# Overview of the Marine Environment

## 2

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**Abstract**

Fish, cephalopod, shrimp, and other economic marine species are widely distributed in the ocean, but they are not evenly distributed in the ocean. This means that these marine economic species are not concentrated in all areas, nor can they form commercial fishing grounds in any sea area. A large number of scientific investigations and production practices have shown that the spatial distribution, life history, and resources of fish and other marine economic species are closely related to the marine environment, they are usually concentrated in the area around the front of the two currents and near waters of eddy, so it is very important to understand and master the state of the ocean environment, such as the shape of the ocean, the distribution of the ocean current, the distribution of the water temperature, and so on. This chapter briefly describes the division of the world's oceans, the topography of the seabed and the ocean sediments, the concept of ocean circulation and its causes, the generation of upwelling and downwelling currents, and the distribution of the world's ocean circulation; the distribution and characteristics of main currents in the Pacific Ocean, Atlantic Ocean, Indian Ocean, and Antarctic Ocean are described. Water temperature, nutrient salt, and primary productivity are the important environmental factors that affect the distribution of marine economic species, such as fish and the formation of fishing grounds, and are also the environmental factors that have been applied in fisheries forecasting. Therefore, this chapter briefly describes the distribution of water temperature, nutrient salt, and primary productivity in different sea areas of the world. To master the distribution law of ocean current, water temperature and other important environmental factors will help us to correctly carry out the research of fisheries forecasting and provide the theoretical basis for establishing scientific models of fisheries forecasting.

**Keywords**

Ocean current · Water temperature · Primary productivity · Global ocean

## 2.1 The Marine Morphology

### 2.1.1 Marine Area and Partitioning

The marine area on the earth is 316 million km$^2$, accounting for approximately 70.8% of the total area of earth. Oceans are distributed unevenly in the northern and southern hemispheres. In the northern hemisphere, oceans account for 60.7%

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of the total area, while land accounts for 39.3%; in the southern hemisphere, oceans account for 80.9%, with land accounting for only 19.1%. Moreover, earth can also be divided into the water hemisphere, which contains mostly surface water, accounting for approximately 91% of the area, and the land hemisphere, which contains most of the land but still only accounts for 47% of the area (Fig. 2.1).

Based on marine elements and morphological characteristics, marine waters can be divided into main parts and their subsidiary parts. The main parts are oceans, and the subsidiary parts are seas, bays, and straits.

### Oceans

Oceans refer to waters offshore of continents that have a depth of more than 2000–3000 meters. Their area accounts for approximately 89% of the total marine area. Marine factors such as salinity and temperature, among others, are unaffected by the continents. The average salinity of oceanic water is 35‰, with little annual change; oceans have high water color with great transparency, and they have their own independent tidal and ocean current systems.

Based on the aforementioned characteristics, the world's oceanic water can be divided into three oceans, that is, the Pacific Ocean, the Atlantic Ocean, and the Indian Ocean. The boundary between the Pacific Ocean and the Atlantic Ocean is at Cape Horn, the apex of South America, at 70°W longitude, the boundary between the Atlantic Ocean and the Indian Ocean is the Cape of Good Hope (20°E longitude), and the boundary between the Pacific Ocean and the Indian Ocean is from the Malay Peninsula, Sumatra, Java, and East Timor via Cape Londonderry in Australia to Tasmania to the South Pole (147 °E longitude as the boundary). Some people also refer to the ocean surrounding the Antarctic continent as the Southern Ocean or Antarctic Ocean, and some people also refer to the Arctic Sea as the Arctic Ocean.

### Seas

Seas refer to waters with a comparatively shallow depth, generally 200 to 300 m. The total area of seas is comparatively small, accounting for only 11% of the total marine area. The temperature of seas is greatly affected by the continents, and there are significant seasonal changes. The salinity is higher in inland sea areas, where there is no inflow of fresh water, and evaporation is strong but lower in sea areas with abundant river water inflow and little evaporation capacity, generally below 32‰. The water color is low, and there is little transparency. There are almost no independent tidal and ocean current systems, and they are mainly affected by the oceans into which they drain. Seas can be divided into two types: intercontinental seas and marginal seas. Intercontinental seas lie between continents or extend into the interior of continents, such as the Mediterranean Sea in Europe, Baltic Sea, South China Sea, Gulf of Mexico, Persian Gulf, and Red Sea, among others. Marginal seas are located on the margins of continents, such as the North Sea, Sea of Japan, East China Sea, and Yellow Sea, among others.

### Bays

Bays refer to waters that are a part of oceans or seas that extend into continents, and their depths gradually decrease. In general, the connecting line between capes at the mouth of a bay or the isobath at the mouth of a bay is used as the boundary with the ocean or sea. The properties of the sea water in a bay are therefore very similar to the marine conditions of the connecting ocean or sea due to free water interchange with the adjacent sea or ocean. The maximum tidal range often occurs in a bay because of the continuous decrease in depth and width.

### Straits

Straits refer to waterways that are comparatively narrow in width between adjacent sea areas in a sea or ocean. The main marine condition in straits is fast water flow, especially a very fast tidal flow rate, with mostly rock or sand and gravel as the substrate and very little fine sediments, a property that is related to the greater flow rate. Some ocean currents flow in or flow out of the upper or lower layer, such as the Strait of Gibraltar; some currents flow in or flow out from one side or the other, such as the Bohai Strait. Because there are

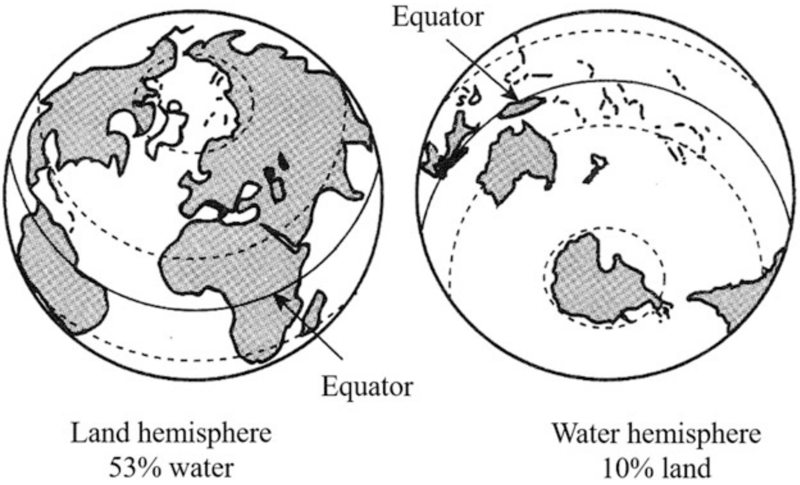


**Fig. 2.1** Land hemisphere and water hemisphere (Chen 2014, 2016)

two types of water masses from different sea areas in a strait, the marine environmental conditions are quite different.

### 2.1.2 Seabed Morphology

Oceans are a continuous whole, but in different areas of oceans, environmental factors still differ greatly. Different species of organisms inhabit different habitats, and no organism can live in all of the environments of oceans.

Oceans can be divided into the water layer and the seabed. The former refers to the entire body of water of an ocean, and the latter refers to the entire seabed, and they can each be divided into different environmental zones. There are two major categories for marine organisms: species that float or swim in the water layer and species that inhabit the bottom of the ocean (on the bottom or in the bottom).

Seabed topography is an important factor in the formation of fishing grounds, for example, flat continental shelf fishing grounds, raised seabeds, and so on. Seabed topography is generally divided into the continental shelf, continental slope, ocean floor (deep-ocean basin), ocean trench, etc. In addition, there are also shoals, banks, reef piles, and so on, which all have a relationship with the formation of fishing grounds. Protruding topography, such as sea rises or rises, ocean ridges or submarine ridges, submarine plateaus, banks, crests, reefs, shoals, and so on, are all related to the formation of fishing grounds and the schooling of fish. Seabed morphology can be roughly divided as follows: coast, continental margins (including the continental shelf, continental slope, and continental rise), and deep-ocean basin (including abyssal plains, various submarine highlands, marshlands, and so on).

#### Coast

The coast is the boundary between the sea and the land and refers to those regions where interactions of sea and land processes occur, namely, regions that are submerged when the water level rises (due to the increase in water caused by the tides, wind, and other factors) and exposed when the water level lowers.

Because the coast is an area where the land and the sea or ocean interacts, changes in the contour of the coast, changes in the topography of the seabed, and the displacement of marine sediments occur rapidly. The coastline refers to the dividing line between land and sea, and it is not fixed to a certain extent. Due to the rise and fall of tidal levels and the effect of the increase or decrease in water caused by wind, coastlines can shift; the range of the sea surface in the vertical direction can reach 10–15 m, but advancement and retreat in the horizontal direction can sometimes reach tens of kilometers. In coastal zones, areas affected by the rise and fall of tides are referred to as intertidal zones. Intertidal zones have a certain importance in fisheries production and scientific research.

### Continental Margins

Continental margins specifically include the continental shelf, continental slope, and continental rise (Fig. 2.2).

#### Continental Shelf (Referred to as the Shelf)

The continental shelf is also named as the shelf. According to the *Convention on the Continental Shelf* passed at the International Conference on the Law of the Sea in 1958 (United nations 2005), the continental shelf is defined as “the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or, beyond that limit, to where the depth of the super adjacent waters admits the exploitation of the natural resources of the said areas,” as well as “the seabed and subsoil of similar submarine areas adjacent to the coasts of islands.” Based on the viewpoint of natural science, the continental shelf is the shallow water zone submerged by sea water around a continent and a natural extension of the continent toward the bottom of the sea or ocean. Its scope starts from the low tide line, with an extremely gentle slope, and extends to the location where the slope increases suddenly. Although this zone is submerged in sea water, it is still a part of the continent. The depth of the continental shelf generally does not exceed 200 meters, and the depth of some individual areas is greater than 800 meters or less than 130 m. The average depth is approximately 130 m.

The shelf has a gentle slope, with an average slope of 7′; most shelves are a continuation of the submerged coastal plains. Near rocky coasts, the slope of the shelf is greater, but it still does not exceed 1°–2° in ordinary circumstances.

The width and depth of the shelf vary greatly and are closely related to the land topography. Adjacent to coasts with high mountains and steep hills, the shelf is narrow; conversely, the shelf is very wide adjacent to coasts formed by glaciers, broad plain, or estuaries of large rivers. In terms of the world, the average width of the shelf is approximately 70 km, but the range can vary from 0 to 700 km. The shelf along the coast of northern Europe and Siberia is very wide, reaching 600–800 km, and the shelf along the coast of China is very wide, with the shelf accounting for approximately 7.6% of the entire seabed area.

Many marine phenomena in the shelf area undergo significant seasonal changes, and the actions of tides, waves, and ocean currents are more intense; therefore, vertical mixing between the water layers is very active, and the bottom layer of sea water is constantly renewed, thereby generating a large amount of dissolved oxygen and various nutrient salts in sea water. As a result, the shelf, particularly estuarine zones, is an important place for fisheries and cultivation enterprises.

The shelf floor is mainly composed of terrigenous detrital sediments, including large rocks, gravel, pebbles, sand, fine mud, and so on, brought by rivers and streams of the continent and formed by the action of wave erosion. The distribution of these sediments on the seabed is regular; the farther away from the coast, pebbles and sand are gradually replaced by fine sand and mud.

#### Continental Slope

The continental slope refers to the steeper area at the outer margin of the shelf; it actually refers to the area within the margin of continental tectonics and is located above the transition zone from thick continental crust to thin oceanic crust. The slope ranges from 4° to 7°, sometimes reaching 13°–14°, such as in the Bay of Biscay. However, the dip angle near the coast of volcanic islands can be particularly large; the maximum can reach 40°, and sometimes it is almost vertical.

