In a sudden awakening, incredible in its swiftness, the simplest plants of the sea begin to multiply. Their increase is of astronomical proportions. The spring sea belongs at first to the diatoms and to all the other microscopic plant life of the plankton. In the fierce intensity of their growth they cover vast areas of ocean with a living blanket of their cells. Mile after mile of water may appear red or brown or green, the whole surface taking on the color of the infinitesimal grains of pigment contained in each of the plant cells.

The plants have undisputed sway in the sea for only a short time. Almost at once their own burst of multiplication is matched by a similar increase in the small animals of the plankton. It is the spawning time of the copepod and the glassworm, the pelagic shrimp and the winged snail. Hungry swarms of these little beasts of the plankton roam through the waters, feeding on the abundant plants and themselves falling prey to larger creatures.

Rachel Carson,
from *The Sea Around Us*
The word plankton comes from the Greek term planktos, meaning to wander, and the plant and animal plankton are the wanderers and drifters of the sea. They exist in vast swarms, limited in their mobility, moving with the currents. The diversity of planktonic organisms is so great that it is not possible to discuss all of their life-forms here. Instead, representative animals, plants, and groups of animals and plants have been chosen for discussion. Because it is the plant life that is able to use the sun's energy to form the basis of life for all the animals, we begin by considering the ocean's floating plant life, the primary producers of chapter 14, and then go on to describe the animals that drift with the plant plankton, grazing upon it and upon each other.

15.1 The Kinds of Plankton

Although many plankton have a limited ability to move toward and away from the sea surface, they make no purposeful motion against the ocean's currents and are carried from place to place suspended in the seawater. Some plankton are quite large; jellyfish may be the size of a large washbuck, trailing 15 m (50 ft) of tentacles. But the phytoplankton and many zooplankton are generally too small for our unassisted vision and must be observed under a microscope.

Bacteria and very small phytoplankton cells are called ultraplankton; they are less than 0.005 mm in diameter and can only be collected using special filtering techniques. Slightly larger phytoplankton, called nannoplankton, have a size range between 0.005 and 0.07 mm. Zooplankton and phytoplankton between 0.07 and 1 mm are called microplankton or net plankton, because they are usually captured in tow nets made of very fine mesh nylon.

The microscopic phytoplankton are the "grasses of the sea." Just as a land without grass and herbs could not support the insects, small rodents, and birds that serve as food for the larger, meat-eating carnivores, a sea without phytoplankton could not support the zooplankton and the other larger animals. As the British biological oceanographer Sir Alister Hardy has said, "All flesh is grass."

Phytoplankton

The phytoplankton are mainly unicellular (or single-celled) plants known as algae. Each phytoplankton cell is autotrophic (or self-feeding) by the process of photosynthesis (refer back to chapter 14). Each cell is an independent individual, and even in the species in which the cells attach together in filaments (long chains) or other aggregations, there is no division of labor between the cells. There is only one large planktonic alga, the seaweed Sargassum that is found floating in the area of the North Atlantic known as the Sargasso Sea. Sargassum reproduces vegetatively by fragmentation to form large mats, which provide shelter and food for a wide variety of organisms, including fish and crabs. The specialized organisms found living in the Sargassum mats occur nowhere else.

Groups of organisms belonging to the phytoplankton include the diatoms, dinoflagellates, and eucarathophores; silicoflagellates, cryptomonads, chrysomonads, green algae, and cyanobacteria or blue-green algae are present but less numerous. A generalized phytoplankton sample is shown in figure 15.1. In the following discussion the emphasis is placed on the diatoms and the dinoflagellates, as they are the most abundant and most important members of the marine phytoplankton.

Diatoms are single-celled plants found in areas of cold, nutrient-rich water. They are sometimes called golden algae, because their characteristic yellow-brown pigment, fucoxanthin, masks their chlorophyll. Some diatoms have radial symmetry; they are round, shaped like pillboxes, and are called centric diatoms. Others have bilateral symmetry, are elongate, and are called pennate diatoms. Centric diatoms float better than pennate diatoms; therefore pennate diatoms are often found on the shallow seafloor or attached to floating objects, while centric diatoms are more truly planktonic. Some common diatoms from temperate waters are shown in figures 15.2 and 15.3.

Around the outside of each diatom is a frustule (or cell wall) of pectin, a jellylike carbohydrate, impregnated with silica. The frustule is hard, rigid, transparent, and
Figure 15.2
The diatoms are the most important members of the phytoplankton; they are found in a wide variety of forms. (a) Two species of *Thalassiosira*. (b) The large centric diatom *Asterionella*. (c) An enlarged detail of (b) showing the intricate details of the diatom's frustule. (d) The diatoms arranged in star-shaped groups are members of the genus *Asterionella*. 
Figure 15.2 continued
(c) These *Nitzschia* cells show the characteristic yellow-brown color of diatoms;
(f) *Chaetoceros* forms chains of cells with long spines.
Figure 15.3
Centric and pennate diatoms. Diatoms exist as single cells or in chains.

Figure 15.4
Stereoscopic micrographs of diatom frustules.

delicately marked with pores that connect the living portion of the cell inside to its outside environment (see fig. 15.4). The two halves of a centric diatom's frustule fit together like a pillbox, and when the cell has grown sufficiently large, the cell inside divides, the two halves of the pillbox separate, a new inner half to each pillbox is formed, and two new daughter diatoms are produced. By this process, one of the new cells will remain the same size as the parent, while the other is always smaller, as its larger pillbox half is formed by the smaller bottom half of the parent pillbox.

This process is shown in figure 15.5. When a cell reaches a size level of about 25% of the original parent's size, it stops dividing and begins a sexual cycle. In this cycle it produces a naked auxospore, which increases in size, forms a new frustule, and begins to divide again. Diatoms divide very rapidly, every twelve to twenty-four hours under conditions of plentiful sunlight and nutrients. When this rapid division increases the population so that the water becomes discolored by the presence of millions and millions of cells, it is called a bloom.
Figure 15.5
The division of a parent centric diatom into two daughter diatoms. The two halves of the bellshaped cell separate, the cell contents divide, and a new inner half is formed for each gillbox. One daughter cell remains the same size as the parent, the other is smaller.

Figure 15.6
Dinoflagellates. _Noctiluca_, _Gymnodinium_, and _Gonyaulax_ produce red tides. _Noctiluca_ is a bioluminescent, non-toxic dinoflagellate. _Gymnodinium_ and _Gonyaulax_ produce toxic red tides and paralytic shellfish poisoning.

