Sea surface temperature and salinity

As noted earlier, the map of sea surface salinity (SSS; Figure 2.5b) resembles the *P-E* distribution (Figure 1.7) outside the polar and subpolar regions. Poleward of the Westerlies, the SSS values decrease further, despite the decrease in rainfall and *P-E* values, as a result of freshwater supply from glaciers and icebergs. In the north Atlantic Ocean this effect is concentrated in the west and linked with advection by the East and West Greenland Currents and the Labrador Current. This produces a sharp salinity increase across the boundary between the Labrador Current and the Gulf Stream (the Polar Front). A similar effect is seen in the southern hemisphere along the boundary between the Malvinas and Brazil Currents. The low SSS values along South Africa and Namibia, on the other hand, are the result of Indian Ocean water extrusions from the Agulhas Current, which were discussed in Chapters 11 and 12.

In the subtropics, the water with high salinities flows westward with the North and South Equatorial Currents. Continuous evaporation along its way increases the surface salinity further. The SSS maxima are therefore shifted westward relative to the *P-E* maxima. In the southern hemisphere this process continues into the South American shelf, where the Brazil Current advects the high salinity water southward. In the northern hemisphere the region of high surface salinity does not reach the American shelf because the North Brazil, Guyana, and Antilles Currents carry tropical water of low salinity across the equator into the northern hemisphere. This water is needed to feed the Gulf Stream and its extensions and is therefore not available to dilute the waters to the east. (This contrasts with the situation in the Pacific Ocean, where the low salinity water of the western region is recirculated in the Equatorial Countercurrent.) The highest sea surface salinities of the world ocean are therefore found in the region of the Canary and North Equatorial Currents.

The distribution of sea surface temperature (SST; Figure 2.5a) shows similarities with the Pacific Ocean, particularly in the southern hemisphere where surface temperatures are much the same in the central parts of both oceans. Advection by the Brazil Current and upwelling along the Namibian coast are responsible for the marked SST differences between west and east in the subtropics. The thermal equator is at about 5°N and coincides with the Doldrums or ITCZ. In the west it extends northward into the Gulf of Mexico. The region of weak and variable winds is limited to the narrow band of the ITCZ; there is no analogue to the large region of extremely light winds found in the region north of Papua New Guinea. This is probably the reason why maximum SST values in the Atlantic Ocean are 2°C lower than in the Pacific Ocean. The contouring interval of Figure 2.5a shows the highest temperatures as above 26.0°C; actual annual mean SST values are in fact above 27.0°C over most of the region.

The major feature of the SST distribution is the marked departure of the isotherms from a zonal distribution and the associated crowding along the Polar Front in the northern hemisphere. The temperature difference between the east and west coasts north of 40°N and its consequences for the local climate have often been noted. In fact, the SST difference between the shelves off northern Japan and Oregon is only marginally smaller than the SST difference between the shelves off Newfoundland and France (about 6°C and 8°C, respectively). But in the Pacific Ocean this difference develops over more than twice the zonal distance available in the Atlantic Ocean, and the isotherms cross the latitude circles at a much smaller angle. The departure from zonal isotherm orientation in the North Atlantic Ocean is enhanced by water exchange with the Arctic Mediterranean Sea; the 5°C isotherm

through mixing with the overlying waters. It also indicates how Antarctic Bottom Water enters the eastern basins north of the Walvis Ridge from the equator by passing through the Romanche Fracture Zone (Figure 8.2). As a result, potential temperature increases slowly both northward and southward from the equator in the eastern basins, and potential temperatures north and south of the Walvis Ridge differ by more than 1°C.