The slope of the continental slope varies with the properties of the coast. The average slope of the continental slope along the coast of mountainous areas is 3°33′, but the average slope of the continental slope outside the coastal plain is only 2°. The depth to which the continental slope can

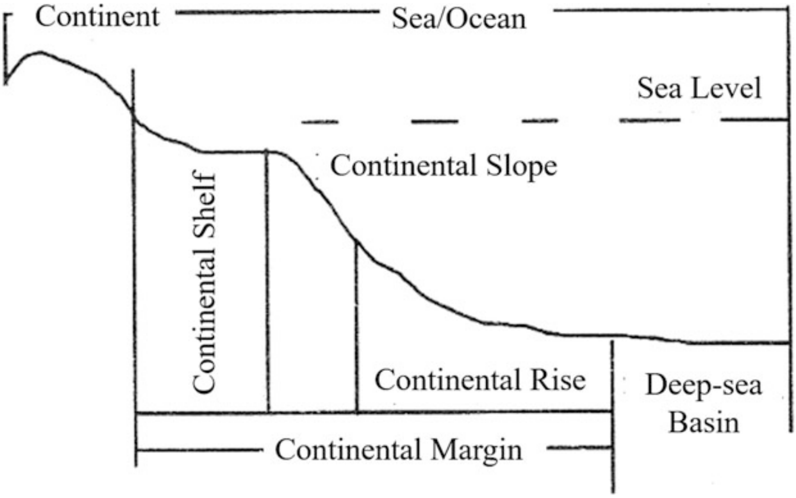


**Fig. 2.2** Schematic diagram of seabed morphology (Chen 2014, 2016)

extend is inconsistent, and most researchers think it should include a depth of 200–2500 m.

The sea areas located on the continental slope are less affected by the continent due to being farther from the continent; therefore, the marine conditions of the continental slope are more stable than those of the sea areas associated with the continental shelf. Daily changes in marine elements cannot affect the bottom water layer, and even annual changes are very weak. The movement of the bottom sea water layer is derived mainly from the action of ocean currents and tides, and the effects of wind and waves have already dissipated. The deposition of the seabed also differs from that at the continental shelf; it is mainly terrigenous detrital ooze. Solar energy is absorbed and scattered by the upper sea water layer, and the energy that reaches the bottom is extremely weak or has completely dissipated; therefore, there are basically no plants in deep oceans and ocean bottoms, and plant-feeding animals become less abundant than mud-feeding animals. The skeletons of these animals form biogenic ooze that mixes with the terrigenous detrital ooze. Landslides often occur in seabeds with the greatest inclination, making loose sediment slide deeper along the surface of the slope; therefore, the seabed in these areas is often a rocky reef.

The most special topography on the continental slope is submarine canyons; they have cliffs, have a V shape, and can be tens of kilometers to hundreds of kilometers long. It is believed that most submarine canyons are generated by changes in the stratigraphic configuration. The continental slope is an active zone of the earth's crust, and crustal fractures acting on the continental slope give rise to some very large fissures. Submarine canyons are formed under the actions of powerful submarine turbidity, currents, and ice. There are submarine canyons along the coast of the Sea of Japan and along the west coast of North America, India, Africa, South America, and other areas.

### Continental Rise

If the continental slope becomes flat before reaching the deep seabed, then the lower part is referred to as the continental rise or the continental apron. It is a sedimentary apron that slowly inclines from the base of the continental slope toward the depths of the sea or ocean. The water depth at these rises ranges from 2500 to 4000 meters, and the rises can traverse the ocean floor and extend as much as 1000 kilometers. Continental rises total approximately 1900 km$^2$, accounting for approximately 5% of the entire ocean floor. Continental rises are particularly broad in the vicinity of large deltas, such as the deltas of the Indus River, Ganges River, Amazon River, Zambia River, Congo River, and Mississippi River.

### Deep-Ocean Basin (Ocean Floor)

The deep-ocean basin is the main part of an ocean. The topography is broad and flat and accounts for 72% or more of the marine area. The degree of inclination is small, at approximately 0°20′–0°40′. The depth can continuously extend to approximately 6000 m from the continental rise. Based on the topographical properties, the ocean floor is a flat plain that adapts to the curvature of the earth and is slightly arched. There are many horizontal and vertical ocean ridges that are interlaced and stretched, dividing the seabed into a series of sea basins. In the ocean, there are also individual highlands formed by coral islands and volcanic islands that rise from the seabed to a height of 5000–9000 m and sunken zones deeper than 6000 m. The following types of topography are commonly seen in deep-ocean basins:

1. Ocean trenches – long and narrow deep depressions in the deep-sea seabed, with two comparatively steep walls.
2. Ocean troughs – long and wide submarine depressions in the deep-sea seabed, with gentle slopes on both sides.
3. Oceanic basins – depressions with a very large area and more or less basin-like shape.
4. Submarine ridges – narrow and long highlands on the deep-sea bottom, with steeper margins and irregular topography compared with that of a continental rise.
5. Ridged lands (oceanic rises) – long and wide highlands on the deep-sea bottom, with a gradual protrusion.
6. Seamounts and table mountains – isolated or relatively isolated highlands at the deep-sea bottom (nearly 1000 m or greater) are called seamounts; seamounts at a depth of greater than 1200 m with roughly flat plateaus at their top are referred to as table mountains. When seamounts and table mountains are arranged in a line or are densely grouped within a range, they are referred to as a seamount chain.
7. Abyssal plains – wide and unobvious highlands on the deep-sea bottom with tops that can vary widely due to smaller fluctuations.

Due to the lack of light and very low temperatures, there are sparse submarine fauna in the deep ocean, and therefore, significant deposition cannot be formed. All sediments in deep-ocean basins are formed from the deposition of the calcareous and siliceous skeletons of plankton propagating in the upper ocean layers. The biogenic ooze in this oceanic area is mainly globigerina ooze, diatomaceous ooze, and radiolarian ooze from rhizopods.

### Ocean Trenches

Ocean trenches refer to the long and narrow sunken zones deeper than 6000 meters in the ocean. Ocean trenches and ocean ridges are often linked together, and they usually present an arced shape. Ocean ridges are sometimes exposed, forming islands or archipelagoes. Deep-ocean trenches are generally located on the convex surface of arc-shaped ocean ridges. There are a total of five deep-ocean trenches with a depth of more than 10,000 m, all of which are in the Pacific Ocean; the deepest ocean trench is the Mariana Trench (11,500 m). Pacific Ocean trenches are mostly concentrated in the western Pacific Ocean and along the coast of Asia, extending as a single arc at the intersection between the Pacific Ocean and the Indian Ocean until reaching Australia.

## 2.1.3 Marine Sediments

Because the relationship between seabed substrate and the distribution of benthic organisms is particularly close, it is important for us to understand the ecology and reasonable exploit of fish, especially fish that feed on benthic organisms. The bottom of the oceans is covered by different substances of various sources and properties, composing marine sediment through physical, chemical, and biological sedimentation.

Based on origin, marine sediments can be divided into two major categories: terrigenous sediments and pelagic sediments. The sediments of the continental margins are terrigenous debris carried into the sea from the mainland or neighboring islands through the action of rivers, wind, glaciers, and so on, including shore and shelf sedimentation and land slope and slope apron sedimentation. Shore and shelf sedimentation refers to the sediments distributed in the intertidal zone and on the continental shelf; their granulometric composition varies greatly but is mainly sand and mud. Land slope and slope apron sedimentations are distributed in the sediments of the flat zone beyond the continental slope and its steep slope; except for being mainly local substances from organisms or volcanoes, the vast majority of the sediments are composed of terrigenous debris, including various types of sand, silt, mud, and so on.

Pelagic sedimentation (also referred to as deep-sea sedimentation) mainly includes red clay ooze, calcareous ooze, and siliceous ooze. Among them, red clay ooze is a sediment formed by submarine weathering of red (brown) clay minerals and some volcanic substances brought from the mainland. Calcareous ooze is mainly composed of foraminifera *Globigerina* and the shells of planktonic Mollusca (pteropoda and heteropoda) and is widely distributed in the Pacific Ocean, Atlantic Ocean, and Indian Ocean, covering approximately 47% of the world's ocean floor area. Siliceous ooze is mainly siliceous sedimentation composed of the cell walls of diatoms and radiolarian bone needles.

The seabed substrate of the continental shelf is mainly sourced to land. In the absence of strong currents, the general rule is that from the shore to the open sea, the grains that appear in the substrate have belt-like distribution from coarse to fine, with coarser sands near the shore; moving away from the shore, the sediments are fine sand, silt, silty mud, sludge, and so on. However, in sea areas with very strong ocean currents, coarse grains will be carried very far, thereby breaking the aforementioned distribution rule.

## 2.2 Distribution of the Ocean Currents

### 2.2.1 Concept of Ocean Circulation and Its Genesis

Ocean current refers to the relatively stable flow of sea water on a large scale, and it is one of the important general movement forms for sea water. "Large scale" refers to a large spatial scale, i.e., several hundreds to thousands of kilometers, even a global scope; the meaning of "relatively stable" is that within a longer period, such as 1 month, one season, 1 year, or multiple years, the flow direction, speed, and path are roughly similar.

Ocean currents are generally three-dimensional; that is, there is not only flow in the horizontal direction but also flow in the vertical direction. Because the horizontal scale of the oceans is far greater than the vertical scale, flow in the horizontal direction is far stronger than flow in the vertical direction. Although the latter is relatively weak, it has its special importance in oceanography. Customarily, the horizontal movement of ocean currents is usually referred to as ocean currents, in a narrow sense, and movement in the vertical direction is referred to as upwelling and downwelling.

Ocean circulation generally refers to the relatively independent circulation systems connected end to end formed by ocean currents in a sea area. For all oceans on earth, the temporal and spatial changes in ocean circulation are continuous. Ocean circulation connects the oceans and enables the various hydrological and chemical elements and physical conditions of the oceans to remain relative stable long term.

Although there are many causes of ocean current formation, there are mainly two types. The first is wind power on the sea surface, generating wind-induced ocean currents. The second is changes in sea temperature and salinity. In addition, the densification effect on the sea surface can also directly cause sea water movement in the vertical direction. After ocean currents form, because of the continuity of sea water, upwelling and downwelling will form in places where the sea water generates divergence or convergence.

### 2.2.2 Generation of Upwelling and Downwelling

Upwelling refers to the upward surge of sea water from a deep layer, and downwelling refers to the vertical movement of sea water resulting from sinking from the upper layer. The ocean is bounded, and the wind field is not uniform and stable. Therefore, the volumetric transport of wind and ocean currents inevitably leads to the occurrence of sea water divergence or convergence in certain sea areas or shores. Because of continuity, the sea water can rise or sink in these areas, thus changing the structure of the density field and pressure field of the ocean and thereby deriving other flows.

The volumetric transport of infinite deep-sea wind and ocean currents indicates that wind energy parallel to the shore leads to the greatest sea water convergence or divergence by the shore, thereby causing the sinking of surface sea water or a surge of sea water from a lower layer. However, wind that is perpendicular to the shore does not generate the same effect. For shallow seas, for wind that blows at a certain angle to the shoreline, components that are parallel to the shoreline can also cause similar movement. For example, along the coast of Peru and California in the United States, there are strong southeast trade winds and northeast trade winds, respectively, that blow along the coast in the direction of the equator. Because the drifting volumetric transport moves sea water away from the shore, sea water from the lower layer surges to the upper layer, forming world-famous upwelling areas. Another example is along the northwest coast of Africa and along the coast of Somalia (during the southwest monsoon period); for the same reason, there is also upwelling. Upwelling generally originates from a depth of 200 to 300 meters below the sea surface, and the ascending speed is very slow. Although the upwelling speed is very slow, because the upwelling is perennial, it continuously brings nutrient salts to the surface layer, which is conducive to biological reproduction. Therefore, upwelling areas are often well-known fishing grounds; for example, one of the world-famous fishing grounds is near the shore of Peru.

In sea areas in the vicinity of the equator, because the trade winds cross the equator, the volumetric transport of sea water on either side of the equator is opposite in direction and away from the equator, thereby causing divergence in the surface sea water at the equator and forming upwelling. In the ocean, upwelling and downwelling can also be generated by an uneven wind field. The divergence and convergence of surface sea water have a certain relationship with the horizontal vorticity of wind stress; their relation can be expressed as:

$$Divergence\ (sea\ water\ divergence) = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}$$

When divergence takes a positive value, the sea water is divergent, which generates upwelling; when the divergence takes a negative value, the sea water is convergent, which generates downwelling.

Cyclones and anticyclones above the ocean can also cause sea water to rise or sink. For example, the “cold wake” observed on the surface layer of the sea over which a typhoon (tropical cyclone) has passed is the cooling caused by the rising of low-temperature water from a lower layer to the sea surface.

In an uneven wind field, due to the uneven drifting volumetric transport, divergence and convergence can be generated (Fig. 2.3). In a cyclonic wind field, upwelling will similarly be generated due to divergence (Fig. 2.3). In the northern hemisphere, surface divergence and convergence in an uneven wind field and upwelling in a cyclonic wind field are the upwelling and the downwelling generated by wind power acting on a coastal area (Fig. 2.4).

