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Recent Changes in the Heat and Salt Content of the Labrador Sea

by

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Abstract

The late-1980s and early-1990s saw relatively cold winters and high heat fluxes over the Labrador Sea. Recent years have shown generally warmer conditions. Heat fluxes from the NCEP/NCAR Reanalysis averaged over 12-month June-May periods for 2001-2002 and 2002-2003 were both about 20% less than normal. The upper 1 000 m of the west-central Labrador Sea warmed during the 12-month interval between surveys in July 2002 and July 2003, continuing the general trend noted since 1994. These waters also became saltier. Changes in potential vorticity and apparent oxygen utilization between the July 2002 and July 2003 surveys suggest that convective overturning during the winter of 2002-2003 reached depths of at least 1 000 m. A rare early-winter survey in December 2002 provides supporting evidence. Below the developing winter mixed layer, the upper water column to depths of 1 000 m was warmer and saltier in December 2002 than in either July 2002 or July 2003. This is a signature of a possibly seasonal increase in the input of warm and saline waters originating in the West Greenland Current. Intense surface cooling and convective overturning subsequent to the December 2002 survey provide a means to return the water column to the relatively cooler conditions observed in July 2003.

Introduction

Hydrographic conditions in the Labrador Sea depend on a balance of atmospheric forcing, advection, and ice melt. Wintertime heat loss to the atmosphere in the central Labrador Sea is offset by warm waters carried northward by the offshore branch of the West Greenland Current. The excess salt accompanying the warm inflows is balanced by exchanges with cold, fresh polar waters carried by the Labrador Current, freshwater from river run-off, and ice melt. Atmospheric forcing plays a relatively small role in the mean freshwater balance of the Labrador Sea compared with advective effects.

Wintertime cooling and evaporation increase the density of surface waters in the central Labrador Sea. Wind mixing and vertical overturning form a mixed layer whose depth increases through the cooling season. The winter heat loss, the resulting density increase, and the depth to which the mixed layer penetrates vary with the severity of the winter. The density of the mixed layer and the depth of convection depend critically on the salinity of the waters exposed to the atmosphere. In extreme winters, mixed layers deeper than 2 000 m have been observed. Labrador Sea Water (LSW) formed by these deeper overturning events spreads throughout the northern North Atlantic. During milder years, the vertical stratification of temperature, salinity, and density is re-established.

Deep convection associated with severe winters in the early-1990s created a pool of new LSW. In the process, the Labrador Sea lost heat to the overlying atmosphere. In the following years mild winters produced relatively shallow convection. Even though the Labrador Sea was still losing heat to the atmosphere over the annual cycle, advective effects led to a net warming of the upper layers. By Year 2000 the heat content of the upper 1 000 m had increased to values close to those observed before the onset of deep convection in the early-1990s.

During the restratification phase from 1995 to 2000, intermediate-depth layers that were removed from direct contact with the atmosphere become notably warmer and saltier. Remnants of the earlier deep convection were replaced with warmer and saltier waters of the same density. The replacement waters had properties similar to Irminger Water found along the continental slope southwest of Greenland.

Recent winters have continued mild. The hydrographic conditions in the Labrador Sea have been relatively stable over the past three years, with a continued slow rise in temperature and salinity of the upper waters (0-2 000 m) of the west-central Labrador Sea. There is evidence of enhanced convective renewal at intermediate depths in the west-central Labrador Sea during the past two winters. This has resulted in a noticeable accumulation of a warm and saline pool of Labrador Sea Water near 1 000 m depths with potential temperature near 3.2^{o}C, salinity near 34.83, and potential density anomaly near 27.73 kg/m^3.

