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Temperature and salinity in the central Labrador Sea during the 1990s and in the context of the longer-term change

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In the early years of the 1990s, in the Labrador Sea winters were exceptionally severe, while in the later years winters were relatively mild. High heat losses during the severe winters produced mixed layers increasing in depth to a maximum of 2300 m. This pool of convectively mixed water, Labrador Sea Water (LSW), is a well-recognized intermediate water mass in the North Atlantic Ocean. In the latter half of the decade, mixed layer depths, at less than 1500 m, were too shallow to maintain the recently created LSW. It slowly drained away from the Labrador Sea to other regions of the North Atlantic Ocean. This loss was balanced by a flow of warmer more saline water from the boundary currents. Changes in temperature and salinity associated with the build-up and decline of LSW over the decade are presented. Property variations in the Northeast Atlantic Deep Water and Denmark Strait Overflow Water lying below the LSW are also discussed.

Keywords: climate change, convection, Labrador Sea, North Atlantic Ocean, stratification, vertical mixing.

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Introduction

During winter, cold air from northeastern Canada flows over the Labrador Sea creating a convectively mixed surface layer that can reach deeper than 2000 m in the centre of the sea during exceptionally cold years. When the convection is greater than ≈ 1500 m the mixed water is recognized as a unique water mass known most commonly as Labrador Sea Water (LSW). Production of LSW varies greatly from year to year in step with the severity of the winter weather in the area (Curry *et al.*, 1998).

The formation of LSW provides an important pathway for atmospheric gases such as oxygen, carbon dioxide, and the chlorofluorocarbons (CFCs) to pass from the surface mixed layer to intermediate depths. As the convected water, LSW, flows to other regions of the ocean (Sy *et al.*, 1997), it distributes these dissolved gases to a large area of the ocean, thereby ventilating the deeper layers. Because of the importance of this process and because of the large variability in the production rate of LSW, the Bedford Institute of Oceanography has occupied a line of CTD stations across the Labrador Sea in the early summers of each year since 1990 (Figure 1). In addition multi-line surveys were conducted in the autumn of 1996 and the spring of 1997. Between 1990 and 1997 the work was a contribution to the World Ocean Circulation Experiment (WOCE) and since 1997 to the Climate Variability Program (CLIVAR).

The purpose of this article is to present a general description of the temperature and salinity variations which occurred during the years 1990–2001 within the three principal water masses found in the central Labrador Sea – the LSW, the Northeast Atlantic Deep Water (NEADW), and the Denmark Strait Overflow Water (DSOW) – and compare the recent state of these water masses with the history of more than five decades. We first describe the data in section 2, then in section 3 focus on each water mass in turn. This is followed in section 4 by a discussion of the results in section 3 with reference to the longer-term record and a summary in section 5.

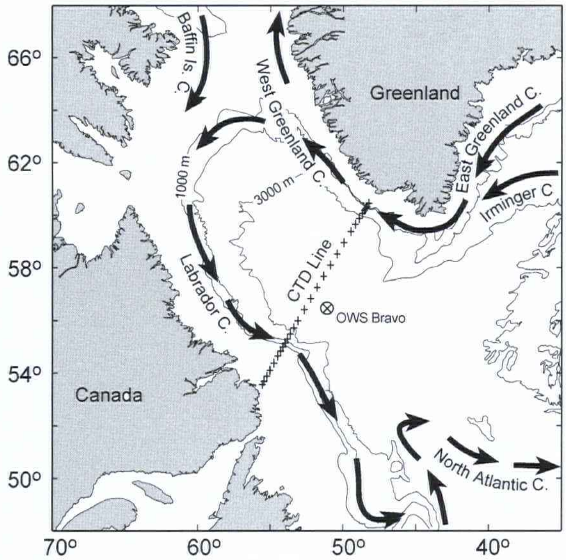

Figure 1. Map of the Labrador Sea showing the major currents in the region. The CTD line occupied each summer between 1990 and 2001 is indicated by the line of station positions indicated by crosses. OWS "Bravo" was an Ocean Weather Ship which regularly collected oceanographic data between 1964 and 1973.

