CHAPTER 34

THE OCEANS

INTRODUCTION

3400. The Importance of Oceanography

Oceanography is the scientific study and exploration of the oceans and their phenomena. It includes a study of their physical, chemical, and geological forms, and biological features. It is an Earth Science, which covers a wide range of topics. It embraces the widely separated fields of geography, geology, plate tectonics, chemistry, physics and biology, along with their many subdivisions, such as sedimentation, ecology, bacteriology, biochemistry, hydrodynamics, acoustics, and optics. These diverse topics reflect multiple disciplines that oceanographers blend to further knowledge of the world's ocean and understanding of processes.

The oceans cover 70.8 percent of the surface of the Earth. The Atlantic covers 16.2 percent, the Pacific 32.4 percent (3.2 percent more than the land area of the entire Earth), the Indian Ocean 14.4 percent, and marginal and adjacent areas (of which the largest is the Arctic Ocean) 7.8 percent. Their extent alone makes them an important subject for study. However, greater incentive lies in their use for transportation, their influence upon weather and climate, and their potential as a source of power, food, fresh water, minerals, and organic substances.

3401. Origin of the Oceans

The structure of the continents is fundamentally different from that of the oceans. The rocks underlying the ocean floors are more dense than those underlying the continents. According to one theory, all the Earth's crust floats on a central liquid core, and the portions that make up the continents, being lighter, float with a higher freeboard. Thus, the thinner areas, composed of heavier rock, form natural basins where water has collected.

The shape of the oceans is constantly changing due to continental drift. The surface of the Earth consists of many different "**plates**." These plates are joined along **fracture** or **fault lines**. There is constant and measurable movement of these plates at rates of 0.02 meters per year or more.

The origin of the water in the oceans is unclear. Although some geologists have postulated that all the water existed as vapor in the atmosphere of the primeval Earth, and that it fell in great torrents of rain as soon as the Earth cooled sufficiently, another school holds that the atmosphere of the original hot Earth was lost, and that the water gradually accumulated as it was given off in steam by volcanoes, or worked to the surface in hot springs.

Most of the water on the Earth's crust is now in the oceans–about 1,370,000,000 cubic kilometers, or about 85%. The mean depth of the ocean is 3,795 meters, and the total area is 360,000,000 square kilometers.

CHEMISTRY OF THE OCEANS

3402. Chemical Description

Oceanographic chemistry may be divided into three main parts: the chemistry of (1) seawater, (2) marine sediments, and (3) organisms living in the sea. The first is of particular interest to the navigator.

Chemical properties of seawater are usually determined by analyzing samples of water obtained at various locations and depths. Samples of water from below the surface are obtained with special bottles designed for this purpose. The open bottles are mounted in a **rosette** which is attached to the end of a wire cable which contains insulated electrical wires. The rosette is lowered to the depth of the deepest sample, and a bottle is closed electronically (see Figure 3402). As the rosette is raised to the surface, other bottles are closed at the desired depths.

Sensors have also been developed to measure a few chemical properties of sea water continuously.

Physical properties of seawater are dependent primarily upon salinity, temperature, and pressure. However, factors like motion of the water and the amount of suspended matter affect such properties as color and transparency, conduction of heat, absorption of radiation, etc.

3403. Salinity

Salinity is a measure of the amount of dissolved solid salts material in the water. Salts are compounds like sodium chloride and potassium nitrate. The units to express salinity have changed over the years. Up to the 1980s, salinity was measured by titration and expressed as parts per thousand (ppt or ‰). After 1980, the **practical salinity unit (psu),**

Figure 3402. CTD Rosette is lowered to measure the salinity, temperature, depth and concentration of particles in the water column. Image courtesy of NOAA.

measured by electrical conductivity, was used. Starting in 2010 the thermodynamic equation of seawater with units of grams per kilogram of solution began to be employed. A sample of seawater with a salinity of 35.00 ‰, would have a psu of 35.00, and in the newest system would have a value of 35.2 g/kg.

In 2016, the most common scale employed is the **practical salinity unit**. Using this scale, the salinity of a seawater sample is defined as the ratio between the conductivity of the sample and the conductivity of a standard potassium chloride (KCl) sample.

Salinity generally varies between about 33 and 37 psu. However, when the water has been diluted, as near the mouth of a river or after a heavy rainfall, the salinity is somewhat less; and in areas of excessive evaporation, the salinity may be as high as 40 psu. In certain confined bodies of water, notably the Great Salt Lake in Utah, and the Dead Sea in Asia Minor, the salinity is several times this maximum.

3404. Temperature

Temperature in the ocean varies widely, both horizontally and with depth. Maximum values of about 32°C are encountered at the surface in the Persian Gulf in summer, and the lowest possible values of about –2°C (the usual minimum freezing point of seawater) occur in polar regions.

Except in the polar regions, the vertical distribution of temperature in the sea in the majority of the seas show a decrease of temperature with depth. Since colder water is denser (assuming the same salinity), it sinks below warmer water. This results in a temperature distribution just opposite to that of the Earth's crust, where temperature increases with depth below the surface of the ground.

In the sea there is usually a mixed layer of isothermal water below the surface, where the temperature is the same as that of the surface. This layer is caused by two physical processes: wind mixing and convective overturning. As surface water cools it becomes more dense. This layer is best developed in the Arctic and Antarctic regions, and in seas like the Baltic and Sea of Japan during the winter, where it may extend to the bottom of the ocean. In the Tropics, the wind-mixed layer may exist to a depth of 125 meters, and may exist throughout the year. Below this layer is a zone of rapid temperature decrease, called the **thermocline**. At a depth greater than 400 meters, the temperature is below 15°C. In the deeper layers, fed by cooled waters that have sunk from the surface in the Arctic and Antarctic, temperatures as low as –2°C exist.

In the colder regions, the cooling creates the convective overturning and isothermal water in the winter; in the summer, a seasonal thermocline is created as the upper water becomes warmer. A typical curve of temperature at various depths is shown in Figure 3410a. Temperature is commonly measured with either a platinum or copper resistance thermometer or a thermistor (devices that measure the change in conductivity of a semiconductor with change in temperature).

The **CTD (conductivity-temperature-depth)** is an instrument that generates continuous signals as it is lowered into the ocean; temperature is determined by means of a platinum resistance thermometer, salinity by conductivity, and depth by pressure. These signals can be transmitted to the surface through a cable and recorded, or recorded internally. Accuracy of temperature measurement is 0.005°C and resolution an order of magnitude better (see Figure 3402).

A method commonly used to measure upper ocean temperature profiles from a vessel which is underway is the **expendable bathythermograph (XBT)**. The XBT uses a thermistor and is connected to the vessel by a fine wire. The wire is coiled inside the probe; as the probe free-falls in the ocean, the wire pays out. Depth is determined by elapsed time and a known sink rate. Depth range is determined by the amount of wire stored in the probe; the most common model has a depth range of 450 meters. At the end of the drop, the wire breaks and the probe falls to the ocean bottom. One instrument of this type is dropped from an aircraft; the data is relayed to the aircraft from a buoy to which the wire of the XBT is attached. The accuracy and precision of an XBT is about 0.1°C.

3405. Pressure

The appropriate international standard (SI) unit for pressure in oceanography is 1 $kPa = 10^3$ Pa where Pa is a Pascal and is equal to one Newton per square meter. A more commonly used unit is a bar, which is nearly equal to 1 atmosphere (atmospheric pressure is measured with a barometer and may be read as hectopascals). Water pressure is expressed in terms of decibars, 10 of these being equal to 1 bar. One decibar is equal to nearly $1^1/_2$ pounds per square inch. This unit is convenient because it is very nearly the pressure exerted by 1 meter of water. Thus, the pressure in decibars is approximately the same as the depth in meters, the unit of depth.

Although virtually all of the physical properties of seawater are affected to a measurable extent by pressure, the effect is not as great as those of salinity and temperature. Pressure is of particular importance to submarines, directly because of the stress it induces on the hull and structures, and indirectly because of its effect upon buoyancy.

3406. Density

Density is mass per unit of volume. The appropriate SI unit is kilograms per cubic meter. The density of seawater depends upon salinity, temperature, and pressure. At constant temperature and pressure, density varies with salinity. A temperature of 0°C and atmospheric pressure are considered standard for density determination. The effects of thermal expansion and compressibility are used to determine the density at other temperatures and pressures. Slight density changes at the surface generally do not affect the draft or trim of a ship, though a noticeable change may occur as a ship travels from salt to fresh water. Density changes at a particular subsurface pressure will affect the buoyancy of submarines because they are ballasted to be neutrally buoyant. For oceanographers, density is important because of its relationship to ocean currents.

Open ocean values of density range from about 1,021 kilograms per cubic meter at the surface to about 1,070 kilograms per cubic meter at 10,000 meters depth. As a matter of convenience, it is usual in oceanography to define a density anomaly which is equal to the density minus 1,000 kilograms per cubic meter. Thus, when an oceanographer speaks of seawater with a density of 25 kilograms per cubic meter, the actual density is 1,025 kilograms per cubic meter.

The greatest changes in density of seawater occur at the surface, where the water is subject to influences not present at depths. At the surface, density is decreased by precipitation, run-off from land, melting ice, or heating. When the surface water becomes less dense, it tends to float on top of the denser water below. There is little tendency for the water to mix, and so the condition is one of stability. The density of surface water is increased by evaporation, formation of sea ice, and by cooling. If the surface water becomes more dense than that below, convection currents cause vertical mixing. The denser surface water sinks and mixes with less dense water below. The resultant layer of water is of intermediate density. This process continues until the density of the mixed layer becomes less than that of the water below. The convective circulation established as part of this process can create very deep uniform mixed layers.

If the surface water becomes sufficiently dense, it sinks all the way to the bottom. If this occurs in an area where horizontal flow is unobstructed, the water which has descended spreads to other regions, creating a dense bottom layer. Since the greatest increase in density occurs in polar regions, where the air is cold and great quantities of ice form, the cold, dense polar water sinks to the bottom and then spreads to lower latitudes. In the Arctic Ocean region, the cold, dense water is confined by the Bering Strait and the underwater ridge from Greenland to Iceland to Europe. In the Antarctic, however, there are no similar geographic restrictions and large quantities of very cold, dense water formed there flow to the north along the ocean bottom. This process has continued for a sufficiently long period of time; the entire ocean floor is covered with this dense water, thus explaining the layer of cold water at great depths in all the oceans.

In some respects, oceanographic processes are similar to those occurring in the atmosphere. Masses of water of uniform characteristics are analogous to air masses.

3407. Compressibility

Seawater is nearly incompressible, its coefficient of compressibility being only 0.000046 per bar under standard conditions. This value changes slightly with changes in temperature or salinity. The effect of compression is to force the molecules of the substance closer together, causing it to become more dense. Even though the compressibility is low, its total effect is considerable because of the amount of water involved. If the compressibility of seawater were zero, sea level would be about 90 feet higher than it is now.

Compressibility is inversely proportional to temperature, i.e., cold water is more compressible than warm water. Waters which flow into the North Atlantic from the Mediterranean and Greenland Seas are equal in density, but because the water from the Greenland Sea is colder, it is more compressible and therefore becomes denser at depth. These waters from the Greenland Sea are therefore found beneath those waters which derive their properties from the Mediterranean.

3408. Viscosity

Viscosity is resistance to flow. Seawater is slightly more viscous than freshwater. Its viscosity increases with greater salinity, but the effect is not nearly as marked as that occurring with decreasing temperature. The rate is not uniform, becoming greater as the temperature decreases. Because of the effect of

temperature upon viscosity, an incompressible object might sink at a faster rate in warm surface water than in colder water below. However, for most objects, this effect may be more than offset by the compressibility of the object.

The actual relationships existing in the ocean are considerably more complex than indicated by the simple explanation here, because of turbulent motion within the sea. The effect of disturbing the water is called **eddy viscosity**.

3409. Specific Heat

Specific heat is the amount of heat required to raise the temperature of a unit mass of a substance a stated amount. In oceanography, specific heat is stated, in SI units, as the number of Joules needed to raise 1 kilogram of a given substance 1°C. Specific heat at constant pressure is usually the quantity desired when liquids are involved, but occasionally the specific heat at constant volume is required. The ratio of these two quantities is directly related to the speed of sound in seawater.

The specific heat of seawater decreases slightly as salinity increases. However, it is much greater than that of land. The ocean is a giant storage area for heat. It can absorb large quantities of heat with very little change in temperature. This is partly due to the high specific heat of water and partly due to mixing in the ocean that distributes the heat throughout a layer. Land has a lower specific heat and, in addition, all heat is lost or gained from a thin layer at the surface; there is no mixing. This accounts for the greater temperature range of land and the atmosphere above it, resulting in monsoons, and the familiar land and sea breezes of tropical and temperate regions.

3410. Sound Speed

The speed of sound in sea water is a function of its density, compressibility and, to a minor extent, the ratio of specific heat at constant pressure to that at constant volume. As these properties depend on the temperature, salinity and pressure (depth) of sea water, it is customary to relate the speed of sound directly to the water temperature, salinity and pressure. An increase in any of these three properties causes an increase in the sound speed; the converse is true also. Figure 3410a portrays typical mid-ocean profiles of temperature and salinity; the resultant sound speed profile is shown in Figure 3410b.

The speed of sound changes by 3 to 5 meters per second per °C temperature change, by about 1.3 meters per second per psu salinity change and by about 1.7 meters per second per 100 m depth change. A simplified formula adapted from Wilson's (1960) equation for the computation of the sound speed in sea water is:

$$U = 1449 + 4.6T - 0.055T^2 + 0.0003T^3 + 1.39(S - 35) + 0.017D$$

where U is the speed (m/s), T is the temperature (°C), S is the salinity (psu), and D is depth (m).
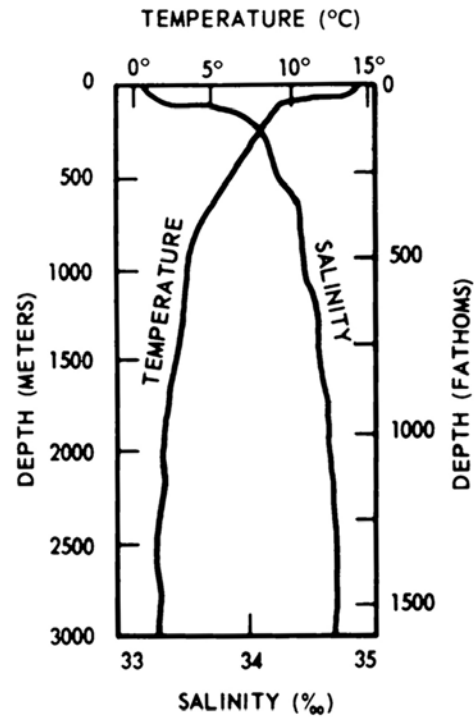

Figure 3410a. Typical variation of temperature and salinity with depth for a mid-latitude location.
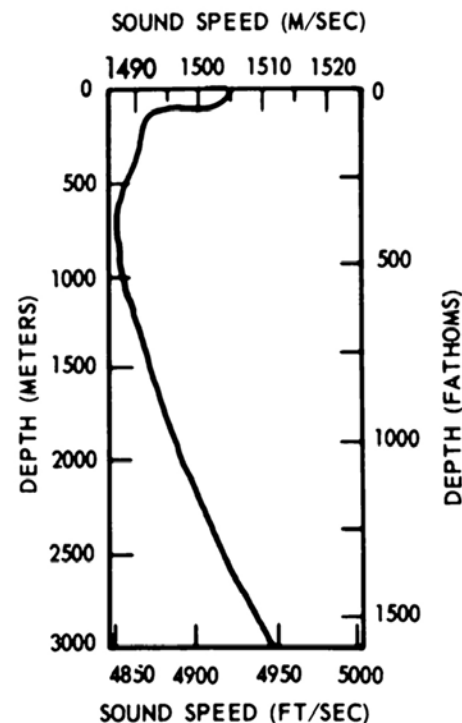

Figure 3410b. Resultant sound speed profile based on the temperature and salinity profile in Figure 3410a.

3411. Thermal Expansion

One of the more interesting differences between salt and fresh water relates to thermal expansion. Saltwater continues to become more dense as it cools to the freezing point; freshwater reaches maximum density at 4°C and then expands (becomes less dense) as the water cools to 0°C and freezes. This means that the convective mixing of freshwater stops at 4°C; freezing proceeds very rapidly beyond that point. The rate of expansion with increased temperature is greater in seawater than in fresh water. Thus, at temperature 15°C, and atmospheric pressure, the coefficient of thermal expansion is 0.000151 per degree Celsius for freshwater, and 0.000214 per degree Celsius for average seawater. The coefficient of thermal expansion increases not only with greater salinity, but also with increased temperature and pressure. At a salinity of 35 psu, the coefficient of surface water increases from 0.000051 per degree Celsius at 0°C to 0.000334 per degree Celsius at 31°C. At a constant temperature of 0°C and a salinity of 34.85 psu, the coefficient increases to 0.000276 per degree Celsius at a pressure of 10,000 decibars (a depth of approximately 10,000 meters).

3412. Thermal Conductivity

In water, as in other substances, one method of heat transfer is by conduction. Freshwater is a poor conductor of heat, having a coefficient of thermal conductivity of 582 Joules per second per meter per degree Celsius. For seawater it is slightly less, but increases with greater temperature or pressure.

However, if turbulence is present, which it nearly always is to some extent, the processes of heat transfer are altered. The effect of turbulence is to increase greatly the rate of heat transfer. The "eddy" coefficient used in place of the still-water coefficient is many times larger, and so dependent upon the degree of turbulence, that the effects of temperature and pressure are not important.

3413. Electrical Conductivity

Water without impurities is a very poor conductor of electricity. However, when salt is in solution in water, the salt molecules are ionized and become carriers of electricity. (What is commonly called freshwater has many impurities and is a good conductor of electricity; only pure distilled water is a poor conductor.) Hence, the electrical conductivity of seawater is directly proportional to the number of salt molecules in the water. For any given salinity, the conductivity increases with an increase in temperature.

3414. Radioactivity

Although the amount of radioactive material in seawater is very small, this material is present in marine sediments to a greater extent than in the rocks of the Earth's crust. This is probably due to precipitation of radium or other radioactive material from the water. The radioactivity of the top layers of sediment is less than that of deeper layers. This may be due to absorption of radioactive material in the soft tissues of marine organisms.

3415. Transparency

The two basic processes that alter the underwater distribution of light are absorption and scattering. Absorption is a change of light energy into other forms of energy; scattering entails a change in direction of the light, but without loss of energy. If seawater were purely absorbing, the loss of light with distance would be given by $I_x = I_0 e\text{-}ax$ where I_x is the intensity of light at distance x, I_0 is the intensity of light at the source, and "a" is the absorption coefficient in the same units with which distance is measured. In a pure scattering medium, the transmission of light is governed by the same power law, only in this case the exponential term is $I_0 e\text{-}bx$, where "b" is the volume scattering coefficient. The attenuation of light in the ocean is defined as the sum of absorption and scattering so that the attenuation coefficient, c, is given by c = a + b. In the ocean, the attenuation of light with depth depends not only on the wavelength of the light but also the clarity of the water. The clarity is mostly controlled by biological activity although at the coast, sediments transported by rivers or resuspended by wave action can strongly attenuate light.

Attenuation in the sea is measured with a **transmissometer**. Transmissometers measure the attenuation of light over a fixed distance using a monochromatic light source which is close to red in color. Transmissometers are designed for in situ use and are usually attached to a CTD.

Since sunlight is critical for almost all forms of plant life in the ocean, oceanographers developed a simple method to measure the penetration of sunlight in the sea using a white disk 31 centimeters (a little less than 1 foot) in diameter which is called a **Secchi disk** (see Figure 3415a). This is lowered into the sea, and the depth at which it disappears is recorded. In coastal waters the depth varies from about 5 to 25 meters. Offshore, the depth is usually about 45 to 60 meters. The greatest recorded depth at which the disk has disappeared is 79 meters in the eastern Weddell Sea. These depths, D, are sometimes reported as a diffuse attenuation (or "extinction") coefficient, k, where k = 1.7/D and the penetration of sunlight is given by $I_z = I_0 e^{-kz}$, where z is depth and I_0 is the energy of the sunlight at the ocean's surface.

3416. Color

The color of seawater varies considerably. Water of the Gulf Stream is a deep indigo blue, while a similar current off Japan was named Kuroshio (Black Stream) because of

Figure 3415a. A Secchi disk is use to measure sunlight penetration through the water.

the dark color of its water. Along many coasts the water is green. In certain localities a brown or brownish-red water has been observed. Colors other than blue are caused by biological sources, such as plankton, or by suspended sediments from river runoff.

Offshore, some shade of blue is common, particularly in tropical or subtropical regions. It is due to scattering of sunlight by minute particles suspended in the water, or by molecules of the water itself. Because of its short wavelength, blue light is more effectively scattered than light of longer waves. Thus, the ocean appears blue for the same reason that the sky does. The green color often seen near the coast is a mixture of the blue due to scattering of light and a stable soluble yellow pigment associated with phytoplankton. Brown or brownish-red water receives its color from large quantities of certain types of **algae**, microscopic plants in the sea, or from river runoff.

3417. Bottom Relief

Compared to land, relatively little is known of relief below the surface of the sea. The development of an effective echo sounder in 1922 greatly simplified the determination of bottom depth. Later, a recording echo sounder was developed to permit the continuous tracing of a bottom profile. The latest sounding systems employ an array of echosounders aboard a single vessel, which continuously sound a wide swath of ocean floor. This has contributed immensely to our knowledge of bottom relief. Beginning in the 1980's, satellite altimeters were launched, providing a global 'view' of the ocean's bathymetry. By these means, many undersea mountain ranges, volcanoes, rift valleys, and other features have been discovered.

Along most of the coasts of the continents, the bottom slopes gradually to a depth of about 130 meters or somewhat less, where it falls away more rapidly to greater depths. This **continental shelf** averages about 65 kilometers in width, but varies from the shoreline to about 1400 kilometers, the widest area being off the Siberian Arctic coast. A similar shelf extending outward from an island or group of islands is called an **island shelf**. At the outer edge of the shelf, the steeper slope of 2° to 4° is called the **continental slope**, or the **island slope**, according to whether it surrounds a continent or a group of islands. The shelf itself is not uniform, but has numerous hills, ridges, terraces, and canyons, the largest being comparable in size to the Grand Canyon.

The relief of the ocean floor is comparable to that of land. Both have steep, rugged mountains, deep canyons, rolling hills, plains, etc. Most of the ocean floor is considered to be made up of a number of more-or-less circular or oval depressions called **basins**, surrounded by walls (**sills**) of lesser depth.

A wide variety of submarine features have been identified and defined. Some of these are shown in Figure 3417. The term **deep** may be used for a very deep part of the ocean, generally that part deeper than 6,000 meters.

