Fundamentals of Physical Oceanography

for

MS 201: Introduction to Ocean Resources Management

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Introduction

Marine is all about water & the sea and whatever marine science you take, you need to know about water. Although most of us know that water is essential to all life, the full range of water's unique and anomalous properties is less known to many people. Do you know the following as a Marine Scientist?

- Water helps to create and control climate and weather
- Water influences the formation and modification of the land and sea floor
- Water enables essential chemicals to be transported to and within living organisms
- Water controls many features of our physical environment such as rain, snow, and the waves on oceans and lake
- Water underlies the functioning of many aids to human society, ranging from cooling systems for automobile engines and power plants to ice cubes that keep drinks cold in summer

Origin of Water

According to early history of the Earth, it was hot and mostly molten. Heavy elements such as iron, nickel etc migrated towards the Earth's centre while lighter elements, such as silicon, aluminium, etc moved upward towards the surface. The lightest elements, which include H_2 and O_2, and compound of light elements, CO_2, CH_4 and water vapour, migrated upwards to form an atmosphere. The lightest gaseous elements, H and He, were largely lost to space. After the Earth cooled, the crust solidified and water vapour in the atmosphere condensed into liquid water. In the billions of years the Earth's water first condensed, the temperature of the atmosphere has changed relatively little. Hence, liquid, and solid water probably were present throughout that period in oceans and ice sheets.

How can water contribute to us?

Covering more than 70 % of the Earth's surface, the world's oceans have an enormous effect on climate as they interact with the atmosphere and the land. We are used to seeing water in liquid form or in solid form as ice, but it is also present in the air around us as an invisible gas called water vapour. In short, water is an essential element in our weather and exists in many forms, from invisible water vapour to solid lumps of ice.

Around 90 % of the water vapour in the air comes from the oceans. The water changes from a liquid to a gas (water vapour) through a process called evaporation, which occurs when the Sun heats the water. Air can hold only a certain amount of water vapour. This amount varies according to the temperature of the air: the warmer the air is, the more water vapour it can hold. When air can hold no more water vapour, it is said to have reached saturation point or is saturated. The water in the air will then begin to condense, that is, form a liquid.

When condensation takes place above the surface of the Earth, clouds form. If the condensation takes place at a temperature of more than 0 ºC, water droplets condense as liquid. If the condensation occurs at a lower temperature, then the water vapour may turn, or sublimate, into ice crystals. Hundreds of millions of crystals and droplets together form a cloud.

A variety of processes can cause air to rise and form clouds of all shapes and sizes. Varying greatly in form and colours, clouds are classified according to their shape and their height above the ground. Rain, snow and other forms of precipitation result from the build-up of water vapour or ice crystals within a cloud.

An air mass will continue to rise as long as its temperature is higher than that of the surrounding air. If this situation persists as the air mass rises, conditions are said to be unstable. If, however, an air mass quickly reaches the temperature of the surrounding air [and therefore stops rising], conditions are said to be stable.

As long as condensation is not taking place, rising air gradually cools at a rate of 9.8 ºC per km. Therefore, if we know the temperature of a rising air mass at ground level and the temperature at different level of the troposphere, we can calculate how high the air will rise. As water vapour in a rising air mass condenses, it releases latent heat. This warms the air mass and increases atmospheric instability. Latent heat is a highly significant factor in the development of thunderstorms. Everyday, about 40 000 thunder storms occur throughout the world, with the most frequent storms brewing in equatorial regions.
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Major Role of the Ocean

Because of the remarkable properties of ocean water, the climate everywhere on Earth is extremely mild compared to that of our planetary neighbours. Interactions between the ocean surface waters and atmosphere dominate the Earth's climate. Because of turbulence and mixing that are caused by wind, waves, density variations, surface currents, these interactive surface waters extend to depths of several hundreds metres.

The surface waters in the tropics tend to be warm and salty, due to heating and evaporation by the intense sunlight in these latitudes. In temperate latitudes, the surface waters vary with seasons, but are always warmer and lighter than the deep waters below. In the polar region, the surface waters are cold. During the winter, they cool still further, becoming sufficiently dense to sink and mix with the deeper waters.