Data

The data collected between 1990 and 2001 are presented in three diagrams. Salinity sections (Figure 2) show the distribution across the sea at the beginning and end of the observing period and in 1993. The 1993 salinity section represents the distribution following the series of most severe winters when the LSW appeared most extensive and most homogeneous. Figure 3 presents distributions of potential temperature (hereafter temperature), salinity, and potential density anomaly relative to 2000 db (σ_2) in the central region of the Labrador Sea in time–depth coordinates. The time-series of the vertical distributions were composed from the medians of temperature (T) and salinity (S) measurements in σ_2 bins for each year. The size of σ_2 bins was varied with depth to maintain even vertical separation between the centres of the bins and to provide sufficient data coverage. The σ_2 bin size was in the range between 0.02 and 0.005. The T–S diagrams in Figure 4 cover two time intervals associated with the build-up and decline of LSW. The data set for the analyses presented in Figures 3–6 was restricted to the central region of the sea (with water depth greater than 3300 m).

The 1993 salinity section in Figure 2 shows the distribution along the line following a winter of deep convection. The large mass of nearly homogeneous water between 500 and 2300 m between 360 and 800 km is the pool of LSW transformed through the deep convection during the previous winter.

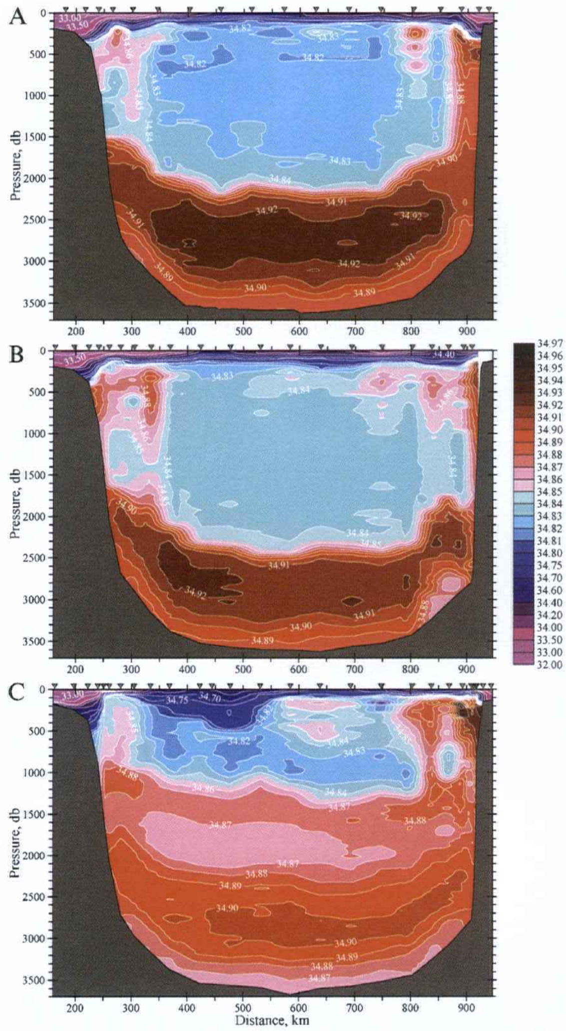

Figure 2. Salinity sections along the Labrador Sea CTD line (Figure 1) in the early summer of 1990 (A), 1993 (B), and 2001 (C). The distance scale is from the Labrador coast. Station positions are indicated by inverted triangles at the surface.

Above 500 m the water is more stratified than the layer between 500 and 2300 m. These observations were obtained in July about 3 months after deep convection ceased at the end of the cooling season, which was about 1 April. Since that time the surface layer has been flooded with freshwater derived from melting ice and river run-off. Solar heating has added to the stratification. In addition, the layer below this low salinity surface layer, to about 500 m, has been invaded by higher salinity water from the right, that is, the northeast. This more saline water is known as the Irminger Water (IW), because it is transported into the Labrador Sea from the Irminger Sea in the East and West Greenland Currents, which lie over the continental shelf and slope (Figure 1). On the left or southwest end of the section there is again a salinity maximum at about

