Chapter 12

Hydrology of the Indian Ocean

The distribution of hydrological properties in the Indian Ocean is much less affected by the seasonal monsoon cycle than the near-surface current field. Direct monsoonal influence is restricted to the surface mixed layer and the western boundary currents. The two most important factors which make Indian Ocean hydrology different from the hydrology of the other oceans are the closure of the Indian Ocean in the northern subtropics and the blocking effect of the equatorial current system for the spreading of water masses in the thermocline. In the Pacific and Atlantic Oceans, mixing of water in the tropics and subtropics occurs mainly on isopycnal surfaces (the exception being the Equatorial Undercurrent). This is not so in the northern Indian Ocean, because conservation of mass under isopycnal conditions is impossible, given the geographical and dynamic constraints.

Precipitation, evaporation, and river runoff

The most striking characteristic of the rainfall distribution over the Indian Ocean is the anomalous difference between the eastern and western regions in the north. Annual mean precipitation varies between 10 cm per year in the west (on the Arabian coast) and 300 cm per year or more in the east (near Sumatra and over the Andaman Sea). This is the reverse of the situation usually encountered in the subtropics, where the Trades bring dry continental air out over the sea in the east and rain to the western coast. The normal situation of little rain in the east and high rainfall in the west prevails in the southern Indian Ocean; western Australia receives less than 50 cm per year but Madagascar some 200 cm per year. As a result, contours of equal precipitation show more or less zonal orientation in the south but meridional orientation in the north.

Given the small variation of evaporation over the region, the precipitation-evaporation balance (*P-E*; Figure 1.7) reflects the rainfall distribution closely. The change from zonal to meridional direction of the *P-E* gradient occurs near 10°S in the west and closer to the equator in the east. The continuation of the Pacific Intertropical Convergence Zone (ITCZ) and associated rainfall region into the Indian Ocean along 5°S brings rain to the seas west of Sumatra throughout the year; it dominates the annual mean distribution between 10°S and the equator. North of the equator the annual mean is a poor representation of the actual situation. *P-E* values vary from 600 cm per year along the western Indian coast and in the eastern Bay of Bengal during the Summer Monsoon to -150 cm per year during the Winter Monsoon. As with the winds and the currents, the Summer Monsoon produces the stronger signal and dominates the annual mean *P-E* distribution, which shows the eastern Bay of Bengal as a region of freshwater gain comparable in importance to the ITCZ.

Although the land drainage area of the Indian Ocean is rather small - the west coast of Africa (the Sambesi being the most important freshwater source), Madagascar, the coastal strip of western Australia, Sumatra, Java, and the Indian and Indochinese subcontinent - the influence of the Asian rivers is amplified by the monsoonal climate. The summer floodwaters which the Ganges and Brahmaputra empty into the Gulf of Bengal, the Indus into the Arabian Sea, and the Irrawady and Salween Rivers into the Andaman Sea, influence the salinity of the surface waters over thousands of kilometers offshore.