The polar water's influence on the world's climate is much smaller than that of the temperate and tropical waters for several reasons. First, the tropical and temperate regions encompass a much greater fraction of the ocean surface, since the world is much fatter at the equator than it is at higher latitudes. Second, large regions of polar waters are covered by ice, which insulates them from the atmosphere and prevents their influencing the climate. Third, the processes that exchange heat between ocean and atmosphere operate much more slowly when the water is cold.

Sources and Sinks of Chemical dissolved in Sea Water

Seawater is a solution of many different chemical compounds: positively charged ions, negatively charged ions, and both organic and inorganic compounds that are not ionised.

Continental rocks are weathered and transported to the oceans both as particles and as dissolved ions. The particles are deposited as ocean sediment. Many dissolved elements are used in biological processes. [In short, ocean's saltiness is basically resulted from the ability of rain, groundwater, or crashing surf to dissolve crustal rock, recognising the effectiveness of water as a solvent]. The concentration of each element in sea water is determined by the rate of at which it enters the ocean water and the rate at which it is removed. If the rate of input exceeds the rate of removal, the concentration will rise, and vice versa. These processes have been going on for billions of years and they are believed to be at an approximate *steady state*. The effectiveness of removal is expressed by the *residence time*, which is a measure of the mean length of time an atom of the element spends in the oceans before being removed to the sediment.

Sea Water Concentration of Several Elements			
Element	Crustal Abundance [%]	Oceanic Residence Time [y]	Concentration [mgl^{-1}]
Na	2.4	60 000 000	10 770
Cl	0.013	80 000 000	19 500
Mg	2.3	10 000 000	1 290
K	2.1	6 000 000	380
S (SO_4)	0.026	9 000 000	905
Ca	4.1	1 000 000	412
Mn	0.5	7 000	0.0002
Pb	0.001	400	0.0000005
Fe	2.4	100	0.002
Al	6.0	100	0.002

It is believed that the proportion of each element in continental rocks, sediment, subducted sediments and the atmosphere has remained approximately constant for more than 500 million years. Hence, the concentrations of dissolved constituents in sea water have similarly remained almost constant.

Seawater composition is constant when considered as an annual and regional average. Marine life prospers only when important nutrient elements are above critical concentrations. Thus, life in the ocean has evolved dependent on the constancy of seawater composition.

Salinity

Many of the properties of water are modified by the presence of dissolved salts. The total quantity of dissolved salts in seawater is expressed as *salinity.* Until the early 1980s, salinity was expressed in grams of dissolved salts per kilogram or water or in parts per thousands, for which the symbol is ‰. Open ocean sea seawater contains about 35 grams of dissolved salts per kilogram of seawater, or has a salinity of 35 ‰.

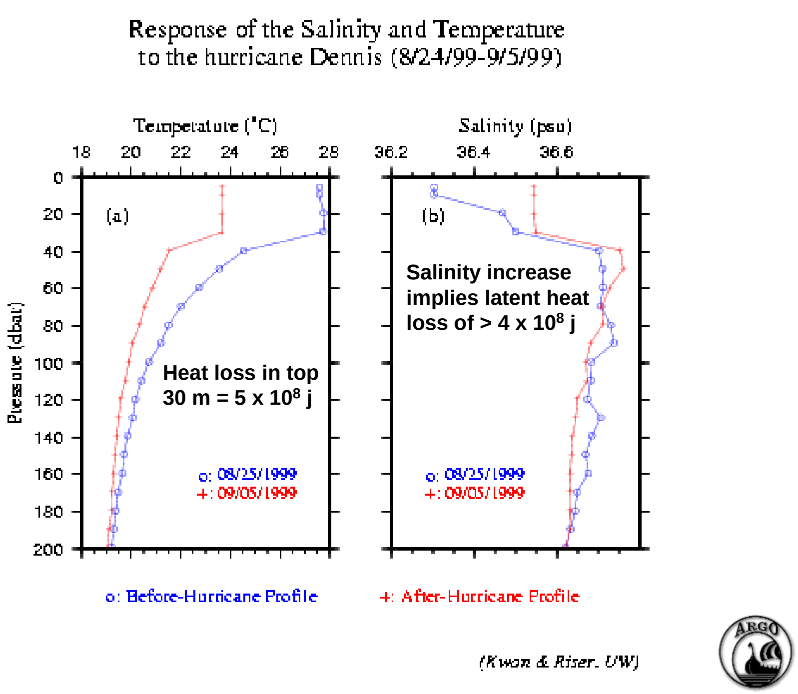
Originally, salinity was measured by evaporating the water and weighing the salt residue. This tedious procedure was inaccurate because some dissolved ions such as bromide and iodide decomposed in the process and the elements were lost as gases. Various other methods have been used to determine salinity, including measurements of the chloride concentration (which is closely related to total dissolved solids) because seawater follows the principle of constant proportions.

