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Chapter 1

BASIC CONCEPTS IN OCEANOGRAPHY

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Abstract

Basic concepts in oceanography include major wind patterns that drive ocean currents, and the effects that the earth's rotation, positions of land masses, and temperature and salinity have on oceanic circulation and hence global distribution of radioactivity. Special attention is given to coastal and near-coastal processes such as upwelling, tidal effects, and small-scale processes, as radionuclide distributions are currently most associated with coastal regions.

1.1. INTRODUCTION

Introductory information on ocean currents, on ocean and coastal processes, and on major systems that drive the ocean currents are important to an understanding of the temporal and spatial distributions of radionuclides in the world ocean.

1.2. GLOBAL PROCESSES

1.2.1 Global Wind Patterns and Ocean Currents

The wind systems that drive aerosols and atmospheric radioactivity around the globe eventually deposit a lot of those materials in the oceans or in rivers. The winds also are largely responsible for driving the surface circulation of the world ocean, and thus help redistribute materials over the ocean's surface. The major wind systems are the Trade Winds in equatorial latitudes, and the Westerly Wind Systems that drive circulation in the north and south temperate and sub-polar regions (Fig. 1). It is no surprise that major circulations of surface currents have basically the same patterns as the winds that drive them (Fig. 2). Note that the Trade Wind System drives an Equatorial Current-Countercurrent system, for example. There is a North Equatorial Current running from east to west in every ocean: Indian, Pacific and Atlantic (although monsoon winds affect the currents in the Indian Ocean, as we'll see later). There is a South Equatorial Current, just into the southern hemisphere, running in the same direction, from east to west. There is an Equatorial Countercurrent, running in the opposite direction, that essentially splits the two.

At about 40 to 60°S and N, the Westerly Wind systems prevail (Fig. 1). The southern-hemisphere westerlies essentially blow completely around the globe almost unimpeded by land. The current system established by these winds (West Wind Drift) thus is driven completely around the globe, almost unobstructed by land (Fig. 2). Comparable to this, in the northern hemisphere, the North Pacific and North Atlantic Currents move from west to east. In the Indian Ocean there is no comparable northern westerly current because of the Asian land mass. The ocean flows coupling the equatorial and westerly current systems are the Kuroshio and California Currents in the north Pacific, and the East Australian and Peru Currents in the south Pacific (Fig. 2). In the north Atlantic, the Florida Current/Gulf Stream is comparable to the Kuroshio in the Pacific, and the Canary Current is comparable to the California. In the south Atlantic, the Falkland/Brazil Current and the Benguela Current connect the equatorial and westerly currents.

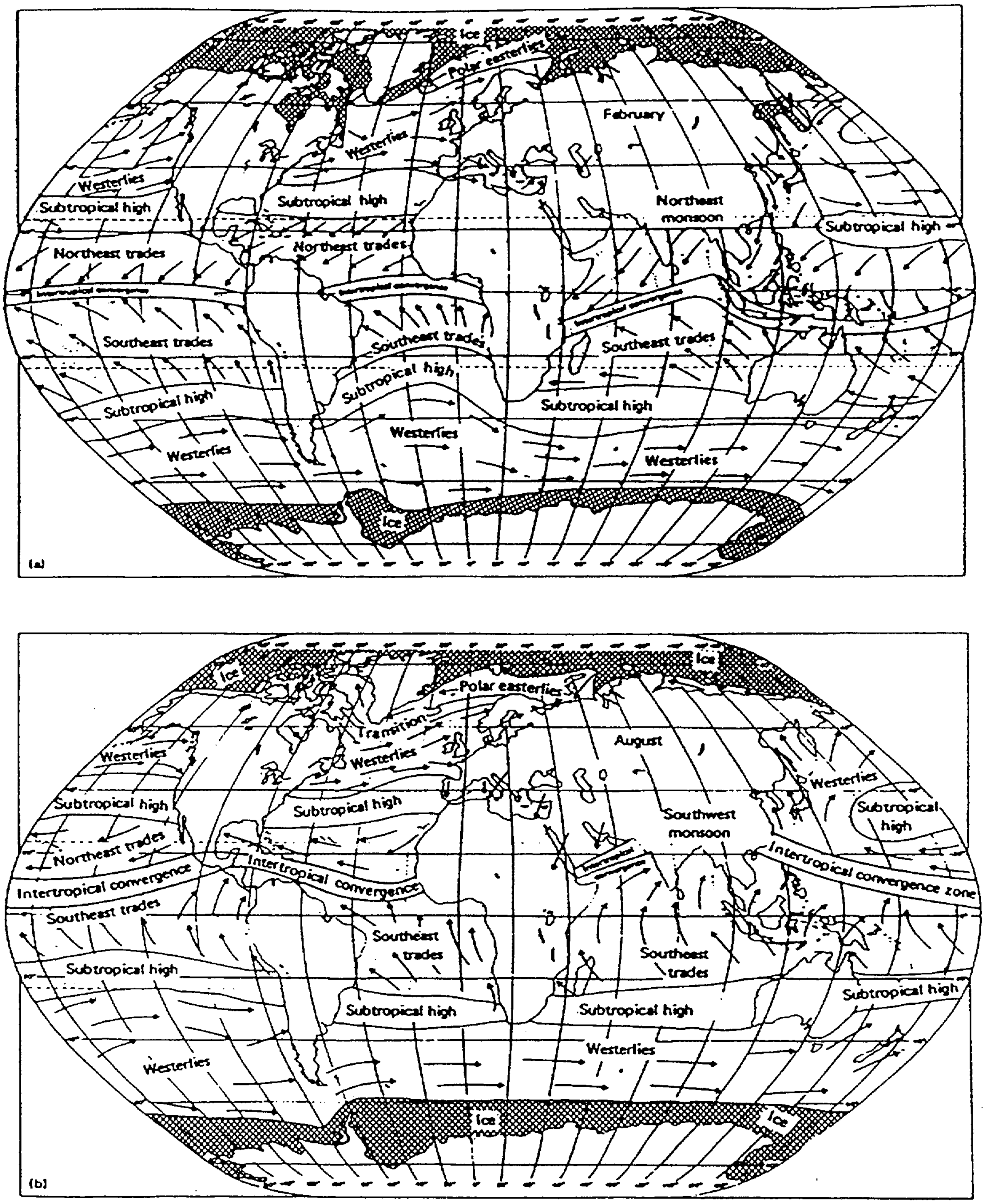

FIG. 1. Prevailing winds over the ocean in (a) February, and (b) August [1].

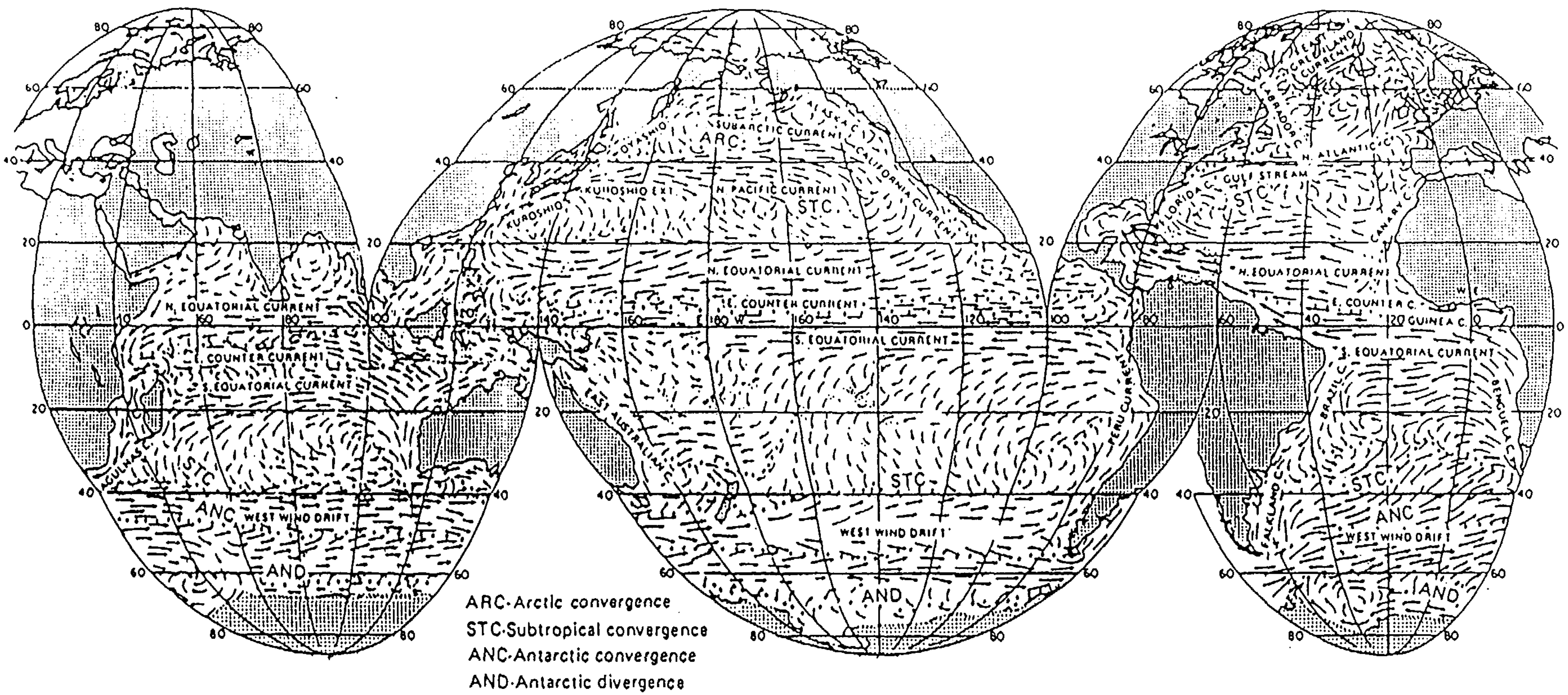

FIG. 2. Surface ocean currents in February-March. Length and thickness of arrows denote relative current speeds. Note the major easterly and westerly currents, and the mid-ocean gyres [1].

