Chapter 7

Arctic oceanography; the path of North Atlantic Deep Water

The importance of the Southern Ocean for the formation of the water masses of the world ocean poses the question whether similar conditions are found in the Arctic. We therefore postpone the discussion of the temperate and tropical oceans again and have a look at the oceanography of the Arctic Seas.

It does not take much to realize that the impact of the Arctic region on the circulation and water masses of the World Ocean differs substantially from that of the Southern Ocean. The major reason is found in the topography. The Arctic Seas belong to a class of ocean basins known as mediterranean seas (Dietrich *et al*., 1980). A mediterranean sea is defined as a part of the world ocean which has only limited communication with the major ocean basins (these being the Pacific, Atlantic, and Indian Oceans) and where the circulation is dominated by thermohaline forcing. What this means is that, in contrast to the dynamics of the major ocean basins where most currents are driven by the wind and modified by thermohaline effects, currents in mediterranean seas are driven by temperature and salinity differences (the salinity effect usually dominates) and modified by wind action. The reason for the dominance of thermohaline forcing is the topography: Mediterranean Seas are separated from the major ocean basins by sills, which limit the exchange of deeper waters.

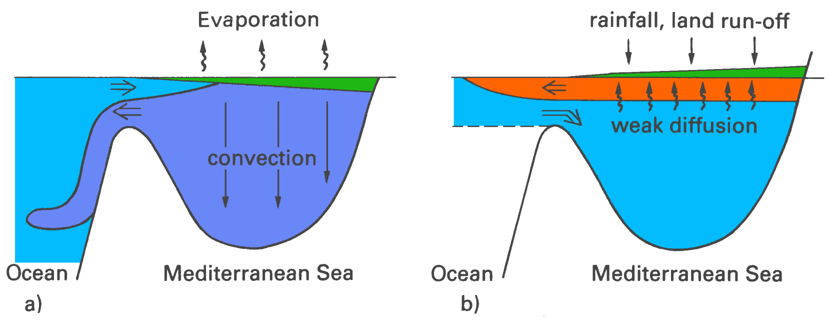


Fig. 7.1. Schematic illustration of the circulation in mediterranean seas; (a) with negative precipitation - evaporation balance, (b) with positive precipitation - evaporation balance.

The circulation in mediterranean seas can be divided into two classes, depending on the freshwater budget at the surface (Figure 7.1). If evaporation over the mediterranean sea exceeds precipitation, freshwater loss in the upper layers increases the density of the surface waters, resulting in deep vertical convection and frequent renewal of the water below the sill depth. The circulation at the connection between the mediterranean sea and the ocean basin consists of inflow of oceanic water in the upper layer and outflow of mediterranean water in the lower layer. The inflow is driven by the freshwater loss in the mediterranean sea; in addition, the density difference between the salty mediterranean water and the fresher oceanic water causes outflow of mediterranean water in the deeper part of the connecting channel with a compensating inflow above it. The outflowing water sinks until it reaches the depth

Iceland, and Norwegian Seas communicate with the North Polar Sea through Fram Strait, which between Greenland and West Spitsbergen (the westernmost island of the Svalbard group) is 450 km wide and generally deeper than 3000 m, with a sill depth somewhat less than 2500 m. The North Polar Sea itself is structured through three ridges into a series of four basins. The nomenclature for these features is not uniform; the GEBCO charts identify the Canada Basin with a depth of 3600 - 3800 m, the Makarov Basin with approximately 3900 m depth, the Amundsen Basin with depths of 4300 - 4500 m, and the Nansen Basin with depths between 3800 m and 4000 m. The ridges between these basins are the Alpha and Mendeleyev Ridge system which rises to between 1200 m and 1500 m, the Lomonossov Ridge with depths between 850 m and 1600 m, and the Arctic Mid-Ocean Ridge, sometimes referred to as the Nansen Ridge, which reaches 2500 m depth. The Amundsen and Nansen Basins and the Arctic Mid-Ocean Ridge are often combined into what is then called the Eurasian Basin. Herman (1974) lists other names.