Until the early 1980s, the comparison was made with a standard seawater whose salinity was determined precisely by a reference laboratory in Copenhagen, Denmark and later in England. This method worked well but became very difficult as oceanography grew and the reference laboratory had to supply standard water samples to hundreds of laboratories world wide. For this reason, and to improve the precision of salinity measurements, salinity has been redefined as a ratio of the electrical conductivity of a standard concentration of potassium chloride solution. The most precise and widely used method of salinity determination is measurement of electrical conductivity. Salinity is measured by comparing the conductivity of two solutions, one of which has a precisely known salinity.

Because salinity is now defined as a ratio of electrical conductivities, it is no longer measured in parts per thousand but in practical salinity units [psu]. The average seawater is now expressed as 35 without the ‰ symbol. Seawater with a salinity of 35 psu does have a concentration of almost exactly 35 grams of dissolved salt per kilogram.

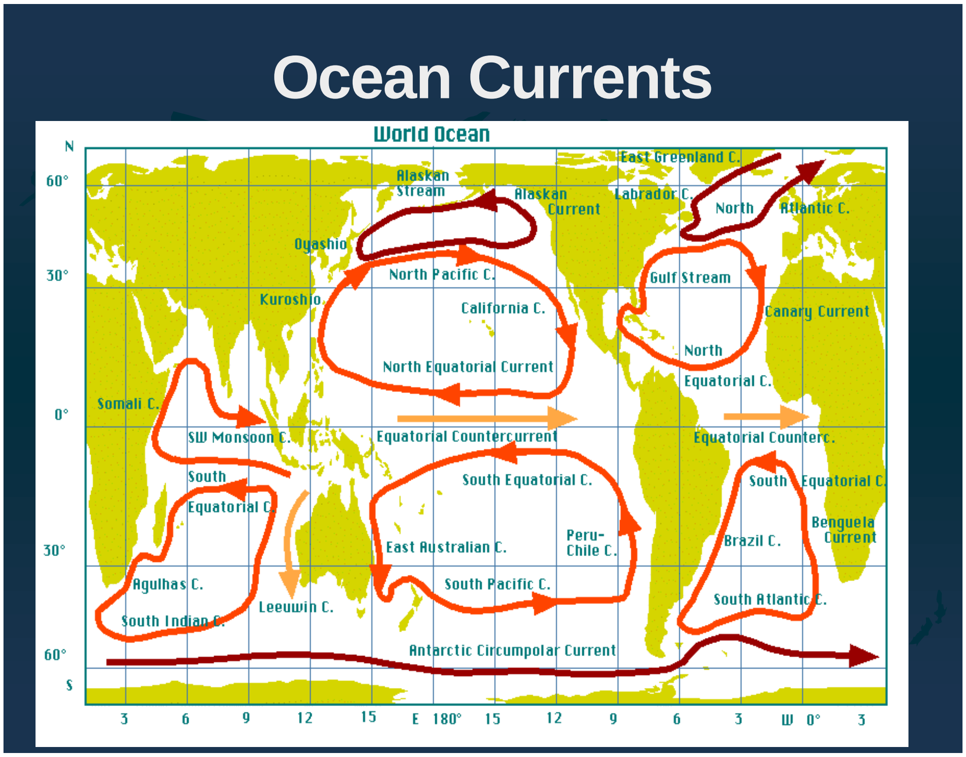
Many water movements in the oceans are driven by differences in density. Solid objects that have higher density than water sink and ones that have lower density rise and float. Liquid water can also rise or sink if its density is different from that of the surrounding water. Water density is controlled by changes in pressure, temperature, and concentration of dissolved constituents (salinity).

