be small. The major water exchange between the Pacific Ocean proper and the deep basins of the Bering Sea is believed to occur between 168°E and 172°E where the sill depth is 1589 m. A significant part of the Alaskan Stream enters the Bering Sea through this passage, turning east almost immediately and driving a cyclonic gyre in the deep part of the Bering Sea (Figure 10.1). Velocities in the inflow are near and above 0.2 m s^{-1}; in the gyres they are closer to 0.1 m s^{-1}. As explained during the discussion of the Antarctic Circumpolar Current in Chapter 6, the water temperature in subpolar ocean regions (i.e. regions poleward of the Subtropical Front) varies little with depth and currents reach very deep. The current therefore experiences the Shirshov and Bowers Ridges as obstacles to its progress, and a system of two eddies over the two basins is set up. Current shear between the gyre interior and the current axis appears to be strong; large eddies have been observed separating from the Bering Slope Current (the gyre section over the steep continental rise) into the gyre interior. The Bering Slope Current is associated with a countercurrent attached to the slope. Maximum velocities exceed 0.25 m s^{-1} and are usually found at 150 - 170 m depth. The current appears to be an eastern boundary current in a subpolar gyre circulation, i.e. the dynamics of eastern boundary currents explained in Chapter 8 apply here as well, if poleward and equatorward directions are reversed.

An amount of water nearly equivalent to that carried by the inflow from the Alaskan Stream leaves the Bering Sea with the Kamchatka Current (also known as the East Kamchatka Current), with some leakage (0.6 - 1.5 Sv, see Chapters 7 and 18) through Bering Strait. Typical velocities in the Kamchatka Current are 0.2 - 0.3 m s^{-1}.

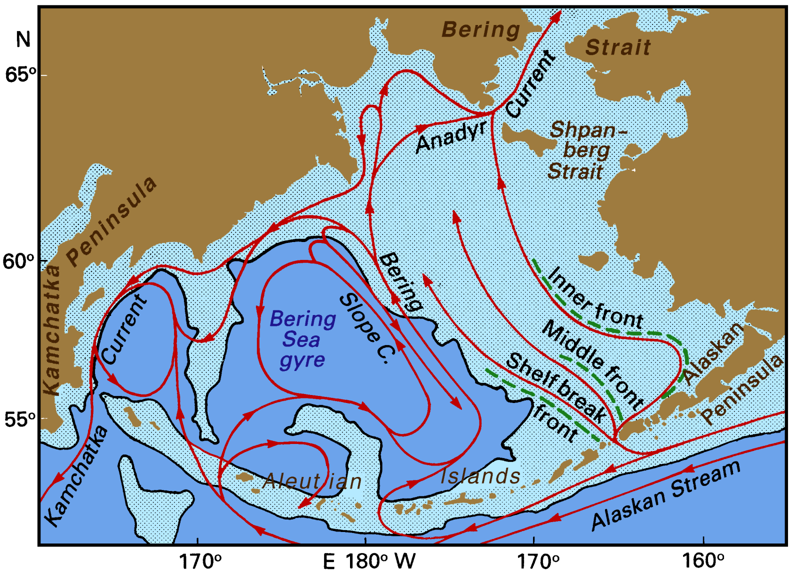


Fig. 10.1. Surface currents in the Bering Sea. Shading indicates water depth less than 3000 m; in the region of the Bering Slope Current the 200 m isobath runs close to the 3000 m isobath. The Shirshov Ridge is seen near 171°E, the Bowers Ridge north of the Aleutian Islands near 180°.

minimum is surface water from the area south of the Aleutian Islands imported by the Alaskan Stream. The water below the minimum is Pacific Deep Water also transported by the Alaskan Stream. As Pacific Intermediate Water is formed well south of the Alaskan Stream and does not enter the Bering Sea (compare Figures 9.4 and 9.7), Pacific Deep Water fills the entire water column below about 250 m depth where it mixes with the water of the temperature minimum. This water originates on the shelf during winter as a result of convection under the ice. Its salinity of about 33 corresponds to the highest salinities found on the shelf during the year. (The range of surface temperatures and salinities on the shelf covers -1.6 - 10°C and 22 - 33, respectively.) It sinks to 100 - 200 m depth and joins the general circulation of the deeper western part. It can be traced well into the western gyre (Figure 10.2) and into the recirculation from the Kamchatka Current to the Pacific inflow in the south.

