Chapter 13

Adjacent seas of the Indian Ocean and the Australasian Mediterranean Sea (the Indonesian throughflow)

Being the smallest of all oceans, the Indian Ocean does not have the large number of distinct subregions found in the Pacific and Atlantic Oceans. Regions known under their own names include the Bay of Bengal and the Arabian Sea already discussed in the previous chapter, the Mozambique Strait (mentioned in the discussion of the western boundary currents), and the Great Australian Bight, clearly the least researched part of the Indian Ocean. Malacca Strait and the Andaman Sea form the transition region between the Bay of Bengal and the adjacent seas of the Pacific Ocean in Southeast Asia. The only regional seas that have some impact on the hydrography of the Indian Ocean and therefore require separate discussion are the Red Sea and the Persian Gulf. Since that discussion will not provide sufficient material for a full-length chapter, we include here the description of the Australasian Mediterranean Sea and what is often known as the Indonesian throughflow, i.e. the exchange of water between the Pacific and Indian Oceans. The Australasian Mediterranean Sea is of course a regional sea of the Pacific Ocean; but its impact on the Indian Ocean is much bigger than its influence on Pacific hydrography, and its inclusion in this chapter is justified on that ground alone.

The Red Sea

The Red Sea can be considered the prototype of a concentration basin. It is a deep mediterranean sea with a relatively shallow sill in a region where evaporation vastly exceeds precipitation (evaporation 200 cm per year, rainfall 7 cm per year, giving a net annual water loss of nearly 2 m). In such a basin water entering from the ocean in the surface layer undergoes a salinity increase and gets denser as it flows towards the inner end of the sea. This provokes vertical convection and guarantees continuous renewal of the water in the lower layer, which eventually leaves the basin in an undercurrent over the sill.

Geologically, the Red Sea is a rift valley formed during the separation of Africa and Arabia. Its topography (Figure 13.1) shows a maximum depth near 2900 m and a sill depth of about 110 m, significantly less than the average depth of 560 m. It is about 2000 km long but on average only 250 km wide. At its northern end it includes the shallow Gulf of Suez with average depths between 50 - 80 m and the Gulf of Aqaba, a smaller version of the Red Sea itself with a maximum depth near 1800 m and a sill depth close to 300 m.

Figure 13.2 gives a hydrographic section along the axis of the Red Sea and into the Gulf of Suez. The most notable feature is the extremely high salinity which makes the Red Sea the most saline region of the world ocean and gives it the character of an inverse estuary. The long and narrow shape of the basin isolates the inner part from direct exchange with the open ocean, so surface salinity increases continuously from 36 at the Strait of Bab el Mandeb to above 40 in the interior. Highest salinities above 42 are attained in the northern Red Sea and the shallow Gulf of Suez. In both regions the winter months, when the sea surface temperature in the Gulf of Suez sinks below 20°C (it ranges between 27 - 30°C

