Geography Optional - 2024

TIDES AND OCEANIC CURRENTS

NEETU SINGH

Tides are defined as periodic, short-term changes in the height of the ocean surface caused by the moon and sun’s gravitational forces and the rotation of the earth. Tides can be considered waves – the largest on Earth’s surface. But tides are considered forced waves (ocean waves are free waves) because they are never free from the forces that cause them.

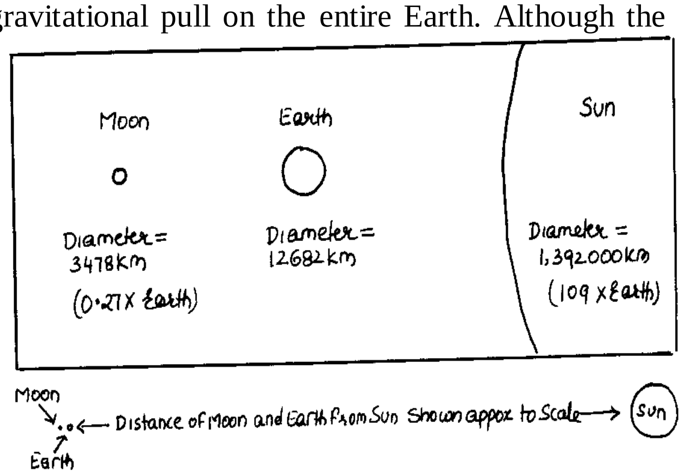
Tide-Generating Forces

Tides are generated by two main energy sources – **gravitational forces and centripetal forces**. We will discuss the basics of each force in this section.

Gravity

Newton’s law of gravitation states that all bodies in the universe are attracted to one another and that attraction between the bodies is directly proportional to the masses of the bodies, but inversely proportional to the square of the distance between them. In simpler terms, larger (heavier) bodies attract more strongly to one another than smaller ones. And the attraction between the two quickly weakens as the distance between them grows. For objects the size of planets, we find that distance is the main factor in determining the strength of the gravitational pull.

The moon and the sun are also exerting a gravitational pull on the entire Earth. Although the moon is very small in relationship to the sun, it exerts a much stronger pull on Earth. The reason is because the Earth is closer to the moon than the sun. Although the sun is larger than the moon, it is significantly farther away from Earth so its pull is not felt as much.



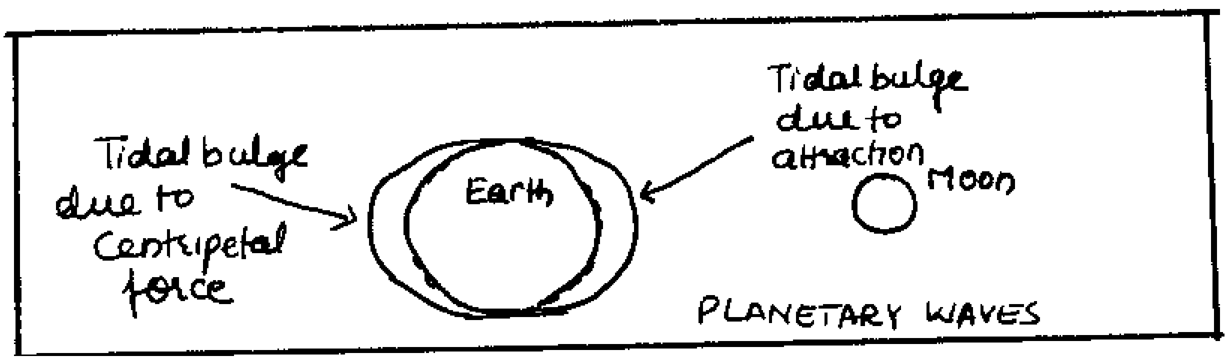
Orbital Motion and Centripetal Force

The moon orbits around Earth – meaning it makes a complete circle around the earth every 24 hours and 55 minutes. Actually, the moon does not orbit around a stationary Earth, but they both rotate their common center of mass. A common center of mass (also called a barycenter) is the point between the two at which the mass on either side of the point is equal – the two then orbit around this point.

The Equilibrium Theory of Tides

It assumes the Earth is completely covered with water, that interaction with the seafloor does not influence the tides and that the ocean is always in equilibrium with the tidal forces.

Under these idealized conditions, we find that the moon's gravity attracts the surface of the ocean toward the moon. This creates a tidal bulge on the side of the Earth that faces the moon, like in the image below.



On the opposite side of the earth, another tidal bulge also is created. This is because the centripetal force of the rotation of the earth and moon "throws" water to this side of the Earth to balance the center of mass. You can think of this as similar to the example of swinging around a bucket of water. The water moves to the far end of the bucket to maintain the centripetal force. So, with the inward gravitational pull of the moon, and the outward-flinging force of rotation, we see a situation similar to the image below, with tidal bulges on the side of the Earth facing the moon AND the side of the Earth directly opposite the moon.

In this idealized equilibrium model, these bulges of water stay aligned with the moon even as the earth rotates on its axis. Therefore, different places on the Earth's surface will move into and out of the high water created by the tide-generating forces. The two bulges stay aligned with the moon, and the earth rotates underneath them. We call these bulges created by the pull of the moon lunar tides.

