Waves and Tides

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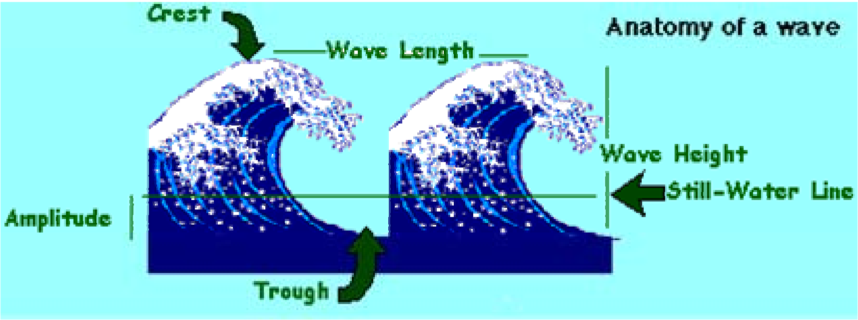
Waves

Without waves, the world would be a different place. Waves cannot exist by themselves for they are caused by winds. Winds in turn are caused by differences in temperature on the planet, mainly between the hot tropics and the cold poles but also due to temperature fluctuations of continents relative to the sea. Without waves, the winds would have only a very small grip on the water and would not be able to move it as much. The waves allow the wind to transfer its energy to the water's surface and to make it move. Currents and eddies mix the layers of water which would otherwise become stagnant and less conducive to life. Nutrients are thus circulated and re-used.

In its simplest scientific form, a wave is an expression of the movement or progression of energy through a medium. Such waves are often called progressive waves, a category that includes seismic waves, sound waves, light waves and ocean waves. As energy is transmitted through a fluid, the particles in the fluid may move up and down and back and forth in a kind of orbital motion as a sinusoidal line, i.e., as a sine wave. From our experience observing waves in nature, we know that real waves are much more complex.

The winds cause waves on the surface of the ocean (and on lakes). The wind transfers some of its energy to the water, through friction between the air molecules and the water molecules. Stronger winds (like storm surges) cause larger waves. Waves of water do not move horizontally, they only move up and down (a wave does not represent a flow of water). Tsunamis (sometimes called tidal waves) are different from surface waves; they are usually caused by underwater earthquakes, volcanic eruptions, or landslides.

Anatomy of a wave



- **STILL-WATER LINE** - The level of the ocean if it were flat without any waves.
- **CREST** - The highest part of the wave above the still-water line.
- **TROUGH** - The lowest part of the wave below the still-water line.
- **WAVE HEIGHT** - The vertical distance between the crest and the trough.
- **WAVE LENGTH** - The horizontal distance between each crest or each trough.
- **WAVE PERIOD** - The time it takes for two successive waves to pass a particular point.
- **WAVE FREQUENCY** - The number of waves that pass a particular point in a given time period.
- **AMPLITUDE** - The amplitude is equal to one-half the wave height or the distance from either the crest or the trough to the still-water line.

Characteristics of different waves

The table below describes some of the characteristics of different waves.

Wave	Period	Wavelength	Wave Type	Cause
Capillary	< 0.1 sec	< 2 cm	deep to shallow	local winds
Chop	1-10 sec	1-10 m	deep to shallow	local winds
Swell	10-30 sec	up to hundreds of m	deep or shallow	distant storm

Seiche	10 min-10 hr	up to hundreds of km	shallow or intermediate	wind, tsunami, tidal resonance
Tsunami	10-60 min	up to hundreds of km	shallow or intermediate	submarine disturbance i.e. earthquakes or volcanic eruptions under (or near) the ocean
Tide	12.4-24.8 hr	thousands of km	shallow	gravitational attraction of sun and moon

Wind and Waves

On a perfectly calm sea, the wind has practically no grip. As it slides over the water surface film, it makes it move. As the water moves, it forms eddies and small ripples. Ironically, these ripples do not travel exactly in the direction of the wind but as two sets of parallel ripples, at angles 70-80º to the wind direction. The ripples make the water's surface rough, giving the wind a better grip. The ripples, starting at a minimum wave speed of 0.23 m/s, grow to wavelets and start to travel in the direction of the wind. At wind speeds of 4-6 knots (7-11 km/hr), these double wave fronts travel at about 30º from the wind. The surface still looks glassy overall but as the wind speed increases, the wavelets become high enough to interact with the air flow and the surface starts to look rough. The wind becomes turbulent just above the surface and starts transferring energy to the waves. Strong winds are more turbulent and make waves more easily.

