Waves in the Ocean

In this document we will discuss three types of waves: **wind-driven waves, tides and tsunamis**. When the wind blows on the surface of the ocean it produces ripples, waves, and swell. Gravitational forces (mostly from the moon and sun) plus centrifugal forces in the solar system produce tides. Tectonic forces such as earthquakes that cause vertical displacements of the ocean floor, submarine volcanic eruptions, landslides and meteorite impacts on the ocean all cause tsunamis.

The typical periods, wavelengths, and forcing mechanisms of the waves in the ocean that we discuss are presented in the following table.

Name	Typical Periods	Wave lengths	Forcing mechanism
Ripples	<0.2 sec	10^{-2} m	wind on sea surface
Sea	0.2 - 9 sec	130 m	wind on sea surface
Swell	9 - 30 sec	100s of meters	wind on sea surface
Tsunamis	15 minutes - 1 hour	few 100s of km	seismic
Tides	several hours	several 100s - few 1000s km	gravitational (mainly sun and moon)

The first class of waves that we will cover is that produced by the **wind** blowing on the ocean's surface. Wind can generate waves locally, called **sea**, which travel in different directions and at different speeds. Wind can also generate waves that travel from a remote location in the open ocean, called **swell**, which travel in one direction and are more regular than sea waves. **Ripples** are the smallest and most irregular undulations produced by wind on the sea surface. To study wind waves, we should use ideal waves with **sinusoidal** shape. We define the properties of waves from these ideal waves (Figure 1). The wave **crest** is the point of maximum elevation, and the wave **trough** is the point of minimum elevation. The wave **amplitude** *A* equals one half the wave **height** *H*, which is the distance between the crest and the trough. The **wavelength** λ (the Greek letter lambda) is the distance between two crests (or two troughs or two inflection points with the same curvature above and below the points). The **period** *T* is the time it takes one wavelength or two consecutive troughs (or crests or any other wave reference point) to pass by a fixed position. The **speed** *C* (C stands for **celerity**) of the wave is the quotient of the wavelength over period.

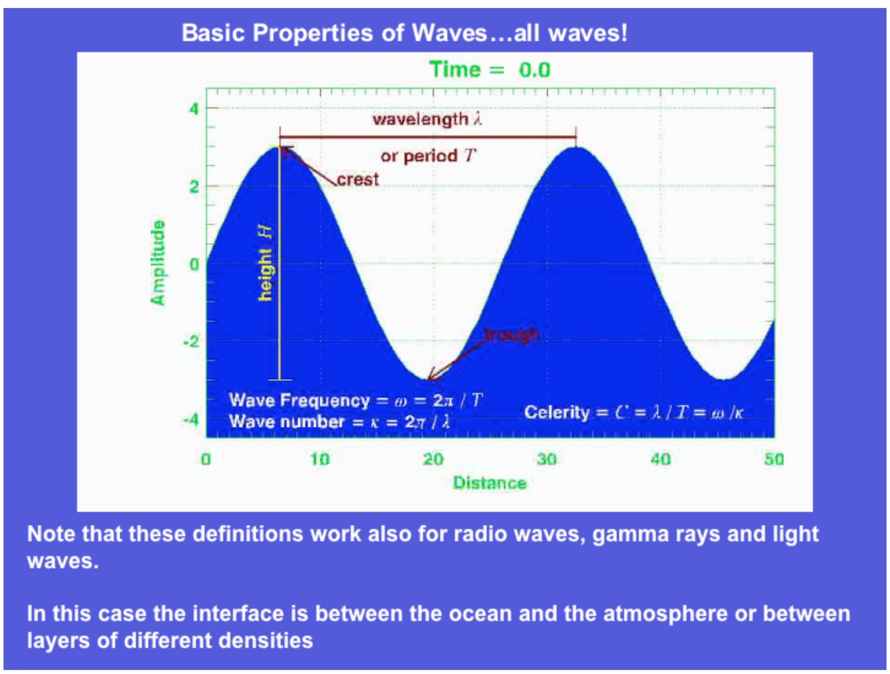


Figure 1

The wave height depends on the energy transferred to the surface by the wind; it does not depend on C, λ, or T. As you probably have seen in the ocean or a lake, the stronger the wind, the higher the waves. The period and wavelength can be expressed in terms of their reciprocals, the wave frequency **ω = 2(pi)/T**, and the wave number **κ = 2(pi)/λ**. (**ω** is the Greek letter omega, and **κ** is the Greek letter kappa.) The frequency and the wave number are spatial and temporal analogs of each other: frequency is the measurement of the number of repeating units of a propagating wave per unit of time, and wave number is the measurement of the number of repeating units of a propagating wave per unit of space. The units of frequency are time^{-1}, and the units of wave number are distance^{-1}.

