types of trees.

History



The Samoan tsunami of September 2009

A devastated Marina beach in Chennai after the Indian Ocean Tsunami

Destructive tsunamis have been recorded throughout history, for example there were 26 that caused 200 or more deaths in the last century alone. Of these, many were recorded in the Asia–Pacific region, particularly around Japan and Indonesia.

Ancient history

As early as 426 B.C. the Greek historian Thucydides inquired in his book *History of the Peloponnesian War* about the causes of tsunami, and was the first to argue that ocean earthquakes must be the cause.

The cause, in my opinion, of this phenomenon must be sought in the earthquake. At the point where its shock has been the most violent the sea is driven back, and suddenly recoiling with redoubled force, causes the inundation. Without an earthquake I do not see how such an accident could happen.

The Roman historian Ammianus Marcellinus (*Res Gestae* 26.10.15-19) described the typical sequence of a tsunami, including an incipient earthquake, the sudden retreat of the sea and a following gigantic wave, after the 365 A.D. tsunami devastated Alexandria.

2004 Indian Ocean tsunami

The 2004 Indian Ocean earthquake and tsunami killed over 200,000 people with many bodies either being lost to the sea or unidentified.

According to an article in *Geographical* magazine (April 2008), the Indian Ocean tsunami of December 26, 2004 was not the worst that the region could expect. Professor Costas Synolakis of the Tsunami Research Center at the University of Southern California co-authored a paper in *Geophysical Journal International* which suggests that a future tsunami in the Indian Ocean basin could affect locations such as Madagascar, Singapore, Somalia, Western Australia, and many others.

As a weapon

There have been studies and some attempt to create tsunami waves as a weapon. In World War II, the army in New Zealand trialled explosives in the area of today's Shakespeare Regional Park to create small tsunamis, an attempt which failed.

Chapter- 8

Wind Wave

North Pacific storm waves as seen from the NOAA M/V *Noble Star*, Winter 1989.

Ocean waves

In fluid dynamics, **wind waves** or, more precisely, **wind-generated waves** are surface waves that occur on the free surface of oceans, seas, lakes, rivers, and canals or even on small puddles and ponds. They usually result from the wind blowing over a vast enough stretch of fluid surface. Waves in the oceans can travel thousands of miles before reaching land. Wind waves range in size from small ripples to huge rogue waves. When directly being generated and affected by the local winds, a wind wave system is called a **wind sea**. After the wind ceases to blow, wind waves are called *swell*. Or, more generally, a swell consists of wind generated waves that are not — or hardly — affected by the local wind at that time. They have been generated elsewhere, or some time ago. Wind waves in the ocean are called **ocean surface waves**.

Tsunamis are a specific type of wave not caused by wind but by geological effects. In deep water, tsunamis are not visible because they are small in height and very long in wavelength. They may grow to devastating proportions at the coast due to reduced water depth.

Wave formation

NOAA ship *Delaware II* in bad weather on Georges Bank.

The great majority of large breakers one observes on a beach result from distant winds. Five factors influence the formation of wind waves:

- Wind speed
- Distance of open water that the wind has blown over (called the *fetch*)
- Width of area affected by fetch
- Time duration the wind has blown over a given area
- Water depth

All of these factors work together to determine the size of wind waves. The greater each of the variables, the larger the waves. Waves are characterized by:

- Wave height (from trough to crest)
- Wavelength (from crest to crest)
- Wave period (time interval between arrival of consecutive crests at a stationary point)
- Wave propagation direction

Waves in a given area typically have a range of heights. For weather reporting and for scientific analysis of wind wave statistics, their characteristic height over a period of time is usually expressed as *significant wave height*. This figure represents an average height of the highest one-third of the waves in a given time period (usually chosen somewhere in the range from 20 minutes to twelve hours), or in a specific wave or storm system. Given the variability of wave height, the largest individual waves are likely to be about twice the reported significant wave height for a particular day or storm.

Types of wind waves

Three different types of wind waves develop over time:

- Capillary waves, or ripples
- Seas
- Swells

Ripples appear on smooth water when the wind blows, but will die quickly if the wind stops. The restoring force that allows them to propagate is surface tension. Seas are the larger-scale, often irregular motions that form under sustained winds. They tend to last much longer, even after the wind has died, and the restoring force that allows them to persist is gravity. As seas propagate away from their area of origin, they naturally separate according to their direction and wavelength. The regular wave motions formed in this way are known as swells.

Individual "rogue waves" (also called "freak waves", "monster waves", "killer waves", and "king waves") much higher than the other waves in the sea state can occur. In the case of the Draupner wave, its 25 m (82 ft) height was 2.2 times the significant wave height. Such waves are distinct from tides, caused by the Moon and Sun's gravitational pull, tsunamis that are caused by underwater earthquakes or landslides, and waves generated by underwater explosions or the fall of meteorites — all having far longer wavelengths than wind waves.

Yet, the largest ever recorded wind waves are common – not rogue – waves in extreme sea states. For example: 29.1 m (95 ft) high waves have been recorded on the RRS Discovery in a sea with 18.5 m (61 ft) significant wave height, so the highest wave is only 1.6 times the significant wave height.

Wave breaking

Big wave breaking

Surf in a rocky irregular bottom. Porto Covo, west coast of Portugal

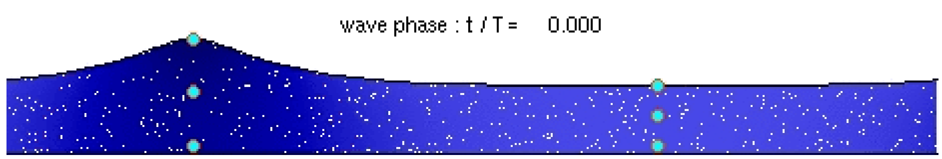
Some waves undergo a phenomenon called "breaking". A breaking wave is one whose base can no longer support its top, causing it to collapse. A wave breaks when it runs into shallow water, or when two wave systems oppose and combine forces. When the slope, or steepness ratio, of a wave is too great, breaking is inevitable.

Individual waves in deep water break when the wave steepness — the ratio of the wave height H to the wavelength λ — exceeds about 0.17, so for $H > 0.17\ \lambda$. In shallow water, with the water depth small compared to the wavelength, the individual waves break when their wave height H is larger than 0.8 times the water depth h, that is $H > 0.8\ h$. Waves can also break if the wind grows strong enough to blow the crest off the base of the wave.

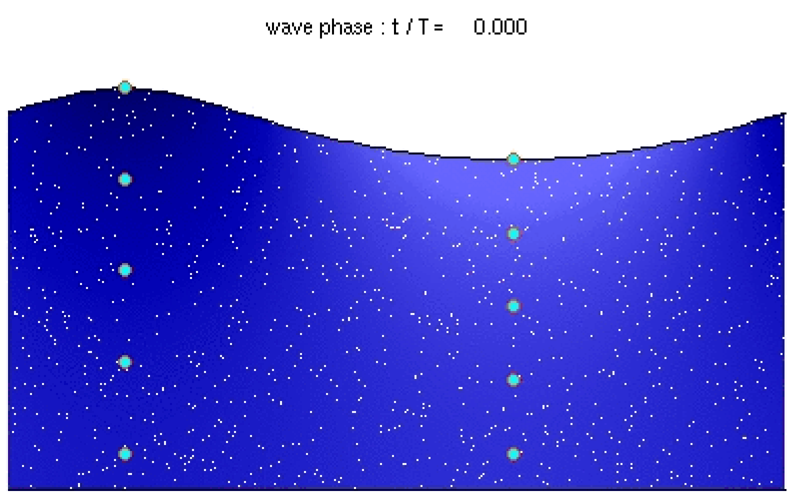
Three main types of breaking waves are identified by surfers or surf lifesavers. Their varying characteristics make them more or less suitable for surfing, and present different dangers.