### 2.2.3 Distribution of the Ocean Circulation

The general characteristics of upper ocean circulation on earth can be additionally explained by using the theory of wind-driven circulation (Fig. 2.5). There are similarities in the circulation patterns of the Pacific Ocean and the Atlantic Ocean. A very large anticyclonic circulation corresponding to a subtropical high is present in both the northern and southern hemispheres (clockwise in the northern hemisphere and counterclockwise in the southern hemisphere), and the Equatorial Counter current is between the hemispheres. The western-boundary currents of both oceans in the northern hemisphere (referred

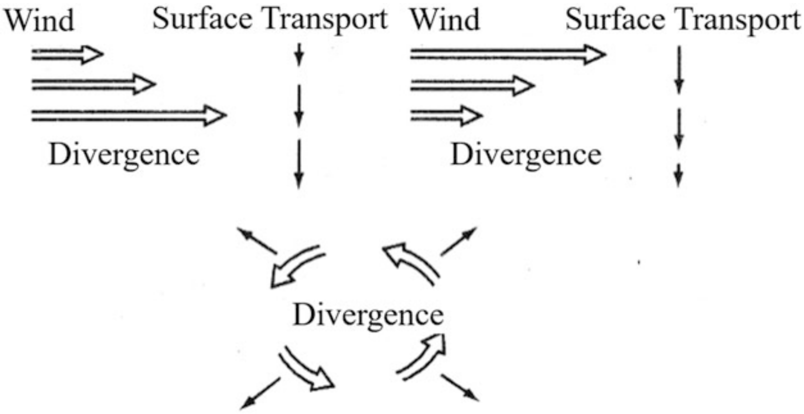


**Fig. 2.3** Diagram of divergence and convergence generated in an uneven wind field and a cyclonic wind field (Chen 2014, 2016)

to as the Gulf Stream in the Atlantic Ocean and referred to as the Kuroshio Current in the Pacific Ocean) are very powerful, but the western-boundary currents in the southern hemisphere (the Brazil Current and the East Australian Current) are comparatively weak. There are cold currents from the north along the west side of the ocean basin in both the North Pacific Ocean and the North Atlantic Ocean, and there is a small cyclonic circulation in the northern part of the main vortex.

The differences in the various ocean circulation patterns are caused by their different geometric shapes. The circulation pattern in the southern part of the Indian Ocean is similar, in general characteristics, to the circulation patterns of the South Pacific Ocean and the South Atlantic Ocean, but the northern pattern is a monsoon-type circulation, with circulation in opposite directions for two halves (summer and winter). In the high-latitude sea areas of the southern hemisphere, there is a powerful circumpolar current from west to east corresponding to westerlies. In addition, there is a circumpolar wind-induced current from east to west along the coast near the Antarctic continent.

## Equatorial Currents

Corresponding to the trade-wind zones in the two hemispheres are the westward North Equatorial Current and South Equatorial Current, also referred to as the trade-wind currents (Fig. 2.6). These are two comparatively stable wind-induced drift currents caused by the trade winds, and both are a component of the very large cyclonic circulation in the northern and southern hemispheres. Between the northern and southern trade winds and corresponding to the equatorial calm belt is the Equatorial Countercurrent that moves eastward, with a flow range of approximately 300 to

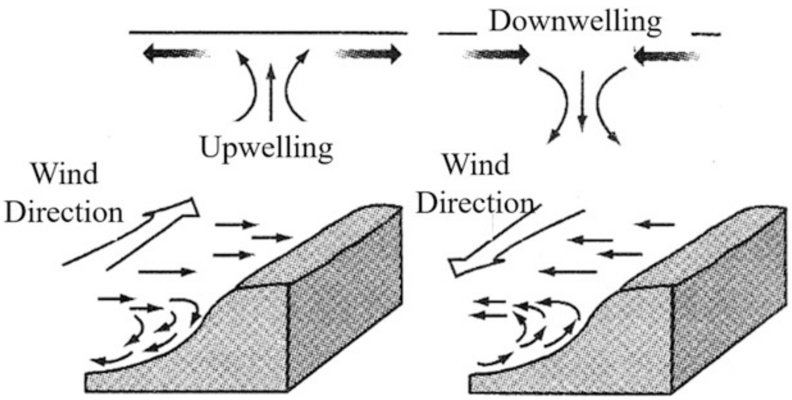
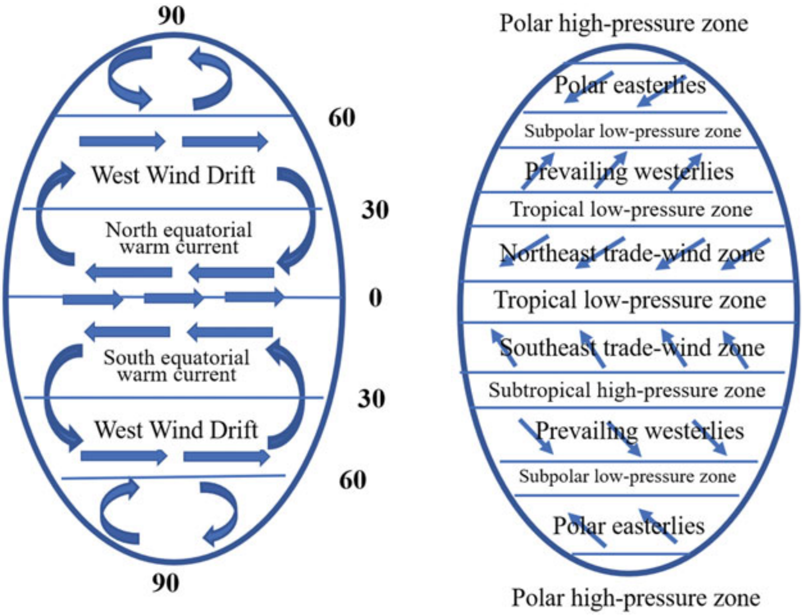


**Fig. 2.4** Schematic diagram of the generation of wind and ocean currents in the northern hemisphere (Chen 2014, 2016)

**Fig. 2.5** Schematic diagram of atmospheric circulation and ocean currents (Chen 2014, 2016)



500 kilometers. Because the average position of the equatorial calm belt is between 3 and 10°N, the North Equatorial Current and South Equatorial Current are asymmetric with the equator. In the summer (August), the North Equatorial Current is approximately between 10°N and 20 to 25°N, and the South Equatorial Current is approximately between 3°N and 20°S. They are slightly southerly in the winter.

The equatorial current gradually strengthens from east to west. The equatorial current system is mainly limited to the upper layer 100 to 300 meters below the surface, with an average flow rate of 0.25–0.75 m/s. There is a powerful thermocline in the lower part. Above the thermocline is fully mixed surface water that is warm and has a high salinity content and dissolved oxygen content but a very low nutrient salt content, which is not preferable for plankton reproduction, thus resulting in high transparency and high water color. In short, the equatorial currents are current systems that feature high temperature, high salinity, high water color, and great transparency.

The equatorial current system in the Indian Ocean is mainly controlled by monsoons. The wind direction at the equatorial region is dominated by the meridian direction and changes in the seasons. The northeast monsoon prevails from November to March of the following year, and the southwest monsoon prevails from May to September. There is a South Equatorial Current all year round south of 5°S, and the Equatorial Countercurrent exists south of the equator all year round. The North Equatorial Current flows westward from November to March of the following year, when the northeast monsoon prevails, and it flows eastward under the influence of the southwest monsoon at other times, becoming confluent with the Equatorial Countercurrent and difficult to distinguish.

There is abundant precipitation in the Equatorial Countercurrent region; therefore, the equatorial current region features high temperatures and low salinity. There is a divergent rising movement of sea water between the Equatorial Countercurrent and the equatorial current that transports sea water with low temperature but high-nutrient salts upward, making the water fertile, which is conducive to the growth of plankton; therefore, water color and transparency are relatively reduced.

There is an Equatorial Undercurrent flowing from west to east, opposite in direction to the equatorial currents in the South Equatorial

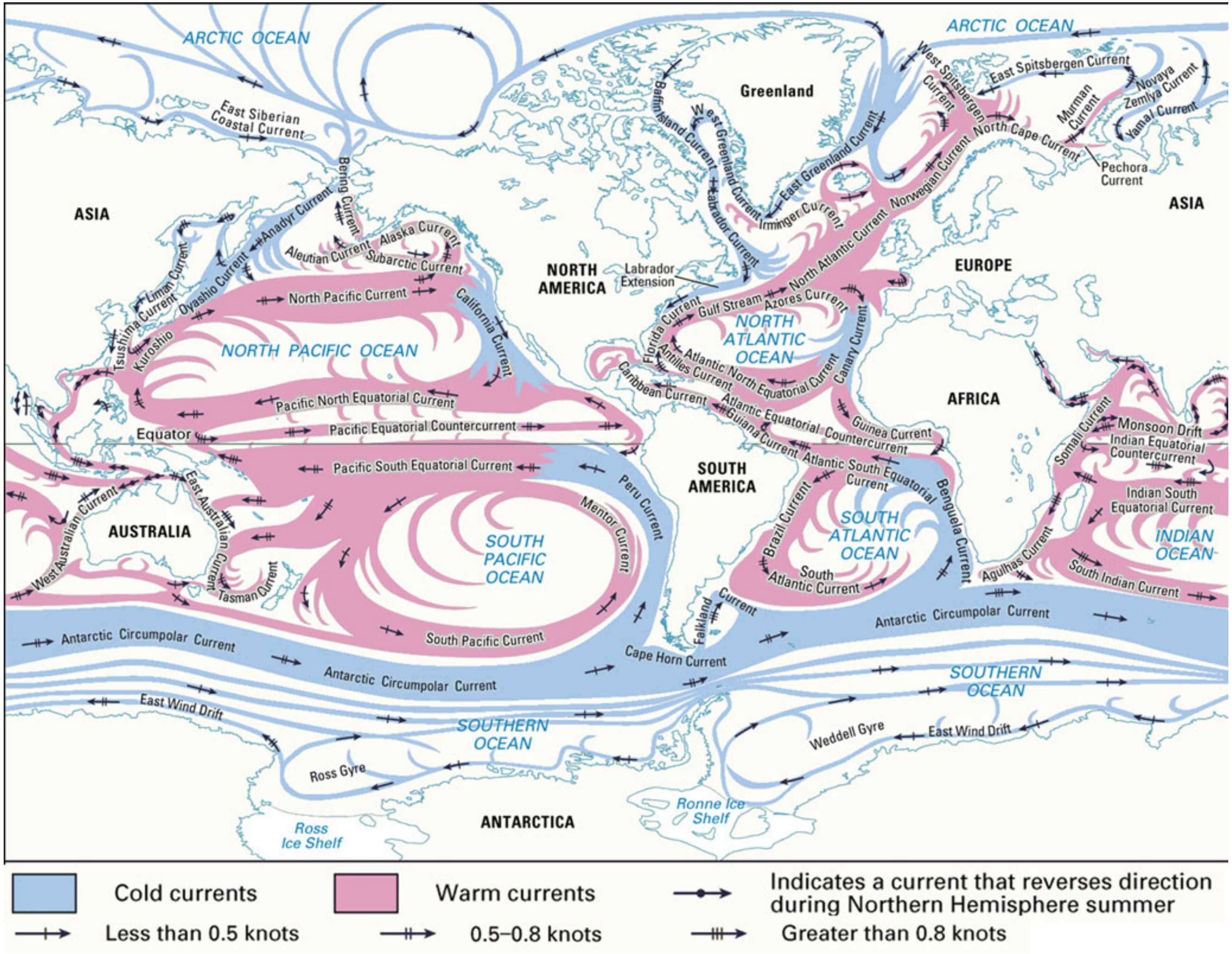


**Fig. 2.6** Schematic diagram of surface current in three oceans during the winter of north hemisphere (Cenedese and Gordon 2021)

Current region of the Pacific Ocean. It generally forms a banded distribution with a thickness of approximately 200 m, a width of approximately 300 km, and a maximum flow rate as high as 1.5 m/s. The current axis is often consistent with the thermocline, which is located at a depth of 50 meters or shallower in the eastern part of the ocean and at a depth of 200 m or greater in the western part of the ocean. The generation of the Equatorial Undercurrent is not directly caused by wind, and there are many viewpoints in regard to its formation and maintenance mechanism. This type of undercurrent has been discovered successively in the Atlantic Ocean and the Indian Ocean.

