Sea surface temperature and salinity

As in the other oceans, sea surface salinity (SSS; Figure 2.5b) follows the *P-E* distribution (Figure 1.7) outside the polar and subpolar regions closely. The *P-E* minimum near 30°S is reflected by a SSS maximum. The decrease of SSS values further south continues into the Southern Ocean, reflecting freshwater supply from melting Antarctic ice. However, the lowest surface salinities are found in the northern subtropics, where they reach values of 33 and below on annual mean; during the Summer Monsoon season, surface salinity in the inner Andaman Sea is below 25.

Surface salinity in the eastern tropical region is rather uniform near and below 34.5, close the values found in the western tropical Pacific Ocean. SSS values increase towards the African coast and north into the Arabian Sea, where the annual mean reaches its maximum with values above 36. Higher salinities are reached in the Red Sea and Persian Golf, two mediterranean seas with extreme freshwater loss from evaporation (see Chapter 13).

When it comes to the distribution of sea surface temperature (SST) the entire northern Indian Ocean appears as a continuation of the western Pacific "warm pool" (the equatorial region east of Mindanao which is generally regarded the warmest region of the open ocean). The contouring interval chosen for Figure 2.5a displays it with temperatures above 28°C; over most of the region, annual mean temperatures are in fact above 28.5°C. Only the Somali Current region shows annual mean temperatures below 28°C, a result of upwelling during the Southwest Monsoon which brings SST down to below 20°C during summer (Figure 11.16). A remarkable feature of the seasonal SST cycle in the northern Indian Ocean is that the SST maximum does not occur during summer but during the spring transition from Northeast to Southwest Monsoon. May SST values are above 28°C everywhere north of the equator and north of 10°S in the east. As the Southwest Monsoon develops, advection of upwelled water reduces summer SST values to 25 - 27°C.

Lack of upwelling along the western Australian coast means that surface isotherms in the southern hemisphere show nearly perfect zonal orientation. Small deviations along both coastlines reflect the poleward boundary (Agulhas and Leeuwin) currents. There is also no upwelling along the equator, so the equatorial SST minimum which is so prominent in the Pacific and also visible in the Atlantic Ocean is not found in the Indian Ocean.

Abyssal water masses

Antarctic Bottom Water (AABW) fills the Indian Ocean below approximately 3800 m depth. By the time it leaves the Circumpolar Current its properties correspond to those of Antarctic Circumpolar Water (potential temperature 0.3°C, salinity 34.7; see Figure 6.13). The situation is not really much different from that in the Atlantic Ocean, where the water at the ocean floor is usually called Antarctic Bottom Water; however, most authors refer to the bottom water in the Indian Ocean as Circumpolar Water. The distribution of potential temperature below 4000 m (Figure 12.1) indicates two entry points. Entry into the Madagascar Basin has been well documented and occurs through gaps in the Southwest Indian Ridge near 30°S, 56 - 59°E. The flow gradually finds its way across to the Madagascar continental slope, where it forms a deep western boundary current (Swallow and Pollard, 1988). In a zonal temperature section (Figure 12.2) it is seen as a steep rise of the deep isotherms against the slope, consistent with northward geostrophic movement in

Mozambique Strait; nevertheless, AABW recirculation in the basin must be swift, since observations of bottom currents in the 4500 m deep channel between the Agulhas Plateau and the African shelf gave average northward speeds underneath the Agulhas Current of 0.2 m s^{-1} (Camden-Smith *et al*., 1981).