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

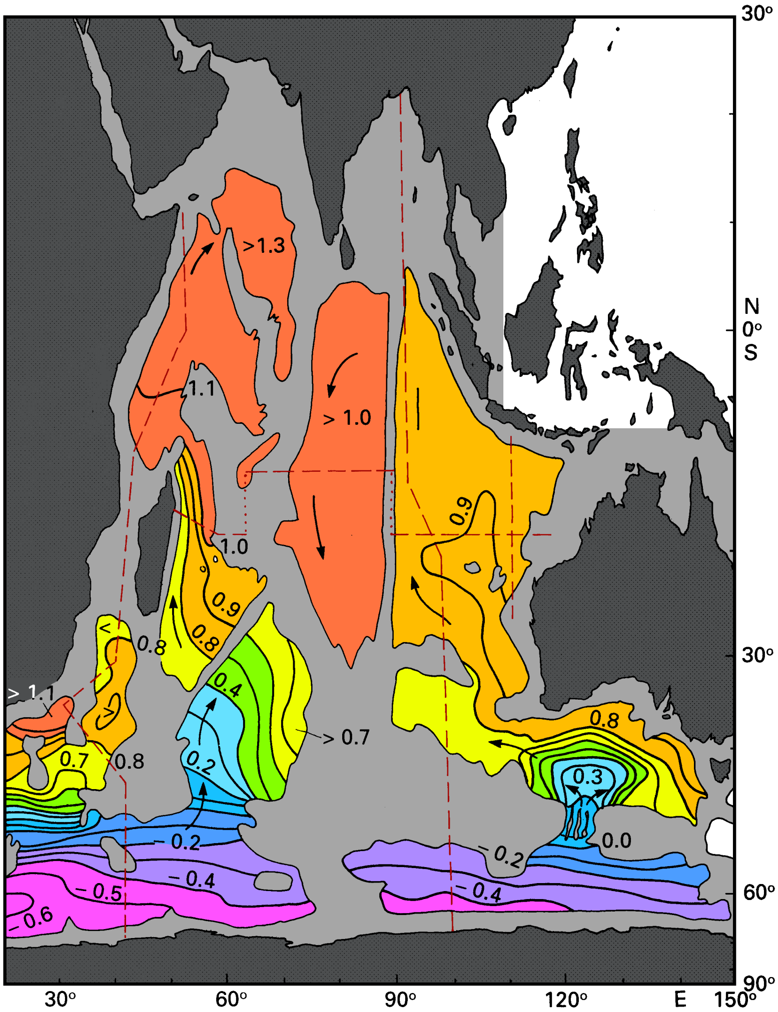


Fig. 12.1. Potential temperature at 4000 m depth. The approximate 4000 m contour is shown as a thin line. Arrows indicate the path of Antarctic Bottom Water. Thin broken lines indicate the locations of the sections shown in Figs. 12.2 - 12.4, 12.6c, and 12.10. Adapted from Wyrtki (1971), with modifications from Rodman and Gordon (1982).

which the speed increases with depth (rule 2a of Chapter 3). In the east, AABW enters the South Australia Basin via the Australian-Antarctic Discordance, a region in the inter-oceanic ridge system with multiple fractures near 50°S, 124°E south of Australia. Having filled the depths of the Great Australian Bight it moves west and then north into the Perth, Wharton, and North Australia Basins, forming a western boundary current along the Ninety East Ridge (Figure 12.2). Flow of AABW through the Mozambique Basin is blocked by

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).

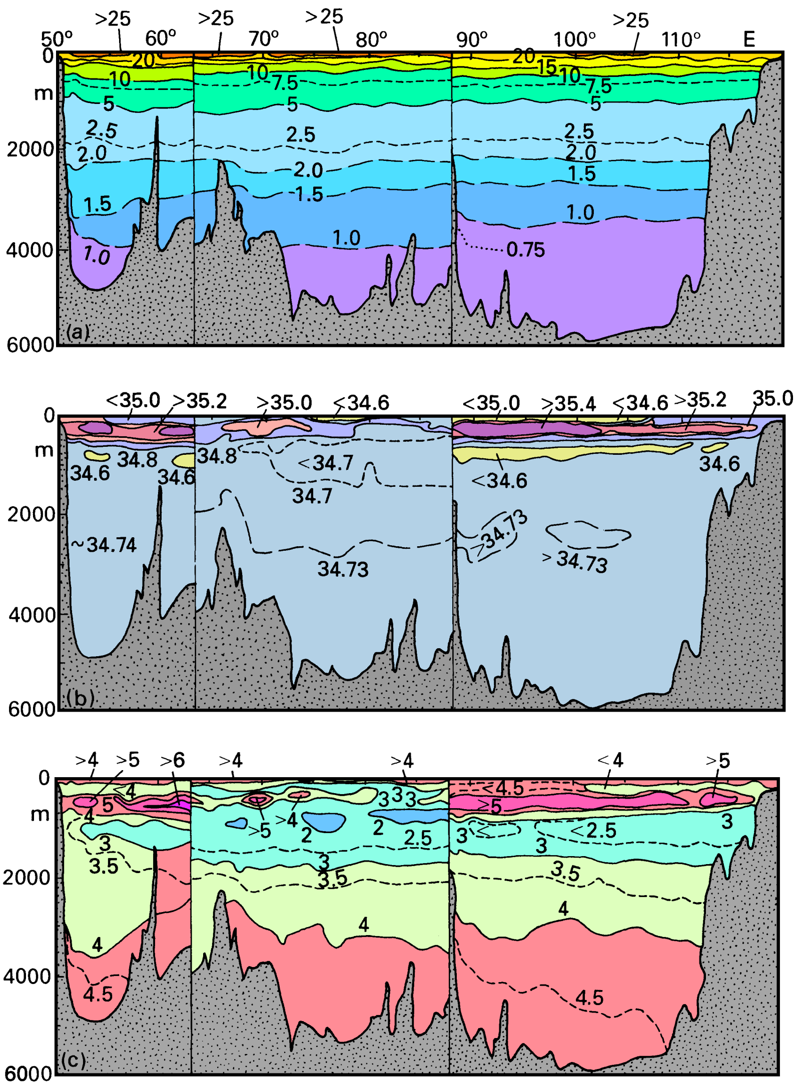


Fig. 12.2. A section across the Indian Ocean from Madagascar to Australia along 18°S, between 63°E and 88°E along 12°S. (a) Potential temperature (°C), (b) salinity, (c) oxygen. Adapted from Warren (1981b, 1982). See Fig. 12.1 for location of section.

It is likely that both deep western boundary currents of Antarctic Bottom Water continue into the northern hemisphere, although direct observations exist only for the western pathway in the Somali Basin. This water eventually enters the Arabian Basin, where it must disappear through gradual upwelling into the overlying Deep Water. AABW from the eastern path proceeds into the Mid-Indian Ocean Basin, flowing over deep saddles in the Ninety East Ridge near 10°S and 5°S, and turns south; the differences in temperature and oxygen across the Ninety East Ridge below 3000 m (Figure 12.2) testify for the different ages of the waters on either side of the ridge. The inflow into the Mid-Indian Ocean Basin is a trickle of 0.5 Sv, but entrainment of Deep Water during the overflow may increase transport in the western boundary current to 2 Sv. Again, the AABW must eventually disappear through upwelling.