### Western-Boundary Currents

The western-boundary currents refer to the ocean currents from low latitudes to high latitudes along the continental slope on the west side of the ocean; these currents include the Kuroshio Current and the East Australian Current in the Pacific Ocean (Fig. 2.6), the Gulf Stream and the Brazil Current in the Atlantic Ocean, and the Mozambique Current in the Indian Ocean, among others. They are a major part of the anticyclonic circulation in the northern and southern hemispheres and are also continuations of the North and South Equatorial Currents. Therefore, compared with nearshore sea water, the western-boundary currents have high temperatures, high salinity, high water color, and great transparency.

### West Wind Drift

Corresponding to the prevailing westerlies in the northern and southern hemispheres is the powerful West Wind Drift that moves from west to east, that is, the North Pacific Current and the North Atlantic Current in the northern hemisphere and the Antarctic circulation in the southern hemisphere, which are the components of a large anticyclonic circulation in the northern and southern hemispheres, respectively (Fig. 2.6). Their boundaries are as follows: the polar side is bounded by the Polar Ice Fields, and the equatorial side stops at the subtropical convergence zone. Their common feature is that there is an obvious temperature gradient in the meridian direction in the West Wind Drift zone, and this area with an observable gradient is referred to as the Ocean Polar Front. The hydrological and climate conditions on both sides of the polar front have obvious differences.

The convergence of polar fronts in the northern hemisphere is not obvious, and only a stronger convergent sinking phenomenon is present in the confluence area between the Kuroshio Current and the Oyashio Current in the northwestern part of the Pacific Ocean and in the confluence area between the Gulf Stream and the Labrador Current in the northwestern part of the Atlantic Ocean, which is generally referred to as the Northwest Convergence Zone. Due to the strong mixing generated by the confluence of cold and warm currents, the marine productivity is high, thereby making the Northwest Convergence Zone a good fishing ground. This is the sea area where the world-famous Hokkaido fishing grounds and Newfoundland fishing grounds are located.

### Eastern-Boundary Currents

The eastern-boundary currents are the California Current and the Peru Current in the Pacific Ocean, the Canary Current and the Benguela Current in the Atlantic Ocean, and the West Australian Current in the Indian Ocean. Because they flow from high latitudes to low latitudes, they are all cold currents (Fig. 2.6). Additionally, they are all located on the eastern boundary of the ocean; therefore, they are referred to as the eastern-boundary currents. Compared with western-boundary currents, their flow range is broad, the flow rate is small, and the depth of influence is shallow.

Upwelling is an important marine hydrological feature in sea areas with eastern-boundary currents. This is due to the trade winds that blow along the coast almost all year round; the wind speed is unevenly distributed, that is, it is slower near the shore and faster on the sea surface, which then results in the movement of sea water away from the shore. The upwelling formed in the aforementioned sea areas often produces good fishing grounds.

### Polar Circulation (Fig. 2.6)

In the Arctic Ocean, circulation is generated mainly by the Norway Current, which enters from the Atlantic Ocean, and some currents along the coast. There is a very large anticyclonic circulation in the Canada Basin, which reaches the Greenland Sea by passing through the North Pole from the Chukchi Sea at the junction between Asia and America. Part of the circulation turns and flows westward, and part of it merges into the East Greenland Current; together they carry large ice floes into the Atlantic Ocean. Other small cyclonic circulations are also present.

The Antarctic circulation has a very narrow scope at the Antarctic continental margins. Due to the action of the polar easterlies, a small circulation forms around the Antarctic continental margins from east to west, referred to as the East Wind Drift. Between the East Wind Drift and the Antarctic circulation, the Antarctic Divergence Zone is formed due to the dynamic action. Convergence and the sinking of sea water along the continental shelf form between the Antarctic Divergence Zone and the Antarctic continent, that is, the Antarctic continental convergence. These dynamics cause the surface sea water to sink in the Antarctic shelf area.

There are common characteristics of the polar sea areas. They are covered by ice almost all year round or all year round, and the freezing and thawing process leads to comparatively low sea temperature and salinity the whole year, forming low-temperature and low-salinity surface water.

## 2.2.4 Main Ocean Currents in Various Oceans

### Pacific Ocean

In the North Pacific Ocean, the main circulation systems are the North Equatorial Current, the Kuroshio Current, the North Pacific Current, and the California Current, and the ocean currents in the adjacent seas are the Alaska Current, the Oyashio Current, the East Karafuto Current, the Liman Current, the China Coastal Current, the Tsushima Current, and the South China Sea Monsoon Current. In the South Pacific, the main circulation systems are the South Equatorial Current, the East Australian Current, the West Wind Drift, and the Humboldt Current (Peru Current) (Fig. 2.6). The ocean currents in the equatorial Pacific are the Equatorial Countercurrent and the Equatorial Undercurrent (Cromwell Current). The following provides an analysis of the main ocean currents with greater influence on fisheries science.

### Kuroshio Current

The North Pacific circulation starts from the North Equatorial Current and flows westward to the western land boundary, where it is divided into two; one part goes south and the other part goes north. The northward branch forms a powerful western-boundary current in the Pacific Ocean, that is, the Kuroshio Current. The southward branch is referred to as the Mindanao Current. The main current in the Kuroshio Current flows eastward along 36°–37°N, passing the southern coast of Honshu, Japan. After leaving Japan, it continues to flow to the east to approximately 170°E; this section is referred to as the Kuroshio Extension, becoming the North Pacific Current after the Extension. As the Kuroshio Current flows in the vicinity of the Ryukyu Islands, there is a branch that ascends northward along the margins of the continental shelf, becoming the Tsushima Warm Current, which flows into the Sea of Japan through the Korea Strait.

In the offshore waters of Sanriku, Japan, the Kuroshio Current meets the Oyashio Current from the north, forming a boundary fishing ground at the intersection of the warm and cold currents that teems with Pacific saury, cetaceans, tuna, etc.

### Oyashio Current

The Oyashio Current mainly comes from the Bering Sea and partly comes from the Okhotsk Sea. When the North Pacific Current approaches the North American continent, it divides into north and south branches; the southern branch is the California Current, which ultimately connects with the North Equatorial Current; the northern branch forms the Alaska circulation in the Gulf of Alaska, with a portion flowing between the Aleutian Islands and entering the Bering Sea. The Oyashio Current has high biological productivity and is rich in phytoplankton, and the water color and transparency are both lower than those of the Kuroshio Current.

### California Current

The California Current descends southward along the west coast of North America and becomes the eastern-boundary current of the ocean. Its surface flow rate is generally comparatively slow, at approximately 1 km/h. In the summer, under the powerful action of the northerlies, the surface water of the California Current, which descends southward along the coast, flows toward the open sea, and the deep-layer water acts as the compensating current and rises along the coast, becoming the famous California upwelling. Part of the California Current descends southward along the coast of Central America, reaching the low-latitude sea areas of the East Pacific Ocean. In addition, the eastern end of the Equatorial Countercurrent that flows eastward along and in the vicinity of the equator flows and turns north and west in the offshore waters of Mexico and becomes the North Equatorial Current, which flows westward with 10°N as the center. The North Equatorial Current merges with the California Current where it turns to a westward flow and continues to flow westward, becoming part of the large-scale horizontal cycle of the North Pacific Ocean. In the vicinity of this confluence, a purse seine fishing ground for tuna has formed.

### Equatorial Currents and Their Undercurrent

There are at least four main ocean currents included in the equatorial current system of the Pacific Ocean, three of which extend to the sea surface, with the other below the sea surface. The three main upper-layer ocean currents are all observable on the surface: the first is the westward North Equatorial Current, which is approximately in the range of 2°–8°N; the second is the westward South Equatorial Current, which is approximately in the range of 3°N–10°S; and the third is the narrower and eastward-flowing North Equatorial Countercurrent between the aforementioned two ocean currents. In addition, the Equatorial Undercurrent that flows to the east below the sea surface crosses over the equator and occupies a range from 2°N to 2°S; this ocean current can be traced from Panama Bay in the east to the Philippines in the west, with a distance of approximately 15,000 km. In the summer, the Equatorial Countercurrent changes its direction of flow toward the offshore waters of Costa Rica, forming a vortex that rotates counterclockwise, thereby inducing strong upwelling. This upwelling is the Costa Rica Dome, which is an important marine condition for the formation of tuna fishing grounds.

In equatorial sea areas, the surface water of the westward-flowing North and South Equatorial Currents flows northward in the northern hemisphere, and that in the southern hemisphere flows southward. Therefore, an upwelling with a stronger divergent phenomenon is generated in the sea areas of the equator, causing the ascent of deep-layer water rich in nutrient salts, promoting an increase in biological productivity, and forming a cline of sea temperature and dissolved oxygen. The thermocline of the North Equatorial Current watershed gradually becomes shallower from west to east. The depth of the thermocline affects the water layer in which tuna is distributed, having important significance for fisheries.

### Peru Current

The Peru Current is equivalent to the cold current portion of the circulation that rotates counterclockwise in the Southeast Pacific Ocean, which originates from the subarctic sea area. The high-latitude West Wind Drift reaches the west coast of South American in the vicinity of 40°S, and the ocean current that flows northward is the Peru Current. The Peru Current near the coast is referred to as the Peru Coastal Current, and the branch in the open sea is referred to as the Peru Ocean Current. These two ocean currents are separated by the irregular Peru Countercurrent, which descends southward, and this Countercurrent is referred to as the Pacific equatorial waters, which is usually a subsurface current 180–500 km away from shore. From November to March, when the Peru Countercurrent is strongest, the current is closer to the surface. The flow potential is weak before November, and the current remains below the sea surface. During this time, the Peru Current becomes a single ocean current, without dividing into the two coastal and ocean branches, and it is the time when the Peru Current is strongest. The southern end of the ocean currents along the coast of Peru is the southern limit of the upwelling area formed along the coast of Chile, and its position is in the vicinity of approximately 36°S.

### Atlantic Ocean

In the Atlantic Ocean, the main ocean currents are the Gulf Stream, the North Atlantic Current, the Labrador Current, the Canary Current, the Benguela Current, the Brazil Current, and the Falkland Current, among others (Fig. 2.6). These ocean currents are closely related to fishing grounds.

### Gulf Stream

In the Northwest Atlantic, the oceanographic features that are extremely important to fisheries are the result of the warm current system of the Gulf Stream and the cold current system of the Labrador Current. The Gulf Stream flows in a northeasterly direction along the North American continent and results from the confluence of the Florida Current and the Antilles Current, which originates from the North Equatorial Current. It is similar to the Kuroshio Current in the Pacific Ocean, becoming the western-boundary current of the Atlantic Ocean; its flow rate is 7–9 km/h in the offshore waters of the east coast of North America, where the flow is strongest, and it reaches a thickness of 1500–2000 m.

The movement of the Gulf Stream presents is serpentine, with such movement gradually developing eastward from Cape Hatteras, thereby forming a complex flow boundary accompanied by a vortex system. Some people refer to the movement of the Gulf Stream as multiple ocean currents. In the sea area in the vicinity of Nova Scotia in Canada, due to the influence of the surrounding topography, a very complex local vortex area forms, especially in the summer, and this oceanographic condition is deemed one of the major factors for the formation of many fishing grounds.

The flow range of the Gulf Stream expands when it reaches south of Grand Bank in southern Newfoundland, where it becomes the North Atlantic Current, which flows in a northeasterly direction. One branch of this current continues to flow in the northeasterly direction, becoming the Norway Current, which reaches the sea area off the west coast of Norway. This current is the main cause for the distribution of tuna fishing grounds in the vicinity of 70°N. The branch that flows northward moves south of Iceland and flows westward, becoming the Irminger Current, and most of the current forms a confluence with the East Greenland Current, which descends southward along the east coast of Greenland.

### East Greenland Current

The East Greenland Current originates from the Arctic Ocean, and a current boundary is formed between the East Greenland Current and the Irminger Current. Part of the East Greenland Current combines with the Irminger Current and becomes the West Greenland Current. This current then merges with the southward-descending current from Baffin Bay and becomes the Labrador Current, which descends southward along the east coast of North America, forming a polar front at the intersection between the inshore waters of Newfoundland and the Gulf Stream, making this sea area rich in fishery resources; this area is traditionally one of the three major fishing grounds in the world.

### North Atlantic Current

Due to the influence of the North Atlantic Current, a warm climate is present in the United Kingdom to places in northern Europe and along the coast of Norway. After the North Atlantic Current ascends northward along the west coast of Norway through the Faroe Islands, it divides into two branches: one branch ascends northward toward the western part of Spitzbergen, and the other branch flows into the Arctic Ocean along the north coast of Norway, warming the western and southern parts of the Barents Sea.