The same phenomenon occurs with the sun's gravitational pull on the Earth. The resultant tides are called solar tides and are smaller than the lunar bulges – because the sun is much farther away from the Earth.

Monthly Tides – the Influence of the Sun and Moon

Relative positions of the sun, moon and Earth during spring and neap tides. During spring tides, the solar and lunar tides are additive creating the highest high tides and lowest low tides. During neap tides, the sun, Earth and moon form a right angle and create the lowest high tides and highest low tides.

The ocean responds to the Sun and the Moon's gravitational and centripetal forces at the same time. When the Earth, Moon, and Sun are all in a line the lunar and solar tides will add together creating a higher high tide and a lower low tide. This tide is very large due to constructive interference as the crests of the lunar and solar tides coincide. This is called a spring tide and it occurs at the new and full moons of each lunar month. **Spring tides** are therefore the Earths most extreme tides – have the greatest difference between high and low tides.

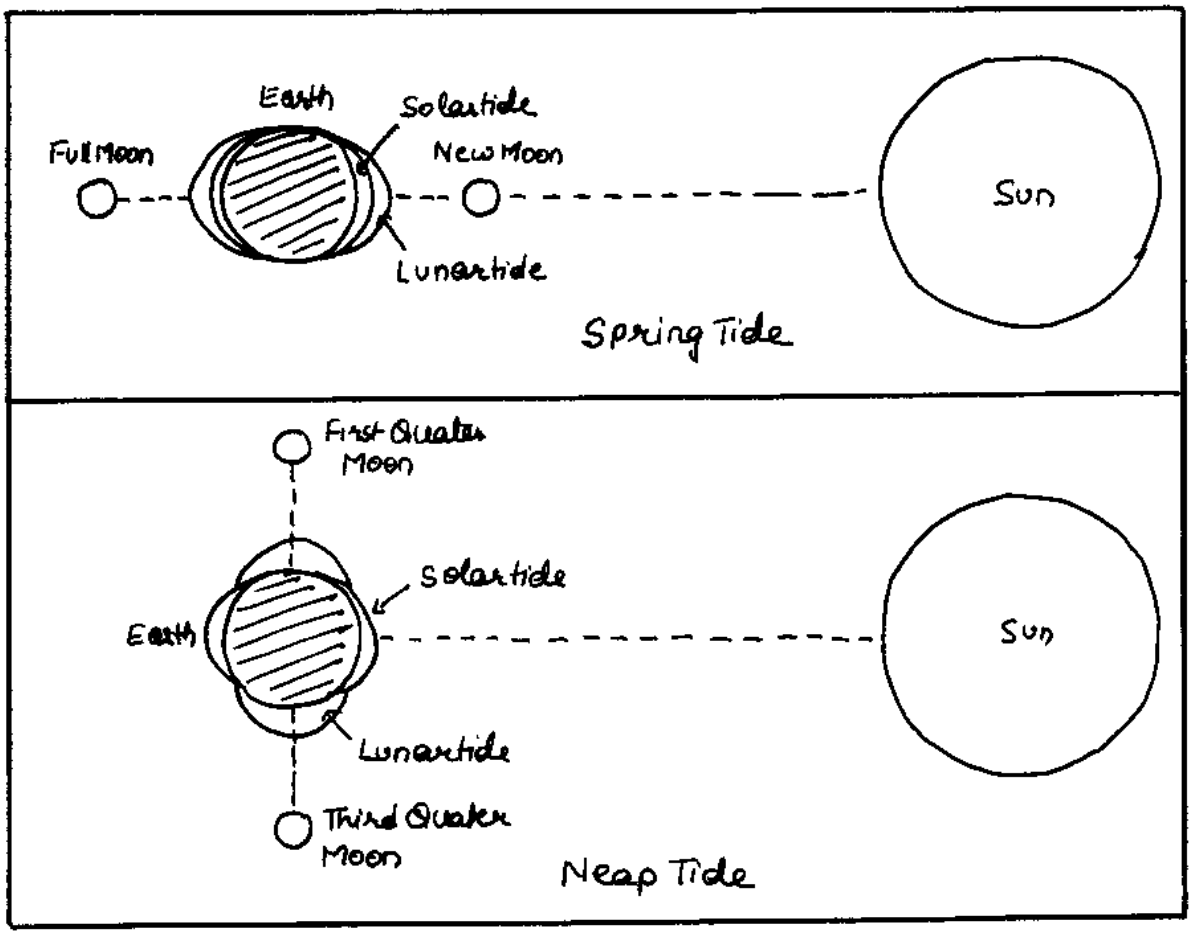
When the Earth, Moon and Sun form a right angle to one another, the solar tide will make the lunar tide smaller. This tide is smaller due to destructive interference as the two tides come together crest to trough. Because the lunar tide is bigger than the solar tide, the two will not completely cancel each other out. This tide is called a neap tide and occurs during the first and three-quarters phases of the moon. **Neap tides** are Earth's least extreme tides – have the least difference between high and low tide.