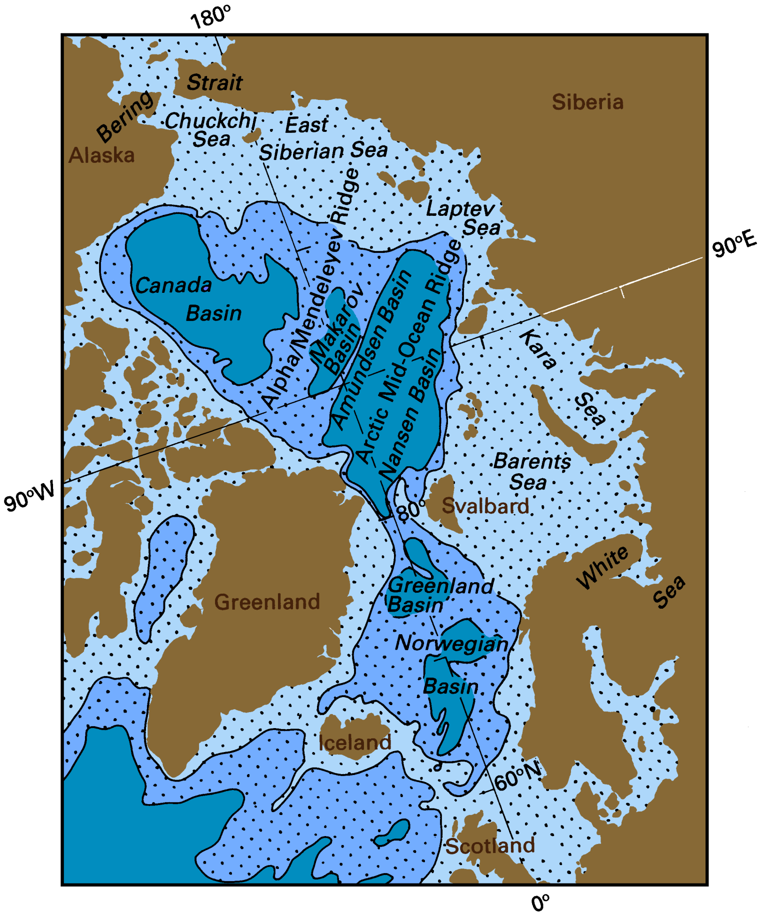
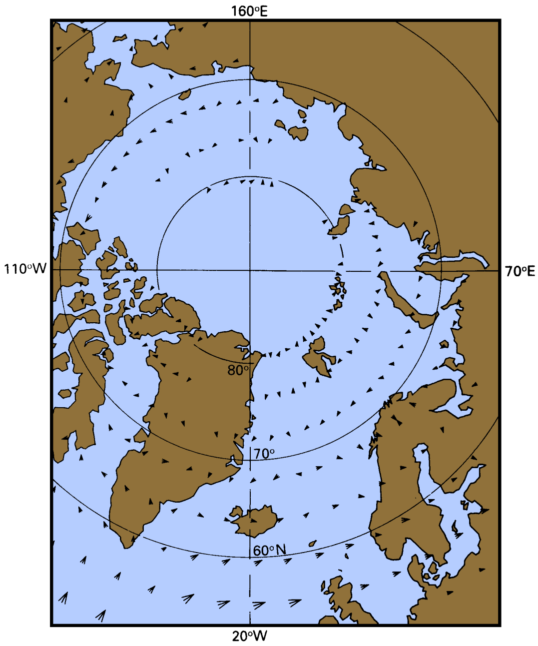


Fig. 7.2. Bottom topography of the Arctic Mediterranean Sea. The 1000, 3000, and 5000 m isobaths are shown, and regions less than 3000 m deep are shaded. Sv: Svalbard island group.



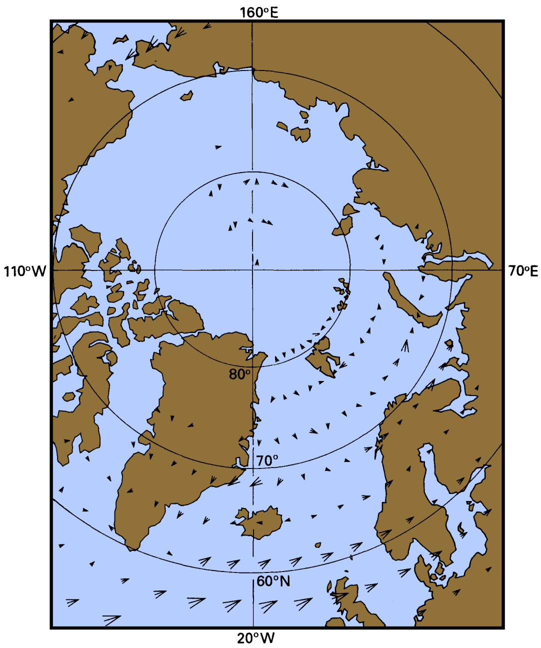


Fig. 7.4. Surface winds over the Arctic Mediterranean Sea.