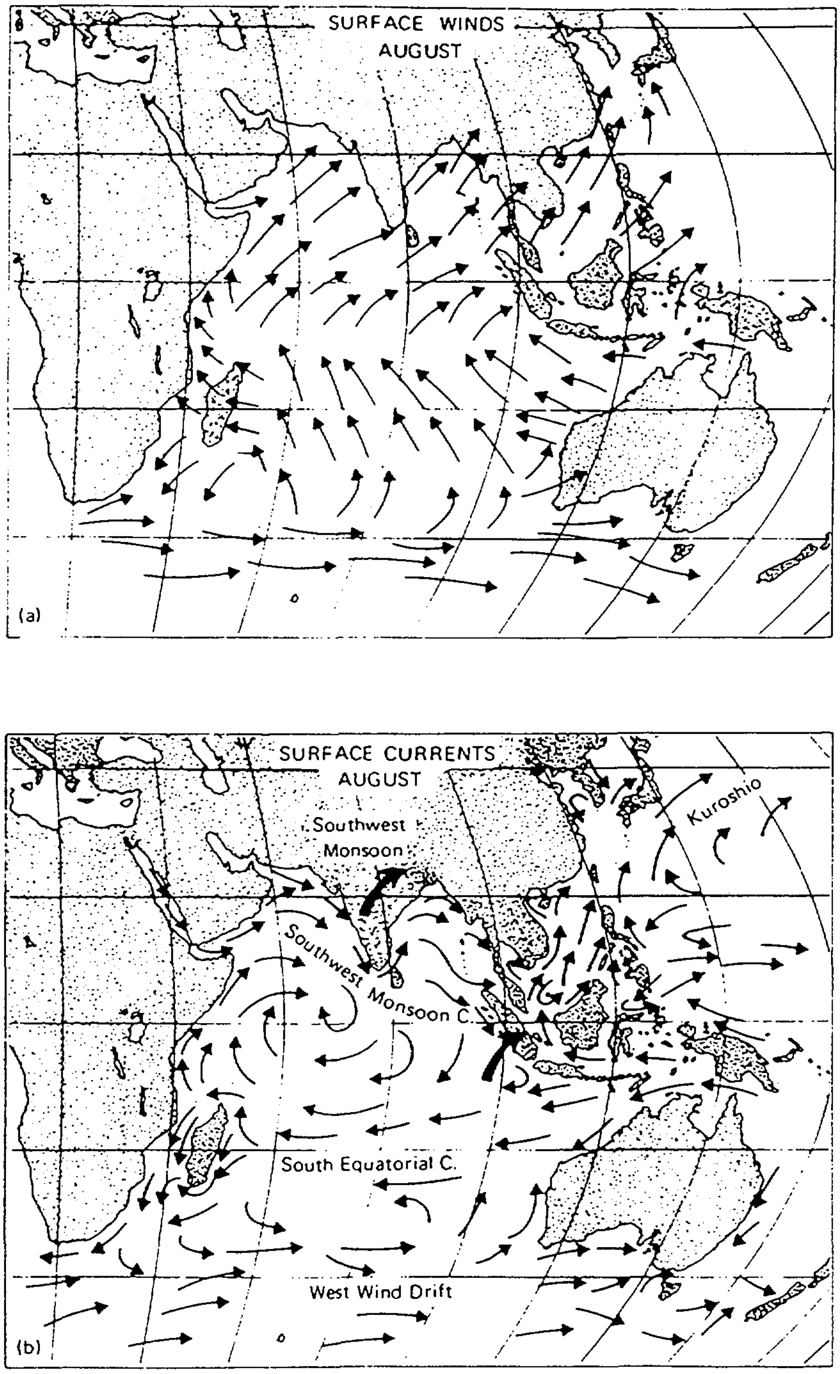

FIG. 3. Surface winds (a) and currents (b) in summer during the Southwest Monsoon [1].

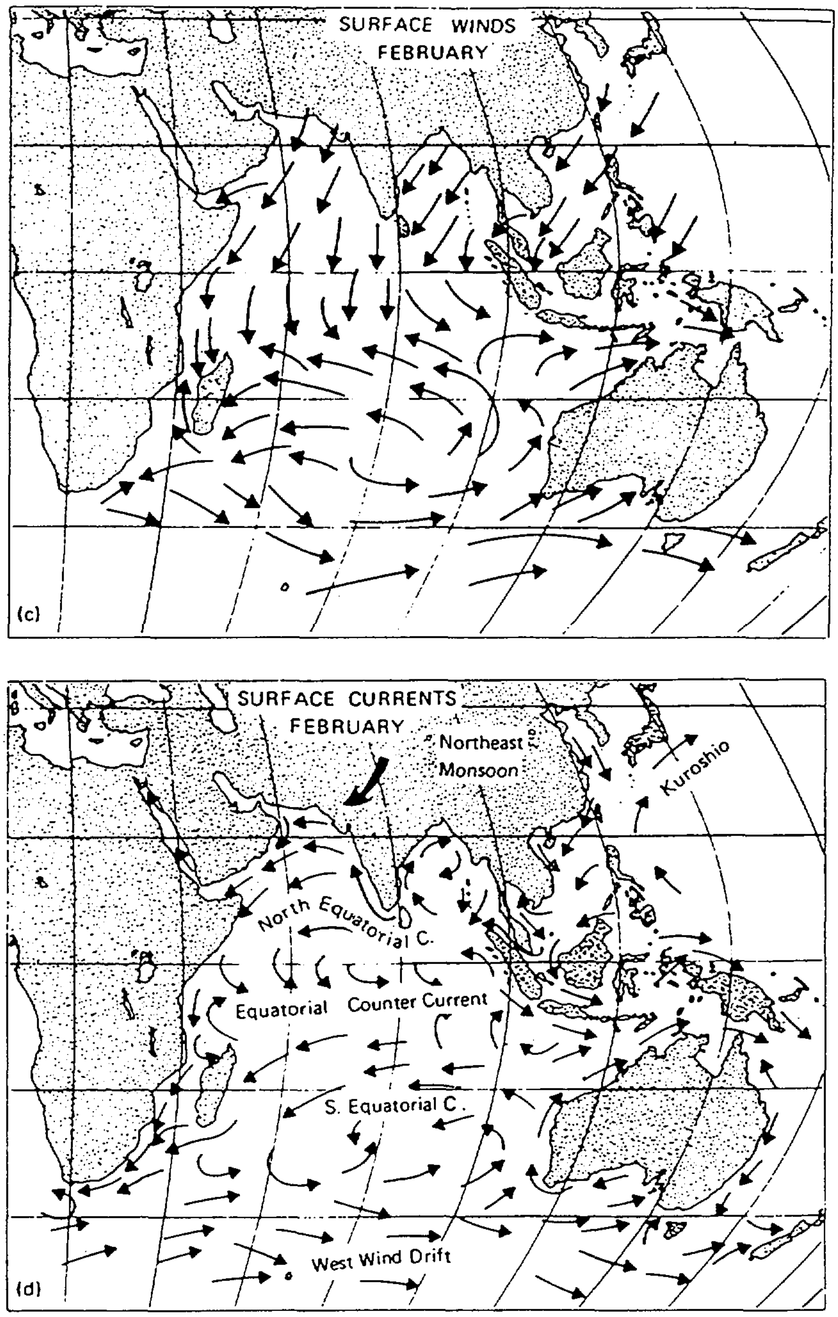

FIG. 4. Surface winds (a) and currents (b) in winter during the Northeast Monsoon [1].

In Fig. 2, one can see that the current systems circumscribe large oval regions in each ocean basin. These oval regions are the open-ocean gyres. The gyre systems essentially are the parts of the ocean usually described as oligotrophic, or with relatively little biological productivity in the surface waters (although recent work suggests they are more productive than originally thought). The gyres actually have a different topography than the regions of major currents. The sea surface is slightly higher in the center of each gyre than it is in other places, and that is important for distributions of properties, including radioactivity.

In the high polar regions, particularly in the northern hemisphere where there is no land mass comparable to the Antarctic continent, easterly winds (Polar Easterlies, Fig. 1) move surface currents eastward (Fig. 2); however, because of land interference, easterly currents are often turned into complex patterns (see Atlantic and Pacific Oceans above 60°N, for example).

The basic pattern is thus one of major wind systems driving surface currents around the perimeters of each ocean basin in each hemisphere on the earth's surface, piling water up a bit in the central gyres. Complexities in this simple pattern occur because of the positions of the continents with respect to the wind/current systems, and sometimes because of major changes in the wind systems themselves either on a seasonal basis (as in the Indian Ocean monsoons) or on less frequent time scales (as in El Niño-Southern Oscillation events).

1.2.2. **Seasonal Monsoons**

The most striking seasonal changes in current pattern usually occur in the Indian Ocean, and these are intimately tied in with monsoon winds. During summer (generally May to September), the land mass of Asia is greatly warmed relative to the adjacent Indian Ocean. When the land mass is warm and the ocean is cold, the continental air rises and draws the cooler air off the marine system. The air drawn from the ocean to the land creates the Southwest Monsoon (Fig. 3). At this time of year surface currents in the western Indian Ocean move northward while those in the eastern Indian Ocean generally move southward to join the westward-moving South Equatorial Current (Fig. 3). This Southwest Monsoonal circulation becomes very important from the standpoint of biological productivity, as we'll see later. When the land mass of Asia cools in the winter, the situation reverses. The high heat capacity of the water causes the air mass above the Indian Ocean to warm, and thus to rise and draw the colder air off the land mass (Fig. 4). This creates the Northeast Monsoonal circulation of the sea surface (Fig. 4). The general pattern shown in Fig. 2, with the North Equatorial Current and Equatorial Countercurrent reformed, is thus reestablished.

1.2.3. **Other Seasonal Changes**

There are other seasonal shifts that occur, which can be very important to the distributions and redistributions of radionuclides and other materials, and therefore to the potential effects these radionuclides may have on marine life. Patterns of sea ice change seasonally in both polar regions, for example. Seasonal changes in prevailing wind directions along coastlines other than those in the Indian Ocean often create movements of surface water away from or toward the coasts, thus either transporting materials away from the land or onto the beaches. We will deal with some of these effects later. However, it is important to recognize that meteorological high- and low-pressure systems do vary in position by season over the surface of the Earth, thereby seasonally re-positioning major and minor wind systems (Fig. 1), which in turn affect the positioning and strengths of most ocean currents on a seasonal basis.