Complicating Factors

Two other factors also influence the size of tides: the declination of the moon and sun and the elliptical (oval) shape of the Earth and Moon's orbits. Each are discussed briefly here, and in more detail in your readings.

Declination. Declination is the angular distance of the sun and moon above or below Earth's equator. Over the course of a month, the moon moves from a position 28° above the equator to a position 28° below the equator. The tides caused by the moon follow this angle. Similarly, over the course of a year, the sun moves from a position 23° above the equator to a position 23° below the equator (this is why we have seasons). The solar tides also follow this movement. Watch the animation from your reading again to better understand this concept.

Elliptical orbits. The moon-earth and sun-earth orbits are not perfect circles; rather they are more elongate like ovals. This means that at some points during their orbits, the moon and sun



are closer to the Earth. This closeness will result in a more extreme tide because gravitational forces will increase.

The equilibrium theory of tides provides the foundation for us to understand tidal patterns. As we have shown, a purely ocean-covered Earth would experience tidal bulges due to the gravitational pulls of the Sun and Moon on its oceans. This gravitational force, combined with the centripetal force of the Moon-Earth and Sun-Earth orbits creates tidal bulges both on the side of the Earth facing the Moon and Sun and on the opposite side of the Earth.

The ocean water will always be pulled towards the sun and moon and the Earth rotates beneath these bulges. The bulges are not always centered at the equator because the angle of the Sun and Moon with the Earth's equator changes on a yearly (sun) and monthly (moon) timescale. With the equilibrium theory of tides we would expect any location on Earth's surface to have two high and two low tides each day as the location rotates into and out of the tidal bulges.

The most extreme tides are created when the sun, moon and Earth are in a straight line and the tidal bulges from the Sun and Moon add to one another. The least extreme tides occur when the sun and moon form a right angle with the earth. These are called spring and neap tides, respectively, and the Earth's ocean experiences two of each per month. The position of the sun and moon within their orbits will also affect the extremeness of the tide – when they are closer to the Earth more extreme tides will occur.

The Proxigean Spring Tide is a rare, unusually high tide. This very high tide occurs when the moon is both unusually close to the Earth (at its closest perigee, called the proxigee) and in the New Moon phase (when the Moon is between the Sun and the Earth). The proxigean spring tide occurs at most once every 1.5 years.

"The Moon follows an elliptical path around the Earth which has a perigee distance of 356,400 kilometers, which is about 92.7 percent of its mean distance. Because tidal forces vary as the third power of distance, this little 8 percent change translates into 25 percent increase in the tide-producing ability of the Moon upon the Earth. If the lunar perigee occurs when the Moon is between the Sun and the Earth, it produces unusually high Spring high tides. When it occurs on the opposite side from the Earth that where the Sun is located (during full moon) it produces unusually low, Neap Tides. The High, High Tide is called the Proxigean Spring Tide and it occurs not more than once every 1.5 years. Some occurrences are more favorable than others.

Dynamic Tidal Method

Since Newton's time, scientists have investigated tides by considering how the ocean responds to tide-generating forces in a model in which the waters of the ocean do not move- in other words, using the static or equilibrium model just discussed. A more realistic approach involves a dynamic rather than a static ocean. It also involves the consideration of the effects on tides of the size and shape of ocean basins of the Coriolis effects.

Based on our equilibrium theory of tides, ocean water always stayed in direct line with the sun and moon, meaning that in theory the waves traveled at the speed of rotation of the Earth. However, if we calculate the maximum speed tides can reach (being shallow water waves) we find that they travel slightly slower. This means that the bulge created by the gravitational pulls and centripetal force actually lags somewhat behind the moon as the moon orbits the earth. So when the moon is directly overhead a certain location, that location is not experiencing its high tide at that moment, it comes later.

Continents and the Coriolis Effect. Landmasses on Earth's surface prevent the Earth from simply rotating into and out of tidal bulges. When the tidal bulge "hits" the side of a continent some of its energy is dissipated, and some of the energy is reflected back into the ocean basin. This reflection, coupled with the Coriolis Effect causes water to be rotated around an ocean basin, much in the way water would rotate around a cup if you move the cup back and forth.

This oscillation of water around an ocean basin is called an amphidromic system and causes the high tide wave crests and low tide wave troughs to move around ocean basins in a clockwise (S. Hemisphere) or counterclockwise (N. Hemisphere) pattern. In the center of this rotating wave is a node where the tidal range is zero. These systems have been found to occur in all the ocean basins except the Southern Ocean, where tide crests and troughs simply move east to west.

The dynamic method treats tides as waves that can be separated mathematically into several components; each component can be treated individually. The tide-generating forces exerted by the Sun and the Moon can also be resolved into be related to the effects of the Sun or Moon and the interactions. Four principal constituents account for about 70% of the tidal range.

The tide for any location thus can be predicted by combining partial tides, just as complicated waves in a sea can be reconstructed by combining several simple wave trains. When predicting tides using the dynamic model, the first step is to analyze tidal, using computers. Today's more powerful computers permit the use of more sophisticated tidal models, resulting in more accurate predictions.