(a, page 86) annual mean,

(b) July mean,

(c) January mean. See Figure 1.2 for data sources.

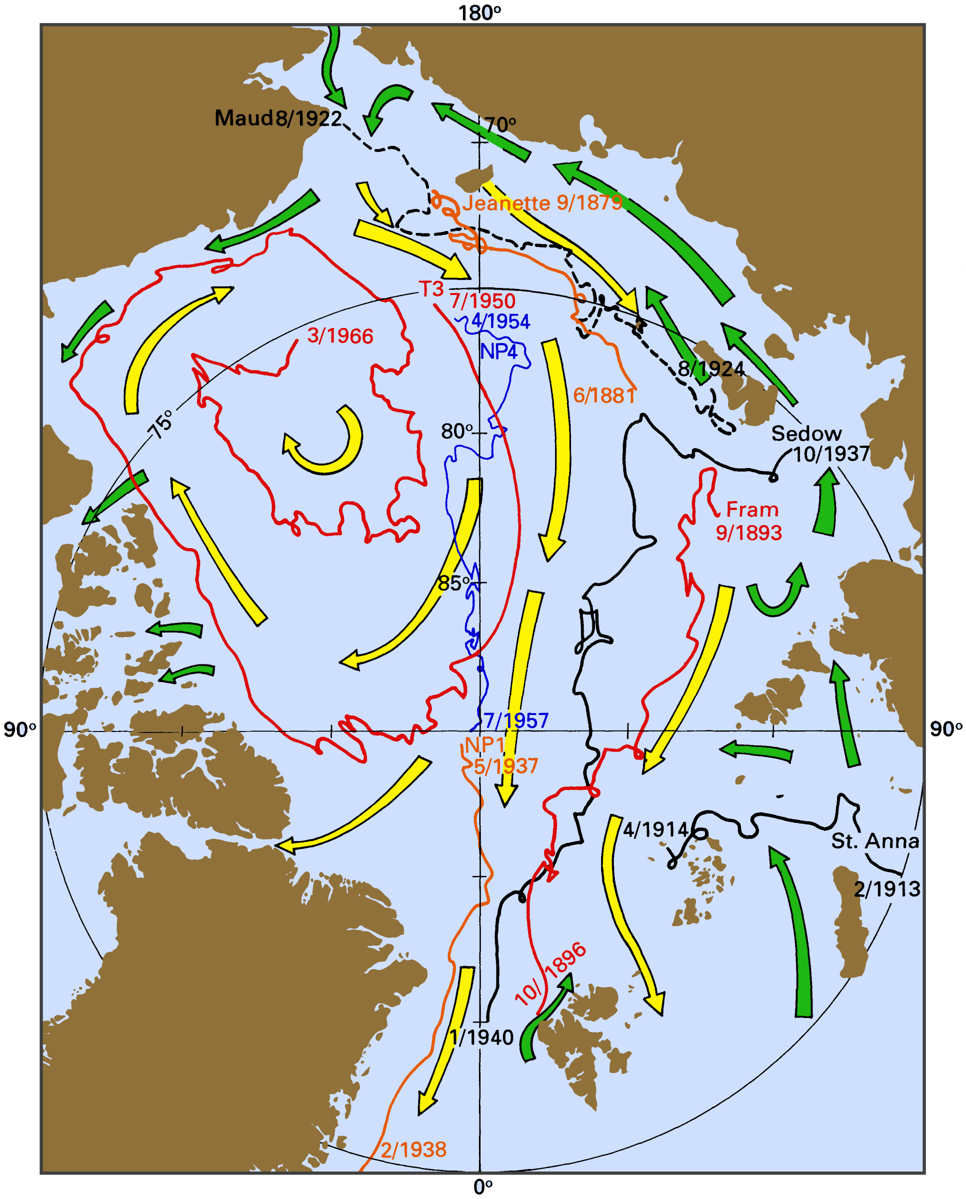


Fig. 7.5. Mean circulation of surface waters, with some tracks of vessels and ice stations.