1.2.4. **The Coriolis Effect**

The Earth's rotation about its axis causes the winds and surface ocean currents to follow curved paths instead of the straight ones that we might witness if the Earth were not rotating. This

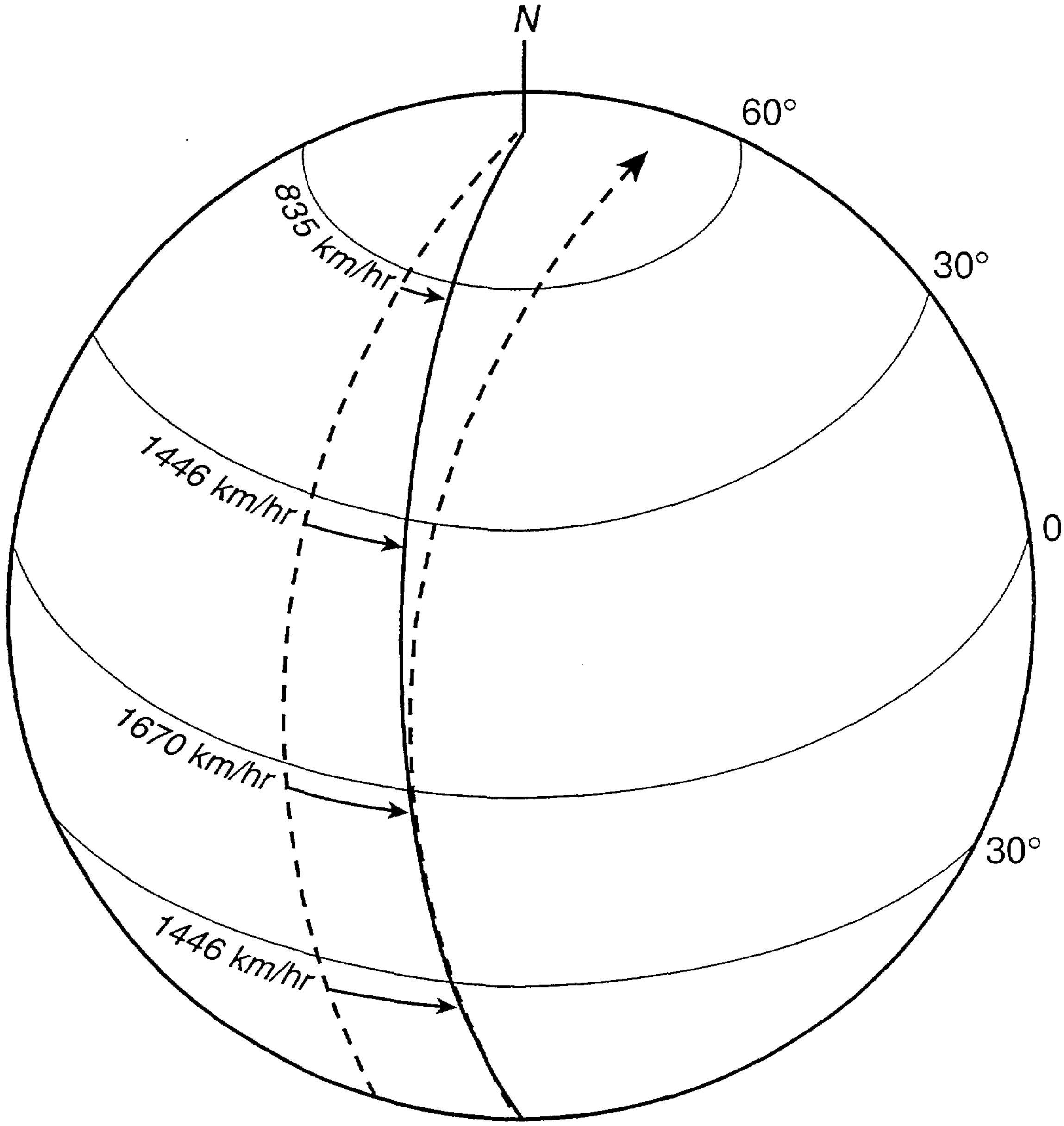

FIG. 5. Apparent deflection to the right of a hypothetical parcel of water moving from the equator to the North Pole, due to Coriolis effect. The deflection would be to the left for the water parcel moving from the equator to the South Pole. Note that these deflections are due to the decreasing speeds of the Earth's surface at higher latitudes as the Earth rotates in an eastward direction [1].

apparent curvature is accounted for by the Coriolis effect. To give an example of the Coriolis effect, let us presume that we have an air mass resting at the equator. While sitting at the equator, the air mass is moving east at 1670 km/hr, because that is the speed of the Earth's rotation at the equator (Fig. 5). If the air mass is put into motion toward the North Pole (i.e., if we create a northward-blowing wind), that air mass still moves eastward at 1670 km/hr, in addition to its speed toward the North Pole. As the air mass proceeds northward it moves over portions of the Earth's surface rotating at ever decreasing speeds; e.g., at 30°N the Earth's surface is rotating at only 1446 km/hr, and at 60°N only 835 km/hr (Fig. 5). The northward-moving air mass still maintains its 1670 km/hr eastward speed, however, and is therefore moving eastward at a speed faster than the Earth beneath it. To a person standing at the Equator, at the initial site of the air mass, the air mass appears to veer ever more to the right as it proceeds ever more northward. A person on a stationary platform in space, however, would see that the air mass actually travels in a straight line, with the Earth turning beneath it. had the air mass at the equator been put in motion toward the South Pole, the deflection would still be eastward but would appear to the person standing at the equator to veer to the left, not the right (Fig. 5). Had the equatorial air mass been put into motion *along* the equator rather than perpendicular to it, it would have moved in a straight line, with no veering. There is no Coriolis effect at the equator.

The coupling of the winds to the surface ocean currents, given the Coriolis effect, makes the surface currents veer to the right of the wind direction in the northern hemisphere and to the left of the wind direction in the southern hemisphere. With the equatorial Trade Winds blowing from east to west, and the higher-latitude Westerlies blowing from west to east in both hemispheres (Fig. 1), the global surface current systems tend to turn in a clockwise direction in the northern hemisphere and in a counterclockwise direction in the southern hemisphere (Fig. 2). Seasonal changes in wind direction, such as the different monsoons in the Indian Ocean, can change the direction of surface flows, as we've seen.

1.2.5. **Ekman Spiral and Ekman Transport**

The ocean is a three-dimensional system, and distributions of surface-injected radionuclides are affected not only by atmospheric-oceanic interactions at the immediate surface, but also by the interaction of surface waters with water layers below. In the northern hemisphere, the average deflection of surface waters from the prevailing wind direction is about 45° to the right, due to the Coriolis effect (in the southern hemisphere it averages 45° to the left). Frictional drag of the surface layer on the next layer below it causes that next layer to decrease in current speed and to change direction slightly further to the right. Proceeding downward through succeeding water layers yields ever-decreasing current speeds with continual directional change to the right (Fig. 6). At some depth the current, now greatly reduced in velocity, actually reverses direction, and eventually a depth is reached whereby no energy is left to produce any current at all. This spiralling phenomenon is called the Ekman spiral, after the scientist who first described it, and the depth range from the water surface to the depth of no measurable wind-induced energy is called the Ekman layer. Depth of the Ekman layer varies depending mainly on the wind strength imparted to the ocean surface. If one calculates the net directional movement of all water in the Ekman layer, one finds that it is approximately 90° to the right of the surface wind direction in the northern hemisphere (90° to the left in the southern hemisphere). The amount of water transported in the Ekman layer over some horizontal distance has been called the Ekman transport. One can see how knowledge of Ekman transport would be vital to predicting distributions of surface-injected radionuclides throughout the top layers of ocean waters. In most cases the Ekman layer does not exceed about 100 m depths, so Ekman transport is still a near-surface feature; however, the upper 100 m usually encompasses all, or most, of the lighted zone (euphotic zone) of the sea, where all photosynthetic production by single-celled algae (phytoplankton) takes place, and of course it is the interactive link between the atmosphere and the ocean, as we've seen. Thus, the Ekman layer is an extraordinarily significant, though small, part of the total volume of the global ocean, accounting for much of the dispersal of all manner of organic and inorganic materials.