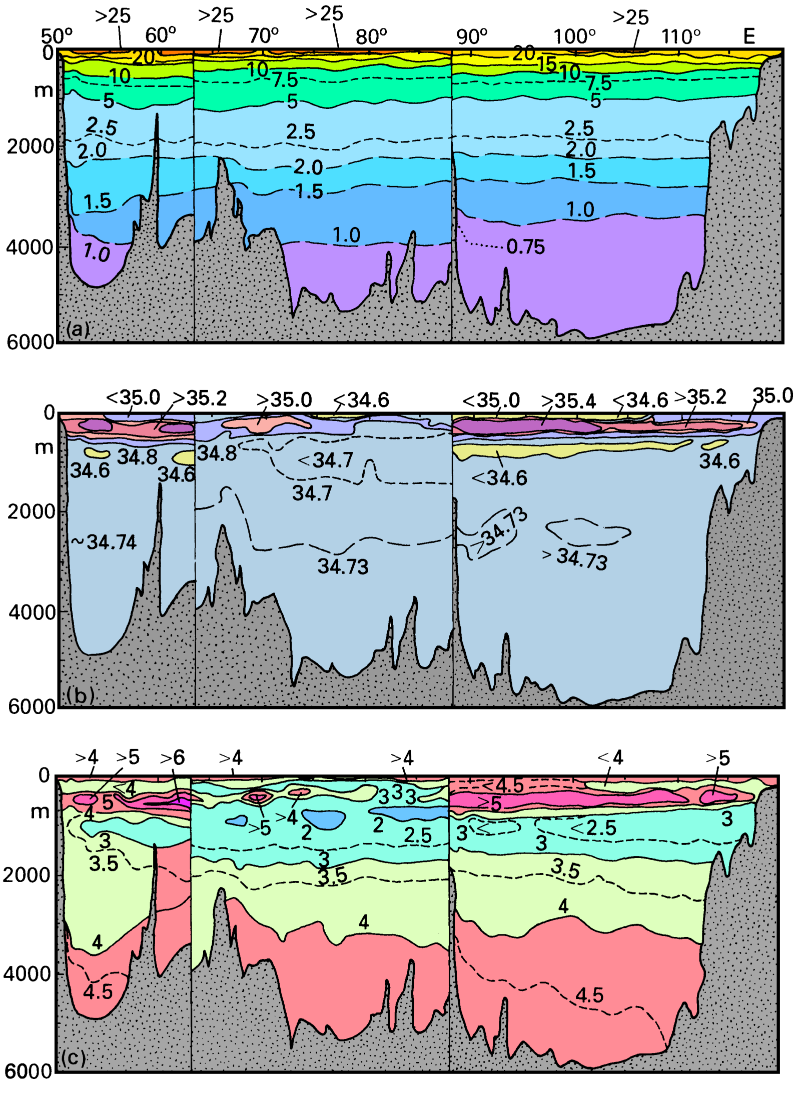

Fig. 12.2. A section across the Indian Ocean from Madagascar to Australia along 18°S, between 63°E and 88°E along 12°S. (a) Potential temperature (°C), (b) salinity, (c) oxygen. Adapted from Warren (1981b, 1982). See Fig. 12.1 for location of section.

incapable of reaching much deeper than 1000 m in the northern hemisphere and 1500 m in the south. It appears therefore that Indian Deep Water penetrates northward in the western boundary current from where it spreads eastward and upward into the Arabian Sea and Bay of Bengal. Its properties are modified along the way by mixing with thermocline water above, upwelling of Antarctic Bottom Water from below, and injections of Red Sea and Persian Gulf Water at their respective densities.

To compensate for northward flow of Bottom Water below and Intermediate Water above, some southward movement must occur in the depth range of Indian Deep Water in both hemispheres. The distribution of salinity and oxygen (Figure 12.3) indicates this for the depth range 2000 m and below, i.e. the upper range of the distribution of Deep Water.