The North Atlantic Current, which ascends northward along the west coast of the United Kingdom, has a feeder current that descends southward along the east coast of the United Kingdom in the vicinity of the Shetland Islands in the north and another ocean current that flows in from the English Channel on the south coast of the United Kingdom. These are all major factors dominating the oceanographic conditions at the fishing grounds in the North Sea.

### Canary Current

The southward-descending feeder current of the North Atlantic Current descends southward along the northwest coast of Europe and Portugal and the inshore waters of the northwest coast of Africa, forming the Canary Current. Changes in the flow direction and rate of the Canary Current are affected by wind. After the current arrives at the west coast of the African continent, it usually flows westward as a compensating current of the North Equatorial Current. Part of the Canary Current continues to descend southward along the west coast of Africa. Usually, this ocean current develops in the northern hemisphere in the summer and becomes the eastward-flowing Guinea Current. The Guinea Current also exists in the winter.

### Brazil Current

The South Equatorial Current flows westward in the vicinity south of the equator and along the coast of South America and divides into two branches—a northward-ascending current and a southward-descending current. The southward-descending branch is the Brazil Current and has very high salinity. This ocean current merges with the Falkland Current, which ascends northward from the subantarctic waters at approximately 35 to 40°S, forming a subtropical convergence line; a surface temperature of 14.5 °C is an indicator in the summer. The Patagonian Seas are in the convergence zone between the Brazil Current and the Falkland Current; this sea area is rich in marine biological resources, and it is a major fishing ground.

### Indian Ocean

The scope of the Indian Ocean is approximately 25°N to the north and approximately 40°S to the south, comprising sea areas of the subtropical convergence zone. The sea currents in the northern sea area of the Indian Ocean, particularly in the Arabian Seas, are greatly affected by monsoons. The main ocean currents in this sea area are the Southwest Monsoon Current in the summer and the Northeast Monsoon Current in the winter. In the southern sea area of the Indian Ocean, the main ocean currents are the Mozambique Current, the Agulhas Current, the West Australian Current, and the West Wind Drift (Fig. 2.6).

The circulation system in the northern sea area of the Indian Ocean is not quite the same as those in the Pacific Ocean and the Atlantic Ocean. From November to March of the following year, i.e., the northeast monsoon season, the following currents predominate: the westward-flowing North Equatorial Current from 8°N to the equator, the eastward Equatorial Countercurrent from the equator to 8°S, and the westward South Equatorial Current from 8°S to between 15 and 20°S. From May to September, i.e., the southwest monsoon season, the ocean currents north of the equator flow eastward, in reverse; together with the eastward-flowing Equatorial Countercurrent, this current is referred to as the (Southwest) Monsoon Current, which approximately occupies a scope from 15°N to 7°S. The South Equatorial Current flows west, as before, south of 7°S, but it is somewhat stronger than when the northeast monsoon is blowing. During the northeast monsoon season, there is an Equatorial Undercurrent at the depth of the thermocline east of 60°E, but it is weaker than those in the Pacific Ocean and the Atlantic Ocean; the undercurrent cannot be observed when the southwest monsoon is blowing.

In the coastal waters of Africa, from November to March of the following year, i.e., the northeast monsoon season, after the South

Equatorial Current flows near the coast of Africa, a branch turns north and enters the Equatorial Countercurrent, and the other branch heads south and merges with the Agulhas Current. This ocean current is deep and narrow, with a width of approximately 100 kilometers; it flows to the south along the coast of Africa and enters the Antarctic circulation by flowing eastward at the southern tip of Africa. When the southwest wind blows from May to September, part of the South Equatorial Current turns northward, becoming the Somalia Current, which extends to the east coast of Africa and continues ascending northward; most of current is within 200 meters of the surface layer. The South Equatorial Current, the Somalia Current, and the Monsoon Current constitute a considerably strong wind-blowing circulation in the North Indian Ocean.

During the southwest monsoon season from May to September, the Somalia Current is a low-temperature water area; it is similar to the Kuroshio Current and the Gulf Stream, and all are representative western-boundary currents. In the winter, the flow rate of the Northeast Monsoon Current in the offshore waters along the coast of Somalia is less than the flow rate of the Somalia Current. In other sea areas of the Indian Ocean, upwelling occurs when the southeast trade winds are strong; upwelling also occurs in the eastern Arafura Sea during the period in which the southeast trade winds are prevailing. During the upwelling development period, primary production is higher than that of the surrounding sea areas.

## 2.3 Sea Temperature Distribution in the Oceans

### 2.3.1 Basic Concept

Sea temperature is a physical quantity that represents the thermal state of sea water and, in oceanography, is generally expressed in degree Celsius (°C), with a required measurement precision of ±0.02 °C. Solar radiation and the heat exchange between seas or oceans and the atmosphere are the two main factors that affect sea temperature. Ocean currents also have an influence on temperature in the sea. In the open ocean, the distribution of isotherms for surface sea water is roughly parallel to the latitude. In nearshore areas, because of the effects of ocean currents, among other factors, the isotherms move in the north-south direction. The vertical distribution of sea temperature generally decreases with the increase in depth and presents seasonal changes.

Sea temperature is one of the most important factors in marine hydrological conditions and is often used as a basic indicator for studying the properties of water masses and describing the movement of water masses. Studying and mastering the spatial-temporal distribution and changing patterns of sea temperature is an important topic in fisheries science, and it has important significance for fisheries forecasting.

### 2.3.2 Sea Temperature Distribution Pattern

#### Horizontal Distribution Pattern of Sea Surface Temperature

The latitudinal distribution pattern for the average sea surface temperature is a progressive decrease from low latitude to high latitude because the amount of solar radiant heat received by the earth's surface is affected by the shape of the earth; the amount of solar heat received decreases progressively from the equator to the two poles.

The following are characteristics of changes in sea surface temperature: sea surface temperature is affected by season, restricted by latitude, and affected by ocean current properties.

#### Vertical Changes in Sea Temperature

The vertical distribution pattern for sea temperature is a progressive decrease as depth increases. From the sea surface to 1000 m of water layer, the decrease in sea temperature progresses quickly as depth increases; for water layer already below 1000 meters, the decrease in sea temperature slows. The main reason for this effect is that the surface of oceans is greatly affected by solar radiation, while deep water layers in oceans are less affected by solar radiation and heat conduction and convection currents that occur on the surface layer.

The sea temperature of the oceans generally varies between −2 and 30 °C, of which the area where the annual average sea temperature exceeds 20 °C accounts for more than half of the entire marine area. Observations show that the daily variation in sea temperature is very small and that the scope of variation occurs at water depths from 0 to 30 m; however, the annual variation can reach a water depth of approximately 350 m. At a water depth of approximately 350 m, there is a constant-temperature layer. However, as the depth increases, the sea temperature gradually drops (a drop of approximately 1°–2 °C per 1000 m in depth), and at a water depth of 3000–4000 meters, the temperature reaches 1 °C to 2°.

The following factors affect sea temperature.

(1) Latitude – the solar radiation at different latitudes is different, and thus, the temperature is different. The global distribution pattern of sea temperature is a progressive decrease from low-latitude sea areas to high-latitude sea areas.
(2) Ocean currents – in sea areas at the same latitude, the temperature of sea water where warm currents flow is higher, and the temperature of sea water where cold currents flow is lower.
(3) Seasons – sea temperature is high in the summer and low in the winter.
(4) Depth – the progressive decrease in temperature is significant as the depth of the surface sea water increases, with variations being more obvious within 1000 m. There is less variation from 1000 meters to 2000 meters, and low temperature is maintained all year at depths below 2000 m.

The annual average sea temperature at the surface of the three oceans is approximately 17.4 °C; that of the Pacific Ocean is the highest, reaching 19.1 °C, followed by that of the Indian Ocean, reaching 17.0 °C, and that of the Atlantic Ocean, at 16.9 °C. Sea temperature generally decreases as depth increases; the sea temperature is approximately 4–5 °C at a depth of 1000 m, 2–3 °C at 2000 m, and 1–2 °C at 3000 m. The sea temperature that accounts for 75% of the total volume of oceans is between 0 and 6 °C, and the average global sea temperature is approximately 3.5 °C. Sea temperature can also have daily, monthly, yearly, multiple-year, and other periodic variations and irregular variations.

### 2.3.3 Distribution of Global Sea Surface Temperature

The sea surface temperature is the sea temperature at the junction between the atmosphere and the oceans (sea surface). In fact, we cannot possibly measure the temperature of the sea surface itself. The measured surface temperature is in accordance with the observed depth difference and is generally a measurement of the temperature from the sea surface to a depth of 10 m.

Because the earth is spherical, the amount of heat (amount of solar radiation) the oceans receive from the sun varies with the latitude. Figure 2.7(a) shows the distribution of the mean sea surface temperature in the three oceans. Generally, the sea temperature distribution is higher in low-latitude areas and lower in high-latitude areas. Figure 2.7b, c is the sea surface temperature distributions for January and July, respectively. In mid-to-high-latitude areas, compared with the annual average sea surface temperature, the sea surface temperature in January is lower in the northern hemisphere and higher in the southern hemisphere. On the other hand, the sea surface temperature in July is higher in the northern hemisphere and lower in the southern hemisphere.

Sea surface temperature is also affected by atmospheric movement. For example, in the vicinity of the sea surface in the equatorial sea areas of the Pacific Ocean, an eastward trade wind exists. Under the action of this east wind, the warm water in the vicinity of the sea surface is blown to the western part of the Pacific Ocean; to compensate, in the eastern part of the South American sea area, ice-cold water surges to the vicinity of the sea surface. Figure 2.7a indicates that the sea surface temperature in the equatorial

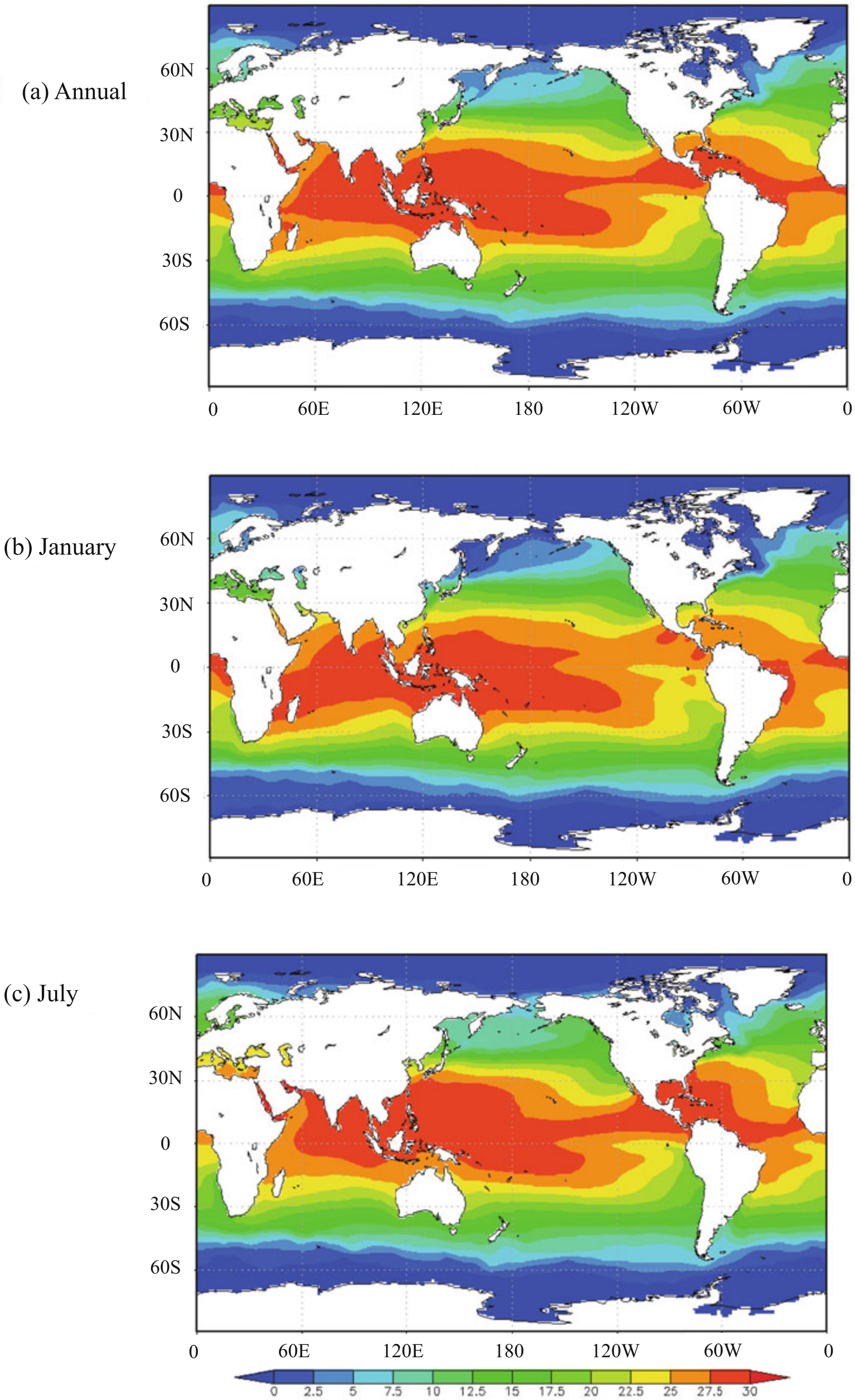


**Fig. 2.7** Distribution of mean sea surface temperature in the three oceans (unit: °C). (**a**) Annual mean, (**b**) January, and (**c**) July

sea areas of the Pacific Ocean is higher in the western part and lower in the eastern part.