Frustules made with silica are more dense than seawater, but the diatom must stay afloat in the sunlit surface waters to survive. The internal cell material has a low density and increases its buoyancy by the production of oil as a storage product; fish that feed on large quantities of diatoms may have a distinctly oily taste. The diatom’s small size also helps it to stay afloat, because small particles that are only slightly more dense than the liquid in which they are suspended sink very slowly. A small, as opposed to a large, spherical particle has a large surface area in comparison to its volume or mass, and this large surface area to volume ratio helps keep the cell afloat. Some diatoms possess spines, wings, or other projections that increase their surface area still more. A large surface area also provides the diatoms with increased exposure to sunlight and to water containing the necessary gases and nutrients for photosynthesis and growth.

Diatoms are most important as the first level of food production. Those that are not consumed by herbivores eventually die and sink to the ocean floor. In shallow areas of the oceans, the cells reach the seafloor with some organic matter still locked inside. Deposits made long ago in this manner have formed petroleum, or oil. Diatom frustules sinking to the greater depths of the oceans build up siliceous sediments under areas of abundant diatom populations. (Refer back to the section on biogenic sediments in chapter 2.) Sometimes geologic processes lift these silica-rich sediments above the sea, where they are mined as _diatomaceous earth_, which is used in industrial filtration systems, in the filtering of wine as well as swimming pools, and as an abrasive in toothpaste and silver polish.

The dinoflagellates differ from the diatoms in several respects. Dinoflagellates usually have two _flagella_, or whiplike appendages, that beat within grooves in the cell wall. One groove encircles the cell like a belt, and the other lies at right angles to it. The beating of these flagella makes the cells motile and causes them to spin like tops as they move through the water. They also tend to migrate vertically in response to sunlight, but this ability to move is limited, and they are still at the mercy of the waves and currents. Representative dinoflagellates are shown in figure 15.6.
Dinoflagellates are red to green in color and can exist at lower light levels than diatoms, because they can both photosynthesize like a plant and ingest organic material like an animal. They have both autotrophic and heterotrophic abilities. Heterotrophic organisms feed on other organisms or on organic substances. Their external walls do not contain silica, but may be armored with plates of cellulose, giving them the appearance of spinning armored helmets. Other dinoflagellates have a smooth, flexible outer surface showing no such plate structures. Some dinoflagellates are called fire algae, because they glow with bioluminescence at night. (Refer back to chapter 13 for a discussion of this phenomenon.)

Dinoflagellates are found over most of the oceans but do not contribute to the bottom sediments, because both the cell walls and the soft parts decay completely. Although they do make up a substantial portion of the phytoplankton, dinoflagellates are not as important as the diatoms as a primary ocean food source. The cells reproduce by a division process similar to that found in diatoms, but without the reduction in size. They can, under favorable conditions, multiply even more rapidly than diatoms to form blooms.

Coccolithophores and silicoflagellates are relatives of the diatoms. The coccolithophores are single-celled plants with coccoliths, or outer calcareous plates, that are deposited as sediment when the cells die (see fig. 2.19b). These coccoliths are soluble under the conditions of low temperature and high pressure found in the deep oceans; therefore, calcareous coccolith deposits are limited to shallow regions of less than 4000 m (13,200 ft). Coccolithophores are also limited by the surface-water temperatures to the warm tropic regions, and so coccolith deposits are to be found in shallow areas at the lower latitudes. Like the dinoflagellates, they possess two flagella, and like both diatoms and dinoflagellates, they may reproduce by simple division, although some species do have a form of sexual reproduction. Silicoflagellates are small autotrophic cells with flagella and an internal hollow skeleton of silica. They are not believed to occur in large numbers.

Zooplankton

The animal members of the plankton, or the zooplankton, are either grazers on phytoplankton (herbivores), feeders on other members of the zooplankton (carnivores), or feeders on both plants and animals (omnivores). A general zooplankton sample is shown in figure 15.7. Many of the zooplankton have some ability to swim and can even dart rapidly over short distances in pursuit of prey or to escape from predators. They may move vertically in the water column, but they are still at the mercy of the waves and currents and so are considered planktonic (or drifting) organisms.
Representatives of nearly every animal phylum are found in the zooplankton. The life histories of organisms that make up the zooplankton are varied and show a variety of strategies for survival in a world where reproduction rates are high and life spans are short. These animals may produce three to five generations a year in warm waters, where food supplies are abundant and temperatures accelerate life processes. At high latitudes, where the season for phytoplankton growth is brief, the zooplankton may produce only a single generation in a year. The voracious appetites and rapid growth rates of the carnivorous zooplankton are responsible for liberating nutrients to be recycled by the phytoplankton.

Zooplankton exist in patches of high population density between areas that are much less heavily populated. The high population patches attract predators, and the more sparse populations between the denser patches preserve the stock, as fewer predators feed there. Turbulence and eddies disperse individuals from the densely populated patches to the intervening sparser areas. Convergence zones and boundaries between water types concentrate zooplankton populations, which attract predators.

Plankton accumulate at the density boundaries caused by the layering of the surface waters, and the variation of light with depth and the day-night cycle play additional roles. Some zooplankton migrate toward the sea surface each night and return to depth each day, either in an attempt to maintain their light level or in response to the movement of their food resource. This daily migration may be as much as 500 m (1650 ft) or less than 10 m (33 ft).

Accumulations of organisms in a thin band extending horizontally along a pycnocline or at a preferred light intensity or food resource level are capable of partially reflecting sound waves from depth sounders. The zooplankton layer is seen on a bathymetric recording as a false bottom or a deep scattering layer, the DSL. (Refer to chapter 4.) Echo-sounding studies are used to record the vertical migration of this layer of plankton and predators and to measure the vertical and horizontal extent of the layer.

Among the most common and widespread zooplankton types worldwide are the small crustaceans (shrimplike animals): copepods and euphausiids (fig. 15.8). These animals are basically herbivorous and consume more than half their body weight daily. Copepods are smaller than euphausiids; euphausiids move more slowly and live longer than the copepods. The euphausiids, because of their size, also eat some of the smaller zooplankton along with the phytoplankton that make up the bulk of their food. Both reproduce much more slowly than the diatoms, doubling their populations only three to four times a year. They may make up more than 60% of the zooplankton in any of the world's oceans and serve as a food source for small fish. In the Arctic and Antarctic, the euphausiids are the krill, occurring in such quantities that they provide the main food for the
balen whales. Baleen (or whalebone) whales have no teeth; instead they have a netlike strainer of baleen suspended from the roofs of their mouths. After the whales gulp the water and plankton, they expel the water through the baleen, leaving the tiny krill behind. Whales of this type include the blue, right, humpback, sei, and finback whales.