- **Spilling**, or **rolling**: these are the safest waves on which to surf. They can be found in most areas with relatively flat shorelines. They are the most common type of shorebreak
- **Plunging**, or **dumping**: these break suddenly and can "dump" swimmers—pushing them to the bottom with great force. These are the preferred waves for experienced surfers. Strong offshore winds and long wave periods can cause dumpers. They are often found where there is a sudden rise in the sea floor, such as a reef or sandbar.
- **Surging**: these may never actually break as they approach the water's edge, as the water below them is very deep. They tend to form on steep shorelines. These waves can knock swimmers over and drag them back into deeper water.

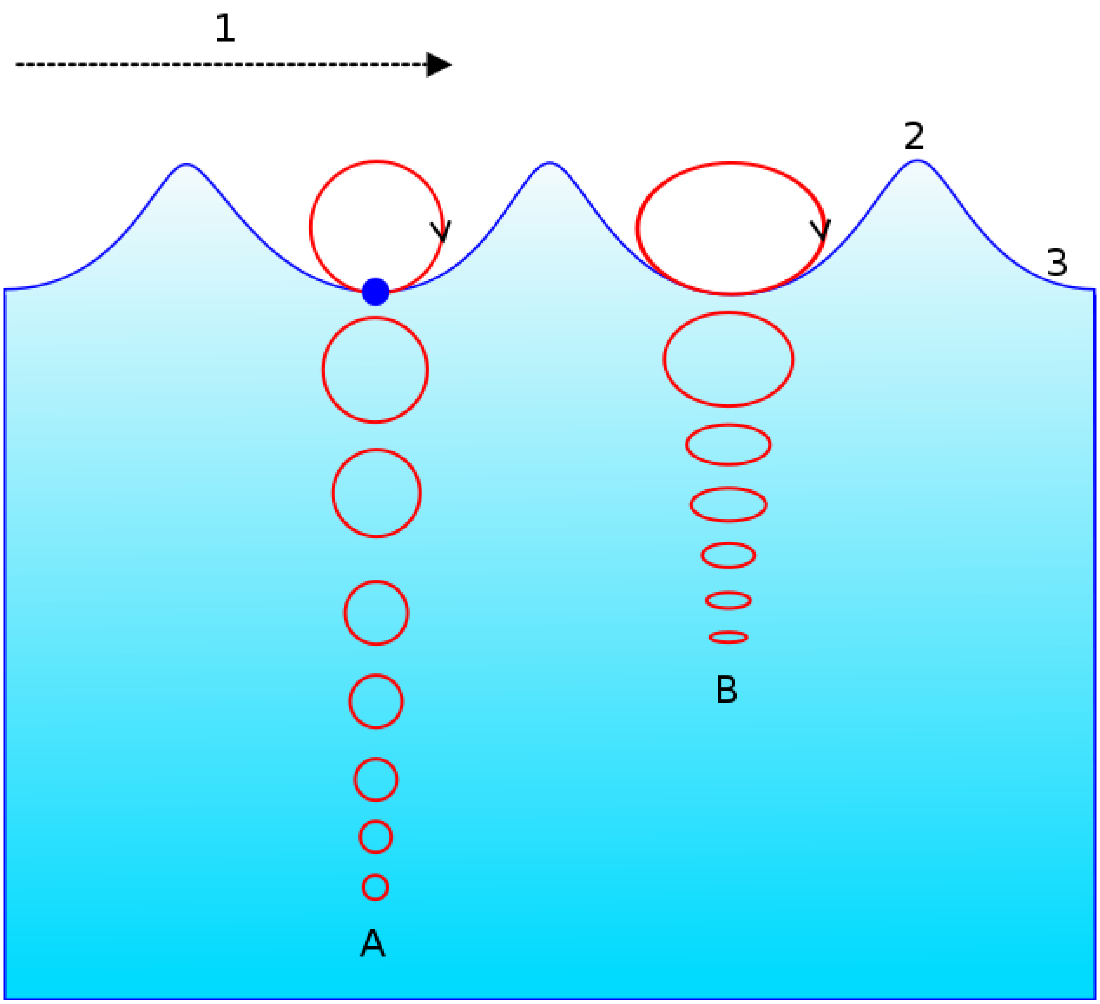
Science of waves



Shallow water wave



Deep water wave



Motion of a particle in a wind wave.
A = At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface.
B = At shallow water (sea floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth.
1 = Propagation direction.
2 = Wave crest.
3 = Wave trough.

Wind waves are mechanical waves that propagate along the interface between water and air; the restoring force is provided by gravity, and so they are often referred to as surface gravity waves. As the wind blows, pressure and friction forces perturb the equilibrium of the water surface. These forces transfer energy from the air to the water, forming waves. The initial formation of waves by the wind is described in the theory of Phillips from

1957, and the subsequent growth of the small waves has been modeled by Miles, also in 1957.

In the case of monochromatic linear plane waves in deep water, particles near the surface move in circular paths, making wind waves a combination of longitudinal (back and forth) and transverse (up and down) wave motions. When waves propagate in shallow water, (where the depth is less than half the wavelength) the particle trajectories are compressed into ellipses.

As the wave amplitude (height) increases, the particle paths no longer form closed orbits; rather, after the passage of each crest, particles are displaced slightly from their previous positions, a phenomenon known as Stokes drift.

For intermediate and shallow water, the Boussinesq equations are applicable, combining frequency dispersion and nonlinear effects. And in very shallow water, the shallow water equations can be used.

As the depth below the free surface increases, the radius of the circular motion decreases. At a depth equal to half the wavelength λ, the orbital movement has decayed to less than 5% of its value at the surface. The phase speed of the surface wave (also called the celerity) is well approximated by

$$c = \sqrt{\frac{g\lambda}{2\pi} \tanh\left(\frac{2\pi d}{\lambda}\right)}$$

where

c = phase speed;
λ = wavelength;
d = water depth;
g = acceleration due to gravity at the Earth's surface.

In deep water, where $d \geq \frac{1}{2}\lambda$, so $\frac{2\pi d}{\lambda} \geq \pi$ and the hyperbolic tangent approaches 1, the speed c, in m/s, approximates $1.25\sqrt{\lambda}$, when λ is measured in meters. This expression tells us that waves of different wavelengths travel at different speeds. The fastest waves in a storm are the ones with the longest wavelength. As a result, after a storm, the first waves to arrive on the coast are the long–wavelength swells.

When several wave trains are present, as is always the case in nature, the waves form groups. In deep water the groups travel at a group velocity which is half of the phase speed. Following a single wave in a group one can see the wave appearing at the back of the group, growing and finally disappearing at the front of the group.

As the water depth *d* decreases towards the coast, this will have an effect: wave height changes due to wave shoaling and refraction. As the wave height increases, the wave may become unstable when the crest of the wave moves faster than the trough. This causes *surf*, a breaking of the waves.

The movement of wind waves can be captured by wave energy devices. The energy density (per unit area) of regular sinusoidal waves depends on the water density ρ, gravity acceleration *g* and the wave height *H* (which, for regular waves, is equal to twice the amplitude, *a*):

$$E = \frac{1}{8}\rho g H^2 = \frac{1}{2}\rho g a^2.$$

The velocity of propagation of this energy is the group velocity.