In addition, in the vicinity of the west coast of the continents in the northern hemisphere (southern hemisphere), when the south wind (north wind) blows along the coast, the warm sea water in the vicinity of the sea surface is acted on by the force of the wind direction and drawn into the sea due to the force generated by the earth's rotation. To compensate, cold deep water may surge into the vicinity of the sea surface. This is one of the reasons the sea surface temperature in the vicinity of the west coast of North America is lower than the surrounding areas in July (Fig. 2.7c).

As mentioned above, through various factors, such as solar radiation, atmospheric movement, sea water movement, and topography, sea surface temperature has a complicated distribution.

## 2.4 Distribution of Nutrient Salts and Primary Production in the Oceans

### 2.4.1 Nutrient Salts

#### Basic Concept

The nutrient salts in sea water refer to the elements dissolved in sea water that act as growth factors for marine plants. In addition to requiring carbon dioxide, oxygen, and other gases, marine plants also require phosphorus, nitrogen, silicon, sulfur, magnesium, calcium, and various other elements to constitute protein, cell nuclei, and other substances. Vertical convection currents and upwellings in oceans bring bottom sea water rich in nitrogen, phosphorus, silicon, and other nutrient salts to the upper layer; therefore, in estuaries, along fronts, at the confluence of warm and cold currents, and at upwellings, among other areas, the phytoplankton production volume is high, the fishery resources are abundant, and the fishing yield is high.

There are relatively small amounts of phosphate, nitrate, nitrite, ammonium salts, and silicate in sea water. There are many primary components and trace metals in sea water that are also nutritional components, but traditionally, in chemical oceanography, sea water nutrient salts only refer to salts such as nitrogen, phosphorus, and silicon because they are essential components for the growth and reproduction of marine phytoplankton and are also the basis of marine primary production and the food chain. The distribution of nutrient salt content in sea water is affected by marine biological activities, and such distribution is usually not greatly related to sea water salinity.

#### Sources of Nutrient Salts and Their Distribution

The sources of sea water nutrient salts are mainly weathered rock products, decomposed organic matter, and waste discharged into rivers and streams that have been brought by continental runoff. In addition, the decomposition of marine organisms, weathering, polar glaciers, volcanoes, submarine hot spring, and dust in the atmosphere all provide nutrients to the sea water and provide the basic conditions for the formation of fishing grounds.

The nutrient salt content in sea water has a vertical distribution and regional distribution. Generally, the water in oceans can be divided into four layers based on the vertical distribution of nutrient salts: (1) surface layer, low nutrient salt content, more even distribution; (2) sublayer, nutrient salt content increases rapidly with depth; (3) sub-deep layer, 500–1500 m, maximum nutrient salt content; and (4) deep layer, although this layer is thick, the phosphate and nitrate content variations are very small, and silicate content increases slightly with depth.

In terms of regional distribution, due to ocean currents, the activities of living organisms, and the characteristics of each sea area, nutrient salts in sea water are distributed differently in different sea areas. For example, the deep-water circulation between the Atlantic Ocean and the Pacific Ocean transports nutrient salts from deep water in the Atlantic Ocean toward deep water in the Pacific Ocean. A large amount of nutrient salts is consumed during phytoplankton growth and reproduction in the Antarctic sea areas, but because there are sufficient sources, the nutrient salts in the sea water remain considerably abundant. In inshore areas, because of the thriving reproduction and growth of phytoplankton during the summer, the nutrient salts in the water of the surface layer are consumed to exhaustion. The growth and reproduction of phytoplankton decline during the winter, and the vertical mixing of sea water intensifies, allowing the nutrient salts formed by the decomposition of organic matter and deposited on the seabed to replenish the surface layer via upwelling, increasing the nutrient salt content in the surface layer. Shallow seas near shores and estuarine zones are different from oceans; the distribution of the nutrient salt content in sea water is not only affected by the growth and dying of phytoplankton and seasonal variations but is also very largely related to variations in continental runoff, the growth and decline in thermoclines, and other hydrological conditions.

### 2.4.2 Primary Production

#### Related Concepts

Gross primary production refers to the total amount of organic carbon produced via photosynthesis. However, marine plants, like other living organisms, carry out continuous respiration, requiring the consumption of part of the organic carbon produced. Therefore, net primary production is the remaining yield after the respiratory consumption of the producers is deducted from gross primary production: net primary production = gross primary production – respiratory consumption of the autotrophic organism. Marine primary production [mgC/($m^2$ day)] is often expressed as the amount of organic carbon produced per unit area ($m^2$) per unit time (day or year).

The factors that affect primary production are mainly light conditions and the content of nutrients required by plants, including other hydrological conditions related to the two. Under natural conditions, these factors are constantly changing. The main methods for determining primary production are (1) the $^{14}C$ tracer method, (2) chlorophyll fluorimetry, (3) the oxygen light and dark bottle method, and (4) water color remote sensing and scanning.

Water color remote sensing and scanning is one of the main methods for determining primary production. A coastal zone color scanner (CZCS) carried by satellites can record the color of sea water, determine the concentrations of chlorophyll and other pigments of algae and colored dissolved organic matter (CDOM) in a sea area, and identify particles suspended in the water. Therefore, the prominent contribution of the CZCS is overcoming the large-area sampling problem that is difficult to achieve in field surveys; the scope of its survey coverage can extend over the entire ocean. Furthermore, macro- and meso-scale physical processes that affect the spatial distribution and primary production of marine phytoplankton can also be analyzed through the CZCS, including the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO), among others. With the continuous improvement in remote sensing technology, it will be possible to more comprehensively understand the relationship between phytoplankton biomass and productivity and the features of marine hydrology. Products such as chlorophyll content determined by the remote sensing of marine water color have already gained wide application in fisheries science.

### 2.4.3 Distribution of Marine Productivity

The distribution of marine primary production is very uneven. Overall, the high-value areas of primary production are located in upwelling areas, continental shelves, and inshore sea areas with divergence, followed by the temperate subpolar region of the northern hemisphere and the Southern Ocean fronts. Low-value areas are located in the tropical and subtropical ocean regions of both the northern and southern hemispheres, with the lowest primary production in the sea areas of the Arctic Ocean (Fig. 2.8).

In the last several decades, satellite remote sensing technology has gained wide application in ocean monitoring, promoting the development of fisheries science and fisheries forecasting. The utilization of high-resolution satellite remote sensing enables continuous observation of the abundance of phytoplankton in different sea

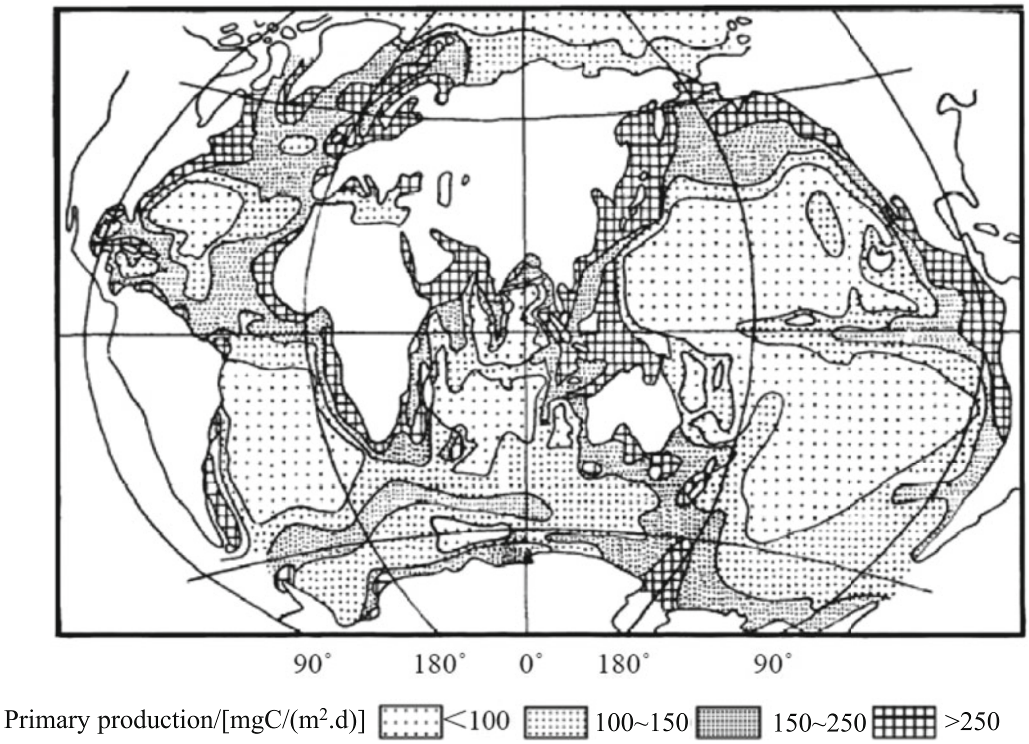


**Fig. 2.8** Map of the distribution of primary production in the oceans (Koblentz-Mishke et al. 1970)

areas, the depth of the euphotic layer, and variations in primary production. Based on these satellite remote sensing data, combined with animal composition and physical oceanographic features such as wind and ocean currents, UK scholar Longhurst (1971) divided the seas and oceans into four basic biomes: the polar biome, the westerlies biome, the trades biome, and the coastal biome. Each biome is further divided into a number of ecological provinces. There are annual and seasonal variations at the boundaries of these subregions. Now, in combination with the characteristics of the aforementioned biomes, the geographic distribution of marine primary production is introduced.

## Tropical and Subtropical Ocean Regions and the Equatorial Zone

### Tropical and Subtropical Ocean Regions

The scope of the trades biome is between approximately 30°N and 30°S, and its boundary just passes through the central circulation area of the subtropics, with the central axis located in the equatorial zone. The depth of the mixed layer in this sea area is mainly affected by macro-scale marine circulation.