It should be noted that **waves do not change their period *T***. The wavelength λ is a function of *T*, and the celerity *C* is a function of λ. Thus, long waves travel faster than short waves. The study of wind waves is simplified by treating them as "small amplitude" waves. Small amplitude means that the wave steepness, which is ratio of wave height *H* to wavelength λ, is smaller than one twentieth, in idealized situations. In real cases, the steepness of small amplitude waves is 1/50.

The wave celerity or speed depends only on the wavelength λ and on the water depth *h*. A **deep water wave** also called a **short** wave is found where the wavelength is shorter than twice the water column depth, i.e., $\lambda < 2h$. Therefore, the celerity of a deep water wave depends on the period (or on the wavelength because period and wavelength are related as $\lambda = CT$). Wave speed does not change with depth, in other words, the phase speed of a deep water wave is independent of depth *h*.

A **shallow water wave or long wave** is found where $\lambda > 20h$. For shallow water waves, the phase speed, $C = (gh)^{0.5}$, depends on the local water depth but not on the wavelength. This is an important relationship because it says that long waves such as tides propagating over coastal areas will have phase speeds that are proportional to the square root of the water depth.

Intermediate waves are those that fall between long and short waves. The range of depths at which these waves may exist increases with wavelength. There is an alternative way of representing the phase speed or celerity, in terms of the wave frequency ω:

$$C = \frac{\omega}{\kappa} = \left[\frac{g}{\kappa}\tanh(\kappa h)\right]^{1/2} \Rightarrow \frac{\omega^2}{\kappa^2} = \frac{g}{\kappa}\tanh(\kappa h)$$
$$\therefore \quad \omega^2 = g\kappa\tanh(\kappa h)$$

Equation 1 - The Dispersion Relation

This is called the **dispersion relation** because it relates the wave period (or its inverse, frequency ω) to the wavelength (or its inverse, wavenumber κ). This relation describes how waves of different periods travel at different speeds and get sorted according to their period. Deep water waves are **dispersive (get sorted)** as their speed depends on λ and on their period *T*. This means that short waves will travel at different speeds over a given depth. Hence, the waves that travel fast will separate from the slow ones (Figure 2). In contrast, shallow water waves are **non-dispersive** because their speed is independent of λ and *T*. The dispersion relation (equation 1) leads to the concept of **group speed of waves**.

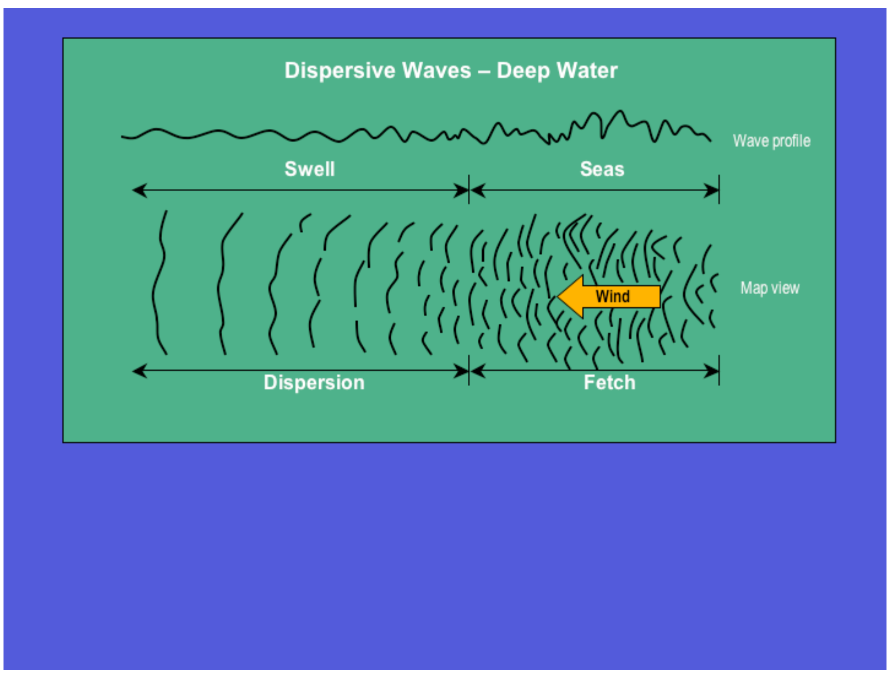


Figure 2

Group Speed

The group speed is the speed at which a group of waves travel. This is illustrated by a series of distinct waves that you see arriving at the beach consecutively. The quantitative notion of **group speed** C_g is derived form the dispersion relation, by estimating the changes of frequency with respect to the wave number, or the change of the wavelength with respect to the period (Figure 3).

