Chapter 15

Hydrology of the Atlantic Ocean

The hydrology of the Atlantic Ocean basins is deeply affected by the formation and recirculation of North Atlantic Deep Water, which was discussed in Chapter 7. The injection of surface water into the deeper layers is responsible for the high oxygen content of the Atlantic Ocean. It is also intricately linked with high surface salinities, as will become evident in Chapter 20. When compared with other ocean basins, the basins of the Atlantic Ocean are therefore characterized by relatively high values of salinity and dissolved oxygen.

Precipitation, evaporation, and river runoff

Precipitation over the Atlantic Ocean varies between 10 cm per year in the subtropics, with minima near St. Helena and the Cape Verde Islands, and more than 200 cm per year in the tropics. The region of highest rainfall follows the Intertropical Convergence Zone (ITCZ) in a narrow band along 5°N. A second band of high rainfall, with values of 100 - 150 cm per year, follows the path of the storm systems in the Westerlies of the North Atlantic Ocean from Florida (28 - 38°N) to Ireland, Scotland, and Norway (50 - 70°N). In contrast to the situation in the Pacific Ocean, no significant decrease in annual mean precipitation is observed from west to east; however, rainfall is not uniform across the band through the year. Most of the rain near Florida falls during summer, whereas closer to Europe it rains mainly in winter. A third band of high rainfall with similar precipitation values is associated with the Westerlies of the South Atlantic Ocean and extends along 45 - 55°S.

The precipitation-evaporation balance (*P-E*; Figure 1.7) reflects the rainfall distribution closely, since over most of the region evaporation varies much less than precipitation. The influence of the ITCZ is seen as a region of positive *P-E* values north of the equator. In the vicinity of South America the region extends to 30°S and along the coast of Panama, a result of extreme annual mean rainfall conditions over land. A similar southward extension is found near the African continent. The band of high rainfall in the northern hemisphere Westerlies is also evident as a region of positive *P-E* balance; its counterpart in the southern hemisphere does not come out very well due to lack of data.

Compared to the Pacific and Indian Oceans, the total downward freshwater flux (i.e. the *P - E* balance averaged over the ocean area) is obviously smaller in the Atlantic than in the other two oceans. Maximum *P - E* values are considerably less, and the areas with less than 100 cm per year cover a proportionately much larger area. The effect on the sea surface salinity is somewhat alleviated by the fact that the land drainage area of the Atlantic Ocean is much larger; it includes nearly all of the American continent, Europe, large parts of Africa, and northern Asia (Siberia). Many of the world's largest rivers - including the Amazon, Orinoco, Mississippi, St.Lawrence, Rhine, Niger, and Congo Rivers - empty into the Atlantic Ocean, others - the Nile, Ob, Jenisej, Lena, and Kolyma Rivers - into its mediterranean seas. In these adjacent seas river runoff plays an important role in the salinity balance and consequently influences their circulation. Overall, however, the contribution from rivers to the fresh water flux of the Atlantic Ocean cannot compensate for the low level of rainfall over the sea surface.

(and the 35 isohaline) angles across the ocean basin from 45°N near Newfoundland to 72°N off Spitsbergen.

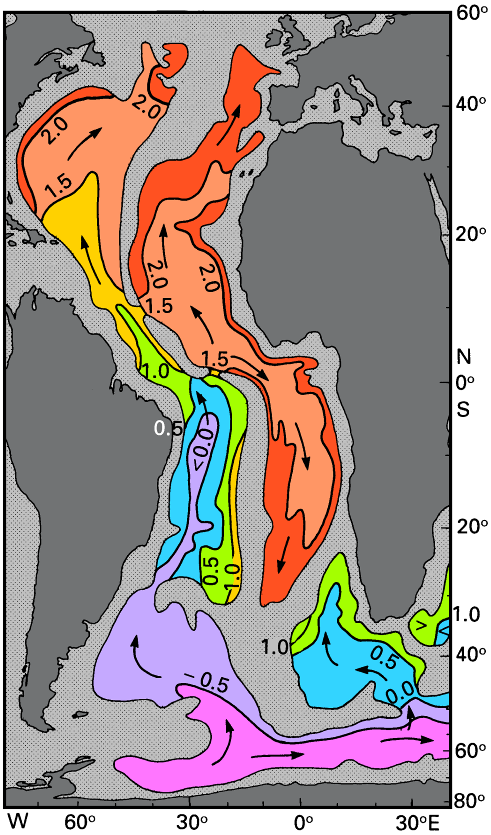

Fig. 15.1. Potential temperature below 4000 m depth and inferred movement of Antarctic Bottom Water. Adapted from Wüst (1936).