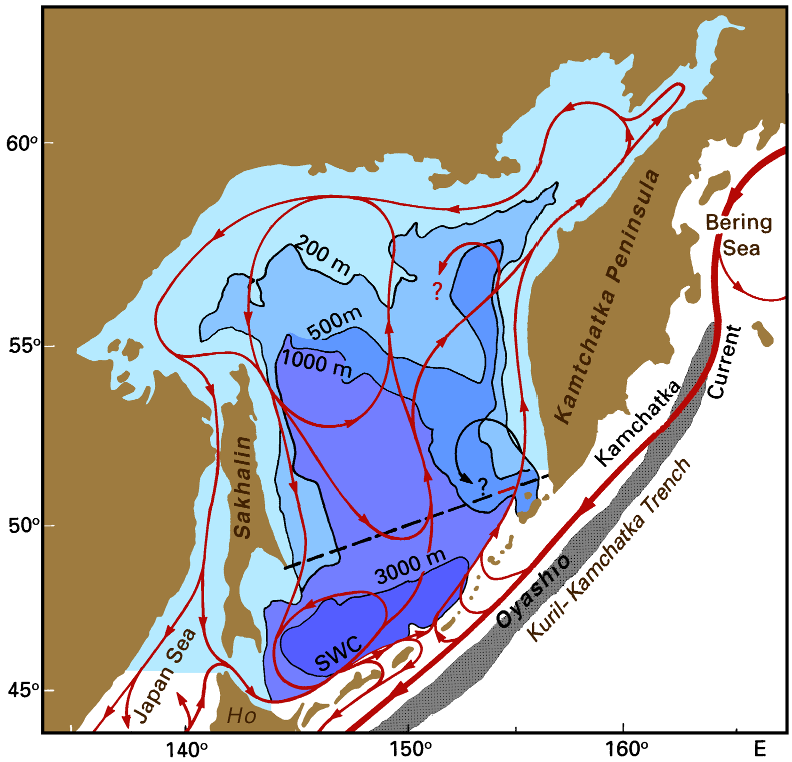


Fig. 10.3. Surface currents in the Sea of Okhotsk and major topographic features. Shading indicates regions deeper than 6000 m. The heavy broken line indicates the location of the section of Fig. 10.5. Ho: Hokkaido, SWC: Soya Warm Current.

The *Sea of Okhotsk* is set between the Siberian coast in the west and north, the Kamchatka Peninsula in the east, and the Kurile Islands in the south and southeast. The distinction between a deep and shallow region is not quite as straightforward as in the case

west of Kamchatka. Typical depths in the basin to the southwest of the dividing line are around 1500 m or less. South of 49°N the ocean floor falls off further to 3000 m and more in the Kurile Basin. Numerous deep passages between the Kurile Islands connect this basin with the Pacific Ocean proper, the most important ones being Boussole Strait near 46.5°N which accounts for 43% of the total cross-sectional area and has a sill depth of 2318 m, and Kruzenshtern Strait near 48.5°N which accounts for 24% with a sill depth of 1920 m. Two additional passages connect the Sea of Okhotsk with the Japan Sea in the south. Tatarskyi Strait between Siberia and Sakhalin Island has a sill depth of less than 50 m and provides a very restricted exit for cold water from the northern shelves. Soya Strait (also known as La Pérouse Strait) between Sakhalin Island and the island of Hokkaido is less than 200 m deep and dominated by strong inflow of warm water from the Japan Sea.