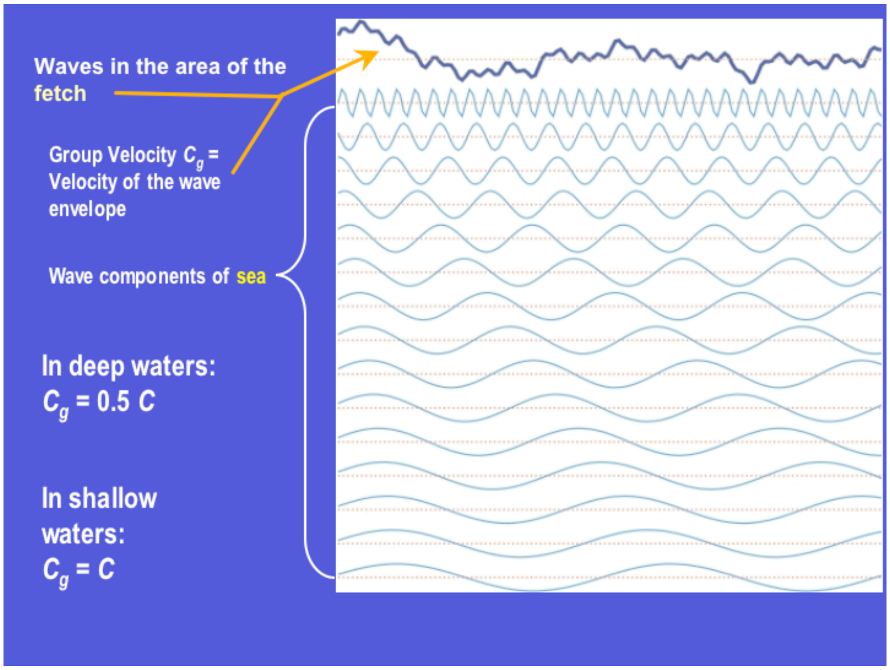


Figure 3

The horizontal and vertical velocities of wave particles, as well as their displacements, describe **circular trajectories for short waves** (Figure 4) and **elliptical trajectories for long waves** (Figure 5). Note that the shape of the wave is the feature that moves continuously forward (at speed C_s). The wave particle velocities contribute little to the currents, except when the waves have large amplitudes in shallow waters.