Tides are very-long-period waves. Neglecting Earth's curvature, we see that the two water bulges are the crests of a simple wave and the intervening low areas are its trough. Because of their immense size relative to the ocean basins, tides behave as shallow-water waves. Their wavelength, one-half of Earth's circumference, is about 20,000 kilometers.

The ocean basins average about 4 kilometers deep; thus, D/L = 4/20,000. This depth-to-wavelength ratio is much smaller than the limit of 1/20 for shallow-water waves. If tides were free waves, they would move at a speed of about 200 meters per second (720 kilometers per hour). In order to "Keep up with the Moon," however, the tides need to move around Earth in 24 hours, 50 minutes, meaning they must move at a speed of 1,600 kilometers per hour at the equator.

For tide waves to move as fast enough at the equator to keep up with the Moon, the ocean would need to be about 22 kilometers deep. Because it is much shallower, the tidal bulge move as forced waves the speed of which is determined by the movements of the Moon. The position of tidal bulges relative to the Moon is determined by a balance between the attraction of the Sun and Moon and frictional effects of the ocean bottom.

Because the tides behave as shallow-water waves, they are felt on the bottom of the deepest ocean basins. Twice a day, the deep-ocean bottom experiences strong currents.

Open-Ocean Tides

Because the continents separate the world ocean into three north-south basins, it is impossible for tides to move east west across Earth as forced waves. Only around Antarctica can tides move all the way around Earth. This restriction imposed by the continents adds to the complexity of open-ocean tides. In addition, because the waters in an open-ocean tide move over substantial distances for long times, the tide is modified by the Coriolis effect. The results is a swirling motion such as we might get if we swirled water in a round-bottomed cup.

Diurnal Tides. Diurnal means "daily" – this tidal pattern consists of one high tide and one low tide per lunar day (remember a lunar day is 24 hours 50 minutes). In North America, diurnal tides only occur in the Gulf of Mexico.

Semidiurnal Tides. This tidal pattern has two high tides and two low tides each lunar day. The height of the two high tides is the same, and the height of the two low tides is the same. Semidiurnal tides occur along the Atlantic Coast of the United States and southern Canada.

Mixed Tides. This tidal pattern also has two high tides and two low tides each day, but the heights of the two high tides and the two low tides are different. Mixed tides are the most common coastal tides and occur along the Pacific Coast, along the northern Atlantic Coast of Canada, in the Caribbean Sea and in some parts of the Gulf of Mexico.

Behavior here is typical of all three oceans. The southern basin, is open to its north and south and acts like a channel. The northern basin, however, is nearly closed off at its northern end. The tide in the Atlantic has some characteristic of a progressive wave and some characteristic of a standing wave.

After entering the South Atlantic from the Southern Ocean, the tide moves northward. In the South Atlantic, its course is relatively simple. As it progresses northward, the wave from the Antarctic tide interacts with the independent tide generated in the Atlantic. Each ocean basin has a distinct tide. Unlike tides in the South Atlantic basin, tides in the North Atlantic are altered by interactions with the complicated coastline. A standing wave is set up- not a simple wave, but rather a swirling, Coriolis-influenced wave in which the water surface rotates around a point called an amphidromic point. As the tide continues to move northward into the North Atlantic basin, the water is deflected to the right because of the Coriolis effect, causing a tilted water surface. As the wave continues to rotate in the basin, the water surface tilts in the opposite sense. The tilted wave surface rotates around the basin, once during each wave period. Near the center of such a system, called an amphidrome system (from the Greek amphi "around" and dromas "running"), is a point where the water level does not change, the amhphidromic point.

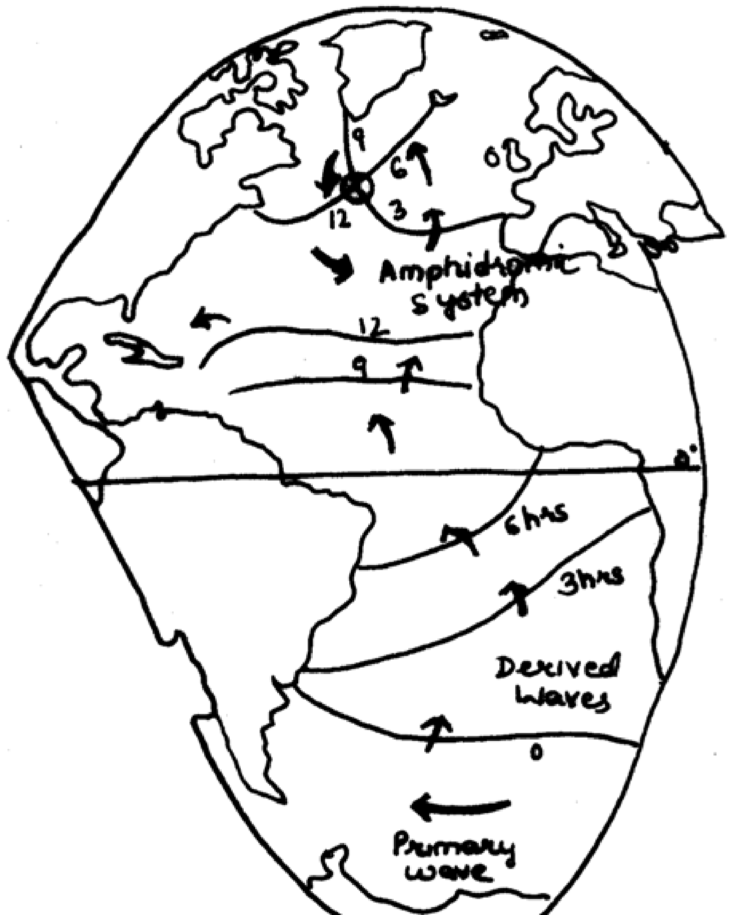
The movement of the high water associated with the principal lunar partial tide (the strongest of the tidal constituents) in the Atlantic. We see a large amphidrome system in the North Atlantic. Other, smaller amphidrome systems (not shown on the map) occur in the English Channel and the North Sea. Sites near an amphidromic point for one partial tide are, by definition, not affected by that partial tide but may be affected by other tidal constituents. For example, the water at the amphidromic point for a semidaily tide may well experience a daily tide.