Here is an interesting story, we do not want hurricanes or tropical cyclones, but they are not as bad as you usually think if you look at it from the science point of view.



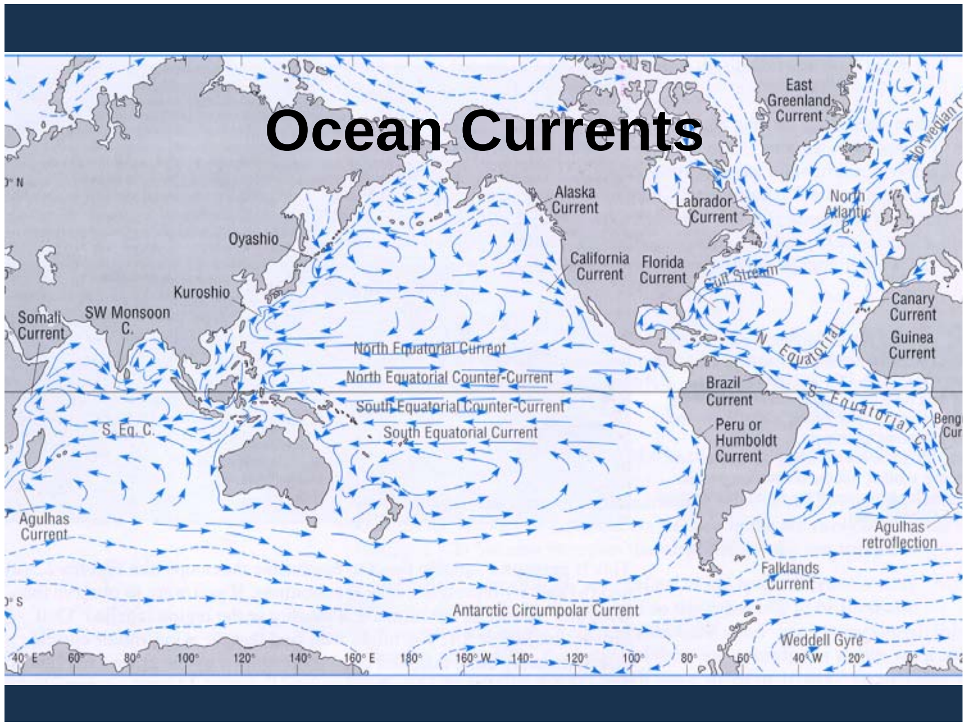
Water Circulation

One consequence of the intimate connection between ocean and atmosphere is that we do not know which drives the other. The wind and weather are driven by the heat that the atmosphere receives from the Earth (mostly the ocean) beneath it. Some of this energy is returned to the ocean as the winds drive currents along the ocean surface. The wind and weather also produce the denser water that sinks and flows through the dark deep regions of the ocean. Because the ocean is so massive, however, its motions are much steadier and more predictable than those of the atmosphere. The following figure is the main pattern of the world ocean and the names of major currents and gyres formation in the oceans.