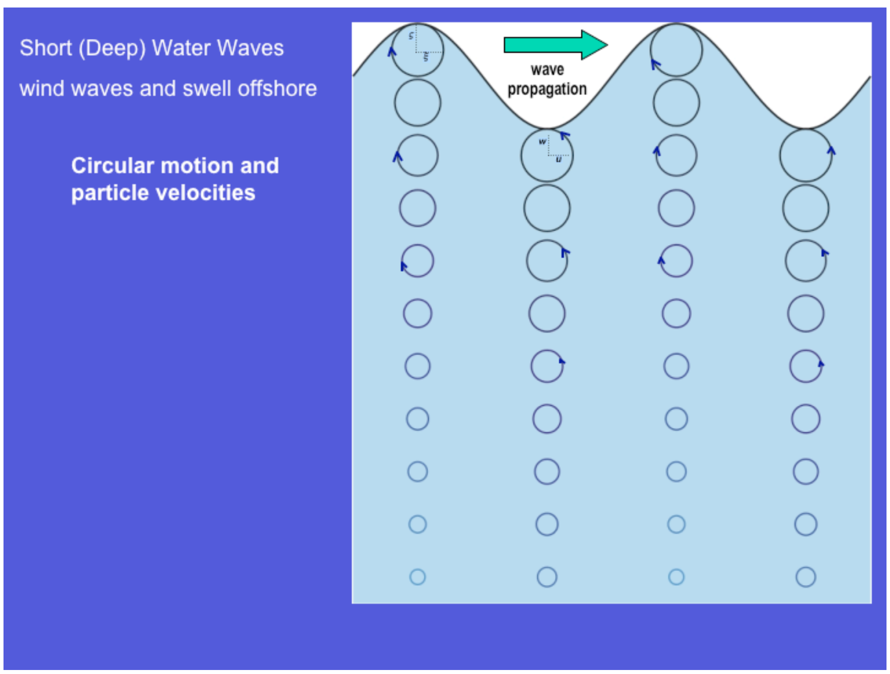


Figure 4

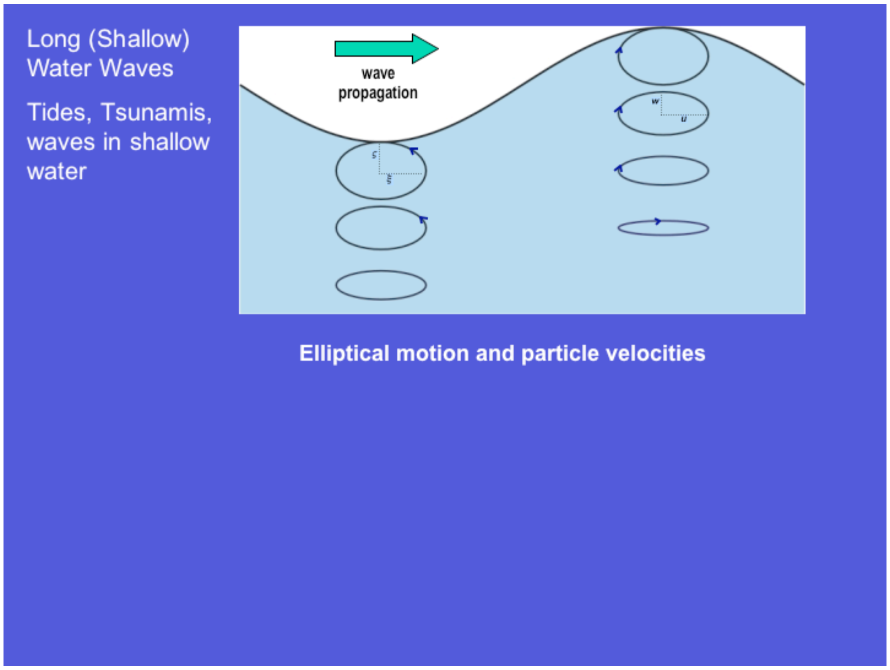


Figure 5

In reality, wave shapes are not perfectly sinusoidal nor are their orbits perfectly closed. This is illustrated in Figure 6. **Stokes drift** becomes important as wave grows and breaks. There is a net onshore transport produced by Stokes drift, markedly by long (shallow water) waves. Furthermore, when these waves arrive forming an angle with the coast they drive a current, a longshore current, between the breaking zone and the shore, i.e., at the surf zone. This current is caused by the added mass of water that breaking waves bring to the surf zone (analogous to the Stokes drift). Part of this added mass also causes **rip currents**, which are currents directed offshore for approximately one hundred meters. Rip currents form at an alongshore irregularity of the coast and may extend offshore past the breaking zone. An additional current caused by this added mass on the surf zone is the undertow. The **undertow** is typically observed offshore of the breaking zone and consists of an offshore directed current, a few centimeters per second strong, that is strongest between the surface and the bottom.

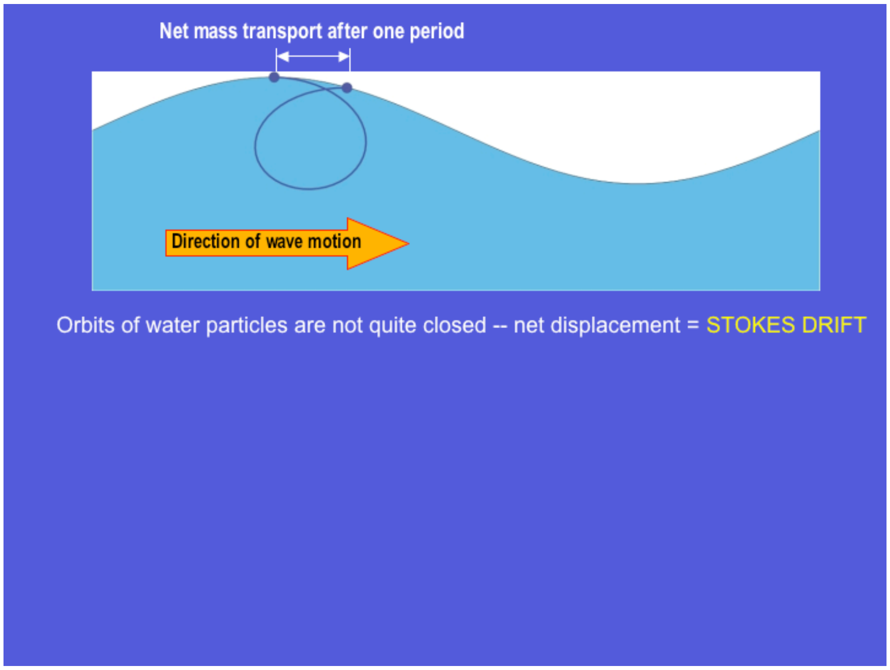


Figure 6

Wind-wave alterations on their approach to coasts

Waves experience modifications as they approach the coast. These modifications consist of **refraction, breaking, reflection, and diffraction**. The first two types of modifications are mainly due to bathymetric changes, or changes in water depth. Diffraction and reflection arise from an obstacle that hinders the energy propagation associated with the wave.