Atmospheric conditions over the northern Okhotsk Sea are similar to those over the Bering Sea, and most of the region is covered with drift ice during 6 - 7 months every year. The effect of the monsoon system that dominates the climate of the marginal seas further south is felt in the southern part. The combination of winter monsoon conditions in the south and polar conditions in the north produces strong northerly or northwesterly winds blowing out of the atmospheric high pressure cell over Siberia from October to April, often reaching storm conditions and causing waves to reach up to 10 m in height. In contrast, the southeasterly winds of the summer monsoon from May to September are rather weak, and calm conditions are encountered during 30% of the time. Both wind systems support cyclonic circulation of the surface waters along the coast with moderate velocities (0.1 - 0.2 m s^{-1}). Currents in the inner parts of the Okhotsk Sea are weaker and irregular; the limited observational data available indicate some closed circulation features particularly in the northwest and over the Kurile Basin (Figure 10.3).

An important element of the surface circulation is the Soya Warm Current, an extension of the Tsushima Current from the Japan Sea which passes through the southern part of the Sea of Okhotsk. It has the character of a boundary current with velocities reaching 1.0 m s^{-1} and traverses the Okhotsk Sea rapidly, staying close to the coast along its way. Strong current shear between the fast-flowing inshore waters and the offshore region persistently produces eddies, typically of 10 - 50 km diameter, which are easily seen when the sea is partly covered with ice (Figure 10.4).

The hydrographic structure shows strong similarities with the Bering Sea, indicating similar layering of water masses (Figure 10.5). The temperature minimum at or above 100 m is again the result of winter convection on the shelf, particularly those parts which extend deep into the Siberian land mass; as a result, water temperatures at the minimum are much lower here than in the Bering Sea. The waters above and below the minimum are again advected from the Pacific Ocean.

The Japan Sea

The Japan Sea or Sea of Japan consists of an isolated deep sea basin and its connections to the East China Sea in the south, the Sea of Okhotsk in the north, and the Pacific Ocean proper in the east. Exchange with the surrounding seas is through mostly narrow passages with sill depths not exceeding 100 m. North of about 40°N bottom depths generally exceed 3500 m; this region is known as the Japan Basin. South of 40°N the Yamato Ridge

mediterranean sea is not applied to the Japan Sea. The influence of the western boundary currents is seen clearly in the distribution of sea surface temperature which shows a distinct frontal region between central Korea and Tsugaru Strait with salinities well above 34 to the south but around and below 34 to the north (Figure 10.6). The situation looks remarkably similar to the situation found east of Japan where large horizontal temperature and salinity gradients are produced by the Polar Front through the confluence of the Kuroshio and Oyashio. The Japan Sea is indeed a meeting place for warm currents from the south and cold currents from the north; its separation into a warm part on the Japanese side and a cold part on the Siberian and Korean side indicates that the Polar Front does not terminate at the east coast of Japan but continues in modified form into the Asian mainland.

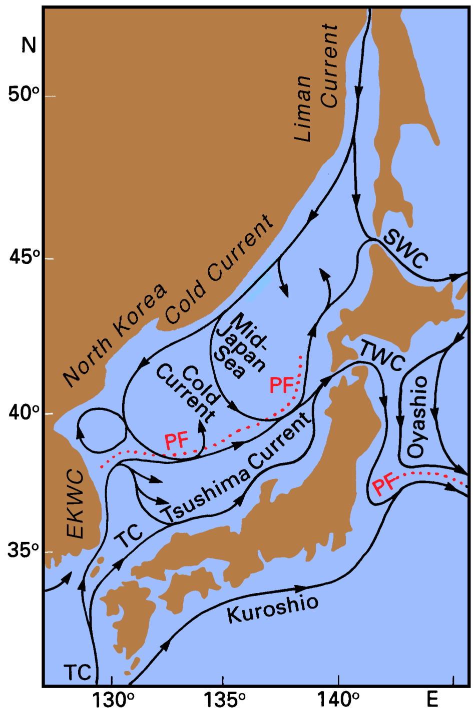


Fig. 10.7. Surface currents in the Sea of Japan. EKWC: East Korea Warm Current, PF: Polar Front, SWC: Soya Warm Current, TC: Tsushima Current, TWC: Tsugaru Warm Current.