Abyssal water masses

When compared with the other two oceans, the abyssal layers of the Atlantic Ocean display a hydrographic structure full of texture and variety. This results mainly from water exchange with mediterranean basins, particularly the Arctic and Eurafrican Mediterranean Seas.

Below 4000 m depth, all Atlantic Ocean basins are occupied by *Antarctic Bottom Water* (ABW). This water mass spreads northward from the Circumpolar Current and penetrates the basins east and west of the Mid-Atlantic Ridge. On the eastern side its progress comes to a halt at the Walvis Ridge; but on the western side it penetrates well into the northern hemisphere past 50°N. A map of potential temperature below 4000 m depth (Figure 15.1) shows a gradual temperature increase from the Southern Ocean to the Labrador Basin

Water (NADW) which fills the depth range between 1000 m and 4000 m. In vertical sections (Figure 15.2) it is seen as a layer of relatively high salinity (above 34.9) and oxygen (above 5.5 ml/l) extending southward from the Labrador Sea to the Antarctic Divergence. More detailed inspection reveals two oxygen maxima in the subtropics, at 2000 - 3000 m and 3500 - 4000 m depth, indicating the existence of two distinct Deep Water varieties. The upper maximum can be traced back to the surface near 55°N and reflects the spreading of NADW formed by mixing Arctic Bottom Water with the product of deep winter convection in the Labrador Sea. The lower maximum has its origin in the Greenland-Iceland-Scotland overflow region and indicates that some Deep Water is formed before the Arctic Bottom Water reaches the Labrador Sea, through mixing of overflow water with the surrounding waters. East of the Mid-Atlantic Ridge this is the only mechanism for the formation of Deep Water, and this NADW variety, variably known as lower or eastern NADW, is therefore particularly prominent in the eastern basins. Deep Water of Labrador Sea origin, referred to as middle or western NADW, is less dense than the eastern variety, and the two varieties remain vertically layered along their southward paths.

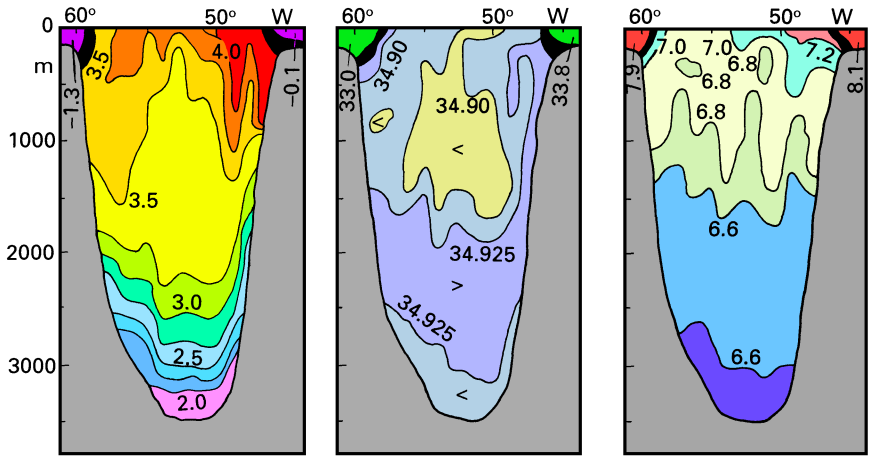

Fig. 15.3. A section through the southern Labrador Sea along approximately 60°N. (a) temperature (°C), (b) salinity, (c) oxygen (ml/l). Data from Osborne *et al.* (1991).