The AR7W Section

Ocean Sciences Division, Department of Fisheries and Oceans, Maritimes Region has monitored hydrographic properties on the AR7W line across the Labrador Sea in the early summer of each year since 1990. The 2003 AR7W survey took place during 23-29 July 2003 under the scientific direction of Allyn Clarke. Figure 1 shows a map of the Labrador Sea with AR7W station positions occupied during the July 2003 survey. The 2003 results will be compared in some detail to results from the Spring 2002 AR7W survey on CCGS Hudson Cruise 2002-032 during 2-8 July 2002, also under the scientific direction of Allyn Clarke. A rare early winter occupation of the AR7W section was obtained on CCGS Hudson Cruise 2002-075 during 1-9 December 2002 under the scientific direction of Erica Head. The December 2002 survey was principally devoted to biological studies and the hydrographic program was reduced compared to the summer surveys. Selected stations near the Labrador and Greenland ends of the line were not occupied and measurements were restricted to the upper part of the water column at every other station in waters deeper than about 3 000 m.

Atmospheric Forcing

On an annual average, the Labrador Sea loses heat to the overlying atmosphere. Monthly-averaged air-sea flux fields produced by the co-operative Reanalysis Project (Kistler *et al*., 2001) of the U.S. National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) were used to quantify these heat exchanges.

Figure 2 shows a time series of anomalies of December-January-February (DJF) average sea-air heat flux near the Bravo mooring site in the west-central Labrador Sea at 56.2°N, 52.5°W for the 55-year period December 1948 to February 2003. The wintertime heat flux anomalies are autocorrelated on decadal time scales. Each of the past three winters has yielded lower-then-normal sea–air heat fluxes. The mean DJF heat loss for the 2002-2003 winter was 90 W/m^2 less than the normal 300 W/m^2, a reduction of about 30%.

Results and Discussion

Property distributions in 2003 are illustrated by contoured gridded sections of potential temperature, salinity, and potential density anomaly in Fig. 3(a)-3(c). Along-section distance in kilometres increasing from southwest (Labrador) to northeast (Greenland) is used as the horizontal coordinate.

Notable in the upper levels of Fig. 3(a) (potential temperature) are cold waters (<2°C) over the Labrador Shelf. Similarly cold waters in the upper few hundred metres over the outer edge of the West Greenland shelf are associated with the inshore branch of the northward-flowing West Greenland Current. Warmer waters (>4°C) in the upper 500 m of the water column over the West Greenland slope are associated with the offshore branch of the West Greenland Current.

Figure 3(a) shows a seasonal thermocline with a maximum surface temperature of just over 10°C. In the central Labrador Sea at depths between 600 m and 1 200 m below the seasonal thermocline, reduced vertical temperature gradients mark recently-formed LSW with potential temperature less than 3.2°C. The LSW layer extends over much of the section, but its thickness is less on the Greenland half of the section than on the Labrador half. Waters in the upper 500 m on the Greenland side are notably warmer than on the Labrador side, showing a greater influenced of the warm Irminger Waters. The deeper Irminger Water influence centred near 1 500 m below the LSW creates a layer with potential temperature greater than 3.3°C. An energetic eddy near 800 km is resolved by a single station.

In the salinity section in Fig. 3(b), waters in the upper 500 m on the Greenland half of the section are notably saltier than waters in the same depth range on the Labrador half, again showing the Irminger Water influence. Patches of relatively fresh water near 2 000 m depth are remnants of the extraordinarily deep convection of the early-1990s.

The potential density anomaly section in Fig. 3(c) shows reduced vertical gradients in the recently-formed LSW near 1 000 m depths.

The shallower of the pair of dashed lines near 1 000 m depth in Fig. 3(a)-3(c) traces a relative minimum in the vertical of potential temperature (<3.2°C) in the recently-formed LSW. Waters shallower than this layer have been warmed by seasonal surface heating and lateral advection. It is not immediately clear if the relative minimum in potential temperature observed in July 2003 comes from convection during the previous winter, is a cumulative effect of convection during several recent winters, or is a remnant of convection during an earlier winter that was more severe than the most recent winter. This point is discussed below.

The deeper of the pair of dashed lines near 1 500 m depth in Fig. 3(a)-3(c) traces a relative maximum in the vertical of potential temperature (generally >3.3°C) marking the core of the intermediate-depth warm, saline layer.