Figure 10.7 shows how the various currents combine to shape the hydrography of the Japan Sea. Warm water is brought in by the *Tsushima Current*, a branch of the Kuroshio, through Korea Strait. The branching of the North Pacific western boundary current caused by the islands of Japan pushes the position of the Polar Front in the Japan Sea much further north than in the Pacific Ocean east of Japan. Warm water from the subtropics can thus enter the Pacific Ocean proper with the *Tsugaru Warm Current* and meet the cold subpolar Oyashio as far north as 42°N. (The identification of currents as warm or cold is an east Asian tradition; elsewhere these currents would simply be called the Tsugaru and Soya Currents.) It can even proceed to 45°N, pass through the Sea of Okhotsk with the *Soya Warm Current*, and encounter the Oyashio some 800 km north of the latitude where the

combination of sinking at the Polar Front and on the northern shelf; an oxygen maximum of 8 ml/l near 200 m depth indicates recent contact of this water with the atmosphere.

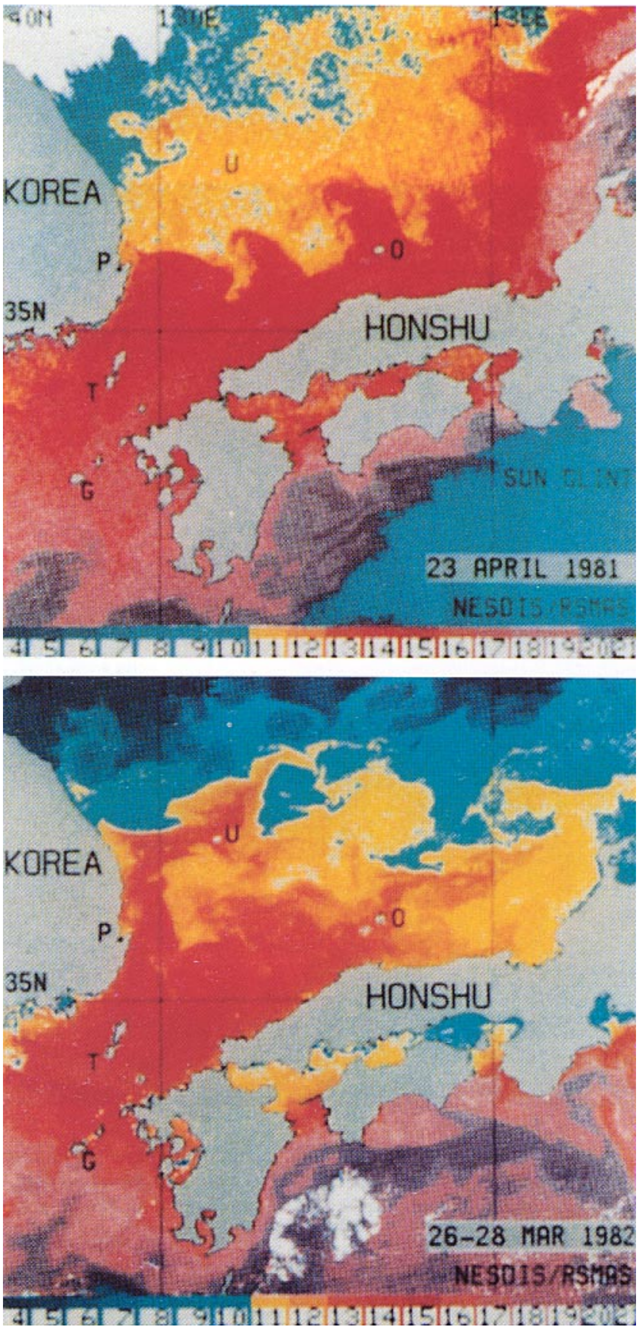


Fig. 10.8

The Tsuchima Current and the associated Polar Front seen in satellite images of sea surface temperature.