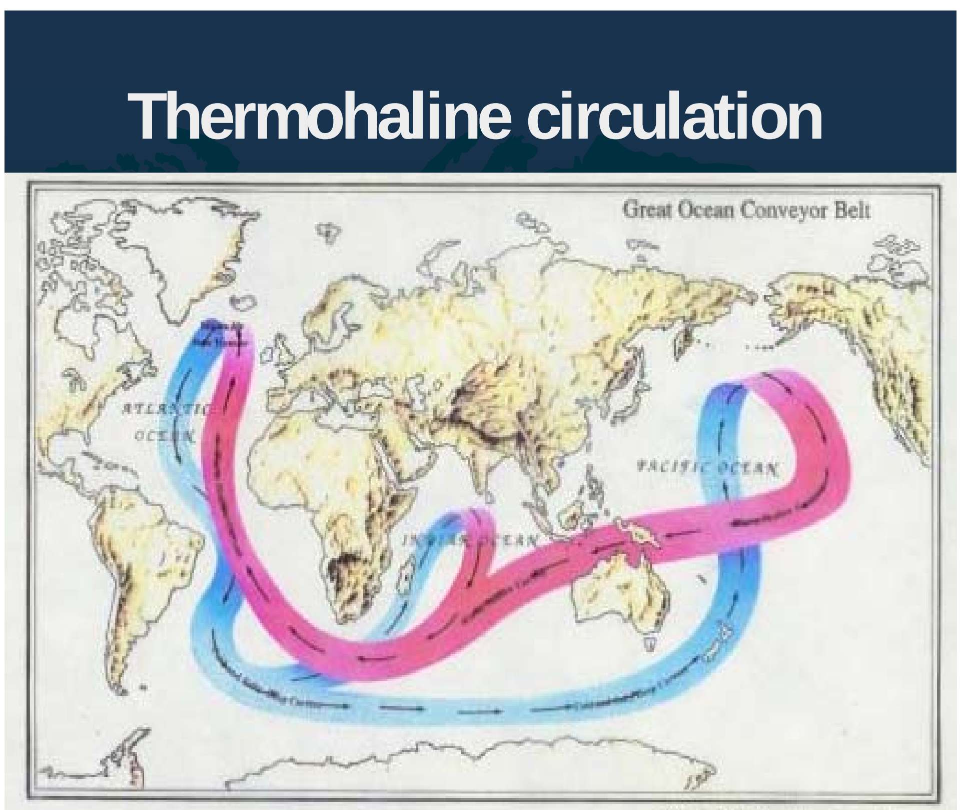


The surface currents are subject to the forceful but sometimes capricious influences of the wind and weather, whereas the deeper currents are not. The surface currents tend to be swifter, but the deeper currents are more voluminous. Surface water is less dense than the water beneath it. Within the deeper water, the denser water sinks or slides downward and buoys the less dense water upward as it goes. Therefore, an understanding of the factors that influence the density of sea water is essential for understanding both the difference between the surface and deep waters, and the motions of the various deeper water masses as well.

Slightly more detailed pattern of currents of the world ocean is given in the next figure. If you look at both of them together, they will look the same.



Regarding the recent Climate Change phenomenon, there are reasons to believe the following pattern of world current, it is also called "*Conveyer Belt Theory*" is responsible. Density driven current is usually known as thermohaline currents [another is wind driven currents]. Switching On-Off of Conveyer Belt theory will be discussed separately to stimulate your interest in Oceanography.



Conclusions
In most of the ocean, temperature and salinity are of approximately equal importance in determining the density of ocean waters. However, their relative importance varies with location and depth. For example, temperature changes are more important to density variations in the tropical water column whereas salinity is more important in some high latitude regions.

In short, salinity and temperature are the major controlling parameters of the seawater density that in turn controls the water movement in the ocean. As mentioned earlier, ocean circulation is the major contributor to the climate. From these arguments, it can simply be inferred that salinity and temperature of the ocean along the depth at a particular place and at different locations are vitally important to understand the issue of climate change.

It is to be noted for your future research project in marine science, these salinity and temperature data of the area of interest are readily available on ARGO Floats website for free.