The rougher the water becomes, the easier it is for the wind to transfer its energy. The waves become steep and choppy. Further away from the shore, the water's surface is not only stirred by the wind but also by waves arriving with the wind. These waves influence the motion of the water particles such that opposing movements gradually cancel out, whereas synchronising movements are enhanced. The waves start to become more rounded and harmonious. Depending on **duration** and **distance** (**fetch**), the waves develop into a **fully developed sea**.

Anyone familiar with the sea, knows that waves never assume a uniform, harmonious shape. Even when the wind has blown strictly from one direction only, the resulting water movement is made up of various waves, each with a different speed and height. Although some waves are small, most waves have a certain height and sometimes a wave occurs which is much higher.

Surf breakers are classified in three types:

- **Spilling breakers:** result from waves of low steepness (long period swell) over gentle slopes. They cause rows of breakers, rolling towards the beach. Such breakers gradually transport water towards the beach during groups of high waves. Rips running back to sea, transport this water *away* from the beach during groups of low waves. When caught swimming in a rip, do not attempt to swim back to shore because such rips can be very strong (up to 8 km/hr). Swim parallel to the beach towards where the waves are highest. This is where water moves *towards* the beach. The next group of tall waves should assist you to swim back to shore. However, when launching (rescue) boats, this is best done in a rip zone.
- **Plunging breakers:** result from steeper waves over moderate slopes. The slope of a beach is not constant but may change with the tide. Some beaches are steep toward high tide, others toward low tide. A plunging breaker is dangerous for swimmers because its intensity is greatly augmented by backwash from its predecessor. This strong backwash precludes easy exit from the breaker zone, particularly for divers. Often a steep bank of loose sand prevents one from standing upright. In order to exit safely, wait for a group of low waves.
- **Surging breakers:** occur where the beach slope exceeds wave steepness. The wave does not really curl and break but runs up against the shore while producing foam and large surges of water. Such places are dangerous for swimmers because the rapidly moving water can drag swimmers over the rocks.

When waves break, their energy is absorbed and converted to heat. The gentler the slope of the beach, the more energy is converted. Steep slopes such as rocky shores do not break waves as much but reflect them back to sea, which 'shelters' marine life.

The interrelationship between the wind and the waves is so important to skippers that a completely new classification system was designed as a guideline incorporating both wind speed and the wave conditions most readily found at those speeds. This system, called the **Beaufort Scale**, was developed in 1805 by Admiral Sir Francis Beaufort of the British Navy. It is a guideline for what can be expected in certain conditions and a weather classification system. It assumes open ocean conditions with unlimited fetch.

Beaufort scale:

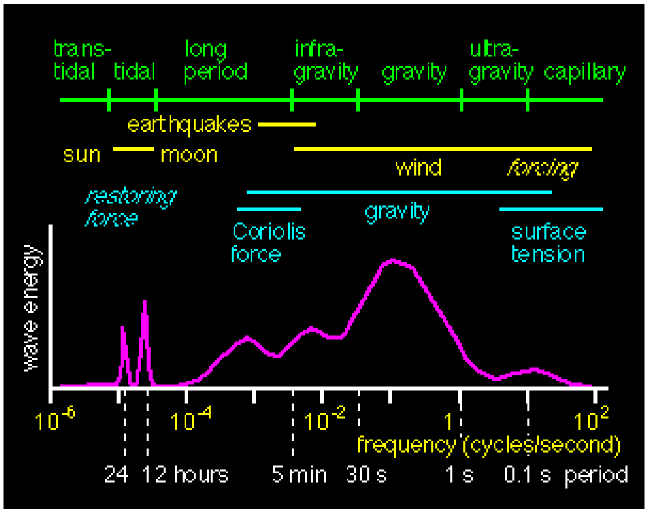
Force	Wind Speed	Description	Sea Conditions	Waves
0	0	Calm	Smooth, like a mirror.	0
1	1 - 3 knots	Light Air	Small ripples, like fish scales.	1/4' - 1/2'
2	4 - 6 knots	Light Breeze	Short, small pronounced wavelets with no crests.	1/4' - 1/2'
3	7 - 10 knots	Gentle Breeze	Large wavelets with some crests.	2'
4	11 - 16 knots	Moderate Breeze	Increasingly larger small waves, some white caps and light foam.	4'
5	17 - 21 knots	Fresh Breeze	Moderate lengthening waves, with many white caps and some light spray.	6'
6	22 - 27 knots	Strong Breeze	Large waves, extensive white caps with some spray.	10'
7	28 - 33 knots	Near Gale	Heaps of waves, with some breakers whose foam is blown downwind in streaks.	14'
8	34 - 40 knots	Gale	Moderately high waves of increasing length and edges of crests breaking into spindrift (heavy spray). Foam is blown downwind wind in well-marked streaks.	18'
9	41 - 47 knots	Strong Gale	High wind with dense foam streaks and some crests rolling over. Spray reduces visibility.	23'
10	48 - 55 knots	Storm	Very high waves with long, overlapping crests. The sea looks white, visibility is greatly reduced and waves tumble with force.	29'
11	56 - 63 knots	Violent Storm	Exceptionally high waves that may obscure medium size ships. All wave edges are blown into froth and the sea is covered with patches of foam.	37'
12	64 - 71 knots	Hurricane	The air is filled with foam and spray, and the sea is completely white.	45'