The depth range from 3800 m upward to about 1500 - 2000 m and above is occupied by *Indian Deep Water* (IDW). Based on water mass properties the transition from Bottom to Deep Water is gradual, and some authors refuse to use the terms Bottom and Deep Water, referring to lower and upper deep water instead. This may appear logical since in the southern Indian Ocean both water masses have been observed to move northward together. A look at meridional hydrological sections (Figs. 12.3 and 12.4) proves, however, that the distinction between Deep and Bottom Water is justified. Indian Deep Water is characterized by a salinity maximum in the southern hemisphere exceeding 34.8 in the west and reaching 34.75 in the east. It occupies the depth range 2000 m - 3800 m north of 45°S and comes to within 500 m of the surface further south. Its properties in the high-salinity core near 40°E (temperature 2°C, salinity 35.85, oxygen 4.7 ml/l) match the properties of North Atlantic Deep Water in the Atlantic sector of the Southern Ocean (Figure 6.13) exactly. The obvious conclusion is that IDW is of NADW origin. Unlike Antarctic Bottom Water, Indian Deep Water is not formed in the Southern Ocean; it represents that fraction of NADW which is not converted into Intermediate Water in the Atlantic sector but carried across into the Indian Ocean with the upper Circumpolar Current, along the path already discussed in Chapter 9 (Figure 9.6).

Like the flow of Bottom Water, the flow of Indian Deep Water is northward and concentrated in western boundary currents. In Figure 12.2 it is clearly seen in the oxygen data along the Ninety East Ridge and in the temperature and oxygen data below 2500 m along the Madagascar shelf. The transport of the combined flow of AABW and IDW in these boundary currents is estimated at 6 Sv in the eastern basin and 5 Sv in the western basin. A third western boundary current of Deep Water is indicated in Figure 12.2 along the Central Indian Ridge at 2200 m - 3200 m, since water depths south of the Mid-Indian Ocean Basin are deep enough to allow direct advection of IDW from the Southern Ocean. It flows against the slow southward spread of AABW underneath, carrying about 3 - 5 Sv.

Little is known at present about the sub-thermocline circulation in the northern Indian Ocean. The only northern sources capable of supplying water to depths below the permanent thermocline are the Red Sea and the Persian Gulf. *Red Sea Water* enters the Indian Ocean with a temperature close to 22°C and a salinity near 39 (Figure 12.5), giving it a density (σ_t) of about 27.25. In the Arabian Sea the same density is found at depths of 600 - 800 m and progressively deeper toward south until it reaches 1000 - 1100 m near 30°S. *Persian Gulf Water* has similar temperatures and salinities but slightly lower densities (σ_t 26.7 and above) found at about 250 - 300 m in the Arabian Sea and at 500 - 600 m south of Madagascar. Compared with the flow of IDW from the south, supply from the two mediterranean seas is small, and given their densities, both sources are 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.