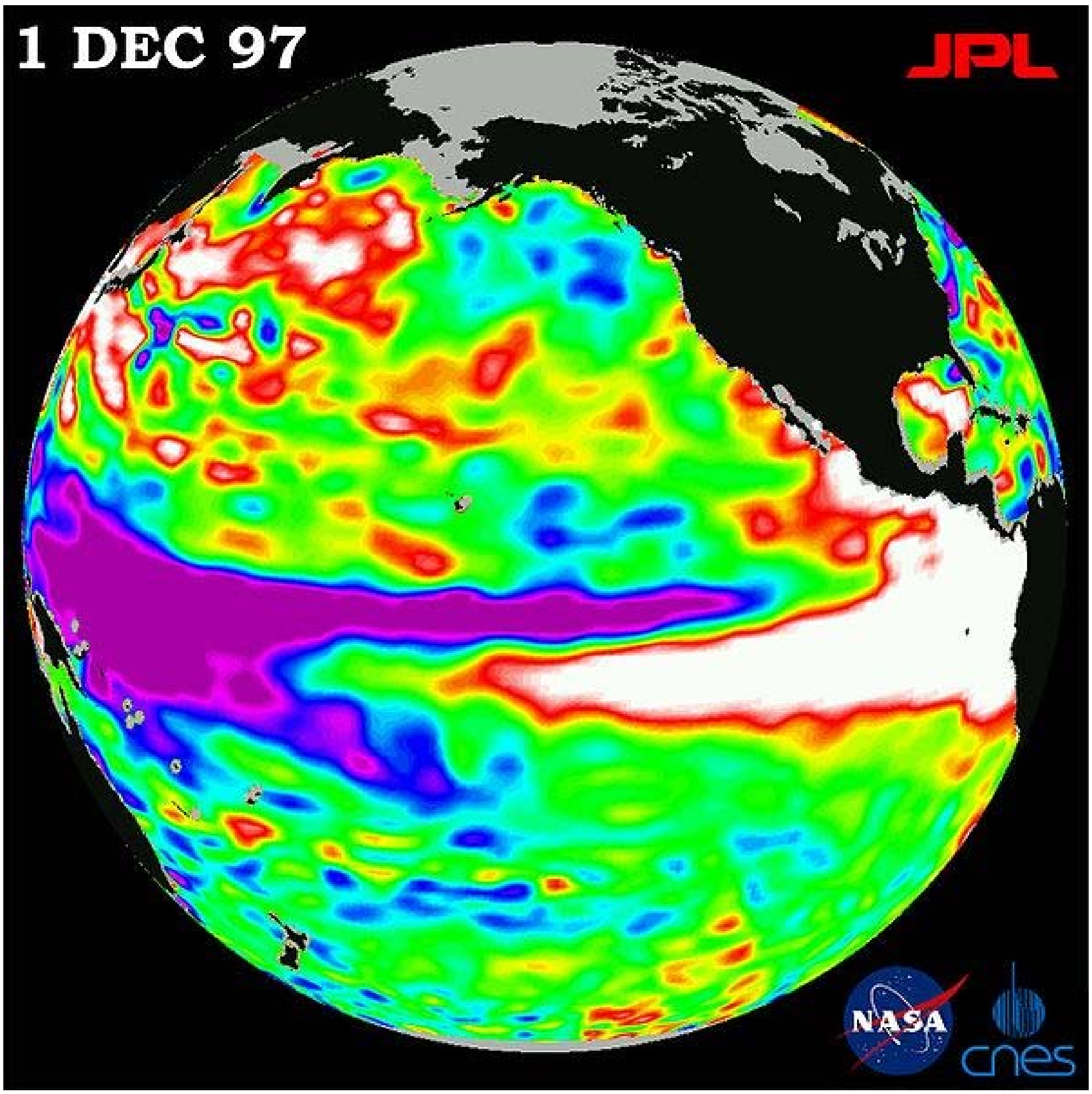
Wind wave models

Surfers are very interested in the wave forecasts. There are many websites that provide predictions of the surf quality for the upcoming days and weeks. Wind wave models are driven by more general weather models that predict the winds and pressures over the oceans, seas and lakes.

Wind wave models are also an important part of examining the impact of shore protection and beach nourishment proposals. For many beach areas there is only patchy information about the wave climate, therefore estimating the effect of wind waves is important for managing littoral environments.

Chapter- 9

El Niño-Southern Oscillation



The 1997 El Niño observed by TOPEX/Poseidon. The white areas off the tropical coasts of South and North America indicate the pool of warm water.

El Niño/La Niña-Southern Oscillation, or **ENSO**, is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean on average every five years, but over a period which varies from three to seven years. It is characterized by variations in the temperature of the surface of the tropical eastern Pacific Ocean - warming or cooling known as *El Niño* and *La Niña* respectively - and air surface pressure in the tropical western Pacific - the *Southern Oscillation*. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific. Mechanisms that cause the oscillation remain under study.

ENSO causes extreme weather such as floods, droughts and other weather disturbances in many regions of the world. Developing countries dependent upon agriculture and fishing, particularly those bordering the Pacific Ocean, are the most affected. In popular usage, the El Niño-Southern Oscillation is often called just "El Niño". El Niño is Spanish for "the boy" and refers to the Christ child, because periodic warming in the Pacific near South America is usually noticed around Christmas.

Definition

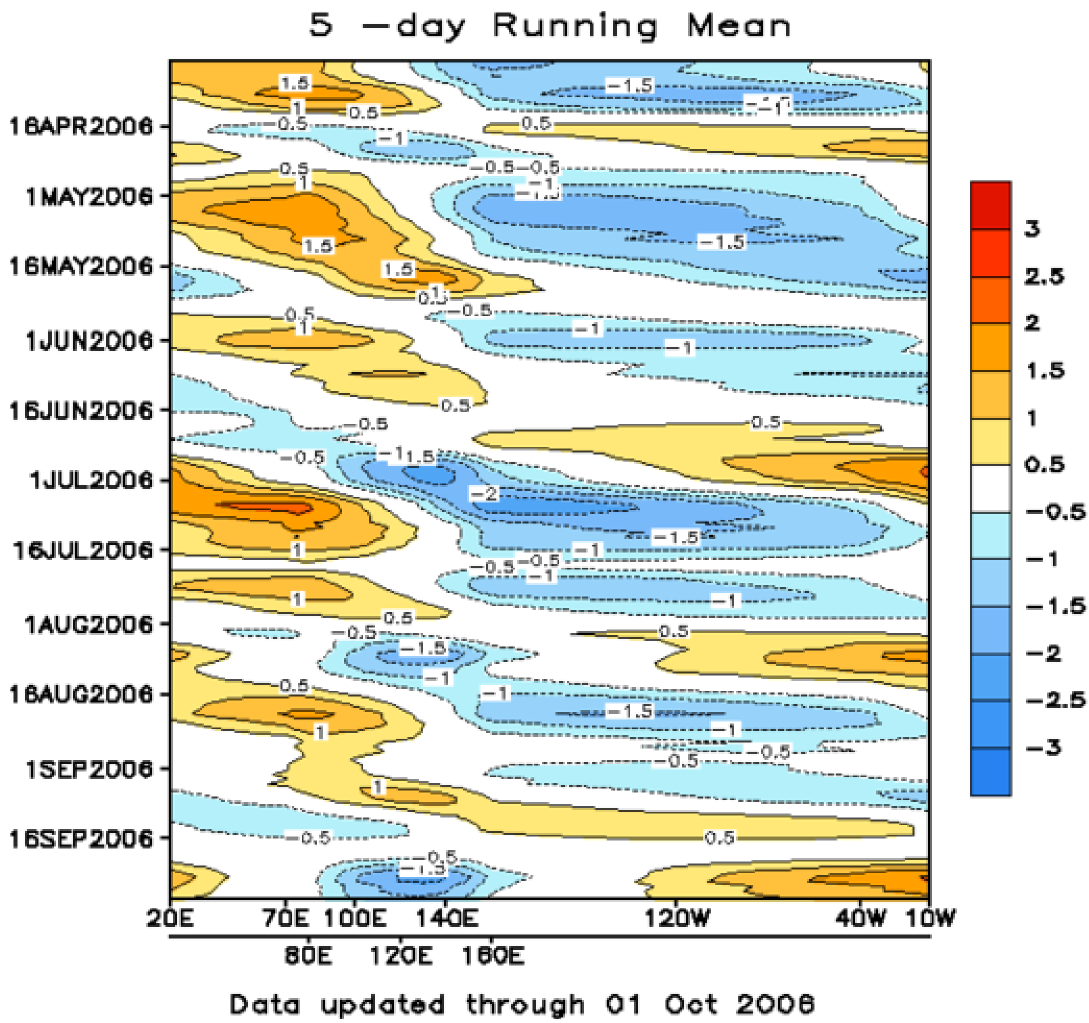
El Niño is defined by prolonged differences in Pacific Ocean surface temperatures when compared with the average value. The accepted definition is a warming or cooling of at least 0.5 °C (0.9 °F) averaged over the east-central tropical Pacific Ocean. Typically, this anomaly happens at irregular intervals of 2–7 years and lasts nine months to two years. When this warming or cooling occurs for only seven to nine months, it is classified as El Niño/La Niña "conditions"; when it occurs for only five to seven months, it is classified as El Niño/La Niña "episodes".