The average depth of water in the oceans is 3795 meters (2,075 fathoms), as compared to an average height of land above the sea of about 840 meters. The greatest known depth is 11,524 meters, in the Marianas Trench in the Pacific. The highest known land is Mount Everest, 8,840 meters. About 23 percent of the ocean is shallower than 3,000 meters, about 76 percent is between 3,000 and 6,000 meters, and a little more than 1 percent is deeper than 6,000 meters.
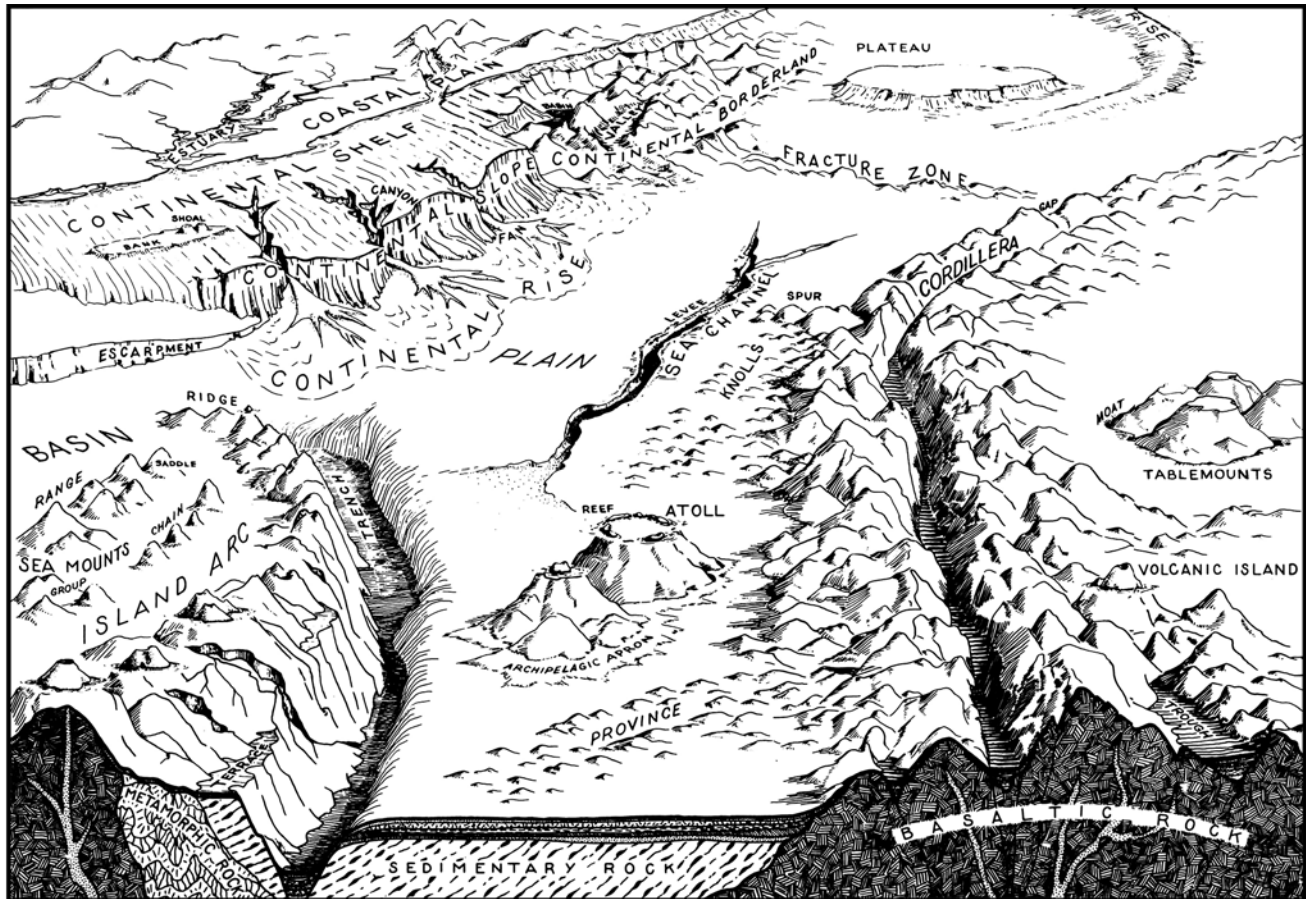
Figure 3417. Ocean basin features.

3418. Marine Sediments

The ocean floor is composed of material deposited through the ages. This material consists principally of (1) earth and rocks washed into the sea by streams and waves, (2) volcanic ashes and lava, and (3) the remains of marine organisms. Lesser amounts of land material are carried into the sea by glaciers, blown out to sea by wind, or deposited by chemical means. This latter process is responsible for the **manganese nodules** that cover some parts of the ocean floor. In the ocean, the material is transported by ocean currents, waves, and ice. Near shore the material is deposited at the rate of about 8 centimeters in 1,000 years, while in the deep water offshore the rate is only about 1 centimeter in 1,000 years. Marine deposits in water deep enough to be relatively free from wave action are subject to little erosion. Recent studies have shown that some bottom currents are strong enough to move sediments. There are **turbidity currents,** similar to land slides, which move large masses of sediments. Turbidity currents have been known to rip apart large transoceanic cables on the ocean bottom. Because of this and the slow rate of deposit, marine sediments provide a better geological record than does the land.

Marine sediments are composed of individual particles of all sizes from the finest clay to large boulders. In general, the inor-ganic deposits near shore are relatively coarse (sand, gravel, shingle, etc.), while those in deep water are much finer (clay). In some areas the siliceous remains of marine organisms or calcareous deposits of either organic or inorganic origin predominate on the ocean floor.

A wide range of colors is found in marine sediments. The lighter colors (white or a pale tint) are usually associated with coarse-grained quartz or limestone deposits. Darker colors (red, blue, green, etc.) are usually found in mud having a predominance of some mineral substance, such as an oxide of iron or manganese. Black mud is often found in an area that is little disturbed, such as at the bottom of an inlet or in a depression without free access to other areas.

Marine sediments are studied primarily through bottom samples. Samples of surface deposits are obtained by means of a "snapper" (for mud, sand, etc.) or "dredge" (usually for rocky material). If a sample of material below the bottom surface is desired, a "coring" device is used. This device consists essentially of a tube driven into the bottom by weights or explosives. A sample obtained in this way preserves the natural order of the various layers. Samples of more than 100 feet in depth have been obtained using coring devices.

3419. Satellite Oceanography

Weather satellites are able to observe ocean surface temperatures in cloud free regions by using infrared sensors. Although these sensors are only able to penetrate a few millimeters into the ocean, the temperatures that they yield are representative of upper ocean conditions except when the air is absolutely calm during daylight hours. For cloud covered regions, it is usually possible to wait a few days for the passage of a cold front and then use a sequence of infrared images to map the ocean temperature over a region. The patterns of warm and cold water yield information on ocean currents, the existence of fronts and eddies, and the temporal and spatial scales of ocean processes.

Other satellite sensors are capable of measuring ocean color, ice coverage, ice age, ice edge, surface winds and seas, ocean currents, and the shape of the surface of the ocean. The latter is controlled by gravity and ocean circulation patterns (see Chapter 2 for more information). The perspective provided by these satellites is a global one and in some cases they yield sufficient quantities of data that synoptic charts of the ocean surface, similar to weather maps and pilot charts, can be provided to the mariner for use in navigation.

The accuracy of satellite observations of the ocean surface depends, in many cases, on calibration procedures, which use observations of sea surface conditions provided by mariners. These observations include marine weather observations, expendable bathythermograph soundings, and currents measured by electromagnetic logs or acoustic Doppler current profilers. Care and diligence in these observations will improve the accuracy and the quality of satellite data.

3420. Synoptic Oceanography

Oceanographic data provided by ships, buoys, and satellites are analyzed by the Naval Oceanographic Office (NAVO), the National Oceanic and Atmospheric Administration (NOAA) and NOAA's National Weather Service. This data is utilized in computer models both to provide a synoptic view of ocean conditions and to predict how these conditions will change in the future. These products are available to the mariner via radio or satellite.

The Naval Oceanographic Portal may be accessed through the following link (see Figure 3420).

Figure 3420. Naval Oceanographic Portal
https://metoc.ndbc.noaa.gov/web/guest/navo

3421. References

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CHAPTER 35

TIDES AND TIDAL CURRENTS

ORIGINS OF TIDES

3500. Introduction

Tides are the periodic motion of the waters of the sea due to changes in the attractive forces of the Moon and Sun upon the rotating Earth. Tides can either help or hinder a mariner. A high tide may provide enough depth to clear a bar, while a low tide may prevent entering or leaving a harbor. Tidal current may help progress or hinder it, may set the ship toward dangers or away from them. By understanding tides and making intelligent use of predictions published, the navigator can plan an expeditious and safe passage through tidal waters.

3501. Tide and Current

The rise and fall of tide is accompanied by horizontal movement of the water called tidal current. It is necessary to distinguish clearly between tide and tidal current, for the relation between them is complex and variable. For the sake of clarity mariners have adopted the following definitions: Tide is the vertical rise and fall of the water, and tidal current is the horizontal flow. The tide rises and falls, the tidal current floods and ebbs. The navigator is concerned with the amount and time of the tide, as it affects access to shallow ports. The navigator is concerned with the time, speed, and direction of the tidal current, as it will affect his ship's position, speed, and course.

Tides are superimposed on nontidal rising and falling water levels, caused by weather, seismic events, or other natural forces. Similarly, tidal currents are superimposed upon non-tidal currents such as normal river flows, floods, and freshets.

3502. Causes of Tides

The principal tidal forces are generated by the Moon and Sun. The Moon is the main tide-generating body. Due to its greater distance, the Sun's effect is only 46 percent of the Moon's. Observed tides will differ considerably from the tides predicted by equilibrium theory because size, depth, and configuration of the basin or waterway, friction, land masses, inertia of water masses, Coriolis acceleration, and other factors are neglected in this theory. Nevertheless, the equilibrium theory is sufficient to describe the magnitude and distribution of the main tide-generating forces across the surface of the Earth.

Newton's universal law of gravitation governs both the orbits of celestial bodies and the tide-generating forces which occur on them. The force of gravitational attraction between any two masses, m_1 and m_2, is given by:

$$F = \frac{Gm_1m_2}{d^2}$$

where d is the distance between the two masses, and G is the universal gravitational constant which depends upon the units employed. This law assumes that m_1 and m_2 are point masses. Newton was able to show that homogeneous spheres could be treated as point masses when determining their orbits.

However, when computing differential gravitational forces, the actual dimensions of the masses must be taken into account.

Using the law of gravitation, it is found that the orbits of two point masses are conic sections about the **barycenter** of the two masses. If either one or both of the masses are homogeneous spheres instead of point masses, the orbits are the same as the orbits which would result if all of the mass of the sphere were concentrated at a point at the center of the sphere. In the case of the Earth-Moon system, both the Earth and the Moon describe elliptical orbits about their barycenter if both bodies are assumed to be homogeneous spheres and the gravitational forces of the Sun and other planets are neglected. The Earth-Moon barycenter is located 74/100 of the distance from the center of the Earth to its surface, along the line connecting the Earth's and Moon's centers. See Figure 3502a.

Thus the center of mass of the Earth describes a very small ellipse about the Earth-Moon barycenter, while the center of mass of the Moon describes a much larger ellipse about the same barycenter. If the gravitational forces of the other bodies of the solar system are neglected, Newton's law of gravitation also predicts that the Earth-Moon barycenter will describe an orbit which is approximately elliptical about the barycenter of the Sun-Earth-Moon system. This barycentric point lies inside the Sun. See Figure 3502b.

3503. The Earth-Moon-Sun System

The fundamental tide-generating force on the Earth has two interactive but distinct components. The tide-generating forces are differential forces between the
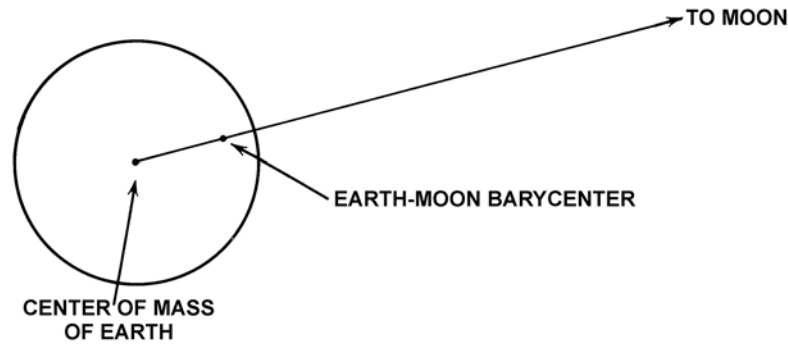
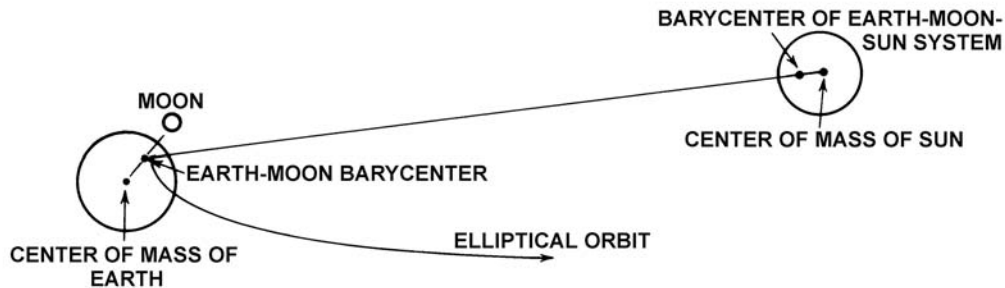*Figure 3502a. Earth-Moon barycenter.*

Figure 3502b. Orbit of Earth-Moon barycenter (not to scale).

gravitational attraction of the bodies (Earth-Sun and Earth-Moon) and the centrifugal forces on the Earth produced by the Earth's orbit around the Sun and the Moon's orbit around the Earth. Newton's Law of Gravitation and his Second Law of Motion can be combined to develop formulations for the differential force at any point on the Earth, as the direction and magnitude are dependent on where you are on the Earth's surface. As a result of these differential forces, the tide generating forces F_{dm} (Moon) and F_{ds} (Sun) are inversely proportional to the cube of the distance between the bodies, where:

$$F_{dm} = \frac{GM_m R_e}{d_m{}^3}; \quad F_{ds} = \frac{GM_s R_e}{d_s{}^3}$$

where M_m is the mass of the Moon and M_s is the mass of the Sun, R_e is the radius of the Earth and d is the distance to the Moon or Sun. This explains why the tide-generating force of the Sun is only 46/100 of the tide-generating force of the Moon. Even though the Sun is much more massive, it is also much farther away.

Using Newton's second law of motion, we can calculate the differential forces generated by the Moon and the Sun affecting any point on the Earth. The easiest calculation is for the point directly below the Moon, known as the **sublunar point**, and the point on the Earth exactly opposite, known as the **antipode**. Similar calculations are done for the Sun.

If we assume that the entire surface of the Earth is covered with a uniform layer of water, the differential forces may be resolved into vectors perpendicular and parallel to the surface of the Earth to determine their effect. See Figure 3503a.

The perpendicular components change the mass on which they are acting, but do not contribute to the tidal effect. The horizontal components, parallel to the Earth's surface, have the effect of moving the water in a horizontal direction toward the sublunar and antipodal points until an equilibrium position is found. The *horizontal* components of the differential forces are the principal tide-generating forces. These are also called **tractive forces**. Tractive forces are zero at the sublunar and antipodal points and along the great circle halfway between these two points. Tractive forces are maximum along the small circles located 45° from the sublunar point and the antipode. Figure 3503b shows the tractive forces across the surface of the Earth.
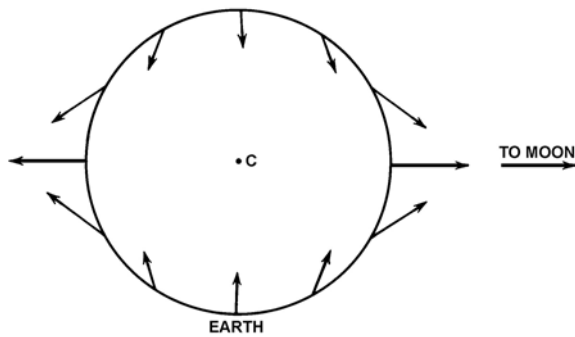
Figure 3503a. Differential forces along a great circle connecting the sublunar point and antipode.
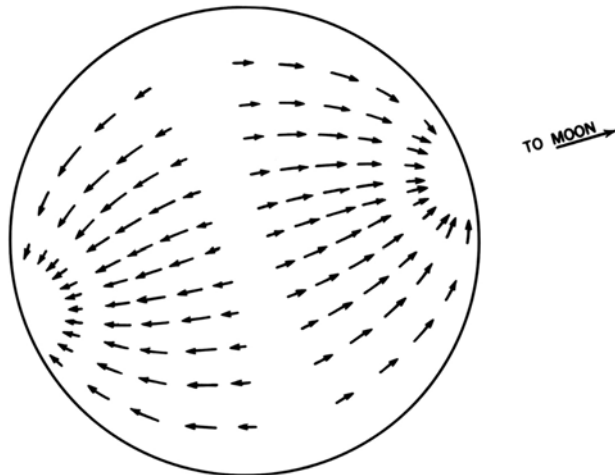

Figure 3503b. Tractive forces across the surface of the Earth.

Equilibrium will be reached when a bulge of water has formed at the sublunar and antipodal points such that the tractive forces due to the Moon's differential gravitational forces on the mass of water covering the surface of the Earth are just balanced by the Earth's gravitational attraction (Figure 3503c).

Now consider the effect of the rotation of the Earth. If the declination of the Moon is 0°, the bulges will lie on the equator. As the Earth rotates, an observer at the equator will note that the Moon transits approximately every 24 hours and 50 minutes. Since there are two bulges of water on the equator, one at the sublunar point and the other at the antipode, the observer will also see two high tides during this interval with one high tide occurring when the Moon is overhead and another high tide 12 hours 25 minutes later when the observer is at the antipode. He will also experience a low tide between each high tide. The theoretical range of these equilibrium tides at the equator will be less than 1 meter.

In theory, the heights of the two high tides should be equal at the equator. At points north or south of the equator, an observer would still experience two high and two low tides, but the heights of the high tides would not be as great as they are at the equator. The effects of the declination of the Moon are shown in Figure 3503d, for three cases, A, B, and C.

A. When the Moon is on the plane of the equator, the forces are equal in magnitude at the two points on the same parallel of latitude and 180° apart in longitude.

B. When the Moon has north or south declination, the forces are unequal at such points and tend to cause an inequality in the two high waters and the two low waters each day.

C. Observers at points X, Y, and Z experience one high tide when the Moon is on their meridian, then another high tide 12 hours 25 minutes later when at X', Y', and Z'. The second high tide is the same at X' as at X. High tides at Y' and Z' are lower than high tides at Y and Z.

The preceding discussion pertaining to the effects of the Moon is equally valid when discussing the effects of the Sun, taking into account that the magnitude of the solar effect is smaller. Hence, the tides will also vary according to the Sun's declination and its varying distance from the Earth. A second envelope of water representing the equilibrium tides due to the Sun would resemble the envelope shown in Figure 3503c except that the heights of the high tides would be smaller, and the low tides correspondingly not as low. The theoretical tide at any place represents the combination of the effects of both the Moon and Sun.

FEATURES OF TIDES

3504. General Features

At most places the tidal change occurs twice daily. The tide rises until it reaches a maximum height, called **high tide** or **high water**, and then falls to a minimum level called **low tide** or **low water**.

The rate of rise and fall is not uniform. From low water, the tide begins to rise slowly at first, but at an increasing rate until it is about halfway to high water. The rate of rise then decreases until high water is reached, and then the rise ceases.

The falling tide behaves in a similar manner. The period at high or low water during which there is no apparent change of level is called **stand**. The difference in height between consecutive high and low waters is the **range**.
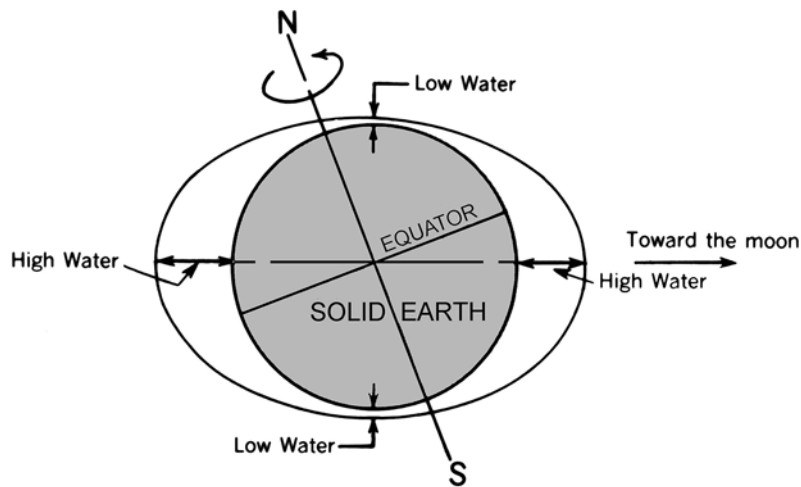
Figure 3503c. Theoretical equilibrium configuration due to Moon's differential gravitational forces. One bulge of the water envelope is located at the sublunar point, the other bulge at the antipode.
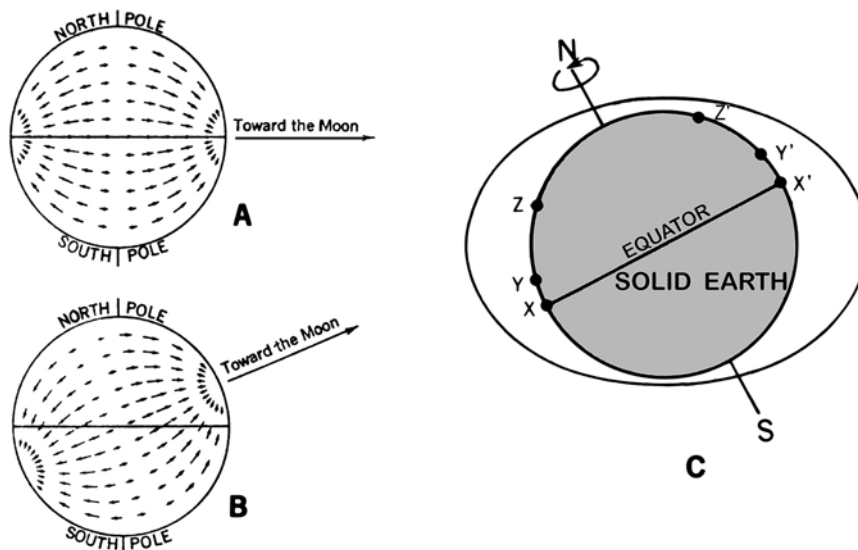

Figure 3503d. Effects of the declination of the Moon.

Figure 3504a is a graphical representation of the rise and fall of the tide at New York during a 24-hour period. The curve has the general form of a variable sine curve.

3505. Types of Tide

A body of water has a natural period of oscillation, dependent upon its dimensions. None of the oceans is a single oscillating body; rather each one is made up of several separate oscillating basins. As such basins are acted upon by the tide-producing forces, some respond more readily to daily or diurnal forces, others to semidi-urnal forces, and others almost equally to both. Hence, tides are classified as one of three types, semidiurnal, diurnal, or mixed, according to the characteristics of the tidal pattern.

In the **semidiurnal tide**, there are two high and two low waters each tidal day, with relatively small differences in the respective highs and lows. Tides on the Atlantic coast of the United States are of the semidiurnal type, which is illustrated in Figure 3505a by the tide curve for Boston Harbor.

In the **diurnal tide**, only a single high and single low water occur each tidal day. Tides of the diurnal type occur along the northern shore of the Gulf of Mexico, in the Java
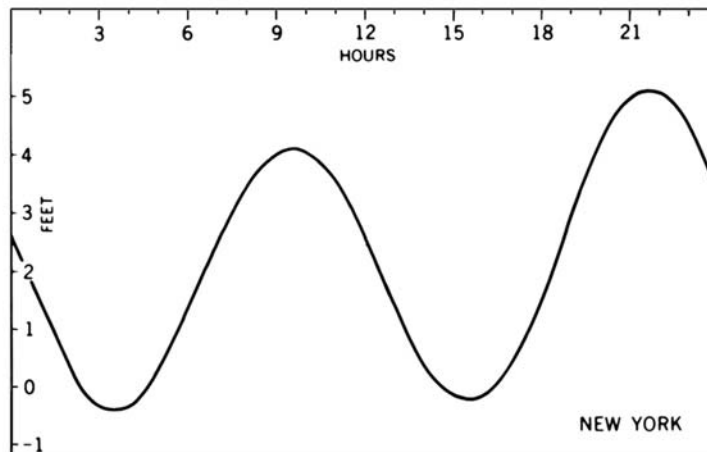
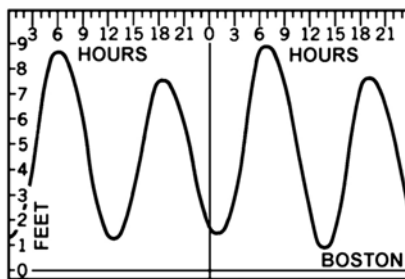*Figure 3504a. The rise and fall of the tide at New York, shown graphically..*

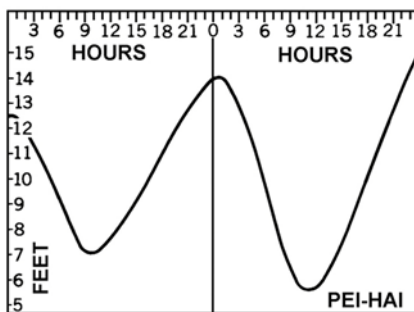
Figure 3505a Semidiurnal tide

Figure 3505b. Diurnal tide.