Brief History of Tides
In Europe, the ancients knew hardly anything about tides, because there are virtually none in the Mediterranean Sea. The first Greek to report tides was the explorer *Pytheas*, who explored the North Atlantic in 270 BC and he also produced the correct explanation for them. Even so, when *Julius Caesar* invaded Britain over two centuries later, he lost many ships because he did not beach them high enough. It did not occur to him to take tides into account. In fact, the history of observing the sea level can be traced back to 2000 BC. The earliest reference to rising and ebbing of sea level is found in an ancient Indian Book *Sumevada* (2000-1600 BC), but the connection between the Moon and tides was noted by Greeks in the fourth century BC.

People have observed the rise and fall of tides since they first inhabited the coastal regions of the continents. But it was not until *Sir Isaac Newton* (1642-1727) developed his universal law of gravitation that the tides could be explained adequately. In fact, *Pytheas* was 2000 years ahead of his time, for it took that long for tides to be attributed [by Newton] properly to the influence of the Moon. Until Newton's time, most scholars refused to believe that the Moon could have any effect on the ocean, especially because tide took place when the Moon was not even visible in the sky. The explanation of and attempt at tidal prediction was one of people's earliest scientific ventures. Many of the theories and techniques of tidal predictions were developed in the eighteenth and nineteenth centuries. Techniques for tidal prediction have been improved, mainly through the use of high speed computers.

Tides
One of the most fascinating aspects of the ocean is the tide:- the slow, up and down movement of sea level that occurs each day. Even more baffling is the explanation of this phenomenon.

Generally, tides are most commonly seen as a regular rise and fall of *Sea Level* at the coast. This rise and fall also occurs offshore and in the deep ocean. Tides also produce *tidal currents* [*tidal stream*] which are required to move water from one place to another to accommodate the sea level changes.

> Tides are generated by the gravitational attraction of the Moon and Sun on the Earth. This attraction affects water, solid Earth and the atmosphere, but the results on the last two cannot be observed by the unaided eye. The tides are a consequence of the simultaneous action of the Moon's, Sun's and Earth's gravitational forces, and the revolution about one another of the Earth and Moon and the Earth and Sun.

In principle, the other planets in the solar system also exert tidal forces on the earth but their values are so small compared with those of the Moon and Sun that they are quite negligible. Because the relative motions of the Earth, Sun and Moon are complicated, it follows that their influence on tidal events results in an equally complex pattern.

Generally, we may define the ocean tides as the *response of the ocean to the periodic fluctuations in the tide-generating forces of the Moon and the Sun*. According to Albert Defant: "*The tides are the heartbeat of the Ocean, a pulse that can be felt all over the world*."

Tide Generating Forces
The magnitude of the tide-generating force is only of the order of 10^{-7} times due to the Earth's gravity but as it is a body force, acting on the total mass of the ocean, and has *horizontal components*, it is significant.

It should be noted that tidal movements occur in the atmosphere and in the solid earth as well as in the sea but will only be concerned with the oceanic tides.

Tides are generated basically because of two forces: the *gravitational force* of attraction from the Moon [and Sun], and the *centrifugal force* [meaning a force 'away from the centre'] due to the mutual rotation of the Moon and the Earth, around their common centre of masses.

If the acceleration due to gravity, g = 9.8 m s^{-2}, E, is mass of the Earth, M, is mass of the Moon, e, is radius of the Earth and r, is the distance between Earth and the Moon, the Differential Force which pushes water to create tide can be given as follows:

$$Differential\ Force = 2g\,\frac{M}{E}\,\frac{e^3}{r^3}$$

Similar expression may be obtained for the tidal attractive force exerted by the Sun. Here it is to be noted that the ratio of the masses of Sun and Moon is 27,100,000 to 1. But the mean distances of Sun and Moon from the Earth are in the ratio of 389:1. In the above expression of differential force notes that the distance is cubed and this more than counterbalances the greater mass of the sun.

The Solar tidal forces are less than the Lunar tidal forces in the ratio:

$$\frac{27100000}{(389)^3} = \frac{27100000}{58863869} = 0.46$$

The Solar tidal forces (S) are slightly less than half the Lunar tidal forces (L) [i.e. S = 0.46 L].