The Antarctic krill, *Euphausia superba* (fig. 15.9), are present in enormous quantities. Estimates of total biomass have varied from 5 million to 6 billion metric tons, and are probably in excess of 900 million metric tons. Because of these large biomass estimates, the krill in the Southern Ocean are considered a potentially valuable international fishery. They are harvested commercially by fishing fleets from the former USSR, Japan, Korea, Poland, and Chile. In 1981 and 1982 Japan and the former Soviet Union, using large stem trawlers with nets 80 m (264 ft) wide and catching 8–12 tons of krill in a single haul, harvested 448,000 metric tons in 1981 and 529,000 metric tons in 1982.

Marketing the krill for human consumption has not been very successful. Fresh krill are almost flavorless, and when dried the flavor becomes strong and somewhat unpleasant. The shell has been found to contain extremely high amounts of fluoride and must be removed for human consumption. In the former Soviet Union, the catch was fed mainly to livestock and poultry; the Japanese use their krill as feed on their fish farms. In addition there is the expense of the long distance to the fishing grounds, and because the krill deteriorate rapidly, they must be processed between hauls, limiting the daily harvest. Because of these difficulties the krill catch dropped between 1983 and 1985 to less than 200,000 metric tons and since then has averaged less than 400,000 metric tons. The 1990 catch was 381,000 metric tons; after the breakup of the Soviet Union the catch dropped to 289,000 metric tons during the Antarctic 1991–92 season.

All the nations presently harvesting krill in the Southern Ocean are members of the Convention for the Conservation of Antarctic Marine Living Resources, and all have agreed not to overharvest this resource. However, any evaluation of the krill fishery requires us to remember that while the krill are available in huge numbers, they are the food of many whales, and they form a basic link in the food web for the seals, penguins and other birds, squid, and fish of the Antarctic region; see the box in this chapter.

Arrowworms, or chaetognaths (see fig. 15.8), are abundant in ocean waters from the surface to the great depths. These macroscopic (2–5 cm) (1 in), nearly transparent, voracious carnivores feed on other members of the zooplankton. Several species of arrowworms are found in the sea, and in some cases a particular species is found only in a certain water mass. The association between organism and water mass is so complete that the species can be used to identify the origin of the water sample in which it is found. In the North Atlantic, the arrowworm, * Sagitta setosa*, inhabits only the North Sea water mass and *S. elegans* is found only in oceanic waters.

Foraminifers and radiolarians are microscopic, single-celled, amoebalike protozoans; they are shown in figure 15.10. Foraminifers, such as the common *Cribigerina*, are encased in a compartmented calcareous covering, or shell, while the radiolarians are surrounded by a siliceous test, or shell. The radiolarian tests are ornately sculptured and covered with delicate spines. Openings in the tests allow a continuity between internal protoplasm and an external layer of protoplasm. Pseudopodia (false feet), many with skeletal elements, radiate out from the cell. Radiolarians feed on diatoms and small protozoa caught in these pseudopodia. Both foraminifers and radiolarians are found in the warmer regions of the oceans. After death, their shells and tests accumulate on the ocean floor, contributing to the sediments. Calcareous foraminiferan tests are found in shallow-water sediments, while the siliceous radiolarian tests, which are resistant to the dissolving action of the seawater, predominate at greater depths, commonly below 4000 m (13,200 ft) (see chapter 2, figs. 2.19 and 2.20). Tintinnids (see fig. 15.10) are tiny protozoans with moving hairlike structures, or cilia. These organisms are often called bell animals and are found in coastal waters and in the open ocean.

Pteropods (fig. 15.11) are mollusks; they are related to the snails and slugs. They may or may not have a small calcareous shell, depending on the species, but all have a foot that is modified into a transparent and gracefully undulating wing. Their hard, calcareous remains contribute to the bottom sediments in shallow tropic regions. Some pteropods are herbivores and some are carnivores.

Transparent, delicate, and luminous, the ctenophores, or comb jellies (fig. 15.12), float in the surface waters. Some have trailing tentacles; all are propelled slowly by eight rows of beating cilia. The small, round forms are familiarly called sea gooseberries or sea walnuts; by contrast, the beautiful, tropical, narrow, flattened Venus' girdle may grow to 30 cm (12 in) or more in length. A group of Venus' girdles drifting at the surface and catching the sunlight with their beating cilia is a spectacular sight from the deck of a ship. All ctenophores are carnivores, feeding on other zooplankton.
The tunicate, another transparent member of the zooplankton, is related to the more advanced vertebrate animals (animals with backbones) through its tadpole-like larval form. Salps (see fig. 15.12) are pelagic tunicates that are cylindrical and transparent; they are commonly found in dense patches scattered over many square kilometers of sea surface.

Both ctenophores and pelagic tunicates, although jellylike and transparent, are not to be confused with jellyfish (fig. 15.13). True jellyfish come from another and unrelated group of animals, the Coelenterata or Cnidaria. Some jellyfish, such as the common Aurelia and the colorful Cyanea with its trailing stinging tentacles, spend their entire lives as drifters. Others, such as Gonionemus, a small jellyfish of the Atlantic and Pacific oceans, and Aequorea, found in many temperate waters, are members of the plankton for only a portion of their lives, as they eventually settle and change to a bottom-dwelling, attached form similar to a sea anemone. Another group of unusual jellyfish are the

Figure 15.10
Selected members of the radiolaria (Acanthonia, Acanthometron, and Aulacantha), a foraminifer (Globigerina), and a tintinnid.

Figure 15.11
The pteropods are planktonic mollusks.
Figure 15.12
The comb jellies (ctenophores) Pleurobrachia and Beroe. Pleurobrachia is often called a sea gooseberry. Saipa and Doliolum are gymnactes.

Colonial forms, including the Portuguese man-of-war, Physalia, and the small by-the-wind-sailor, Velella. Both are collections of individual but specialized animals, some of which have the task of gathering food, reproducing, or protecting the colony with stinging cells, while some form a float.