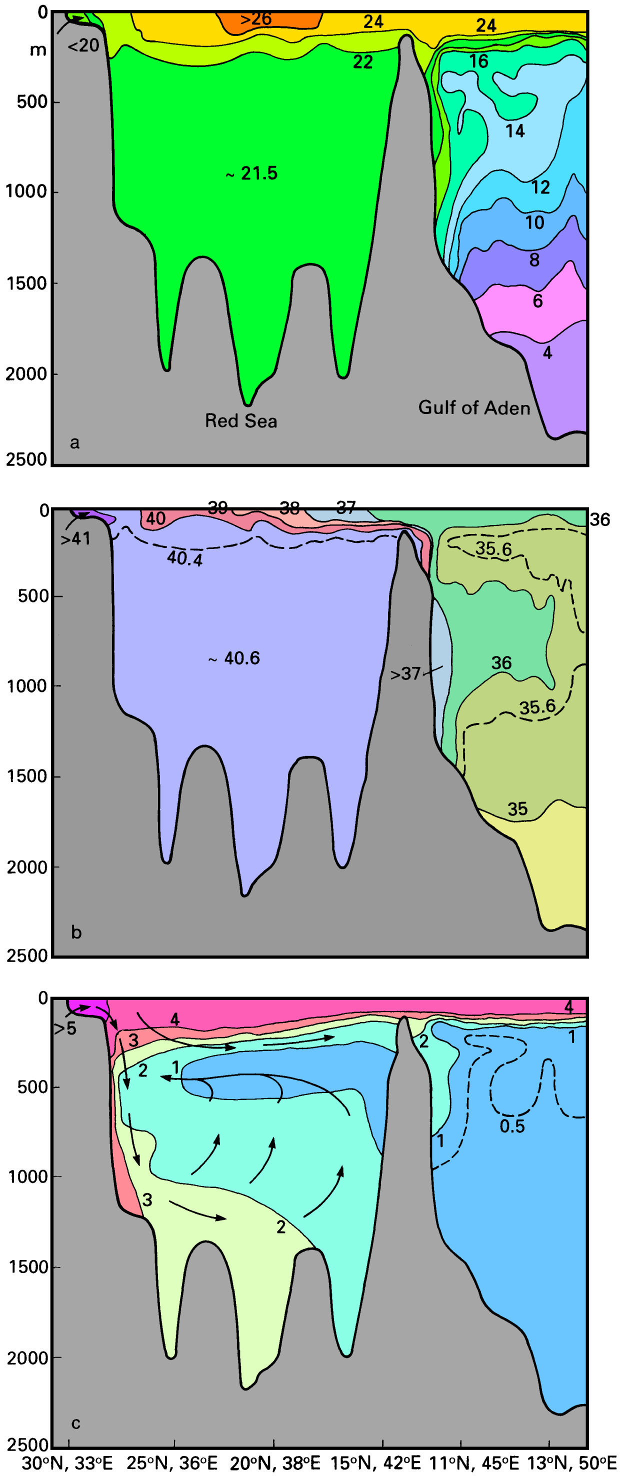


Fig. 13.2. Hydrographic section along the axis of the Red Sea, winter conditions.

(a) Potential temperature (°C)

(b) salinity

(c) oxygen (ml/l).

Arrows indicate the flow of deep water as derived in Cember (1988).

normal salinity mix. Gravimetric salinity determinations (weighing the sample before and after evaporation of the water) are more accurate; they still give salinities in excess of 250.

The Red Sea was the first region where hot brines were discovered at the sea floor (Figure 13.1). Similarly high temperatures and salinities are now known to exist above fissures in mid-ocean ridges of other ocean regions; temperatures in excess of 320°C have been measured at hydrothermal vents in the Pacific Ocean. More commonly, vents are associated with seepage of hypersaline water at environmental temperatures; this is the case for the majority of vents in the Pacific Ocean and those reported from the Gulf of Mexico. Large brine deposits can only accumulate where such vents are located in topographic depressions. The deposits in the Red Sea are possibly large enough to warrant commercial metal extraction at some time in the future.

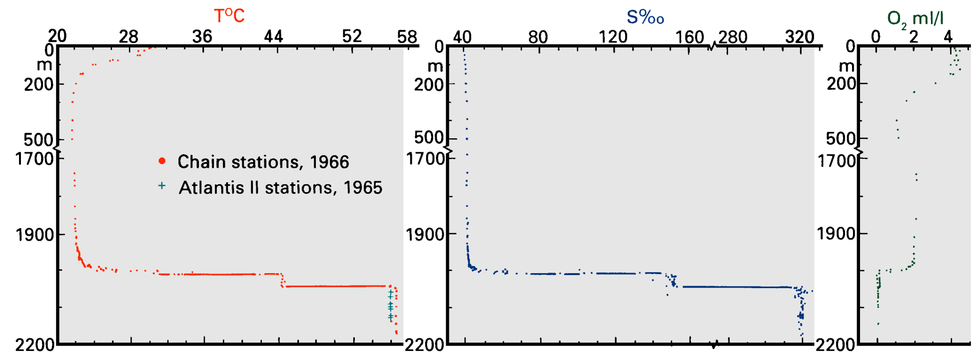


Fig. 13.3. Temperature and "salinity" (see explanation in text) in a hydrothermal vent of the Red Sea. From Brewer *et al*. (1969).