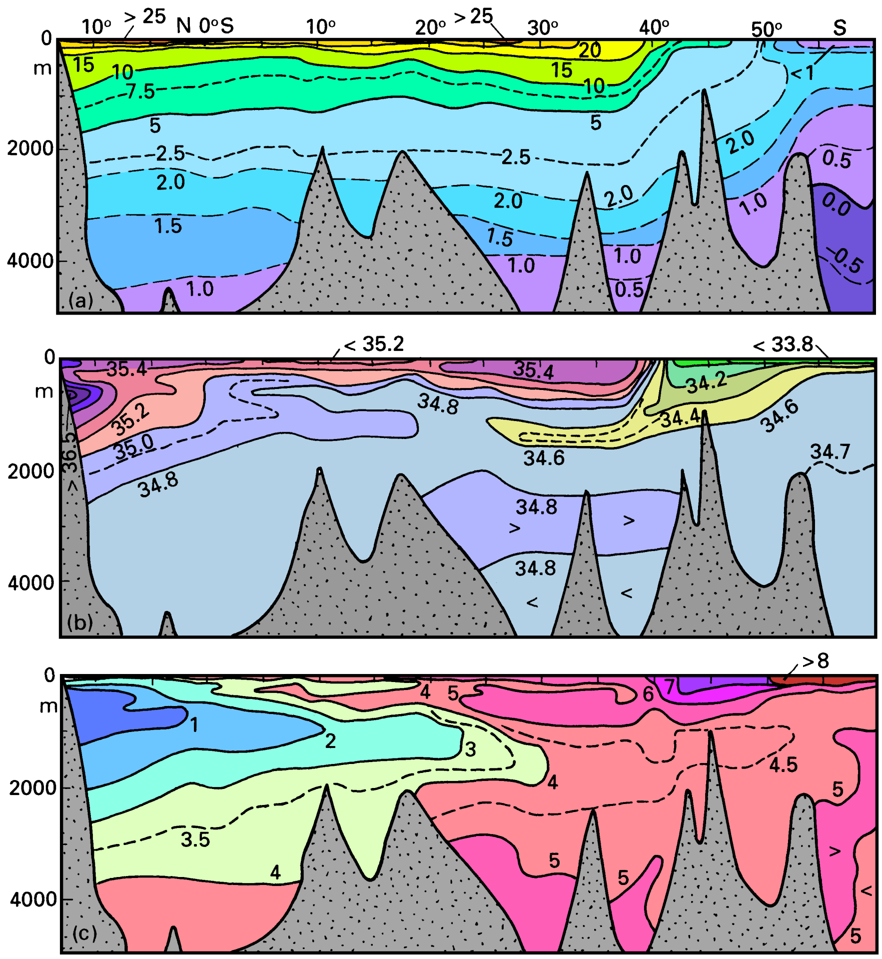


Fig. 12.3. A section across the Indian Ocean along approximately 40°E and following the African coast. (a) Potential temperature (°C), (b) salinity, (c) oxygen (ml/l). From Wyrtki (1971). See Fig. 12.1 for location of section.

The influence of Red Sea Water and Persian Gulf Water on the water mass structure of the northern Indian Ocean is seen in the salinity maximum found in the upper kilometer in the north and closer to 1500 m some 3000 km further south (Figure 12.3). Details of their spreading are only known from the Somali Current region where both water masses are seen as density-compensated lenses and intrusions about 200 - 500 m thick and some 100 km in diameter (Figure 12.6a). Circulation outside the Somali Current at the depth of these intrusions and of the Intermediate Water must be extremely sluggish; at 1000 m the oxygen concentration falls below 1.2 ml/l everywhere north of the equator. Mixing in the boundary current must therefore be important in converting the lenses and intrusions into the smooth salinity maximum seen in the large-scale distribution of properties.

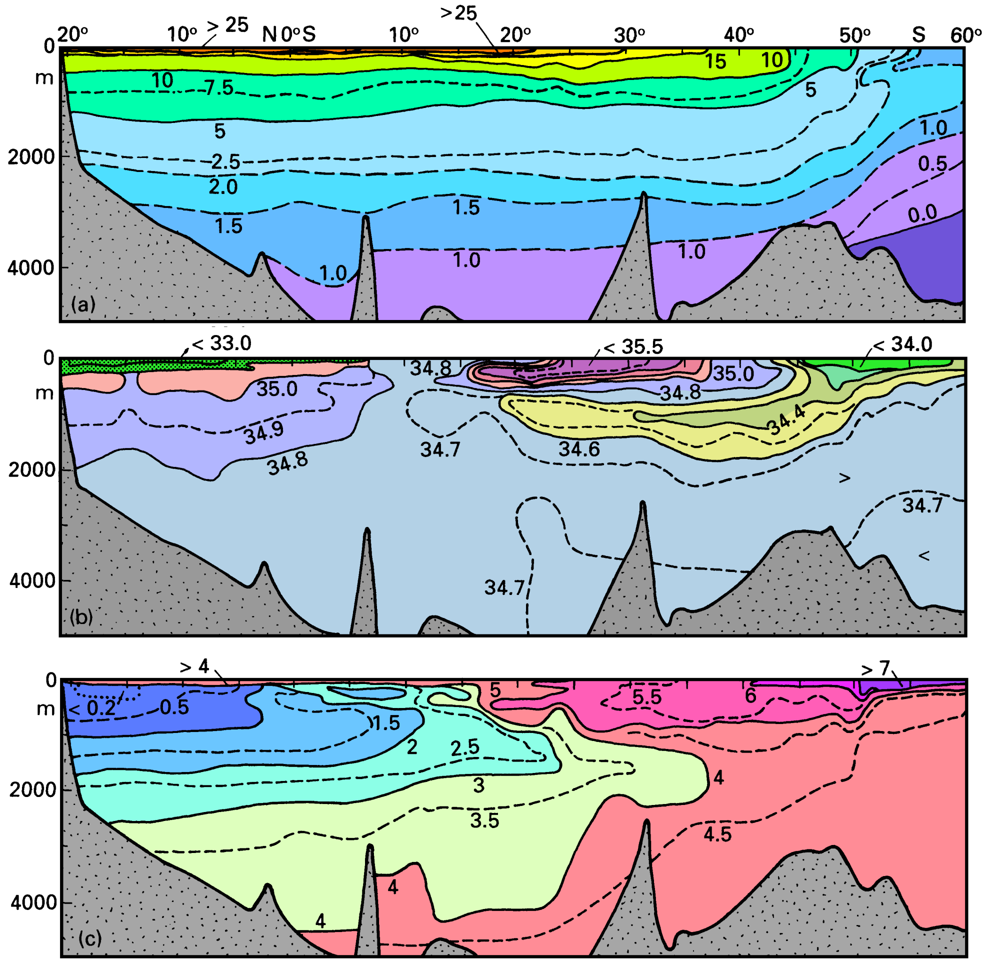


Fig. 12.4. A section across the Indian Ocean along approximately 95°E. (a) Potential temperature (°C), (b) salinity, (c) oxygen (ml/l). From Wyrtki (1971). See Fig. 12.1 for location.