Sea, the Gulf of Tonkin, and in a few other localities. The tide curve for Pei-Hai, China, illustrated in Figure 3505b, is an example of the diurnal type.

In the **mixed tide**, the diurnal and semidiurnal oscillations are both important factors and the tide is characterized by a large inequality in the high water heights, low water

heights, or in both. There are usually two high and two low waters each day, but occasionally the tide may become diurnal. Such tides are prevalent along the Pacific coast of the United States and in many other parts of the world. Examples of mixed types of tide are shown in Figure 3505c. At Los Angeles it is typical that the inequalities in the high and low waters are about the same. At Seattle the greater inequalities are typically in the low waters, while at Honolulu it is the high waters that have the greater inequalities.

3506. Solar Tide

The natural period of oscillation of a body of water may accentuate either the solar or the lunar tidal oscillations. Though as a general rule the tides follow the Moon, the relative importance of the solar effect varies in different areas. There are a few places, primarily in the South Pacific and the Indonesian areas, where the solar oscillation is the more important, and at those places the high and low waters occur at about the same time each day. At Port Adelaide, Australia the solar and lunar semidiurnal oscillations are equal and nullify one another at neaps.

3507. Special Tidal Effects

As a wave enters shallow water, its speed is decreased. Since the trough is shallower than the crest, it is retarded more, resulting in a steepening of the wave front. In a few estuaries, the advance of the low water trough is so much retarded that the crest of the rising tide overtakes the low, and advances upstream as a breaking wave called a **bore**. Bores that are large and dangerous at times of large tidal ranges may be mere ripples at those times of the month when the range is small. Examples occur in the Petitcodiac River in the
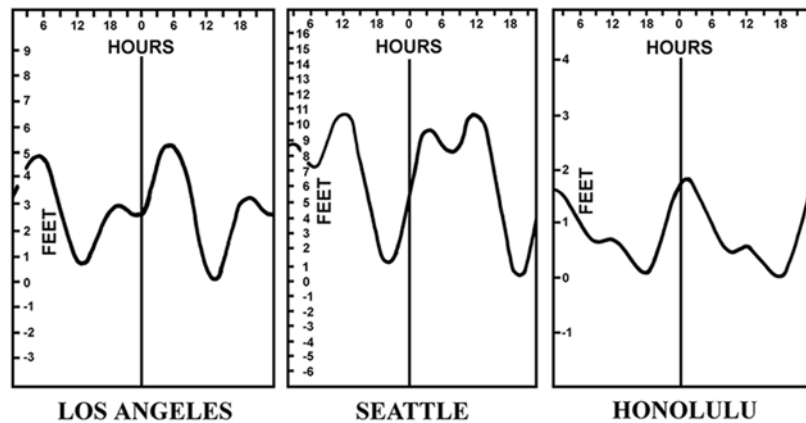
Figure 3505c. Mixed tide.

Bay of Fundy, and at Haining, China, in the Tsientang Kaing. The tide tables indicate where bores occur.

Other special features are the **double low water** (as at Hoek Van Holland) and the **double high water** (as at Southampton, England). At such places there is often a slight fall or rise in the middle of the high or low water period. The practical effect is to create a longer period of stand at high or low tide. The tide tables list these and other peculiarities where they occur.

3508. Variations in Range

Though the tide at a particular place can be classified as to type, it exhibits many variations during the month (Figure 3508a). The range of the tide varies according to the intensity of the tide-producing forces, though there may be a lag of a day or two between a particular astronomic cause and the tidal effect.

The combined lunar-solar effect is obtained by adding the Moon's tractive forces vectorially to the Sun's tractive forces. The resultant tidal bulge will be predominantly lunar with modifying solar effects upon both the height of the tide and the direction of the tidal bulge. Special cases of interest occur during the times of new and full Moon (Figure 3508b). With the Earth, Moon, and Sun lying approximately on the same line, the tractive forces of the Sun are acting in the same direction as the Moon's tractive forces (modified by declination effects). The resultant tides are called **spring tides**, whose ranges are greater than average.

Between the spring tides, the Moon is at first and third quarters. At those times, the tractive forces of the Sun are acting at approximately right angles to the Moon's tractive forces. The results are tides called **neap tides**, whose ranges are less than average.

With the Moon in positions between quadrature and new or full, the effect of the Sun is to cause the tidal bulge to either lag or precede the Moon (Figure 3508c). These effects are called **priming** and **lagging** the tides.

Thus, when the Moon is at the point in its orbit nearest the Earth (at perigee), the lunar semidiurnal range is increased and **perigean tides** occur. When the Moon is farthest from the Earth (at apogee), the smaller **apogean tides** occur. When the Moon and Sun are in line and pulling together, as at new and full Moon, **spring tides** occur (the term spring has nothing to do with the season of year); when the Moon and Sun oppose each other, as at the quadratures, the smaller **neap tides** occur. When certain of these phenomena coincide, **perigean spring tides** and **apogean neap tides** occur.

These are variations in the semidiurnal portion of the tide. Variations in the diurnal portion occur as the Moon and Sun change declination. When the Moon is at its maximum semi-monthly declination (either north or south), **tropic tides** occur in which the diurnal effect is at a maximum. When it crosses the equator, the diurnal effect is a minimum and **equatorial tides** occur.

When the range of tide is increased, as at spring tides, there is more water available only at high tide; at low tide there is less, for the high waters rise higher and the low waters fall lower at these times. There is more water at neap low water than at spring low water. With tropic tides, there is usually more depth at one low water during the day than at the other. While it is desirable to know the meanings of these terms, the best way of determining the height of the tide at any place and time is to examine the tide predictions for the place as given in the tide tables, which take all these effects into account.

3509. Tidal Cycles

Tidal oscillations go through a number of cycles. The shortest cycle, completed in about 12 hours and 25 minutes for a semidiurnal tide, extends from any phase of the tide to the next
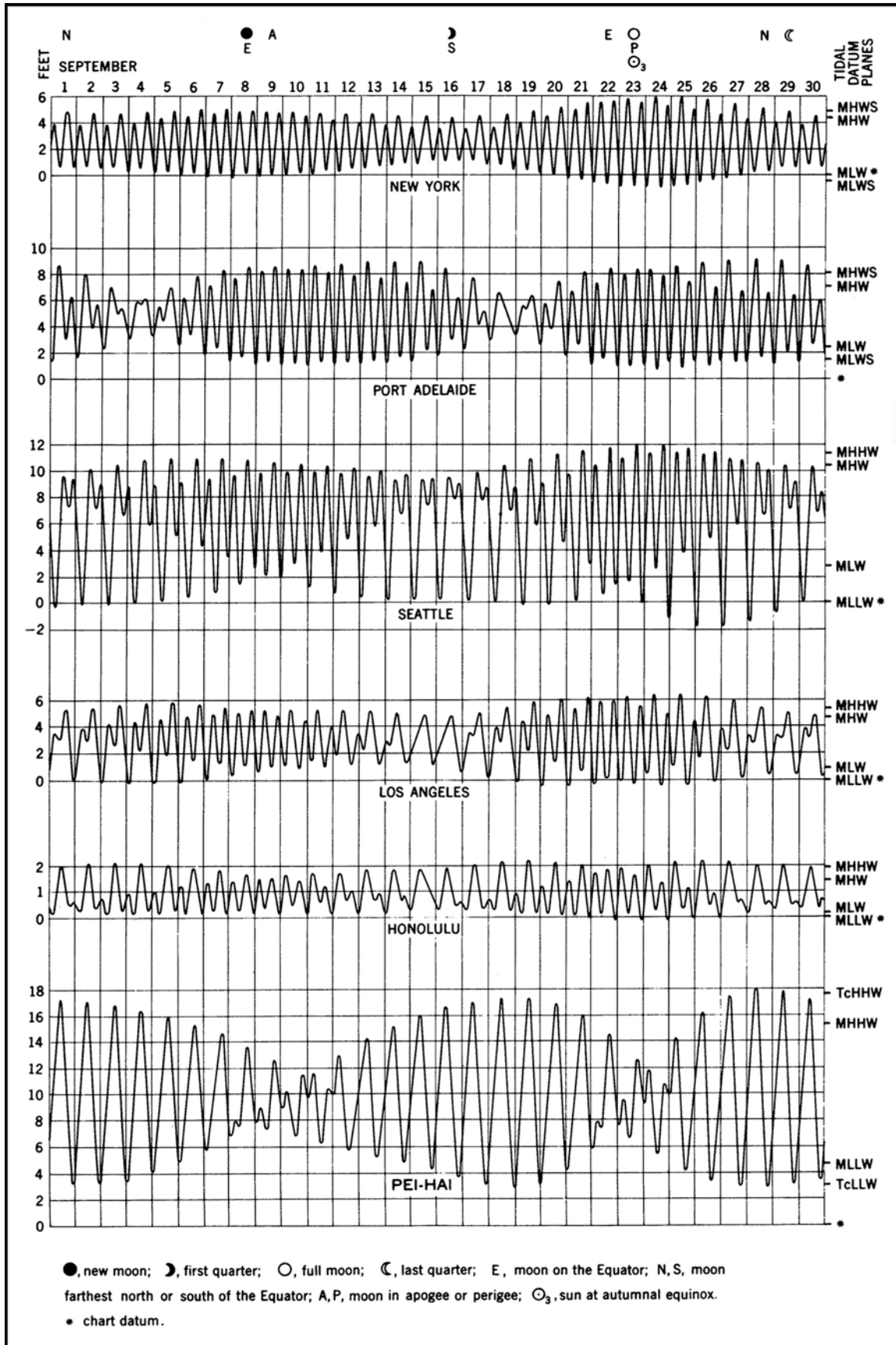
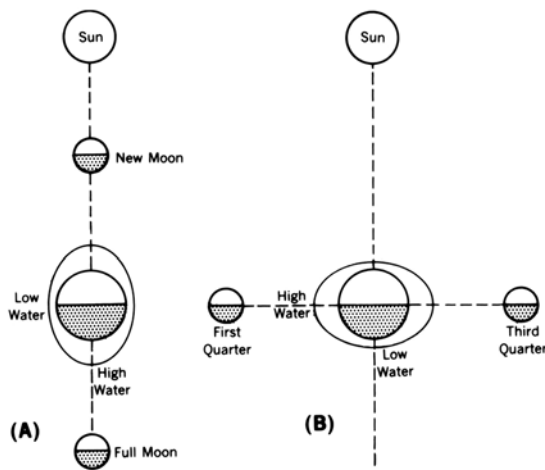*Figure 3508a. Monthly tidal variations at various places.*

Figure 3508b. (A) Spring tides occur at times of new and full Moon. Range of tide is greater than average since solar and lunar tractive forces act in same direction. (B) Neap ties occur at times of first and third quarters. Range of tide is less than average since solar and lunar tractive forces act at right angles.

recurrence of the same phase. During a lunar day (averaging 24 hours and 50 minutes) there are two highs and two lows (two of the shorter cycles) for a semidiurnal tide. The Moon revolves around the Earth with respect to the Sun in a **synodical month** of about 29 1/2 days, commonly called the **lunar month**. The effect of the phase variation is completed in one-half of a synodical month or about 2 weeks as the Moon varies from new to full or full to new.

The effect of the Moon's declination is also repeated in one-half of a **tropical month** of 27 1/3 days, or about every 2 weeks. The cycle involving the Moon's distance requires an **anomalistic month** of about 27 1/2 days. The Sun's declination and distance cycles are respectively a half year and a year in length.

An important lunar cycle, called the **nodal period** or Metonic cycle (after Greek philosopher Meton, fifth century B.C., who discovered the phenomenon) is 18.6 years (usually expressed in round figures as 19 years). For a tidal value, particularly a range, to be considered a true mean, it must be either based upon observations extended over this period of time, or adjusted to take account of variations known to occur during the nodal period.

The nodal period is the result of axis of the Moon's rotation being tilted 5 degrees with respect to the axis of the Earth's rotation. Since the Earth's axis is tilted 23.5 degrees with respect to the plane of its revolution around the sun, the combined effect is that the Moon's declination varies from 28.5 degrees to 18.5 degrees in a cycle lasting 18.6 years. For practical purposes, the nodal period can be considered as the time between the Sun and Moon appearing in precisely the same relative positions in the sky.
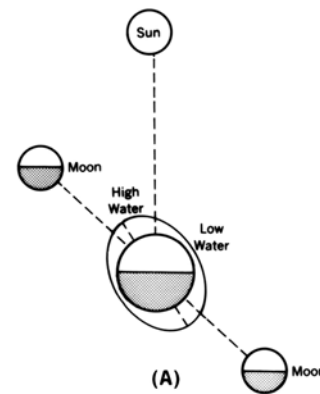
Priming occurs when moon is between new and first quarter and between full and third quarter. High tide occurs before transit moon.
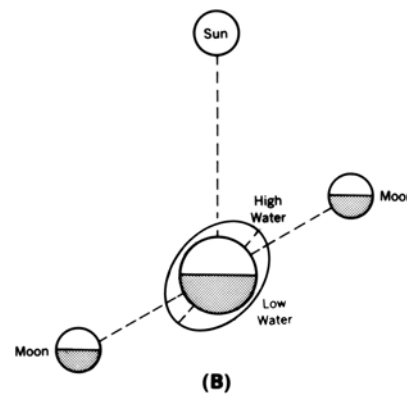
Lagging occurs when moon is between first quarter and full and between third quarter and new. High tide occurs after transit of moon.

Figure 3508c. Priming and lagging the tides.

3510. Time of Tide

Since the lunar tide-producing force has the greatest effect in producing tides at most places, the tides "follow the Moon." Because the Earth rotates, high water lags behind both upper and lower meridian passage of the Moon. The **tidal day**, which is also the lunar day, is the time between consecutive transits of the Moon, or 24 hours and 50 minutes on the average. Where the tide is largely semidiurnal in type, the **lunitidal interval** (the interval between the Moon's meridian transit and a particular phase of tide) is fairly constant throughout the month, varying somewhat with the tidal cycles. There are many places, however, where solar or diurnal oscillations are effective in upsetting this relationship. The interval generally given is the average elapsed time from the meridian transit (upper or lower) of the Moon until the next high tide. This may be called **mean high water lunitidal interval** or **corrected** (or **mean**) **establishment**. The **common establishment** is the average interval on days of full or new Moon, and approximates the mean high water lunitidal interval.

In the ocean, the tide may be in the nature of a progressive wave with the crest moving forward, a stationary or standing wave which oscillates in a seesaw fashion, or a combination of the two. Consequently, caution should be used in inferring the time of tide at a place from tidal data for nearby places. In a river or estuary, the tide enters from the sea and is usually sent upstream as a progressive wave so that the tide occurs progressively later at various places upstream.

3511. Tides and Water Levels Online Tutorial

An excellent **online tutorial** created by NOAA's National Ocean Service is available via the link provided in Figure 3511. Topics in this tutorial include: *What are Tides,*

What Causes Tides; Gravity, Inertia and Bulges; Changing Angles and Tides, Frequency of Tides, Tidal Variations, and *Types and Causes of Tidal Cycles.*

Figure 3511. NOAA's Tides and Water Levels tutorial.
http://oceanservice.noaa.gov/education/tutorial_tides/

TIDAL DATUMS

3512. Low Water Datums

A tidal datum is a given average tide level from which heights of tides and overhead clearances are measured. It is a vertical datum, but is not the same as vertical geodetic datum, which is a mathematical quantity developed as part of a geodetic system used for horizontal positioning. There are a number of tidal levels of reference that are important to the mariner. See Figure 3512.

The most important level of reference is the **sounding datum** shown on charts. The sounding datum is sometimes referred to as the **reference plane** to distinguish it from vertical geodetic datum. Since the tide rises and falls continually while soundings are being taken during a hydrographic survey, the tide is recorded during the survey so that soundings taken at all stages of the tide can be reduced to a common sounding datum. Soundings on charts show depths below a selected low water datum (occasionally mean sea level), and tide predictions in tide tables show heights above and below the same level. The depth of water available at any time is obtained by adding algebraically the height of the tide at the time in question to the charted depth.

By international agreement, the level used as chart datum should be low enough so that low waters do not fall very far below it. At most places, the level used is one determined from a mean of a number of low waters (usually over a 19 year period); therefore, some low waters can be expected to fall below it. The following are some of the datums in general use.

Mean low water (MLW) is the average height of all low waters at a given place. About half of the low waters fall below it, and half above.

Mean low water springs (MLWS), usually shortened to low water springs, is the average level of the low waters that occur at the times of spring tides.

Mean lower low water (MLLW) is the average height of the lower low waters of each tidal day.

Tropic lower low water (TcLLW) is the average height of the lower low waters (or of the single daily low

waters if the tide becomes diurnal) that occur when the Moon is near maximum declination and the diurnal effect is most pronounced. This datum is not in common use as a tidal reference.

Indian spring low water (ISLW), sometimes called **Indian tide plane** or **harmonic tide plane**, is a low water datum that includes the spring effect of the semi-diurnal portion of the tide and the tropic effect of the diurnal portion. It is about the level of lower low water of mixed tides at the time that the Moon's maximum declination coincides with the time of new or full Moon.

Mean lower low water springs (MLLWS) is the average level of the lower of the two low waters on the days of spring tides.

Some lower datums used on charts are determined from tide observations and some are determined arbitrarily and later referred to the tide. Most of them fall close to one or the other of the following two datums.

Lowest normal low water is a datum that approximates the average height of monthly lowest low waters, discarding any tides disturbed by storms.

Lowest low water is an extremely low datum. It conforms generally to the lowest tide observed, or even somewhat lower. Once a tidal datum is established, it is sometimes retained for an indefinite period, even though it might differ slightly from a better determination from later observations. When this occurs, the established datum may be called **low water datum**, **lower low water datum**, etc. These datums are used in a limited area and primarily for river and harbor engineering purposes. Examples are Boston Harbor Low Water Datum and Columbia River Lower Low Water Datum.

Some sounding datums are based on the predicted tide rather than an average of observations. A British sounding datum that may be adopted internationally is the Lowest Astronomical Tide (LAT). LAT is the elevation of the lowest water level predicted in a 19-year period. Canadian coastal charts use a datum of Lower Low Water, Large Tide (LLWLT) which is the average of the lowest low waters, one from each of the 19 years of predictions.
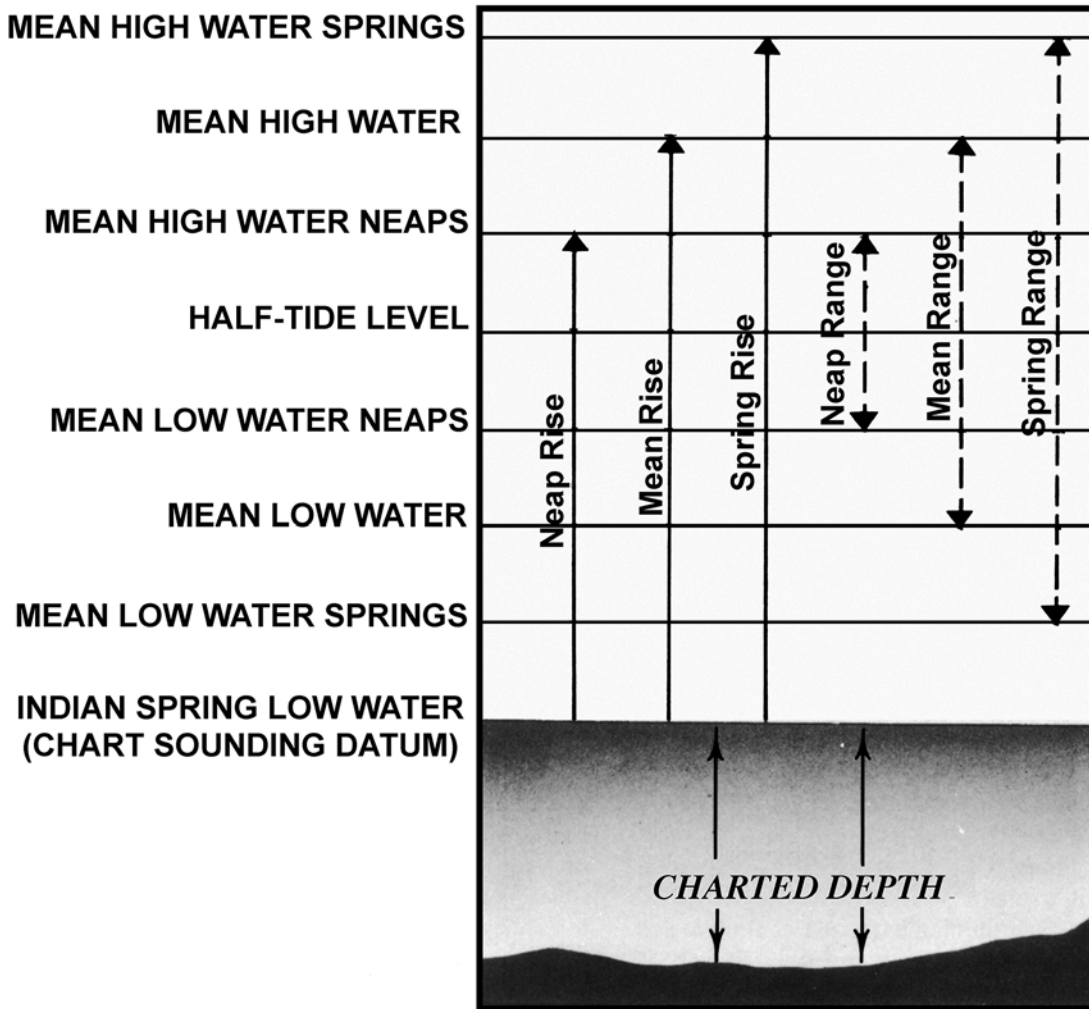
Figure 3512. Variations in the ranges and heights of tide where the chart sounding datum is Indian Spring Low Water.

Figure 3512 illustrates variations in the ranges and heights of tides in a locality such as the Indian Ocean, where predicted and observed water levels are referenced to a chart sounding datum that will always cause them to be additive relative to the charted depth.

In areas where there is little or no tide, various other datums are used. For the Black Sea for instance, Mean Sea Level (MSL, sometimes referred to as Mean Water Level or MWL) is used, and is the average of the hourly heights observed over a period of time and adjusted to a 19-year period. In the United States, a Low Water Datum (LWD) is used in those coastal areas that have transitioned from tidal to non-tidal (e.g. Laguna Madre, Texas and Pamlico Sound, North Carolina) and is simply 0.5 foot below a computed MLW. For the Great Lakes, the United States and Canada use a separate LWD for each lake, which is designed to ensure that the actual water level is above the datum most of the time during the navigation season. Lake levels vary by several feet over a period of years.

Inconsistencies of terminology are found among charts of different countries and between charts issued at different times.

Large-scale charts usually specify the datum of soundings and may contain a tide note giving mean heights of the tide at one or more places on the chart. These heights are intended merely as a rough guide to the change in depth to be expected under the specified conditions. They should not be used for the prediction of heights on any particular day, which should be obtained from tide tables.

3513. High Water Datums

Heights of terrestrial features are usually referred on nautical charts to a high water datum. This gives the mariner a margin of error when passing under bridges, overhead cables, and other obstructions. The one used on charts of the United States, its territories and possessions, and widely used elsewhere, is **mean high water (MHW)**, which is the average height of all high waters over a 19 year period. Any other high water datum in use on charts is

likely to be higher than this. Other high water datums are **mean high water springs (MHWS)**, which is the average level of the high waters that occur at the time of spring tides; **mean higher high water (MHHW)**, which is the average height of the higher high waters of each tidal day; and **tropic higher high water (TcHHW)**, which is the average height of the higher high waters (or the single daily high waters if the tide becomes diurnal) that occur when the Moon is near maximum declination and the diurnal effect is most pronounced. A reference merely to "high water"

leaves some doubt as to the specific level referred to, for the height of high water varies from day to day. Where the range is large, the variation during a 2 week period may be considerable.

Because there are periodic and apparent secular trends in sea level, a specific 19 year cycle (the **National Tidal Datum Epoch**) is issued for all United States datums. The National Tidal Datum Epoch officially adopted by the National Ocean Service is presently 1983 through 2001. The Epoch is reviewed for revision every 20 -25 years.