(a) in April 1981,

(b) in March 1982.

From Kim and Legeckis (1986).

Japan and Yamato Basins has been used to infer deep winter convection in the Yamato Basin. The residence time of Bottom Water has been estimated at 300 years. At these depths there are some obvious similarities between the Sea of Japan and true mediterranean seas.

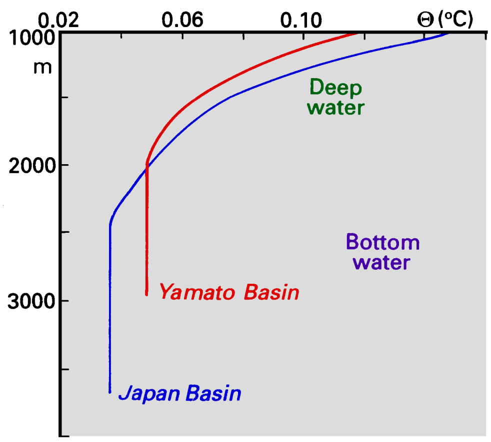


Fig. 10.10. Potential temperature (°C) in the northern Japan Basin (41.5°N, 138°E) and in the Yamato Basin (38.5°N, 135.5°E) showing different thermal gradients in Japan Sea Deep Water and Japan Sea Bottom Water. Note the extremely expanded temperature scale. From Gamo *et al*. (1986)

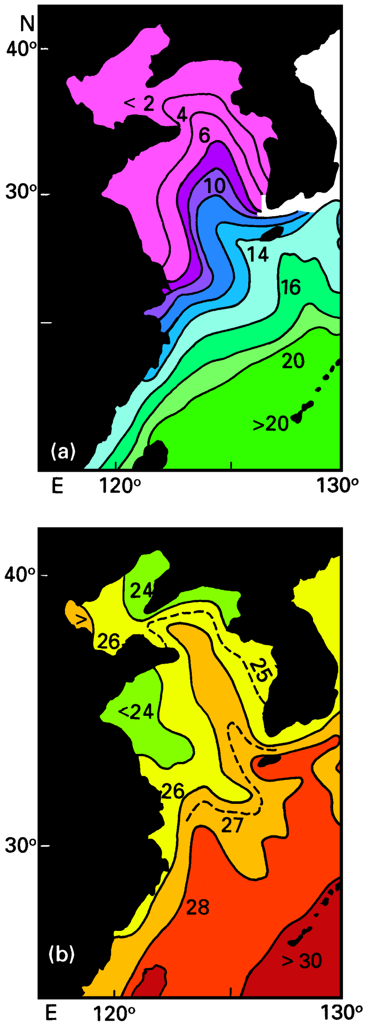
The East China Sea and the Yellow Sea

South of Tsushima Strait and adjoining the Japan Sea is a vast expanse of continental shelf which reaches from the Chinese mainland to Taiwan and stretches as far south as Vietnam. The East China and Yellow Seas encompass the region to the north of Taiwan (the southern shelf belonging to the South China Sea). Both seas form a hydrographic and dynamic unit but are distinguished by tradition. The East China Sea is usually defined as reaching from the northern end of Taiwan Strait to the southern end of Kyushu, where according to some it adjoins the Yellow Sea along a line just north of 33°N; others draw the line from Kyushu to Shanghai (the mouth of the Yangtze River). To the east the East China Sea is bordered by the Ryukyu and Nansei Islands, while the Yellow Sea continues northward between China and Korea. Its innermost part, which is fully enclosed by Chinese provinces and separated from the Yellow Sea proper by the Shandong and Liaodong peninsulas, is known as the Bohai Gulf. The Yellow Sea derives its name from the huge quantities of sediment discharged into the Bohai Gulf by the Yellow River.