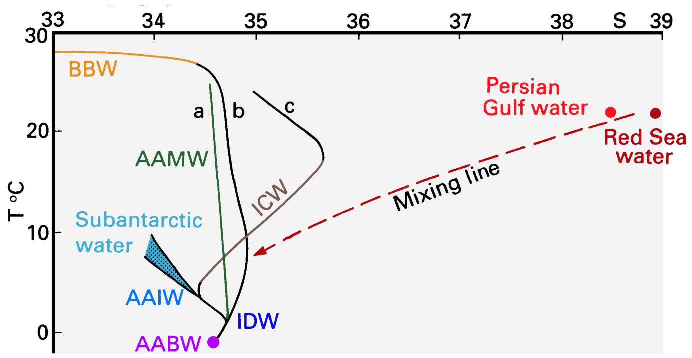
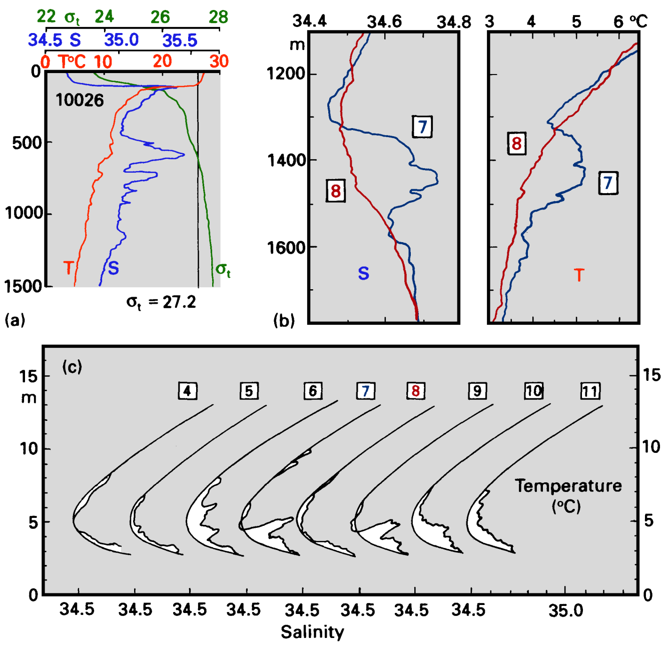


Fig. 12.5. T-S diagram showing the source water masses for the Indian Ocean and their effect on the temperature - salinity structure in different regions. Curve *a* is representative for the region between Australia and Indonesia (120°E), curve *b* for the Bay of Bengal (88°E) to 10°S, curve *c* for 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").



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).

South of 10°S a conspicuous salinity minimum near 1000 m (Figs. 12.3 and 12.4) indicates the presence of *Antarctic Intermediate Water* (AAIW). Although the minimum can be followed to the surface in the Polar Front (Antarctic Convergence), this may not indicate formation in the Indian Ocean sector but be the result of advection from the Atlantic Ocean. AAIW source properties in the Indian are the same as in the other oceans, with temperatures near 2.0 - 2.5°C and salinities around 33.8. When it enters the subtropical gyre, AAIW has a temperature of 3 - 4°C and 34.3 salinity. Its depth range comes within reach of the equatorial current system, which blocks its progress into the northern hemisphere. The distribution of AAIW is therefore limited to the region south of 10°S. Cross-equatorial flow underneath the Zanzibar Current is southward, allowing the passage of Red Sea Water but no northward propagation of AAIW. Red Sea Water is therefore found embedded in AABW in the Agulhas Current (Figure 12.6b and c). It occurs as layers of 300 - 800 m thickness at about 1500 m depth; occasionally, it is contained in lenses of 50 - 100 km diameter.

The final fate of Antarctic Intermediate Water in the Indian Ocean still has to be established. It is possible that all Antarctic Intermediate Water from the Indian Ocean manages to escape into the Atlantic Ocean with Agulhas Current eddies. An alternative exit would be passage through the Great Australian Bight into the Pacific Ocean. Comparison of T-S diagrams for the latitude band 40 - 45°S shows little variation of T-S properties in the AAIW in each ocean but significant differences between the three oceans. This has been interpreted as an indication that the circulation of AAIW in the southern subtropical gyres is closed within each ocean. The data certainly exclude contact of AAIW of Indian and Atlantic origin at 40 - 45°S latitude; but Agulhas eddies are formed just north of 40°S and drift away toward the equator. Export of AAIW into the Atlantic Ocean thus remains a possibility. The other route, passage into the Pacific Ocean, is very unlikely despite the apparent similarity of AAIW properties in both oceans, as an AAIW variety with particularly high salinity in the southern Tasman Sea and southeast of New Zealand breaks the continuity of water mass properties (Figure 12.7). This suggests little contact between the Great Australian Bight and the Pacific Ocean at the level of the AAIW north of 45°S. South of that latitude observations of subsurface float movement obtained only very recently show westward movement at AAIW level, from the Pacific Ocean into the Great Australian Bight.