Aside from just wind speed, the temperature is also a factor in creating waves. Warm air (which rises) moving over water has a less acute angle of attack on the surface than does cool air (which sinks). A cold front moving across open water will create much steeper waves and hence create breakers sooner than a warm front moving at the same speed.

Also, a change in wind direction over existing waves can create confusion and hence larger waves. If a wind has been blowing northeast over an open body of water for three days and suddenly switches to northwest over that same body of water, new wavelets will form within the existing system of waves. The energy of both systems will multiply to create larger waves.

When a wave system meets a current flow one of two things can happen. If the wind and current are both going the same direction, it tends to smooth out the waves, creating long swells. If the current and wind are moving in contradicting directions, it will create much steeper and more aggressive waves.

Wave Classification



Ocean waves can be classified in various ways. One classification uses the forces which generate the waves. In ascending order of wave lengths we have:

1. Meteorological forcing (wind, air pressure); sea and swell belong to this category.

2. Earthquakes; they generate tsunamis, which are shallow water or long waves.
3. Tides (astronomical forcing); they are always shallow water or long waves.

Another classification is based on the frequency spectrum representation of all oceanic waves and distinguishes between capillary waves, gravity waves, long period waves and tides.

TIDES

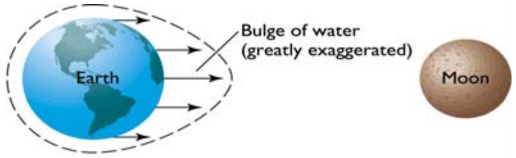
In oceanography, tides are commonly defined as the periodic variations in sea level that occur as a result of the gravitational forces of the Sun and the Moon. We most commonly observe tides along the coast but tides occur in the open ocean as well.

Tides are a planetary phenomenon, caused by the gravitational attraction of other planetary bodies on Earth—namely the Sun and the Moon. The force of this attraction creates a very predictable rise and fall of sea level as the Earth rotates on its axis. When sea level is at its greatest height, the tide is said to be high. When sea level is at its lowest extent, the tide is said to be low. High tides bring water far up on the shore. When wave action is high, these high tides may damage homes and undercut coastal cliffs. On the other hand, low tides expose great expanses of the beach. Low tides are ideal for activities like observing tidepools or digging in the mud for clams. Many marine organisms synchronize their behavior to the tides. The mass spawning of corals in the Great Barrier Reef, the swarming of bioluminescent palolo worms, the release of spores by kelp and the laying of eggs on the beach by the California grunion occur at times governed by the tides. The daily alternating submergence and exposure of rocks on the shore, combined with the action of the waves and heat from the sun, accelerate weathering and erosion along the coast.