Coastal-Ocean Tides Tides in coastal areas effect bays, river mouths, and harbors. The tide enters a bay as progressive wave and move inland. In many bays the wave is gradually damped (reduced in height) by friction and opposing river flow. **In some cases, however, the tide wave reaches the end of the bay and** is reflected back.

Tidal-Related Phenomena

Tidal currents moving rapidly into or out of enclosed areas can create whirlpools. One of the largest whirlpools in the world, sometimes referred to as Old Sow, is located near Eastport, Maine.

The large scale movement of the ocean in response to tidal forces sets up some interesting events in bays and river mouths. This is because the large amount of energy within a tide becomes contained and often amplified when confined to a very small area. These phenomena include extreme tidal ranges, tidal bores, tidal currents and whirlpools.



Major Tidal Components

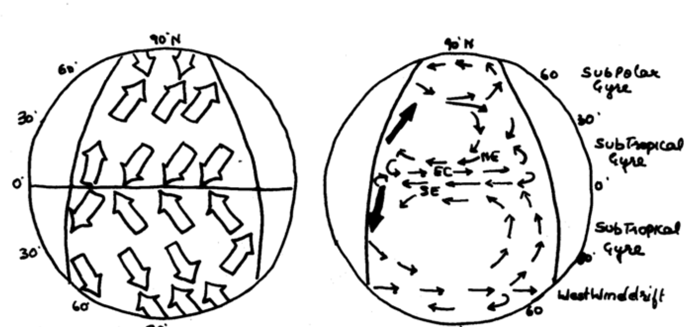
Tides are used to generate electrical power in a few favorable coastal locations, primarily in France, Russia, Canada and China. Three factors limit the usefulness of tidal power: tidal ranges, topography, and timing. Even with special turbines designed to work on the ebb and flood tidal range must exceed 5 meters to be useful. Such ranges are rare, and the range for most coasts is only about 2 meters. Furthermore, many potential sites having sufficiently large tidal range are in remote areas. It would be expensive to transmit any power generated in these remote areas to urban industrial centers.

Topography is a limiting factor because most tidal power schemes involve one or more dams. In a typical system, gates in the dam are opened when the tide is high and then closed. Keeping the water behind the dam at high-tide level. When the water level outside the basin has dropped sufficiently, the dam gates are opened and water in the basin allowed flowing out through turbines, thereby generating power.

Finally, there is a timing problem. Tidal power generation is tied to tidal cycle, which usually does not coincide with periods of peak power demand. The tidal power plant on the Rance estuary in France, for instance, produces about four times as much power during spring tides as during neap tides. Several ideas have been advanced to solve this problem. One is network of power lines that allow the electricity to be used somewhere, regardless of when it is generated. Another uses multiple dams to store water at high levels, so that one basin serves as reservoir and another as collector. Finally, there is the option of generating electricity and storing it in some way for later use.

OCEANIC CURRENTS

Currents – large scale water movements – occur everywhere in the ocean, but on the surface and far below it. There are two entirely different ocean current system. Subsurface currents, driven by chilled water sinking in the polar and subpolar oceans, are less familiar. These deep water masses spread out to flow through all the oceans and eventually return to the surface to be warmed by incoming heat from the sun.