Spring and Neap Tides

The lunar and solar ellipsoids [rugby balls] are independent and not normally lined up. When they do line up [when the Earth, Moon and Sun are all in line] the two tidal effects combine and very large or *spring tides* will be obtained.

When the Moon is in *quadrature*, so that the Earth-Moon line is perpendicular to the Earth-Sun line, the tidal effects are subtractive, and the smallest tidal range, or *neap tides* will be obtained.

Spring-Neap Cycle

The period of the spring-neap cycle is not quite the same as the time it takes for the Moon to orbit the Earth [27.3 days], because during that time the Earth has moved approximately 1/13th of the way around the Sun. So, it takes another [27.3/13] days to catch up with the Sun [so they line up again], i.e.

27.3 + [27.3/13] = 29.5 days

We have 2 springs and 2 neaps occurrences during this period, so the spring-neap cycle is [29.5/2 days] or about 14.7 days long [or about one week separates spring from neap tides].

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The Rotating Earth

Let us now consider the basic effect of the Earth's rotation [spin] on the prediction of tides in the world ocean that covers the entire surface of the Earth to a uniform depth. This ideal ocean is modified by the tide generating forces that cause bulges on opposite sides of the Earth as shown before. If we assume that the stationary Moon is directly above the equator so that maximum bulge will occur on the equator on opposite sides of the Earth. Since the Earth requires 24 h for one complete rotation, an observer on the equator would experience 2 high tides per day. The time that would elapse between high tides, the *tidal period*, would be 12 h. An observer at any latitude North or South of the equator would experience a similar period, but the high tides would not be so high at higher latitudes since the observer would be at the edge of the bulge rather than the apex.

To make the story short, we have two tides a day because of the Earth's spinning on its axis [24 hours for one complete revolution]. While spinning, a fixed point on the Earth [a specific location] will pass the condition of two bulges in one day.

But high tides do not occur every 12 h on the Earth's surface. This is due to the fact that the Earth-Moon system is rotating about its centre of mass while the Earth is spinning on its own axis.

Semi-Diurnal Tides

There are two tides per day [semi-diurnal tides] because the Earth spins below the two bulges of the ellipsoid of revolution, once everyday. But, in the time it takes the earth to spin once [24 hours], the Moon has moved further round. so it takes another approximately 50 minutes to catch up with the sub-lunar point [the Moon rises about 50 minutes later everyday]. The times it takes to go from the Sun being overhead, to being overhead again is defined to be 24 hours. So, the solar semi-diurnal period is exactly 12 hours.

Lunar Semi-Diurnal Tide	2 high and 2 low waters	separated by ~12 h 25 min
Solar Semi-Diurnal Tide	2 high and 2 low waters	separated by exactly 12 h

Diurnal Tides

The Moon's declination angle, δ, is the angle between the line joining the Earth and Moon centres, and the equatorial plane. If the declination angle is non-zero, then the two high waters are unequal. We still have semi-diurnal tides, but with a diurnal inequality [which increases as the Moon's declination angle increases]. At high latitudes near the poles, higher than the co-latitude (90-δ), the equilibrium theory predicts only diurnal tides [i.e. one high water and one low water per day].

Do you know some Pacific islands have diurnal tides only? Which islands are they?

Sea Level

Sea level is a measurable quantity and it can be generally defined as the results of all influences [*tides* (attraction of the Moon and the Sun), atmospheric pressure, winds, thermal effect, seismic activity (*tsunami*), vertical land movement, oceanographic effect such as El Niño, etc] which affect the height of sea surface.

Sea Level =Daily Tides + Atmospheric Effects + Seismic Effect + <u>Thermal Effect</u> + Vertical Land Movement + Oceanographic Effects

Among all these influences, it is to be noted that the daily tidal motion is the major component of the periodic sea level change. Accordingly, basic understanding of the fundamentals of tides is essential in sea level issue. Without having a sound knowledge of tides, one cannot introduce the study of sea level properly.