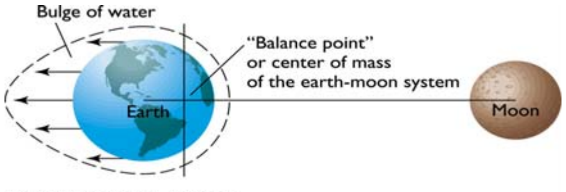
Knowledge of tides and their patterns dates back to at least 2300 BC in the ruins of coastal cities along the Gulf of Cambay in India. Here archaeologists have uncovered evidence of tidal docks, structures that allow boats to enter at high tide and, by means of a gate, trap the water and keep the boat afloat when the tide recedes. Indian religious texts from 300-400 BC suggest a link between the tides and the phases of the moon, a highly advanced claim for its time. Because tides may rise and fall in excess of 30 feet (10 meters) in this region, they obviously played an important role in the culture and commerce of these ancient people.

Several notable scholars advanced theories of the tides, including Galileo, but the first complete and fundamentally correct explanation was published in 1687 by Sir Isaac Newton (1642-1727) in his *Principia*. In his epic work, Newton introduced the Law of Gravitation which states that the gravitational attraction between two planetary bodies is the product of their masses divided by the square of their distance, times the gravitational constant. Differences in gravity at different points on Earth's surface cause vertical and horizontal forces but the vertical forces are much too small to generate tides. The tide-causing forces result from the horizontal forces acting along the surface of the Earth (i.e., tangential to the surface), causing motions of water towards points directly beneath and on the opposite side of the Moon (and Sun.) Newton's equilibrium theory of the tides remains the most popular, albeit often misstated, theory of tidal forces in modern textbooks.

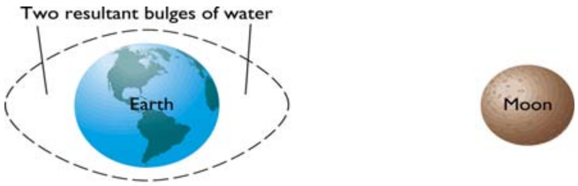
Despite these theoretical developments, the measurement of tides remained a challenge. A vertical measuring device like a yard stick worked easily enough but determining the exact time and height of a low or high tide with the complication of waves and storms made early tide measurements highly subjective. In 1831, the first tide gauge was deployed in the Thames Estuary. The device, afloat on a rod that raised and lowered a pen across a rotating drum of paper, provided the first continuous record of the tides over a 15-day period, the spring-neap cycle (see below). Float gauges remained in use for more than 150 years until acoustic sensors and pressure sensors began to take their place in the 1990s.



(a) GRAVITATIONAL FORCE



(b) CENTRIFUGAL FORCE



(c) GRAVITATIONAL AND CENTRIFUGAL FORCE

An ocean tide refers to the cyclic rise and fall of seawater. Tides are caused by slight variations in gravitational attraction between the *Earth* and the *moon* and the sun in geometric relationship with locations on the Earth's surface. Tides are periodic primarily because of the cyclical influence of the Earth's rotation.

The moon is the primary factor controlling the temporal rhythm and height of tides. The moon produces two tidal bulges somewhere on the Earth through the effects of gravitational attraction. The height of these tidal bulges is controlled by the moon's gravitational force and the Earth's gravity pulling the water back toward the Earth. At the location on the Earth closest to the moon, seawater is drawn toward the moon because of the greater strength of gravitational attraction. On the opposite side of the Earth, another tidal bulge is produced away from the moon. However, this bulge is due to the fact that at this point on the Earth the force of the moon's gravity is at its weakest. Considering this information, any given point on the Earth's surface should experience two tidal crests and two tidal troughs during each tidal period.

The timing of tidal events is related to the Earth's rotation and the revolution of the moon around the Earth. If the moon was stationary in space, the tidal cycle would be 24 hours long. However, the moon is in motion revolving around the Earth. One revolution takes about 27 days and adds about 50 minutes to the tidal cycle. As a result, the **tidal period** is 24 hours and 50 minutes in length.

The second factor controlling tides on the Earth's surface is the sun's gravity. The height of the average solar tide is about 50 % the average lunar tide. At certain times during the moon's revolution around the Earth, the direction of its gravitational attraction is aligned with the sun's. During these times the two tide producing bodies act together to create the highest and lowest tides of the year. These **spring tides** occur every 14-15 days during full and new moons.