The Persian Gulf

The hydrography of the Persian Gulf is very similar to that of the Red Sea; but the much smaller volume of the Persian Gulf greatly reduces its impact on the Indian Ocean. Its length of 800 km together with an average width of 200 km gives it an area comparable to that of the Red Sea. Atmospheric conditions do not differ much between the two mediterranean seas (except that winds are from the north or northeast throughout the year over the entire area). The Persian Gulf is therefore a concentration basin, too. The rate of water loss at the surface is only slightly reduced by river runoff from the Euphrates and Tigris rivers. The main difference is that the Persian Gulf belongs entirely to the continental shelf, has a mean water depth of only 25 m and, with a sill depth at the Strait of Hormuz only marginally above its average depth, cannot hold back large quantities of salty deep water.

Figure 13.4 gives a hydrographic section through the Persian Gulf and the adjoining part of the Arabian Sea. Despite the difference in volume and residence time, the waters entering the Indian Ocean from the Persian Gulf and the Red Sea have very similar characteristics. The major difference is in oxygen content, which is markedly higher in Persian Gulf Water

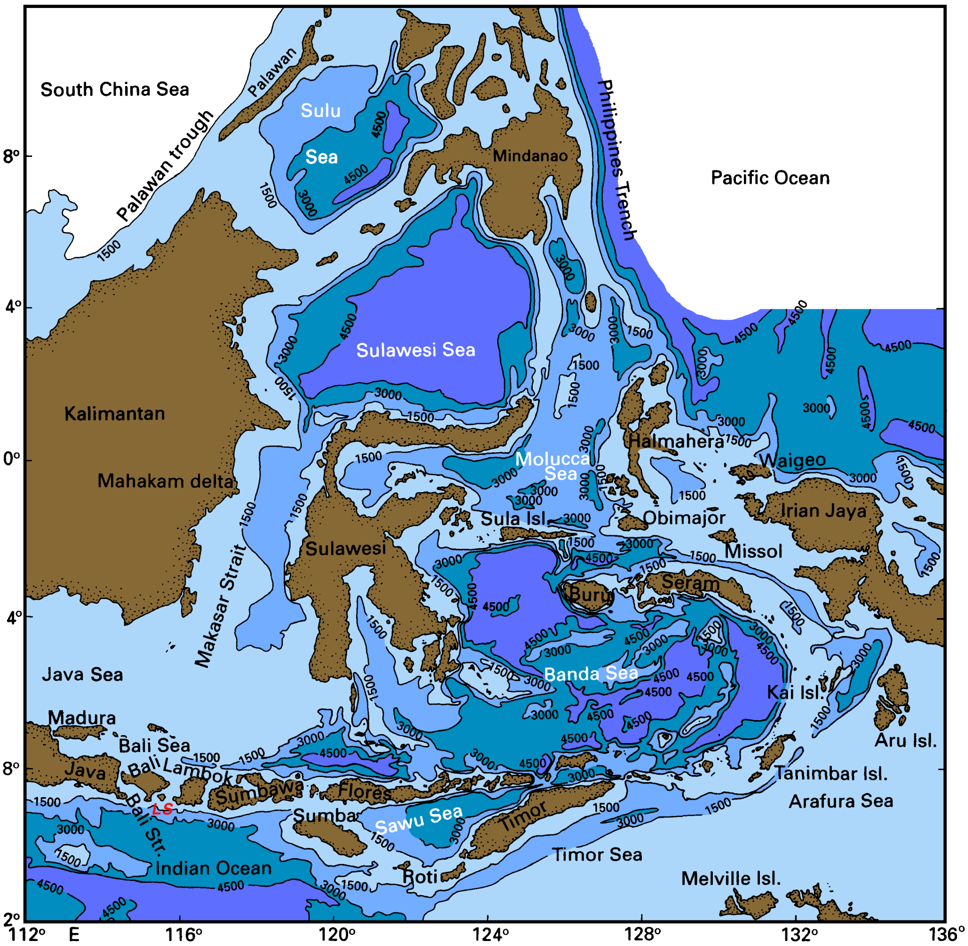
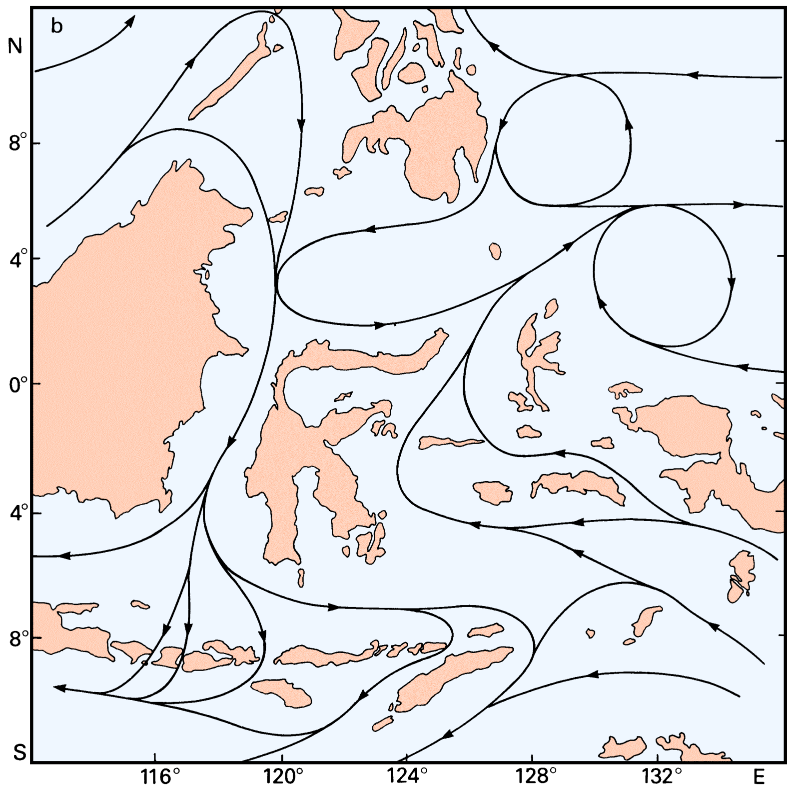


Fig. 13.5. Topography of the Australasian Mediterranean Sea. Depths are in m. LS: Lombok Strait.

(Figure 13.5). The largest and deepest is the Banda Sea which has depths in excess of 4500 m in the southeast (also known as the South Banda Sea) and in the northwest (the North Banda Sea), separated by a ridge of less than 3000 m depth; largest depths are near 7440 m in the south and 5800 m in the north. The Sulawesi Sea (formerly known as the Celebes Sea) is a single basin of similar size deeper than 5000 m over most of its area. Between these two major basins are three basins deeper than 3000 m, the Molucca, Halmahera, and Seram Seas, the latter being deeper than 5300 m. North of the Sulawesi Sea and enclosed by the islands of the Philippines is the Sulu Sea, which has depths in excess of 4500 m. The Flores Sea is located in the south, connecting the Banda Sea with the shallow Java Sea and reaching nearly 6400 m in a deep depression. The Sawu Sea, which reaches nearly 3500 m depth, is the southernmost basin between Timor, Sumba, and Flores. Another important topographic feature is Makassar Strait between the Sulawesi and