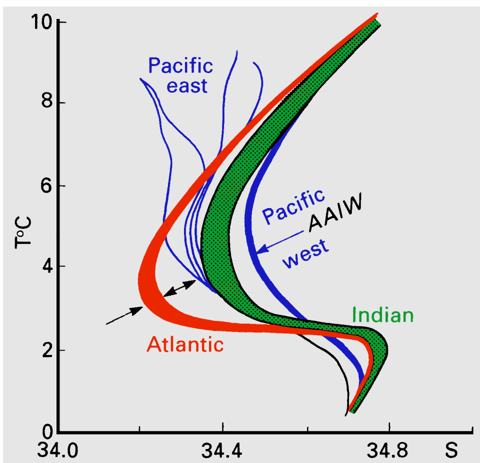


Fig. 12.7. T-S diagrams for various regions in the latitude band 40 - 45°S. The range of T-S diagrams in the Indian Ocean is shaded, while a variety of individual T-S curves is shown for the eastern Pacific Ocean (80° - 160°W). The region marked "Pacific west" is located in the southern Tasman Sea and south east of New Zealand (150°E - 160°W); its higher salinity indicates that any exchange between the Great Australian Bight and the Pacific Ocean cannot pass through these regions but has to pass to the south. From Piola and Georgi (1982).

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.

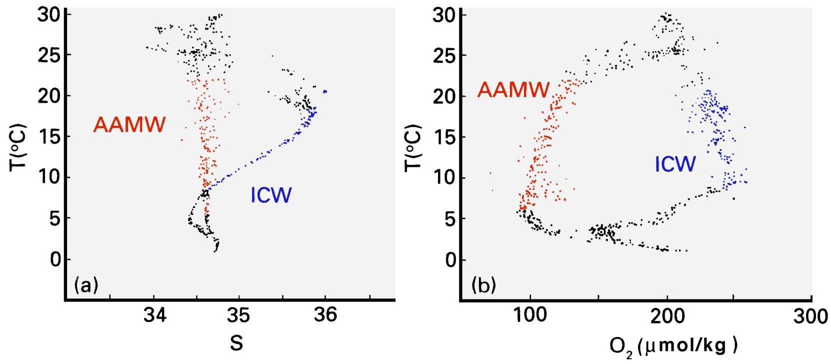


Fig. 12.8. Water mass properties of Indian Central Water (ICW) and Australasian Mediterranean Water (AAMW). (a) T-S diagram, (b) T-O_2 diagram. The data for ICW are from 25 - 30°S and east of 105°E, the data for AAMW from 7 - 15°S, 120 - 125°E. From Tomczak and Large (1989).

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

(Figure 12.9) show the path of AAMW as a band of low salinity centred on 10°S, from the entry point in the east to Madagascar in the west. Below 600 m the same pattern can be seen in the silicate distribution, where the presence of AAMW down to 1000 m depth is indicated by a silicate maximum. The jet-like inflow of AAMW produces one of the strongest frontal systems of the world ocean's thermocline (Figure 12.10). The front indicates that there is little meridional motion in the thermocline across 10 - 15°S from the point of AAMW inflow in the east to the point where the South Equatorial Current splits into two branches on approaching Madagascar. This leaves the western boundary current as the only region for advective transfer of thermocline water between the southern and northern Indian Ocean.