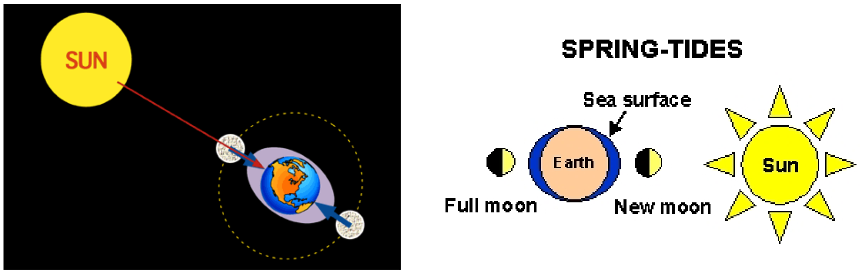


Fig. 1. Forces involved in the formation of a spring tide

When the gravitational pull of the moon and sun are at right angles to each other, the daily tidal variations on the Earth are at their least (**Figure 2**). These events are called **neap tides** and they occur during the first and last quarter of the moon.

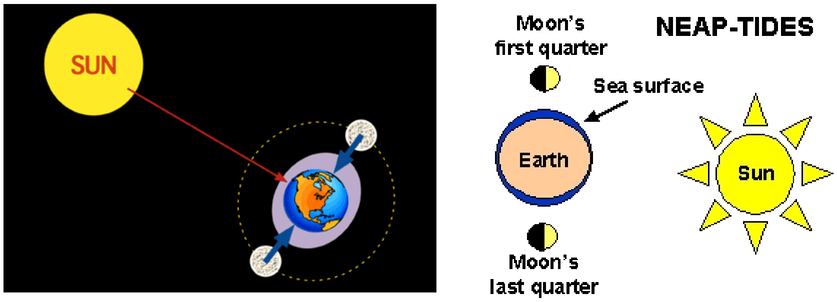


Fig. 2. Forces involved in the formation of a neap tide

Types of Tides

The geometric relationship of moon and sun to locations on the Earth's surface results in creation of **three different types** of tides.

In parts of the northern Gulf of Mexico and Southeast Asia, tides have one high and one low water per tidal day (Figure 3). These tides are called **diurnal tides**.

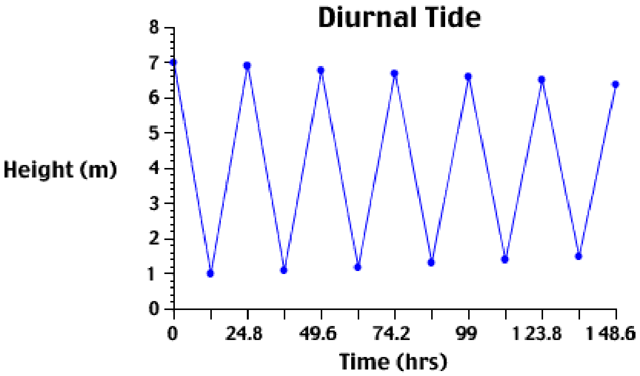


Fig. 3. Cyclical tidal cycles associated with a diurnal tide

Semi-diurnal tides have two high and two low waters per tidal day (Figure 4). They are common on the Atlantic coasts of the United States and Europe.

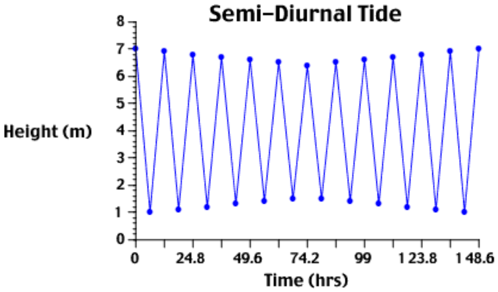


Fig. 4. Cyclical tidal cycles associated with a semi-diurnal tide

Many parts of the world experience **mixed tides** where successive high-water and low-water stands differ appreciably (Figure 5). In these tides, we have a higher high water and lower high water as well as higher low water and lower low water. The tides around west coast of Canada and the United States are of this type.

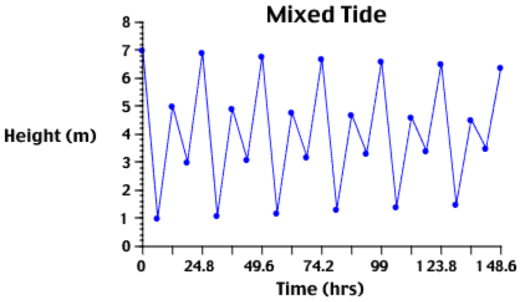


Fig. 5. Cyclical tidal cycles associated with a mixed tide

The map in Figure 6 shows the geographic distribution of these three tide types on the Earth.