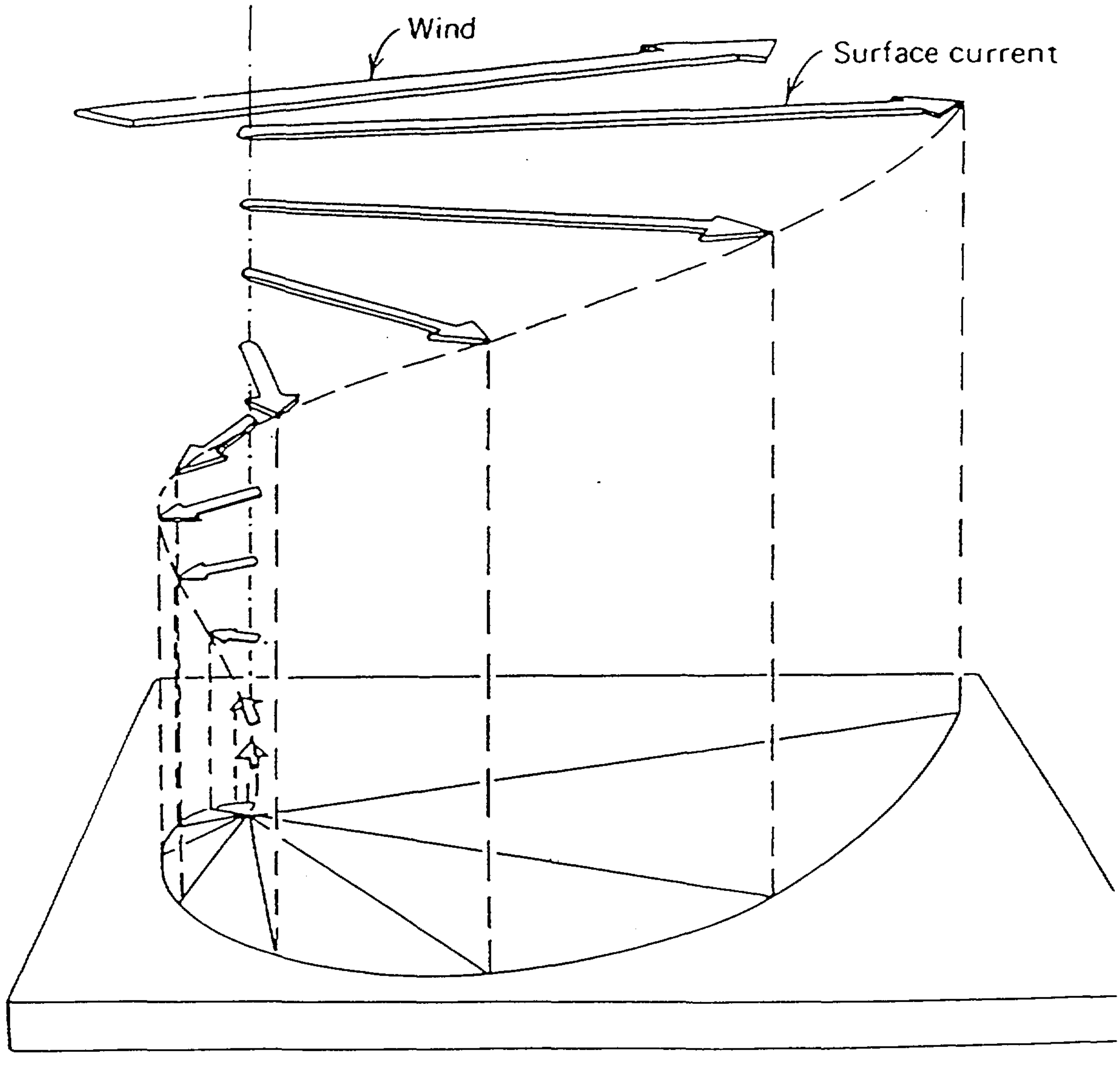

FIG. 6. Schematic representation of the Ekman spiral formed by a wind-driven current in deep water. Note the change in current direction and speed with increased depth below the surface [1].

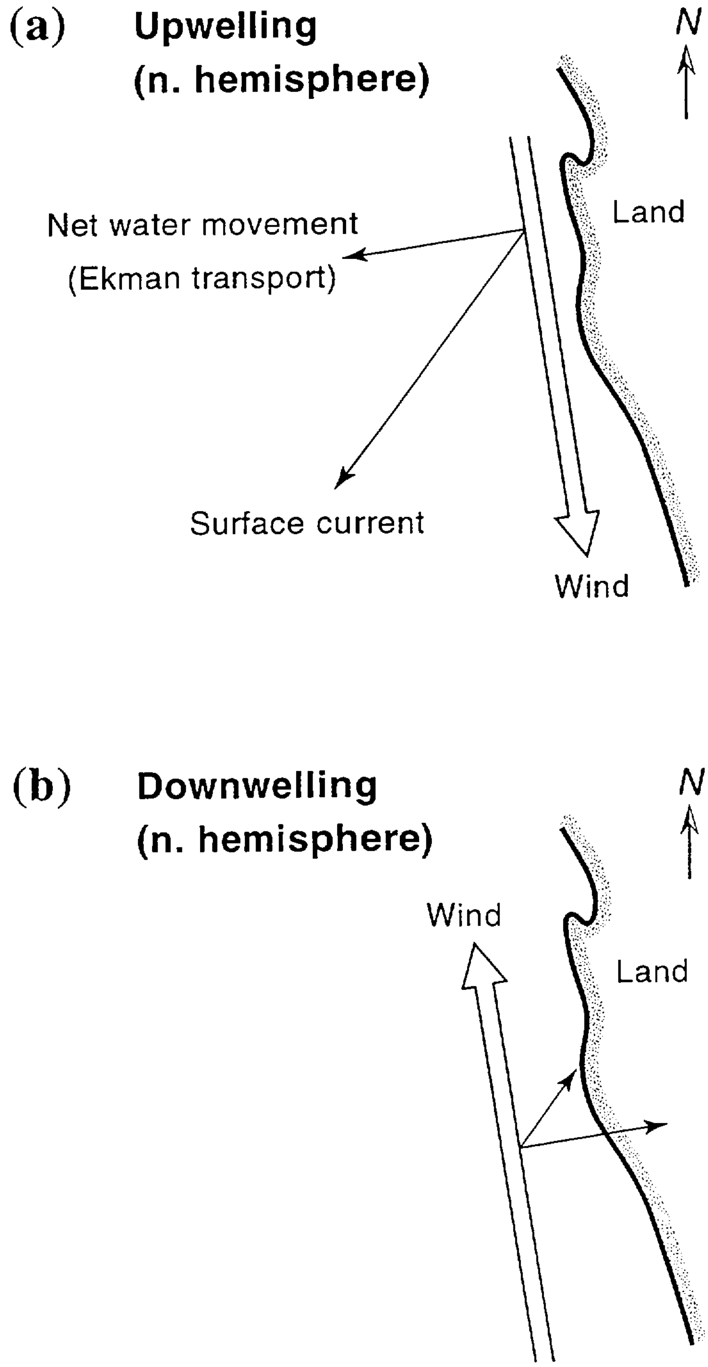

FIG. 7. Schematic representation of coastal upwelling (a) and downwelling (b) in the northern hemisphere. The directions of the surface current and Ekman transport relative to wind direction would be reversed in the southern hemisphere, for both upwelling and downwelling events.

1.2.6. **Coastal Upwelling and Downwelling**

Surface winds which generally move surface currents 45° to the right (or left), and Ekman transport which averages 90° to the right (or left) of the prevailing wind direction, help establish significant circulation patterns when land masses "interfere with" or "disrupt" classical wind-induced circulations unimpeded by land. A wind blowing from the north or northwest along a western coastline in the northern hemisphere, for example, will move surface water away from the coast at an approximate 45° angle (Fig. 7a), and will move water from the Ekman layer away from the coast at an angle of about 90°. Mass balance must take place, so water to replace that moved away from the coast must come from somewhere. It is brought up from a depth below the Ekman layer, in a process called coastal upwelling. Off the northwest coast of North America, as an example, the prevailing wind in spring and summer is from the NNW. Surface waters against the coast are thus moved offshore at this time, and colder, nutrient-rich water from below upwells to replace that surface water moved offshore. In addition, the large Columbia River Estuary empties into this upwelling system between the states of Washington and Oregon in northwestern USA. Some years ago the Hanford Nuclear Site on the Columbia River discharged small amounts of several radionuclides into the river, and the river carried those nuclides into the coastal ocean. In spring and summer, the tongue of Columbia River water at sea could be identified on the surface by its signature of radioactivity. The tongue proceeded in a general south-southwesterly direction, about 45° to the right of the wind, as expected. Because these same NNW winds delivered non-radioactive, upwelled waters to the surface waters immediately adjacent to the coast, however, a fairly sharp gradient between the relatively warm, fresh, radioactive river water and the colder, saltier upwelled water was established; that is, the river water could not spread toward the coast at the surface, and the upwelled water could not spread seaward at the surface, creating a distinct frontal region. These and other scenarios will be treated later in more detail, but the illustration is given to show that the effects given by the positions of land masses and by such things as river discharges into the oceans, can greatly contort general circulation patterns expected under a given wind regime. These contorting effects are particularly noticeable in the relatively shallow waters over continental shelves — and of course these are the regions having most direct impact on humans, and on which humans have the greatest impact.

During the autumn and winter, the prevailing winds off northwestern USA blow from the south. Coriolis effect remains the same (to the right of the wind), so transport of surface and near-surface waters is toward the coast (this is the time of year for beachcombing, as materials are brought onto the coast and often stranded there). At this time the Columbia River tongue, with its radioactive signature, is moved north and kept tightly against the coast of Washington state. Upwelling ceases because surface water is not moved away from the coast, but tends to pile up toward the coast, as mentioned previously. At this time there can be downwelling of water (Fig. 7b) as some of that which tends to pile up at the coast must sink to maintain mass balance (some also moves laterally along the coast, intensifying a winter-time coastal current called the Davidson Current).

1.2.7. **Convergence and Divergence Systems**

As water is transported to the right of the prevailing wind systems in the northern hemisphere, and to the left in the southern hemisphere on our rotating Earth, there is a tendency for surface water coming from opposing directions to pile up slightly in subtropical regions (particularly on the western sides of ocean basins in the sub-tropics), where winds are lighter than those in the polar regions. As the surface water tends to pile into a slight "hill", the pycnocline (a layer of strong density discontinuity below the surface) becomes depressed into a "valley". This creates a *convergence* (Fig. 8a, top panel). The most prominent convergences are the subtropical convergences between 20-40° N and S and the Antarctic convergence between 40-50°S (Fig. 2). These mid-ocean convergences are very hard to detect, because the elevations of the water surface, and depressions of the pycnocline, are very small over large lateral distances.