The long-term stability of NADW properties depends on the degree of atmospheric and oceanic variability during its formation period. A section through the Labrador Sea (Figure 15.3) shows a huge volume of nearly homogeneous water, with temperatures of 3.0 - 3.6°C and salinities of 34.86 - 34.96 and consistently high oxygen content, surrounded by strong cyclonic circulation. This *Labrador Sea Water* is the product of deep convection during the winter months. Observations show that deep winter convection is not an annual event; Clarke and Gascard (1983) report the formation of 10^5 km^3 of water with 2.9°C and 34.84 salinity in 1976 but virtually no formation of new water in 1978. Present estimates are that convection occurs in 6 out of 10 years. This produces significant variation in the properties of Labrador Sea Water; for the years 1937, 1966, and 1976

NADW in the form of subsurface eddies, rotating lenses which contain a high proportion of Mediterranean Water in its core. The rotation shelters EMW from the surrounding NADW; it prevents mixing and keeps the lens together over large distances. Lenses of Mediterranean Water, often referred to as "meddies" (Figure 15.5), have been found as far afield as in the Sargasso Sea. Direct observations in eddies from the Canary Current region showed rotational velocities of 0.2 m s^{-1} in general southward movement of about 0.05 m s^{-1}. The salinity and temperature anomalies found in the long-term average distribution have to be seen as the result of a process in which many such meddies travel through the upper NADW range at any particular moment in time, slowly releasing their load of extra salt and heat into the surrounding Deep Water.

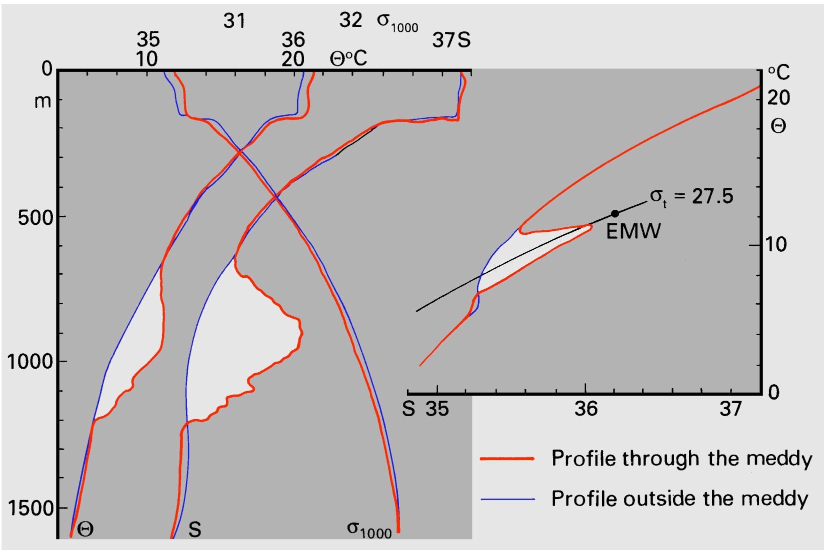

Fig. 15.5. An example of a "meddy", a rotating lens of Mediterranean Water found some 2500 km south-west of the Strait of Gibraltar near 26°N, 29°W. Note that the density profiles inside and outside are nearly identical. (σ_t gives density at atmospheric pressure, σ_{1000} at a pressure equivalent to 1000 m depth.) Adapted from Armi and Stommel (1983).

Along the western boundary of the ocean the mean flow of Deep and Bottom Water becomes stronger than eddy-related movement and can therefore be seen in hydrographic sections. Figure 15.6 shows the Deep Water as a salinity maximum at 2000 - 3000 m and a temperature maximum at 1400 - 2000 m, concentrated against the South American shelf. Both features are nearly 1000 km wide, probably wider than the associated boundary current as a result of mixing. Intensification of Antarctic Bottom Water flow is indicated by the shape of the isotherms and isohalines below 4000 m; upward slope towards the coast is consistent with a northward "thermal wind" increasing in speed with depth (Rule 2a of Chapter 3). A similar intensification occurs on the western side of the Cape Basin along the Walvis Ridge. Because the basin is closed in the north below the 3000 m level, the flow follows the depth contours in cyclonic motion, and the Bottom Water leaves the basin on

Antarctic Circumpolar Water has the same density as North Atlantic Deep Water but is colder and fresher (Figure 6.13). In the absence of NADW it would take its place in the Atlantic Ocean; however, the southward advance of the Deep Water reduces its influence. Detailed analysis (Reid, 1989) shows northward propagation of some Circumpolar Water both below and above the Deep Water.