TIDAL CURRENTS

3514. Tidal and Nontidal Currents

Horizontal movement of water is called **current**. It may be either "tidal" and "nontidal." **Tidal current** is the periodic horizontal flow of water accompanying the rise and fall of the tide. **Nontidal current** includes all currents not due to the tidal movement. Nontidal currents include the permanent currents in the general circulatory system of the oceans as well as temporary currents arising from meteorological conditions. The current experienced at any time is usually a combination of tidal and nontidal currents.

3515. General Features

Offshore, where the direction of flow is not restricted by any barriers, the tidal current is rotary; that is, it flows continuously, with the direction changing through all points of the compass during the tidal period. This rotation is caused by the Earth's rotation, and unless modified by local conditions, is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The speed usually varies throughout the tidal cycle, passing through two maximums in approximately opposite directions, and two minimums about halfway between the maximums in time and direction. Rotary currents can be depicted as in Figure 3515a, by a series of arrows representing the direction and speed of the current at each hour. This is sometimes called a **current rose**. Because of the elliptical pattern formed by the ends of the arrows, it is also referred to as a **current ellipse**.

In rivers or straits, or where the direction of flow is more or less restricted to certain channels, the tidal current is reversing; that is, it flows alternately in approximately opposite directions with an instant or short period of little or no current, called **slack water**, at each reversal of the current. During the flow in each direction, the speed varies from zero at the time of slack water to a maximum, called strength of flood or ebb, about midway between the slacks. Reversing currents can be indicated graphically, as in Figure 3515b, by arrows that represent the speed of the current at each hour. The flood is usually depicted above the slack waterline and the ebb below it. The tidal current curve formed by the ends of the arrows has the same characteristic
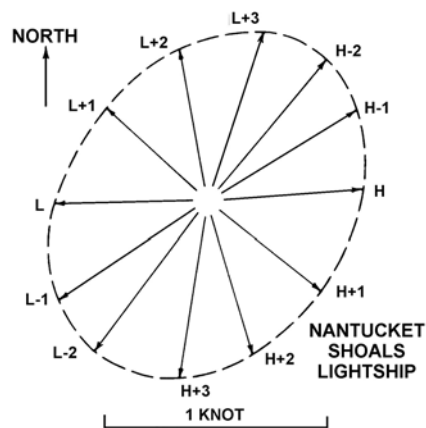
Figure 3515a. Rotary tidal current. Times are hours before and after high and low tide at Nantucket Shoals. The bearing and length of each arrow represents the hourly direction and speed of the current.
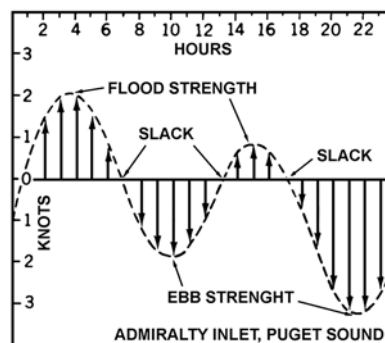
Figure 3515b. Reversing tidal current.

sine form as the tide curve. In illustrations and for certain other purposes it is convenient to omit the arrows and show only the curve.

A slight departure from the sine form is exhibited by the reversing current in a strait that connects two different tidal basins, such as the East River, New York. The tides at the two ends of a strait are seldom in phase or equal in range, and the current, called **hydraulic current**, is

generated largely by the continuously changing difference in height of water at the two ends. The speed of a hydraulic current varies nearly as the square root of the difference in height. The speed reaches a maximum more quickly and remains at strength for a longer period than shown in Figure 3515b, and the period of weak current near the time of slack is considerably shortened.

The current direction, or **set**, is the direction toward which the current flows. The speed is sometimes called the **drift**. The term "velocity" is often used as the equivalent of "speed" when referring to current, although strictly speaking "velocity" implies direction as well as speed. The term "strength" is also used to refer to speed, but more often to greatest speed between consecutive slack waters. The movement toward shore or upstream is the **flood**, the movement away from shore or downstream is the **ebb**. In a purely semidiurnal current unaffected by nontidal flow, the flood and ebb each last about 6 hours and 13 minutes. But if there is either diurnal inequality or nontidal flow, the durations of flood and ebb may be quite unequal.

3516. Types of Tidal Current

Tidal currents, like tides, may be of the **semidiurnal**, **diurnal**, or **mixed** type, corresponding to a considerable degree to the type of tide at the place, but often with a stronger semidiurnal tendency.

The tidal currents in tidal estuaries along the Atlantic coast of the United States are examples of the semidiurnal type of reversing current. Along the Gulf of Mexico coast, such as at Mobile Bay entrance, they are almost purely diurnal. At most places, however, the type is mixed to a greater or lesser degree. At Tampa and Galveston entrances there is only one flood and one ebb each day when the Moon is near its maximum declination, and two floods and two ebbs each day when the Moon is near the equator. Along the Pacific coast of the United States there are generally two floods and two ebbs every day, but one of the floods or ebbs has a greater speed and longer duration than the other, the inequality varying with the declination of the Moon.

The inequalities in the current often differ considerably from place to place even within limited areas, such as adjacent passages in Puget Sound and various passages between the Aleutian Islands. Figure 3516a shows several types of reversing current. Figure 3516b shows how the flood disappears as the diurnal inequality increases at one station.

Offshore rotary currents that are purely semidiurnal repeat the elliptical pattern each tidal cycle of 12 hours and 25 minutes. If there is considerable diurnal inequality, the plotted hourly current arrows describe a set of two ellipses of different sizes during a period of 24 hours and 50 minutes, as shown in Figure 3516c, and the greater the diurnal inequality, the greater the difference between the sizes of the two ellipses. In a completely diurnal rotary current, the smaller ellipse disappears and only one ellipse is produced in 24 hours and 50 minutes.
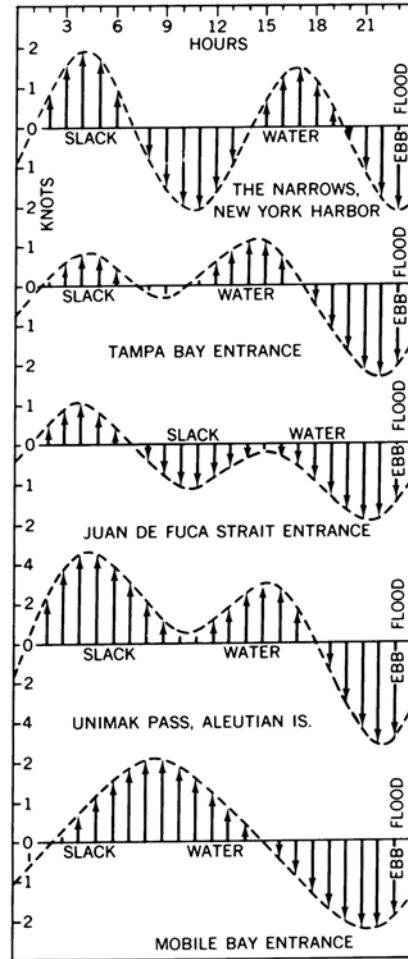
Figure 3516a. Several types of reversing current. The pattern changes gradually from day to day, particularly for mixed types, passing through cycles.

3517. Tidal Current Periods and Cycles

Tidal currents have periods and cycles similar to those of the tides, and are subject to similar variations, but flood and ebb of the current do not necessarily occur at the same times as the rise and fall of the tide.

The speed at flood or ebb strength increases and decreases during the 2 week period, month, and year along with the variations in the range of tide. Thus, the stronger spring and perigean currents occur near the times of new and full Moon and near the times of the Moon's perigee, or at times of spring and perigean tides; the weaker neap and apogean currents occur at the times of neap and apogean tides. Tropic currents with increased diurnal speeds or with larger diurnal inequalities in speed occur at times of tropic tides and equatorial currents with a minimum diurnal effect occur at times of equatorial tides.

As with the tide, a mean value represents an average obtained from a 19 year series. Since a series of current observations is usually limited to a few days, and seldom
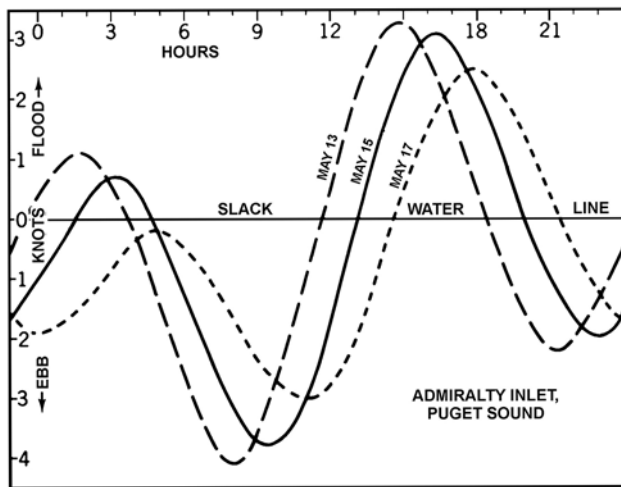
Figure 3516b. Changes in a current of the mixed type. Note that each day as the inequality increases, the morning slacks draw together in time until on the 17th the morning flood disappears. On that day the current ebbs throughout the morning.

Figure 3516c. Rotary tidal current with diurnal inequality. Times are in hours referred to tides (higher high, lower low, lower high, and higher low) at Swiftsure Bank.

covers more than a month or two, it is necessary to adjust the observed values, usually by comparison with tides at a nearby place, to obtain such a mean.

3518. Effect of Nontidal Flow

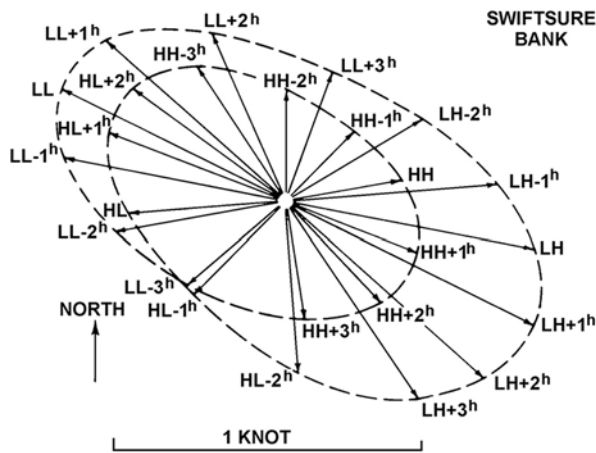The current existing at any time is seldom purely tidal, but usually includes also a nontidal current that is due to drainage, oceanic circulation, wind, or other causes. The method in which tidal and nontidal currents combine is best

explained graphically, as in Figure 3518a and Figure 3518b. The pattern of the tidal current remains unchanged, but the curve is shifted from the point or line from which the currents are measured, in the direction of the nontidal current, and by an amount equal to it. It is sometimes more convenient graphically merely to move the line or point of origin in the opposite direction. Thus, the speed of the current flowing in the direction of the nontidal current is increased by an amount equal to the magnitude of the nontidal current, and the speed of the current flowing in the opposite direction is decreased by an equal amount.

In Figure 3518a, a nontidal current is represented both in direction and speed by the vector AO. Since this is greater than the speed of the tidal current in the opposite direction, the point A is outside the ellipse. The direction and speed of the combined tidal and nontidal currents at any time is represented by a vector from A to that point on the curve representing the given time, and can be scaled from the graph. The strongest and weakest currents may no longer be in the directions of the maximum and minimum of the tidal current. If the nontidal current is northwest at 0.3 knot, it may be represented by BO, and all hourly directions and speeds will then be measured from B. If it is 1.0 knot, it will be represented by AO and the actual resultant hourly directions and speeds will be measured from A, as shown by the arrows.

In a reversing current (Figure 3518b), the effect is to advance the time of one slack, and to retard the following one. If the speed of the nontidal current exceeds that of the reversing tidal current, the resultant current flows continuously in one direction without coming to a slack. In this case, the speed varies from a maximum to a minimum and back to a maximum in each tidal cycle. In Figure 3518b, the horizontal line A represents slack water if only tidal currents are present. Line B represents the effect of a 0.5 knot nontidal ebb, and line C the effect of a 1.0 knot nontidal ebb. With the condition shown at C there is only one flood each tidal day. If the nontidal ebb were to increase to approximately 2 knots, there would be no flood, two maximum ebbs and two minimum ebbs occurring during a tidal day.

3519. Time of Tidal Current and Time of Tide

At many places where current and tide are both semidiurnal, there is a definite relationship between times of current and times of high and low water in the locality. Current atlases and notes on nautical charts often make use of this relationship by presenting for particular locations, the direction and speed of the current at each succeeding hour after high and low water, at a place for which tide predictions are available.

Where there is considerable diurnal inequality in tide or current, or where the type of current differs from the type of tide, the relationship is not constant, and it may be hazardous to try to predict the times of current from times
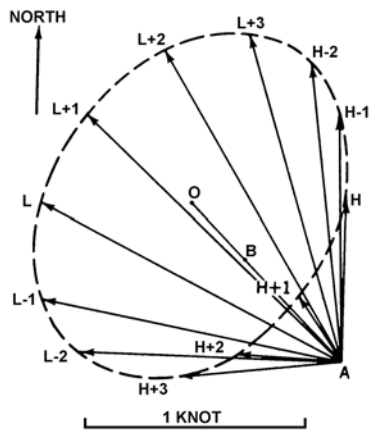
Figure 3518a. Effect of nontidal current on the rotary tidal current of Figure 3515a.
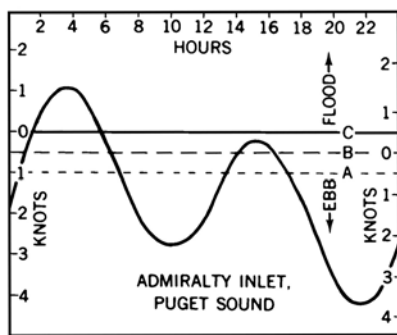

Figure 3518b. Effect of nontidal current on the reversing tidal current of Figure 3515b.

of tide. Note the current curve for Unimak Pass in the Aleutians in Figure 3516a. It shows the current as predicted in the tidal current tables. Predictions of high and low waters in the tide tables might have led one to expect the current to change from flood to ebb in the late morning, whereas actually the current continued to run flood with some strength at that time.

Since the relationship between times of tidal current and tide is not the same everywhere, and may be variable at the same place, one should exercise extreme caution in using general rules. The belief that slacks occur at local high and low tides and that the maximum flood and ebb occur when the tide is rising or falling most rapidly may be approximately true at the seaward entrance to, and in the upper reaches of, an inland tidal waterway. But generally this is not true in other parts of inland waterways. When an inland waterway is extensive or its entrance constricted, the slacks in some parts of the waterway often occur midway between the times of high and low tide. Usually in such waterways the relationship changes from place to place as one progresses upstream, slack water getting progressively

closer in time to the local tide maximum until at the head of tidewater (the inland limit of water affected by a tide) the slacks occur at about the times of high and low tide.

3520. Relationship Between Speed of Current and Range of Tide

The speed of the tidal current is not necessarily consistent with the range of tide. It may be the reverse. For example, currents are weak in the Gulf of Maine where the tides are large, and strong near Nantucket Island and in Nantucket Sound where the tides are small. However, at any one place the speed of the current at strength of flood and ebb varies during the month in about the same proportion as the range of tide, and this relationship can be used to determine the relative strength of currents on any given day.

3521. Variation Across an Estuary

In inland tidal estuaries the time of tidal current varies across the channel from shore to shore. On the average, the current turns earlier near shore than in midstream, where the speed is greater. Differences of half an hour to an hour are not uncommon, but the difference varies and the relationship may be nullified by the effect of nontidal flow.

The speed of the current also varies across the channel, usually being greater in midstream or midchannel than near shore, but in a winding river or channel the strongest currents occur near the concave shore, or the outside corner of the curve. Near the opposite (convex) shore the currents are weak or eddying.

3522. Variation with Depth

In tidal rivers the subsurface current acting on the lower portion of a ship's hull may differ considerably from the surface current. An appreciable subsurface current may be present when the surface movement appears to be practically slack, and the subsurface current may even be flowing with appreciable speed in the opposite direction to the surface current.

In a tidal estuary, particularly in the lower reaches where there is considerable difference in density from top to bottom, the flood usually begins earlier near the bottom than at the surface. The difference may be an hour or two, or as little as a few minutes, depending upon the estuary, the location in the estuary, and freshet conditions. Even when the freshwater runoff becomes so great as to prevent the surface current from flooding, it may still flood below the surface. The difference in time of ebb from surface to bottom is normally small but subject to variation with time and location.

The ebb speed at strength usually decreases gradually from top to bottom, but the speed of flood at strength often is stronger at subsurface depths than at the surface.

3523. Tidal Current Observations

Observations of current are made with sophisticated electronic **current meters**. Current meters are suspended from a buoy or anchored to the bottom with no surface marker at all. Very sensitive current meters measure and record deep ocean currents; these are later recovered by triggering a release mechanism with a signal from the surface. Untended current meters either record data internally or send it by radio or satellite to a base station on ship or land. The period of observation varies from a few hours to few years.

TIDE AND CURRENT PREDICTION

3524. Tidal Height Predictions

To measure the height of tides, hydrographers select a reference level, sometimes referred to as the reference plane, or vertical datum. This vertical tidal datum is not the same as the vertical geodetic datum. Soundings shown on the largest scale charts are the vertical distances from this datum to the bottom. At any given time the actual depth is this charted depth plus the height of tide. In most places the reference level is some form of low water. But all low waters at a given place are not the same height, and the selected reference level is seldom the lowest tide occurring at the place. When lower tides occur, these are indicated in the tide tables by a negative sign. Thus, at a spot where the charted depth is 15 feet, the actual depth is 15 feet plus the tidal height. When the tide is three feet, the depth is $15 + 3 = 18$ feet. When it is -1 foot, the depth is $15 - 1 = 14$ feet. The actual depth can be less than the charted depth. In an area where there is a considerable range of tide (the difference between high water and low water), the height of tide might be an important consideration when using soundings to determine if the vessel is in safe water.

The heights given in the tide tables are predictions, and when assumed conditions vary considerably, the predictions shown may be considerably in error. Heights lower than predicted can be anticipated when the atmospheric pressure is higher than normal, or when there is a persistent strong offshore wind. The greater the range of tide, the less reliable are the predictions for both height and current.

3525. Tidal Heights

The nature of the tide at any place can best be determined by observation. The predictions in tide tables and the tidal data on nautical charts are based upon detailed observations at specific locations, instead of theoretical predictions.

Tidal elevations are usually observed with a continuously recording gage. A year of observations is the minimum length desirable for determining the harmonic constants used in prediction. For establishing mean sea level and long-term changes in the relative elevations of land and sea, as well as for other special uses, observations have been made over periods of 20, 30, and even 120 years at important locations. Observations for a month or less will establish the type of tide and suffice for comparison with a longer series of observations to determine tidal differences and constants.

Mathematically, the variations in the lunar and solar tide-producing forces, such as those due to changing phase, distance, and declination, are considered as separate constituent forces, and the harmonic analysis of observations reveals the response of each constituent of the tide to its corresponding force. At any one place this response remains constant and is shown for each constituent by **harmonic constants** which are in the form of a phase angle for the time relation and an amplitude for the height. Harmonic constants are used in making technical studies of the tide and in tidal predictions on computers.

3526. Meteorological Effects

The foregoing discussion of tidal behavior assumes normal weather conditions. However, sea level is also affected by wind and atmospheric pressure. In general, onshore winds raise the level and offshore winds lower it, but the amount of change varies at different places. During periods of low atmospheric pressure, the water level tends to be higher than normal. For a stationary low, the increase in elevation can be found by the formula:

$$R_0 = 0.01(1010 - P),$$

in which R_0 is the increase in elevation in meters and P is the atmospheric pressure in hectopascals. This is equal approximately to 1 centimeter per hectopascal depression, or about 13.6 inches per inch depression. For a moving low, the increase in elevation is given by the formula:

$$R = \frac{R_0}{1 - \frac{C^2}{gh}}$$

in which R is the increase in elevation in feet, R_0 is the increase in meters for a stationary low, C is the rate of motion of the low in feet per second, g is the acceleration due to gravity (32.2 feet per second per second), and h is the depth of water in feet.

Where the range of tide is very small, the meteorological effect may sometimes be greater than the normal tide. Where a body of water is large in area but shallow, high winds can push the water from the windward to the lee shore, creating much greater local differences in water levels than occurs normally, and partially or completely

masking the tides. The effect is dependent on the configuration and depth of the body of water relative to the wind direction, strength and duration.

3527 Tidal Current Predictions

Tidal currents are due primarily to tidal action, but other causes are often present. The ***Tidal Current Tables*** give the best prediction of total current. Following heavy rains or a drought, a river's current prediction may be considerably in error. Set and drift may vary considerably over different parts of a harbor, because differences in bathymetry from place to place affect current. Since this is usually an area where small errors in a vessel's position are crucial, a knowledge of predicted currents, particularly in reduced visibility, is important. Strong currents occur mostly in narrow passages connecting larger bodies of water. Currents of more than 5 knots are sometimes encountered at the Golden Gate in San Francisco, and currents of more than 13 knots sometimes occur at Seymour Narrows, British Columbia.

In straight portions of rivers and channels, the strongest currents usually occur in the middle of the channel. In curved portions the swiftest currents (and deepest water) usually occur near the outer edge of the curve. Countercurrents and eddies may occur on either side of the main current of a river or narrow passage, especially near obstructions and in bights.

In general, the range of tide and the velocity of tidal current are at a minimum in the open ocean or along straight coasts. The greatest tidal effects are usually encountered in estuaries, bays, and other coastal indentations. A vessel proceeding along an indented coast may encounter a set toward or away from the shore; a similar set is seldom experienced along a straight coast.

PUBLICATIONS FOR PREDICTING TIDES AND CURRENTS

3528. *Tide Tables*

Usually, tidal information is obtained from tide and tidal current tables, or from specialized computer software or calculators. However, if these are not available, or if they do not include information at a desired place, the mariner may be able to obtain locally the **mean high water lunitidal interval**. The approximate time of high water can be found by adding either interval to the time of transit (either upper or lower) of the Moon. Low water occurs approximately 1/4 tidal day (about $6^h 12^m$) before and after the time of high water. The actual interval varies somewhat from day to day, but approximate results can be obtained in this manner. Similar information for tidal currents (**lunicurrent interval**) is seldom available.

The National Ocean Service (NOS) has traditionally published hard copy tide tables and tidal current tables. Tide and tidal current data continue to be updated by NOS, but hardcopy publication has been transferred to private companies working with NOS data.

Tidal data for various parts of the world is published in 4 volumes by the National Ocean Service. These volumes are:

- Central and Western Pacific Ocean and Indian Ocean
- East Coast of North and South America (including Greenland)
- Europe and West Coast of Africa
- West Coast of North and South America (including the Hawaiian Islands)

A small separate volume, the Alaskan Supplement, is also published.

Each volume has 5 common tables:

- **Table 1** contains a complete list of the predicted times and heights of the tide for each day of the year at a number of places designated as **reference stations**.
- **Table 2** gives tidal differences and ratios which can be used to modify the tidal information for the reference stations to make it applicable to a relatively large number of **subordinate stations**.
- **Table 3** provides information for finding the approximate height of the tide at any time between high water and low water.
- **Table 4** is a sunrise-sunset table at five-day intervals for various latitudes from 76°N to 60°S (40°S in one volume).
- **Table 5** provides an adjustment to convert the local mean time of Table 4 to zone or standard time.

For the East Coast and West Coast volumes, each contains a Table 6, a moonrise and moonset table; Table 7 for conversion from feet to centimeters; Table 8, a table of estimated tide prediction accuracies; a glossary of terms; and an index to stations. Table 9, an explanation and table of the lowest and highest astronomical tide and other datums. Each table is preceded by a complete explanation. Sample problems are given where necessary. The inside back cover of each volume contains a calendar of critical astronomical data to help explain the variations of the tide during each month and throughout the year.

3529. Tide Predictions for Reference Stations

For each day, the date and day of week are given, and the time and height of each high and low water are listed in chronological order. Although high and low waters are not

labeled as such, they can be distinguished by the relative heights given immediately to the right of the times. If two high tides and two low tides occur each tidal day, the tide is semidiurnal. Since the tidal day is longer than the civil day (because of the revolution of the Moon eastward around the Earth), any given tide occurs later each day. Because of later times of corresponding tides from day to day, certain days have only one high water or only one low water.