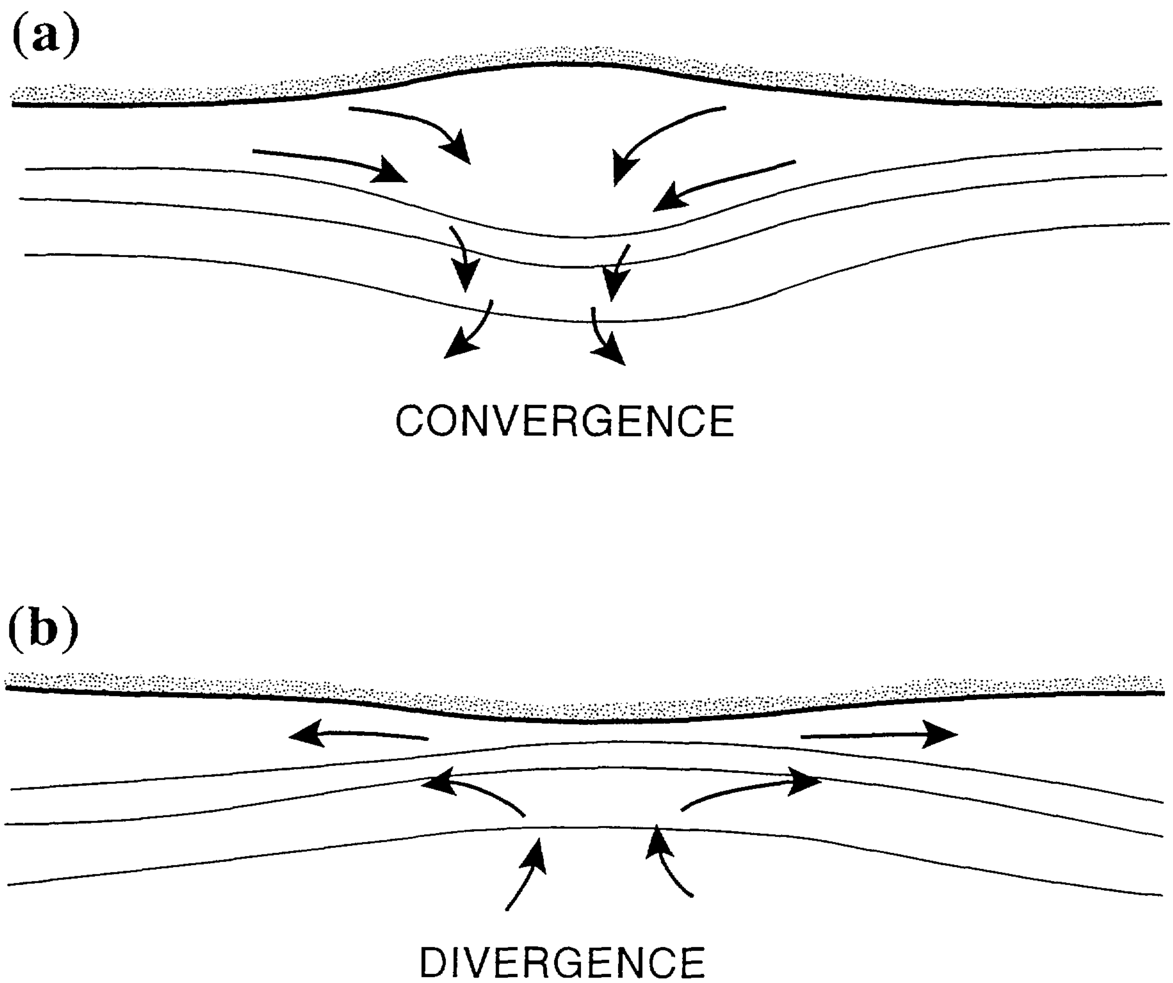

FIG. 8. Schematic representation of oceanic convergence (a) and divergence (b) regions.

Conversely, where water is moved away in opposite directions in a given region (by winds yielding Ekman transports in opposite directions), subsurface waters move to the surface to replace the surface waters that have been moved away, creating an oceanic *divergence* (Fig. 8b). It should be recognized that an oceanic divergence develops through a process similar to coastal upwelling, but with no coastal land barrier. Two prominent oceanic divergences are the Antarctic divergence (65-70°S) and the equatorial divergence created by the NE and SE Trade Winds imparting NW and SW Ekman transports to near-surface waters near the equator. We will discuss these more fully later. Divergences are usually easier to spot than convergences because they often are rich with phytoplankton growth sustained by the nutrients being brought into surface waters from below (Fig. 8b). In this sense, open-ocean divergence zones again are similar to coastal upwelling regions.

1.2.8. **Geostrophic Currents**

So-called geostrophic currents can arise as water from the slightly elevated portions of the ocean (the "hills") tends to run down toward the more depressed regions (the "valleys") under the influence of gravity. However, the Coriolis effect also is in play, so that the eventual current that ensues is a result of the balance between these two forces. The current does not run straight "downhill" into the "valley", as forced by gravity, nor does it run around the "hill" in one plane, under the sole influence of Coriolis: rather, it tends to describe a curving path down the "hill" toward the "valley". Satellite techniques are now used to accurately measure the sea-surface "hills" and "valleys", and thus more accurately map geostrophic currents in the world ocean.

1.2.9. **Global Thermohaline Circulation and Water Mass Movement**

A final type of global water movement, large-scale thermohaline circulation, needs to be addressed, because this, too, redistributes huge volumes of water and therefore redistributes all manner of dissolved and tiny particulate matter (including radionuclides and pollutants). Global thermohaline circulation largely involves *vertical* water movements that initiate the horizontal movement of water from polar regions (particularly the North Atlantic and Antarctic Oceans). This circulation phenomenon controls temperature and salinity distribution in the *deep* ocean, and has a profound effect on distribution of other properties as well.

This massive vertical circulation is not caused by regional winds, but by density differences of different water masses. Density is controlled by temperature and salinity, with warm, fresh waters being less dense than cold, salty waters. When the density of water at the surface exceeds the density at depths below the surface (when surface water cools as a result of cooling air temperatures, for example), the water column becomes unstable and the more dense water sinks, displacing the less dense water immediately below it; hence a vertical circulation is set up. The water sinks until it reaches a depth of slightly more dense water, at which time the sinking mass moves laterally. On a global scale, particularly in the Atlantic Ocean near Greenland and in waters near Antarctica, large water masses of very low temperature and high salt content become very dense and sink quickly to depth. The Antarctic system provides a good example (Fig. 9). Antarctic Bottom Water (AABW) is extremely cold (0-1° C) and salty enough so as not to freeze at those temperatures -- it is the coldest water on Earth. It is slightly more dense than the cold North Atlantic Deep Water (NADW), so this latter water mass flows southward to replace, and override, the AABW. The AABW penetrates northward along the sea floor to about 45° S latitude before it loses its identity through warming and mixing with other water masses. Similarly, Antarctic Intermediate Water (AAIW) overrides the denser NADW, and the warmer surface subantarctic water makes up the top layers. Enormous amounts of heat are transported into the system by the NADW, and lesser amounts are carried away from the Antarctic in AABW. Heat balance is generally maintained because huge quantities of heat are lost to the atmosphere at the Antarctic Convergence (Figs. 2 and 9), with relatively small heat gains from solar radiation. The Antarctic system is thus an enormous heat exchanger for the global ocean, and the thermohaline circulation is also responsible for large movements of dissolved gases and other materials. Extensive mixing with waters in the West Wind Drift around Antarctica (the Antarctic Circumpolar Current) allows large volumes of Antarctic water to be carried into the Pacific Ocean. The Pacific itself is not so intensely charged with cold, dense water as the Atlantic, as North Pacific waters are less salty than North Atlantic Waters and so do not sink as deeply as those in the North Atlantic. Nor is the southerly excursion of the densest North Pacific water so prominent as that of the North Atlantic. North Atlantic Deep Water reaches the Antarctic region (Fig. 9), whereas sinking North Pacific water does not reach the equator. Knowledge of these vast, deep circulation patterns is crucial to understanding potential effects and hazards of deep-sea waste disposal.

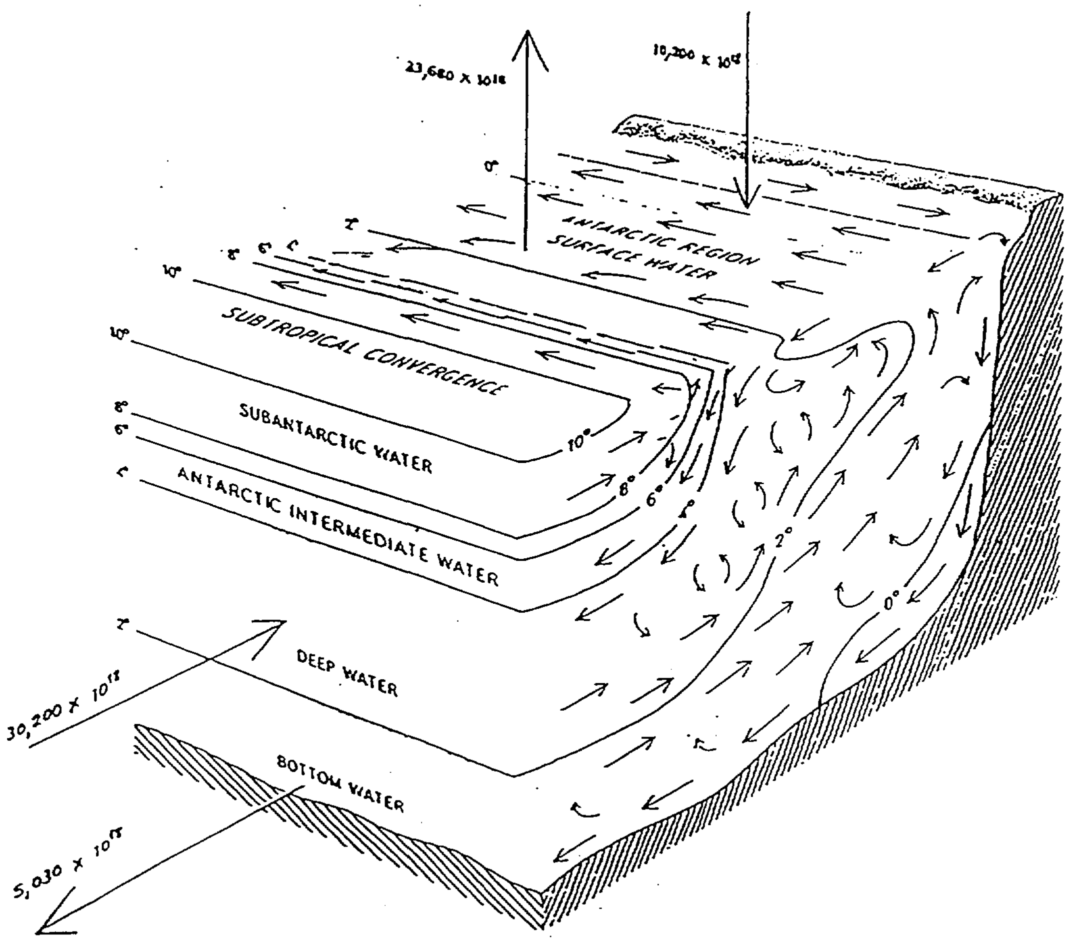

FIG. 9. Schematic representation of the complex current flow in the Southern Ocean. Figures at the left are estimates of the amount of heat, in calories, transported annually by the deep and bottom waters. Figures at the top show that the annual heat given off to the atmosphere by the Southern Ocean greatly exceeds the heat received from the sun. (From: The Antarctic Oceans, *by V.C. Kort. Copyright © 1962 by Scientific American, Inc. All rights reserved.) [2].*

1.3. COASTAL AND NEAR-SURFACE PROCESSES

1.3.1. **Significance of Coastal Processes**

Now, knowing something about large-scale wind-driven surface circulation, geostrophic currents, and deep thermohaline circulation, which affect redistributions of materials in the global ocean, we can look more closely at smaller-scale coastal processes that affect radionuclide distributions. Coastal processes often become relatively more significant than open-ocean processes because mankind is most closely associated with coastal environments, through fishing, recreational pursuits, transportation routing, mineral extraction (including oil and gas), and dumping of wastes.