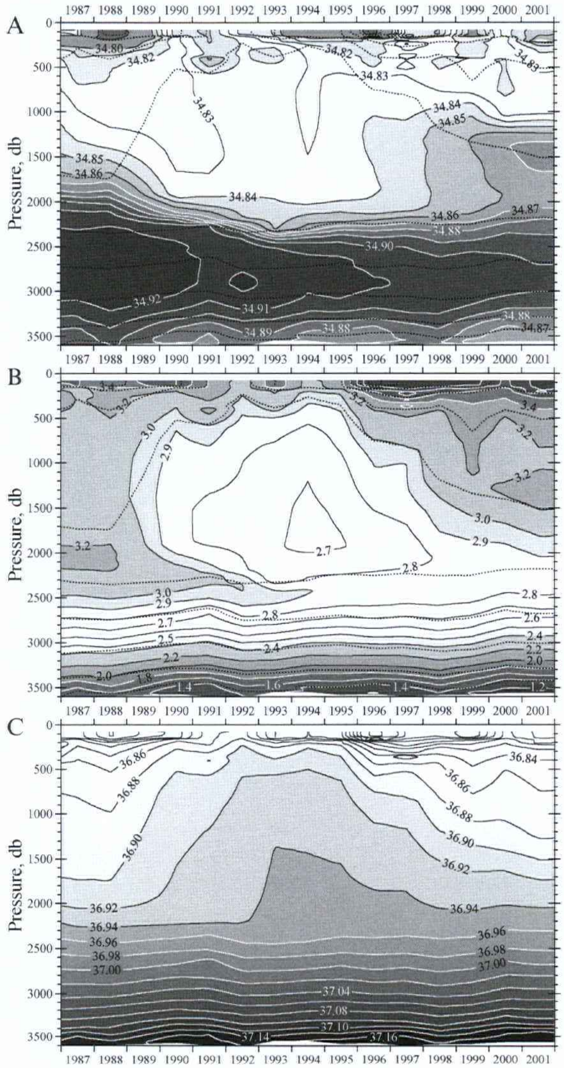

Figure 3. Time-series of the vertical distributions of salinity (A), temperature (B), and σ_2 (C) between 1987 and 2001. The black dashed lines in (A) and (B) indicate σ_2 contours.

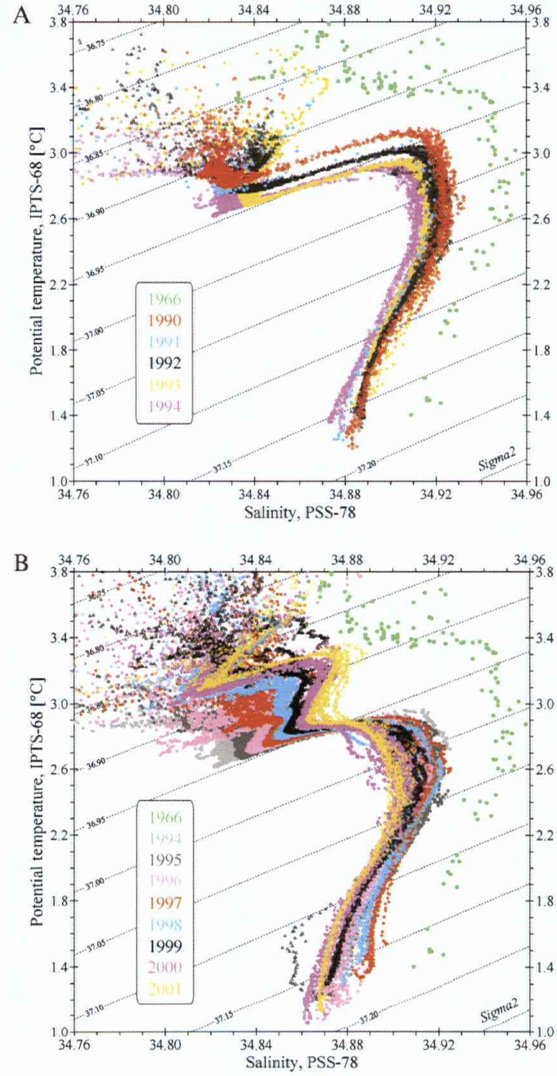

Figure 4. Temperature vs. salinity curves representing the average conditions in the centre of the Labrador Sea during the early summers of 1990–1994 (A) and 1994–2001 (B). We also show the *Hudson* 1966 data to indicate the longer-term freshening in the intermediate and deep layers.

300 m over the Labrador continental slope which also tends to invade the central region. This is again Irminger Water, which has been transported around the Labrador Sea in the West Greenland and Labrador Currents.