Changes from Spring 2002 to Spring 2003

Properties observed in July 2003 can be compared to results from the July 2002 and December 2002 Labrador Sea campaigns. A question of particular interest is the extent of vertical convection during the winter of 2002-2003.

Contoured gridded sections of apparent oxygen utilisation (AOU) for the July 2002 and July 2003 surveys are shown in Fig. 4(a)-4(b). Comprehensive oxygen measurements were not made during the December 2002 survey. AOU is defined as the difference between the saturation value of dissolved oxygen concentration at the measured temperature and salinity and the measured dissolved oxygen concentration. It is related to the time elapsed since the water was in contact with the atmosphere, since biological processes tend to reduce oxygen concentration with time. AOU values increase from less than 0.5 mL/L within the seasonal thermocline to values greater than 1 mL/L near 3 000 m depths. The deep convection of the early-1990's shows up as a patchy and relative minimum in AOU near 2 000 m depth with values less than 0.9 mL/L. The July 2003 survey shows AOU values less than 0.6 mL/L down to 1 000 m depths near the 400 km distance mark. The July 2002 survey tends to show higher values in this depth and distance range. This suggests that the upper 1 000 m depth range may have been reoxygenated by convection during the 2002-2003 winter. The comparison is complicated because no bottle oxygen samples were available for one of the 2002 stations in this distance range.

Figure 5 shows average AOU profiles for the July 2002 and July 2003 surveys in the upper 2 000 m for stations in the 320-520 km distance range. Selected standard deviations are also shown. This particular distance range is selected to represent the area in the deep west-central Labrador Sea where deep convection has been observed to occur. It excludes the Greenland half of the section where the influence of the warm and saline Irminger Water is greatest. There is a relative maximum in AOU near 1 500 m depth in the warm, saline layer influenced by Irminger Waters. AOU values between 500 m and the deep relative maximum from the July 2003 survey are notably lower than seen in July 2002.

Contoured gridded sections of potential vorticity in the upper 2000 m for the three surveys are shown in Fig. 6(a)-6(c). Potential vorticity is defined as

$$PV = -\frac{f}{\rho}\frac{\partial \rho}{\partial z}$$

where ρ is potential density, f the Coriolis parameter, and z the vertical coordinate. Potential vorticity is conserved in the absence of direct forcing. Thus potential vorticity provides the equivalent of a scalar tracer. The low potential vorticity of winter mixed layers in the Labrador Sea has been used to trace LSW over large areas of the North Atlantic (Talley and McCartney, 1982).

Recent conditions in the context of the past 15 years

To place the last few years in a longer-term context, time-series plots of pressure on selected potential density anomaly surfaces from average profiles in the 320-520 km distance range for each of the fourteen early summer AR7W cruises during the 1990-2003 period plotted as a function of the median station time are shown in Fig. 8. This provides an update of Fig. 4 in Lazier *et al.* (2002). The deep convection of the early-1990s is reflected in the 1993-1994 maximum in the separation of the 27.77 and 27.79 kg/m^3 potential density anomaly surfaces. The volume of water in this potential density range decreased steadily from 1994 to 2000. Since 2000, changes in the separation of these isopycnals have been small. At the same time, there has been an increase in the separation of isopycnals in the 27.72-27.75 kg/m^3 potential density anomaly range, especially during the past two years. The pressures corresponding to the minimum potential temperature in the 27.72-27.75 kg/m^3 layer for each survey are noted in Fig. 7. The depth of the relative minimum potential temperature shows an increasing trend in recent years. The property values at the relative minimum in potential temperature for 2001-2003 were similar: potential temperature near 3.2^{o}C, salinity near 34.83, and potential density anomaly near 27.73 kg/m^3. This suggests a strengthening cycle of intermediate-depth convective renewal in the west-central Labrador Sea during recent years.

Acknowledgments

The AR7W data set owes its existence to the sustained efforts of many individuals at the Bedford Institute of Oceanography. Dr. R. A. Clarke in particular has provided scientific leadership for this program over many years.