3530. Tide Predictions for Subordinate Stations

For each subordinate station listed, the following information is given:

1. **Number**. The stations are listed in geographical order and assigned consecutive numbers. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in finding the entry in Table 2.
2. **Place**. The list of places includes both subordinate and reference stations; the latter are in bold type.
3. **Position**. The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south, and the longitude east or west, depending upon the letters (N, S, E, W) next above the entry. These may not be the same as those at the top of the column.
4. **Differences**. The differences are to be applied to the predictions for the reference station, shown in capital letters above the entry. Time and height differences are given separately for high and low waters. Where differences are omitted, they are either unreliable or unknown.
5. **Ranges**. Various ranges are given, as indicated in the tables. In each case this is the difference in height between high water and low water for the tides indicated.
6. **Mean tide level**. This is the average between mean low and mean high water, measured from chart datum.

The **time difference** is the number of hours and minutes to be applied to the reference station time to find the time of the corresponding tide at the subordinate station. This interval is added if preceded by a plus sign (+) and subtracted if preceded by a minus sign (-). The results obtained by the application of the time differences will be in the zone time of the time meridian shown directly above the difference for the subordinate station. Special conditions occurring at a few stations are indicated by footnotes on the applicable pages. In some instances, the corresponding tide falls on a different date at reference and subordinate stations.

Height differences are shown in a variety of ways. For most entries, separate height differences in feet are given for high water and low water. These are applied to the height given for the reference station. In many cases a ratio is given for either high water or low water, or both.

The height at the reference station is multiplied by this ratio to find the height at the subordinate station. For a few stations, both a ratio and difference are given. In this case the height at the reference station is first multiplied by the ratio, and the difference is then applied. An example is given in each volume of tide tables. Special conditions are indicated in the table or by footnote. For example, a footnote indicates that "Values for the Hudson River above George Washington Bridge are based upon averages for the six months May to October, when the fresh-water discharge is a minimum."

OPNAV 3530/40 (4-73) HT OF TIDE	
Date	
Location	
Time	
Ref Sta	
HW Time Diff	
LW Time Diff	
HW Ht Diff	
LW Ht Diff	
Ref Sta HW/LW Time	
HW/LW Time Diff	
Sub Sta HW/LW Time	
Ref Sta HW/LW Ht	
HW/LW Ht Diff	
Sub Sta HW/LW Ht	
Duration	Rise
	Fall
Time Fm	Near
	Tide
Range of Tide	
Ht of Neap Tide	
Corr Table 3	
Ht of Tide	
Charted Depth	
Depth of Water	
Draft	
Clearance	

Figure 3531a. OPNAV 3530/40 Tide Form.

3531. Finding Height of Tide at any Time

Table 3 provides means for determining the approximate height of tide at any time. It assumes that plotting height versus time yields a sine curve. Actual values may vary from this. The explanation of the table contains directions for both mathematical and graphical solutions. Though the mathematical solution is quicker, if the vessel's ETA changes significantly, it will have to be done for the new ETA. Therefore, if there is doubt about the ETA, the graphical solution will provide a plot of predictions for several hours and allow quick reference to the predicted height for any given time. This method will also quickly show at what time a given depth of water will occur. shows the OPNAV form used to calculate heights of tides. shows the importance of calculating tides in shallow water.
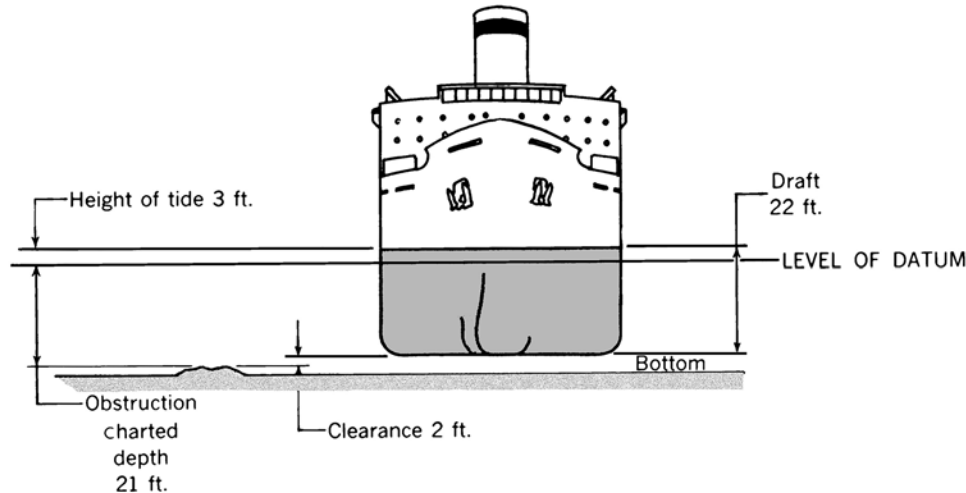

Figure 3531b. Height of tide required to pass clear of charted obstruction.

3532. *Tidal Current Tables*

Tidal Current Tables are somewhat similar to *Tide Tables*, but the coverage is less extensive. NOS publishes 2 volumes on an annual basis: Atlantic Coast of North America, and Pacific Coast of North America and Asia. Each of the two volumes is arranged as follows:

Each volume also contains current diagrams and instructions for their use. Explanations and examples are given in each table.

- **Table 1** contains a complete list of predicted times of maximum currents and slack water, with the velocity of the maximum currents, for a number of reference stations.
- **Table 2** gives differences, ratios, and other information related to a relatively large number of subordinate stations.
- **Table 3** provides information to determine the current's velocity at any time between entries in tables 1 and 2.
- **Table 4** gives duration of slack, or the number of minutes the current does not exceed stated amounts, for various maximum velocities.
- **Table 5** (Atlantic Coast of North America only) gives information on rotary tidal currents.

The volumes also contain general descriptive information on wind-driven currents, combination currents, and information such as Gulf Stream currents for the east coast and coastal currents on the west coast.

3533. Tidal Current Prediction for Reference Stations

For each day, the date and day of week are given; current information follows. If the cycle is repeated twice each tidal day, currents are semidiurnal. On most days there are four slack waters and four maximum currents, two floods (F) and two ebbs (E). However, since the tidal day is longer than the civil day, the corresponding condition occurs later each day, and on certain days there are only three slack waters or three maximum currents. At some places, the current on some days runs maximum flood twice, but ebbs only once, a minimum flood occurring in place of the second ebb. The tables show this information.

3534. Tidal Current Predictions for Subordinate Stations

For each subordinate station listed in Table 2 of the tidal current tables, the following information is given:

1. **Number**: The stations are listed in geographical order and assigned consecutive numbers, as in the tide tables. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in locating the entry in Table 2.
2. **Place**: The list of places includes both subordinate and reference stations, the latter given in bold type.

3. **Position**: The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south and the longitude east or west as indicated by the letters (N, S, E, W) next above the entry. The current given is for the center of the channel unless another location is indicated by the station name.

4. **Time difference**: Two time differences are tabulated. One is the number of hours and minutes to be applied to the tabulated times of slack water at the reference station to find the times of slack waters at the subordinate station. The other time difference is applied to the times of maximum current at the reference station to find the times of the corresponding maximum current at the subordinate station. The intervals, which are added or subtracted in accordance with their signs, include any difference in time between the two stations, so that the answer is correct for the standard time of the subordinate station. Limited application and special conditions are indicated by footnotes.

5. **Velocity ratios**: Speed of the current at the subordinate station is the product of the velocity at the reference station and the tabulated ratio. Separate ratios may be given for flood and ebb currents. Special conditions are indicated by footnotes.

6. **Average Speeds and Directions**: Minimum and maximum velocities before flood and ebb are listed for each station, along with the true directions of the flow. Minimum velocity is not always 0.0 knots.

3535. Finding Velocity of Tidal Current at any Time

Table 3 of the tidal current tables provides means for de-

OPNAV 3530/40 (4-73)
VEL OF CURRENT

Date
Location
Time
Ref Sta
Time Diff Stack Water
Time Diff Max Current
Vel Ratio Max Flood
Vel Ratio Max Ebb

Figure 3535. OPNAV 3530/40 Tide Form.

OPNAV 3530/40 (4-73)
VEL OF CURRENT

Flood Dir
Ebb Dir
Ref Sta Stack Water Time
Time Diff
Local Sta Stack Water Time
Ref Sta Max Current Time
Time Diff
Local Sta Max Current Time
Ref Sta Max Current Vel
Vel Ratio
Local Sta Max Current Vel
Int Between Slack and Desired Time
Int Between Slack and Max Current
Max Current
Factor Table 3
Velocity
Direction

Figure 3535. OPNAV 3530/40 Tide Form.

termining the approximate velocity at any time. Directions are given in an explanation preceding the table. Figure 3535 shows the OPNAV form used for current prediction.

3536. Duration of Slack Water

The predicted times of slack water listed in the tidal current tables indicate the instant of zero velocity. There is a period each side of slack water, however, during which the current is so weak that for practical purposes it may be considered negligible. Table 4 of the tidal current tables gives, for various maximum currents, the approximate period of time during which currents not exceeding 0.1 to 0.5 knots will be encountered. This period includes the last of the flood or ebb and the beginning of the following flood or ebb; that is, half of the duration will be before and half after the time of slack water.

When there is a difference between the velocities of the maximum flood and ebb preceding and following the slack for which the duration is desired, it will be sufficiently accurate to find a separate duration for each maximum velocity and average the two to determine the duration of

the weak current.

Of the two sub-tables of Table 4, Table A is used for all places except those listed for Table B; Table B is used for just the places listed and the stations in Table 2 which are referred to them.

3537. Additional Tide Prediction Publications

NOS also publishes a special *Regional Tide and Tidal Current Table for New York Harbor to Chesapeake Bay*, and a *Tidal Circulation and Water Level Forecast Atlas for Delaware River and Bay*.

3538. *Tidal Current Charts*

Tidal Current charts present a comprehensive view of the hourly velocity of current in different bodies of water. They also provide a means for determining the current's velocity at various locations in these waters. The arrows show the direction of the current; the figures give the speed in knots at the time of spring tides. A weak current is defined as less than 0.1 knot. These charts depict the flow of the tidal current under normal weather conditions. Strong winds and freshets, however, may cause nontidal currents, considerably modifying the velocity indicated on the charts.

Tidal Current charts are provided for Boston Harbor, Charleston Harbor SC, Long Island Sound and Block Island Sound, Narragansett Bay, Narragansett Bay to Nantucket Sound, Puget Sound (Northern Part), Puget Sound (Southern Part), Upper Chesapeake Bay, and Tampa Bay.

The tidal current's velocity varies from day to day as a function of the phase, distance, and declination of the Moon. Therefore, to obtain the velocity for any particular day and hour, the spring velocities shown on the charts must be modified by correction factors. A correction table given in the charts can be used for this purpose.

All of the charts except Narragansett Bay require the use of the annual *Tidal Current Tables*. Narragansett Bay requires use of the annual *Tide Tables*.

3539. Current Diagrams

A current diagram is a graph showing the velocity of the current along a channel at different stages of the tidal current cycle. The current tables include diagrams for Martha's Vineyard and Nantucket Sounds (one diagram); East River, New York; New York Harbor; Delaware Bay and River (one diagram); and Chesapeake Bay. These diagrams are no longer published by NOS, but are available privately and remain useful as they are not ephemeral.

On Figure 3539, each vertical line represents a given instant identified by the number of hours before or after slack water at The Narrows. Each horizontal line represents a distance from Ambrose Channel entrance, measured along the usually traveled route. The names along the left margin are placed at the correct distances from Ambrose

Channel entrance. The current is for the center of the channel opposite these points. The intersection of any vertical line with any horizontal line represents a given moment in the current cycle at a given place in the channel. If this intersection is in a shaded area, the current is flooding; if in an unshaded area, it is ebbing. The velocity can be found by interpolation between the numbers given in the diagram. The given values are averages. To find the value at any time, multiply the velocity found from the diagram by the ratio of maximum velocity of the current involved to the maximum shown on the diagram. If the diurnal inequality is large, the accuracy can be improved by altering the width of the shaded area to fit conditions. The diagram covers 1 1/2 current cycles, so that the right 1/3 duplicates the left 1/3.

Use Table 1 or 2 to determine the current for a single station. The current diagrams are intended for use in either of two ways: to determine a favorable time for passage through the channel and to find the average current to be expected during a passage through the channel. For both of these uses, a number of "velocity lines" are provided. When the appropriate line is transferred to the correct part of the diagram, the current to be encountered during passage is indicated along the line.

If the transferred velocity line is partly in a flood current area, all ebb currents (those increasing the ship's velocity) are given a positive sign (+), and all flood currents a negative sign (-). A separate ratio should be determined for each current (flood or ebb), and applied to the entries for that current. In the Chesapeake Bay, it is common for an outbound vessel to encounter three or even four separate currents during passage. Under the latter condition, it is good practice to multiply each current taken from the diagram by the ratio for the current involved.

If the time of starting the passage is fixed, and the current during passage is desired, the starting time is identified in terms of the reference tidal cycle. The velocity line is then drawn through the intersection of this vertical time line and the horizontal line through the place. The average current is then determined in the same manner as when the velocity line is located as described above.

3540. Computer Predictions

Until recently, tidal predictions were compiled only on mainframe or minicomputers and then put into hardcopy table form for the mariner. There are several types of commercial software available now for personal computers (PC's) that provide digital versions of the NOS tide tables and also graph the tidal heights. The tabular information and graphs can be printed for the desired locations for pre-voyage planning. There are also several types of specialized hand-held calculators and tide clocks that can be used to predict tides for local areas.

Newer versions of PC software use the actual harmonic constants available for locations, the prediction equation,
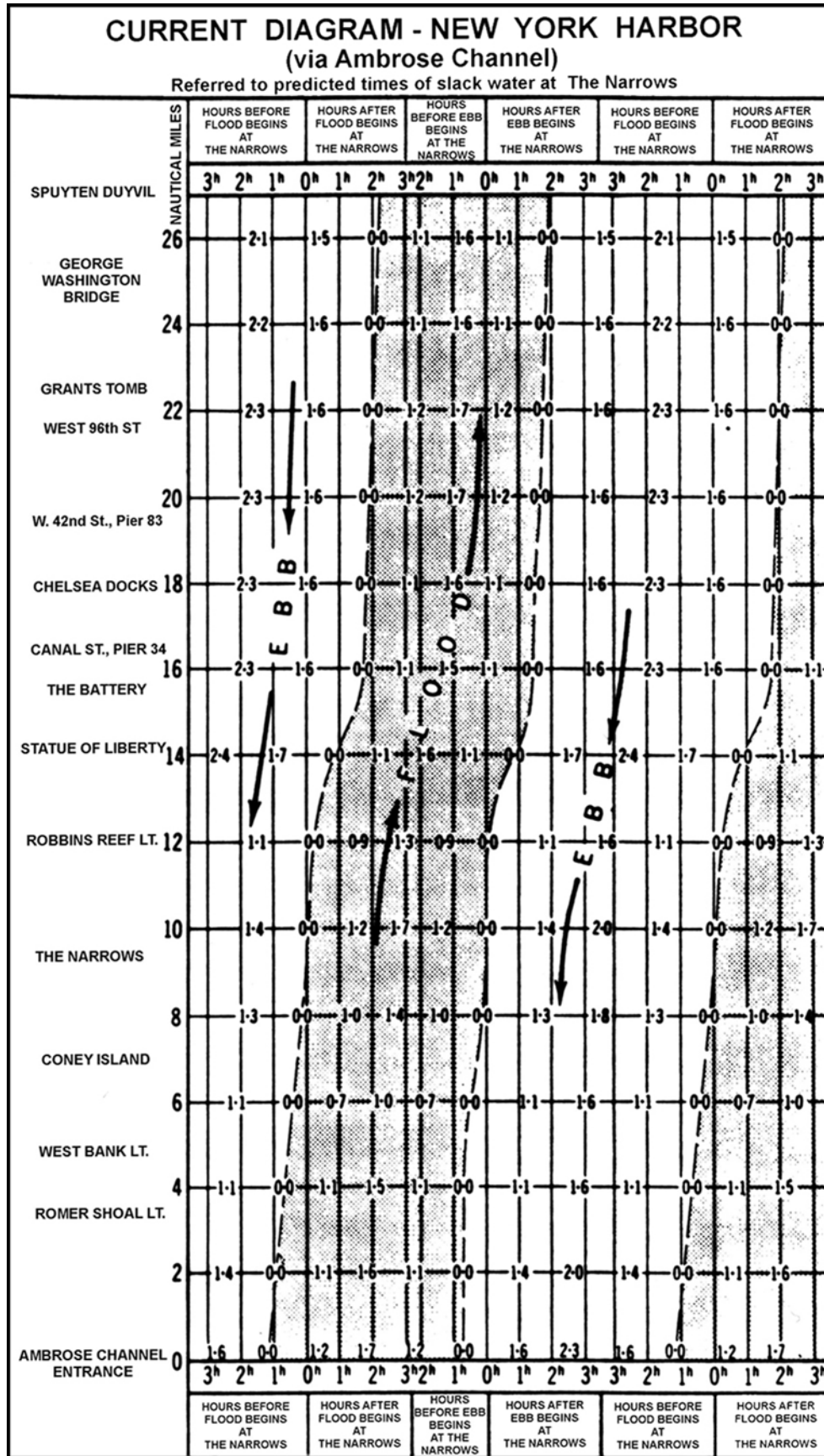
Figure 3539. Current diagram for New York Harbor.

and digital versions of Table 2 in the *Tide Tables* to produce even more products for the navigator's use. Since NOS has published the data, even inexpensive navigation electronics such as handheld GPS receivers and plotters for small craft navigation often include graphic tide tables.

Emerging applications include integration of tidal prediction with positioning systems and vessel traffic systems which are now moving towards full use of GPS. In addition, some electronic chart systems are already able to integrate tide prediction information. Many of these new systems will also use real-time water level and current information. Active research also includes providing predictions of total water level that will include not only the tidal prediction component, but also the weather-related component.

CHAPTER 36

OCEAN CURRENTS

TYPES AND CAUSES OF CURRENTS

3600. Definitions

The movement of ocean water is one of the two principal sources of discrepancy between dead reckoned and actual positions of vessels (the other source is the wind). Water in motion is called a current; the direction toward which it moves is called **set**, and its speed is called **drift**. Modern shipping speeds have lessened the impact of currents on a typical voyage, and since electronic navigation allows continuous adjustment of course, there is less need to estimate current set and drift before setting the course to be steered. Nevertheless, a knowledge of ocean currents can be used in cruise planning to reduce transit times, and current models are an integral part of ship routing systems.

Oceanographers have developed a number of methods of classifying currents in order to facilitate descriptions of their physics and geography. Currents may be referred to according to their forcing mechanism as either **wind driven** or **thermohaline**. Alternatively, they may be classified according to their depth (surface, intermediate, deep or bottom). The surface circulation of the world's oceans is mostly wind driven. Thermohaline currents are driven by differences in heat and salt and are associated with the sinking of dense water at high latitudes; the currents driven by thermohaline forces are typically subsurface. Note that this classification scheme is not unambiguous; the circumpolar current, which is wind driven, extends from the surface to the bottom.

A **periodic current** is one for which the speed or direction changes cyclically at somewhat regular intervals, such as a tidal current. A **seasonal current** is one which changes in speed or direction due to seasonal winds. The mean circulation of the ocean consists of semi-permanent currents which experience relatively little periodic or seasonal change.

A **coastal current** flows roughly parallel to a coast, outside the surf zone, while a **longshore current** is one parallel to a shore, inside the surf zone, generated by waves striking the beach at an angle. Any current some distance from the shore may be called an **offshore current**, and one close to the shore an **inshore current**.

General information on ocean currents is available from NOAA's National Center for Environmental Information (NCEI), formerly the National Ocean Data Center (NODC). See Figure 3600 for a link to the NCEI website.

Figure 3600. NOAA's National Center for Environmental Information (NCEI) formerly the National Ocean Data Center (NODC).
https://www.nodc.noaa.gov/General/current.html

3601. Causes of Ocean Currents

The primary generating forces of ocean currents are wind and differences in water density caused by variations in heat and salinity. Currents generated by these forces are modified by such factors as depth of water, underwater topography (including shape of the basin in which the current is running), extent and location of land, and deflection by the rotation of the Earth.

3602. Wind Driven Currents

The friction or stress of wind blowing across the sea causes a surface layer of water to move. Due to the low viscosity of water, this stress is not directly communicated to the ocean interior, but is balanced by the Coriolis force within a relatively thin surface layer, 10-200m thick. This layer is called the **Ekman layer** and the motion of this layer is called the **Ekman transport**. Because of the deflection by the Coriolis force, the Ekman transport is not in the direction of the wind, but is 90° to the right in the Northern Hemisphere and 90° toward the left in the Southern Hemisphere. The amount of water flowing in this layer depends only upon the wind and the Coriolis force. It is independent of the depth of the Ekman layer and the viscosity of the water.

The large scale convergence or divergence of Ekman transport serves to drive the general ocean circulation. Consider the case of the Northern Hemisphere subtropics. To the south lie easterly winds (**Trade Winds**) with associated northward Ekman transport. To the north lie westerly winds with southward Ekman transport. The convergence of these Ekman transports is called **Ekman**

pumping and results in a thickening of the upper ocean and a increase in the depth of the thermocline. The resulting subsurface pressure gradients, balanced by the Coriolis force, give rise to the anticyclonic subtropical gyres found at mid latitudes in each ocean basin. In subpolar regions, Ekman suction produces cyclonic gyres.

These wind driven gyres are not symmetrical. Along the western boundary of the oceans, currents are narrower, stronger, and deeper, often following a meandering course. These currents are sometimes called a **stream**, i.e. the Gulf Stream in the Atlantic Ocean. In contrast, currents in mid-ocean and at the eastern boundary, are often broad, shallow and slow-moving. Sometimes these are called **drift currents**.

Within the Ekman layer, the currents actually form a spiral. At the surface, the difference between wind direction and surface wind-current direction varies from about 15° along shallow coastal areas to a maximum of 45° in the deep oceans. As the motion is transmitted to successively deep layers, the Coriolis force continues to deflect the current. At the bottom of the Ekman layer, the current flows in the opposite direction to the surface current. This shift of current directions with depth, combined with the decrease in velocity with depth, is called the **Ekman spiral**.

The velocity of the surface current is the sum of the velocities of the Ekman, geostrophic, tidal, and other currents. The Ekman surface current or wind drift current depends upon the speed of the wind, its constancy, the length of time it has blown, and other factors. In general, however, wind drift current is about 2 percent of the wind speed, or a little less, in deep water where the wind has been blowing steadily for at least 12 hours.

3603. Currents Related to Density Differences

The density of water varies with salinity, temperature, and pressure. At any given depth, the differences in density are due only to differences in temperature and salinity. With sufficient data, maps showing geographical density distribution at a certain depth can be drawn, with lines connecting points of equal density. These lines would be similar to isobars on a weather map and serve an analogous purpose, showing areas of high density and those of low density. In an area of high density, the water surface is lower than in an area of low density, the maximum difference in height being about 1 meter in 100 km. Because of this difference, water tends to flow from an area of higher water (low density) to one of lower water (high density). But due to rotation of the Earth, it is deflected by the Coriolis force or toward the right in the Northern Hemisphere, and toward the left in the Southern Hemisphere. This balance, between subsurface pressure fields and the Coriolis force, is called **geostrophic equilibrium**. At a given latitude, the greater the density gradient (rate of change with distance), the faster the geostrophic current.

OCEANIC CIRCULATION

3604. Introduction

A number of ocean currents flow with great persistence, setting up a circulation that continues with relatively little change throughout the year. Because of the influence of wind in creating current, there is a relationship between this oceanic circulation and the general circulation of the atmosphere. The oceanic circulation is shown on the Stream Drift Chart of the World insert (winter N. hemisphere), with the names of the major ocean currents. Some differences in opinion exist regarding the names and limits of some of the currents, but those shown are representative. Speed may vary somewhat with the season. This is particularly noticeable in the Indian Ocean and along the South China coast, where currents are influenced to a marked degree by the monsoons.