With the exception of the Okinawa Trough west of the Ryukyu Islands which reaches 2700 m depth, the East China and Yellow Seas are part of the continental shelf. A complete analysis of their hydrography and dynamics is therefore only possible in the framework of coastal and shelf oceanography which is beyond the scope of this book. The following brief discussion concentrates on aspects relevant and interpretable in the context of dynamics on oceanic scales.

Two factors determine the characteristics of the East China and Yellow Seas, their proximity to the Kuroshio, and the monsoon winds which bring northerly winds during winter and southerly or southeasterly winds during summer to the entire region (Figure 1.2). Advection of warm saline Kuroshio water in the *Yellow Sea Warm Current* (Figure 10.11) raises the sea surface temperature of the central Yellow Sea several degrees

in most of the waters of the Yangtze River, it contributes greatly to the increased summer transport of the Tsushima Current.



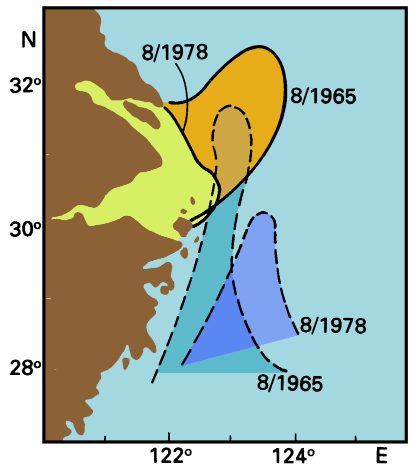


Fig. 10.13 (above). Evidence for subsurface flow of Taiwan Warm Current water underneath low-salinity water from the Yangtze River. Data are from August of 1965 and 1978. Full lines give the 26 isohalines near the surface, broken lines the 20°C isotherms near the bottom. The two-layer structure of the flow is particularly clear during 1965. From Weng and Wang (1988).

Fig. 10.12 (left). Sea surface temperature (°C) in the East China and Yellow Seas. (a) During the winter monsoon, (b) during the summer monsoon.

From the point of view of global climate the East China and Yellow Seas can be described as a radiator. Water is withdrawn from the oceanic circulation through the Yellow Sea Warm Current, circulated through a region with a very large surface to volume ratio where it is exposed to increased air-sea interaction, and returned to the oceanic circulation in the coastal currents. The two seas also serve as a huge mixing bowl, blending large quantities of freshwater into the oceanic environment. Recent estimates derived from radiocarbon measurements (Nozaki *et al.*, 1989) put the shelf water contribution to the Tsushima Current at 20% and the residence time of the shelf water at 2.3 years.

The only connection between the South China Sea and the Pacific Ocean proper is the Bashi Channel between Taiwan and Luzon, which has a sill depth of about 2600 m. Mindoro Channel and Balabac Channel connect the region with the Australasian Mediterranean Sea to the east and have sill depths of 450 m and 100 m. The connection to the Java Sea in the south is through Karimata Strait and Gasper Strait, which are simply openings of the shallow shelf between islands without sills. Taiwan Strait in the north, the connection to the East China Sea, has a sill depth of about 70 m. Malacca Strait, the only connection to the Indian Ocean, is extremely restricted in cross-section; it has a sill depth of 30 m and a width of only 32 km. It is dominated by large tidal currents which produce periodically shifting sand dunes of 4 - 7 m height and 250 - 450 m wave length at the bottom of the Strait.

The entire region of the South China Sea is under the influence of the monsoon system, and in the absence of major oceanic inflow the currents undergo a seasonal reversal of direction. This is particularly true for currents on the shelf which are easily forced by pressure gradients established through coastal sea level set-up. Direct current measurements are rare but some inferences can be made from the distribution of salinity. During May to September the southwest monsoon pushes the shelf water northward; this is believed to result in some compensatory southward movement over the deep basins (Figure 10.14). High rainfall during this season lowers salinities on the eastern shelf. During November to March the northeast monsoon reverses the direction of flow and the salinity adjusts accordingly. Along the coast of Vietnam this may develop into a strong boundary current. Further north, observations show that at least in the area north of 18°N poleward flow persists throughout winter in the inshore zone (Guan, 1986); detailed analysis of shallow water dynamics would be required to discuss this feature further.