Refraction

As waves move into shallow water their phase speed C decreases because C is proportional to the square root of the depth h. Remember that the period T remains unchanged. The decrease in C causes then a corresponding decrease in wavelength λ because $\lambda = CT$. This decrease in λ with decreased depth causes the wave rays (lines orthogonal to wave crests) to concentrate over shoals and to diverge over **bathymetric** depressions (Figure 7) (bathymetric means relating to the depth of water). This has important implications for the distribution of wave energy at the coast, i.e., energy convergence at promontories and points, and energy divergence at coastal indentations. **Refraction** is then the **change of direction** of wave crests associated with the change of speed **due to bathymetry**.

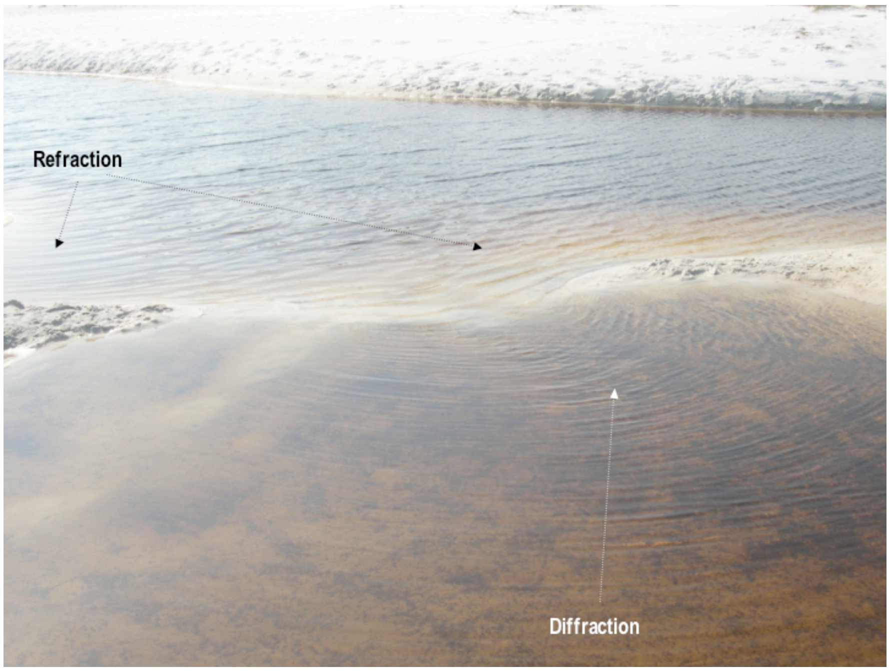


Figure 7

Diffraction

Diffraction is the change of direction of wave crests associated with an obstacle. The obstacle can many times be a breakwater or a seawall. Diffraction develops in the "shadow" or "protected" area of the obstacle, i.e., leeward of the wave direction of propagation.

Reflection

Reflection is the rebound of energy in the opposite direction to an incident wave due to the presence of an obstacle (Figure 8). Reflection occurs before the incident wave dissipates all its energy. The reflected wave develops over the **exposed** side of the obstacle, in contrast to diffraction, which develops on the **protected** side of the obstacle.

Figure 8

Breaking

Anybody interested in the study of waves has seen a wave breaking. Theoretically, waves break when their steepness (H/λ) equals 1/7. In reality, waves are rarely steeper than 1/12. Waves will break when H/h is approximately 0.8, regardless of the steepness. There are three main types of breaking waves: **spilling breaker, plunging breaker, and surging breaker** as illustrated in Figure 9. See also http://www.eustis.army.mil/weather/sea/waves.htm for different illustrations.