Beneath the LSW, between 2300 and 3300 m, lies a water mass identified by the salinity maximum at about 2800 m. This is the NEADW. It originates in the eastern basin of the North Atlantic from the overflow crossing the Iceland–Scotland Ridge (Turrell *et al.*, 1999). The Iceland–Scotland Overflow vigorously mixes with upper warm and saline water and LSW in the Iceland Basin and flows into the western basin through gaps in the Mid-Atlantic Ridge. NEADW found in the Labrador Sea is about 3°C warmer than the cold and dense overflow entering the Iceland Basin. However, we expect that the changes in the properties and transport of the overflow contribute to the long-term variability of NEADW in the Labrador Sea.

At the bottom of the section is the DSOW, with a slightly lower salinity than in the NEADW. DSOW is the densest water in the northern North Atlantic. It originates in the seas north of Iceland and comes to the Labrador Sea after flowing over the sill in Denmark Strait between Greenland and Iceland.

The last water mass of note in the section is the low salinity water over the Labrador continental shelf, which flows south out of Baffin Bay in the Baffin Island Current and the Labrador Current. A

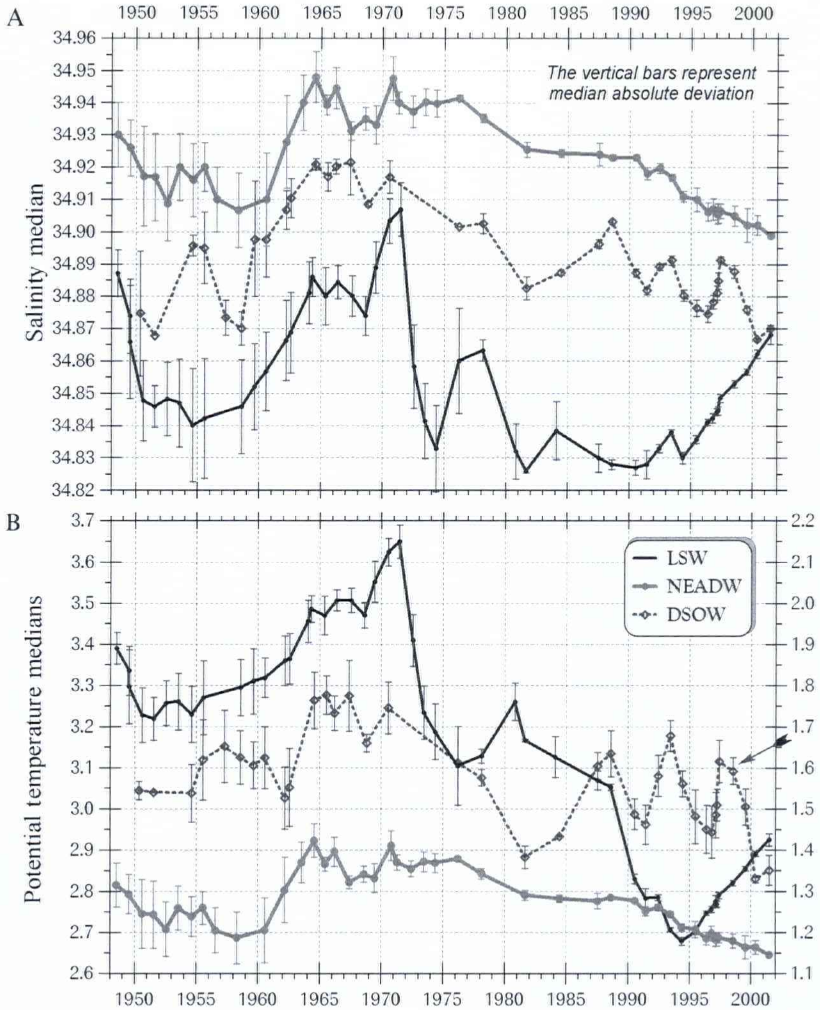

Figure 5. Salinity and temperature at the core of the Labrador Sea Water (LSW), Northeast Atlantic Deep Water (NEADW), and the Denmark Strait Overflow Water (DSOW) between 1948 and 2001. Note that the temperature scale for the DSOW is on the right.

similar band of low salinity water of Arctic origin lies over the Greenland continental shelf but it was covered by heavy ice in July 1993 and not sampled when the rest of these data were collected. However, it is visible in the other two sections. The rapid transition between the low salinity waters over the shelves and the higher salinity waters of the sea's interior mark the baroclinic currents lying over the upper part of the continental slopes, the Labrador, and West Greenland Currents.