All of the zooplankton discussed to this point, with the exception of certain jellyfish, spend their entire lives as plankton and are called holoplankton (see fig. 15.14). However, an important portion of the zooplankton spends only part of its life as plankton; these are members of the meroplankton. The meroplankton include the eggs, larval and juvenile stages of many organisms that spend most of their lives as either free swimmers (such as fish) or bottom dwellers (such as crabs and starfish). For a few weeks, the larvae (or young forms) of oysters, clams, barnacles, crabs, worms, snails, starfish, and many other organisms are a part of the zooplankton. The currents carry these larvae to new locations, where they find areas to settle and food sources.

In this way, repopulation of areas in which a species may have died out occurs, and overcrowding in the home area is reduced. Sea animals produce larvae in enormous numbers, and so these meroplankton are an important food source for other members of the zooplankton and other animals. The parent animals may produce millions of spawn, but only small numbers of males and females need survive to adulthood to guarantee survival of the stock.

Larvae often look very unlike the adult forms into which they develop (see figs. 15.15 and 15.16). Early scientists who found and described these larvae gave each a name, thinking they had discovered a new type of animal. We keep some of these names today, referring, for example, to the trochophore larvae of worms, the veliger larvae of sea snails, the zoea larvae of crabs, and the nauplius larvae of barnacles.

Other members of the meroplankton include fish eggs, larvae, and juvenile fish. The young fish feed on other larvae, until they grow large enough to hunt for other.
Figure 15.13

Jellyfish belong to the Coelenterata or Cnidaria. *Velella*, the by-the-wind-sailor, and *Physalia*, the Portuguese man-of-war, are colonial forms.
Figure 15.14

Animals that spend their entire lives in the zooplankton are known as holoplankton and include the single-celled (a) foraminifers and (b) radiolarians, and the more complex organisms such as (c) the jellyfish (*Polychora penicillata*) and (d) a copepod.
Figure 15.15
Members of the micoplankton. All are larval forms of nonplanktonic adults.
Figure 15.16
Larval forms of benthic marine organisms or nekton and neum plankton are an important part of the zooplankton: (a) The larva of a marine snail; (b) the larva of a starfish; (c) the zoea larva, a stage of crab development.
**A Krill-Based Ecosystem**

Almost all the life of Antarctica and the surrounding Southern Ocean depends on the sea. The food web of the Southern Ocean is based on the phytoplankton, mainly diatoms, that harness the energy of the sun. Estimates of primary production vary; in summer, in ice-free areas, the average lies between 20 and 100 g of carbon per square meter per year (gC/m²/year). Among the herbivorous zooplankton one species, Euphausia superba, or krill, probably amounts to half the total zooplankton biomass. Krill are the key organisms of the Southern Ocean ecosystem, a unit that includes the area’s community of organisms and the environment with which it interacts. Although krill are circumpolar in distribution, their concentration is not uniform, and the greatest concentration occurs in the Weddell Sea, between 0° and 60°W. Some swarms have been estimated at more than 2 million tons.

In summer, the ice pack melts back, the primary production increases, and the krill move toward the surface to graze the phytoplankton over large areas. In winter, primary production is practically gone from the surface waters due to reduced light, ice-pack cover, and increased turbulence; at this time, the krill appear to descend into deeper water and feed on the phytoplankton detritus. The annual production of krill biomass in the Southern Ocean has been estimated at 750 million–1,300 million tons.

Squid are an important part of the Antarctic food web. There may be more than twenty species, some depending on krill as their most important food. The total annual consumption of squid by whales, birds, and seals is calculated at about 35 million tons. Some species of Antarctic fish stay in the Southern Ocean year-round, feeding on krill; other species migrate into Antarctic waters each summer to feed on krill. It has been estimated that all Antarctic fish combined may consume as much as 100 million tons of krill each year.

There are few species of birds in Antarctica, but populations are usually very large. Birds of Antarctica feed principally on crustacea (mainly krill and copepods), squid, fish, and carrion. Krill amounts to 78% of all the food they eat. Recent estimates indicate about 115 million tons of krill are eaten annually by birds, either directly or indirectly. In winter, the birds either switch to a diet of squid or fish or they migrate northward. Most penguin species feed on krill supplemented, in some cases, by fish. The two largest penguins, the emperors and the kings, take fish and squid only.

Seven species of seals are found in the Southern Ocean; four species, the crabeater, leopard, Ross, and Weddell, are almost totally confined to the ice zones. Weddell seals eat mainly fish and squid; the crabeater’s diet is about 94% krill; krill makes up 37% of the leopard seal’s diet. The crabeater seal, now numbering about thirty million, is the most abundant seal in the world. The fur seals at South Georgia feed almost exclusively on krill. Stocks of Antarctic seals at present total about 33 million with a biomass of about 7 million tons. These seal populations annually consume over 130 million tons of krill (two or three times the current consumption by whales) and at least 10 million tons of squid.

Baleen, or plankton-feeding, whales of the Southern Ocean include the blue, fin, sei, minke, humpback, and southern right whales. Before whaling exploitation, they were probably about four times more abundant and had a biomass five times greater than at present. The major food of the baleen whales is krill. In 1904, the whale biomass was about 45 million tons, and whales consumed an estimated 190 million tons of krill. Competition for food probably limited their size and their numbers. By 1973, the whales had declined to a biomass of about 9 million tons, and they ate about 43 million tons of krill. The reduction in the whale population means that some 150 million tons of krill formerly eaten by whales have become available to the remaining whales, other predators, and human harvesters.

In the past thirty years, there has been an increase in the pregnancy rate of fin and sei whales and an apparent, but controversial, decrease in their age at maturity due, presumably, to the greater availability of food. The minke population may be double what it was before whaling. The crabeater seal populations have also experienced a decrease in the age of sexual maturity (4 years in the 1950s to 2.5 years in the early 1960s), also thought to be the result of increased growth rates based on food abundance. The 14%-17% increase in the population of the South Georgia fur seals is unusually high, probably related to the abundance of krill.

The three most abundant penguins, the chinstrap, Adelie, and macaroni, have shown increases in population. Large increases in king penguins are thought to be due to their feeding on krill-eating squid. We do not know the response of the fish and squid stocks to the increase in available krill, but it is likely to be similar. The total quantity of krill taken by all predators in the Southern Ocean may be about 500 million tons per year. Populations and numbers may change, but directly or indirectly the Antarctic ecosystem depends on krill, which in turn depends on the primary production of the Southern Ocean waters.