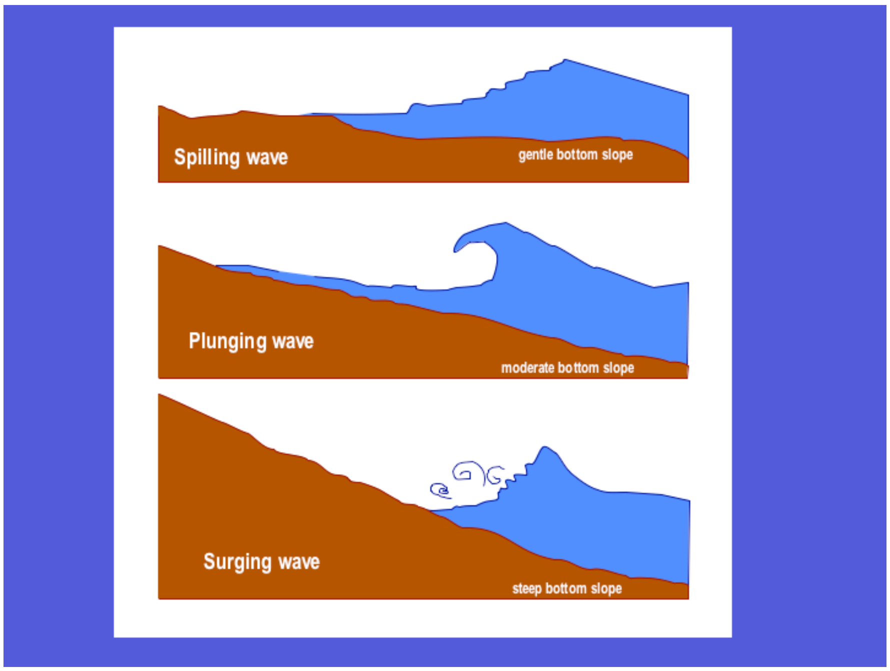
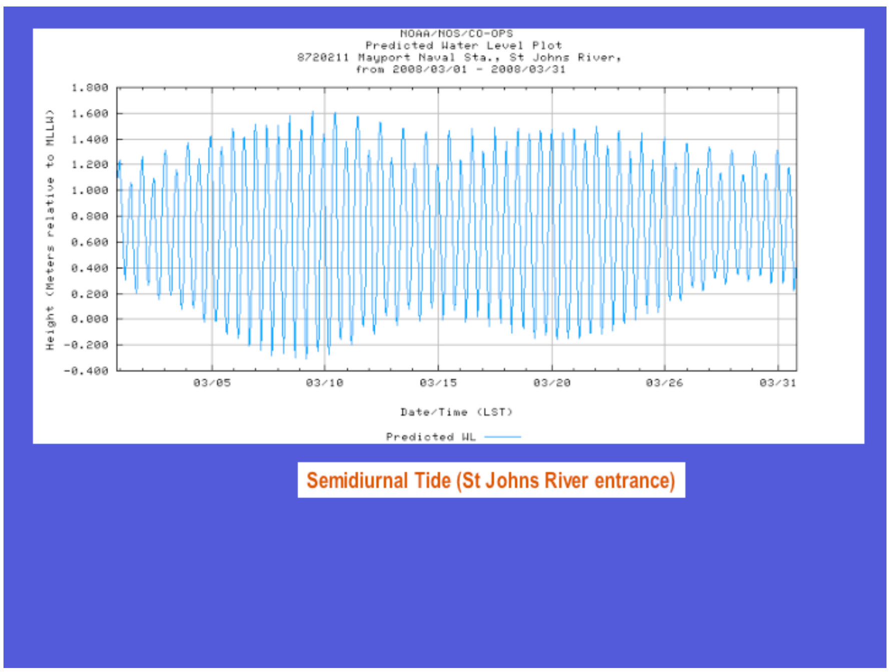


Figure 9

Tides

Tides are the rhythmic rise and fall of sea level at every coast of the world. Tides are generated by the imbalance in the solar system between gravitational forces and centrifugal forces. The main gravitational forces acting on Earth are exerted by the moon and the sun. The centrifugal force is the force caused by the translation of the earth as it moves in space. The tide generating force by the moon is a bit more than twice (2.17 times) the tide generating force from the sun. The imbalance between centrifugal and gravitational forces on Earth causes tides to have typical periods of 12 hours with wavelengths of thousands of kilometers. Their ratio of wavelength λ to water depth h is greater than 250, i.e., $\lambda/h > 250$ so that λ is definitely $> 20h$ (the criterion for a long wave) and tides are considered **long waves**. As long waves, their travel speed is given by $(gh)0.5$. When the sun and the moon are aligned in space with the earth, then their tide generating forces add and cause spring tides, which represent the largest tidal ranges of the month. When the earth, moon and sun form a 90 degree angle, the tide generating forces from the sun and moon act in perpendicular directions and cause the smallest tidal ranges of the month. Tides are a superposition of waves of different period and can be represented as a sum of many waves like the one shown back in Figure 1.