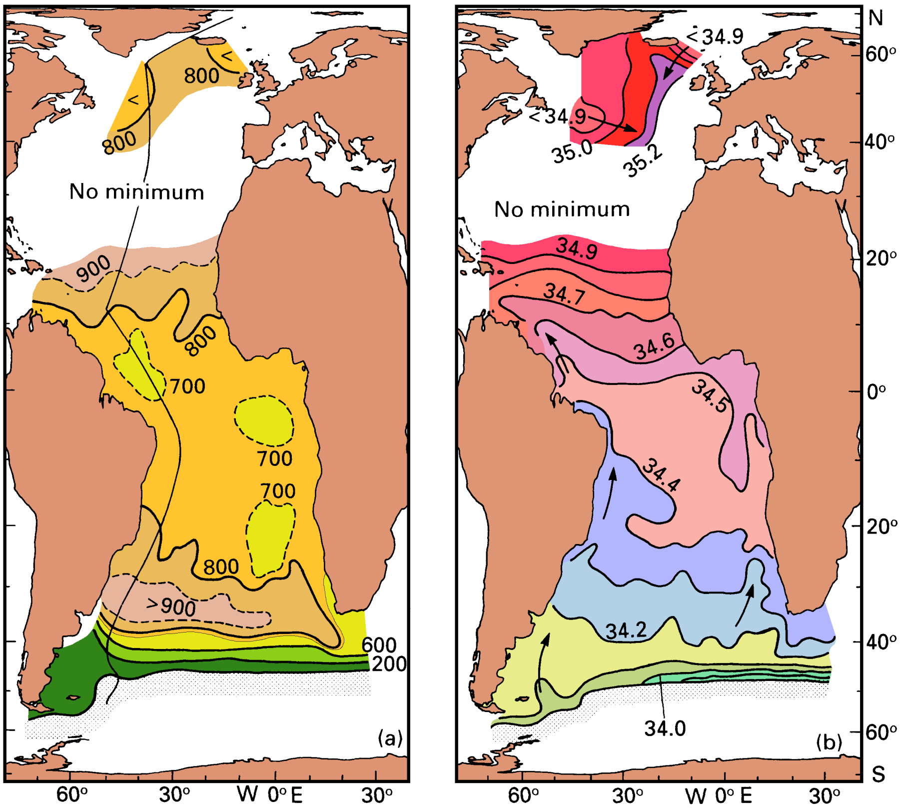

Fig. 15.7. Maps of the salinity minimum produced by the Intermediate Waters. (a) Depth of the minimum, (b) salinity at the depth of the minimum. The location of the section shown in Fig. 15.2 is also indicated in (a). After Wüst (1936) and Dietrich *et al*. (1980).

Above the Deep and Circumpolar Waters is the Intermediate Water, characterized as in the other oceans by its low salinity. Figure 15.7 gives the depth of the salinity minimum produced by the spreading of this water mass and the salinity at that depth. The outstanding feature is the pronounced lack of symmetry relative to the equator. The dominant water mass is the *Antarctic Intermediate Water* (AAIW). Formed mostly in the eastern south Pacific and entering into the Atlantic Ocean through Drake Passage and with the Malvinas Current, it spreads isopycnally into the northern hemisphere. Concentration of its flow along the western boundary is indicated by the northward extension of the isohalines with

ignored. A hydrographic section across the Iceland-Scotland Ridge (Figure 15.8), however, gives clear evidence that this water fits our definition of a water mass as a body of water with a common formation history: The Arctic Bottom Water, with salinities near 35.0 and temperatures below 3°C, is retained behind the sill and enters the Atlantic Ocean episodically, while the Intermediate Water sinks from the surface and is continuously subducted.