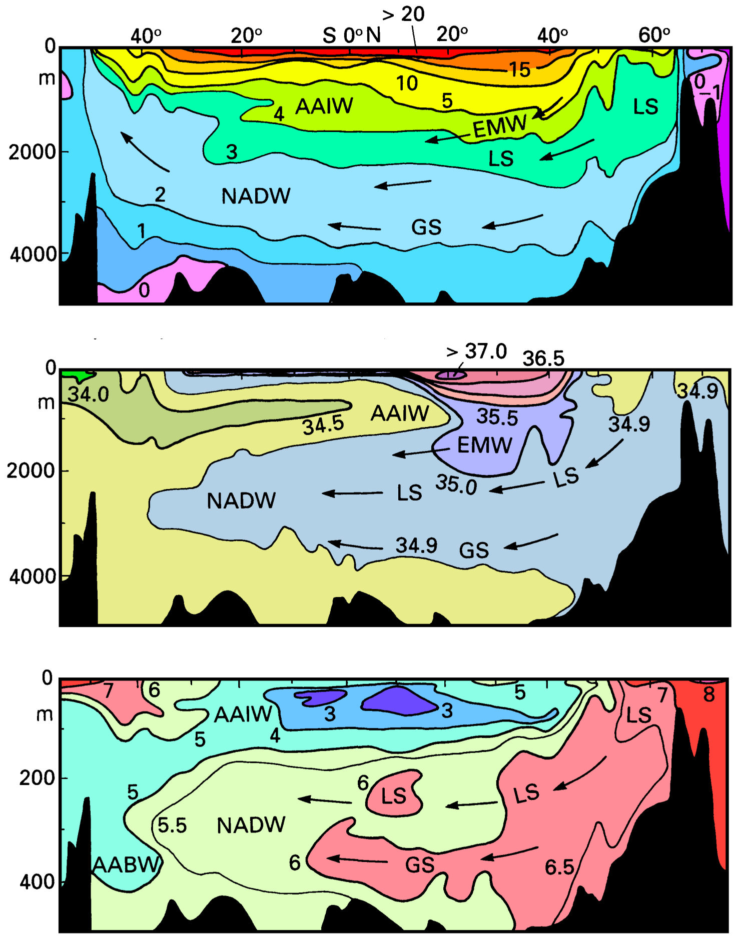

Fig. 15.2. A section through the western basins of the Atlantic Ocean. (a) Potential temperature (°C), (b) salinity, (c) oxygen (ml/l). See Fig. 15.7 for position of section. AABW: Antarctic Bottom Water, AAIW: Antarctic Intermediate Water, NADW: North Atlantic Deep Water originating from the Labrador Sea (LS) or the Greenland Sea (GS) or containing a contribution of Eurafrican Mediterranean Water (EMW). Adapted from Bainbridge (1980).

The occurrence of *Arctic Bottom Water* (ABW) in undiluted form is restricted to the immediate vicinity of the Greenland-Iceland-Scotland Ridge. As already discussed in Chapter 7 its main impact is its contribution to the formation of *North Atlantic Deep*

Clarke and Gascard report respective T-S combinations of 3.17°C and 34.88, 3.4°C and 34.9, and 2.9°C and 34.84. However, not all of this variability is passed on to the NADW since mixing of Labrador Sea Water with Arctic Bottom Water does not occur during a single passage through the Labrador Sea. Variations in the rate of production of Labrador Sea Water are therefore averaged over the number of loops the Arctic Bottom Water performs around the area. A rough calculation based on the volume transports and velocities of the last chapter gives 2 - 3 loops, performed over 12 - 18 months. This suggests that interannual variations of Labrador Sea Water properties are transmitted into NADW at about half the original magnitude.

A third variety of North Atlantic Deep Water sometimes found in the literature as upper NADW is really NADW from the Labrador Sea (middle or western NADW) with traces of *Eurafrican Mediterranean Water* (EMW). This water mass leaves the Strait of Gibraltar with a temperature of about 13.5°C and a salinity of 37.8; but within less than 250 km its temperature and salinity are reduced by mixing to 11 - 12°C and 36.0 - 36.2. Starting from these characteristics EMW spreads isopycnally across the ocean, mixing gradually with the Deep Water above and below. Relative to NADW of the same density it has anomalously high salinities and temperatures. Figure 15.4 shows it as a salinity and temperature maximum at 1000 m depth near the upper distribution limit of NADW. The Mediterranean Water is carried northward along the Portuguese shelf under the influence of the Coriolis force and mixes into the subtropical gyre circulation, eventually spreading southward and westward. The core of the salinity and temperature anomaly sinks as the water spreads, and at the 2000 m level (Figures 2.5e and f) traces of Mediterranean Water can be seen all across the North Atlantic Ocean, with some high salinity water crossing the equator in the west and proceeding southward.