There are different types of tides in the world according to the period of the waves that dominate the tides. Thus, you may have semidiurnal tides, mixed tides with semidiurnal dominance, mixed tides with diurnal dominance and diurnal tides. (**Diurnal** means daily, and **semidiurnal** means twice daily.) The semidiurnal tides (Figure 10) display two high and two low tides per day. The highs and lows have nearly the same amplitude within the same day but they do change from day to day as the sun and the moon go from being aligned to being in quadrature (forming a 90 degree angle). Mixed tides with semidiurnal dominance (Figure 11) also display two highs and two lows per day but they are quite different. Hence, within a day you will have a higher high water, a lower high water, a lower low water and a higher low water. The mixed tides with diurnal dominance (Figure 12) are characterized by displaying a diurnal signal most of the days and a semidiurnal signal in some days, most markedly toward neap tides. Diurnal tides (Figure 13) only exhibit one high and one low water level per day.



Semidiurnal Tide (St Johns River entrance)

Figure 10

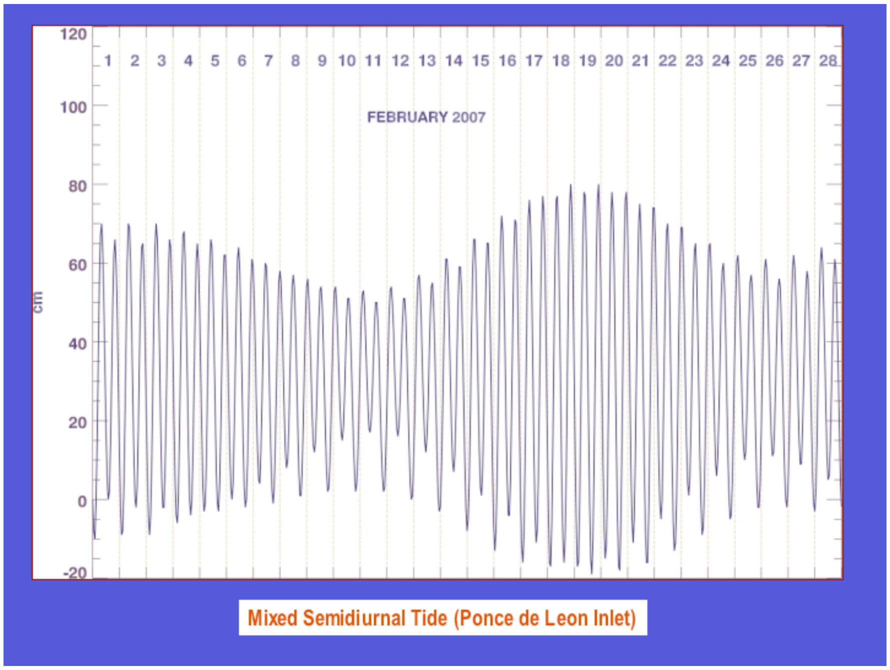


Figure 11

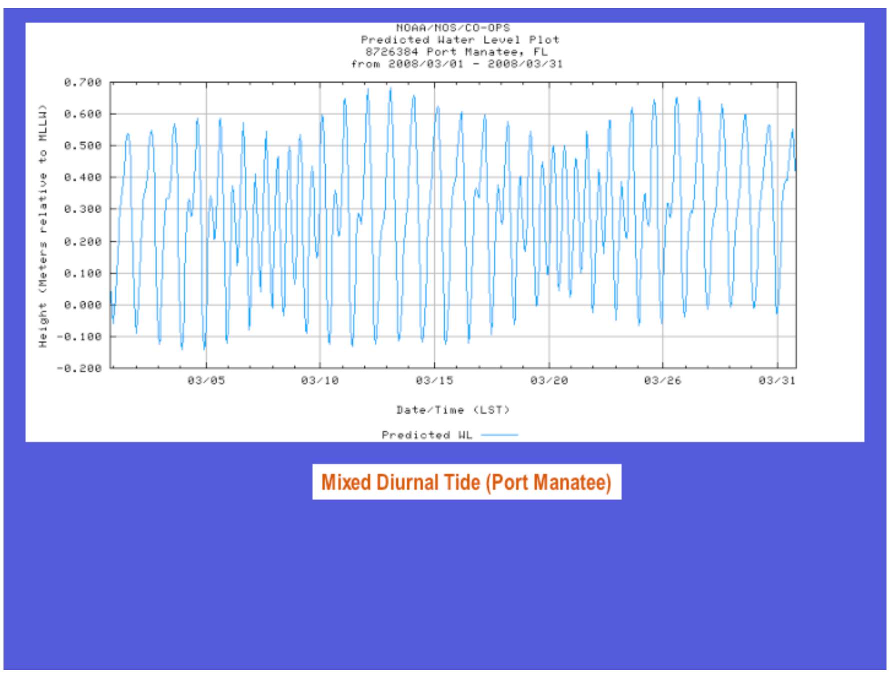


Figure 12

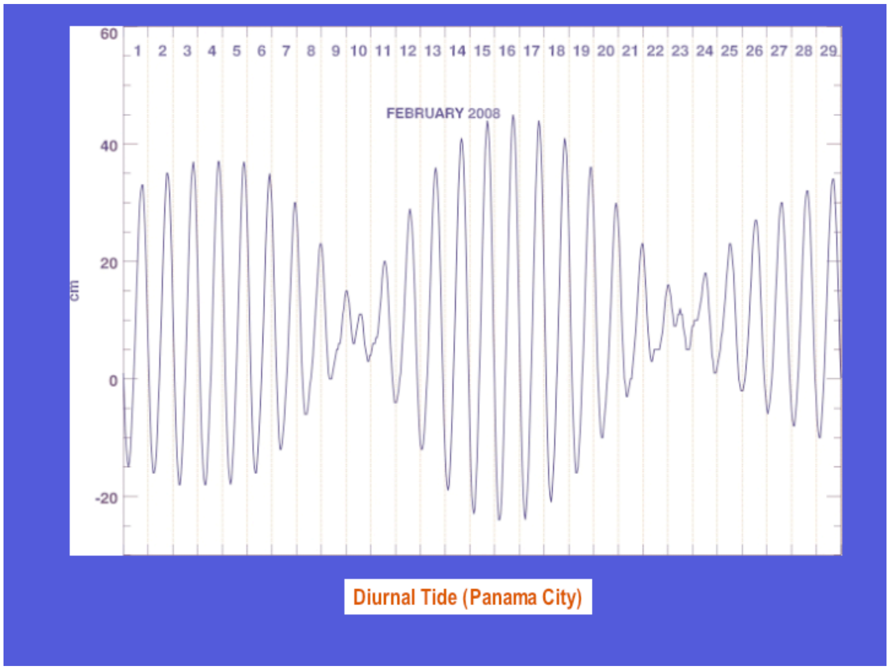


Figure 13

Tides can produce strong tidal currents in the coastal area, most markedly in regions where the coastline opens through an inlet or a narrow estuary. In such cases, the speed of the currents produced by tides is customarily close to 1 m/s (or 2 knots). Just to give you an idea, the fastest swimmer in the world can swim at speeds a bit greater than 2 m/s (or approximately 4 knots). So, most people would have a very hard time swimming against the tidal currents at inlets or at the mouth of estuaries. The strongest tidal currents are approximately 10 m/s (or 20 knots!) and are observed in narrow passages in the area of fjords and channels in high latitudes (British Columbia, Alaska, Scandinavia, Chile). Now, not even the strongest swimmer in the world can swim against those currents!

Tsunamis