The data from the NCEP Reanalysis were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

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Lazier, J., R. Hendry, A. Clarke, I. Yashayaev. and P. Rhines. 2002. Convection and restratification in the Labrador Sea, 1990-2000. *Deep-Sea Research*, 49, 1819-1835.

Talley, L. D. and M. S. McCarthy. 1982. Distribution and circulation of Labrador Sea Water. *Journal of Physical Oceanography*, 12, 1189-1205.

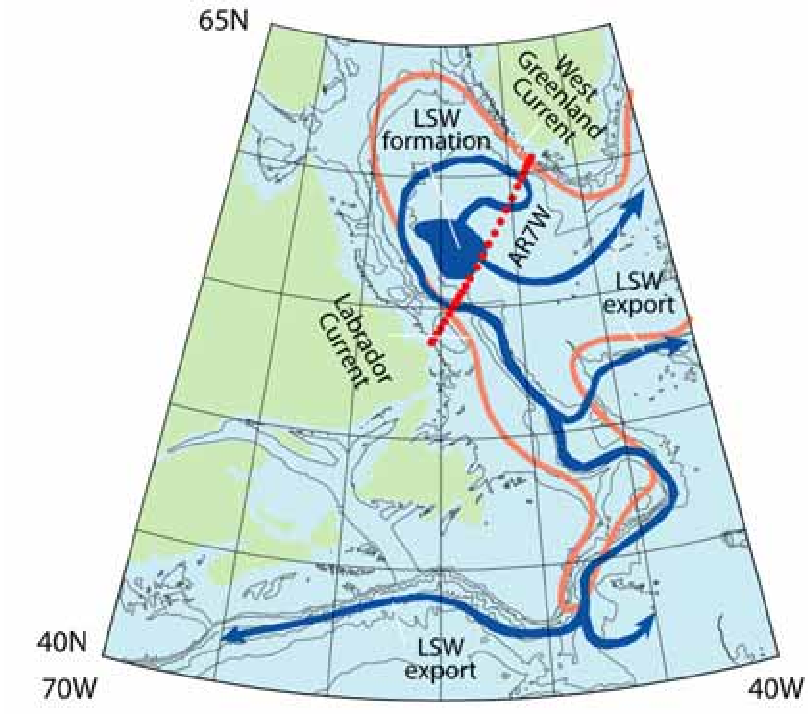

Fig. 1. Positions of the July 2003 AR7W stations (filled red circles) superimposed on a schematic circulation of the Labrador Sea.

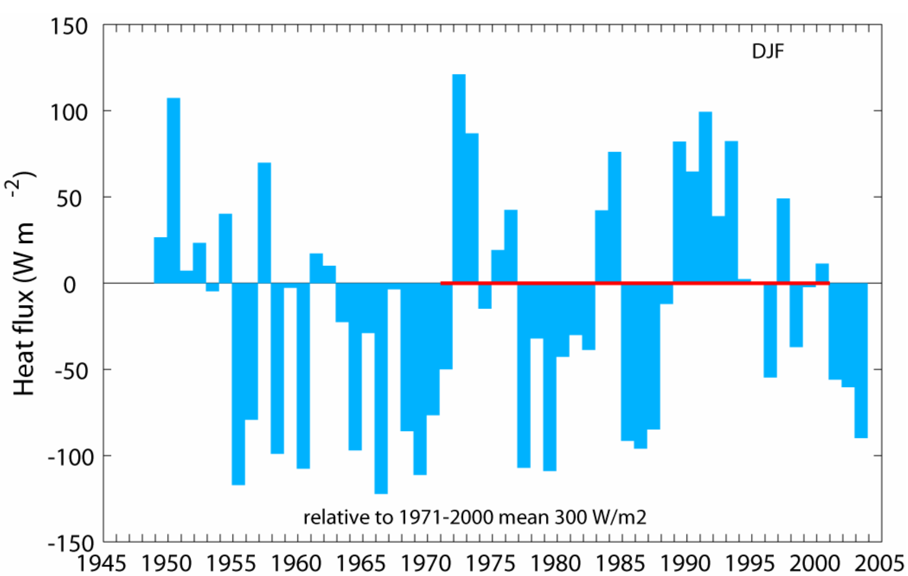

Fig. 2. NCEP DJF heat fluxes in the west-central Labrador Sea.