3605. Southern Ocean Currents

The Southern Ocean has no meridional boundaries and its waters are free to circulate around the globe. It serves as a conveyor belt for the other oceans, exchanging waters between them. The northern boundary of the Southern Ocean is marked by the Subtropical Convergence zone. This zone marks the transition from the temperate region of the ocean to the polar region and is associated with the surfacing of the main thermocline. This zone is typically found at 40°S but varies with longitude and season.

In the Antarctic, the circulation is generally from west to east in a broad, slow-moving current extending completely around Antarctica. This is called the **Antarctic Circumpolar Current** or the **West Wind Drift**, and it is formed partly by the strong westerly wind in this area, and partly by density differences. This current is augmented by the Brazil and Falkland Currents in the Atlantic, the East Australia Current in the Pacific, and the Agulhas Current in the Indian Ocean. In return, part of it curves northward to form the Cape Horn, Falkland, and most of the Benguela Currents in the Atlantic, and the Peru Current in the Pacific.

In a narrow zone next to the Antarctic continent, a westward flowing coastal current is usually found. This current is called the **East Wind Drift** because it is attributed to the prevailing easterly winds, which occur there.

3606. Atlantic Ocean Currents

The trade winds set up a system of equatorial currents which at times extends over as much as 50° of latitude or more. There are two westerly flowing currents conforming

generally with the areas of trade winds, separated by a weaker, easterly flowing countercurrent.

The **North Equatorial Current** originates to the northward of the Cape Verde Islands and flows almost due west at an average speed of about 0.7 knot.

The **South Equatorial Current** is more extensive. It starts off the west coast of Africa, south of the Gulf of Guinea, and flows in a generally westerly direction at an average speed of about 0.6 knot. However, the speed gradually increases until it may reach a value of 2.5 knots, or more, off the east coast of South America. As the current approaches Cabo de Sao Roque, the eastern extremity of South America, it divides, the southern part curving toward the south along the coast of Brazil, and the northern part being deflected northward by the continent of South America.

Between the North and South Equatorial Currents, the weaker **North Equatorial Countercurrent** sets toward the east in the general vicinity of the doldrums. This is fed by water from the two westerly flowing equatorial currents, particularly the South Equatorial Current. The extent and strength of the Equatorial Countercurrent changes with the seasonal variations of the wind. It reaches a maximum during July and August, when it extends from about 50° west longitude to the Gulf of Guinea. During its minimum, in December and January, it is of very limited extent, the western portion disappearing altogether.

That part of the South Equatorial Current flowing along the northern coast of South America, which does not feed the Equatorial Countercurrent, unites with the North Equatorial Current at a point west of the Equatorial Countercurrent. A large part of the combined current flows through various passages between the Windward Islands and into the Caribbean Sea. It sets toward the west, and then somewhat north of west, finally arriving off the Yucatan peninsula. From there, the water enters the Gulf of Mexico and forms the **Loop Current**; the path of the Loop Current is variable with a 13-month period. It begins by flowing directly from Yucatan to the Florida Straits, but gradually grows to flow anticyclonically around the entire Eastern Gulf; it then collapses, again following the direct path from Yucatan to the Florida Straits, with the loop in the Eastern Gulf becoming a separate eddy which slowly flows into the Western Gulf.

Within the Straits of Florida, the Loop Current feeds the beginnings of the most remarkable of American ocean currents, the **Gulf Stream**. Off the southeast coast of Florida this current is augmented by the **Antilles Current** which flows along the northern coasts of Puerto Rico, Hispaniola, and Cuba. Another current flowing eastward of the Bahamas joins the stream north of these islands.

The Gulf Stream follows generally along the east coast of North America, flowing around Florida, northward and then northeastward toward Cape Hatteras, and then curving toward the east and becoming broader and slower. After passing the Grand Banks, it turns more toward the north and
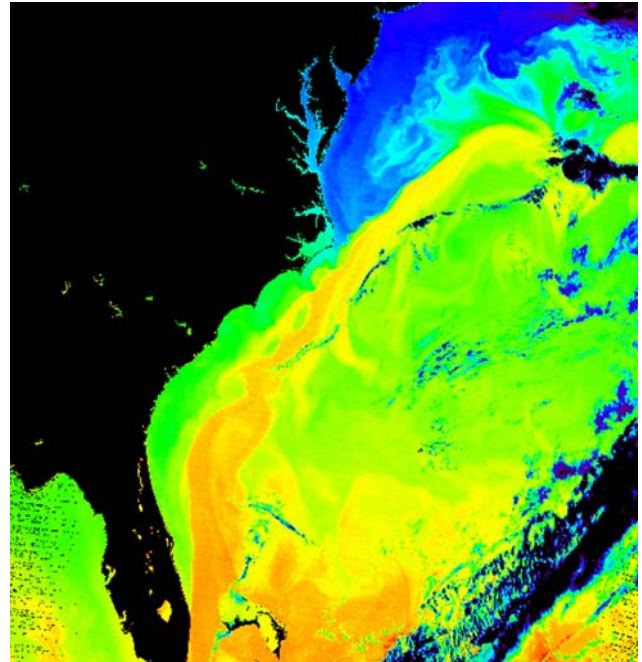

Figure 3606a. Infrared image of the warm water Gulf Stream running northwards along the U.S. East Coast.

becomes a broad drift current flowing across the North Atlantic. The part in the Straits of Florida is sometimes called the **Florida Current**.

A tremendous volume of water flows northward in the Gulf Stream. It can be distinguished by its deep indigo-blue color, which contrasts sharply with the dull green of the surrounding water. It is accompanied by frequent squalls. When the Gulf Stream encounters the cold water of the Labrador Current, principally in the vicinity of the Grand Banks, there is little mixing of the waters. Instead, the junction is marked by a sharp change in temperature. The line or surface along which this occurs is called the **cold wall**. When the warm Gulf Stream water encounters cold air, evaporation is so rapid that the rising vapor may be visible as frost smoke.

Investigations have shown that the current itself is much narrower and faster than previously supposed, and considerably more variable in its position and speed. The maximum current off Florida ranges from about 2 to 4 knots. Northward, the speed is generally less, and it decreases further after the current passes Cape Hatteras. As the stream meanders and shifts position, eddies sometimes break off and continue as separate, circular flows until they dissipate. Vessels in the Newport-Bermuda sailing yacht race have been known to be within sight of each other and be carried in opposite directions by different parts of the same current. This race is generally won by the boat which catches an eddy just right. As the current shifts position, its extent does not always coincide with the area of warm, blue water. When the sea is relatively smooth, the edges of the current are marked by ripples.

Figure 3606b. The Sargasso Sea, located entirely within the Atlantic Ocean, is the only sea without a land boundary.

A recirculation region exists adjacent to and southeast of the Gulf Stream. The flow of water in the recirculation region is opposite to that in the Gulf Stream and surface currents are much weaker, generally less than half a knot.

As the Gulf Stream continues eastward and northeastward beyond the Grand Banks, it gradually widens and decreases speed until it becomes a vast, slow-moving current known as the **North Atlantic Current**, in the general vicinity of the prevailing westerlies. In the eastern part of the Atlantic it divides into the **Northeast Drift Current** and the **Southeast Drift Current**.

The Northeast Drift Current continues in a generally northeasterly direction toward the Norwegian Sea. As it does so, it continues to widen and decrease speed. South of Iceland it branches to form the **Irminger Current** and the **Norway Current**. The Irminger Current curves toward the north and northwest to join the East Greenland Current southwest of Iceland. The Norway Current continues in a northeasterly direction along the coast of Norway. Part of it, the **North Cape Current**, rounds North Cape into the Barents Sea. The other part curves toward the north and becomes known as the **Spitsbergen Current**. Before reaching Svalbard (Spitsbergen), it curves toward the west and joins the cold **East Greenland Current** flowing southward in the Greenland Sea. As this current flows past Iceland, it is further augmented by the Irminger Current.

Off Kap Farvel, at the southern tip of Greenland, the East Greenland Current curves sharply to the northwest following the coastline. As it does so, it becomes known as the **West Greenland Current**, and its character changes from that of an intense western boundary current to a weaker eastern boundary current. This current continues along the west coast of Greenland, through Davis Strait, and into Baffin Bay.

In Baffin Bay the West Greenland Current generally follows the coast, curving westward off Kap York to form the southerly flowing **Labrador Current**. This cold current flows southward off the coast of Baffin Island, through Davis Strait, along the coast of Labrador and Newfoundland, to the Grand Banks, carrying with it large quantities of ice. Here it encounters the warm water of the Gulf Stream, creating the cold wall. Some of the cold water flows southward along the east coast of North America, inshore of the Gulf Stream, as far as Cape Hatteras. The remainder curves toward the east and flows along the northern edge of the North Atlantic and Northeast Drift Currents, gradually merging with them.

The **Southeast Drift Current** curves toward the east, southeast, and then south as it is deflected by the coast of Europe. It flows past the Bay of Biscay, toward southeastern Europe and the Canary Islands, where it continues as the **Canary Current**. In the vicinity of the Cape Verde Islands, this current divides, part of it curving toward the west to help form the **North Equatorial Current**, and part of it curving toward the east to follow the coast of Africa into the Gulf of Guinea, where it is known as the **Guinea Current**. This current is augmented by the **North Equatorial Countercurrent** and, in summer, it is strengthened by monsoon winds. It flows in close proximity to the South Equatorial Current, but in the opposite direction. As it curves toward the south, still following the African coast, it merges with the South Equatorial Current.

The clockwise circulation of the North Atlantic leaves a large central area between the recirculation region and the Canary Current which has no well-defined currents. This area is known as the **Sargasso Sea**, from the large quantities of sargasso or gulfweed encountered there. See Figure 3606b.

That branch of the South Equatorial Current, which curves toward the south off the east coast of South America, follows the coast as the warm, highly-saline **Brazil Current**, which in some respects resembles a weak Gulf Stream. Off Uruguay it encounters the colder, less-salty **Falkland** or **Malvinas Current** forming a sharp meandering front in which eddies may form. The two currents curve

toward the east to form the broad, slow-moving, **South Atlantic Current** in the general vicinity of the prevailing westerlies and the front dissipates somewhat. This current flows eastward to a point west of the Cape of Good Hope, where it curves northward to follow the west coast of Africa as the strong **Benguela Current**, augmented somewhat by part of the **Agulhas Current** flowing around the southern part of Africa from the Indian Ocean. As it continues northward, the current gradually widens and slows. At a point east of St. Helena Island it curves westward to continue as part of the South Equatorial Current, thus completing the counterclockwise circulation of the South Atlantic. The Benguela Current is also augmented somewhat by the **West Wind Drift**, a current which flows easterly around Antarctica. As the West Wind Drift flows past Cape Horn, that part in the immediate vicinity of the cape is called the **Cape Horn Current**. This current rounds the cape and flows in a northerly and northeasterly direction along the coast of South America as the Falkland or Malvinas Current.

3607. Pacific Ocean Currents

Pacific Ocean currents follow the general pattern of those in the Atlantic. The **North Equatorial Current** flows westward in the general area of the northeast trades and the **South Equatorial Current** follows a similar path in the region of the southeast trades. Between these two, the weaker **North Equatorial Countercurrent** sets toward the east, just north of the equator.

After passing the Mariana Islands, the major part of the North Equatorial Current curves somewhat toward the northwest, past the Philippines and Taiwan. Here it is deflected further toward the north, where it becomes known as the **Kuroshio**, and then toward the northeast past the Nansei Shoto and Japan, and on in a more easterly direction. Part of the Kuroshio, called the **Tsushima Current**, flows through Tsushima Strait, between Japan and Korea, and the Sea of Japan, following generally the northwest coast of Japan. North of Japan it curves eastward and then southeastward to rejoin the main part of the Kuroshio. The limits and volume of the Kuroshio are influenced by the monsoons, being augmented during the season of southwesterly winds, and diminished when the northeasterly winds are prevalent.

The Kuroshio (Japanese for "Black Stream") is so named because of the dark color of its water. It is sometimes called the **Japan Current**. In many respects it is similar to the Gulf Stream of the Atlantic. Like that current, it carries large quantities of warm tropical water to higher latitudes, and then curves toward the east as a major part of the general clockwise circulation in the Northern Hemisphere. As it does so, it widens and slows, continuing on between the Aleutians and the Hawaiian Islands, where it becomes known as the **North Pacific Current**.

As this current approaches the North American continent, most of it is deflected toward the right to form a clockwise circulation between the west coast of North America and the Hawaiian Islands called the **California Current**. This part of the current has become so broad that the circulation is generally weak. Near the coast, the southeastward flow intensifies and average speeds are about 0.8 knot. But the flow pattern is complex, with offshore directed jets often found near more prominent capes, and poleward flow often found over the upper slope and outer continental shelf. It is strongest near land. Near the southern end of Baja California, this current curves sharply to the west and broadens to form the major portion of the North Equatorial Current.

During the winter, a weak countercurrent flows northwestward, inshore of the southeastward flowing California Current, along the west coast of North America from Baja California to Vancouver Island. This is called the **Davidson Current**.

Off the west coast of Mexico, south of Baja California the current flows southeastward during the winter as a continuation of part of the California Current. During the summer, the current in this area is northwestward as a continuation of the North Equatorial Countercurrent.

As in the Atlantic, there is in the Pacific a counterclockwise circulation to the north of the clockwise circulation. Cold water flowing southward through the western part of Bering Strait between Alaska and Siberia, is joined by water circulating counterclockwise in the Bering Sea to form the **Oyashio**. As the current leaves the strait, it curves toward the right and flows southwesterly along the coast of Siberia and the Kuril Islands. This current brings quantities of sea ice, but no icebergs. When it encounters the Kuroshio, the Oyashio curves southward and then eastward, the greater portion joining the Kuroshio and North Pacific Current.

The northern branch of the North Pacific Current curves in a counterclockwise direction to form the **Alaska Current**, which generally follows the coast of Canada and Alaska. When the Alaska Current turns to the southwest and flows along the Kodiak Island and the Alaska Peninsula, its character changes to that of a western boundary current and it is called the **Alaska Stream**. When this westward flow arrives off the Aleutian Islands, it is less intense and becomes known as the **Aleutian Current**. Part of it flows along the southern side of these islands to about the 180th meridian, where it curves in a counterclockwise direction and becomes an easterly flowing current, being augmented by the northern part of the Oyashio. The other part of the Aleutian Current flows through various openings between the Aleutian Islands, into the Bering Sea. Here it flows in a general counterclockwise direction. The southward flow along the Kamchatka peninsula is called the **Kamchatka Current** which feeds the southerly flowing Oyashio. Some water flows northward from the Bering Sea through the eastern side of the Bering Strait, into the Arctic Ocean.

The **South Equatorial Current**, extending in width between about 4°N latitude and 10°S, flows westward from

South America to the western Pacific. After this current crosses the 180th meridian, the major part curves in a counterclockwise direction, entering the Coral Sea, and then curving more sharply toward the south along the east coast of Australia, where it is known as the **East Australian Current**. The East Australian Current is the weakest of the subtropical western boundary currents and separates from the Australian coast near 34°S. The path of the current from Australia to New Zealand is known as the **Tasman Front**, which marks the boundary between the warm water of the Coral Sea and the colder water of the Tasman Sea. The continuation of the East Australian Current east of New Zealand is the **East Auckland Current**. The East Auckland Current varies seasonally. In the winter, it separates from the shelf and flows eastward, merging with the West Wind Drift, while in winter it follows the New Zealand shelf southward as the **East Cape Current** until it reaches Chatham Rise where it turns eastward, thence merging with the West Wind Drift.

Near the southern extremity of South America, most of this current flows eastward into the Atlantic, but part of it curves toward the left and flows generally northward along the west coast of South America as the **Peru Current** or **Humboldt Current**. Occasionally a set directly toward land is encountered. At about Cabo Blanco, where the coast falls away to the right, the current curves toward the left, past the Galapagos Islands, where it takes a westerly set and constitutes the major portion of the South Equatorial Current, thus completing the counterclockwise circulation of the South Pacific.

During the northern hemisphere summer, a weak northern branch of the South Equatorial Current, known as the **New Guinea Coastal Current**, continues on toward the west and northwest along both the southern and northeastern coasts of New Guinea. The southern part flows through Torres Strait, between New Guinea and Australia, into the Arafura Sea. Here, it gradually loses its identity, part of it flowing on toward the west as part of the South Equatorial Current of the Indian Ocean, and part of it following the coast of Australia and finally joining the easterly flowing West Wind Drift. The northern part of New Guinea Coastal Current, both curves in a clockwise direction to help form the Pacific Equatorial Countercurrent and off Mindanao, turns southward to form a southward flowing boundary current called the **Mindanao Current**. During the northern hemisphere winter, the New Guinea Coastal Current may reverse direction for a few months.

3608. Indian Ocean Currents

Indian Ocean currents follow generally the pattern of the Atlantic and Pacific but with differences caused principally by the monsoons, the more limited extent of water in the Northern Hemisphere, and by limited communication with the Pacific Ocean along the eastern boundary. During the northern hemisphere winter, the **North Equatorial Current** and **South Equatorial Current** flow toward the west, with the weaker, eastward **Equatorial Countercurrent** flowing between them, as in the Atlantic and Pacific (but somewhat south of the equator). But during the northern hemisphere summer, both the North Equatorial Current and the Equatorial Countercurrent are replaced by the **Southwest Monsoon Current**, which flows eastward and southeastward across the Arabian Sea and the Bay of Bengal. Near Sumatra, this current curves in a clockwise direction and flows westward, augmenting the South Equatorial Current, and setting up a clockwise circulation in the northern part of the Indian Ocean. Off the coast of Somalia, the **Somali Current** reverses direction during the northern hemisphere summer with northward currents reaching speeds of 5 knots or more. Twice a year, around May and November, westerly winds along the equator result in an eastward **Equatorial Jet** which feeds warm water towards Sumatra.

As the South Equatorial Current approaches the coast of Africa, it curves toward the southwest, part of it flowing through the Mozambique Channel between Madagascar and the mainland, and part flowing along the east coast of Madagascar. At the southern end of this island the two join to form the strong **Agulhas Current**, which is analogous to the Gulf Stream. This current, when opposed by strong winds from Southern Ocean storms, creates dangerously large seas.

South of South Africa, the Agulhas Current retroflects, and most of the flow curves sharply southward and then eastward to join the West Wind Drift; this junction is often marked by a broken and confused sea, made much worse by westerly storms. A small part of the Agulhas Current rounds the southern end of Africa and helps form the **Benguela Current**; occasionally, strong eddies are formed in the retroflection region and these too move into the Southeastern Atlantic.

The eastern boundary currents in the Indian Ocean are quite different from those found in the Atlantic and Pacific. The seasonally reversing **South Java Current** has strongest westward flow during August when monsoon winds are easterly and the Equatorial jet is inactive. Along the coast of Australia, a vigorous poleward flow, the **Leeuwin Current**, runs against the prevailing winds.

3609. Arctic Currents

The waters of the North Atlantic enter the Arctic Ocean between Norway and Svalbard. The currents flow easterly, north of Siberia to the region of the Novosibirskiye Ostrova where they turn northerly across the North Pole and continue down the Greenland coast to form the **East Greenland Current**. On the American side of the Arctic basin, there is a weak, continuous clockwise flow centered in the vicinity of 80°N, 150°W. A current north through Bering Strait along the American coast is balanced by an outward southerly flow along the Siberian coast, which

eventually becomes part of the **Kamchatka Current**. Each of the main islands or island groups in the Arctic, as far as is known, seems to have a clockwise nearshore circulation around it. The Barents Sea, Kara Sea, and Laptev Sea each have a weak counterclockwise circulation. A similar but weaker counterclockwise current system appears to exist in the East Siberian Sea.

OCEANIC CURRENT PHENOMENA

3610. Ocean Eddies and Rings

Eddies with horizontal diameters varying from 50-150 km have their own pattern of surface currents. These features may have either a warm or a cold core and currents flow around this core, either cyclonically for cold cores or anticyclonically for warm cores. The most intense of these features are called **rings** and are formed by the pinching off of meanders of western boundary currents such as the Gulf Stream. Maximum speed associated with these features is about 2 knots. Rings have also been observed to pinch off from the Agulhas retroflexion and to then drift to the northwest into the South Atlantic. Similarly, strong anticyclonic eddies are occasionally spawned by the loop current into the Western Gulf Mexico.

In general, **mesoscale** variability is strongest in the region of western boundary currents and in the Circumpolar Current. The strength of mesoscale eddies is greatly reduced at distances of 200-400 km from these strong boundary currents, because mean currents are generally weaker in these regions. The eddies may be sufficiently strong to reverse the direction of the surface currents.

3611. Undercurrents

At the equator and along some ocean boundaries, shallow undercurrents exist, flowing in a direction counter to that at the surface. These currents may affect the operation of submarines or trawlers. The most intense of these flows, called the Pacific **Equatorial Undercurrent**, is found at the equator in the Pacific. It is centered at a depth of 150m to the west of the Galapagos, is about 4 km wide, and eastward speeds of up to 1.5 m/s have been observed. Equatorial Undercurrents are also observed in the Atlantic and Indian Ocean, but they are somewhat weaker. In the Atlantic, the Equatorial Undercurrent is found to the east of 24°W and in the Indian Ocean, it appears to be seasonal.

Undercurrents also exist along ocean boundaries. They seem to be most ubiquitous at the eastern boundary of oceans. Here they are found at depths of 100-200m and may be 100 km wide, and have maximum speeds of 0.5 m/s.

3612. Ocean Currents and Climate

Many of the ocean currents exert a marked influence upon the climate of the coastal regions along which they flow. Thus, warm water from the Gulf Stream, continuing as the North Atlantic, Northeast Drift, and Irminger Currents, arrives off the southwest coast of Iceland, warming it to the extent that Reykjavik has a higher average winter temperature than New York City, far to the south. Great Britain and Labrador are about the same latitude, but the climate of Great Britain is much milder because of the relatively warm currents. The west coast of the United States is cooled in the summer by the California Current, and warmed in the winter by the Davidson Current. Partly as a result of this circulation, the range of monthly average temperature is comparatively small.

Currents exercise other influences besides those on temperature. The pressure pattern is affected materially, as air over a cold current contracts as it is cooled, and that over a warm current expands. As air cools above a cold ocean current, fog is likely to form. Frost smoke occurs over a warm current which flows into a colder region. Evaporation is greater from warm water than from cold water, adding to atmospheric moisture.

3613. Ocean Current Observations

Historically, our views of the surface circulation of the ocean have been shaped by reports of ocean currents provided by mariners. These observations consist of reports of the difference between the dead reckoning and the observed position of the vessel. These observations were routinely collected until the start of World War II.

Today, three observation systems are generally used for surface current studies. The first utilizes **autonomous free-drifting buoys** which are tracked by satellite or relay their position via satellite. These buoys consist of either a spherical or cylindrical surface float which is about 0.5m in diameter with a drogue at a depth of about 35m.

The second system utilizes acoustic Doppler current profilers. These profilers utilize hull mounted transducers, operate at a frequency of 150 kHz, and have pulse repetition rates of about 1 second. They can penetrate to about 300m, and, where water is shallower than this depth, track the bottom. Merchant and naval vessels are increasingly being outfitted with acoustic Doppler current profilers which, when operated with the Global Positioning System, provide accurate observations of currents.

The third system is a high frequency radar system employing land-based radar antennae that can measure surface currents (top ~2m) up to 200 km from shore. These observations are available in near-real time to the mariner with an internet connection.

3614. References

Barrick, D. E., Evans, M. W., and Weber B. L., (14 OCTOBER 1977), SCIENCE, Vol. 198, Issue 4313, *Surface Currents Mapped by Radar*, pp. 138-144.

CHAPTER 37

WAVES, BREAKERS AND SURF

OCEAN WAVES

3700. Introduction

Ocean waves, the most easily observed phenomenon at sea, are probably the least understood by the average seaman. More than any other single factor, ocean waves are likely to cause a navigator to change course or speed to avoid damage to ship and cargo. Wind-generated ocean waves have been measured at more than 100 feet high, and tsunamis, caused by earthquakes, far higher. Mariners with knowledge of basic facts concerning waves are able to use them to their advantage, avoid hazardous conditions, and operate with a minimum of danger if such conditions cannot be avoided. See Chapter 41 - Weather Routing, for details on how to avoid areas of severe waves.