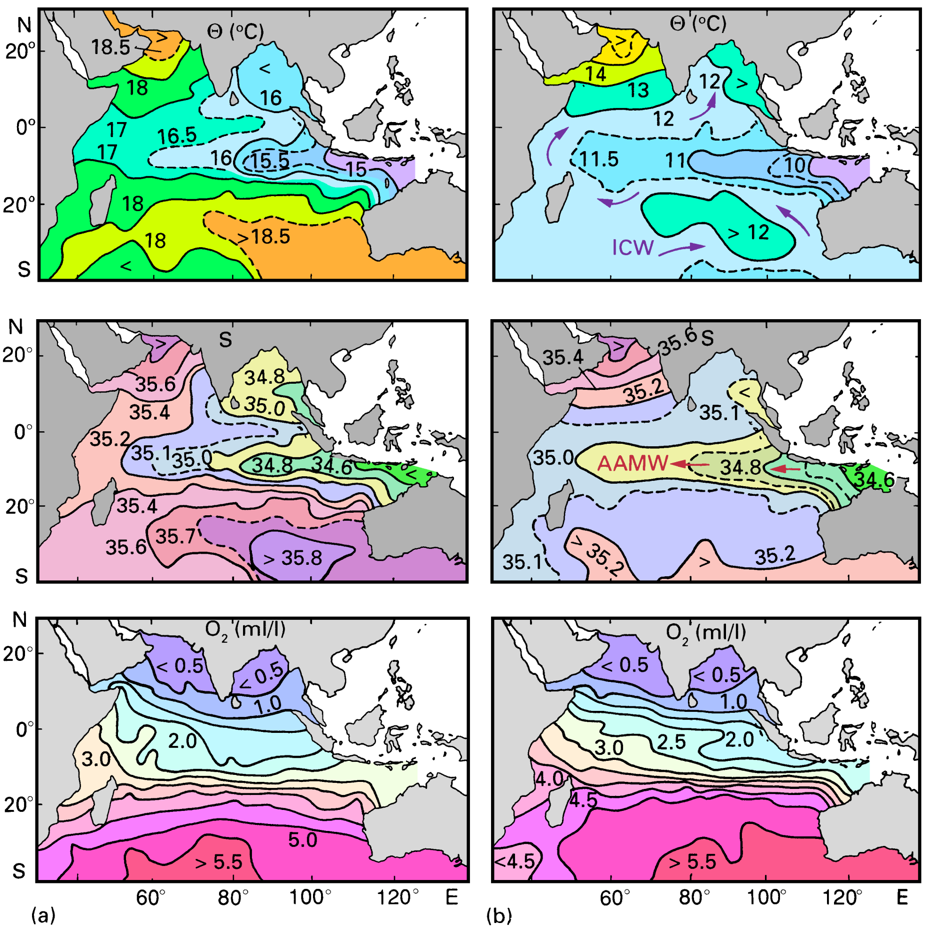


Fig. 12.9. Annual mean temperature (°C), salinity, and oxygen (ml/l) in the thermocline on isopycnal surfaces. (a) On the σ_Θ surface 25.7, located in the depth range 150 - 200 m, (b) on the σ_Θ surface 26.7, located in the depth range 300 - 450 m. Arrows indicate the movement of ICW and AAMW. After You and Tomczak (1993)

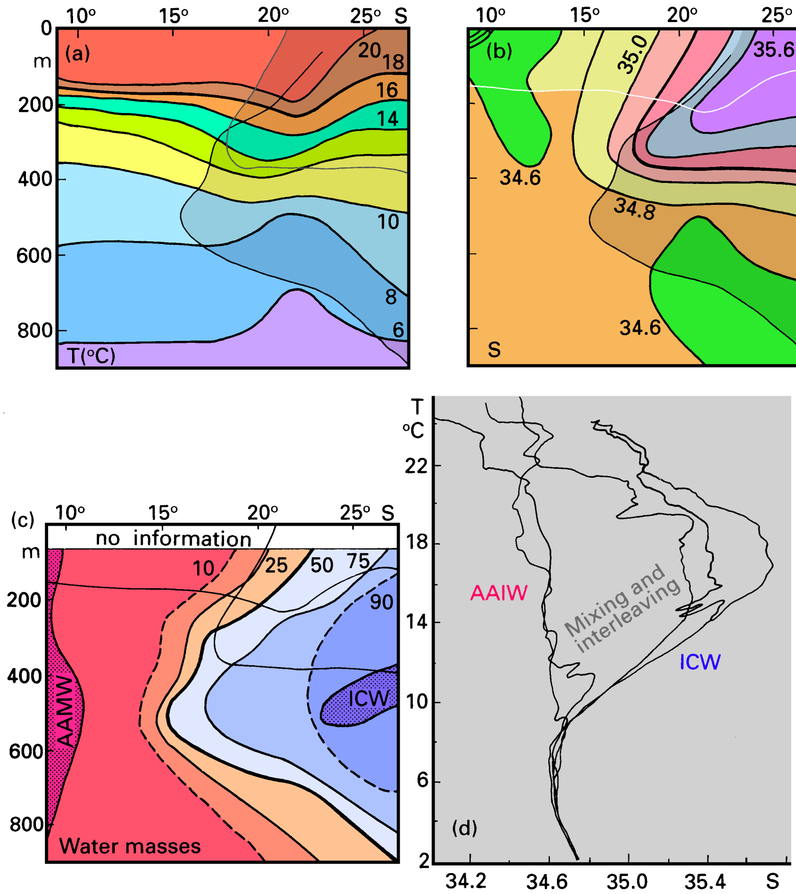


Fig. 12.10. A section through the front between Indian Central Water and Australasian Mediterranean Water along 110°E. (a) Temperature (°C), (b) salinity, and (c) water masses (% of ICW content) from bottle casts along 110°E , (d) T-S diagrams from selected CTD stations, showing evidence of interleaving 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 accompanied by a rapid fall in oxygen values, indicating rapid aging along the path. The decrease in oxygen values continues into the Bay of Bengal, which contains the oldest Central Water. The oxygen decrease in the northern Indian Ocean can be explained if it is recalled that transfer of ICW between the hemispheres is restricted to the Southwest Monsoon season. The annual net transfer rate is therefore small, and circulation of ICW in the northern Indian Ocean is slow.