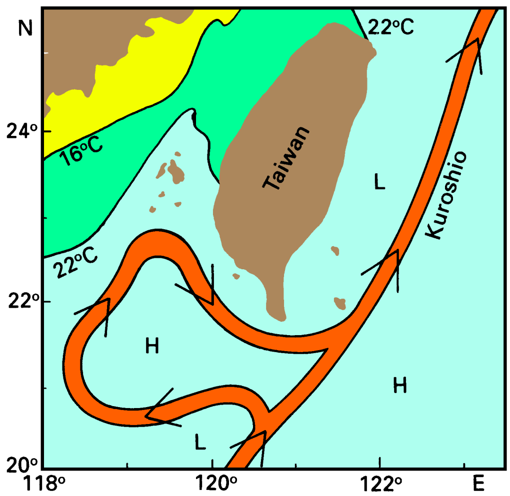


Fig. 10.15. Sea surface temperature and inferred flow direction in Taiwan Strait on 8 January 1986. Observed differences in steric height between high (*H*) and low (*L*) sea level are of the order of 0.15 m. Adapted from Wang and Chern (1988).

By convention, Taiwan Strait is considered part of the South China Sea, so some words on the flow through this strait are included here (it could have been included just as well in the discussion of the East China Sea, on which it exerts considerable influence). For a long time it was believed that water movement along the west coast of Taiwan is towards north

broad shelf in the south. The shelf is generally less than 50 m deep but contains a large central depression, the Bonaparte Basin with a maximum depth of 140 m. Maximum depths in the Timor Trough are near 3200 m. To the southwest the trough is closed to the Indian Ocean by a sill with about 1800 m sill depth; towards the east it is connected with the Aru Basin (which belongs to the Arafura Sea) via a sill with about 1400 m sill depth. Deep water renewal therefore occurs from the Indian Ocean.

The *Arafura Sea* south of the island of New Guinea is mostly a vast expanse of shelf generally 50 - 80 m deep, rising in its northwest to the Aru Islands. These islands are located close to the shelf break, which forms the base of many coral reefs before it falls off into the Aru Basin, a small isolated deep basin with maximum depths around 3650 m (Figure 13.5). Even though the sill depth to the Seram Basin in the north is slightly deeper than the sill depth in the south, a section of potential temperature (Figure 10.16) demonstrates that deep water renewal is from the Timor Trough (see also Figure 13.10).

Currents in the Timor and Arafura Sea are influenced by the winds and the throughflow from the Pacific Ocean through the Australasian Mediterranean Sea (see Chapter 13). There is therefore a steady westward flow along the southern side of the Sunda Islands. Further south and on the shelf currents are variable. This is the region of the shifting boundary between the Monsoon winds and the Trades; and the variability of the winds is reflected in the oceanic circulation.

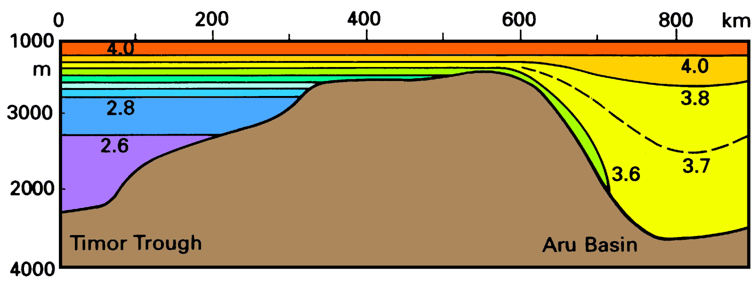


Fig. 10.16. Potential temperature (°C) below 1000 m depth along the axis of the Timor Trough and the Aru Basin. Contouring interval is 0.2°C; potential temperatures >4°C are not contoured.