Water masses in the 1990s

Labrador Sea Water

We divide the discussion of LSW into two parts. The first covers the period from the late 1980s to 1994 when a series of severe winters caused convection to proceed to greater depths until a maximum of 2300 m was reached in 1993 and 1994. The second period, following 1994, is characterized by normal to mild winters and convection limited to 1500 m. During this period the LSW below the mixed layer was isolated from the vertical mixing in the upper layer and changed its properties more by isopycnal mixing than via vertical mixing.

The 1990 and 1993 salinity sections in Figure 2 show LSW as the large mass of homogeneous water to >2000 m created in the central part of the sea via deep convection during the years of severe winters. Temperature in this water mass (Figures 3B, 5) decreased between 1987 and 1994 from greater than 3°C to less than 2.7°C. At the same time in the intermediate depths (400–2000 m), salinity tended to decrease between 1987 and 1990 but to increase

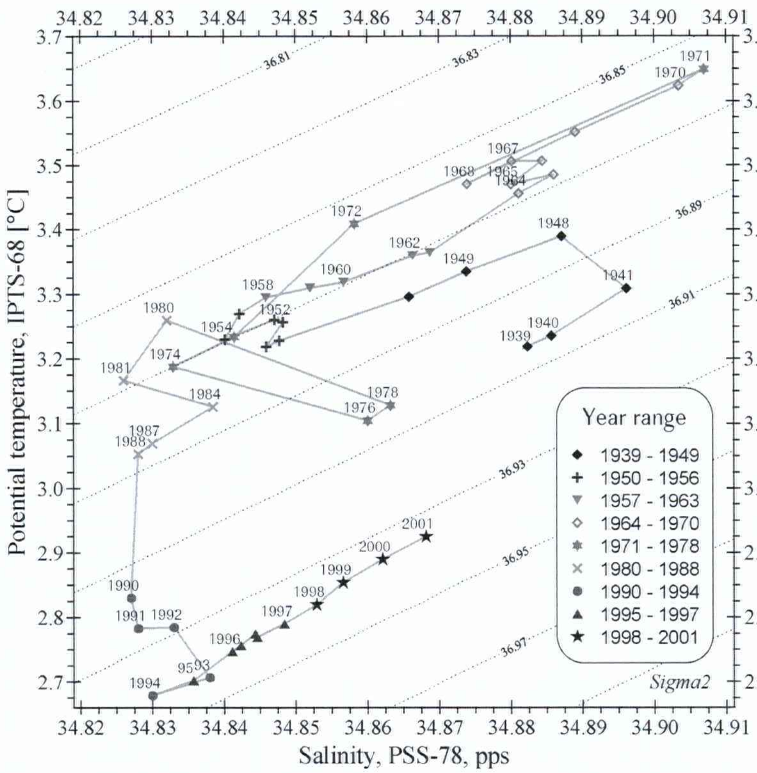

Figure 6. Temperature vs. salinity at the core of the Labrador Sea Water between 1939 and 2001.

from 1991 to 1993 (Figure 3A). In 1990 the average temperature and salinity of the LSW were roughly 2.85°C and 34.828. In 1993 the salinity had increased by 0.01 to 34.838, while the temperature decreased by 0.15°C to 2.7°C. The decrease in temperature was due to winter heat loss to the atmosphere. These changes in temperature and salinity of the LSW resulted in a significant increase in density of this water mass. This is well illustrated in Figure 3C, which shows the general increase in density over the 400 to 2200 m interval between 1987 and 1993 due to heat loss during the severe winters.

We believe that the noted decrease in LSW salinity to 1990 is due to the annual accumulation of freshwater in the upper layer being mixed down to intermediate depths through the development of a deep winter mixed layer. During 1991 to 1993, intense winter convection began eroding the salty NEADW into the expanding LSW layer with increasing salinity. This process will be discussed in more detail in the study of convection and re-stratification in the Labrador Sea that is submitted for publication. The salinity increase from 1990 to 1993 is best illustrated in the T–S diagram in Figure 4A. (The LSW appears there as a narrow temperature and salinity minimum closest to $\sigma_2 = 36.95$ kg m^{-3}.)