Water masses of the thermocline and surface layer

Two well-defined water masses occupy the Atlantic thermocline. Both are characterized by nearly straight T-S relationships. A south to north succession of T-S curves (Figure 15.9) shows a sudden shift to higher salinities some 1500 km north of the equator, indicating different hydrographic properties north and south of about 15°N.

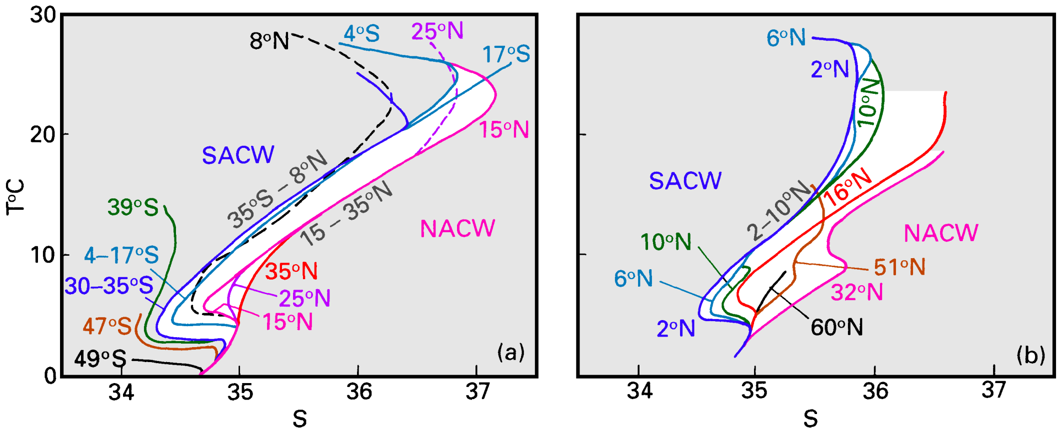

Fig. 15.9. T-S diagrams for stations along two meridional sections. (a) Western basins, (b) eastern basin (northern hemisphere). Note the northward weakening of the AAIW salinity minimum, the deep salinity maximum produced by the inflow of Eurafrican Mediterranean Water (most prominently at 32°N in the east), and the sudden transition from SACW to NACW south of 15°N. Data from Osborne *et al*. (1991).

South Atlantic Central Water (SACW), the water mass south of 15°N, shows rather uniform properties throughout its range. Its T-S curve is well described by a straight line between the T-S points 5°C, 34.3 and 20°C, 36.0 and is virtually the same as the T-S curves of Indian and Western South Pacific Central Water. This reflects the common formation history of all Central Waters in the southern hemisphere, which are subducted in the Subtropical Convergence (STC). Although the STC is well defined and continuous across the south Atlantic Ocean, detailed comparison between the T-S relationship along a

North Atlantic Central Water (NACW) can again be characterized by a nearly straight line in the T-S diagram, with some variation of the T-S relationship within the water mass. Typically, the T-S curve connects the T-S point 7°C, 35.0 with the points 18°C, 36.7 in the east and 20°C, 36.7 in the west. The regional differences stem from property variations in the formation region. Although curl(τ/f) is negative over most of the north Atlantic Ocean (Figure 4.3), a subtropical convergence as a region of more or less uniform subduction of Central Water from the surface cannot be identified. This is apparently because the subtropical gyre extends further north in the eastern north Atlantic than in the north Pacific Ocean, allowing the surface waters of the North Atlantic Current to cool much more during their northeastward passage than those of the North Pacific Current. Winter convection in the north Atlantic Ocean therefore reaches much deeper. Figure 15.10 shows that at the end of winter it reaches the bottom of the thermocline along the European shelf as far south as northern Spain. This affects all temperatures below 12°C. As a consequence, NACW enters the thermocline at those temperatures by a process of horizontal "injection" rather than isopycnal subduction, and its properties are influenced by water masses from the Arctic Mediterranean and Labrador Seas which participate in the convection. The deepest convection occurs in the northeast, and the corresponding vertical transfer of salt from the surface layer reaches its greatest depth there, raising the salt content of the eastern NACW variety.