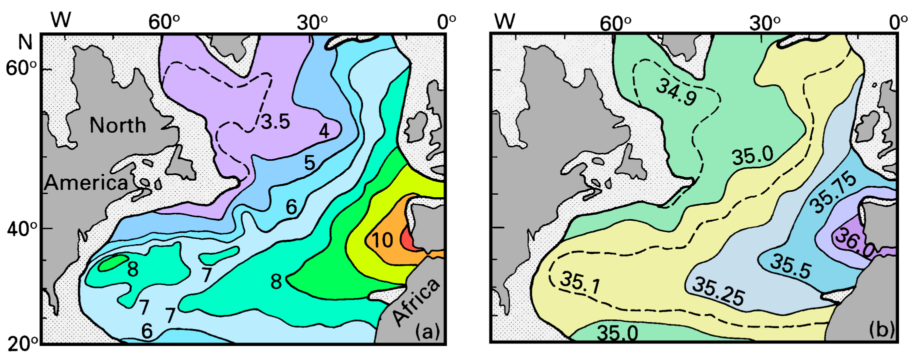

Fig. 15.4. Temperature (°C) (a) and salinity (b) in the North Atlantic Ocean at 1000 m depth.

Although the influence of the Mediterranean Water is strong enough to put its mark on the long-term mean distribution of oceanic properties, it is wrong to imagine the spreading of EMW as a process of smooth isopycnal movement with equally smooth diapycnal diffusion. It has to be remembered that the eastern basins of all oceans are characterized by slow mean motion but high eddy activity. Mediterranean Water is therefore injected into the

the eastern side towards the Indian Ocean (Nelson, 1989). The current is swift enough to remove sediment along the base of the continental rise and produce a band of exposed rock face at 5000 m depth.