In the spring of 1994 the depth of the mixed layer was not noticeably deeper than in the spring of 1993, but the whole layer was colder in 1994 than in 1993. However, unlike that in the previous 3 years, the average salinity in the deep mixed layer decreased from 1993 to 1994 by 0.008 (Figures 5, 6). This 1-year freshening of the LSW is in concurrence with the fact that there was no further deepening of the deep winter mixed layer in 1994, and the water was ventilated to the same depth as in 1993 renewing the LSW of the previous winter. Whatever amount of the underlying NEADW with higher salinity was incorporated into the mixed layer in 1994, it was insufficient (ultimately zero) to compensate for the decrease in the mixed layer salinity derived from the mixing down of the low saline water which was accumulated in the upper layer between the winters. The discussed decrease in LSW salinity also implies that the amount of warm and salty IW involved in the convective mixing in the winter of 1994 was also small to compensate for the freshening in the mixed layer.

In the second half of the decade, when the winters were less severe, the deeper portion of the LSW created during the years of intense cooling is no longer renewed during the winter. Its volume in the central part of the Labrador Sea declines as it drains away to other regions of the ocean. This decline is especially clear in the time-series of temperature and σ_2 in Figure 3B, C. If the limits of LSW are taken as

$36.92 < \sigma_2 < 36.95$ kg m^{-3} its thickness declines from 1900 m to 300 m. This small remnant, even after 7 years' isolation, can still be identified in the T–S curves (Figure 4B) by the characteristic LSW salinity minimum at a σ_2 = 34.94 kg m^{-3}. Between 1994 and 2001 the water at this salinity minimum became warmer and more saline by 0.23°C and 0.039. This increase in temperature and salinity of the deep LSW was due, we assume, to isopycnal mixing, because LSW on isopycnal surfaces exhibits a T–S minimum in the centre of the Labrador Sea. As the volume of LSW decreases (Figure 3C) the volume of water at lower densities increases. The volume of water between 36.84 kg m^{-3} and 36.90 kg m^{-3}, for instance, increased between 1995 and 2001 by about 700 m. We postulate that this increase in volume is derived from water flowing into the central region of the Labrador Sea from the boundary currents. That this incoming water tends to be the warmer more saline IW accounts for the increases in temperature and salinity in the latter half of the decade above the LSW.

The salinity section for 2001 in Figure 2C illustrates the situation at the end of the decade. The remnant of the LSW created by intense convection during the first half of the decade lies within the 34.87 contour between 1500 and 2000 m. Above this is a slight maximum separating it from the upper layer characterized by lower salinity water. This salinity maximum at 34.875 is a prominent feature of the T–S curves (Figure 4B) at σ_2 = 36.89 kg m^{-3} in the years 1997–2001 and can be associated with replacement of the cold and fresh LSW produced between 1993 and 1994 in subsequent years with warmer and more saline water. Vertical and temporal continuity of the year-to-year changes of LSW properties (between 1300 and 2000 m in Figure 3A, B) implies that starting from 1994 the processes of LSW mixing, draining, and replacement with modified warmer and more saline water are steady in time and monotonic with depth.

Above this salinity maximum lies the upper layer influenced by winter convection. In Figure 2C it appears from the concentration of low salinity water on the south side of the central portion of the section (300–500 km) that convection in the previous winter was confined to this region rather than spread evenly across the whole section. On the northern half of the central area (550–700 km) salinity maxima are evident in the upper 700 m at 600 km. We feel this probably indicates a lack of convection in this region below 200 m during the previous winter. The effect of these salinity maxima are evident in the T–S curve for 2001 in Figure 4B. Here the salinity minimum (34.82) at σ_2 = 36.865 kg m^{-3} is capped by the higher salinity water. This layering, which also occurred in 2000, creates a curve similar to that associated with the LSW at σ_2 = 36.94 kg m^{-3}. For this reason the shallower minimum is sometimes referred to as upper LSW.