fact that inflow and outflow both occur near the surface is due to a combination of factors. The width of the Greenland-Iceland-Faroe-Scotland Ridge allows the Coriolis force to exert an influence on the currents; it concentrates the outflow of low salinity water in the East Greenland Current on the western side, leaving room for inflow in the Norwegian Current

difference easily compensates the effect of salinity on density, which is higher (34 - 35) in the Norwegian Current and along the Norwegian coast than in the East Greenland Current (30 - 33); so the water is denser on the western side and isopycnals slope downward to the east, in accordance with the thermal wind relation (Rule 2a). The boundary between the two currents, which coincides more or less with the ice boundary, is characterized by shear-generated eddies, of 10 - 20 km diameter and with a life span of 20 - 30 days, which affect the movement of water to a depth of several hundred meters.

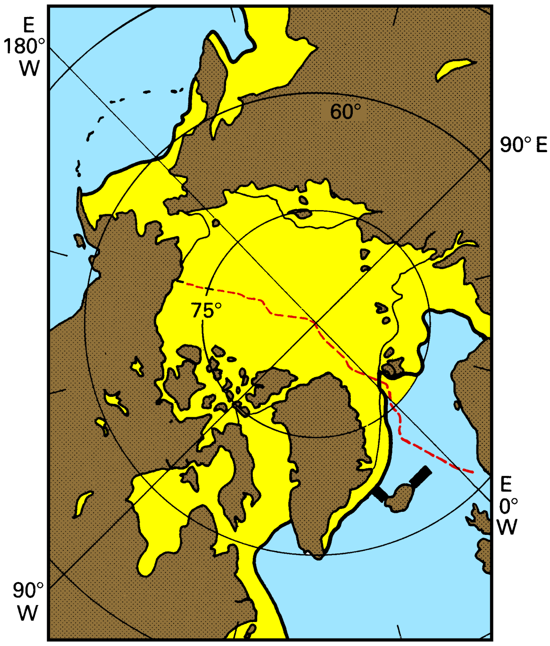


Fig. 7.6. Ice coverage in the Arctic ocean, based on satellite data from 1974 - 1976. The thick line shows the extent if sea ice in late winter (March), the thin line the ice extent in late summer (September). The heavy bars near Iceland give the southern ice limit during March 1968; they are included to indicate the degree of interannual variability. The broken line shows the location of the section shown in Fig. 7.8.

Estimates of variations in ice extent from satellite observations (Gloersen and Campbell, 1988) indicate an area of $8 \cdot 10^6$ km^2 for the summer season and $15 \cdot 10^6$ km^2 for winter, of which 14% is open water. The average life span of large polynya was 75 days, half the life span of polynya in the Southern Ocean where ice movement is less constrained by coastlines, favouring the development of large regions of open water.

Hydrology and water masses

The mediterranean character of the Arctic Seas comes out clearly when we now look at the circulation and water masses at and below the sill depth. Since precipitation over the Arctic Mediterranean Sea exceeds evaporation, the region acts as a dilution basin for the Atlantic Ocean. Water exchange across the sill follows the scheme of Figure 7.1b, with three modifications. The first modification occurs in the surface layer where - as mentioned before - the Coriolis force restricts outflow into the Atlantic Ocean to the western side of

Greenland Sea is therefore never completely ice-covered, and formation of Greenland Sea Deep Water occurs in mainly open water (Rudels and Quadfasel, 1991).

The other source of Arctic Bottom Water is found in the Arctic shelf regions (Aagaard *et al*., 1985b). The low salinity of shelf water, which reflects input of freshwater from rivers, facilitates ice formation. As salt is rejected from the ice, the salinity of the water below the ice is increased. The shelf regions therefore produce a large variety of water bodies through the seasons, some fresh, some salty, some very salty, but all very cold. When the salinity exceeds 35 - which has been observed on occasions in the Chukchi Sea; water in 300 m deep depressions of the Barents Sea has also been found to have salinities above 35 and temperatures below -1.8°C - the water is dense enough to sink to the bottom of the basins of the Arctic Sea, thus contributing to the formation of Arctic Bottom Water. Fjords of the Svalbard island group have also been found to contribute to this input of high salinity water.