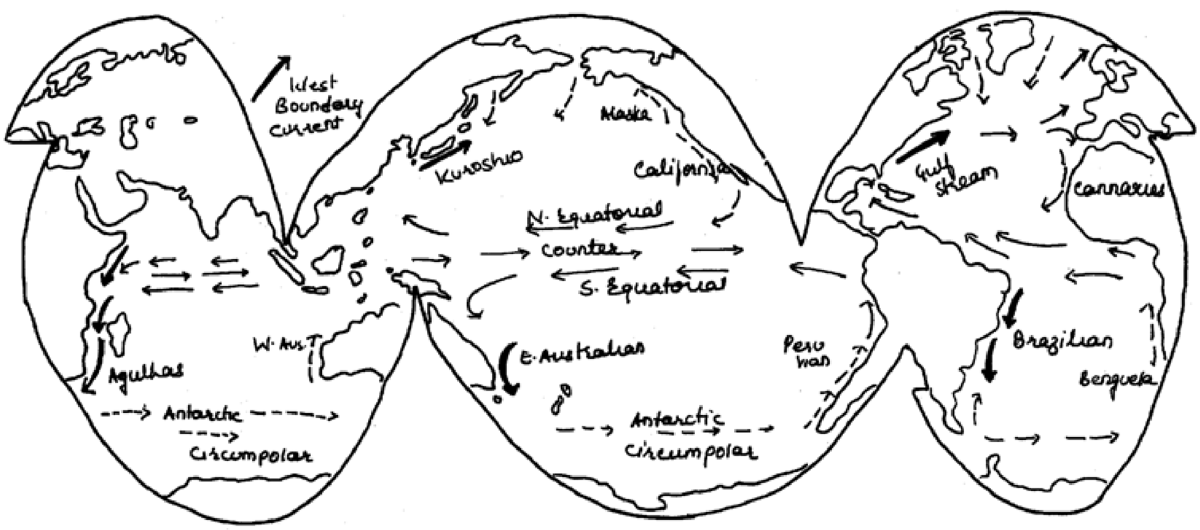


Generalized relation between wind & currents

Both surface and subsurface currents are caused by the unequal heating of earth's surface. Ocean currents of both types transport heat from the tropics towards the poles, partially equalizing surface temperature over earth. They also play an important role in controlling climate in long term.

Open Ocean surface currents

The open ocean currents are similar in the three major ocean basins and closely resemble surface wind patterns. The equatorial ocean is dominated by westerly flowing waters in north and south equatorial currents, driven primarily by trade winds.Between them is the narrow, eastwardly flowing equatorial counter currents which occurs in a region of light and variable winds called the doldrums. Across the bottom of the southern hemisphere is the eastward flowing Antarctic circum polar current and across the north of northern hemisphere are the eastward flowing North Pacific and North Atlantic currents. The combination of these flow forms a nearly closed current system.



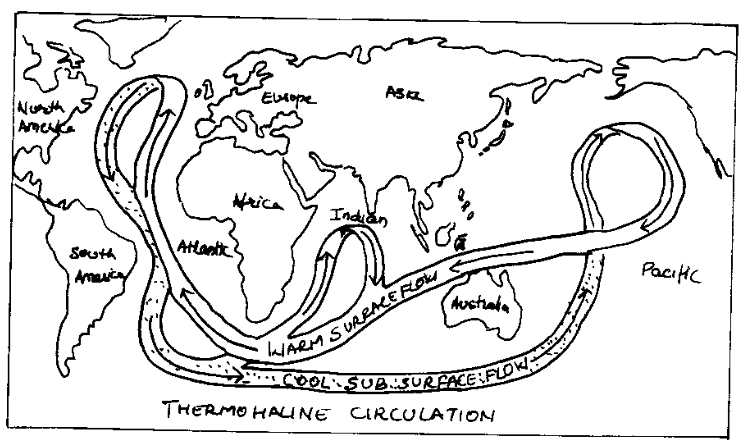
Gyres

The east-west elongated gyre are centred in the sub tropical regions. In the subpolar and polar regions of all the ocean basins, there are also smaller current gyres. The direction of circulation in these high latitude gyres is opposite to that of subtropical gyres – counter clockwise in northern hemisphere. Because there are no land barriers currents flow uninterrupted around Antarctica in the Antarctic circum polar current. Ekman's spiral effect reveals the correlation between surface winds and surface ocean currents. The process begins when wind blows across water and drag on the surface. This surface drag set in motion the thin top layer, which in turn drags on thin layer beneath, setting it in motion, which continues downwards. Such transfers of momentum to successive deeper layers are insufficient, however and therefore energy is lost in the process. Surface currents move at about 2 percent of the speed of the wind that caused them. Owing to the rotation of earth surface waters are deflected to right of the wind in northern hemisphere. This manifestation was first studied by Fridhof Nansen. The change in current direction and speed with increasing depth forms a spiral when viewed from above – Ekman spiral. Water column stability controls the depths to which wind effects penetrate, with a strong pycnocline inhibiting transfer of momentum from the surface to water below the pycnocline. The limit for wind effect is usually taken to be the depth at which the direction of subsurface current is exactly opposite the direction of surface current. A current driven by a strong wind may be as deep as 100 m below the surface. Practically wind driven water movements do not penetrate the pycnocline. The deflection is thus less than predicted in theoretical case referred as Ekman's Transport.