Northeast Atlantic Deep Water

NEADW lies beneath the LSW and is characterized by a salinity maximum at 3000 m. In the T–S curves (Figure 4A, B), this characteristic salinity maximum is clearly visible in the σ_2 range 36.95–37.05 kg m^{-3}. Because it lies beneath the layer of deep convection it was not greatly altered during the years of intense convection at the beginning of the decade. Although, as mentioned above, the deep convection layer did penetrate a few hundred metres into this deeper water mass during the winters of 1990–1993. The higher salinity, lower dissolved oxygen and chlorofluoromethanes of the deeper layer were incorporated into the mixing layer with measurable effects as noted above for salinity. Matching decreases in the dissolved oxygen and CFC concentrations were observed but are not discussed here. In spite of the influence from the convecting layer, temperature and salinity of the NEADW appear to decline uniformly throughout the decade. The declines in both temperature and salinity of this water mass are well seen in the T–S diagrams in Figure 4A, B ($36.97 < \sigma_2 < 37.05$). The decrease in salinity is especially clear in Figure 3A, which shows the salinity at 2800 m decreasing from above 34.92 in 1987 to near 34.90 in 2001. The temperature decrease over the record is also evident in Figure 3B by the slight rise in the isotherms over the record. We estimate the decreases of temperature and salinity at the core of this water mass to be 0.15°C from 2.8°C to 2.65°C and 0.021 from 34.923 to 34.902, respectively. These declines appear to be associated with the general freshening of the subpolar gyre, since the Great Salinity Anomaly (Dickson *et al.*, 1988) in the late 1960s. As the NEADW becomes colder and fresher and the remnant LSW becomes warmer and more saline the difference between the two water masses in both variables decreases. The change is very obvious in the T–S curves in Figure 4B, in which the salinity difference between the LSW minimum and the NEADW maximum has been reduced from about 0.085 to 0.037. Another feature of these changes in the water mass properties is the disappearance of the temperature maximum between the LSW and the NEADW. This maximum appeared at 1900–2400 m in the mid-1980s as LSW became colder than the underlying NEADW and narrowed as convection developed to 2300 m. The deep temperature maximum is illustrated in Figure 3B by the 2.9°C and 3.0°C isotherms at 2400 m, especially in 1990 to 1993. As the contrast between these water masses declines, this maximum fades away.

Denmark Strait Overflow Water

DSOW lies at the bottom of the water column, beneath the NEADW at $\sigma_2 > 37.10$ kg m^{-3}. Since the density of the bottom water fluctuates from year to year (the lowest in the last 12 years was observed in 1993, the highest in 2000 and 2001), we define the core of DSOW in the Labrador Sea as a 200 m bottom layer in the central region of the sea. As can be seen in the T–S diagram in Figure 4B it is colder and fresher than NEADW and like the other water masses its properties vary from year to year. Over the 1990s temperature and salinity at $\sigma_2 =$ 37.15 kg m^{-3} varied between 1.34°C and 1.50°C and 34.866 and 34.890, respectively. However, these variations were not monotonic, as in the NEADW. In Figure 3A, B the water is cooler and fresher in 1990–1991, 1995–1996, and 1999–1901 and warmer and more saline in 1992–1993 and 1997–1998. The coldest and freshest DSOW over the past 4 decades was observed in 2000. The time signal seen in DSOW (Figure 5) is coherent across the Labrador Sea, indicating that three quasi-pentadal cycles in DSOW between 1986 and 2001 can be linked with the variability at its source and the subsequent transformation of this water mass before it fills the abyss of the Labrador Sea. The rapid interannual changes of temperature and salinity are seen at the Denmark Strait sill. Downstream, in the Irminger Basin, the overflow undergoes substantial mixing which, we believe, alters the DSOW along its path. The DSOW properties between the Denmark Strait sill and the Labrador Sea respond to the changes in properties, volumes, and contributions of the entrained waters. One of the key factors here is the production of LSW, which has a great impact on the stratification and coupled dynamics of the intermediate and deep layers of the whole subpolar gyre.

Variations over the longer term

One aim of the ICES Decadal Symposium was to compare the water mass changes observed in the 1990s with those observed over the longer term. We present the longer-term variability in the central region of the Labrador Sea in Figures 5 and 6. Figure 5 shows temperature and salinity at the cores of the LSW, NEADW, and DSOW between 1948 and 2001. The time-series of the LSW properties are also presented in the T–S diagram in Figure 6.