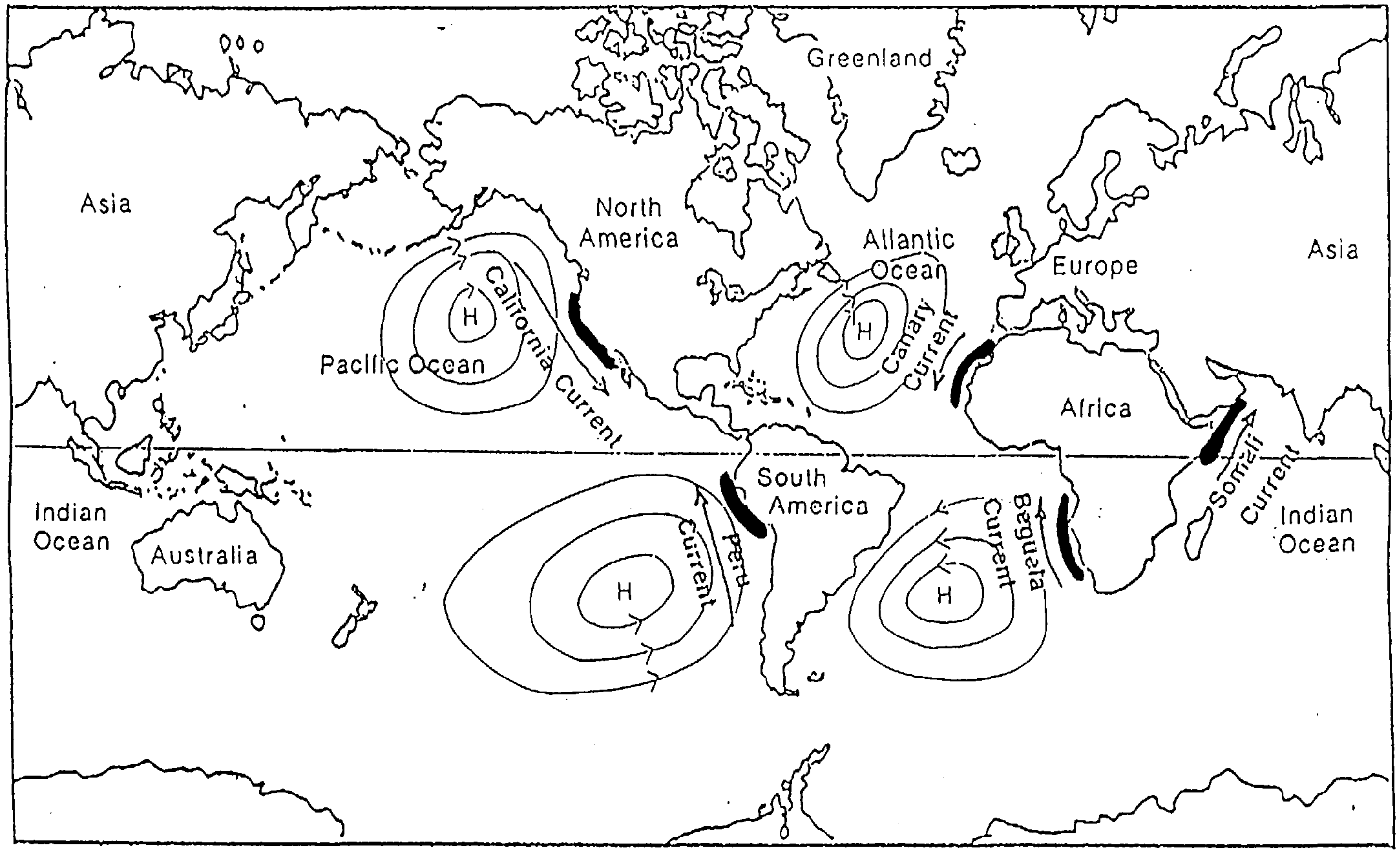

FIG. 10. Major coastal upwelling areas of the world, and the atmospheric pressure systems and prevailing oceanic currents associated with them.

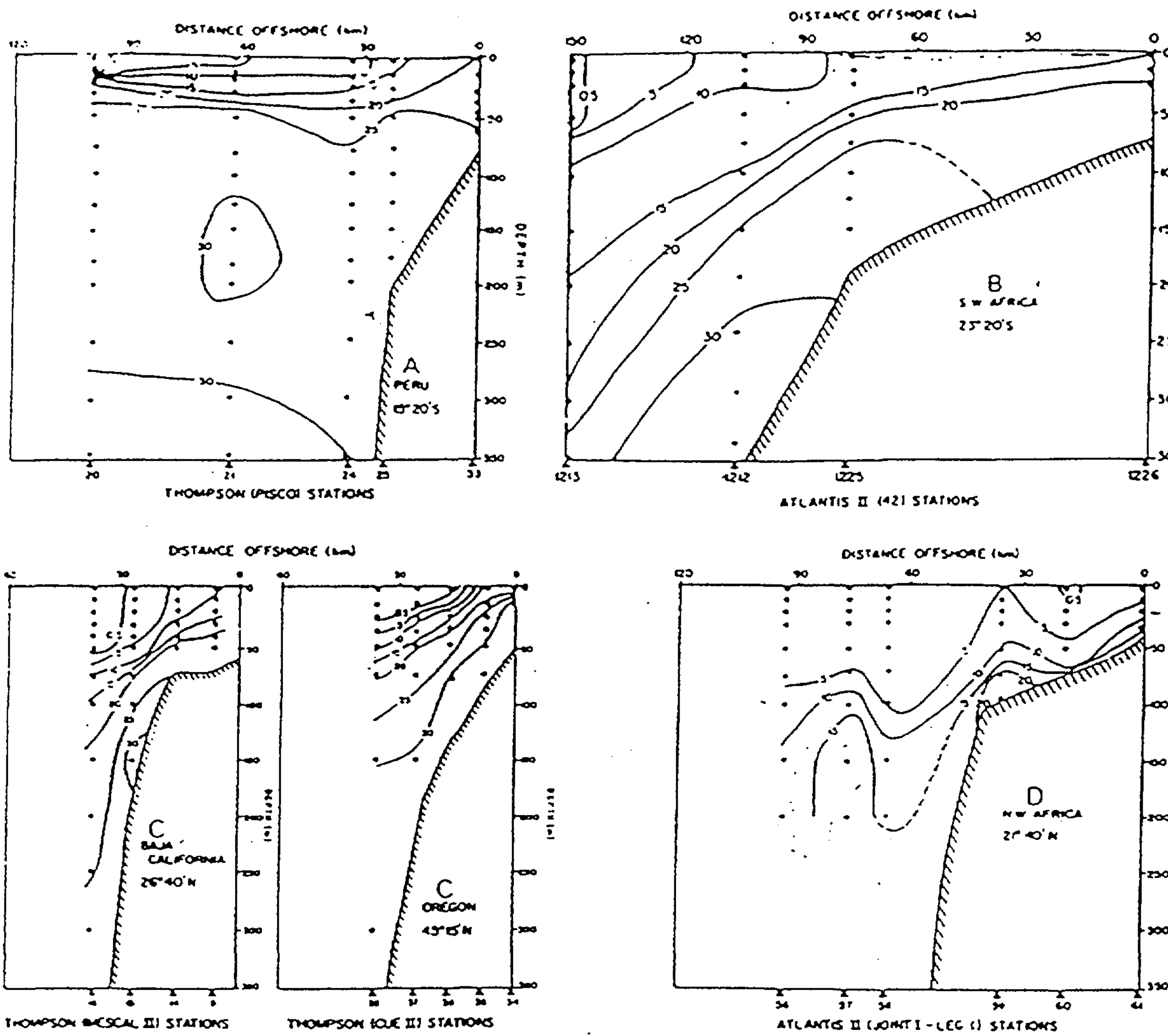

FIG. 11. The gradient of dissolved nitrate (µg-atom/liter) in selected coastal upwelling areas [3].

1.3.2. **Significance of Coastal Upwelling Systems**

Coastal upwelling has already been introduced, but it clearly is one of the most significant coastal processes and deserves further treatment. Major upwelling areas of the world ocean represent only about 0.1% of the ocean's surface area, but perhaps 50% of its fish production. Coastal upwelling areas are characteristically associated with eastern boundary currents (western sides of continents in the Atlantic and Pacific Oceans), although the upwelling zone off the Somali coast is an exception, a product of the SW (summer) monsoon system (Fig. 10). More minor or more ephemeral upwelling systems can be found anywhere that winds, in concert with the Coriolis effect, move surface waters away from a coastline (with subsequent replacement of those waters with waters upwelled from greater depths). The most persistent systems (Fig. 10) are those in which the prevailing winds are steady enough over long enough time periods to keep the upwelling process active for long periods. Long-term upwelling continues to resupply surface waters with dissolved nutrients from below the Ekman layer, thus providing the fertilizer necessary to sustain luxurious phytoplankton growth, which in turn supports food webs stable enough to allow large production of fish biomass. Upwelling areas in the westerly wind belts (western North America, northwest and southwest Africa) are seasonal, as the atmospheric high-pressure systems generating the upwelling-favorable winds themselves are seasonal in position, and the Somali upwelling system is seasonal because of the seasonality of the monsoon winds, as noted earlier. Within any given season upwelling-favorable winds may disappear for short periods, thus turning off the upwelling circulation with its supply of nutrients to the euphotic zone; however, upwelling-favorable winds are the predominant winds during the summer seasons in the westerly wind belts, so that upwelling circulation is persistent enough to maintain a productive food web. The most productive upwelling system is that off northwestern South America, principally Peru and Ecuador (Fig. 10). This system is driven by the Trade Winds, which, although relatively light, are nevertheless persistent throughout the year. This system boasts some of the highest fish production in the world, although overfishing and El Niño events have reduced stocks to very low levels in recent years.