The atmospheric conditions leave no doubt that the Australasian Mediterranean Sea is a dilution basin. However, its circulation differs significantly from the schematic diagram of Figure 7.1. In the diagram, water that enters below the surface layer freshens as it is entrained into the surface layer and exits the basin with reduced salinity; deep water renewal through vertical convection is inhibited during all seasons by the high stability of the water column and is thus extremely slow, being determined by the rate of inflow over the sill. In the Australasian Mediterranean Sea, deep water renewal follows this scheme, but the circulation is markedly different. Nearly all inflow of high salinity water across the sill between the Sulawesi Sea and the Pacific Ocean proper occurs over the entire water depth, and nearly all outflow of low salinity water occurs into the Indian Ocean, again from the surface to the bottom of the passages between the south Indonesian islands. The modification is caused by the need for a net depth-integrated transport from the Pacific to the Indian Ocean. This requirement stems from the necessity to maintain constant pressure around islands. Constant pressure around Australia leads to a difference in depth-integrated steric height of about 70 m^2 between the western Australian coast (which shows the same values as the Australian east coast) and the east coast of the South Pacific Ocean. The net northward flow between Australia and Chile therefore has to pass through the Indonesian seas. Without this requirement, the freshened water would leave the Indonesian basins into both oceans - depending on the monsoon season - in a well defined surface layer.

hundred meters (18 Sv or $^3/_4$ of the total transport of the estimate mentioned above were found in the layer 0 - 150 m). The few observations that are available show, however, that surprisingly large velocities do occur close to the ocean floor at some locations. Current meters moored in Lifamatola Strait during January and February of 1985 in 1940 m water depth gave mean speeds of 0.61 m s^{-1} about 100 m above the bottom and 0.40 m s^{-1} about 400 m above the bottom. At both depths the currents regularly exceeded 1 m s^{-1} during spring tides. Such large velocities have to be associated with strong mixing. This will become evident in the discussion of bottom water renewal below.