Over the past 53 years the properties of LSW have varied over an exceptionally large range. Temperature was as low as 2.7°C and as high as 3.65°C, while salinity ranged between 34.825 and 34.907. Over the years there has been one major maximum, i.e. in 1970–1972. At the same time the LSW temperature was the highest in the record. The minima in the early 1950s, mid-1970s, and early 1990s do not always appear at the same time for both variables. This is best observed in the early 1990s, where the salinity reaches a minimum in 1990 while the temperature minimum is in 1994. In the discussion above we saw that a series of severe winters in the late 1980s and early 1990s caused winter mixed layers of increasing depth. The resulting heat loss is reflected in the decrease in temperature of the water mass. On the T–S curve in Figure 6 this decrease in temperature is accompanied, between 1988 and 1993, by an increase in σ_2 of 0.05 kg m^{-3}. Salinity rises through the years of intense convection as the mixed layer penetrates and incorporates the saltier NEADW water beneath. Following the period of intense convection, the LSW is getting warmer and more saline as it mixes isopycnally with the warmer and saltier waters that surround it. The fact that the salinity minimum in 1974 also precedes the temperature minimum in 1976 suggests a series of events similar to that observed in the 1990s.

The maxima of temperature and salinity in 1971 and the years leading up to it are better known than most of the other years because data were obtained through these years at OWS Bravo (Figure 1). It was during this period that winters in the Labrador Sea were exceptionally mild with shallow mixed layers and that the Great Salinity Anomaly (Dickson *et al.*, 1988) lowered the salinity of the upper layer. The LSW lying at intermediate depths and isolated from the mixed layer became warmer and more saline as it mixed with surrounding waters – as happened in the late 1990s. This situation ended with severe winters in 1972 and 1973, which produced mixed layers deeper than 1500 m (Lazier, 1980) leading to the creation of a new version of LSW which was colder and less saline. Between 1971 and 1974 the salinity, as shown in Figures 5 and 6, dropped from 34.91 to 34.83 and the temperature from 3.65°C to 3.18°C. Following 1974 the salinity and σ_2 increased as the temperature decreased during continued convection. Then following 1976 the LSW, both temperature and salinity, increased as horizontal mixing replaced vertical mixing as the dominant forcing agent.

Temperature and salinity in the NEADW also varied significantly over the longer term; however, not as much as the LSW. As noted above, temperature and salinity steadily declined in the NEADW during the 1990s. These decreases are evident in Figure 5 by a decrease in salinity from 34.923 in 1990 to 34.9 in 2001 and a decrease in temperature from 2.78°C in 1990 to 2.65°C in 2001. Following these curves back in time shows that the cooling and freshening of this water mass has been continuous since the late 1960s. The biggest change, however, occurred in the early 1960s when the salinity increased from 34.91 to 34.94 and the temperature rose from 2.7°C to 2.9°C.

Properties in the DSOW appear to vary on a shorter time scale than those in the other water masses. The oscillations during the 1990s, mentioned above, are clear in Figure 5. Both temperature and salinity were high in 1988, 1993, and 1987 and low in 1992, 1996, and 2000 with amplitudes of 0.15°C and 0.1 for both temperature and salinity, respectively. As in the NEADW, a general cooling and freshening can be traced since the 1960s with preceding abrupt increase in both properties in the early 1960s when salinity increased from 34.87 to 34.92 and temperature increased from 1.55°C to 1.75°C.

Summary

Observations obtained across the Labrador Sea during the 1990s show the water column experienced exceptionally high cooling during the early part of the decade followed in the latter half of the decade by winters with normal to less than normal cooling. The colder winters led to deep convective mixing and the creation of a new version of LSW to 2300 m. During the milder years, most of this LSW was mixed into the boundary currents and drained away from the region while the remaining portion became warmer and saltier as the waters higher in temperature and salinity bordering the sea were mixed toward the centre. The loss of the LSW led to a re-stratification of the upper waters across the sea. This was marked by significant increases in both temperature and salinity as well as a decrease in density. Also noted were a steady cooling and freshening of the NEADW over the past four decades and 5-year oscillations in the DSOW properties.

Examination of the 53-year record of the water mass properties showed that the pattern of temperature and salinity variations noted in the LSW during the 1980s and 1990s was similar to that observed in the 1960s and 1970s. Similar time-series in the NEADW and DSOW showed rapid increases in temperature and salinity in the early 1960s with slow freshening and cooling into the 1990s except for marked oscillations in the DSOW over the past 15 years.

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