The first signs of an El Niño are:

1. Rise in surface pressure over the Indian Ocean, Indonesia, and Australia
2. Fall in air pressure over Tahiti and the rest of the central and eastern Pacific Ocean
3. Trade winds in the south Pacific weaken or head east
4. Warm air rises near Peru, causing rain in the northern Peruvian deserts
5. Warm water spreads from the west Pacific and the Indian Ocean to the east Pacific. It takes the rain with it, causing extensive drought in the western Pacific and rainfall in the normally dry eastern Pacific.

El Niño's warm rush of nutrient-poor tropical water, heated by its eastward passage in the Equatorial Current, replaces the cold, nutrient-rich surface water of the Humboldt Current. When El Niño conditions last for many months, extensive ocean warming and the reduction in Easterly Trade winds limits upwelling of cold nutrient-rich deep water and its economic impact to local fishing for an international market can be serious.

Early stages and characteristics of El Niño



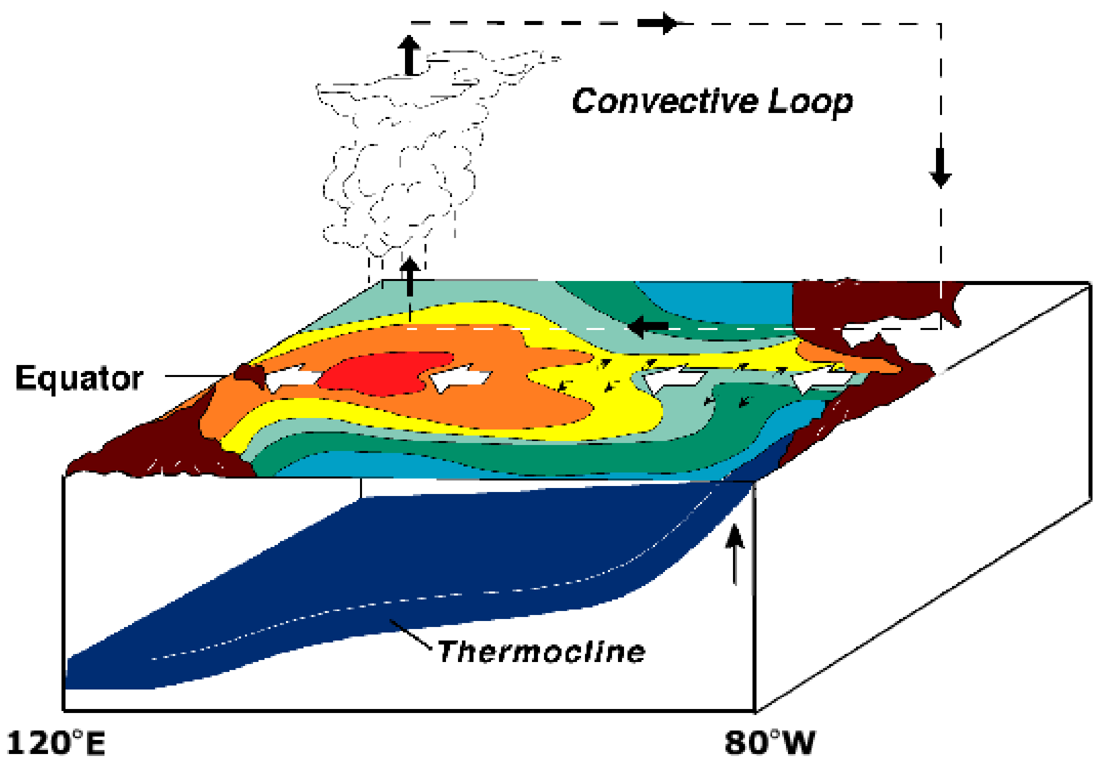
5-day running mean of MJO. Note how it moves eastward with time.

Although its causes are still being investigated, El Niño events begin when trade winds, part of the Walker circulation, falter for many months. A series of Kelvin waves—relatively warm subsurface waves of water a few centimetres high and hundreds of kilometres wide—cross the Pacific along the equator and create a pool of warm water near South America, where ocean temperatures are normally cold due to upwelling. The weakening of the winds can also create twin cyclones, another sign of a future El Niño. The Pacific Ocean is a heat reservoir that drives global wind patterns, and the resulting change in its temperature alters weather on a global scale. Rainfall shifts from the western Pacific toward the Americas, while Indonesia and India become drier.

Jacob Bjerknes in 1969 helped toward an understanding of ENSO, by suggesting that an anomalously warm spot in the eastern Pacific can weaken the east-west temperature difference, disrupting trade winds that push warm water to the west. The result is increasingly warm water toward the east. Several mechanisms have been proposed through which warmth builds up in equatorial Pacific surface waters, and is then dispersed to lower depths by an El Niño event. The resulting cooler area then has to "recharge" warmth for several years before another event can take place.

While not a direct cause of El Niño, the Madden-Julian Oscillation, or MJO, propagates rainfall anomalies eastward around the global tropics in a cycle of 30–60 days, and may influence the speed of development and intensity of El Niño and La Niña in several ways. For example, westerly flows between MJO-induced areas of low pressure may cause cyclonic circulations north and south of the equator. When the circulations intensify, the westerly winds within the equatorial Pacific can further increase and shift eastward, playing a role in El Niño development. Madden-Julian activity can also produce eastward-propagating oceanic Kelvin waves, which may in turn be influenced by a developing El Niño, leading to a positive feedback loop.

Southern Oscillation



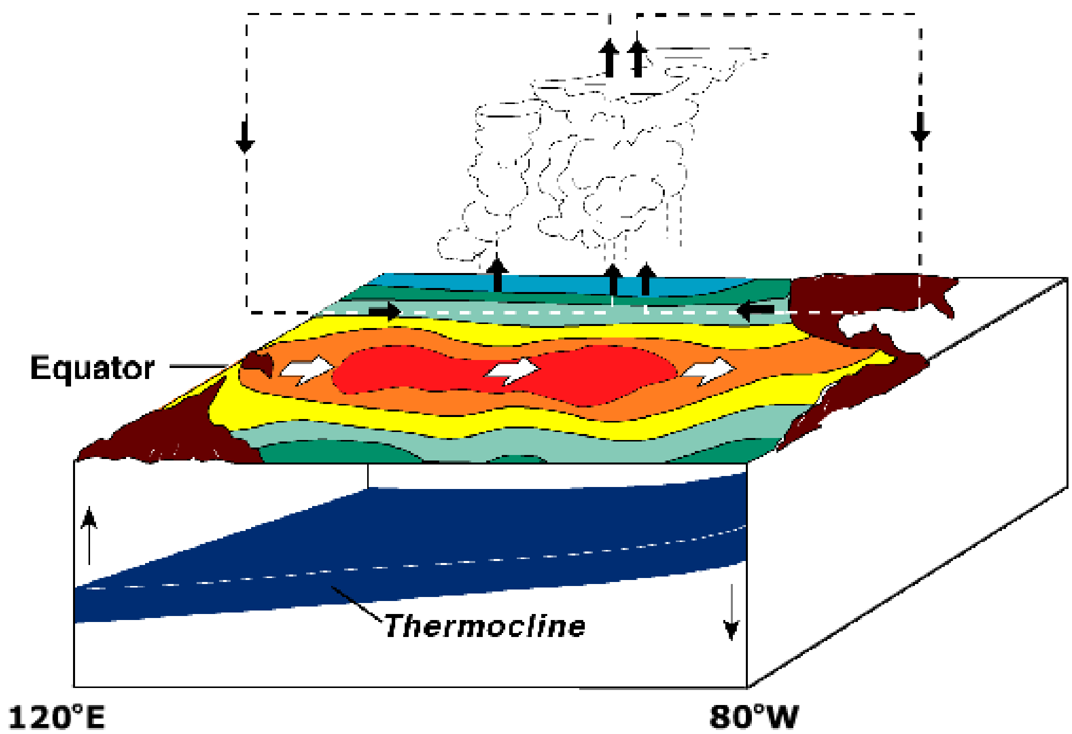
Normal Pacific pattern. Equatorial winds gather warm water pool toward west. Cold water upwells along South American coast. (NOAA / PMEL / TAO)