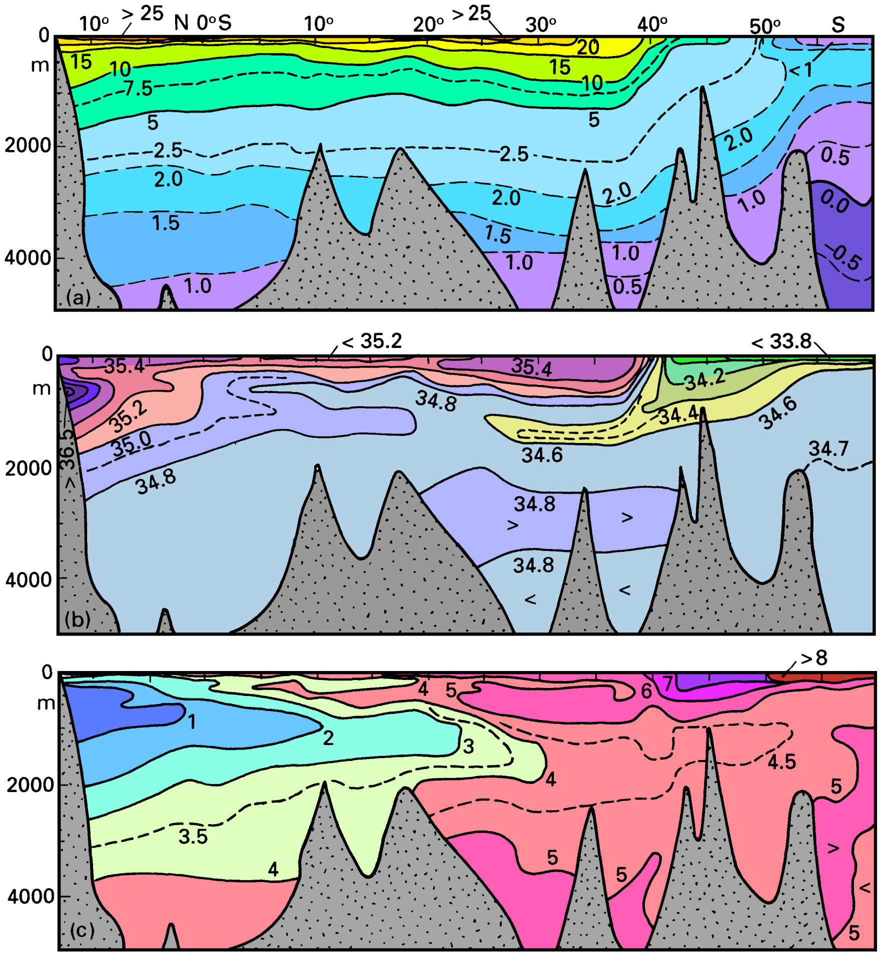

Fig. 12.3. A section across the Indian Ocean along approximately 40°E and following the African coast. (a) Potential temperature (°C), (b) salinity, (c) oxygen (ml/l). From Wyrtki (1971). See Fig. 12.1 for location of section.

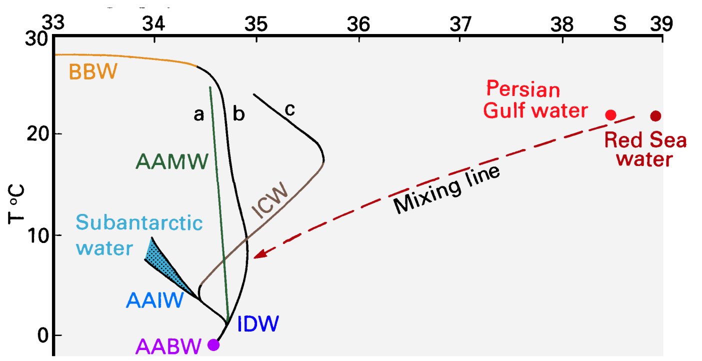

Fig. 12.5. T-S diagram showing the source water masses for the Indian Ocean and their effect on the temperature - salinity structure in different regions. Curve *a* is representative for the region between Australia and Indonesia (120°E), curve *b* for the Bay of Bengal (88°E) to 10°S, curve *c* for the subtropics south of 10°S. Intrusions of Red Sea and Persian Gulf Water can produce departures from the T-S curves near the isopycnal surface σ_t = 27.2 (the "mixing line").