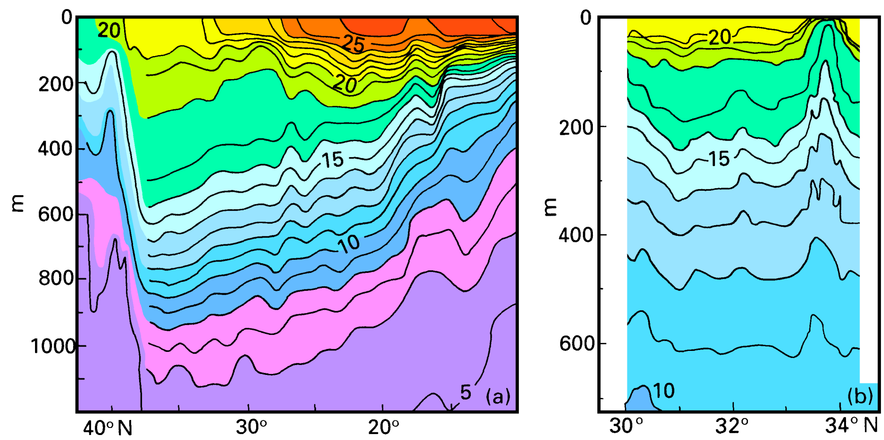

Fig. 15.11. Temperature sections indicating the presence of Subtropical Mode Water. (a) Through the Sargasso Sea along 50°W, (b) near Madeira along approximately 18°W. Note the increased isotherm spacing (thermostad) in the 17 - 18°C range. Adapted from McCartney (1982) and Siedler *et al*. (1987).

Above 12°C NACW is formed through the usual process, i.e. surface subduction of winter water. Again, this process does not occur uniformly across the region but involves Mode Water formation. Large volumes of Central Water are formed every winter in the Sargasso Sea at temperatures around 18°C. They appear in vertical temperature profiles as a permanent thermostad at 250 - 400 m depth (Figure 15.11) and represent a variety of

NACW in the North Equatorial Current erodes the horizontal gradients. Eventually the mixture is carried north in the Guyana and Antilles Currents to complete the route of SACW from the Agulhas Current eddies to the formation region of North Atlantic Deep Water.

Because the separation zone between both Central Waters is located more than 1500 km north of the equator and the SACW/NACW mixture produced in the west is not returned into the equatorial current system but transported northward, there is no opportunity to form a special equatorial water mass in the manner seen in the Pacific Ocean. The opposing eastward and westward equatorial flows leave, however, their mark in the hydrographic properties of SACW. Observations from the region of the Guinea Dome show a small but well-defined salinity decrease, from south to north, across the boundary between the North Equatorial Countercurrent and the North Equatorial Current near 10°N (Figure 15.13). The front between the two SACW varieties slopes downward toward the north, the low salinity variety moving eastward above westward movement of the high salinity variety.

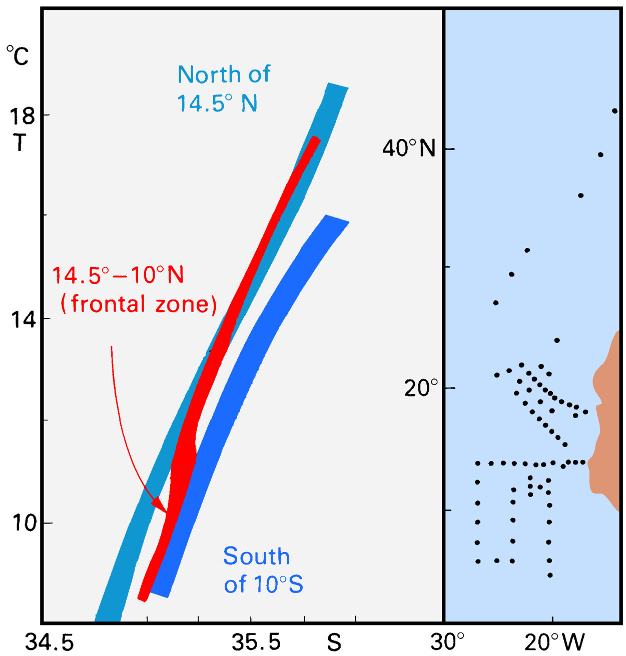

Fig. 15.13. (Right) T-S relationships in the South Atlantic Central Water of the eastern tropical Atlantic Ocean, showing two SACW varieties separated by a frontal zone between the North Equatorial Current and the Equatorial Countercurrent. The stations used for the construction of the T-S diagram are shown on the right.