3701. Causes of Waves

Waves on the surface of the sea are caused principally by wind, but other factors, such as submarine earthquakes, volcanic eruptions, and the tide, also cause waves. If a breeze of less than 2 knots starts to blow across smooth water, small wavelets called **ripples (capillary waves)** form almost instantaneously. When the breeze dies, the ripples disappear as suddenly as they formed, the level surface being restored by surface tension of the water. If the wind speed exceeds 2 knots, more stable **gravity waves** gradually form, and progress with the wind.

While the generating wind blows, the resulting waves may be referred to as **sea**. When the wind stops or changes direction, waves that continue on without relation to local winds are called **swell**.

Unlike wind and current, waves are not deflected appreciably by the rotation of the Earth, but move in the direction in which the generating wind blows. When this wind ceases, friction and spreading cause the waves to be reduced in height, or attenuated, as they move. However, the reduction takes place so slowly that swell often continues until it reaches some obstruction, such as a shore.

The Fleet Numerical Meteorology and Oceanography Center (FNMOC) produces synoptic analyses and predictions of ocean wave heights using a spectral numerical model. The wave information consists of heights and directions for different periods and wavelengths. Verification of projected data has proven the model to be very good. Information from the model is provided to the U.S. Navy on a routine basis and is a vital input to the Optimum Track Ship Routing (OTSR) program.

3702. Wave Characteristics

Ocean waves are very nearly in the shape of an inverted cycloid, the figure formed by a point inside the rim of a wheel rolling along a level surface. This shape is shown in Figure 3702a. The highest parts of waves are called **crests**, and the intervening lowest parts, troughs. Since the crests are steeper and narrower than the troughs, the mean or still water level is a little lower than halfway between the crests and troughs. The vertical distance between trough and crest is called **wave height**, labeled H in Figure 3702a. The horizontal distance between successive crests, measured in the direction of travel, is called **wavelength**, labeled L. The time interval between passage of successive crests at a stationary point is called **wave period** (P). Wave height, length, and period depend upon a number of factors, such as the wind speed, the length of time it has blown, and its **fetch** (the straight distance it has traveled over the surface). Table 3702b indicates the relationship between wind speed, fetch, length of time the wind blows, wave height, and wave period in deep water.
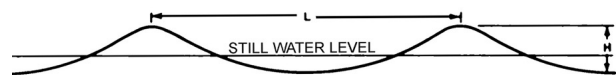
Figure 3702a. A typical sea wave.

If the water is deeper than one-half the wavelength (L), this length in feet is theoretically related to period (P) in seconds by the formula:

$$L = 5.12\ P^2.$$

The actual value has been found to be a little less than this for swell, and about two-thirds the length determined by this formula for sea. When the waves leave the generating area and continue as free waves, the wavelength and period continue to increase, while the height decreases. The rate of change gradually decreases.

The speed (S) of a free wave in deep water is nearly independent of its height or steepness. For swell, its relationship

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	BEAUFORT NUMBER																										
Fetch	3			4			5			6			7			8			9			10			11			Fetch
	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	
10	4.4	1.8	2.1	3.7	2.6	2.4	3.2	3.5	2.8	2.7	5.0	3.1	2.5	6.0	3.4	2.3	7.3	3.9	2.0	8.0	4.1	1.9	10.0	4.2	1.8	10.0	5.0	10
20	7.1	2.0	2.5	6.2	3.2	2.9	5.4	4.9	3.3	4.7	7.0	3.8	4.2	8.6	4.3	3.9	10.0	4.4	3.5	12.0	5.0	3.2	14.0	5.2	3.0	16.0	5.9	20
30	9.8	2.0	2.8	8.3	3.8	3.3	7.2	5.8	3.7	6.2	8.0	4.2	5.8	10.0	4.6	5.2	12.1	5.0	4.7	15.8	5.5	4.4	18.0	6.0	4.1	19.8	6.3	30
40	12.0	2.0	3.0	10.3	3.9	3.6	8.9	6.2	4.1	7.8	9.0	4.6	7.1	11.2	4.9	6.5	14.0	5.4	5.8	17.7	5.9	5.4	21.0	6.3	5.1	22.5	6.7	40
50	14.0	2.0	3.2	12.4	4.0	3.8	11.0	6.5	4.4	9.1	9.8	4.8	8.4	12.2	5.2	7.7	15.7	5.6	6.9	19.8	6.3	6.4	23.0	6.7	6.1	25.0	7.1	50
60	16.0	2.0	3.5	14.0	4.0	4.0	12.0	6.8	4.6	10.2	10.3	5.1	9.6	13.2	5.5	8.7	17.0	6.0	8.0	21.0	6.5	7.4	25.0	7.0	7.0	27.5	7.5	60
70	18.0	2.0	3.7	15.8	4.0	4.1	13.5	7.0	4.8	11.9	10.8	5.4	10.5	13.9	5.7	9.9	18.0	6.4	9.0	22.5	6.8	8.3	26.5	7.3	7.8	29.5	7.7	70
80	20.0	2.0	3.8	17.0	4.0	4.2	15.0	7.2	4.9	13.0	11.0	5.6	12.0	14.5	6.0	11.0	18.9	6.6	10.0	24.0	7.1	9.3	28.0	7.7	8.6	31.5	7.9	80
90	23.6	2.0	3.9	18.8	4.0	4.3	16.5	7.3	5.1	14.1	11.2	5.8	13.0	15.0	6.3	12.0	20.0	6.7	11.0	25.0	7.2	10.2	30.0	7.9	9.5	34.0	8.2	90
100	27.1	2.0	4.0	20.0	4.0	4.4	17.5	7.3	5.3	15.1	11.4	6.0	14.0	15.5	6.5	12.8	20.5	6.9	11.9	26.5	7.6	11.0	32.0	8.1	10.3	35.0	8.5	100
120	31.1	2.0	4.2	22.4	4.1	4.7	20.0	7.8	5.4	17.0	11.7	6.2	15.9	16.0	6.7	14.5	21.5	7.3	13.1	27.5	7.9	12.3	33.5	8.4	11.5	37.5	8.8	120
140	36.6	2.0	4.5	25.8	4.2	4.9	22.5	7.9	5.8	19.1	11.9	6.4	17.6	16.2	7.0	16.0	22.0	7.6	14.8	29.0	8.3	13.9	35.5	8.8	13.0	40.0	9.2	140
160	43.2	2.0	4.9	28.4	4.2	5.2	24.3	7.9	6.0	21.1	12.0	6.6	19.5	16.5	7.3	18.0	23.0	8.0	16.4	30.5	8.7	15.1	37.0	9.1	14.5	42.5	9.6	160
180	50.0	2.0	4.9	30.9	4.3	5.4	27.0	8.0	6.2	23.1	12.1	6.8	21.3	17.0	7.5	19.9	23.5	8.3	18.0	31.5	9.0	16.5	38.5	9.5	16.0	44.5	10.0	180
200				33.5	4.3	5.6	29.0	8.0	6.4	25.4	12.2	7.1	23.1	17.5	7.7	21.5	23.5	8.5	19.3	32.5	9.2	18.1	40.0	9.8	17.1	46.0	10.3	200
220				36.5	4.4	5.8	31.1	8.0	6.6	27.2	12.3	7.2	25.0	17.9	8.0	22.9	24.0	8.8	20.9	34.0	9.6	19.1	41.5	10.1	18.2	47.5	10.6	220
240				39.2	4.4	5.9	33.1	8.0	6.8	29.0	12.4	7.3	26.8	17.9	8.2	24.4	24.5	9.0	22.0	34.5	9.8	20.5	43.0	10.3	19.5	49.0	10.8	240
260				41.9	4.4	6.0	34.9	8.0	6.9	30.5	12.6	7.5	28.0	18.0	8.4	26.0	25.0	9.2	23.5	34.5	10.0	21.8	44.0	10.6	20.9	50.5	11.1	260
280				44.5	4.4	6.2	36.8	8.0	7.0	32.4	12.9	7.8	29.5	18.0	8.5	27.7	25.0	9.4	25.0	35.0	10.2	23.0	45.0	10.9	22.0	51.5	11.3	280
300				47.0	4.4	6.3	38.5	8.0	7.1	34.1	13.1	8.0	31.5	18.0	8.7	29.0	25.0	9.5	26.3	35.0	10.4	24.3	45.0	11.1	23.2	53.0	11.6	300
320							40.5	8.0	7.2	36.0	13.3	8.2	33.0	18.0	8.9	30.2	25.0	9.6	27.6	35.5	10.6	25.5	45.5	11.2	24.5	54.0	11.8	320
340							42.4	8.0	7.3	37.6	13.4	8.3	34.2	18.0	9.0	31.6	25.0	9.8	29.0	36.0	10.8	26.7	46.0	11.4	25.5	55.0	12.0	340
360							44.2	8.0	7.4	38.8	13.4	8.4	35.7	18.1	9.1	33.0	25.0	9.9	30.0	36.5	10.9	27.7	46.5	11.6	26.6	55.0	12.2	360
380							46.1	8.0	7.5	40.2	13.5	8.5	37.1	18.2	9.3	34.2	25.5	10.0	31.3	37.0	11.1	29.1	47.0	11.8	27.7	55.5	12.4	380
400							48.0	8.0	7.7	42.2	13.5	8.6	38.8	18.4	9.5	35.6	26.0	10.2	32.5	37.0	11.2	30.2	47.5	12.0	28.9	56.0	12.6	400
420							50.0	8.0	7.8	43.5	13.6	8.7	40.0	18.7	9.6	36.9	26.5	10.3	33.7	37.5	11.4	31.5	47.5	12.2	29.6	56.5	12.7	420
440							52.0	8.0	7.9	44.7	13.7	8.8	41.3	18.8	9.7	38.1	27.0	10.4	34.8	37.5	11.5	32.5	48.0	12.3	30.9	57.0	12.9	440
460							54.0	8.0	8.0	46.2	13.7	8.9	42.8	19.0	9.8	39.5	27.5	10.6	36.0	37.5	11.7	33.5	48.5	12.5	31.8	57.5	13.1	460
480							56.0	8.0	8.1	47.8	13.7	9.0	44.0	19.0	9.9	41.0	27.5	10.8	37.0	37.5	11.8	34.5	49.0	12.6	32.7	57.5	13.2	480
500							58.0	8.0	8.2	49.2	13.8	9.1	45.5	19.1	10.1	42.1	27.5	10.9	38.3	38.0	11.9	35.5	49.0	12.7	33.9	58.0	13.4	500
550										53.0	13.8	9.3	48.5	19.5	10.3	44.9	27.5	11.1	41.0	38.5	12.2	38.2	50.0	13.0	36.5	59.0	13.7	550
600										56.3	13.8	9.5	51.8	19.7	10.5	47.7	27.5	11.3	43.6	39.0	12.5	40.3	50.0	13.3	38.7	60.0	14.0	600
650													55.0	19.8	10.7	50.3	27.5	11.6	46.4	39.5	12.8	43.0	50.0	13.7	41.0	60.0	14.2	650
700													58.5	19.8	11.0	53.2	27.5	11.8	49.0	40.0	13.1	45.4	50.5	14.0	43.5	60.5	14.5	700
750																56.2	27.5	12.1	51.0	40.0	13.3	48.0	51.0	14.2	45.8	61.0	14.8	750
800																59.2	27.5	12.3	53.8	40.0	13.5	50.6	51.5	14.5	47.8	61.5	15.0	800
850																			56.2	40.0	13.8	52.5	52.0	14.6	50.0	62.0	15.2	850
900																			58.2	40.0	14.0	54.6	52.0	14.9	52.0	62.5	15.5	900
950																						57.2	52.0	15.1	54.0	63.0	15.7	950
1000																						59.3	52.0	15.3	56.3	63.0	16.0	1000

Table 3702b. Minimum Time (T) in hours that wind must blow to form waves of H significant height (in feet) and P period (in seconds). Fetch in nautical miles.
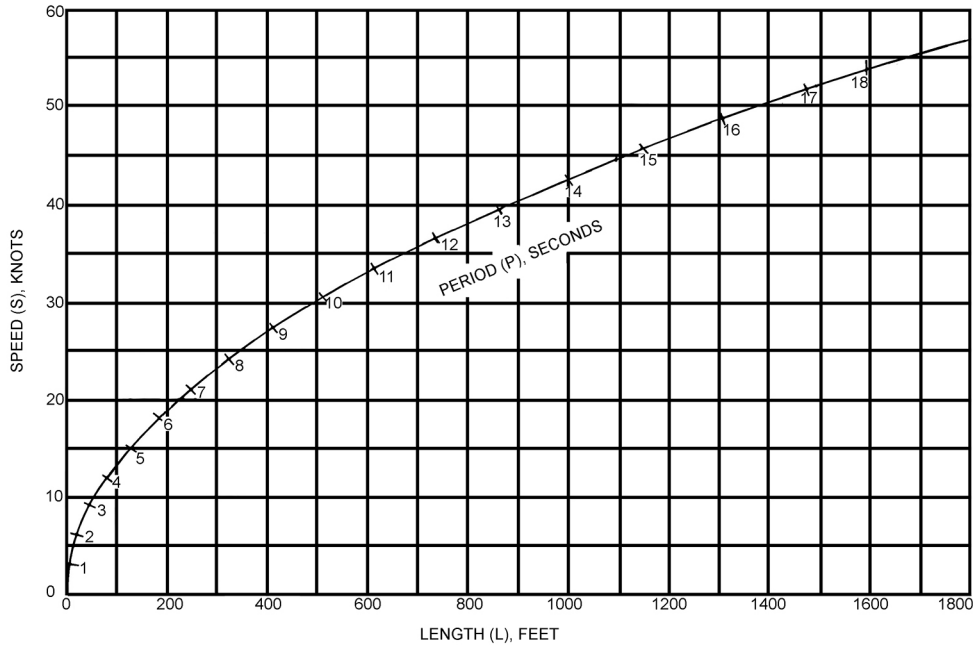
Figure 3702c. Relationship between speed, length, and period of waves in deep water, based upon the theoretical relationship between period and length.

in knots to the period (P) in seconds is given by the formula:

$$S = 3.03P.$$

The relationship for sea is not known.

The theoretical relationship between speed, wavelength, and period is shown in Figure 3702c. As waves continue on beyond the generating area, the period, wavelength, and speed remain the same. Because the waves of each period have different speeds they tend to sort themselves by periods as they move away from the generating area. The longer period waves move at a greater speed and move ahead. At great enough distances from a storm area the waves will have sorted themselves into sets based on period.

All waves are attenuated as they propagate but the short period waves attenuate faster, so that far from a storm only the longer waves remain.

The time needed for a wave system to travel a given distance is double that which would be indicated by the speed of individual waves. This is because each leading wave in succession gradually disappears and transfers its energy to following wave. The process occurs such that the whole wave system advances at a speed which is just half that of each individual wave. This process can easily be seen in the bow wave of a vessel. The speed at which the wave system advances is called **group velocity**.

Because of the existence of many independent wave systems at the same time, the sea surface acquires a complex and irregular pattern. Since the longer waves
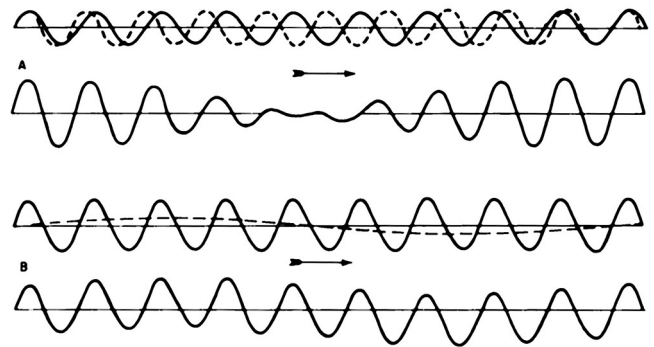

Figure 3702d. Interference. The upper part of A shows two waves of equal height and nearly equal length traveling in the same direction. The lower part of A shows the resulting wave pattern. In B similar information is shown for short waves and long swell.

overrun the shorter ones, the resulting interference adds to the complexity of the pattern. The process of interference, illustrated in Figure 3702d, is duplicated many times in the sea; it is the principal reason that successive waves are not of the same height. The irregularity of the surface may be further accentuated by the presence of wave systems crossing at an angle to each other, producing peak-like rises.

In reporting average wave heights, the mariner has a tendency to neglect the lower ones. It has been found that the reported value is about the average for the highest one-third. This is sometimes called the

"significant" wave height. The approximate relationship between this height and others, is as follows:

Wave	Relative height
Average	0.64
Significant	1.00
Highest 10 percent	1.29
Highest	1.87

3703. Path of Water Particles in a Wave

As shown in Figure 3703, a particle of water on the surface of the ocean follows a somewhat circular orbit as a wave passes, but moves very little in the direction of motion of the wave. The common wave producing this action is called an **oscillatory wave**. As the crest passes, the particle moves forward, giving the water the appearance of moving with the wave. As the trough passes, the motion is in the opposite direction. The radius of the circular orbit decreases with depth, approaching zero at a depth equal to about half the wavelength. In shallower water the orbits become more elliptical, and in very shallow water the vertical motion disappears almost completely.
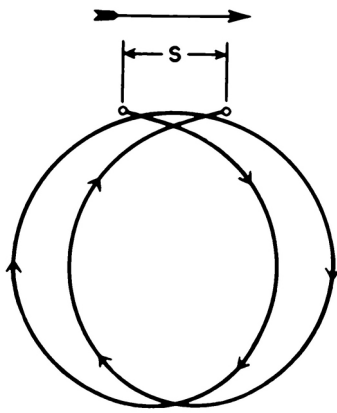

Figure 3703. Orbital motion and displacement, S, of a particle on the surface of deep water during two wave periods.

Since the speed is greater at the top of the orbit than at the bottom, the particle is not at exactly its original point following passage of a wave, but has moved slightly in the wave's direction of motion. However, since this advance is small in relation to the vertical displacement, a floating object is raised and lowered by passage of a wave, but moved little from its original position. If this were not so, a slow moving vessel might experience considerable difficulty in making way against a wave train, a series of waves moving in the same direction. In Figure 3703 the forward displacement is greatly exaggerated.

3704. Effects of Current and Ice on Waves

A following current increases wavelengths and decreases wave heights. An opposing current has the opposite effect, decreasing the length and increasing the height. This effect can be dangerous in certain areas of the world where a stream current opposes waves generated by severe weather. An example of this effect is off the coast of South Africa, where the Agulhas current is often opposed by westerly storms, creating steep, dangerous seas. A strong opposing current may cause the waves to break, as in the case of **overfalls** in tidal currents. The extent of wave alteration is dependent upon the ratio of the still-water wave speed to the speed of the current.

Moderate ocean currents running at oblique angles to wave directions appear to have little effect, but strong tidal currents perpendicular to a system of waves have been observed to completely destroy them in a short period of time.

When ice crystals form in seawater, internal friction is greatly increased. This results in smoothing of the sea surface. The effect of pack ice is even more pronounced. A vessel following a lead through such ice may be in smooth water even when a gale is blowing and heavy seas are beating against the outer edge of the pack. Hail or torrential rain is also effective in flattening the sea, even in a high wind.

3705. Waves and Shallow Water

When a wave encounters shallow water, the movement of the water is restricted by the bottom, resulting in reduced wave speed. In deep water wave speed is a function of period. In shallow water, the wave speed becomes a function of depth. The shallower the water, the slower the wave speed. As the wave speed slows, the period remains the same, so the wavelength becomes shorter. Since the energy in the waves remains the same, the shortening of wavelengths results in increased heights. This process is called **shoaling**. If the wave approaches a shallow area at an angle, each part is slowed successively as the depth decreases. This causes a change in direction of motion, or **refraction**, the wave tending to change direction parallel to the depth curves. The effect is similar to the refraction of light and other forms of radiant energy.

As each wave slows, the next wave behind it, in deeper water, tends to catch up. As the wavelength decreases, the height generally becomes greater. The lower part of a wave, being nearest the bottom, is slowed more than the top. This may cause the wave to become unstable, the faster-moving top falling forward or breaking. Such a wave is called a **breaker**, and a series of breakers is **surf**.

Swell passing over a shoal but not breaking undergoes a decrease in wavelength and speed, and an increase in height, which may be sudden and dramatic, depending on the steepness of the seafloor's slope. This **ground swell** may
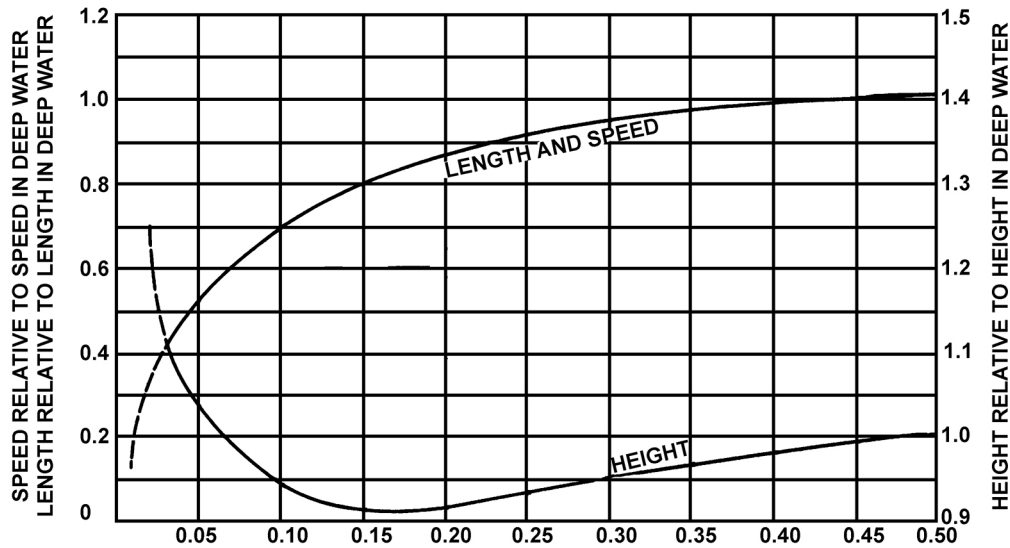
Figure 3705. Alteration of the characteristics of waves crossing a shoal.

cause heavy rolling if it is on the beam and its period is the same as the period of roll of a vessel, even though the sea may appear relatively calm. It may also cause a **rage sea**, when the swell waves encounter water shoal enough to make them break. Rage seas are dangerous to small craft, particularly approaching from seaward, as the vessel can be overwhelmed by enormous breakers in perfectly calm weather. The swell waves, of course, may have been generated hundreds of miles away. In the open ocean they are almost unnoticed due to their very long period and wavelength. Figure 3705 illustrates the approximate alteration of the characteristics of waves as they cross a shoal.

3706. Energy of Waves

The potential energy of a wave is related to the vertical distance of each particle from its still-water position. Therefore potential energy moves with the wave. In contrast, the kinetic energy of a wave is related to the speed of the particles, distributed evenly along the entire wave.

The amount of kinetic energy in a wave is tremendous. A 4-foot, 10-second wave striking a coast expends more than 35,000 horsepower per mile of beach. For each 56 miles of coast, the energy expended equals the power generated at the Hoover Dam. An increase in temperature of the water in the relatively narrow surf zone in which this energy is expended would seem to be indicated, but no pronounced increase has been measured. Apparently, any heat that may be generated is dissipated to the deeper water beyond the surf zone.

3707. Wave Measurement Aboard Ship

With suitable equipment and adequate training, reliable measurements of the height, length, period, and speed of waves can be made. However, the mariner's estimates of height and length often contain relatively large errors. There is a tendency to underestimate the heights of low waves and overestimate the heights of high ones. There are numerous accounts of waves 75 to 80 feet high, or even higher, although waves more than 55 feet high are very rare. Wavelength is usually underestimated. The motions of the vessel from which measurements are made contribute to such errors.

Height. Measurement of wave height is particularly difficult. A microbarograph can be used if the wave is long enough or the vessel small enough to permit the vessel to ride from crest to trough. If the waves are approaching from dead ahead or dead astern, this requires a wavelength at least twice the length of the vessel. For most accurate results the instrument should be placed at the center of roll and pitch, to minimize the effects of these motions. Wave height can often be estimated with reasonable accuracy by comparing it with freeboard of the vessel. This is less accurate as wave height and vessel motion increase. If a point of observation can be found at which the top of a wave is in line with the horizon when the observer is in the trough, the wave height is equal to height of eye. However, if the vessel is rolling or pitching, this height at the moment of observation may be difficult to determine. The highest wave ever reliably reported was 112 feet observed from the USS Ramapo in 1933. On September 15, 2004 the eye of Hurricane Ivan passed over a series of Naval Research Laboratory (NRL) ocean floor sensors in the Gulf of Mexico. The underwater sensors recorded a wave height of 91 feet.