The major upwelling areas have somewhat different patterns of distribution of nutrients, and therefore different patterns of phytoplankton growth and food web structure. These different patterns are brought about by the different configurations of bathymetry and coastal topography in the different areas (Fig. 11), as well as by different wind intensities and persistence. It is clear that disposal of radioactive or other wastes into any upwelling system, or locating processing plants in an upwelling region, would be harmful. The systems are relatively shallow, very productive, and would tend to redistribute near-bottom materials back toward the coast.

1.3.3. **Tides and Tidal Currents**

Coastal areas also experience tides and tidal currents, capable of locally redistributing materials injected into estuarine or nearshore waters. Tide-generating forces include gravitational attraction between the Earth and moon, centrifugal forces created by the rotation of the Earth and moon, and gravitational forces between the Earth/moon system and the sun. A parcel of water on the Earth's surface *nearest* the moon is about 3% *closer* to the moon than a parcel on the Earth's surface farthest from the moon; hence, the moon's gravitational attraction is greatest on the water nearest the moon, and least on the water farthest from the moon. Centrifugal forces are equal over the Earth's surface, however. Thus, on the side nearest the moon, the gravitational attraction of the moon exceeds the centrifugal force, so that the water is pulled out toward the moon. On the side furthest from the moon, the centrifugal force exceeds the gravitational pull, so that there, too, the water is pulled away from the earth. A slightly oval water envelope is thus created around the sphere of the Earth in this idealized scenario (Fig. 12a), with the bulge of the oval on both sides of the Earth being the high tides, and the slightly flattened sides of the oval being the low tides. Remember that the earth revolves under its water covering, so that the tidal bulge (high tide), to someone standing at a fixed point on the revolving Earth, seems to appear (increase) and disappear (decrease) over a fixed period of time. If, for example, the moon is in the plane of the Earth's equator, the two tidal bulges on opposite sides of the Earth will be centered at the equator (Fig. 12a). After the Earth rotates 90°, the same point on the equator would register a low tide. Continual 90° rotations yield successive, equal-sized high and low tides from the fixed point – two high tides and two low tides over a period slightly greater than one full day.

The moon does not maintain a fixed position relative to the Earth, however; i.e., the moon is not always in the plane of the equator, creating tides of equal magnitude each tidal day. Therefore, a person at a fixed position on Earth would see two high tides and two low tides during each tidal day, as before, but over a period of successive days the height of the high tides and depth of the low tides would be different as the position of the moon changed relative to a fixed point on the Earth; thus, higher high tides and lower low tides are registered relative to other times (Fig. 12b).

The sun also exerts a gravitational effect on the Earth's water envelope, but it is more than 50% weaker than that of the moon because of the enormous distance between the Earth and the sun. Also, solar tides have a 12 hr period (the time between two high tides, or between two low tides), while the lunar period is about 12.5 hours. Finally, the Earth takes a full year to cycle the

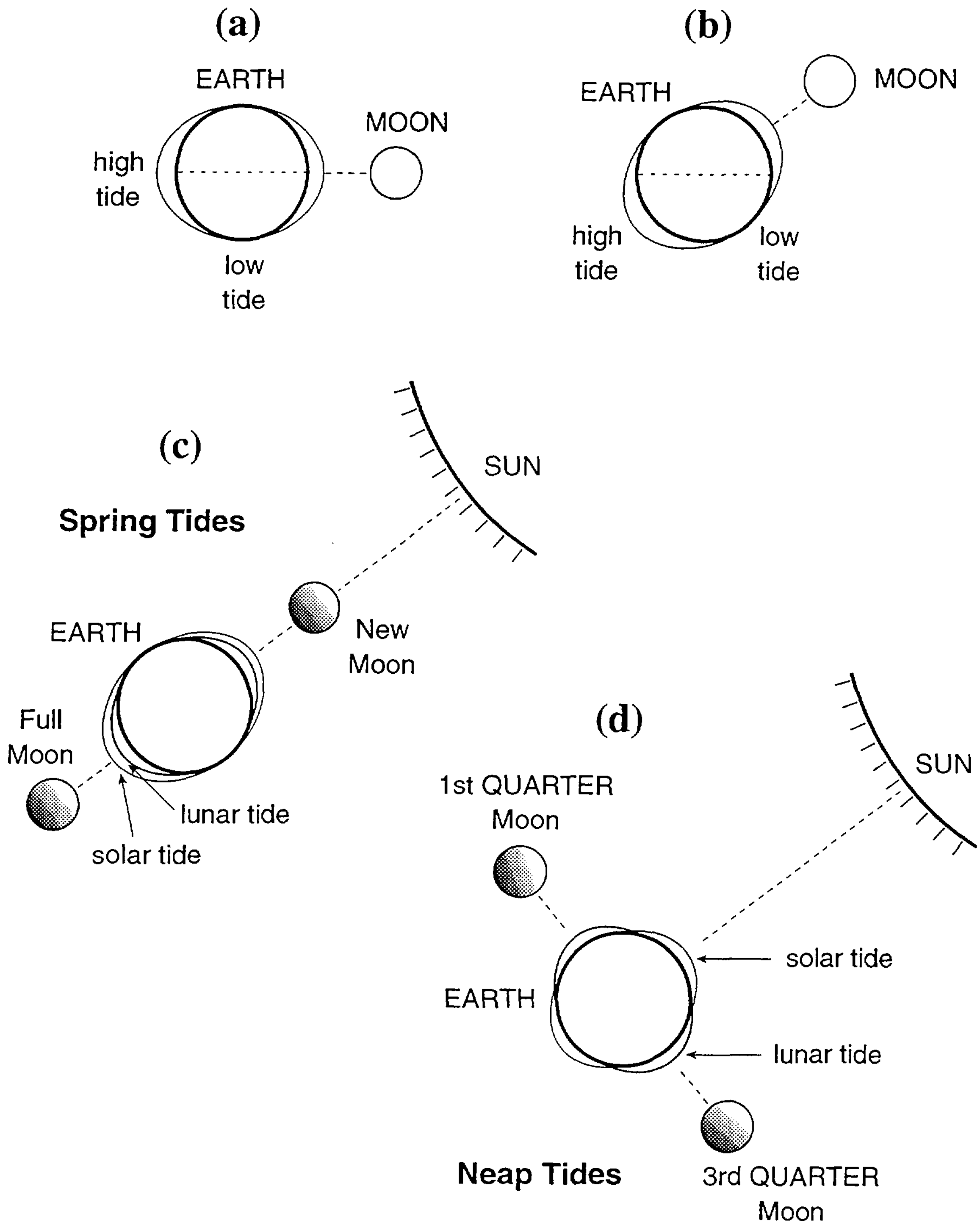

FIG. 12. Schematic representation showing how tides are created.

sun, whereas the moon cycles the Earth once per month. Solar and lunar tides acting together or in opposition create *spring tides* or *neap tides*, respectively (Fig. 12c,d). Spring tides, which occur approximately every two weeks around the times of the new moon and full moon, occur when the sun and moon line up with the Earth, so that their tide-generating forces act together to create extra large bulges in the tidal envelope (i.e., extra high tides). Conversely, during the first and third quarters of the moon, the solar and lunar tide-generating forces partially counteract each other by acting in different directions, resulting in the lowest tidal range – the neap tides. There are further complexities to tides than the above so-called "equilibrium theory" presents, but the above should be enough for our purposes here.

The tide in every marginal sea, bay, harbor, or estuary is greatly influenced not only by the magnitude of the ocean tide at the mouth, but also by the natural period of the basin and the cross-section of the mouth. The small tidal range in the Mediterranean Sea (about 0.5 meter), for example, can be explained by the small opening through the Strait of Gibraltar into the Atlantic, relative to the size and depth of the Mediterranean basin. The effect of tides on distributing radionuclides in the Mediterranean is vanishingly small. On the other hand, in the Bay of Fundy (New Brunswick, Canada), where the natural period of the basin is near the tidal period (12 hours), large standing waves are set up (see below), which course back and forth through the basin giving an extreme tidal range (ranges on the spring tide are about 15 m in the Bay of Fundy). Movement of materials by these tidal bores is extremely great. Thus, tidal effects in coastal areas can be either great or small, alternately exposing and covering great areas of beach or shoreline, or not making much difference at all. Knowledge of the tidal features in a given area of coast or estuary is exceedingly important when considering radionuclide waste discharge or other discharges.

1.3.4. **Nearshore Surface Waves, Internal Waves, and Surf**

Surface waves are not particularly significant in distribution of materials until they crest over to form surf adjacent to beaches. Surf is lateral movement of surface waters, and thus can distribute materials onto beaches. Internal waves, however, can redistribute much heat, dissolved gases, and other materials in the ocean's interior. In principle they are like surface waves, but they are usually found at the interface of water layers of different density. Internal waves can be much higher, longer, and move much more slowly (with longer period) than surface waves, because the density differences between two water layers are much less than between water and air.

1.3.5. **Standing Waves and Tsunamis**

At times the whole water mass in an enclosed basin (e.g., the Red Sea or the Bay of Fundy) can slosh back and forth, much as water in a bathtub can be made to slosh back and forth by applying and releasing some pressure on the water at one end of the tub. An earthquake or some other major phenomenon can often set off these *standing waves* in a natural basin. The edges of a standing wave at the shore alternately exposes and inundates large areas of shoreline, thus potentially redistributing near-shore materials. The ultimate standing waves are seismic sea waves, or tsunamis, which can be devastating when they occur; however, they are rare. Tsunamis are usually caused by large earthquakes beneath the sea floor which act to accelerate a wall of water in some direction. The tsunami is similar to a shallow-water standing wave, but originates in deep water and thus can transport an enormous volume of water very rapidly (up to 800 km/hr). Tsunamis are often undetectable by ships at sea, and only wreak havoc when they encounter a land mass.