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**15.2 Bacteria**

The bacteria are another important group of organisms found in the plankton. Bacteria are the smallest living organisms; they are microscopic, single cells and may have the ability to reproduce by cell division every few minutes when they inhabit a favorable environment. Autotrophic marine bacteria include the photosynthesizing cyanobacteria, most abundant in intertidal and estuarine areas and producing dense blooms in warm-water regions, as well as the bacteria associated with the hydrothermal vents of the deep seafloor where they are the primary producers for the animal communities surrounding the vents (refer to chapter 17). Heterotrophic marine bacteria are free living in seawater.
and exist on every available surface including the seafloor, decaying material, the surface of organisms, and pieces of floating wood and other matter.

Bacteria play an important role in the decay and breakdown of organic matter, returning it to the sea as basic chemicals and compounds to be used again by new generations of plants and animals; refer back to chapter 14. Some are also able to degrade pollutants such as oil; refer back to chapter 12.

They are a significant additional food source for planktonic larvae and a variety of single-celled protozoans. A film of bacteria is found on minute particles of floating organic material; the small size of these particles, with their attached bacterial population, makes them an ideal food for many small zooplankton. They are important in the food webs of the deep sea, where they are consumed by a large number of small animals.

Plant remains sinking into the deep sea have been a recent focus for sampling and research. Bacterial activity on this material decreases with depth and is minimal below 2000 m (6600 ft), but once it has reached the seafloor it is subject to vigorous bacterial activity. Samples collected from the sediment surface 4500 m (14,800 ft) deep in mid-oceanic areas of the northeastern Atlantic show a rich community of active bacteria that are able to degrade and transform the plant material faster than had previously been assumed. Experiments showed that the surface water contained $5 \times 10^5$ bacteria per milliliter; seafloor samples contained $8-20 \times 10^6$ bacteria per milliliter. The deposit of this plant material shortly after the spring phytoplankton bloom represents an important food resource for the deep-sea animal community.

The extreme environment of the deep seafloor may contain bacteria with abilities that could be very useful to humans, and Japan is preparing to search for these organisms. Japan’s Shinkai 6500, the world’s deepest-diving manned submersible, will be used to bring back bacteria, under pressure, from the bottom of the deep oceans. Organisms will be transferred to an automated laboratory where they can be cultured and isolated in water under pressure and with the correct temperature and pH. Japanese scientists intend to search for bacteria with genes that can be useful in Japan’s biotechnology industries.

### 15.3 Classification Summary of the Plankton

The types of plankton can be categorized in the kingdoms, phyla, and classes, as in the following lists.

I. **Kingdom Monera:** cells, simple and unspecialized; single cells, some in groups or chains.
   A. **Bacteria:** single cells, in chains or groups; autotrophic and heterotrophic, aerobic and anaerobic; important as food source, in decomposition.
   B. **Cyanobacteria:** blue-green algae; autotrophic single cells, in chains or groups, produce some red blooms in sea; phytoplankton.

II. **Kingdom Protista:** grouping of microscopic and mostly single-celled organisms; autotrophs (algae) and heterotrophs (protozoa).
   A. **Phylum Chrysophyta:** golden-brown algae; yellow to golden autotrophic single cells, in groups or chains; contribute to deep-sea sediments; phytoplankton.
      1. **Class Bacillariophyceae:** diatoms.
      2. **Class Chrysophyceae:** coccolithophores, silicoflagellates, and other flagellates.
   B. **Phylum Pyrophyta:** fire algae; single cells with flagella; produce red tides; bioluminescence common; usually considered phytoplankton.
      1. **Class Dinophyceae:** dinoflagellates.
   C. **Phylum Sarcomastigophora:** radiolarians, foraminifers, zooplankton.
   D. **Phylum Ciliophora:** ciliates, zooplankton.

III. **Kingdom Plantae:** plants; primarily nonmotile, multicellular, photosynthetic autotrophs.
   A. **Division Phaeophyta:** brown algae; Sargassum maintains a planktonic habit in the Sargasso Sea.

IV. **Kingdom Animalia:** animals; multicellular heterotrophs with specialized cells, tissues, and organ systems; zooplankton. For temporary members of the zooplankton (or meroplankton), see the Meroplankton listed in V.

A. **Phylum Cnidaria:** radially symmetrical with tentacles and stinging cells.
   1. **Class Hydrozoa:** jellyfish as one stage in the life cycle, including such colonial forms as Portuguese man-of-war.
   2. **Class Scyphozoa:** jellyfish.
   B. **Phylum Ctenophora:** comb jellies; translucent; move with cilia; often bioluminescent.
   C. **Phylum Chaetognatha:** arrowworms; free-swimming, carnivorous worms.
   D. **Phylum Mollusca:** mollusks; the snail-like pteropod is planktonic.
   E. **Phylum Arthropoda:** animals with paired, jointed appendages and hard outer skeletons.
   1. **Class Crustacea:** copepods and euphausiids.
   F. **Phylum Chordata:** animals, including vertebrates; with dorsal nerve cord and gill slits at some stage in development.
      1. **Subphylum Urochordata:** saliclike adults with "tadpole" larvae; salps.

V. **Meroplankton:** larval forms from the phyla Annelida (segmented worms), Mollusca (shellfish and snails), Arthropoda (crabs and barnacles), Echinodermata (starfish and sea urchins), and Chordata (fish). See also the classification summaries of the nektan (chapter 16) and the benthos (in chapter 17).

### 15.4 Sampling the Plankton

The biological oceanographer needs to know what species of plants and animals make up the plankton in a given geographic area, the abundance of these organisms, and where
Viruses in the Oceans

A virus is a noncellular particle made up of genetic material surrounded by a protein coat. Viruses are highly successful parasites; they infect plant, animal, and bacterial cells. Viruses are unable to carry on metabolic activities by themselves and can replicate themselves only inside a host cell. During replication the virus may acquire some of the host’s genes; it may then transport these genes to a new cell, leading to exchange of genetic material between organisms.

Recently, microbiologists have discovered an unexpected abundance of viruses in marine waters \(10^7-10^9\) viruses/mL. One series of samples showed concentrations of viruses between \(5 \times 10^9\) and \(15 \times 10^9\) per milliliter during the spring and summer but dropping to less than \(10^9\) viruses per milliliter in the winter. Most of the viruses appeared to be free in the water, but some were associated with bacteria. It has been assumed that marine bacteria production is maintained in balance by the grazing of single-celled heterotrophs, but these high concentrations of viruses indicate that viral infection may be an important factor in the ecological control of planktonic bacteria and that viruses might actively exchange genes between host populations infected by the same viral strain.