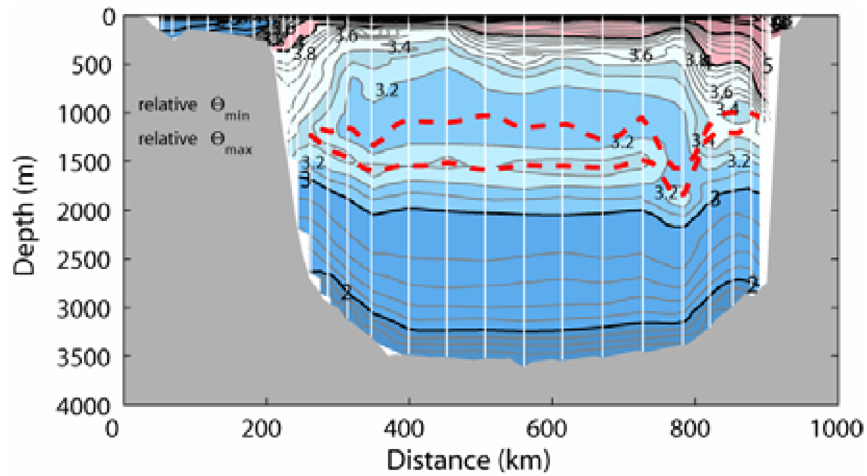

Fig. 3(a). July 2003 potential temperature (°C) section.

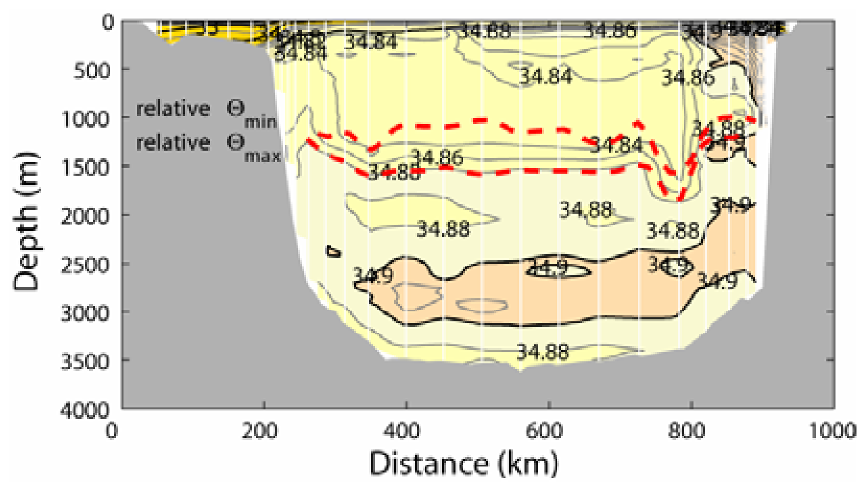

Fig. 3(b). July 2003 salinity section.