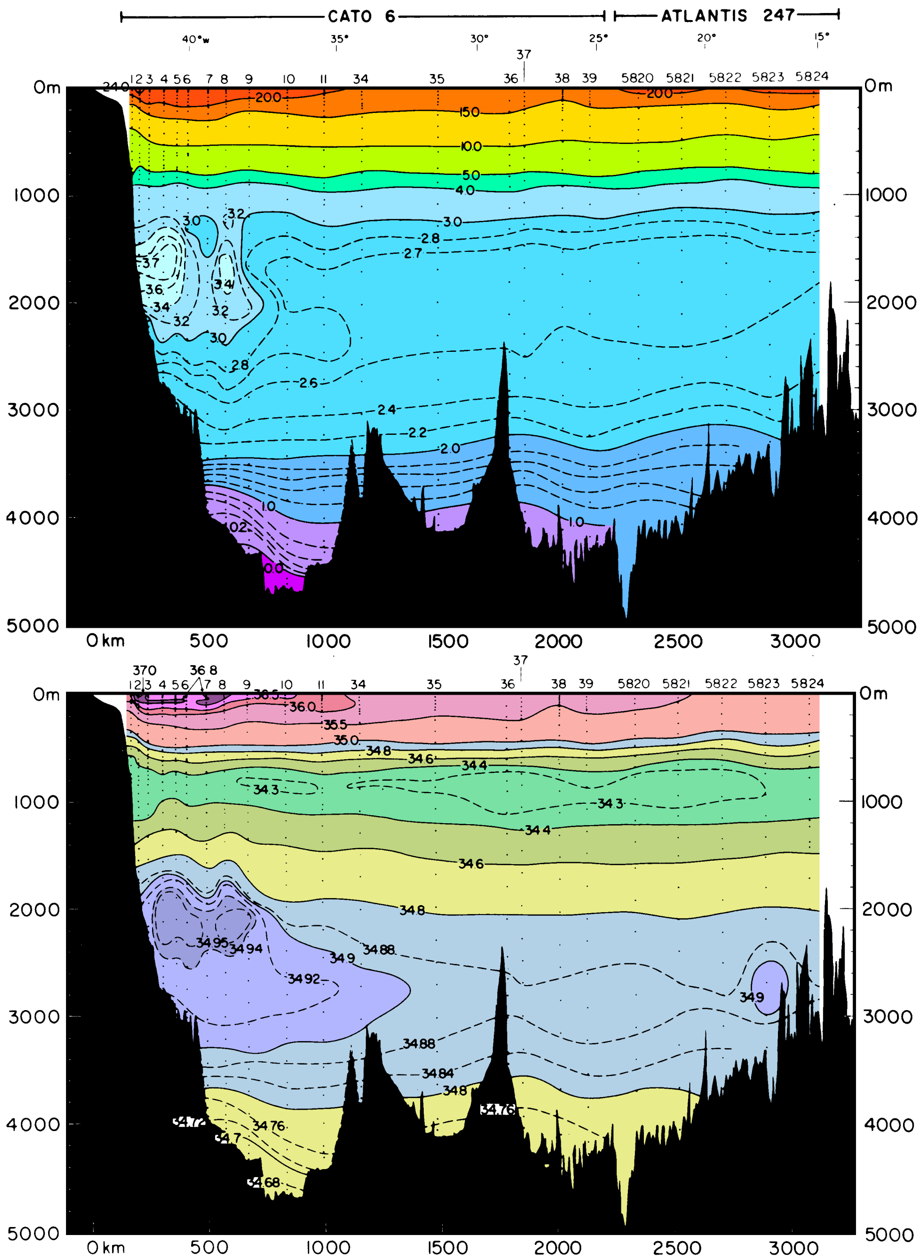

Fig. 15.6. A section through the western Atlantic Ocean along 30°S. (a) Potential temperature (°C), (b) salinity. From Warren (1981a).

the Guyana and Antilles Currents and in Figure 15.6 by the widening of the isohalines around the salinity minimum at 1000 m depth. In the eastern basins its movement is masked by eddies, particularly Agulhas Current eddies propagating northward (Chapter 11). Observations along the south African continental rise near 1000 m depth (Nelson, 1989) indicate that AAIW participates in the cyclonic motion of abyssal water masses in the Cape Basin, even though the Walvis Ridge does not pose a barrier to flow at AAIW level.

As discussed in Chapter 6, formation of AAIW in the Atlantic Ocean occurs through water mass conversion in the Southern Ocean with limited direct atmospheric contact. The only region where winter convection contributes to AAIW formation is in the Scotia Sea. Most of the AAIW enters from a formation region in the eastern Pacific Ocean (England *et al.*, in press). As a consequence, Atlantic AAIW differs little from AAIW in the other two oceans. Close to the formation region it has a temperature near 2.2°C and a salinity of about 33.8. Mixing with water from above and below erodes the salinity minimum; by the time AAIW reaches the Subtropical Convergence it has properties closer to 3°C in temperature and about 34.3 in salinity. The gradual weakening and eventual disappearance of the minimum towards north can also be seen in the T-S diagrams of Figure 15.9.

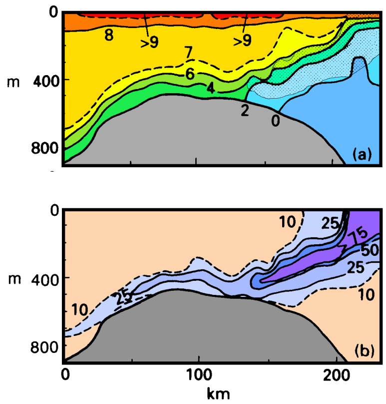

Fig. 15.8. A section across the Iceland-Scotland Ridge 150 km northwest of the Faroe Islands showing the spreading of Arctic Intermediate Water.
(a) Temperature (°C), with the region of low salinity (<34.9) shaded;
(b) presence of Arctic Intermediate Water (percentage of volume).
Adapted from Meincke (1978).