Salinities in the Arctic Bottom Water are generally close to 34.95 but highest in the Canada Basin (Figure 7.8). The contribution of the shelf regions to Bottom Water formation is evident from the fact that salinities in the Canada Basin are higher than could be explained from surface salinities in the Norwegian or Greenland Seas and therefore cannot be the result of mixing with the inflowing high-salinity water alone.

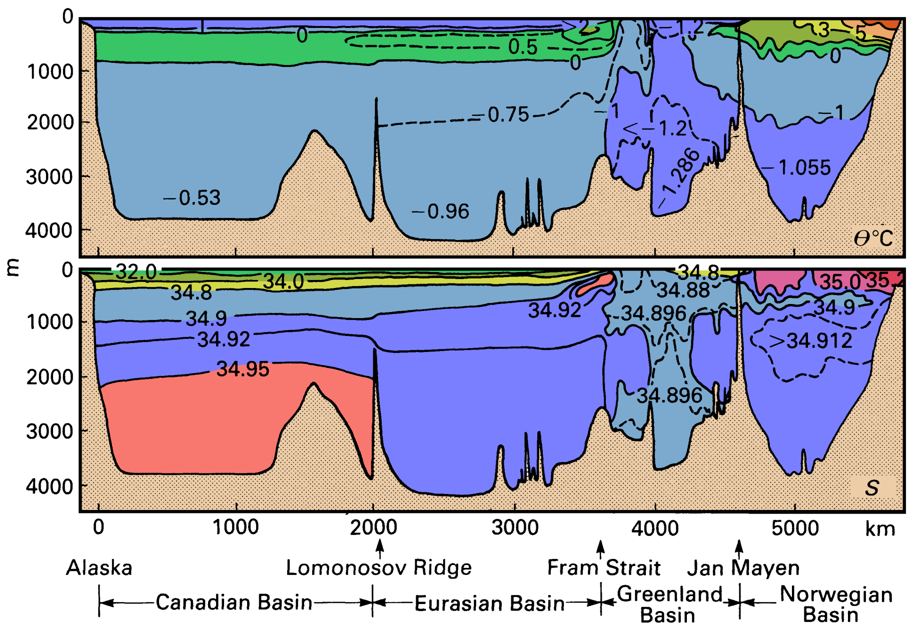


Fig. 7.8. Potential temperature and salinity along a section from the Norwegian Sea into the Canada Basin. The penetration of Atlantic Water - from the surface in the Norwegian Sea to the depth range between Surface and Bottom Water - is indicated by the temperature and salinity maxima near 500 m depth. Note that the temperature and salinity increments between isotherms and isohalines are not constant over the respective ranges. See Fig. 7.6 for location of the section. From Aagaard *et al.* (1985b).

mixes with Norwegian Sea Deep Water, and recirculates into the basins of the Arctic Sea. Eastward flow in a 2000 m deep channel north of Jan Mayen has been verified through direct current meter measurements which for the depth range 1700 - 2000 m gave average current speeds of 0.05 m s^{-1} for a seven month period in 1981 and 0.08 m s^{-1} for a ten month period in 1983 and 1984 (Sælen, 1988).

From the point of view of world ocean water masses, the product of the complex mixing process indicated in Figure 7.9 can justifiably be called Arctic Bottom Water, since it not only fills all deep Arctic basins but also plays an important role in the deep circulation of the world ocean (as will be discussed below). The temperature in the Arctic Bottom Water varies slightly between basins and in each basin shows an apparent increase with depth due to the increase in pressure (potential temperature, which is shown in Figure 7.8, is uniform with depth). In the Norwegian Sea its potential temperature is close to -0.95°C. Further north its temperature is determined by sill depths; in most basins its temperature is between -0.8°C and -0.9°C, but the Lomonossov Ridge prevents Arctic Bottom Water colder than -0.4°C from entering the Canada Basin (Figure 7.8). The effect of the Lomonossov Ridge sill depth, which is near 1500 m, comes out clearly in observations of tritium and radiocarbon concentration (Östlund *et al.*, 1987). They indicate a water renewal time of 30 years for Arctic Bottom Water in the Amundsen and Nansen Basins but 700 years in the Canada and Makarov Basins; in the upper 1500 m, water in all basins is renewed at a rate of 30 years.