Other researchers report high viral abundance in ocean water and also large numbers of bacteria infected with viruses. Up to 7% of the heterotrophic bacteria and 5% of the cyanobacteria from diverse marine locations contained mature viruses. Estimates of total viral infection from this data conclude that about 32% of the heterotrophic bacteria and about 15% of the cyanobacteria contain mature virus particles at any given time, indicating again that viral infection may be a significant mechanism of mortality in marine bacteria.

In laboratory experiments the addition of viral particles reduced primary productivity by as much as 78%, indicating that infection by viruses could be a factor regulating phytoplankton community structure and primary productivity in the oceans. Because viruses can infect a variety of marine phytoplankton, including diatoms, they may affect ocean food webs by restricting or terminating phytoplankton blooms.

The abundance of viruses in ocean waters indicates routine viral infection of aquatic bacteria, and this is likely to mean that natural genetic engineering experiments in bacterial populations have been occurring for a very long time. New research raises the possibility that marine bacteria, via viral exchange of genetic material, might be able to develop resistance to antibiotics used in aquaculture, or even acquire traits from artificially engineered bacteria released into coastal waters.

in the water column they are located. Traditionally, plankton are sampled by towing fine-mesh, cone-shaped nets (fig. 15.17) through the sea behind a vessel or by dropping a net straight down over the side of a nonmoving vessel and pulling it back up like a bucket. After the net is returned to the deck it is rinsed carefully, and the “catch” is collected in a labeled jar. If the net has been hauled vertically through the water in one place, the volume of water that has passed through the net can be calculated from the area of the net’s mouth and the distance through which the net was pulled. If the net was towed behind the vessel, the volume can be calculated from the time of the tow and the speed of the tow, which will tell the distance towed. This information can then be used with the area of the net opening to find the volume of water that passed through the net. However, to measure the water volume directly and accurately, a flow meter is placed in the mouth of the net. The catch is then known for the total volume of water sample, but there is no indication of how the species are distributed within that volume.

It is also possible to raise and lower the net as it is being towed horizontally. This movement allows sampling to be averaged over both distance and depth. If the sample is to be taken at a specific depth, the net may be lowered closed and only opened when the desired depth is reached. After the towing operation, the net is again closed before it is brought up through the shallower water.

Today, oceanographers sampling zooplankton use multiple-net systems mounted on a single frame; the nets are opened and closed on command from the ship.
frame also carries electronic sensors that relay data on salinity, temperature, water flow, light level, net depth, and cable angle to the ship’s computer.

Plankton tows must be rapid enough to catch the organisms but slow enough to let the water pass through the net. If the tow is too fast, the water will be pushed away from the mouth of the net, and less water than expected will be filtered. Size of the mesh from which the net is made also influences the catch; a fine-mesh net clogs rapidly and a large-mesh net loses organisms.

Plankton may also be filtered from samples taken by water bottle or a submersible pump. Whether the sample is taken by net, bottle, or pump, the next step is to determine the number and kinds of plankton in the sample. Because the numbers of organisms are so large, in most cases it is not possible to directly inspect or count the total catch. Instead the catch may be precisely subdivided, and a subsample may be checked under the microscope. If the amount of plankton is of greater interest than the kinds of organisms, an electronic particle counter may be used to find the total count (population density), or a subsample may be dried and weighed to determine its mass.

Sonar may be used to determine the quantity of zooplankton directly, the echo returned to the ship is related to the density of the zooplankton but does not determine the species present. The abundance of phytoplankton can be determined by dissolving the chlorophyll pigment out of the sample and measuring the pigment concentration. New optical instrumentation has been designed to measure the natural fluorescent signal coming from chlorophyll pigment in phytoplankton cells. These measurements are made at sea, directly and instantaneously at depth, and then related to phytoplankton abundance.

All these methods allow scientists to record population densities or to inspect individual organisms, but they do not tell us how these organisms behave in their environment. A new video plankton recorder designed at the Woods Hole Oceanographic Institution uses a strobe light with four video cameras at four different magnifications to photograph the plankton. The strobe flashes sixty times a second, capturing images of the organisms that researchers hope will allow them to learn about the swimming, feeding, and reproduction of the plankton. Eventually they hope to program the system to recognize different kinds of plankton, enabling them to acquire species and population information while the system is running at sea.

15.5 Practical Considerations: Marine Toxins

Red Tides

Toxic blooms of single-celled organisms that discolor seawater are often known as red tides; most are produced by certain species of dinoflagellates. These blooms may or may not be poisonous to fish and other organisms and may or may not produce symptoms of paralytic shellfish poisoning (PSP), neurotoxic shellfish poisoning (NSP), or diarrhetic shellfish poisoning (DSP) in humans eating clams, mussels, and oysters that have ingested the dinoflagellates. In North American waters several different dinoflagellates produce red tides; Gonyaulax, Alexandrium, and Gymnodinium (previously Pyrodiscus) are toxic, but Noctiluca is not. See figure 15.6. Species of Gonyaulax and Alexandrium found in temperate latitudes are generally nontoxic to the shellfish themselves, but the toxins produced by these dinoflagellates are concentrated in the tissues of the shellfish as they feed on the bloom. It is the toxins that produce PSP, NSP, or DSP, in the humans eating the affected shellfish. Gymnodinium and a species of Gonyaulax found in the warmer waters of the Gulf of Mexico kill fish. Gonyaulax also kills shrimp and crab; Gymnodinium does not.

It appears to some scientists that the red tide problem is growing around the world. In 1986 a major outbreak of red tide caused by the dinoflagellate Gymnodinium breve struck the Texas Gulf Coast beaches. It spread 500 km (300 miles) along the coast and killed more than 22 million fish over more than two months. Harvesting of shellfish was banned along three-quarters of the Texas coast south of Galveston. The state of Texas lost at least $1.4 million in oyster production, with a total economic loss of $3.7 million; businesses based on tourism and recreation suffered severely. That same year hundreds of bottlenose dolphins died along the coasts of New Jersey and Maryland. A bloom of G. breve occurred in the warm waters off Florida's west coast. The winter was mild; the red tide survived the winter, and the current carried it around Florida and up the East Coast of the United States. The red tide arrived off the Carolinas at about the same time the menhaden fish began their annual summer migration up the East Coast. The menhaden fed on the G. breve and accumulated the toxin in their livers. After the dolphins fed on the menhaden, the toxin attacked the heart muscles of the dolphins or caused the animals to lose heat uncontrollably, killing them. In 1987 and 1988 a red tide along the Gulf Coast of Florida again spread northward, this time to North Carolina, and again dolphins died. The shellfisheries were closed and economic losses reached $25 million. In 1990 the first confirmed outbreak of DSP appeared in North America and was traced to a dinoflagellate bloom in Canadian waters. In 1992 PSP toxin was detected for the first time in the guts of Dungeness crabs from Alaskan waters.