Main aspects of the hydrographic structure above the permanent thermocline were already discussed in an earlier section of this chapter. A major feature of the tropical Atlantic Ocean is the existence of a barrier layer in the region of the Guyana Current (Figure 15.14). This

A description of the hydrographic conditions in the shelf regions of the Atlantic Ocean is beyond the scope of this book, but one region deserves mention. The large volume of water between the Gulf Stream and the continental shelf is isolated from direct contact with the oceanic water masses of its depth range by the western boundary current. Its properties are formed through a complex process of interaction between water on the shelf, from the Labrador Current, and from the Gulf Stream. Water on the shelf has very low salinity (below 34, a result of freshwater inflow from the St. Lawrence River). The Labrador Current also carries low salinity water. Mixing of the various components produces a water mass known as Slope Water, which extends over the upper 1000 m along the north American continental rise north of Cape Hatteras (35°N) and is characterized by a nearly linear T-S relationship similar to that of NACW but with much lower salinity. This water is frequently trapped in cyclonic Gulf Stream Rings and transported across the Gulf Stream into the Sargasso Sea, as seen in the example of Figure 15.15. As a result, variations of hydrographic properties in the permanent thermocline of the Atlantic Ocean are largest in the northern Sargasso Sea.

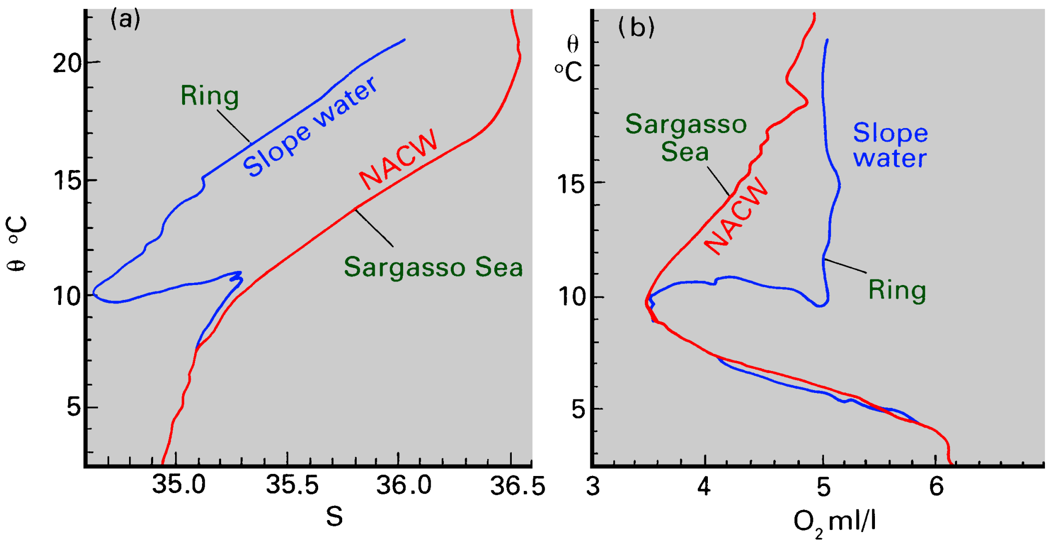

Fig. 15.15. An example of Slope Water advection into the Sargasso Sea in a Gulf Stream ring. (a) Θ-S diagram, (b) Θ−oxygen diagram, for a station outside ("Sargasso Sea") and inside ("Ring") a cyclonic Gulf Stream ring. Higher oxygen concentration in the Slope Water indicates more recent contact with the atmosphere. From Richardson (1983b).