The Southern Oscillation is the atmospheric component of El Niño. This component is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the Southern Oscillation is measured by the ***Southern***

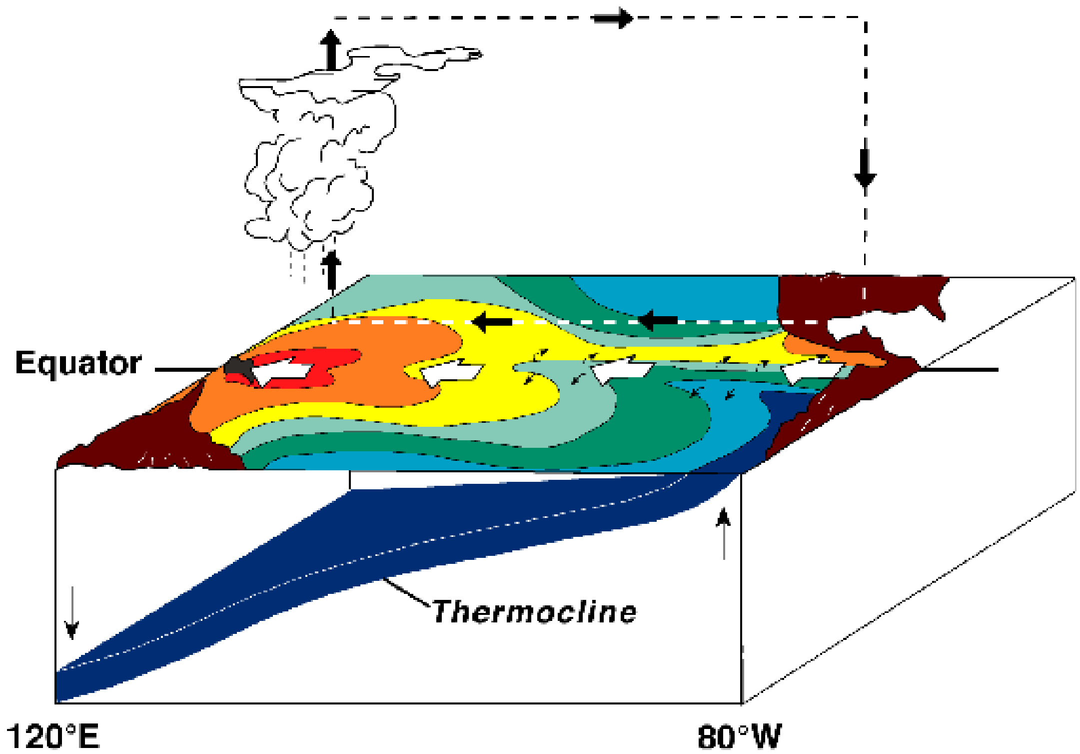
Oscillation Index (SOI). The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia. El Niño episodes are associated with negative values of the SOI, meaning that the pressure at Tahiti is relatively low compared to Darwin.

Low atmospheric pressure tends to occur over warm water and high pressure occurs over cold water, in part because deep convection over the warm water acts to transport air. El Niño episodes are defined as sustained warming of the central and eastern tropical Pacific Ocean. This results in a decrease in the strength of the Pacific trade winds, and a reduction in rainfall over eastern and northern Australia.

Walker circulation



El Niño Conditions. Warm water pool approaches South American coast. Absence of cold upwelling increases warming.



La Niña Conditions. Warm water is further west than usual.

During non-El Niño conditions, the Walker circulation is seen at the surface as easterly trade winds which move water and air warmed by the sun towards the west. This also creates ocean upwelling off the coasts of Peru and Ecuador and brings nutrient-rich cold water to the surface, increasing fishing stocks. The western side of the equatorial Pacific is characterized by warm, wet low pressure weather as the collected moisture is dumped in the form of typhoons and thunderstorms. The ocean is some 60 centimetres (24 in) higher in the western Pacific as the result of this motion.

Effects of ENSO's warm phase (El Niño)

South America

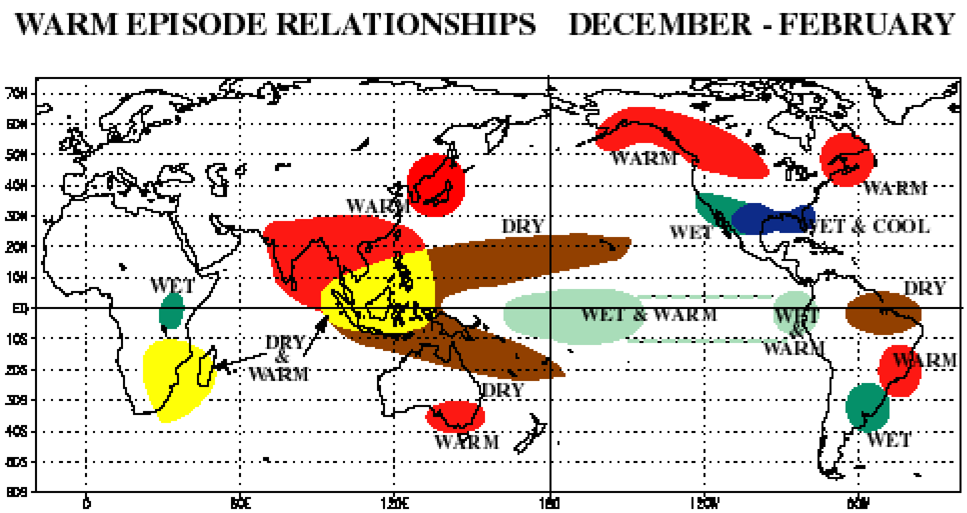
Because El Niño's warm pool feeds thunderstorms above, it creates increased rainfall across the east-central and eastern Pacific Ocean including several portions of the South American west coast. The effects of El Niño in South America are direct and stronger than in North America. An El Niño is associated with warm and very wet weather months December–April along the coasts of northern Peru and Ecuador, causing major flooding whenever the event is strong or extreme. The effects during the months of February, March and April may become critical. Along the west coast of South America, El Niño reduces the upwelling of cold, nutrient-rich water that sustains large fish populations, which in turn sustain abundant sea birds, whose droppings support the fertilizer industry. This leads to fish kills offshore Peru.