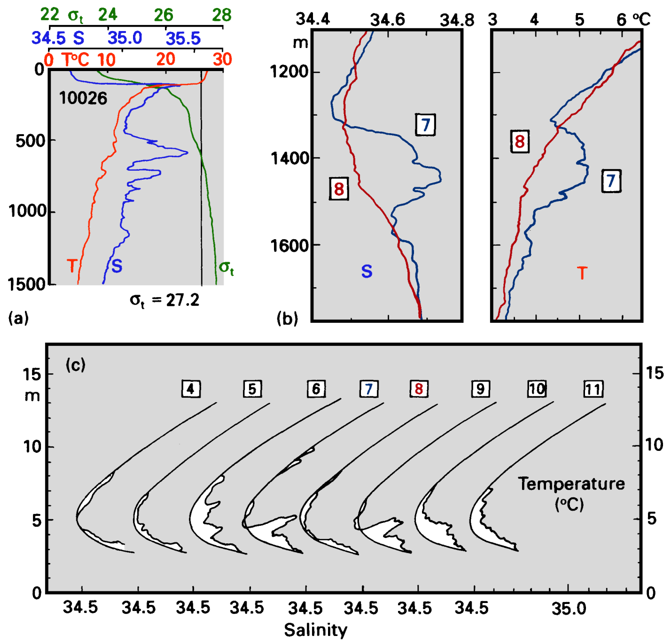

Fig 12.6. Observations of Red Sea and Persian Gulf Water.

(a) Temperature (°C), salinity, and density (σ_t) at a station in the Somali Current near 3°N (the density 27.2 marks the separation between Persian Gulf Water above and Red Sea Water below. Note also the uniform salinity at 300 - 400 m and 800 - 1100 m indicative of the presence of AAMW),

(b) temperature (°C) and salinity against depth at two stations in the Agulhas Current near 29°S, with little (stn 8) and strong (stn 7) presence of Red Sea Water,

(c) T-S diagrams from eight stations (stns 4 - 11) across the Agulhas Current along 29°S (see Fig. 12.1 for location). The diagrams are shifted along the salinity axis by 0.3 units. The smooth curve is the mean from 20 stations without Red Sea Water presence and shows the AAIW salinity minimum. Adapted from Gründlingh (1985b).

Water masses of the thermocline and surface layer

Two water masses occupy the thermocline of the Indian Ocean (Figure 12.8). *Indian Central Water* (ICW) is a subtropical water mass formed and subducted in the Subtropical Convergence (STC), as described in detail in Chapter 5. It originates from the Indian Ocean sector of the STC; negative values in Figure 5.7 indicate that south of 30°S subduction occurs from the Agulhas retroflection into the Great Australian Bight. In hydrological properties ICW is identical to South Atlantic and Western South Pacific Central Water. *Australasian Mediterranean Water* (AAMW), on the other hand, is a tropical water mass derived from Pacific Ocean Central Water and formed during transit through the Australasian Mediterranean Sea, as discussed in Chapter 13. There is no established nomenclature for this water mass; Banda Sea Water, Indonesian Throughflow Water, and other names are found in the literature. The water enters the Indian Ocean between Timor and the Northwest Shelf and through the various passages between the islands east of Bali. The transport of AAMW into the Indian Ocean, a key quantity in models of the recirculation of North Atlantic Deep Water (see Chapter 7), is unknown at present. This question will be addressed in much more detail in Chapter 13 where it will be argued that a transport of 15 Sv or more may be a good estimate.

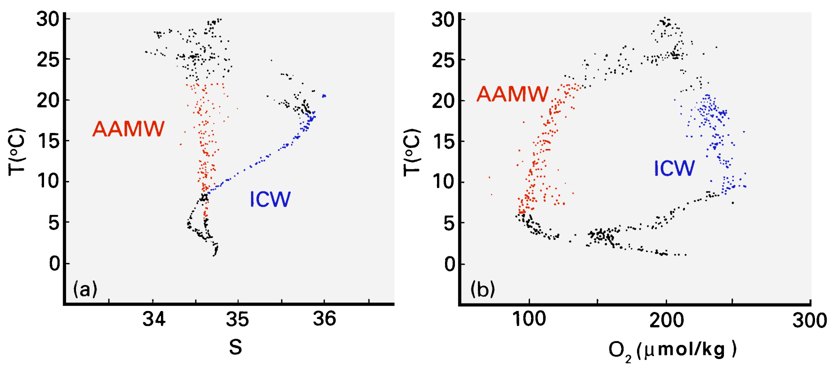

Fig. 12.8. Water mass properties of Indian Central Water (ICW) and Australasian Mediterranean Water (AAMW). (a) T-S diagram, (b) T-O_2 diagram. The data for ICW are from 25 - 30°S and east of 105°E, the data for AAMW from 7 - 15°S, 120 - 125°E. From Tomczak and Large (1989).