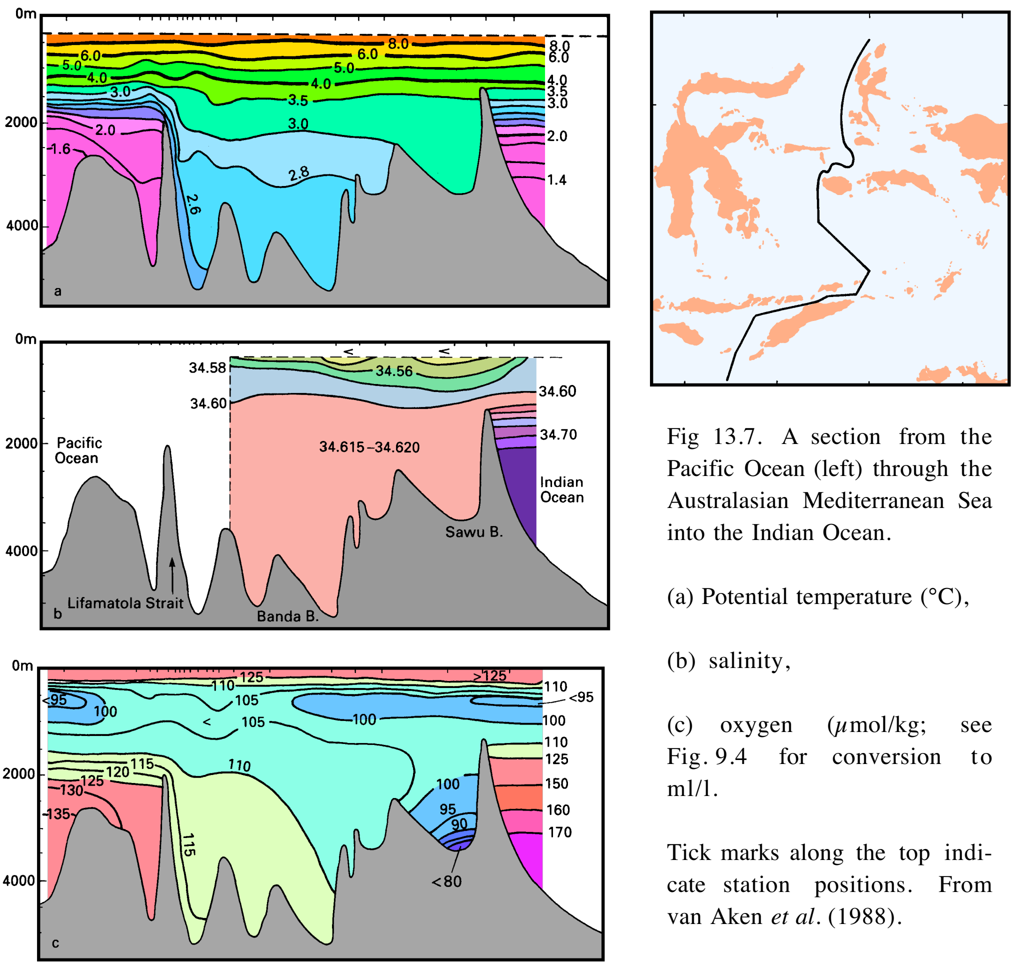


Fig 13.7. A section from the Pacific Ocean (left) through the Australasian Mediterranean Sea into the Indian Ocean.

(a) Potential temperature (°C),

(b) salinity,

(c) oxygen (μmol/kg; see Fig. 9.4 for conversion to ml/l.

Tick marks along the top indicate station positions. From van Aken *et al.* (1988).

the temperature stratification. This excludes deep vertical convection as the main mixing agent and requires highly turbulent flow well below the layer affected by the wind. Most likely the turbulence is concentrated near sills and related to strong tidal currents. The turbulence does, of course, affect salinity and temperature in identical fashion, so different surface boundary conditions for salinity and temperature are required to erase a salinity gradient without eliminating the temperature gradient. While a high freshwater input at the surface is responsible for homogenizing the salinity, maintaining the temperature gradient in the presence of strong mixing is impossible without a large input of heat to keep the sea surface temperature up. The atmospheric conditions found in the Australasian Mediterranean Seas can thus be deduced from its T-S properties.

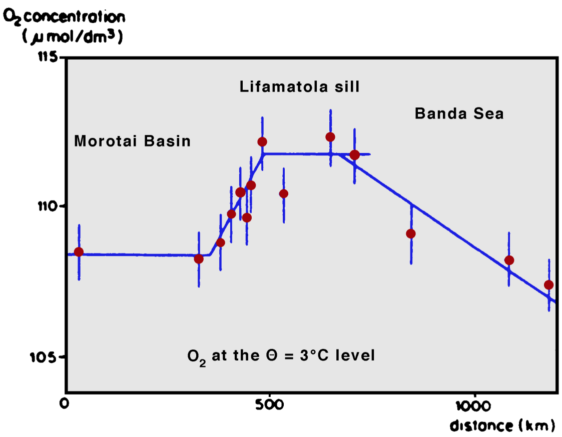


Fig. 13.9. Oxygen (units see Fig. 13.7) at the level of the 3°C potential temperature isotherm in Lifamatola Strait. From van Aken et al. (1988).

The turbulence of the upper layer does not reach much below the sill depths of the various basins. Nevertheless, oxygen values in the deep basins do not differ dramatically from those of the waters above, indicating reasonably short renewal times for the water below the sill depths. Figure 13.10 gives renewal paths and age estimates for bottom water derived from the distribution of dissolved silica. Most of the water participates in the interoceanic throughflow and has transit times of a few years. Water movement through the Seram Sea is from the east, partly in continuation of a loop from Makassar Strait through the South Banda Sea, partly as inflow from the Indian Ocean. The oldest water in the region is probably found towards the end of the loop in the deep depression of the South Banda Sea below 7000 m (the Weber Deep).