The occurrence of *Arctic Intermediate Water* (AIW) is restricted to two small regions in the north, a western variety formed in the southern Labrador Sea at temperatures near 3°C and 34.5 salinity, and an eastern variety which originates in the Iceland Sea at temperatures below 2°C and near 34.6 salinity. Both are subducted in locations along the Polar Front of the north Atlantic Ocean, in the west at the boundary between the Gulf Stream and the Labrador Current and in the east along a frontal region between the North Atlantic and East Iceland Currents. Their influence on the hydrography is limited by their proximity to the formation regions for NADW, which absorbs their low salinities over short distances. The eastern variety in particular cannot be recognized much beyond the sill where it sinks; its salinity minimum does not extend past 60°N (Figure 15.7). The influence of the western variety is felt most strongly in the North Atlantic Current, but its salinity minimum can be traced into the Bay of Biscay and southward to 40°N.

Because of the rapid absorption of Arctic Intermediate Water into the Deep and Bottom Water complex the existence of Intermediate Water in the north Atlantic Ocean is often

meridional track across the STC with the T-S curve of SACW (in the manner described with Figure 5.4) reveals that the T-S properties of SACW in the tropics are closer to those typical for the Subtropical Convergence of the western Indian Ocean near 60 - 70°E, than those found along the STC in the Atlantic Ocean (Sprintall and Tomczak, in press). This indicates that much of the SACW is not subducted at the Atlantic portion of the STC but is in fact Indian Central Water (ICW) brought into the Atlantic Ocean by Agulhas Current eddies (see Chapter 11), in agreement with the ideas of North Atlantic Deep Water recirculation discussed in Chapter 7. Mixing in the eddy separation region and possibly in the Agulhas Current itself does not change the T-S characteristics of the inflowing ICW but redistributes the contributions of the water types which make up the T-S curve, enhancing in particular the volume of water near 13°C. This water type, also known as *13° Water* (Tsuchiya, 1986), thus turns into a variety of Subtropical Mode Water; the associated thermostad can be traced from Namibia to the coast of Brazil near 10°S, along the North Brazil Current and into the eastward flowing components of the equatorial current system. It is worth noting that, unlike other Subtropical Mode Water varieties, 13° Water is not formed in contact with the atmosphere.

Some Central Water formation does occur in the western south Atlantic Ocean, in the confluence zone of the Brazil and Malvinas Currents (Gordon, 1981). It is responsible for a high salinity variety of SACW (36 salinity is reached at 17°C instead of 20°C; see Figure 15.9). This SACW variety is recirculated within the southern subtropical gyre and therefore restricted to the western south Pacific Ocean.