Prevailing wind move surface waters towards subtropical regions, both from tropical areas and high latitude areas – as Ekman's transport. As a result zones of convergence develops where surface water accumulate at the subtropical gyres. This converge leads to water piling which forms slope and the surface layer thickens. The opposite effect of Ekman's pumping is divergence, wind blow surface water away from an area. In divergence subsurface water move upwards to replace waters of the surface, causing the surface layer to be thinner than normal. A prominent divergence occurs around Antarctica. It is also at subpolar gyres and at equator. As a result of convergences and divergences, the ocean surface has a subtle topography – i.e. low hills in the areas of convergence and shallow valleys at the area of divergence. The difference in height between the mid latitude convergences on the western side of the ocean basins and the divergence surrounding Antarctica is about 2 m. This difference occurs over a distance of about half earth's circumference. Thus there are very gentle slopes compared with those on land. Water responds to the slopes of ocean surface. The Coriolis effects deflects it to the right. The deflection continues until the water follows a path that allows it to flow downhill just enough to keep moving. Most of its motion parallels the side of the belt. This results in the development of geo strophic current. Boundary currents flow close to and parallel to the continental margins usually north-south and dominate surface currents patterns on the world oceans. The two principal types of boundary currents –western boundary current are strongest. They are especially conspicuous in northern hemisphere as gulf stream and Kuroshio current. These are narrow of less than 100 km in width. These high velocity currents (100-1000 km/day) and are deep enough to flow on shelf, they thus extend upto continental margins. Eastern boundary currents are much weaker than western. The water moves quite slowly at 10-100 km/day. The fronts are more diffuse and complicated. Eastern boundary currents are relatively shallow and therefore can readily flow over continental shelves. Boundary currents are more changeable than open currents, mainly because of many irregularities in continental coastlines cause the direction of flow of boundary currents to change frequently.

THERMOHALINE CIRCULATION

As opposed to wind-driven currents and tides (which are due to the gravity of moon and sun), the thermohaline circulation is that part of the ocean circulation which is driven by density differences. Sea water density depends on temperature and salinity, hence the name thermohaline. The salinity and temperature differences arise from heating/cooling at the sea surface and from the surface freshwater fluxes (evaporation and sea ice formation enhance salinity; precipitation, runoff and ice-melt decrease salinity). Heat sources at the ocean bottom play a minor role.



In contrast to the wind-driven currents, the THC is not confined to surface waters but can be regarded as a big overturning of the world ocean, from top to bottom. The thermohaline circulation consists of:

Deep water formation: the sinking of water masses, closely associated with (but not to be confused with) convection, which is a vertical mixing process,). Deep water formation takes place in a few localized areas: the Greenland-Norwegian Sea, the Labrador Sea, the Mediterranean Sea, the Weddell Sea, the Ross Sea.

Spreading of deep waters (e.g., North Atlantic Deep Water, NADW, and Antarctic Bottom Water, AABW), mainly as deep western boundary currents (DWBC).

Upwelling of deep waters: this is not as localised and difficult to observe. It is thought to take place mainly in the Antarctic Circumpolar Current region, possibly aided by the wind (Ekman divergence).

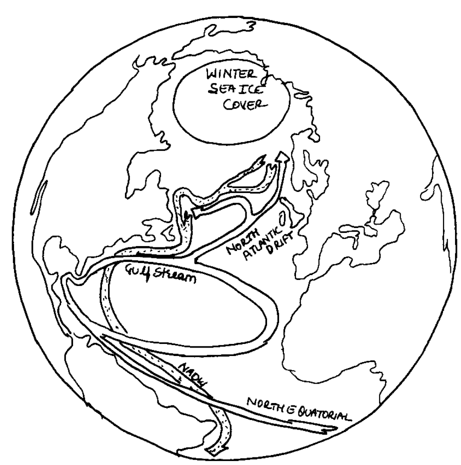
Near-surface currents: these are required to close the flow. In the Atlantic, the surface currents compensating the outflow of NADW range from the Benguela Current off South Africa via Gulf Stream and North Atlantic Current into the Nordic Seas off Scandinavia . (Note that the Gulf Stream is primarily a wind-driven current, as part of the subtropical gyre circulation. The thermohaline circulation contributes only roughly 20% to the Gulf Stream flow.)

This highly simplified cartoon of Atlantic currents shows warmer surface currents and cold north Atlantic Deep Water (NADW,). The thermohaline circulation heats the North Atlantic and Northern Europe. It extends right up to the Greenland and Norwegian Seas, pushing back the winter sea ice margin.

What drives the THC

The short answer would be: **high-latitude cooling**. In cold regions the highest surface water densities are reached, this causes convective mixing and sinking of deep water, which drives the circulation.

Reality is more complex. Pressure gradients at depth, resulting from density gradients in the overlying waters, are the driving force in the equations of motion. As the density forcing occurs at the surface , a subtle question is why the density differences and the circulation affect the whole ocean depth and are not confined to a near-surface layer. showed that a deep circulation only arises when heating (buoyancy source) is at depth and cooling at the surface. The reason that there is a deep circulation after all is turbulent mixing, which brings down the heat on a time scale of ~1000



years. It has been shown that in the long-term equilibrium the strength of the thermohaline circulation in models depends on the turbulent mixing coefficient , and that the energy required for this turbulent mixing comes to a large extent from the moon via tidal currents .