The tropical and subtropical ocean regions receive sufficient solar irradiation and have high sea water transparency, and the depth of the euphotic layer exceeds 100 m, which is a favorable light condition for primary production. However, this sea area is located within the range of oceanic anticyclonic circulation (also referred to as the central circulation area); the surface sea water converges and sinks toward the center of the circulation, and the depth of the mixed layer exceeds the depth of the euphotic layer. The thermocline can reach 100–200 m in the summer and increases to approximately 400 m in the winter. Furthermore, because the high sea temperature strengthens the vertical stability of the sea water, it directly limits the deep-layer water from moving upward to replenish nutrient salts. Inorganic nutrient salts required by phytoplankton in the mixed layer are mainly (more than 90%)

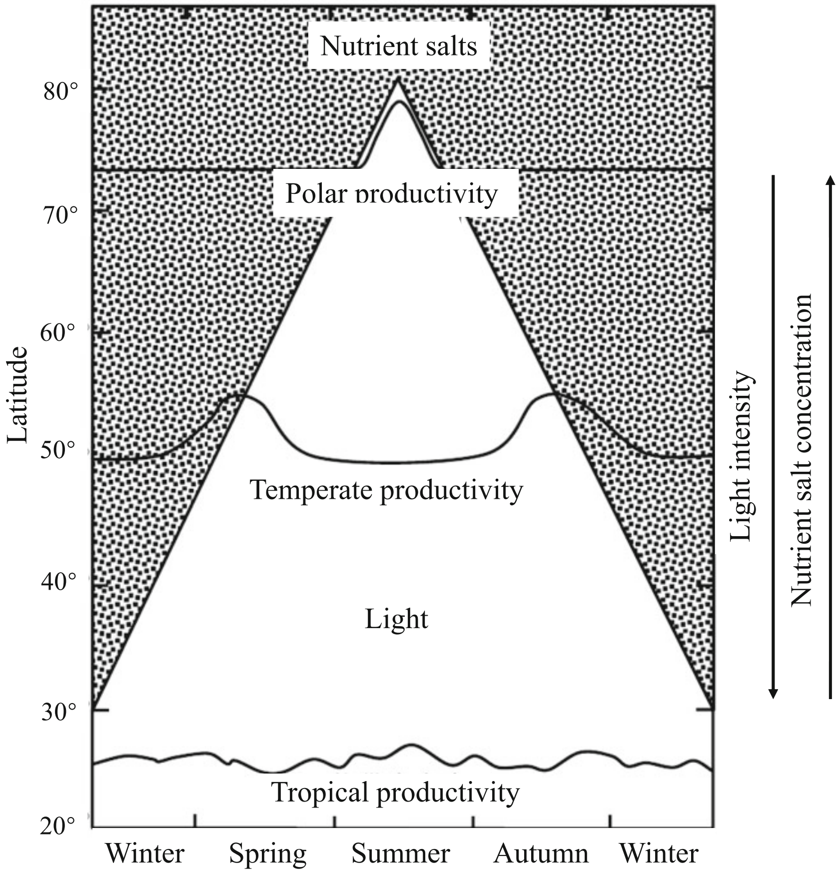


**Fig. 2.9** Schematic diagram of the relationship between seasonal variations in the primary production of tropical and temperate sea areas and light and nutrient salts (Lalli and Parsons 1997)

sourced through recycling and regeneration within the system. The nitrate concentration in the euphotic layer is only 0–5 mg/m$^3$, the chlorophyll content is 5–25 mg/m$^2$, and the average annual primary production is only 50–100 mg C/m$^2$. Therefore, this sea area has the lowest primary production and is referred to as the "biological desert" of the ocean. Compared with that in temperate sea areas, the light intensity and vertical stability of the sea water in tropical sea areas do not have obvious seasonal variations, and primary production can occur all year; moreover, the depth of the production layer is deeper than that of the sea areas at mid to high latitudes, and the turnover rate is high; therefore, these ocean areas do not have obvious seasonal cycles and maintain low production characteristics (Fig. 2.9).

### Equatorial Zone

The North and South Equatorial Currents flow from east to west and are continuous within the anticyclonic-type circulation in the equatorial sea areas of the oceans in the two hemispheres; between the two currents is the west-to-east Equatorial Countercurrent (also referred to as the North Equatorial Countercurrent). Because the horizontal Coriolis force on the equator is zero, sea water in the vicinity of the Equatorial Countercurrent converges. Additionally, the northward and southward water transport components generated by the northeast trade-wind current

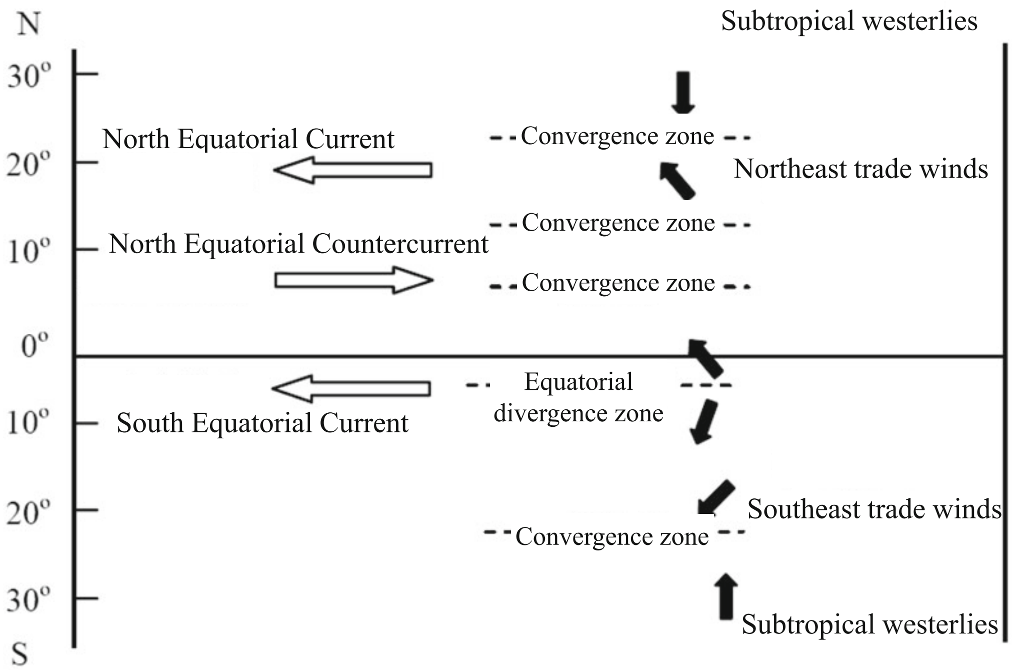


**Fig. 2.10** Schematic diagram of the equatorial divergence area (Chen 2003)

and the southeast trade-wind current thereby form a divergence of sea water on both the north and south sides of the Equatorial Countercurrent (Fig. 2.10).

There is no lack of nutrient salts in the equatorial sea area; in particular, the nitrate concentration in the eastern mixed layer is generally higher than 2 μmol/L, that is, higher than the minimum nutrient salt concentration required to limit the growth of phytoplankton. The lack of iron (Fe) in the equatorial sea area is the main factor that limits the growth of phytoplankton. The main source of iron for this sea area is the small amount of iron provided by the near-surface mixed layer brought in by upwelling generated from the Equatorial Undercurrent and the sedimentation of atmospheric dust to the sea surface. Due to the lack of iron, the production volume of phytoplankton does not match the nutrient salt content; therefore, the equatorial sea area is a typical high-nutrient, low-chlorophyll (HNLC) sea area. The picophytoplankton in this sea area accounts for 90% of its gross biomass, and the consumers that feed on the phytoplankton are mainly microflagellates, dinoflagellates, and ciliates.

There is a difference in productivity between the eastern part and western part of the equatorial zone. The trade-wind currents cause the water level at the western boundary to rise, generating a pressure gradient force, and the depth of the thermocline at the bottom of the mixed layer also rises from west to east. Furthermore, the Equatorial Undercurrent is blocked when it flows to the eastern boundary, and an upwelling that passes through the density-isolines occurs. In addition, the eutrophic water at the surface layer of the upwelling at the eastern boundary of the ocean extends westward with the trade winds. The comprehensive action of the above environmental features makes the productivity level on the eastern side of the equatorial zone higher than that on the western side, which can exceed 0.5 $gC/(m^2 \cdot d)$ on average.

The western side of the equatorial zone does not have upwelling like the eastern side, and its primary production is similar to that of a subtropical ocean area. For example, the equatorial current in the Pacific Ocean pushes the flow of warmer sea water westward, forming a "warm pool" in the western part; the higher sea temperature promotes the evaporation of sea water and precipitation, creating a halocline above the thermocline. The double stratification increases the stability of the body of water in the "warm pool," and the constant quantity of nutrient salts is very quickly depleted; therefore, productivity in the western equatorial waters is very low.

## Temperate (Subpolar) Zone in the Oceans

The temperate zone is situated between the westerlies and the polar oceans, and there are differences in the ecological characteristics in the temperate zone of the two hemispheres.

### Northern Hemisphere

The temperate seas and oceans of the North Pacific Ocean and the North Atlantic Ocean are situated in a cyclonic-type divergent circulation area of the ocean, and the surface sea water spreads outward from the center of circulation, leading the deep-layer water moving toward the surface layer and replenishing the nutrient salts in the euphotic layer. The depth of the mixed layer here is mainly affected by wind force. The nitrate content is 5–25 mg/m$^3$, which is several times higher than that in the southern subtropical ocean area. The concentration of chlorophyll a is 15–150 mg/m$^2$, and the primary production of some sea areas can reach 300–500 gC/(m$^2$·a), much higher than that of the subtropical ocean area.

In the northeastern part of the Pacific Ocean, HNLC sea areas have emerged. For example, although the Gulf of Alaska contains abundant nutrient salts, it contains insufficient iron; in addition, the latitude where it is situated is comparatively high, the light conditions in winter are poor, and the level of primary production cannot be fully determined. The phytoplankton in many waters has a comparatively small particle size, and diatoms only occasionally dominate. Protozoans have become the main plant-eating animals; their growth and reproduction rates are comparatively fast, and they often feed on phytoplankton in large quantities and promote the regeneration of nutrient salts in the early stages of water bloom. Medium-sized zooplankton are dominated by copepods, and many species undergo a dormant period after developing to copepod larvae stage V and sink below 400 meters to escape from predators. The situation in the North Atlantic Ocean is different from that in the North Pacific Ocean. Due to more iron replenishment sourced from the land, spring water blooms, dominated by diatoms, are significant. The phytophagous zooplankton here are calanoids, which are larger individuals, including *C. finmarchicus*, among others.

In the Northwest Pacific Ocean, a branch of the Kuroshio warm current ascends northward along the coast of Japan and generates an intense mixing action with the sea water at the confluence with the Oyashio cold current from the Kuril Islands in a southward direction. The level of productivity here is high, forming the famous fishing grounds in Hokkaido, Japan. Similarly, in the Northwest Atlantic Ocean, the famous Newfoundland fishing grounds are formed at the confluence of the northward Gulf Stream (warm current) and the Labrador Cold Current. The place of confluence for these warm and cold currents is referred to as the Northwest Convergence Zone of the northern hemisphere.

### Southern Ocean

The difference between the southern hemisphere and the northern hemisphere is that the West Wind Drift is not blocked by the continents, thus forming the Antarctic Circumpolar Current, which surrounds the Antarctic continent. An important physical feature of the Southern Ocean is the mixing of strong winds and strong turbulence. Most of the sea area has a very high nitrate content, and an adequate phosphate content, but the primary production is not high. It is a major HNLC sea area among the oceans. The main reason that has caused the mismatch between primary production and the content of nutrient salts such as nitrogen and phosphorus is a low iron content (range, 0.2–0.5 nmol/L) and a very low biogenic silicon content. However, at the Antarctic front, that is, the sea area of the Antarctic Convergence Zone (located in the vicinity of 60°S in the Pacific Ocean and the vicinity of 50°S in the Atlantic Ocean and the Indian Ocean, on average), due to the rise of sea water generated by wind-driven mixing and vertical turbulence, comparatively sufficient iron is provided to the euphotic layer in the frontal zone. The iron content in the surface layer can be ten times higher than that in most of the Southern Ocean, the biogenic silicon is replenished, and the near-surface mixed layer is comparatively shallow (50 to 100 meters); therefore, this frontal zone is conducive to the emergence of water blooms of phytoplankton. The Antarctic front is a high-productivity area in the Southern Ocean. The phytoplankton is dominated by diatoms, but in other sea areas, nondiatoms or species with lower silicon content are dominant.

The zooplankton most abundant in numbers in the HNLC sea area of the Southern Ocean is a new calanoid, *Neocalanus tonsus*. This species is similar to the aforementioned dominant species in the North Pacific Ocean, but it also stores lipids and goes dormant.

In many temperate sea areas, the light conditions, temperature, and vertical stability of the sea water have obvious seasonal cycles, and the comprehensive action of these physical factors causes primary production to also have seasonal variation features, which usually present as a peak in spring and a secondary peak in autumn (Fig. 2.9).

## Polar Zone

The main environmental features of the polar zone are that most of the sea areas are covered with ice, the average sea temperature is very low (<5 °C), the light conditions are poor, and the production season is short, critical factors that affect primary production.

The Arctic Ocean is basically surrounded by continents, most of the zones are situated in high-latitude areas north of 75°N, and sea ice is present all year round or seasonally. The primary production of the Arctic Ocean is not limited by a lack of nutrient salts but, rather, by poor light conditions. There are very long periods of time during the year when light is very weak (the angle of the sun is low, and the daylight hours are short) or when it is dark for several consecutive months (polar nights). This sea area only has a net yield of phytoplankton during the period with light, with only one peak period of production; it is a single-cycle production area. For example, in areas close to the Atlantic Ocean, from Greenland to the Barents Sea, abundant nutrient salts are present from the mixing of the bodies of water before freezing, and water blooms appear in the spring when there is light. The water blooms start from epiphytic communities under ice floes, and as the sea ice melts, there is a net yield in primary production. Closely following the retreat of the sea ice, the scope of the water blooms also moves quickly northward. It is generally held that the annual average primary production of the Arctic Ocean is lower than that of the oligotrophic subtropical ocean areas, but actual surveys have deemed that the traditional view of the Arctic Ocean as a desert of biological productivity is worth debating.