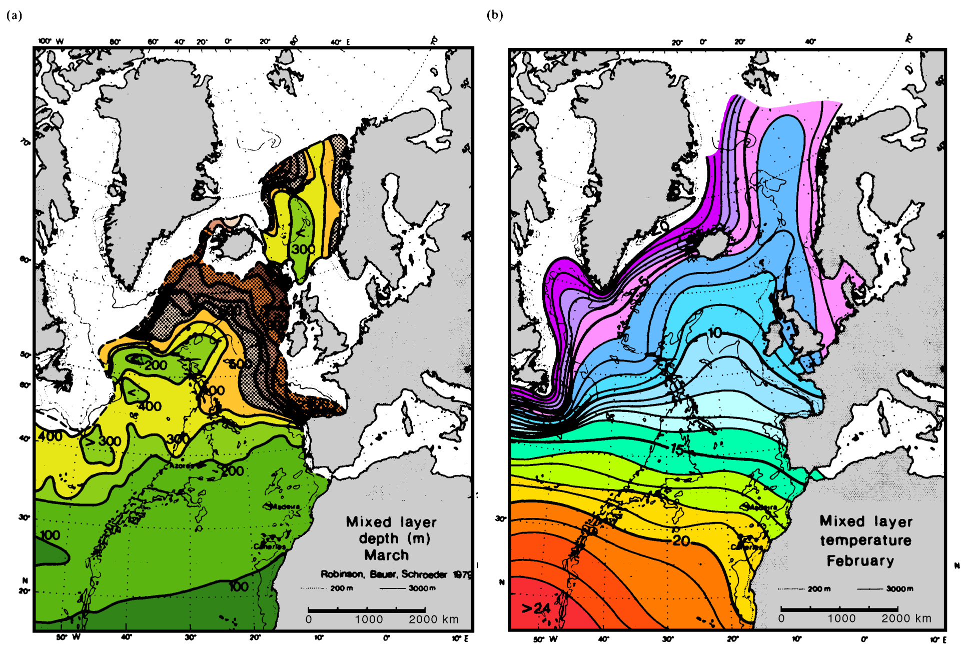

Fig. 15.10. Winter convection in the north Atlantic Ocean. (a) Mean mixed layer depth (m) in March, depths in excess of 600 m are shaded; (b) mean mixed layer temperature (°C) in February. Adapted from Robinson *et al.* (1979).

Subtropical Mode Water known as the *18° Water*. A third variety, the *Madeira Mode Water*, is formed north of Madeira and indicated by a summer thermostad at 70 - 150 m depth (Figure 15.11). Both mode waters together contribute more than half the volume of NACW.

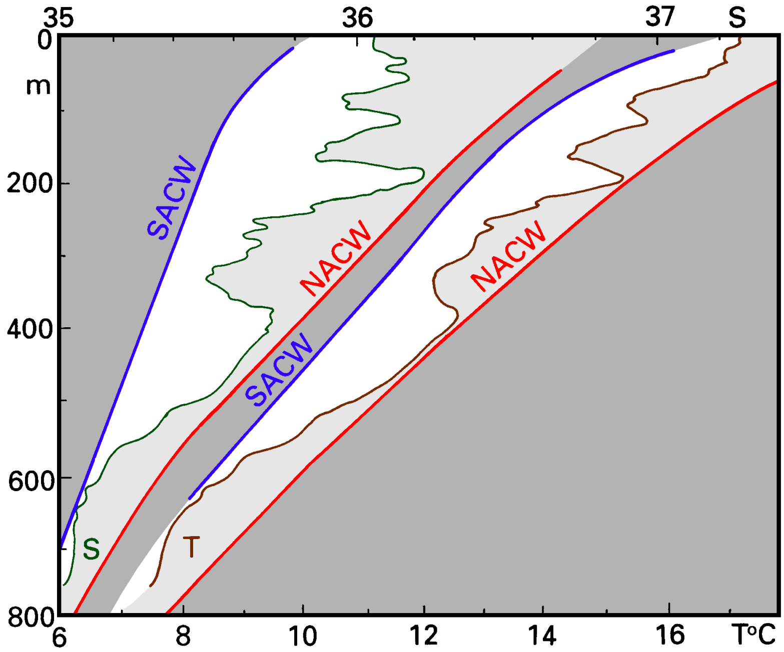

Fig. 15.12. (Left) Temperature (°C) and salinity as functions of depth at a station in the eastern part of the water mass boundary between SACW and NACW, showing strong interleaving. Reference curves for undisturbed SACW and NACW conditions are indicated. The station is located some 25 km west of the position marked in Fig. 14.17. From Tomczak and Hughes (1980).

The transition from South to North Atlantic Central Water occurs as a front along approximately 15°N which extends from below the mixed layer to the bottom of the thermocline. In the east it bends northward past 20°N, following the southern limit of the Canary Current and sharpened by the confluence with the circulation around the Guinea Dome. In general, SACW penetrates northward underneath NACW (see Chapter 14 for details), giving the front a downward slope from south to north. With SACW and NACW occupying the same density range, the front is density-compensated, i.e. the effect of the temperature change across the front is compensated by the effect of the salinity change and the front is not noticed in the density field. Parcels of water from either side of the front can therefore be moved easily across the front on isopycnal surfaces. The resulting multitude of intrusions, filaments, and lenses (Figure 15.12) makes the structure of the front quite complicated. Further west the front loses its identity, as mixing between SACW and