The large impact of AAMW on the hydrological structure of the Indian Ocean thermocline certainly points towards a large supply of Mediterranean Water. Outflow into the Indian Ocean occurs over the entire upper kilometer of the water column. The low salinity of the outflowing water makes salinity a good indicator for the presence of AAMW down to 600 m; at that depth the temperature is in the range 7 - 8°C, the T-S curves of ICW and AAMW intersect (Figure 12.8), and the salinity contrast between the water masses disappears. Above 600 m, maps of salinity on depth or density surfaces

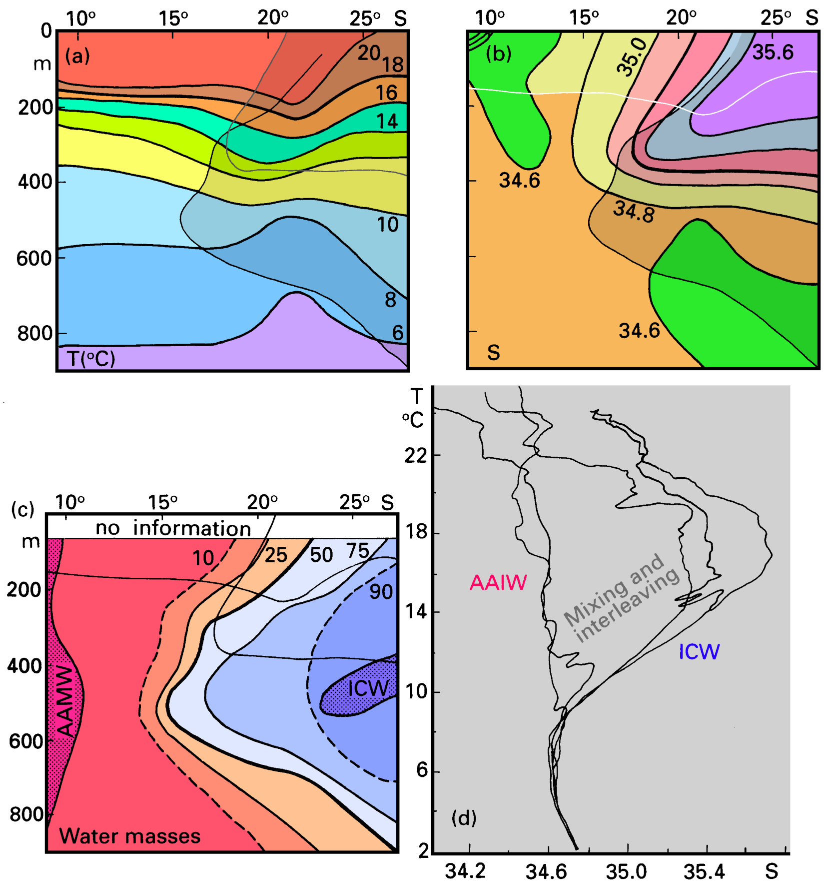

Fig. 12.10. A section through the front between Indian Central Water and Australasian Mediterranean Water along 110°E. (a) Temperature (°C), (b) salinity, and (c) water masses (% of ICW content) from bottle casts along 110°E , (d) T-S diagrams from selected CTD stations, showing evidence of interleaving in the frontal zone. The positions of the thermocline (indicated by the 18°C isotherm), halocline (the 35.2 isohaline), and water mass boundary (defined as the 50% ICW or 50% AAMW contour) are indicated in (a), (b), and (c). See Fig. 12.1 for location of the section.