No one knows precisely what triggers the sudden bloom of these organisms, but red tides often happen in spring and summer after heavy rains have produced a land runoff of nutrient-rich water. Dinoflagellates produce a cyst or resting cell that settles to the bottom and mixes with the sediments. In the shallow waters of bays and harbors along the New England coast, temperature and light appear to play major roles in activating the cysts. In deeper coastal waters the cysts seem to have a natural biological clock or annual cycle of reactivation. It is thought that sudden disturbances of the bottom by either natural or artificial means (such as slumping of sediments or dredging) stimulate the cysts into activity and rapid reproduction.
Some scientists think that the continuous addition of nitrates and phosphates to coastal waters from both sewage and agricultural runoff may be partly to blame for the apparent increase in the number and severity of red tide episodes. Extra nutrients mean extra growth and may explain why instead of a series of small blooms, the world’s coastal areas are experiencing such massive outbreaks. An additional factor may be the increased commercial ship traffic that brings hitchhiking cells to new environments. In a survey of cargo vessels entering Australian ports, 40% were found to have viable dinoflagellate cysts in their ballast tanks. Other scientists do not believe that there is a rise in toxic blooms; they point to better statistics, communication, and reporting as well as increased eating of shellfish and fish. However, the experience of the Japanese in the inland sea of Japan suggests otherwise: Red tides increased from forty a year in 1965 to more than three hundred a year in 1973. In 1972 authorities introduced controls to cut the nutrients entering the sea by half; the frequency of red tides peaked in 1975 and has been declining since.

The toxins that produce PSP are powerful nerve poisons that can cause paralysis and death if the breathing centers are affected. Some species of red tide dinoflagellates produce several toxins; one species of Gymnodiunium can produce at least five different toxins. The saxitoxins that are found in butter clams but are produced by Alexandrium and Gonyaulax are fifty times more lethal than strychnine. The toxins are not affected by heat, so cooking the shellfish does not neutralize the poison. Even after the visible signs of red water due to a dinoflagellate bloom have disappeared, the shellfish can retain the toxin in their tissues for long periods, and so the beaches are kept closed to shellfish harvesting. NSP symptoms are similar to those of basic food poisoning; airborne, wind-spread cells may cause irritated eyes, runny noses, and persistent cough. DSP outbreaks may have been occurring throughout history and been attributed to bacterial contamination; only recently have researchers linked DSP outbreaks to the presence of a dinoflagellate. Between 1976 and 1982 more than thirteen hundred documented cases of DSP occurred in Japan; in 1981 over five thousand cases were reported from Spain. Other outbreaks have occurred in Norway and Sweden and along the French coast. Scientists speculating why the toxin is produced believe it is a defense against predators.

Just as not all red tides are toxic, not all red water is caused by dinoflagellates. The Red Sea received its name because of dense blooms of nontoxic cyanobacteria with large amounts of red pigment. The Gulf of California has been called the Vermilion Sea for the same reason. The Indian Ocean has red tides due to the presence of a toxic cyanobacterium, not a dinoflagellate.

**Other Toxic Blooms**

In 1987, at Prince Edward Island, Canada, three people died and more than one hundred others became sick from eating shellfish contaminated with domoic acid. The domoic acid was traced to a bloom of *Pseudonitzschia pungens*, (fig. 15.18a)—a diatom, not a dinoflagellate; diatoms had not been known to produce toxins until this outbreak occurred. In 1991 pelicans eating anchovies off the California coast were dying from domoic acid produced by another species, *P. australis* (fig. 15.18b). Shellfish and crab fisheries along the California, Oregon, and Washington coasts were closed.

Domoic acid poisoning in humans may cause short-term memory loss and is called amnesic shellfish poisoning (ASP). Other symptoms include nausea, muscle weakness, disorientation, and organ failure.

The reasons for the sudden appearance of toxic levels of domoic acid are unknown, although speculations are similar to those proposed for the dinoflagellate outbreaks. One researcher has suggested that when excess phosphorus and nitrogen are present the diatom populations grow explosively, and when the phosphorus is depleted some
species secrete toxins that kill animals, releasing the phosphorus in the animals' tissues and allowing the diatoms to continue their bloom.

Another diatom, *Chaetoceros*, has been involved in the mortality of pen-reared salmon. It is thought that the spiny cells of these organisms cause mechanical injury or clogging of gill tissue, leading to bacterial invasion and suffocation, but the exact mechanism is unknown. *Heterosigma*, neither a diatom nor a dinoflagellate but a member of a small group of green and golden-brown flagellates, blooms orange-brown in estuaries during periods of sunlight, warm water, and high nutrient concentrations; see figure 15.19. It is associated with fish mortality in Japan, Scotland, New Zealand, and the U.S. Pacific Northwest.

**Ciguatera Poisoning**

It is estimated that each year between ten thousand and fifty thousand people eating fish in the tropical regions of the world are affected by *ciguatera* poisoning. More than four hundred species of fish have been found to be affected, and the presence of ciguatoxin in the fish dramatically affects the development and growth of inshore fisheries in these areas. The situation is complex, because not all of the fish of the same species caught at the same time and in the same place are toxic.

There is no way to prepare an affected fish to make it safe to eat. Symptoms of ciguatera poisoning are extremely variable and may include headache, nausea, vomiting, abdominal cramps, possible irregular pulse beat, reduced blood pressure, and, in severe cases, convulsions, muscular paralysis, hallucinations, and death. Symptoms can occur in various combinations, and no proven antitoxin is known.

In the United States, the number of cases may be over two thousand per year. These are clustered in Florida, Hawaii, the Virgin Islands, and Puerto Rico. Over 80% of the resident adults in the United States and British Virgin Islands report having been poisoned at least once. Ciguatera poisoning is thought to be underreported in Hawaii and more serious than generally acknowledged. An outbreak involving twelve persons in Maryland and a single case in Boston involved consumption of grouper shipped from Florida to local restaurants.