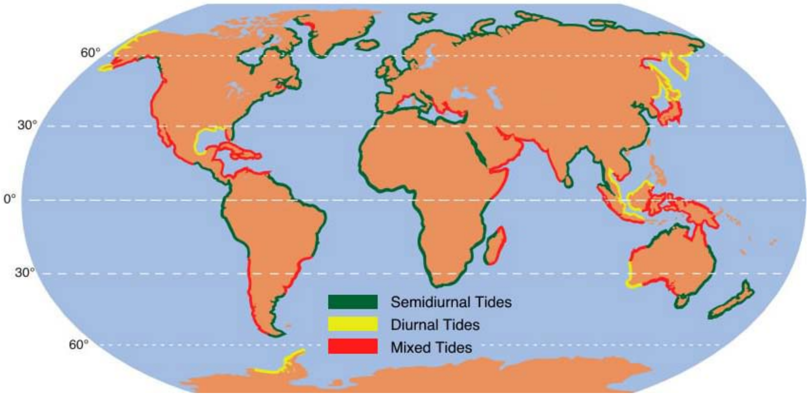


Fig. 6. Global distribution of the three tidal types. Most of the world's coastlines have semidiurnal tides.

Tidal observation and prediction

From ancient times, tides have been observed and discussed with increasing sophistication, first noting the daily recurrence, then its relationship to the Sun and Moon. Eventually the first tide table in China was recorded in 1056 A.D. primarily for the benefit of visitors to see the famous tidal bore in the Qiantang River. In Europe the first known tide-table is thought to be that of John, Abbott of Wallingford (d. 1213), based on high water occurring 48 minutes later each day, and three hours later at London than at the mouth of the Thames. William Thomson led the first systematic harmonic analysis to tidal records starting in 1867. The main result was the building of a tide-predicting machine (TPM) on using a system of pulleys to add together six harmonic functions of time. It was "programmed" by resetting gears and chains to adjust phasing and amplitudes. Similar machines were used until the 1960s.

The first known sea-level record of an entire spring–neap cycle was made in 1831 on the Navy Dock in the Thames Estuary, and many large ports had automatic tide gages stations by 1850.

William Whewell first mapped co-tidal lines ending with a nearly global chart in 1836. In order to make these maps consistent, he hypothesized the existence of amphidromes where co-tidal lines meet in the mid-ocean. These points of no tide were confirmed by measurement in 1840 by Captain Hewett, RN, from careful soundings in the North Sea.

The same tidal forcing has different results depending on many factors, including coast orientation, continental shelf margin, water body dimensions.

In most places there is a delay between the phases of the Moon and the effect on the tide. Springs and neaps in the North Sea, for example, are two days behind the new/full Moon and first/third quarter. This is called the *age of the tide*.

The exact time and height of the tide at a particular coastal point is also greatly influenced by the local bathymetry. There are some extreme cases: the Bay of Fundy, on the east coast of Canada, features the largest well-documented tidal ranges in the world, 16 metres (53 ft), because of the shape of the bay. Southampton in the United Kingdom has a double high tide caused by the interaction between the different tidal harmonics within the region. This is contrary to the popular belief that the flow of water around the Isle of Wight creates two high waters. The Isle of Wight is important, however, as it is responsible for the

'Young Flood Stand', which describes the pause of the incoming tide about three hours after low water. Ungava Bay in Northern Quebec, north eastern Canada, is believed by some experts to have higher tidal ranges than the Bay of Fundy (about 17 metres or 56 ft, but it is free of pack ice for only about four months every year, whereas the Bay of Fundy rarely freezes.

There are only very slight tides in the Mediterranean Sea and the Baltic Sea owing to their narrow connections with the Atlantic Ocean. Extremely small tides also occur for the same reason in the Gulf of Mexico and Sea of Japan. On the southern coast of Australia, because the coast is extremely straight (partly due to the tiny quantities of runoff flowing from rivers), tidal ranges are equally small.