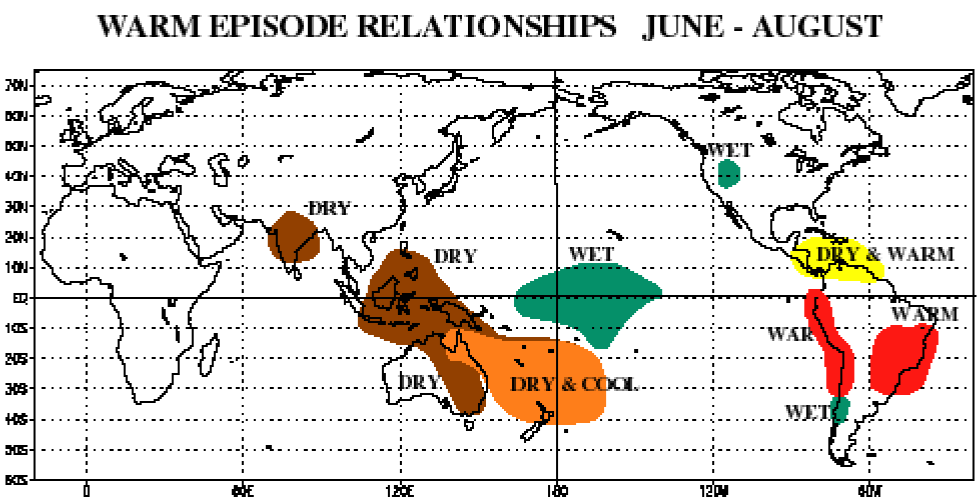
The local fishing industry along the affected coastline can suffer during long-lasting El Niño events. The world's largest fishery collapsed due to overfishing during the 1972 El Niño Peruvian anchoveta reduction. During the 1982–83 event, jack mackerel and anchoveta populations were reduced, scallops increased in warmer water, but hake followed cooler water down the continental slope, while shrimp and sardines moved southward so some catches decreased while others increased. Horse mackerel have increased in the region during warm events. Shifting locations and types of fish due to changing conditions provide challenges for fishing industries. Peruvian sardines have moved during El Niño events to Chilean areas. Other conditions provide further complications, such as the government of Chile in 1991 creating restrictions on the fishing areas for self-employed fishermen and industrial fleets.

The ENSO variability may contribute to the great success of small fast-growing species along the Peruvian coast, as periods of low population removes predators in the area. Similar effects benefit migratory birds that travel each spring from predator-rich tropical areas to distant winter-stressed nesting areas.

Southern Brazil and northern Argentina also experience wetter than normal conditions but mainly during the spring and early summer. Central Chile receives a mild winter with large rainfall, and the Peruvian-Bolivian Altiplano is sometimes exposed to unusual winter snowfall events. Drier and hotter weather occurs in parts of the Amazon River Basin, Colombia and Central America.

North America





Regional impacts of warm ENSO episodes (El Niño).

Winters, during the El Niño effect, are warmer and drier than average in the Northwest, Northmidwest, and Northmideast United States, and therefore those regions experience reduced snowfalls. Meanwhile, significantly wetter winters are present in northwest Mexico and the southwest United States including central and southern California, while both cooler and wetter than average winters in northeast Mexico and the southeast United States (including the Tidewater region of Virginia) occur during the El Niño phase of the oscillation.

In Canada, both warmer and drier winters (due to forcing of the Polar Jet further north) over much of the country occur, although less variation from normal is seen in the Maritime Provinces. The following summer is warmer and sometimes drier creating a more active than average forest fire season over Central/Eastern Canada. Some believed that the ice-storm in January 1998, which devastated parts of Southern Ontario and Southern Quebec, was caused or accentuated by El Niño's warming effects. El Niño warmed Vancouver for the 2010 Winter Olympics, such that the area experienced a subtropical-like winter during the games.

Summers, during the El Niño effect, are wetter than average in the Northwest, Northmidwest, Northmideast, and mountain regions of the United States.

El Niño is credited with suppressing hurricanes and made the 2009 hurricane season the least active in twelve years. El Niño is also associated with increased wave-caused coastal erosion along the United States Pacific Coast.

There is some evidence that El Niño activity is correlated with incidence of red tides off the Pacific coast of California.

Tropical cyclones

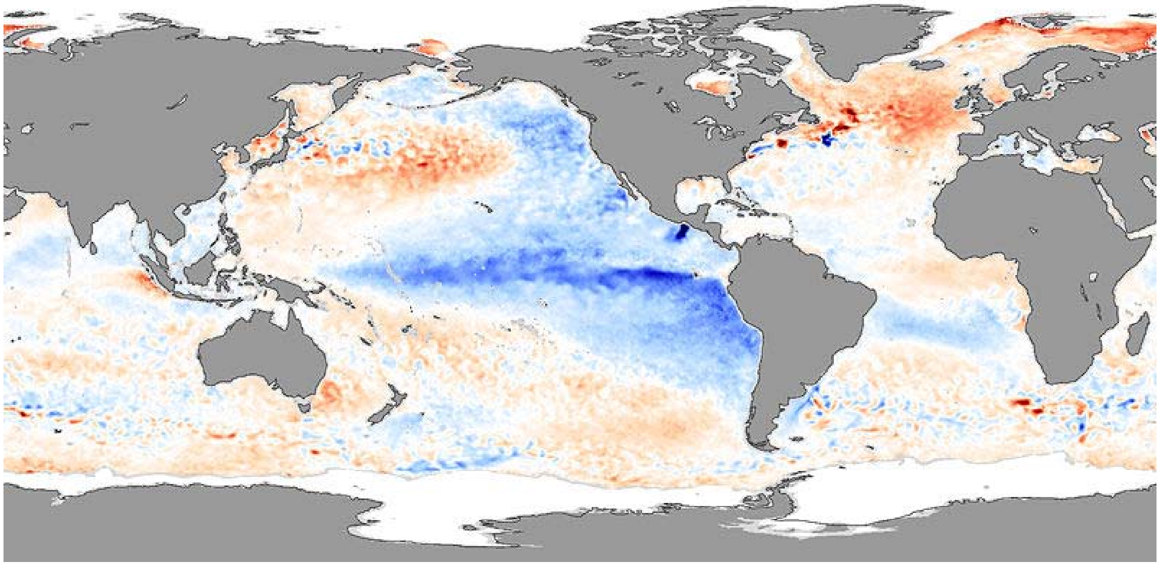
Most tropical cyclones form on the side of the subtropical ridge closer to the equator, then move poleward past the ridge axis before recurving into the main belt of the Westerlies. When the subtropical ridge position shifts due to El Niño, so will the preferred tropical cyclone tracks. Areas west of Japan and Korea tend to experience much fewer September–November tropical cyclone impacts during El Niño and neutral years. During El Niño years, the break in the subtropical ridge tends to lie near 130°E, which would favor the Japanese archipelago. During El Niño years, Guam's chance of a tropical cyclone impact is one-third of the long term average. The tropical Atlantic ocean experiences depressed activity due to increased vertical wind shear across the region during El Niño years.

Elsewhere

In Africa, East Africa, including Kenya, Tanzania and the White Nile basin experiences, in the long rains from March to May, wetter than normal conditions. There are also drier than normal conditions from December to February in south-central Africa, mainly in Zambia, Zimbabwe, Mozambique and Botswana. Direct effects of El Niño resulting in drier conditions occur in parts of Southeast Asia and Northern Australia, increasing bush fires and worsening haze and decreasing air quality dramatically. Drier than normal conditions are also generally observed in Queensland, inland Victoria, inland New South Wales and eastern Tasmania from June to August. West of the Antarctic Peninsula, the Ross, Bellingshausen, and Amundsen Sea sectors have more sea ice during El Niño. The latter two and the Weddell Sea also become warmer and have higher atmospheric pressure. El Niño's effects on Europe are not entirely clear, but certainly it is not nearly as affected as at least large parts of other continents. There is some evidence that an El Niño may cause a wetter, cloudier winter in Northern Europe and a milder, drier winter in the Mediterranean Sea region. The El Niño winter of 2006/2007 was unusually mild in Europe, and the Alps recorded very little snow coverage that season.

Most recently, Singapore experienced the driest February in 2010 since records begins in 1869. With only 6.3 millimetres of rain fell in the month and temperatures hitting as high as 35 degrees Celsius on 26 February. 1968 and 2005 had the next driest Februaries when 8.4 mm of rain fell.