1.3.6. **Small-Scale Thermohaline Circulation**

Thermohaline circulation, on a smaller vertical scale than that addressed earlier, is responsible for much water movement and distribution of properties in the coastal ocean and in

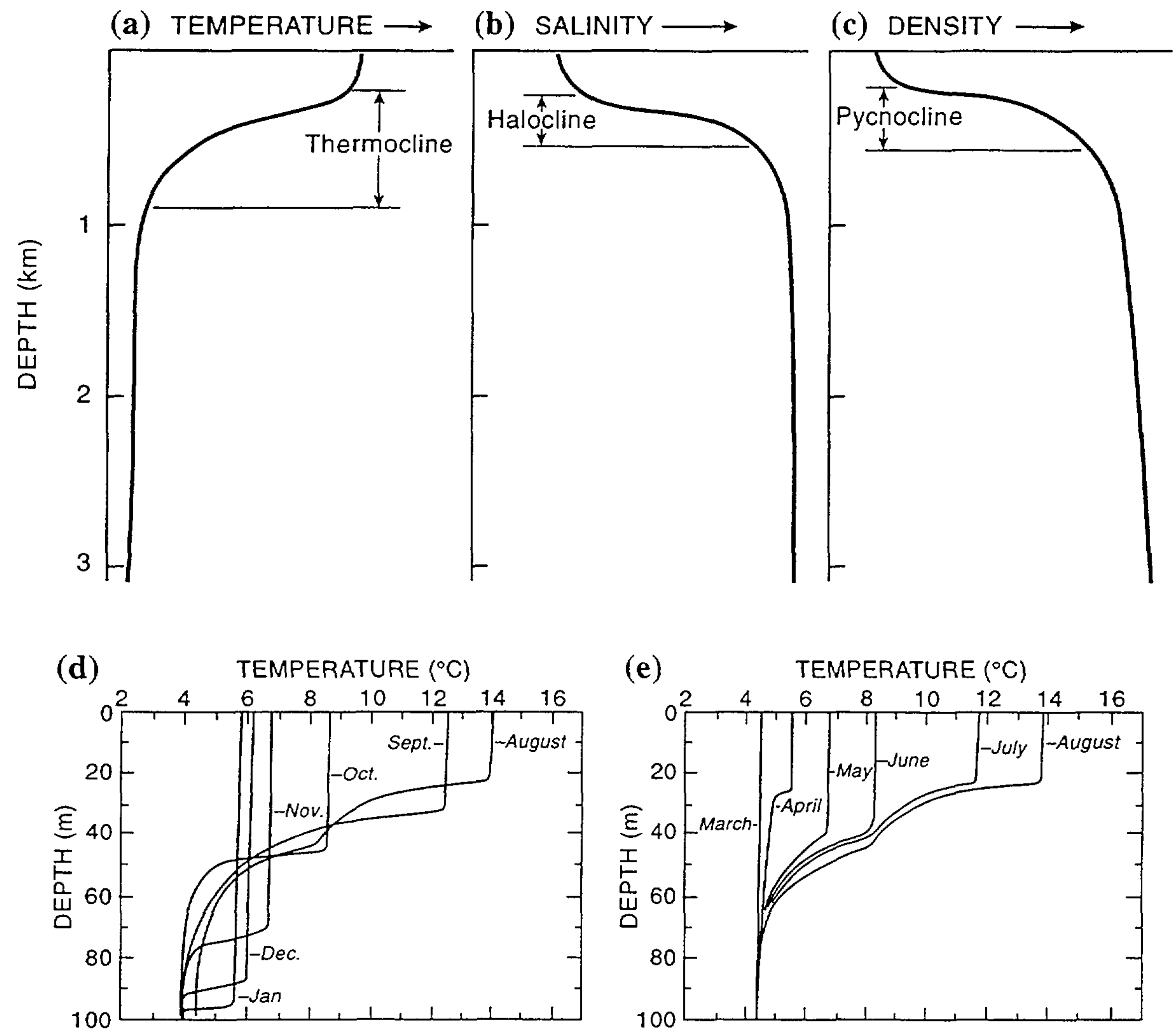

FIG. 13. Schematic representation of a thermocline (a), halocline (b), pycnocline (c), fall-winter decay of a thermocline (d), and spring-summer establishment of a thermocline (e).

upper layers of the open temperate ocean. Because radionuclides and most other materials enter the ocean through the surface layers, these upper-water circulations are very significant. The circulations are generated when stable, near-surface water columns are disrupted (usually seasonally due to seasonal changes in temperature and salinity of those waters). Relatively stable upper-water columns occur when surface waters, warmed by the sun, form a relatively thin mixed layer over a region of fairly rapid temperature change with depth. This layer of temperature discontinuity is the *thermocline* (Fig. 13a). Below the thermocline temperatures remain cold, and change very little all the way to the sea floor. Sometimes salt is the principal agent of stability of near-surface waters in the ocean, so that a shallow region of low-salinity water overrides a zone of maximum salinity change with depth (the *halocline*), which in turn overrides deep waters with high salinity that changes very little with depth (Fig. 13b). The combined effects of temperature and salinity are responsible for the density of the water, so that a stable water column features a shallow surface layer of low-density water (relatively warm and fresh) which overrides a zone of maximum density change with depth (the *pycnocline*), which in turn overrides the densest water (relatively cold and salty) (Fig. 13c). Waters of different densities resist mixing, so that any radionuclides put into surface waters overriding a well-established pycnocline would remain in those surface waters for a long time, if physical processes were the only processes involved in radionuclide distribution (in fact, physical processes are not the only ones involved, and this will be examined later).

In tropical waters, upper water columns can remain relatively stable for long periods of time, the stability mainly being upset by episodic events such as storms at sea, or by internal waves along interfaces between the pycnocline and waters above or below it. In temperate seas, winter lowering of atmospheric temperatures, and/or rainfall and river runoff in the coastal ocean, causes the water-column stability of summer to break down (Fig. 13d). As autumn air begins to cool the immediate water surface layer, that water sinks until it reaches water of equal density. Further cooling of the air acts to cool more surface water, which also sinks. This process continues, setting up a vertical convection of cooler water sinking through the slightly warmer water until the upper layers become equally dense and therefore capable of mixing easily. As spring approaches, the progression reverses (Fig. 13e); i.e., the winter water column begins to warm at the surface. This warmer surface layer resists mixing with the slightly colder water just below it, initiating the formation of a thermocline. As the surface waters continue to warm, the thermocline deepens until the incoming summer radiation attains its maximum possible effect. The progression then begins to reverse again (Fig. 13d). It should be noted that these thermohaline circulations are identical to global thermohaline circulations involving mass transports of deep water, except the former are near-surface phenomena usually occurring on a seasonal basis in temperate and subpolar seas. Seasonal thermohaline circulations rarely involve depths beyond 100 m or so, but note that this depth zone is the approximate productive zone of the sea and the one contiguous with the atmosphere and with river and coastal discharges.

1.4. SMALL-SCALE PROCESSES

1.4.1. **Scaling for Sampling Protocols**

When studying oceanic water movements relative to distributions of radionuclides, the tendency is always to present the large-scale processes and ignore the small-scale processes. However, from the standpoint of knowing how to sample, when to sample, and how often to sample water for valid distributional analysis of radioactivity at sea, it is imperative to have some understanding of time and space scales of physical processes (such as mixing and diffusion) relative to biological and radiochemical processes of interest.

Simple formulae can often be used to determine characteristic scales; for example,

$$T = \frac{(q)}{(\frac{dq}{dt})} = \textit{characteristic time } (T) \textit{ for sampling quantity } (q),$$

where q = concentration of a long-lived radionuclide in the water, for example, and dq/dt = the time rate of change of quantity q in that water (e.g., μg/m3 ÷ μg/m3/hr = hrs). T is the number of hours one has to sample q before q is dissipated to generally unmeasurable levels by dispersion, sinking, biological uptake, or other mechanisms (presuming q is a one-time input to the sampling region). If q is a radionuclide with short half-life, then radioactive decay must also be accounted for. Knowledge of space scales required for sampling are also important, and this involves selection of the numbers and spacing of sampling sites to adequately represent the spatial domain of interest.

1.4.2. **Reynolds Number**

One dimensionless number that has proved useful in delineating time and space scales significant for a particular sampling scheme is the Reynolds number. This number gives the relationship between turbulent processes and molecular processes in a fluid, and is defined as:

$$\mathrm{Re} = \frac{u\ell}{V}$$

where $u\ell$ = a characteristic length scale (ℓ) times a characteristic velocity (u), of water, a particle, or an organism; and V = kinematic viscosity of the fluid (for water, kinematic viscosity = viscosity/density $\approx 10^{-2}$ cm^2 sec^{-1}, a measure of molecular motions). A *low* Re represents more viscous, laminar flow, while a *high* Re represents turbulent flow. A one-micron-sized particle of fallout radioactivity, for example, operates in a very low-Re environment (very tiny "length" scale and very weak sinking velocity relative to the kinematic viscosity of the water in which it was deposited). A zooplankton organism 1mm in length also operates in a relatively low-Re environment (the short length and slow swimming speed of the zooplankter relative to the kinematic viscosity of the water in effect gives the same mobility problem to the zooplankter as a human being would have trying to swim through thick molasses). On the other hand, a full-grown tuna lives in a high-Re environment (long length and rapid swimming ability of the fish relative to the kinematic viscosity of the water). Clearly one would not design a similar sampling program for fallout particles, zooplankton and tuna; however, would one design the same program for 1μm and 100μm particles (e.g., fallout particles and diatoms), for 1mm zooplankton and 10mm zooplankton. Small-scale processes are important, and correct sampling scales are required to adequately assess them.

1.4.3. **Richardson Number**

The Richardson number (*Ri*) is another dimensionless number, relating a stabilizing *buoyancy* to a destabilizing *shear*. This measure is important in determining when a stable upper water column turns into a mixed water column, and to what extent:

$$Ri = \left[\frac{(-\frac{g}{e})(\frac{de}{dz})}{(\frac{du}{dz})^2} \right]$$

where the numerator is a measure of buoyancy (a *sink* for turbulent energy, the so-called Brunt-Vaisala number), and the denominator is a measure of shear (a *source* of turbulent energy). In the formula, g = acceleration due to gravity, e = density of the water, u = velocity, and z = depth. Richardson numbers between zero and one denote the region where shear overcomes stability, leading to a turbulent condition (0.25 is approximately the balance point where neither shear nor buoyancy controls). An *Ri* greater than one is a stable water column (a greater sink than source for turbulent energy).

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