Above Arctic Bottom Water is the *Atlantic Water*, which occupies the depth range between about 150 m and 900 m. Its classification as a water mass is justified since it enters the Arctic Mediterranean Sea from the Atlantic Ocean with distinct properties and can be regarded as formed outside the region under consideration. Atlantic Water has the same salinity as Bottom Water but is much warmer (up to 3°C near Spitsbergen), being effectively the summer version of Norwegian Sea Deep Water (and a source for Atlantic Bottom Water when winter cooling sets in). It is also warmer than Arctic Surface Water; but its high salinity makes it denser than the Surface Water. In a hydrographic station Atlantic Water is therefore seen as a temperature maximum (Figure 7.7), at a depth of 150 m near Spitsbergen and progressively deeper to 500 m in the Canada Basin. The maximum is gradually eroded by mixing, and a plot of temperature at the depth of the temperature maximum (Figure 7.10) indicates the path of Atlantic Water through the Arctic Mediterranean Sea rather well. It is seen that the water enters the North Polar Sea with the West Spitsbergen Current and flows in cyclonic movement, opposite to the circulation of the surface layer above. Movement is again slow, of the order of 0.02 m s^{-1}, except in the West Spitsbergen Current which displays speeds similar to the other two major surface currents.

Arctic Surface Water, which occupies the depth range from the surface to 150 - 200 m, has temperatures close to the freezing point (-1.5°C to -1.9°C), with little variation over depth. Salinity, on the other hand, varies strongly and is sometimes used to distinguish a surface layer of 25 - 50 m thickness and a sub-surface layer below. In the surface layer, Arctic Surface Water shows very much the same characteristics throughout the Arctic Mediterranean Sea, with salinity depending strongly on the degree of ice melting or freezing and varying accordingly between 28 and 33.5. The sub-surface layer is characterized by a strong salinity gradient but uniform temperature. Water in this layer is the product of intense mixing on the Siberian shelf which the Atlantic Water enters through a series of canyons. Production of shelf water with salinities not high enough to contribute to Arctic

size and carry water with distinct property characteristics into a region with different water properties, increasing the area of contact between the different water masses where mixing can occur. The residence time for water in this layer is correspondingly low; tracer observations put it at about ten years.

The sub-surface layer of Arctic Surface Water is also the depth where inflow of water from the Pacific Ocean through Bering Strait has some impact. In summer, water from the Bering Sea is warmer than Arctic Surface Water (2 - 6°C, occasionally up to 10°C) but saltier (31 - 33) and spreads at 50 - 100 m depth, producing a temperature maximum (just as Atlantic Water does between 150 m and 500 m). In winter, it is of comparable temperature (around -1.6°C) but again saltier (32 - 34) and spreads at about 150 m depth, producing a temperature minimum. Using these temperature inversions, the presence of water from the Bering Sea can be verified in the sub-surface layer of most of the Canada Basin.

Figure 7.11 summarizes the character of the Arctic Mediterranean Sea as a dilution basin in a T-S diagram. Although the volume of the surface water masses is small (and the T-S diagram grossly misleading in this respect) their importance for the modification of water properties is evident. The dilution effect can be seen along the path of the Labrador Current into the region of the Polar Front in the Atlantic Ocean.

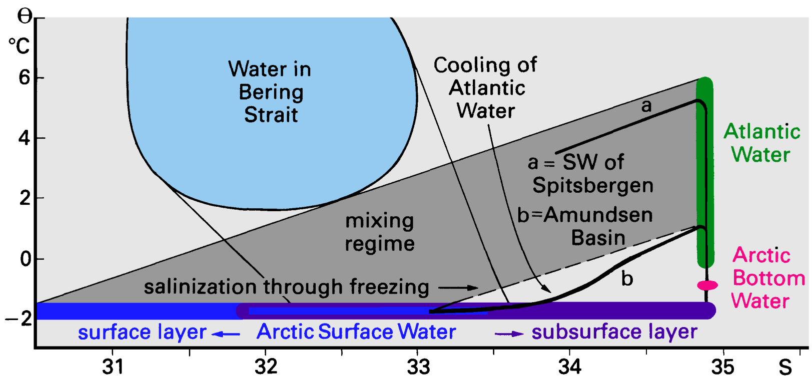


Fig. 7.11. T-S diagram of the Arctic Mediterranean Sea, showing the T-S properties of the water masses and two examples of station data (curves *a* and *b*). The hatched areas give T-S properties of source water masses; the thin lines limit the regions of all possible and observed T-S combinations produced by mixing. T-S curves from individual stations such as curves *a* and *b* generally follow straight mixing paths within the delineated range. Cooling of Atlantic Water through mixing with Surface Water of the subsurface layer is indicated by the departure of the T-S curve from a straight mixing line in the Amundsen Basin.