Length. The dimensions of the vessel can be used to determine wavelength. Errors are introduced by perspective and disturbance of the wave pattern by the vessel. These errors are minimized if observations are made from maximum height. Best results are obtained if the sea is from dead ahead or dead astern.

Period. If allowance is made for the motion of the vessel, wave period can be determined by measuring the interval between passages of wave crests past the observer. The relative motion of the vessel can be eliminated by timing the passage of successive wave crests past a patch of foam or a floating object at some distance from the vessel. Accuracy of results can be improved by averaging several observations.

Speed. Speed can be determined by timing the passage of the wave between measured points along the side of the ship, if corrections are applied for the direction of travel for the wave and the speed of the ship.

The length, period, and speed of waves are interrelated by the relationships indicated previously. There is no definite mathematical relationship between wave height and length, period, or speed.

3708. Tsunamis

A **Tsunami** is an ocean wave produced by sudden, large-scale motion of a portion of the ocean floor or the shore, such as a volcanic eruption, earthquake (sometimes called seaquake if it occurs at sea), or landslide. If they are caused by a submarine earthquake, they are usually called **seismic sea waves**. The point directly above the disturbance, at which the waves originate, is called the **epicenter**. Either a tsunami or a storm tide that overflows the land is popularly called a **tidal wave**, although it bears no relation to the tide.

If a volcanic eruption occurs below the surface of the sea, the escaping gases cause a quantity of water to be pushed upward in the shape of a dome. The same effect is caused by the sudden rising of a portion of the bottom. As this water settles back, it creates a wave which travels at high speed across the surface of the ocean.

Tsunamis are a series of waves. Near the epicenter, the first wave may be the highest. At greater distances, the highest wave usually occurs later in the series, commonly between the third and the eighth wave. Following the maximum, they again become smaller, but the tsunami may be detectable for several days.

In deep water the wave height of a tsunami is probably never greater than 2 or 3 feet. Since the wavelength is usually considerably more than 100 miles, the wave is not conspicuous at sea. In the Pacific, where most tsunamis occur, the wave period varies between about 15 and 60 minutes and the speed in deep water is more than 400 knots. The approximate speed can be computed by the formula:

$$S = 0.6\sqrt{gd} = 3.4\sqrt{d}$$

where S is the speed in knots, g is the acceleration due to gravity (32.2 feet per second), and d is the depth of water in feet. This formula is applicable to any wave in water having a depth of less than half the wavelength. For most ocean waves it applies only in shallow water, because of the relatively short wavelength.

When a tsunami enters shoal water, it undergoes the same changes as other waves. The formula indicates that speed is proportional to depth of water. Because of the great speed of a tsunami when it is in relatively deep water, the slowing is relatively much greater than that of an ordinary wave crested by wind. Therefore, the increase in height is also much greater. The size of the wave depends upon the nature and intensity of the disturbance. The height and destructiveness of the wave arriving at any place depends upon its distance from the epicenter, topography of the ocean floor, and the coastline. The angle at which the wave arrives, the shape of the coastline, and the topography along the coast and offshore, all have an effect. The position of the shore is also a factor, as it may be sheltered by intervening land, or be in a position where waves have a tendency to converge, either because of refraction or reflection, or both.

Tsunamis of 50 feet in height or higher have reached the shore, inflicting widespread damage. On December 26, 2004, a magnitude 9.3 earthquake off the northwest coast of Sumatra triggered a devastating tsunami. The waves, which reached 80 feet in some locations, killed nearly 300,000 people across Indonesia, Thailand, and Sri Lanka. After a particularly devastating tsunami struck Hawaii in 1946, a tsunami warning system was set up in the Pacific. This system monitors seismic disturbances throughout the Pacific basin and predicts times and heights of tsunamis. Warnings are immediately sent out if a disturbance is detected. For more information on tsunamis see the Pacific Marine Environmental Laboratory/NOAA Center for Tsunami Research website (see Figure 3708).

Figure 3708. NOAA Center for Tsunami Research.
http://nctr.pmel.noaa.gov/

In addition to seismic sea waves, earthquakes below the surface of the sea may produce a longitudinal pressure wave that travels upward at the speed of sound. When a ship encounters such a wave, it is felt as a sudden shock which may be so severe that the crew thinks the vessel has struck bottom.

3709. Storm Tides

In relatively tideless seas like the Baltic and Mediterranean, winds cause the chief fluctuations in sea level. Elsewhere, the astronomical tide usually masks these variations. However, under exceptional conditions, either severe extra-tropical storms or tropical cyclones can

produce changes in sea level that exceed the normal range of tide. Low sea level is of little concern except to coastal shipping, but a rise above ordinary high-water mark, particularly when it is accompanied by high waves, can result in a catastrophe.

Although, like tsunamis, these storm tides or storm surges are popularly called tidal waves, they are not associated with the tide. They consist of a single wave crest and hence have no period or wavelength.

Three effects in a storm induce a rise in sea level. The first is wind stress on the sea surface, which results in a piling-up of water (sometimes called "wind set-up"). The second effect is the convergence of wind-driven currents, which elevates the sea surface along the convergence line. In shallow water, bottom friction and the effects of local topography cause this elevation to persist and may even intensify it. The low atmospheric pressure that accompanies severe storms causes the third effect, which is sometimes referred to as the "inverted barometer" as the sea surface rises into the low pressure area. An inch of mercury is equivalent to about 13.6 inches of water, and the adjustment of the sea surface to the reduced pressure can amount to several feet at equilibrium.

All three of these causes act independently and if they happen to occur simultaneously, their effects are additive. In addition, the wave can be intensified or amplified by the effects of local topography. Storm tides may reach heights of 20 feet or more and it is estimated that they cause three-fourths of the deaths attributed to hurricanes.

3710. Standing Waves and Seiches

Previous articles in this chapter have dealt with progressive waves which appear to move regularly with time. When two systems of progressive waves having the same period travel in opposite directions across the same area, a series of **standing waves** may form. These appear to remain stationary. A video of this phenomenon is available through the link provided in Figure 3710a.

Another type of standing wave, called a **seiche**, sometimes occurs in a confined body of water. It is a long wave, usually having its crest at one end of the confined space and its trough at the other. Its period may be anything from a few minutes to an hour or more, but somewhat less than the tidal period. Seiches are usually attributed to strong winds or sudden changes in atmospheric pressure that push water from one end of a body of water to the other. When the wind stops, the water rebounds to the other side of the enclosed area. See Figure 3710b for a graphical depiction of this phenomenon.

Lake Erie is known for seiches, especially when strong winds blow from southwest to northeast. In 1844, a 22 foot seiche breached a 14-foot high sea wall killing 78 people and damming the ice to the extent that Niagara Falls temporarily stopped flowing.

Figure 3710a. Standing wave video link; https://www.youtube.com/watch?v=X8qZO6g_X5Q
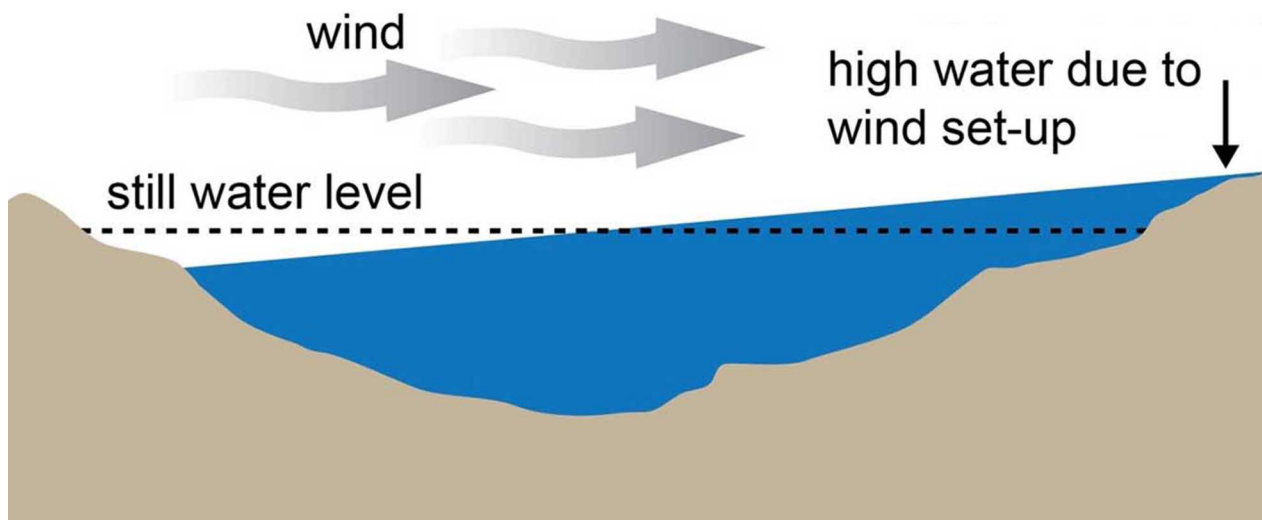
Figure 3710b. How seiches form.

3711. Tide-Generated Waves

There are, in general, two regions of high tide separated by two regions of low tide and these regions move progressively westward around the Earth as the moon revolves in its orbit. The high tides are the crests of these tide waves and the low tides are the troughs. The wave is not noticeable at sea, but becomes apparent along the coasts, particularly in funnel-shaped estuaries. In certain river mouths, or estuaries of particular configuration, the incoming wave of high water overtakes the preceding low tide, resulting in a steep, breaking wave which progresses upstream in a surge called a **bore**.

3712. Internal Waves

Thus far, the discussion has been confined to waves on the surface of the sea, the boundary between air and water. **Internal waves**, or boundary waves, are created below the surface, at the boundaries between water strata of different densities. The density differences between adjacent water strata in the sea are considerably less than that between sea and air. Consequently, internal waves are much more easily formed than surface waves and they are often much larger. The maximum height of wind waves on the surface is about 60 feet, but internal wave heights as great as 300 feet have been encountered.

Internal waves are detected by a number of observations of the vertical temperature distribution, using recording devices such as the bathythermograph. They have periods as short as a few minutes and as long as 12 or 24 hours, these greater periods being associated with the tides.

A slow-moving ship, operating in a freshwater layer having a depth approximating the draft of the vessel, may produce short-period internal waves. This may occur off rivers emptying into the sea, or in polar regions in the vicinity of melting ice. Under suitable conditions, the normal propulsion energy of the ship is expended in generating and maintaining these internal waves and the ship appears to "stick" in the water, becoming sluggish and making little headway. The phenomenon, known as **dead water**, disappears when speed is increased by a few knots.

The full significance of internal waves has not yet been determined, but it is known that they may cause submarines to rise and fall like a ship at the surface and they may also affect sound transmission in the sea.

3713. Waves and Ships

The effects of waves on a ship vary considerably with the type of ship, its course and speed, and the condition of the sea.

A short vessel has a tendency to ride up one side of a wave and down the other side, while a larger vessel may tend to ride through the waves on an even keel. If the waves are of such length that the bow and stern of a vessel are alternately riding in successive crests and troughs, the vessel is subject to heavy sagging and hogging stresses, and under extreme conditions may break in two. A change of heading may reduce the danger. Because of the danger from sagging and hogging, a small vessel is sometimes better able to ride out a storm than a large one.

If successive waves strike the side of a vessel at the same phase of successive rolls, relatively small waves can cause heavy rolling. The same effect, if applied to the bow or stern in time with the natural period of pitch, can cause heavy pitching. A change of either heading or speed can quickly reduce the effect.

A wave having a length twice that of a ship places that ship in danger of falling off into the trough of the sea, particularly if it is a slow-moving vessel. The effect is especially pronounced if the sea is broad on the bow or broad on the quarter. An increase in speed reduces the hazard.

For more detailed information on **avoiding dangerous situations in adverse weather and sea conditions**, see the International Maritime Organization (IMO) Maritime Safety Committee Circular MSC.1/Circ. 1228. This circular is available for free download to public users who register for an IMODOCS account (see Figure 3713). **Circular 1228** provides ship masters with general and cautionary information, including sections on dangerous phenomenon and operational guidance, which collectively may form a basis for decision making.

Figure 3713. IMODOCS registration. https://webaccounts.imo.org/Common/PublicRegistration. aspx

3714. Using Oil to Calm Breaking Waves

Historically oil was used to calm breaking waves and was useful to vessels when lowering or hoisting boats in rough weather. Its effect was greatest in deep water, where a small quantity sufficed if the oil was made to spread to windward of the vessel. Oil increases the surface tension of the water, lessening the tendency for waves to break.

BREAKERS AND SURF

3715. Refraction

As explained previously, waves are slowed in shallow water, causing refraction if the waves approach the beach at an angle. Along a perfectly straight beach, with uniform shoaling, the wave fronts tend to become parallel to the shore. Any irregularities in the coastline or bottom contours, however, affect the refraction, causing irregularities. In the case of a ridge perpendicular to the beach, for instance, the shoaling is more rapid, causing greater refraction towards the ridge. The waves tend to align themselves with the bottom contours. Waves on both sides of the ridge have a component of motion toward the ridge. This convergence of wave energy toward the ridge causes an increase in wave or breaker height. A submarine canyon or valley perpendicular to the beach, on the other hand, produces divergence, with a decrease in wave or breaker height. These effects are illustrated in Figure 3715. Bends in the coast line have a similar effect, convergence occurring at a point, and divergence if the coast is concave to the sea. Points act as focal areas for wave energy and experience large breakers. Concave bays have small breakers because the energy is spread out as the waves approach the beach.
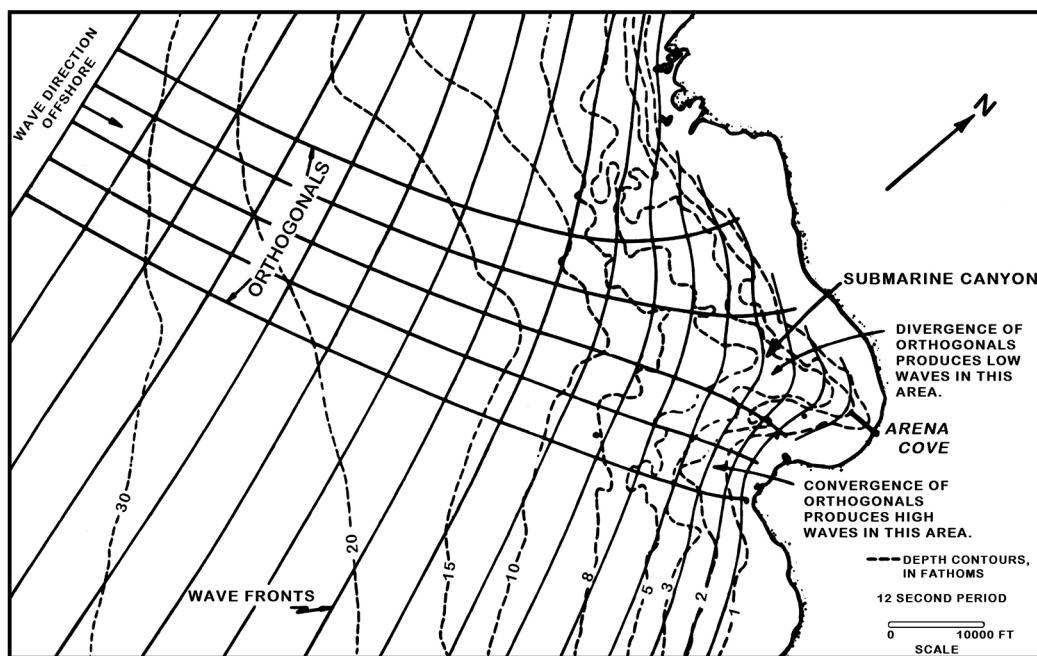

Figure 3715. The effect of bottom topography in causing wave convergence and wave divergence.
Courtesy of Robert L. Wiegel, Council on Wave Research, University of California.

Under suitable conditions, currents also cause refraction. This is of particular importance at entrances of tidal estuaries. When waves encounter a current running in the opposite direction, they become higher and shorter. This results in a choppy sea, often with breakers. When waves move in the same direction as current, they decrease in height, and become longer. Refraction occurs when waves encounter a current at an angle.

3716. Classes Of Breakers

In deep water, swell generally moves across the surface as somewhat regular, smooth undulations. When shoal water is reached, the wave period remains the same, but the speed decreases. The amount of decrease is negligible until the depth of water becomes about one-half the wavelength, when the waves begin to "feel" bottom. There is a slight decrease in wave height, followed by a rapid increase, if the waves are traveling perpendicular to a straight coast with a uniformly sloping bottom. As the waves become higher and shorter, they also become steeper, and the crest narrows. When the speed of the crest becomes greater than that of the wave, the front face of the wave becomes steeper than the rear face. This process continues at an accelerating rate as the depth of water decreases. If the wave becomes too unstable, it topples forward to form a breaker.

There are three general classes of breakers. A **spilling breaker** breaks gradually over a considerable distance. A **plunging breaker** tends to curl over and break with a single crash. A **surging breaker** peaks up, but surges up the beach without spilling or plunging. It is classed as a breaker even though it does not actually break. The type of breaker which forms is determined by the steepness of the beach and the steepness of the wave before it reaches shallow water, as illustrated in Figure 3716.
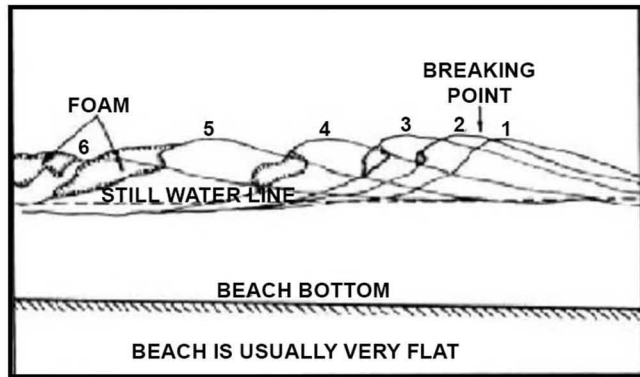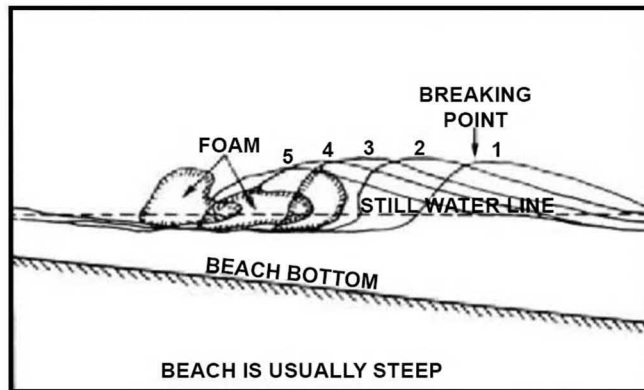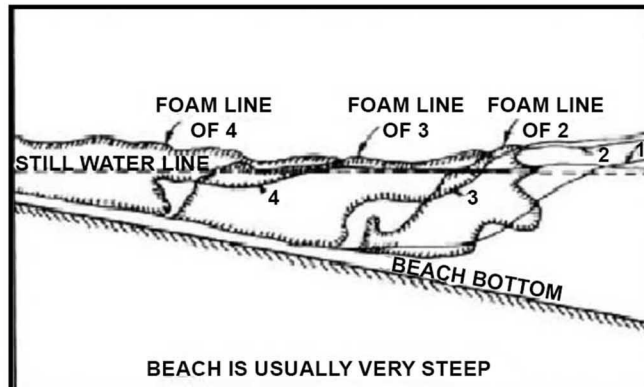
Figure 3716. The three types of breakers. Graphics courtesy of Robert L. Wiegel.

Long waves break in deeper water, and have a greater breaker height. A steep beach also increases breaker height. The height of breakers is less if the waves approach the beach at an acute angle. With a steeper beach slope there is greater tendency of the breakers to plunge or surge. Following the *uprush* of water onto a beach after the breaking of a wave, the seaward *backrush* occurs. The returning water is called **backwash**. It tends to further slow the bottom of a wave, thus increasing its tendency to break. This effect is greater as either the speed or depth of the backwash increases. The still water depth at the point of breaking is approximately 1.3 times the average breaker height.

Surf varies with both position along the beach and time. A change in position often means a change in bottom contour, with the refraction effects discussed before. At the

same point, the height and period of waves vary considerably from wave to wave. A group of high waves is usually followed by several lower ones. Therefore, passage through surf can usually be made most easily immediately following a series of higher waves.

Since surf conditions are directly related to height of the waves approaching a beach and to the configuration of the bottom, the state of the surf at any time can be predicted if one has the necessary information and knowledge of the principles involved. Height of the sea and swell can be predicted from wind data and information on bottom configuration can sometimes be obtained from the largest scale nautical chart. In addition, the area of lightest surf along a beach can be predicted if details of the bottom configuration are available. Surf predictions may, however, be significantly in error due to the presence of swell from unknown storms hundreds of miles away.

3717. Currents in the Surf Zone

In and adjacent to the surf zone, currents are generated by waves approaching the bottom contours at an angle, and by irregularities in the bottom.

Waves approaching at an angle produce a **longshore current** parallel to the beach, inside of the surf zone. Longshore currents are most common along straight beaches. Their speeds increase with increasing breaker height, decreasing wave period, increasing angle of breaker line with the beach, and increasing beach slope. Speed seldom exceeds 1 knot, but sustained speeds as high as 3 knots have been recorded. Longshore currents are usually constant in direction. They increase the danger of landing craft broaching to.

Where the bottom is sandy a good distance offshore, one or more **sand bars** typically form. The innermost bar will break in even small waves, and will isolate the longshore current. The second bar, if one forms, will break only in heavier weather, and the third, if present, only in storms. It is possible to move parallel to the coast in small craft in relatively deep water in the area between these bars, between the lines of breakers.

3718. Rip Currents

As explained previously, wave fronts advancing over nonparallel bottom contours are refracted to cause convergence or divergence of the energy of the waves. Energy concentrations in areas of convergence form barriers to the returning backwash, which is deflected along the beach to areas of less resistance. Backwash accumulates at weak points, and returns seaward in concentrations, forming **rip currents** through the surf. At these points the large volume of returning water has an easily seen retarding effect upon the incoming waves, thus adding to the condition causing the rip current. The waves on one or both sides of the rip, having greater energy and not being retarded by the concentration of

backwash, advance faster and farther up the beach. From here, they move along the beach as feeder currents. At some point of low resistance, the water flows seaward through the surf, forming the neck of the rip current. Outside the breaker line the current widens and slackens, forming the head.

Rip currents may also be caused by irregularities in the beach face. If a beach indentation causes an uprush to advance farther than the average, the backrush is delayed and this in turn retards the next incoming foam line (the front of a wave as it advances shoreward after breaking) at that point. The foam line on each side of the retarded point continues in its advance, however, and tends to fill in the retarded area, producing a rip current. See the National Weather Service - **Rip Current Photos** website for images.

Figure 3718. NWS - Rip Current Photos.
www.ripcurrents.noaa.gov/photos.shtml

Rip currents are dangerous for swimmers, but may provide a clear path to the beach for small craft, as they tend to scour out the bottom and break through any sand bars that have formed. By swimming parallel to the beach, swimmers can extract themselves from the pull of a rip current. Rip currents also change location over time as conditions change.

3719. Beach Sediments

In the surf zone, large amounts of sediment are suspended in the water. When the water's motion decreases, the sediments settle to the bottom. The water motion can be either waves or currents. Promontories or points are rocky because the large breakers scour the points and small sediments are suspended in the water and carried away. Bays tend to have sandy beaches because of the smaller waves.

In the winter when storms create large breakers and surf, the waves erode beaches and carry the particles offshore where offshore sand bars form; sandy beaches tend to be narrower in stormy seasons. In the summer the waves gradually move the sand back to the beaches and the offshore sand bars decrease; then sandy beaches tend to be wider.

Longshore currents move large amounts of sand along the coast. These currents deposit sand on the upcurrent side of a jetty or pier, and erode the beach on the downcurrent side. Groins are sometimes built to impede the longshore flow of sediments and preserve beaches for recreational use. As with jetties, the downcurrent side of each groin will have the best water for approaching the beach.