Being closed in the subtropics, the northern Indian Ocean does not have its own subtropical convergence; its thermocline water has to be replenished from the tropics and further south. Supply of Indian Central Water to the northern hemisphere is clearly seen on the 26.7 σ_Θ surface of Figure 12.9. At that density subduction at the STC occurs at 11.5 - 12.0°C and a salinity near 35.1. This water type dominates the density surface south of the front at 10°S and enters the northern Indian Ocean with the western boundary current. Oxygen values are fairly uniform south of the front, suggesting reasonably swift recirculation of ICW in the subtropical gyre. Transition into the northern hemisphere is

surface salinity in the eastern Bay below 33.0 throughout the year. Its influence extends well into the tropics (Figure 12.11). During October - December it reaches the area along the western Indian coast with the East Indian Winter Jet. Salinities along the western Indian coast return to oceanic values for a brief period during April - June, but the Summer Monsoon season brings increased runoff from rivers and lowers the salinity again. From the point of view of water mass classification the low salinity water along the western Indian coast can be subsumed under Bay of Bengal Water, on account of its nearly identical properties (Figure 12.11).

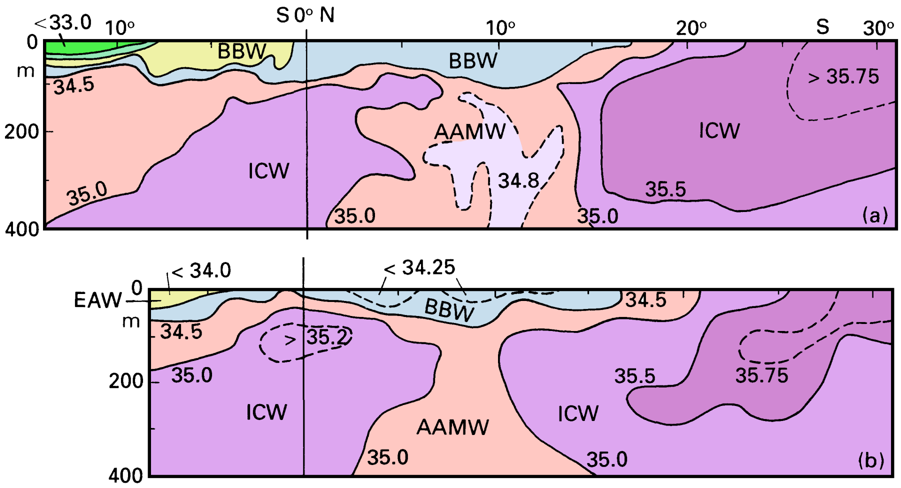

Fig. 12.11. Meridional sections of salinity showing the spreading of Bay of Bengal Water. (a) for the component originating in the inner Bay of Bengal, along 92°E, (b) for the component found along the west coast of India (for the purpose of identification labelled "East Arabian Sea Water" or EAW in the figure), along 75°E. From Wyrtki (1971).

Although the main halocline which delineates the boundary between BBW and ICW is located close to 100 m, small but significant salinity gradients occur well above that depth. They result from the fact that river water spreads across salt water in a thin film. The hydrological structure of BBW is thus somewhat reminiscent of the structure in an estuary: little or no variation of temperature with depth but important variations of salinity. In the surface mixed layer the salinity variations are erased very quickly by wind mixing; but winds in the Bay are usually light, and the mixed layer is rarely deeper than 50 m (Figure 5.6). Salinity variations below the mixed layer but above the main halocline/thermocline are maintained. A characteristic feature of Bay of Bengal Water is therefore the existence of a barrier layer throughout the year (Figure 5.7). In contrast to western Pacific Ocean, where the barrier layer is maintained by surface layer dilution from local rainfall, the barrier layer in the Bay of Bengal owes its existence to advection of low salinity water diluted from monsoonal river runoff. The consequences for the heat budget, outlined in Chapter 5, are the same: The net heat flux into the Bay of Bengal from the