Due to the short production season of phytoplankton, the generation cycle of Arctic Ocean herbivores is comparatively long. For example, the life history of the Arctic calanoid *Calanus glacialis* is as long as 2–3 years, and they overwinter in deep-water areas at a depth of 1000 meters, whereas Arctic cod (*Boreogadus saida*) is the key species in the process of energy and material transfer from phytoplankton to birds and mammals.

The polar seas and oceans of Antarctica refer to the sea areas from south of the Antarctic front to the Antarctic continent. Between the easterly circulation on the Antarctic continental margin and the Antarctic Circumpolar Current on the north side, an Antarctic divergent front forms due to the dynamic action, and the rise of the deep-layer water brings abundant nutrient salts (especially inorganic salts such as nitrogen and phosphorus). In addition, the convergence and sinking of sea water along the shelf form between the easterly circulation and the continent, that is, the Antarctic continental convergence zone. Diatom blooms appear in polar seas and oceans with the seasonal melting and southward retraction of sea ice and the rapid growth of epiphytic algae. The primary production of the polar seas and oceans in the southern hemisphere is higher than that of the Arctic Ocean. Surveys have deemed that the primary production in Prydz Bay and its adjacent sea areas presents the following pattern: high in the bay and low outside the bay, with the lowest at the continental slopes and the deep sea. The survey results also showed that the photosynthesis rate of phytoplankton is highest in the subsurface layer, then decreasing progressively as depth increases. It is generally believed that the supply of trace elements, iron in particular, determines the scale of water blooms. Among the zooplankton, the Antarctic krill (*Euphausia superba*) is the most important. In addition, the Antarctic silverfish (*Pleurogramma antarcticum*) also feeds on phytoplankton such as diatoms. There are also very abundant seal, whale, and bird (penguins) resources.

### Coastal Zones

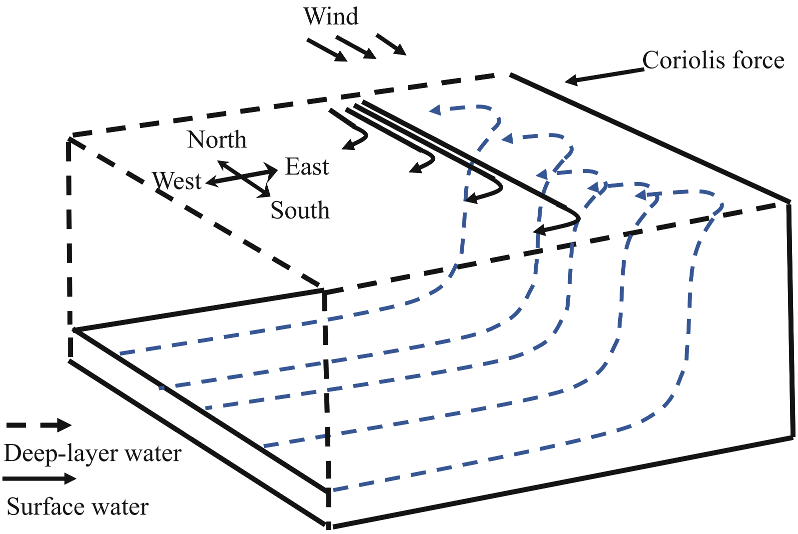
The zones along the coastlines are high-productivity areas within the seas and oceans because of the existence of various marine fronts, which provide abundant nutrient salts for photosynthesis by phytoplankton.

### Upwelling Fronts

The largest coastal upwellings in oceans occur in the eastern upwelling areas of the oceans. The West Wind Drift in the eastern main current of the ocean flows toward low latitudes along the west coast of the continent and finally merges into the trade-wind currents. When surface sea water gradually enters an area affected by trade winds, it is subjected to the actions of the southeast trade winds and the northeast trade winds and flows away from the coast, causing sea water from the lower layer to surge toward the surface layer, resulting in upwelling and the transportation of nutrient salts toward the euphotic layer, which promotes phytoplankton growth (Fig. 2.11). This type of upwelling mainly includes the Peru upwelling and the California upwelling in the Pacific Ocean and the Canada upwelling and the Benguela upwelling in the Atlantic Ocean. For most of the year, these upwellings bring eutrophic water from the deep layer to replenish the surface layer. They are all situated between latitudes 10° and 40° and have sufficient solar irradiation to thereby support the high productivity of phytoplankton and maintain large quantities of fish and bird species. For example, the Peruvian anchovy yield in the Peru upwelling area once accounted for approximately 20% of the world's catch.

Coastal upwellings also appear in other shallow sea areas of the shelf, for example, wind-driven upwelling, bottom-water upwelling caused by topography (such as islands and shoals), and upwelling caused by a combination of the two. These sea areas are also eutrophic, high-

**Fig. 2.11** Schematic diagram of coastal upwelling (Nybakken 1982)



productivity areas, but their localization and seasonality are more apparent.

### Shelf-Slope Break Frontal Zone

Many shelf-slope break frontal zones appear at marine continental shelf-slope breaks. For example, the Kuroshio Current front at the shelf-slope break in China's seas in the West Pacific Ocean and the Gulf Stream front at the boundary between the Gulf Stream and the shelf water in the North Atlantic Ocean are both typical shelf-slope break fronts. The Kuroshio Current and the Gulf Stream both flow from the high-temperature, high-salinity water in the vicinity of the equator, with very low nutrient salt content at the surface layer. They converge with low-temperature, low-salinity coastal water at isobaths that span the continental shelf-slope breaks of the western boundary, generating a narrow zone of sudden change in temperature or salinity, that is, the shelf-slope break front of the Kuroshio Current or the Gulf Stream. In addition, when these two sections of warm currents flow northward in a meandering manner, they often generate cold and warm frontal vortices on both sides of the continental shelf water boundary. When the frontal vortex of a cyclonic warm center emerges at the shelf-slope break, the water near the surface layer rotates in a counterclockwise manner, pulling away from the Kuroshio Current or the Gulf Stream near the shore; the main body enters the open sea, generating a divergent upwelling at the shelf-slope break. Such a vortex front brings deep-layer water that is colder but rich in nutrient salts to the surface layer, replenishing the inorganic salts required for the growth of phytoplankton in the euphotic layer. Under sufficient light conditions, a water bloom of phytoplankton will occur here. The primary production of phytoplankton within the continental shelf sea area of the southeastern United States depends on the nutrient salt transport process of upwelling at the shelf-slope break. The dynamic mechanisms generated by upwelling are the frontal vortex of the Gulf Stream and the prevailing southwesterlies in spring and summer. Research revealed that at the frontal vortex of the Gulf Stream at the shelf-slope break along the southeastern shore of the United States, when upwelling brings nutrient salts from the deep layer to the surface layer, the average primary production is usually about four times higher than that in the mixed layer at the shelf-slope break. After the nutrient salts replenished by the upwelling are consumed, the primary production also decreases. This type of frontal vortex is also commonly seen in the Kuroshio Current system at the shelf-slope breaks in China's seas.

Not all shelf-slope breaks are boundary transition zones resulting from the meeting of ocean water and shelf water. Broadly, any front structure that appears at the shelf-slope break can be classified as a shelf-slope break front.

### Low-Salinity Fronts and Tidal Mixing Fronts

Continental river runoff feeds a steady stream of freshwater into the shallow sea areas of the continental shelf, thereby generating a rapid transition zone between low-salinity water and high-salinity sea water in sea areas; these areas are referred to as low-salinity fronts. Because the input volume from rivers varies seasonally (rainy season and dry season), the intensity and the scope of influence of low-salinity fronts also have seasonal variation features.

River runoff brings large amounts of suspended organic particles, dissolved organic matter, and inorganic nutrient salts to estuaries, and these nutrients are mainly sourced from farmland fertilization and sewage discharge from coastal cities. Among them, inorganic nutrient salts such as nitrogen and phosphorus can be directly absorbed by phytoplankton in estuaries, and organic matter is utilized by phytoplankton through the internal recycling and regeneration of nutrient salts and the release of nutrient salts from suspended sediments. Furthermore, when the freshwater provided by rivers in flowing in shallow seas near shores, vertical circulation will be generated locally in estuaries, bringing the nutrient salts released by the seabed to the upper layer. In estuaries within low-salinity fronts, the high degree of turbulent mixing, the turbid sea water, the very shallow euphotic layer (some are even only approximately 1 m), and the shading effect of phytoplankton themselves will affect the full

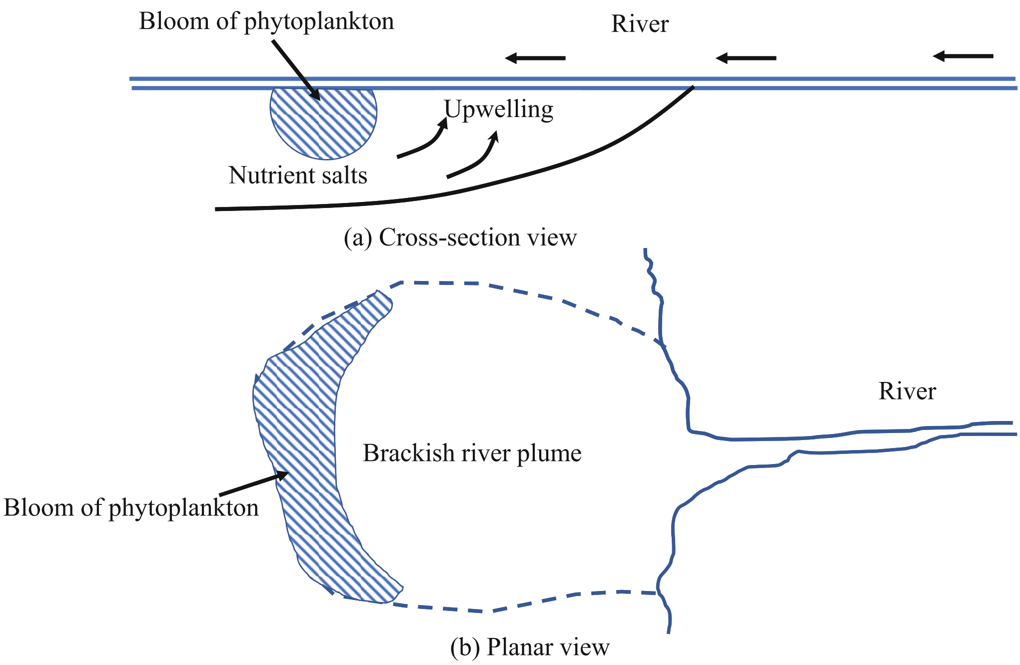


**Fig. 2.12** Entrainment of nutrient salts in an estuary (Lalli and Parsons 1997). (**a**) Cross-section view; (**b**) planar view

utilization of abundant nutrient salts by phytoplankton. However, at low-salinity fronts, the euphotic layer deepens, there are sufficient nutrient salts, and water blooms of phytoplankton are often prone to occur (Fig. 2.12).

Tidal mixing fronts refer to the temperature or salinity (or density) transition zone generated by tidal mixing. Tidal fronts appear in the shallow sea areas of the shelf where tidal currents and seabed friction are comparatively high. Notably, in many estuaries, low-salinity fronts and tidal mixing fronts exist simultaneously, and the fronts observed are really a comprehensive portrayal of the mixed interactions of diluted river water, tides, and the wind.

It can be determined through the above discussion that there are great differences in the primary production of sea areas with different hydrological features (Table 2.1); these differences are mainly related to whether surface nutrient salts can be replenished by the divergence (rising) or convergence (sinking) of surface sea water.

**Table 2.1** Scope of annual primary production in different sea areas (Lalli and Parsons 1997)

| Sea area type | Average annual primary production/[g/C/$m^2$.a] |
|---|---|
| Upwelling areas of continental shelves (such as the Peru Current and the Benguela Current) | 500–600 |
| Continental shelf-slope breaks (such as the European Shelf, the Grand Shoal, and the Patagonia Shelf) | 300–500 |
| Subarctic areas (such as the North Atlantic Ocean and the North Pacific Ocean) | 150–300 |
| Anticyclonic vortex areas (such as the Sargasso Sea and the Pacific subtropical sea area) | 50–150 |
| North Pole (ice-covered) | <50 |

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