Several dinoflagellates are associated with *ciguatera* poisoning, but the dinoflagellate *Gambierdiscus toxicus* is most often associated with the problem. This dinoflagellate was discovered only ten years ago by scientists at the University of Tokyo, but attempts to grow *G. toxicus* in the laboratory have been disappointing because lab-cultured organisms produce less toxin than those living in their natural surroundings. Ciguatoxic dinoflagellates live in close association with many types of seaweeds and appear to need nutrients exuded by the seaweeds. They flourish in areas of human or natural disturbance such as dredging, hurricanes, and destruction of coral reefs. Perhaps the seaweeds and the dinoflagellates are mixed into the water column during such disturbances and dispersed. In some areas it is considered likely that more than one organism produces a combination of toxins contributing to *ciguatera* poisoning.

The dinoflagellates are eaten by herbivores and the ciguatoxins move through the food web. Japanese researchers in the Gilbert Islands found an evolution of toxicity over the years. Initially only a few species are toxic. At the peak of the outbreak almost all reef fish become toxic, and in the final stages only large eels and certain snappers and groupers remain toxic. This cycle appears to take at least eight years and, in this case, points to a food-chain cycle in which the herbivorous fish become toxic first, followed by the carnivores. Exactly how this occurs is not known with certainty because there is no technology to analyze the toxins, and how *ciguatera* moves up a food chain without killing the fish that consume it is also unknown. Present testing can identify toxic fish only by bioassay that requires feeding suspected fish to test animals, but simple color tests are expected to be available in the near future.

*Ciguatera* is an international problem. It has delayed development of Egyptian Red Sea fisheries. Sri Lanka reports hundreds of cases each year. In New Guinea, it is believed that thousands are poisoned each year, but that most cases go unreported as they are attributed to magic. Some islands in the western Pacific have been abandoned because of local ciguatera problems. A bottom fishery in Samoa is required to discard all red snappers (as much as 50% of the catch). It hampers the fledgling Puerto Rico fishing industry, and the loss to the Floridian/Caribbean/Hawaiian seafood industry is estimated at $10 million annually. Other losses include export markets, the loss of use of the banned fish, the cost of treatment and the time lost from employment by victims, and the costs associated with monitoring and implementing fishing and marketing regulations.

**Summary**

The plankton are the drifting organisms. The microscopic plankton are divided into groups by size. Phytoplankton are autotrophic single cells or filaments. *Sargassum* is the only large planktonic seaweed. The diatoms are found in cold, upwelled water; they are yellow-brown, with a hard
transparent frustule, and they store oil, which increases their buoyancy. Centric forms are round, pennate forms are elongate. Diatoms reproduce rapidly by cell division and make up the first trophic level of the open sea.

Dinoflagellates are single cells with both autotrophic and heterotrophic capabilities. Their cell walls are smooth or are heavily armored with cellulose plates. They, too, reproduce by cell division. These organisms are responsible for much of the bioluminescence in the oceans. Coccolithophores and silicoflagellates are very small autotrophic members of the phytoplankton.

Some herbivorous zooplankton reproduce several times a year, while others reproduce only once, depending on the water temperature and phytoplankton food supply. Carnivorous zooplankton are important in the recycling of nutrients to the phytoplankton. Heavy concentrations of zooplankton are found at convergence zones and along density boundaries. Zooplankton migrate toward the sea surface at night and away from it during the day, forming the deep scattering layer.

Zooplankton members that spend their entire lives in the plankton are called holoplankton. The copepods and euphausiids are the most abundant members of the holoplankton. Euphausiids are also known as krill; they form a basic food of the baleen whales. Krill is the zooplankton base for all the Antarctic ecosystems; recently it has been harvested for human consumption with mixed success.

Other small members of the holoplankton are the carnivorous arrowworms, the calcareous-shelled foraminifers, the delicate, silica-shelled radiolarians, the ciliated tintinnids, and the swimming snails, or pteropods. Large zooplankton include the comb jellies, salps, and jellyfish; all are nearly transparent, but each belongs to a different zoologic group.

The meroplankton are the juvenile (or larval) stages of nonplanktonic adults. This group comprises fish eggs, very young fish, and the larvae of barnacles, snails, crabs, starfish, and many other nonplanktonic animals. The spores of seaweeds and the marine bacteria are also planktonic.

Plankton sampling is done with a plankton net or with a water bottle. The kinds of organisms in a sample are determined microscopically: the numbers of organisms are counted, or samples are dried and weighed.

Heavy blooms of dinoflagellates and some other kinds of phytoplankton produce red tides. Some red tides are toxic; others are not. The toxin is concentrated in shellfish and produces paralytic and other types of shellfish poisoning in humans and sometimes in other animals. Red tides appear to be triggered by the particular combination of environmental factors, the disturbance of dormant dinoflagellates, and the addition of increasing amounts of nutrients to coastal waters. Domoic acid produced by diatoms is a newly discovered toxin. Ciguatoxin is another dinoflagellate product that affects humans and hampers fishery development around the world.

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<td>ultraplankton</td>
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**Study Questions**

1. Why does a pycnocline located above the compensation depth promote a phytoplankton bloom?
2. Why are meroplankton produced in such large numbers?
3. When the discoloration has left the water after a PSP red tide, the shellfish may not be safe to eat. Explain why.
4. Patches with abundant populations of zooplankton are frequently found separated by patches with sparse populations. How does this help to assure survival from predators?
5. If the krill of the Southern Ocean were heavily harvested for human consumption, explain the possible effects on the rest of the organisms in that area.
6. Describe four ways to subdivide the plankton.
7. Why are there more planktonic centric diatoms and more benthic pennate diatoms?
8. Discuss what happens to a diatom population if no auxospores form?
9. Why is a planktonic stage important to a nonplanktonic adult?
10. Discuss how plankton may maintain themselves in a given region of the ocean even though there are currents flowing through that region.
11. When you are sampling plankton with a plankton net, how can you determine the quantity of the plankton in a volume of water? Assume that you know (1) the cross-sectional area of the net and (2) the length of time you towed the net and the speed at which you towed the net, or you know (1) the cross-sectional area of the net and (2) the distance you towed the net.
12. Distinguish between diatoms and dinoflagellates, between euphausiids and copepods. Which are heterotrophs and which are autotrophs?

13. Make a simple food web for the Southern Ocean around Antarctica. Include fish, whales, seals, squid, penguins, and sea birds.

14. Episodes of toxic phytoplankton blooms appear to be increasing along the world’s coasts. (1) List possible reasons for this increase. (2) Distinguish among PSP, NSP, ASP, and ciguatera.

15. Toxic materials, such as oil, may form a thin layer at the sea surface where many plankton also accumulate. How might this affect populations of the nekton and the bentos?

Suggested Readings

General

Plankton