Effects of ENSO's cool phase (La Niña)



Sea surface skin temperature anomalies in November 2007 showing La Niña conditions

La Niña is the name for the cold phase of ENSO, during which the cold pool in the eastern Pacific intensifies and the trade winds strengthen. The name La Niña originates from Spanish, meaning "the girl", analogous to El Niño meaning "the boy". It has also in the past been called *anti-El Niño*, and El Viejo (meaning "the old man").

Africa

La Niña results in wetter than normal conditions in Southern Africa from December to February, and drier than normal conditions over equatorial East Africa over the same period.

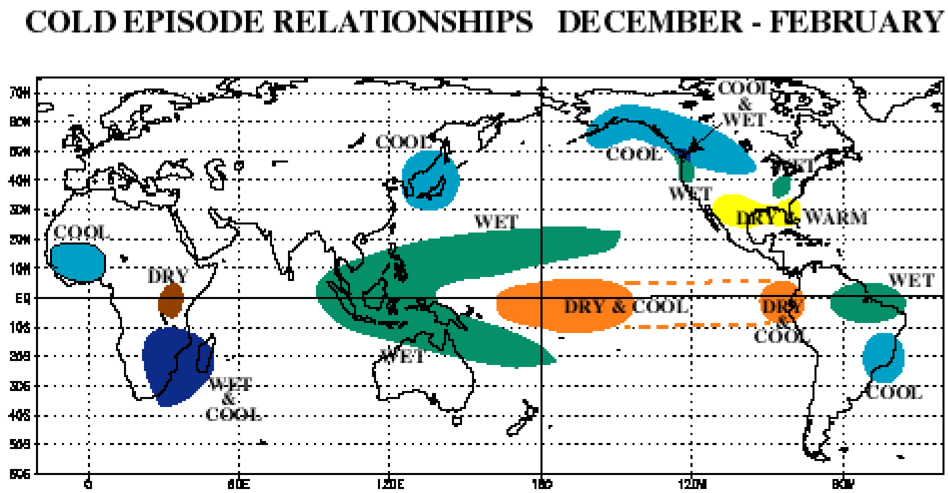
Asia

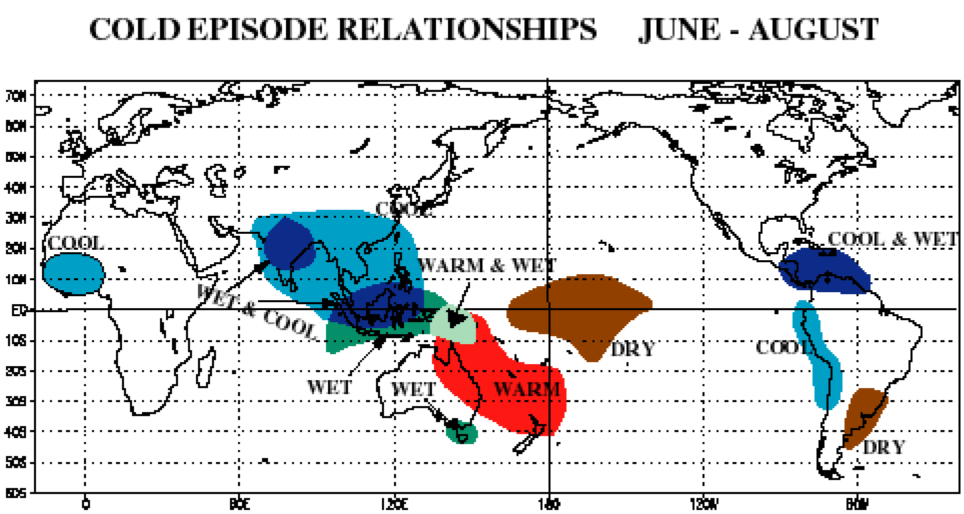
During La Niña years, the formation of tropical cyclones, along with the subtropical ridge position, shifts westward across the western Pacific ocean, which increases the landfall threat to China. In March 2008, La Niña caused a drop in sea surface temperatures over Southeast Asia by an amount of 2 °C. It also caused heavy rains over Malaysia, Philippines and Indonesia.

South America

During a time of La Niña, drought plagues the coastal regions of Peru and Chile. From December to February, northern Brazil is wetter than normal.

North America





Regional impacts of La Niña.

La Niña causes mostly the opposite effects of El Niño. La Niña causes above average precipitation across the North Midwest, the Northern Rockies, Northern California, and in the Pacific Northwest's southern and eastern regions. Meanwhile there is below average precipitation in the southwestern and southeastern states.

La Niñas occurred in 1904, 1908, 1910, 1916, 1924, 1928, 1938, 1950, 1955, 1964, 1970, 1973, 1975, 1988, 1995.

In Canada, La Niña will generally cause a cooler, snowier winter, such as the near record-breaking amounts of snow recorded in the La Niña winter of 2007/2008 in Eastern Canada.

Recent occurrences

There was a strong La Niña episode during 1988–1989. La Niña also formed in 1995, from 1998–2000, and a minor one from 2000–2001. Recently, an occurrence of El Niño started in September 2006 and lasted until early 2007. From June 2007 on, data indicated a moderate La Niña event, which strengthened in early 2008 and weakened by early 2009; the 2007–2008 La Niña event was the strongest since the 1988–1989 event. The strength of the La Niña made the 2008 hurricane season one of the most active since 1944; there were 16 named storms of at least 39 mph (63 km/h), eight of which became 74 mph (119 km/h) or greater hurricanes.

According to NOAA, El Niño conditions were in place in the equatorial Pacific Ocean starting June 2009, peaking in January–February. Positive SST anomalies (El Niño) lasted until May 2010. Since then, SST anomalies have been negative (La Niña) and expected to stay negative for the next northern winter.

Remote influence on tropical Atlantic Ocean

A study of climate records has shown that El Niño events in the equatorial Pacific are generally associated with a warm tropical North Atlantic in the following spring and summer. About half of El Niño events persist sufficiently into the spring months for the Western Hemisphere Warm Pool (WHWP) to become unusually large in summer. Occasionally, El Niño's effect on the Atlantic Walker circulation over South America strengthens the easterly trade winds in the western equatorial Atlantic region. As a result, an unusual cooling may occur in the eastern equatorial Atlantic in spring and summer following El Niño peaks in winter. Cases of El Niño-type events in both oceans simultaneously have been linked to severe famines related to the extended failure of monsoon rains.

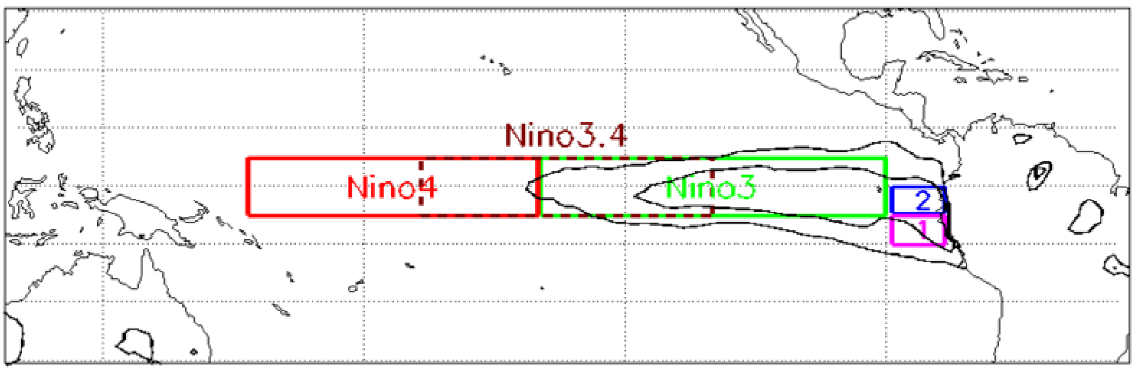
ENSO and global warming

During the last several decades the number of El Niño events increased, and the number of La Niña events decreased. The question is whether this is a random fluctuation or a normal instance of variation for that phenomenon, or the result of global climate changes towards global warming.