As mentioned above, highest surface densities in the world ocean are reached where water is very cold, while lower densities are found in the saltier but warmer tropical and subtropical areas. In this sense the THC is thermally driven. Nevertheless, the influence of salinity is important and is what causes the non-linearity of the system. This was first described in a classic paper by with the help of a simple box model. Salinity is involved in a positive feedback: higher salinity in the deep water formation area enhances the circulation, and the circulation in turn transports higher salinity waters into the deep water formation regions (which tend to be regions of net precipitation, i.e., freshwater would accumulate and surface salinity would drop if the circulation stopped). Put simply, in Stommel's model the high-latitude salinity increases linearly with the flow, and the flow increases linearly with high-latitude salinity, which combined gives a quadratic (i.e., non-linear) equation. This leads to two possible equilibrium states, the system is bistable in a certain parameter range. This becomes more than an academic point as complex circulation models behave in the same way, and as the present North Atlantic in many models is in the bistable regime . The first coupled climate model to show these two equilibria (discovered quite by accident) is the one by .

The THC in anthropogenic global warming

Global warming can affect the THC in two ways: surface warming and surface freshening, both reducing the density of high-latitude surface waters and thus inhibiting deep water formation. was the first to warn that this could lead to a breakdown of the THC and to abrupt climate change. Subsequently, showed that this could indeed occur for strong global warming (i.e., for a quadrupling, but not for a doubling of CO_2). In these scenarios there was no surface cooling, as the high CO_2 levels more than compensated for the reduced ocean heat transport. The possibility of a real cooling (both a relative cooling, i.e. a drop back to roughly pre-industrial temperatures after an initial warming phase, and in the longer run an absolute cooling below preindustrial values) as a result of anthropogenic warming was first demonstrated in a sensitivity study by .

Significant absolute cooling can arise after CO2 levels decline, but the THC remains switched off after its collapse is triggered in a rapid warming phase.

A THC collapse is now widely discussed as one of a number of "low probability - high impact" risks associated with global warming. More likely than a breakdown of the THC, which only occurs in very pessimistic scenarios, is a weakening of the THC by 20-50%, as simulated by many coupled climate models

Cold water, in general, is denser than warm water. Likewise, water with a high salinity is denser than water that contains less salt. Surface ocean currents are primarily driven by winds. Deep ocean currents, on the other hand, are mainly a result of density differences. The thermohaline circulation, often referred to as the ocean's "conveyor belt", links major surface and deep water currents in the Atlantic, Indian, Pacific, and Southern Oceans. Multiple mechanisms conspire to increase the density of surface waters at high latitudes. Cold winds blowing over the oceans chill the waters beneath them. These winds also increase evaporation rates, further removing heat from the water. These chilled waters have increased densities, and thus tend to sink. Formation of sea ice also helps to increase the density of water near Earth's poles. As seawater freezes, salt is forced out of the ice in a process called "brine exclusion". The ice is essentially not salty. The excluded salt increases the salinity of the cold water immediately below the ice, making it denser still. The salty, cold water near the poles sinks toward the ocean floor.

Just as rivers on land flow downhill towards the sea, deep density-driven currents in the oceans move along submarine valleys towards the deepest parts of the ocean. The cold, salty waters that drive the thermohaline circulation form in the Arctic Ocean, the North Atlantic, and the Southern Ocean. The shallow ocean floor along the Bering Straight prevents deep currents from flowing out of the Arctic Ocean into the Pacific. Dense water on the floor of the North Atlantic moves southward, eventually joining the sinking waters of Southern Ocean in the far South Atlantic. Once again, a shallow section of the ocean floor blocks the flow from moving into the Pacific. In this case the Drake Passage, between the Antarctic Peninsula and the southern tip of South America, prevents the current from flowing westward. So the thermohaline circulation turns to the east. Here the current splits; some flows northward along the east coast of Africa into the

Indian Ocean, while the rest continues eastward along the southern coast of Australia and finally, veering northward, makes it into the vast Pacific basin.

At this point the two branches of the thermohaline circulation finally begin to mix with the lighter, warmer waters above and work their way back to the surface. Scientists estimate that the trip from the North Atlantic to the deep water upwelling sites in the Pacific takes about 1,600 years. To balance the flow of deep water into the Indian and Pacific basins, surface water must flow back out. Warm surface waters from the Pacific flow through the Indonesian Archipelago into the Indian Ocean, where they join with other currents that have risen from the depths. This combined flow works its way westward around the southern tip of Africa into the South Atlantic. Next, the surface flow moves northward through the Atlantic. Aided by a nudge from the warm Gulf Stream surface current, this water makes its way once again to the extreme North Atlantic, where the cycle begins again. This global circulation pattern mixes the waters of the world's oceans, turning the ocean reservoirs into a single, vast, interconnected system.

Thermohaline circulation plays an important role in supplying heat to the polar regions. Therefore, it influences the rate of sea ice formation near the poles, which in turn affects other aspects of the climate system (such as the albedo, and thus solar heating, at high latitudes).

Water's long trip through the ocean's depths on the great ocean conveyor belt, far from surface water influences and contact with the atmosphere, contributes to the a lag time between climate forcings and our planet's reactions to them. Heat and dissolved carbon dioxide, carried to the oceans depths by the thermohaline circulation, may remain "buried" in the abyss for centuries. This "burial" may forestall initial effects of global climate change; but like zombies in a horror flick, may come back to haunt us much later when they arise from the depths.