Mass and heat budget

Estimation of mass and heat transport in the Arctic Seas is easier than in the Antarctic region, since water movement is mainly restricted to the layers above the sill depths and can be determined reasonably well through geostrophy. However, transport variations can

leaves with the East Greenland Current exports only $185 \cdot 10^6$ kg. The remainder is exported with the Arctic Surface Water through the Canadian Archipelago and again in the East Greenland Current.

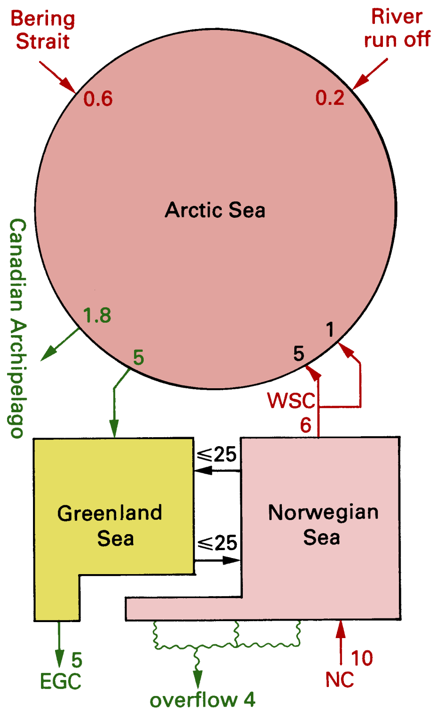


Fig. 7.12. Mass budget for the Arctic Mediterranean Sea and its three major sub-divisions. EGC: East Greenland Current, NC: Norwegian Current, WSC: West Spitsbergen Current. Volume transports are in Sv.

Fate of Arctic Bottom Water, and path of North Atlantic Deep Water

The mass budget of the Arctic Mediterranean Sea includes an outflow of some 4 Sv of Arctic Bottom Water from the Norwegian Sea into the Atlantic Ocean. Arctic Bottom Water is the densest water of the world ocean, but it is not found anywhere outside the Arctic region. The question arises what happens to the 4 Sv that cross the Greenland-Iceland-Faroe-Scotland Ridge.

The answer to this question is well known today and leads us to the formation of North Atlantic Deep Water, which we met during our discussion of the Southern Ocean. Figure 7.13 shows the path of what is called the Arctic Bottom Water overflow. The deepest passage is in the Faroe Bank Channel and has an average transport of 1 Sv. Overflow over the Iceland-Faroe sill also amounts to 1 Sv. A third path is through Denmark Strait, which contributes 2 Sv to the overflow. During the passage across the sill the Coriolis force keeps the overflowing water to the right (Figure 7.14); so the overflow produces intense currents of Arctic Bottom Water along the continental shelves of Iceland and Greenland which cross the depth contours at a very small angle toward greater depth. The two eastern transports combine to form a uniform flow south-east of Iceland,

Arctic Bottom Water is therefore mixed particularly in winter with water which sank from the surface. This water has similar salinities (near 34.9) but higher temperatures (about 3.5°C). The resulting mixture is known as *North Atlantic Deep Water*. Arctic Bottom Water is absorbed entirely by this new water mass and cannot be traced beyond the Labrador Sea.

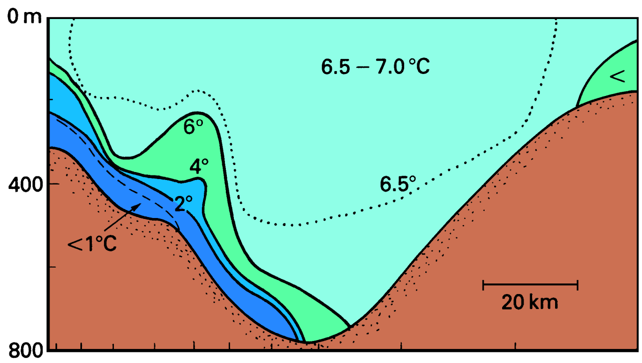


Fig. 7.14. (Right) Temperature section across Denmark Strait at about 65°N, demonstrating the concentration of Arctic Bottom Water overflow on the right of the channel. Ticks along the horizontal scale indicate station positions. From Worthington (1969).