So, if you do not know this definition properly, do **NOT** open your mouth to talk about sea level or sea level rise problem in the future. Because you do not know what you are talking about, it will be very embarrassing. There are many people around you who talk too much about sea level rise issue without knowing what sea level really means. I am sorry, it is true until today. When you hear somebody talking about sea level rise issue, just ask, what sea level means, that person will give you a nasty look. Do not do it to your lecturers!!

Definition of Tsunami [It is NOT Tidal Wave]

A tsunami is a series of ocean waves with very long wavelengths (typically hundreds of kilometres) caused by large-scale disturbances of the ocean, such as:

- earthquakes
- landslide
- volcanic eruptions
- explosions
- meteorites

Note: These disturbances can either be from below (e.g. underwater earthquakes with large vertical displacements, submarine landslides) or from above (e.g. meteorite impacts). Tsunami is a Japanese word with the English translation: "*harbour wave*". In the past, especially by the media people, tsunamis have been referred to as "*tidal waves*" or "*seismic sea waves*". The term "*tidal wave*" is misleading; even though a tsunami's impact upon a coastline is dependent upon the tidal level at the time a tsunami strikes, tsunamis are unrelated to the tides.

N.B. Tide is the result of the gravitational force of the Moon, Sun, and other planets acting on the Earth and tide is totally harmless.

The term "*seismic sea wave*" is also misleading. "*Seismic*" implies an earthquake-related generation mechanism, but a tsunami can also be caused by a non-seismic event, such as a landslide or meteorite impact.

Tsunamis are also often confused with storm surges [effect of wind and pressure on water], even though they are quite different phenomena. A storm surge is a rapid rise in coastal sea level caused by a significant meteorological event - these are often associated with tropical cyclones.

The Indian Ocean Tsunami of 26th December 2004

An undersea earthquake in the Indian Ocean on 26th December 2004 produced a tsunami that caused one of the biggest natural disasters in modern history. Over 200,000 people are known to have lost their lives.

The waves devastated the shores of parts of Indonesia, Sri Lanka, India, Thailand and other countries with waves reported up to 15 m high, reaching as far as Somalia on the east coast of Africa, 4500 km west of the epicentre. Refraction and diffraction of the waves meant that the impact of the tsunami was noticed around the world and sea-level monitoring stations in places such as Brazil and Queensland of Australia also felt the effect of the tsunami.

The earthquake took place at about 1am UTC (8am local time) in the Indian Ocean off the western coast of northern Sumatra. With a magnitude of 9.0 on the Richter scale, it was the largest since the 1964 earthquake off Alaska and equal fourth largest since 1900, when accurate global seismographic record keeping began.

The epicentre of the earthquake was located about 250 km south-south east of the Indonesian city of *Banda Aceh*. It was a rare megathrust earthquake and occurred on the interface of the India and Burma tectonic plates. This was caused by the release of stresses that develop as the India plate subducts beneath the overriding Burma plate. A megathrust earthquake is where one tectonic plate slips beneath another, causing vertical motion of the plates. This large vertical displacement of the sea-floor generated the devastating tsunami, which caused damage over such a large area around the Indian Ocean.

The earthquake was also unusually large in geographical extent. An estimated 1200 km of faultline slipped about 15 m along the subduction zone over a period of several minutes. Because the 1,200 km of faultline affected by the quake was in a nearly north-south orientation, the greatest strength of the waves was in an east-west direction. Bangladesh, which lies at the northern end of the Bay of Bengal, had very few casualties despite being a populous low-lying country.

Due to the distances involved, the tsunami took anywhere from fifteen minutes to seven hours (for Somalia) to reach the various coastlines. The northern regions of the Indonesian island of Sumatra were hit very quickly, while Sri Lanka and the east coast of India were hit roughly two hours later. Thailand was also struck about two hours later, despite being closer to the epicentre, because the tsunami travelled more slowly in the shallow *Andaman* Sea off its western coast.

On its arrival on shore, the height of the tsunami varied greatly, depending on its distance and direction from the epicentre and other factors such as the local bathymetry. Reports have the height ranging form 2-3 m at the African coast (Kenya) up to 10-15 m at Sumatra, the region closest to the epicentre.

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