In the model of NADW recirculation discussed in Chapter 7, AAMW is assumed to enter the Agulhas Current and finally the Atlantic Ocean. Closer inspection of Figure 12.9 shows that this cannot be true for *all* AAMW. Some AAMW contributes to the renewal of thermocline water in the northern Indian Ocean. This is evident from the salinity distribution of Figure 12.9 on the 25.7 σ_t level which shows significant freshening of ICW along its path from the Subtropical Convergence to the Bay of Bengal. The salinity decrease east of Madagascar is apparently the result of mixing with AAMW at the end of the zonal jet. Further freshening is observed in the Bay of Bengal near 90°E, this time presumably resulting from AAMW advection from the southeast. Again, it has to be remembered that the figures show only the net result of a process with strong monsoonal variation. The final fate of ICW and AAMW in the northern Indian Ocean is not known. In the Bay of Bengal oxygen values fall below 0.5 m/l above 600 m depth and below 0.2 ml/l at the 200 m level, and in the inner Arabian Sea they are below 0.2 ml/l from 200 m to 1000 m depth. These values - the lowest in the world ocean thermocline - indicate a very low renewal rate for the thermocline waters of the northern Indian Ocean. Some water, however, must always leave the thermocline, to make room for new supply. Downward diffusion into the Deep Water would only increase the difficulties with the recirculation of Deep and Bottom Water and therefore appears unlikely. Upward diffusion into the surface layer remains as the only alternative. The observed variation of temperature and salinity on the 25.7 σ_Θ surface (Figure 12.9) indicates that some mixing across isopycnals must occur in the upper thermocline. More work is definitely required to clarify these issues.

Nearly uniform salinity over the temperature range of the thermocline, the main characteristic of AAMW, is maintained along the entire length of the zonal jet. Mixing with higher salinity water on either side increases the salinity from less than 34.7 at the inflow point to 34.9 and above in the west (Figure 12.9a). Water with nearly uniform salinity near 35.0 has often been called Indian Equatorial Water. Lack of observations from the Indonesian outflow region led several authors (including Sverdrup *et al.*, 1942) to believe that it is formed in the western equatorial Indian Ocean. It is now clear that water mass formation does not occur in that region and that the so-called Equatorial Water consists of Australasian Mediterranean Water, with a good dose of Central Water to lift its salinity.

Hydrological characteristics of the water masses of the surface layer vary strongly with the seasons, more so in the Indian than in any other ocean. Low surface salinity in the tropics produces a salinity maximum at the top of the permanent thermocline. It is found below 200 m near 15°S and approaches the surface near 35°S (Figure 12.4). The corresponding water type has often been given the status of a water mass; in reality it only identifies the high salinity end of Indian Central Water. Monsoonal river input from the Indian and Indochinese subcontinent produces a low salinity water mass known as *Bay of Bengal Water* (BBW). It spreads across the Bay in a nearly 100 m thick layer, producing a strong halocline underneath (Figure 12.11). Supply of this water is sufficient to keep the 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).

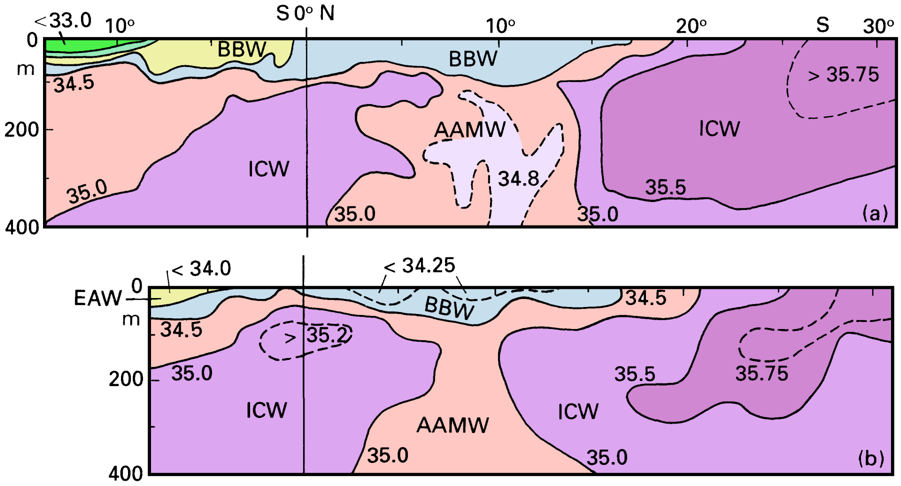


Fig. 12.11. Meridional sections of salinity showing the spreading of Bay of Bengal Water. (a) for the component originating in the inner Bay of Bengal, along 92°E, (b) for the component found along the west coast of India (for the purpose of identification labelled "East Arabian Sea Water" or EAW in 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 atmosphere is small but positive (Figure 1.6), so a weak heat sink is required to close the heat balance. Entrainment of cold water from below, usually the most effective heat sink, is not available as a process where a barrier layer exists. Export of heat to the Indian Ocean is a possibility consistent with the movement of surface water indicated by the surface property distributions. It is also possible that the rivers themselves contribute to the heat balance and not only to the freshwater balance.