Estimates of the rate of sinking in the Labrador Sea vary and are mostly based on indirect arguments because of the lack of direct winter observations. The total flow of North Atlantic Deep Water from the Labrador Sea is believed to be somewhere around 15 Sv; these figures were derived from estimates of mean heat loss to the atmosphere in the north Atlantic Ocean. They indicate sinking of 5 Sv of water in the Labrador Sea. The Deep Water which leaves the Labrador Sea is more saline but distinctly warmer than Antarctic Bottom Water. It therefore does not spread along the bottom of the ocean but above the Antarctic Bottom Water (which explains its name Deep Water).

Although North Atlantic Deep Water forms in the far north of the Atlantic Ocean it has a large impact on the water properties of the world ocean as a whole. We already met this water mass near Antarctica, where it upwells from between 2000 m and 4000 m into the upper layer and leaves the Atlantic Ocean with the Circumpolar Current. What this means is that the Atlantic Ocean loses surface water to the deeper layers near Labrador at the rate of 15 Sv, while the other oceans gain 15 Sv of surface water through the Circumpolar Current. There has to be a return flow somewhere. This problem was investigated by Gordon (1986a) who, on the basis of transport estimates and exchanges of heat and salt, developed the picture sketched in Figure 7.15: North Atlantic Deep Water spreads below the permanent thermocline into the three oceans, where it is slowly lost to the surface layer through weak but continuous upwelling. It returns in the surface layer, from the Pacific Ocean through the passages of the Indonesian seas and from the Indian Ocean with the Agulhas Current extension.

The general concept of Gordon's circulation scheme — with some modifications, discussed in the appropriate chapters — has become an accepted part of oceanography today,

recirculation path of Figure 7.15 it could be said that it is just another transformation of North Atlantic Deep Water. A detailed heat and mass balance between ocean and atmosphere along the surface layer part of the proposed path can assist to establish the relative roles of the various circulation paths.

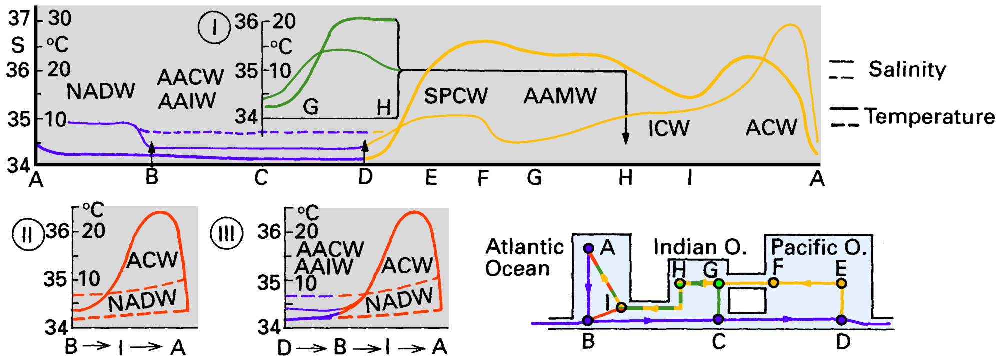


Fig. 7.16. Temperature and salinity along recirculation paths of North Atlantic Deep Water. Pathways are indicated in the lower right. The main diagram follows A-B-C-D-E-F-G-H-I-A, which is Gordon's (1986a) path. Diagram I takes the shorter route A-B-C-G-H-I-A through the Indian subtropical gyre (thus avoiding the reduction of salinity in the AAMW), diagram II recirculates NADW along A-B-I-A within the Atlantic Ocean. Lastly, diagram III gives the path A-B-C-D-B-I-A through Drake Passage. Full lines indicate paths which involve upwelling into the thermocline, broken lines indicate recirculation at depth; heavy lines are temperatures, thin lines salinities. Water masses, described in detail in the chapters on the individual oceans, are abbreviated as NADW: North Atlantic Deep Water, AACW: Antarctic Circumpolar Water (broken lines), AAIW: Antarctic Intermediate Water (full lines), ICW: Indian Central Water, SPCW: South Pacific Central Water, AAMW: Australasian Mediterranean Water, ACW: Atlantic Central Water.