The studies of historical data show that the recent El Niño variation is most likely linked to global warming. For example, one of the most recent results is that even after subtracting the positive influence of decadal variation, shown to be possibly present in the ENSO trend, the amplitude of the ENSO variability in the observed data still increases, by as much as 60% in the last 50 years.

It is not certain what exact changes will happen to ENSO in the future: different models make different predictions (cf.) It may be that the observed phenomenon of more frequent and stronger El Niño events occurs only in the initial phase of the global warming, and then (e.g., after the lower layers of the ocean get warmer as well), El Niño will become weaker than it was. It may also be that the stabilizing and destabilizing forces influencing the phenomenon will eventually compensate for each other. More research is needed to provide a better answer to that question, but the current results do not completely exclude the possibility of dramatic changes.

El Niño "Modoki" and Central-Pacific El Niño



Map showing Nino3.4 and other index regions

The traditional Niño, also called Eastern Pacific (EP) El Niño, involves temperature anomalies in the Eastern Pacific. However, in the last two decades non-traditional El Niños were observed, in which the usual place of the temperature anomaly is not affected, but an anomaly arises in the central Pacific. The phenomenon is called Central Pacific (CP) El Niño, "dateline" El Niño (because the anomaly arises near the dateline), or El Niño "Modoki" (Modoki is Japanese for "similar, but different").

The effects of the CP El Niño are different from those of the traditional EP El Niño—e.g., the new El Niño leads to more hurricanes more frequently making landfall in the Atlantic.

The recent discovery of El Niño Modoki has some scientists believing it to be linked to global warming. However, Satellite data only goes back to 1979. More research must be done to find the correlation and study past El Niño episodes.

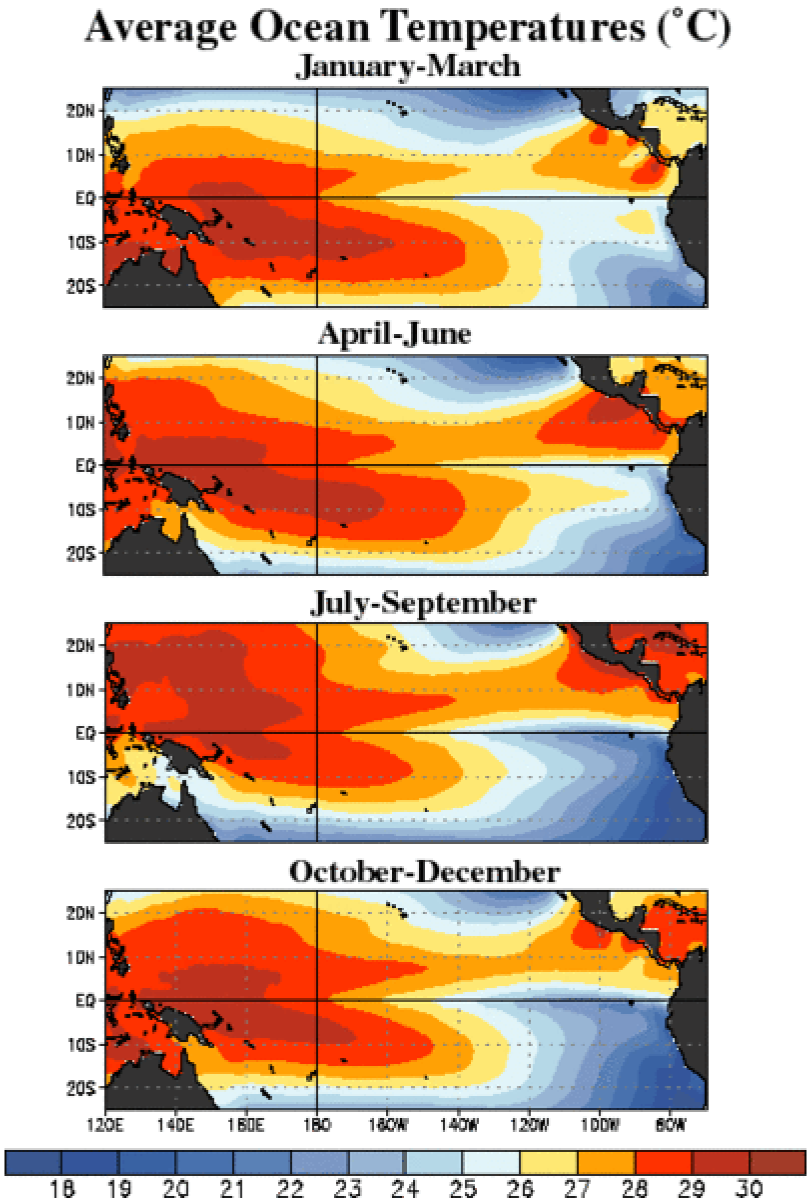
The first recorded El Niño that originated in the central Pacific and moved towards the east was in 1986.

A joint study by the National Aeronautics and Space Administration and the National Oceanic and Atmospheric Administration concluded that climate change may contribute to stronger El Niños. El Niño "Modoki" events occurred in 1991-92, 1994–95, 2002–03, 2004–05 and 2009-10. The strongest such Central Pacific El Niño event known occurred in 2009-2010.

Health Impact of El Niño

Extreme weather conditions related with the El Niño cycle are associated with changes in the incidence of epidemic diseases. For example, the El Niño cycle is associated with increased risks of some of the diseases transmitted by mosquitoes, such as malaria, dengue and Rift Valley fever. Cycles of malaria in India, Venezuela and Columbia have now been linked to El Niño. Outbreaks of another mosquito-transmitted disease, Australian Encephalitis (Murray Valley Encephalitis - MVE), occur in temperate south-east Australia after heavy rainfall and flooding, which are associated with La Nina events. A severe outbreak of Rift Valley fever occurred after extreme rainfall in north-eastern Kenya and southern Somalia during the 1997-98 El Niño.

Cultural history and pre-historic information



Average equatorial Pacific temperatures

ENSO conditions have occurred at two- to seven year intervals for at least the past 300 years, but most of them have been weak. There is also evidence for strong El Niño events during the early Holocene epoch 10,000 years ago.

El Niño affected pre-Columbian Incas and may have led to the demise of the Moche and other pre-Columbian Peruvian cultures. A recent study suggests that a strong El-Niño effect between 1789–93 caused poor crop yields in Europe, which in turn helped touch off the French Revolution. The extreme weather produced by El Niño in 1876–77 gave rise to the most deadly famines of the 19th century.

An early recorded mention of the term "El Niño" to refer to climate occurs in 1892, when Captain Camilo Carrillo told the Geographical society congress in Lima that Peruvian sailors named the warm northerly current "El Niño" because it was most noticeable around Christmas. The phenomenon had long been of interest because of its effects on the guano industry and other enterprises that depend on biological productivity of the sea.

Charles Todd, in 1893, suggested that droughts in India and Australia tended to occur at the same time; Norman Lockyer noted the same in 1904. An El Niño connection with flooding was reported in 1895 by Pezet and Eguiguren. In 1924 Gilbert Walker (for whom the Walker circulation is named) coined the term "Southern Oscillation".

The major 1982–83 El Niño led to an upsurge of interest from the scientific community. The period from 1990–1994 was unusual in that El Niños have rarely occurred in such rapid succession. An especially intense El Niño event in 1998 caused an estimated 16% of the world's reef systems to die. The event temporarily warmed air temperature by 1.5 °C, compared to the usual increase of 0.25 °C associated with El Niño events. Since then, mass coral bleaching has become common worldwide, with all regions having suffered "severe bleaching".

Major ENSO events were recorded in the years 1790–93, 1828, 1876–78, 1891, 1925–26, 1972–73, 1982–83, and 1997–98.