region is characterized by net water loss to the atmosphere (the major region where rainfall exceeds evaporation being east of 40°W; Figure 1.7). Local freshening of the surface layer, the mechanism that produces the barrier layer in the Pacific Ocean, can therefore not be responsible here. It appears that the high salinities found at the surface in the subtropics (Figure 2.5b) are subducted towards the equator at the upper end of the temperature/salinity range of the Central Water. This creates a salinity maximum above the Central Water in the tropics, which is then advected westwards towards the equator into regions of uniform temperature in the equatorial current system. The result is salinity stratification in the isothermal surface layer. Figure 15.14 shows active subduction (indicated by negative barrier layer thickness; see Chapter 5 for an explanation of the mechanism) for August - October south of 12°S, coupled with the formation of a barrier layer to the north. During February - April the same process occurs in the vicinity of 20°N. The two sources alternate in renewing the barrier layer structure in the west, where the barrier layer is found during all seasons. In this region an accurate heat and mass budget of the surface layer cannot be achieved without taking advection into account.

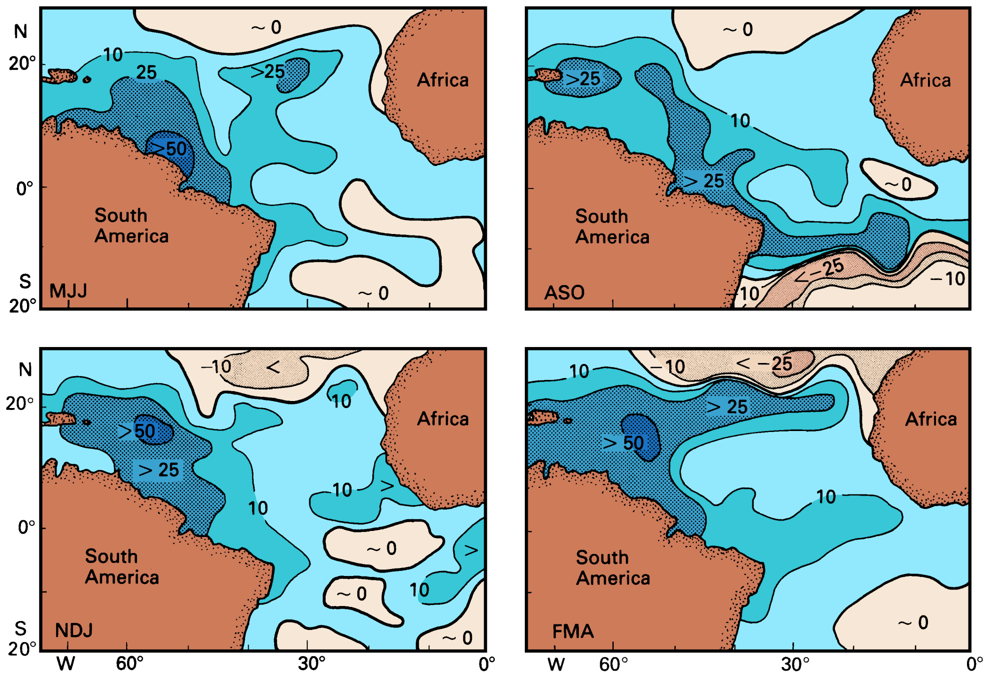

Fig. 15.14. Seasonal mean barrier layer thickness (m) in the tropical Atlantic Ocean. (a) May - July, (b) August - October, (c) November - January, (d) February - April. The barrier layer is located below the mixed layer (see Fig. 5.6 for mixed layer depth). Contours are given for layer thickness of 50 m, 25 m, 10 m, 0 m, -10 m, and -25 m. Subduction regions, indicated by values less than -10 m, are lightly shaded, regions with a barrier layer thickness >25 m are shown with dark shading. Adapted from Sprintall and Tomczak (1992).