Tsunami in the Japanese language means "harbor wave." It is a long wave, a couple of hundred kilometers long, many times produced by a vertical displacement of the ocean bottom. Such vertical displacement of the sea floor, caused by an earthquake, pushes water upward and excites a wave at the surface. This wave then displaces radially, in every direction about the initial sea surface bulging. Tsunamis can also be produced by underwater volcanic eruptions. Such eruptions cause material from the earth's crust to enter the ocean in large volumes. These volumes of material displace water upward and incite a wave at the ocean's surface. An additional mechanism for generation of a tsunami is through large landslides, from land or within the ocean floor. Landslides also add material that displaces water and excites a wave. In a similar way, meteorites impacting the ocean can trigger a tsunami.

The use of the term "tidal wave" to refer to tsunamis is incorrect. Tidal waves are generated by gravitational forces, i.e., a different mechanism than that responsible for tsunamis. Their periods are also completely different. While tidal waves have periods of 12 hours, tsunamis have periods of 15 minutes to 1 hour. However, just like tidal waves, tsunamis behave as long (shallow water) waves even in the deep ocean and can propagate through entire ocean basins. In the animation that illustrates a 1960 Pacific-wide tsunami that started off Chile, see the diffraction of the waves as they go past islands and the reflection after the tsunami waves impact Japan.

Tsunamis in general have typical wavelengths of 200 km and their amplitude is approximately 1 meter in the deep ocean. These characteristics make them difficult to identify in the open ocean. The most dangerous and destructive aspect of a tsunami is the persistence of its currents. For a 2 m tsunami, which is not a very large wave but one of respectable size, the currents resulting from it are approximately 3 m/s. This is faster than any swimmer can swim! It is quite different to experience a 3 m/s current from a wave with a period of, say, 10 seconds (while you are wading at the beach), than a 3 m/s current from a tsunami with a period of 30 minutes. The 10 second wave will have its maximum current in just a couple of seconds, while the tsunami will produce very strong currents for several minutes and in both phases of the wave (flooding and ebbing)!

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