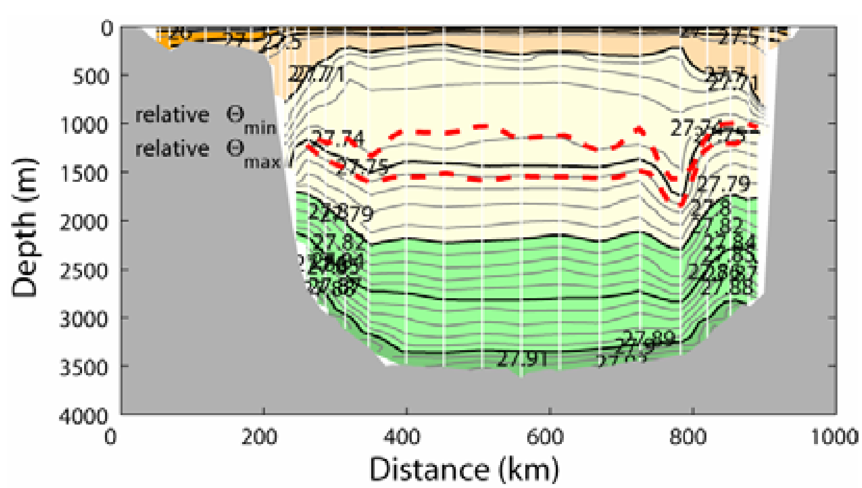

Fig. 3(c). July 2003 potential density anomaly (kg/m^3) section.

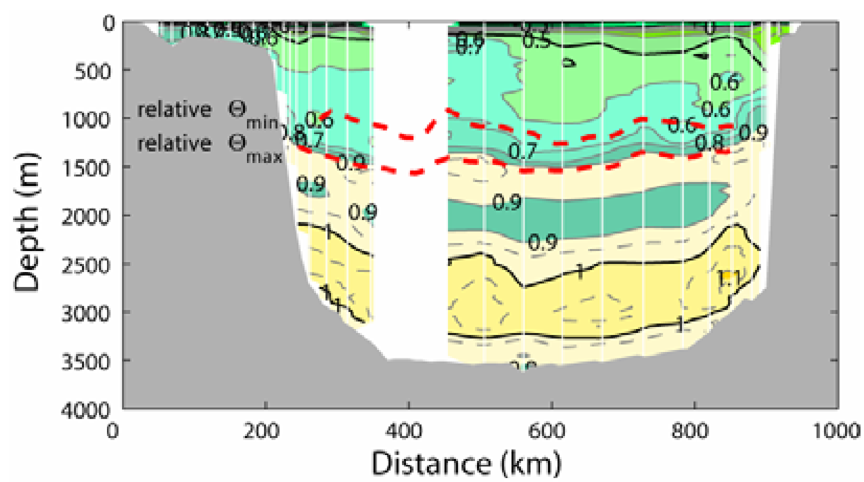

Fig. 4(a). July 2002 apparent oxygen utilization (mL/L) section.

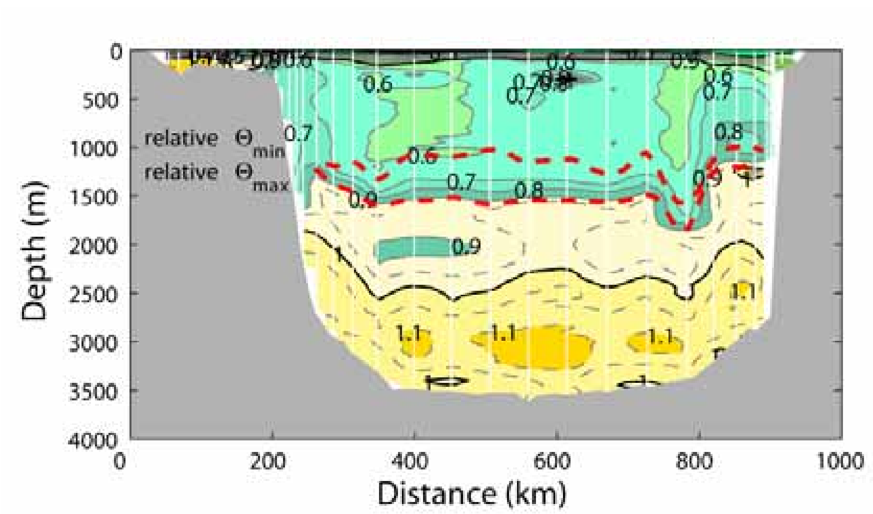

Fig. 4(b). July 2003 apparent oxygen utilization (mL/L) section.

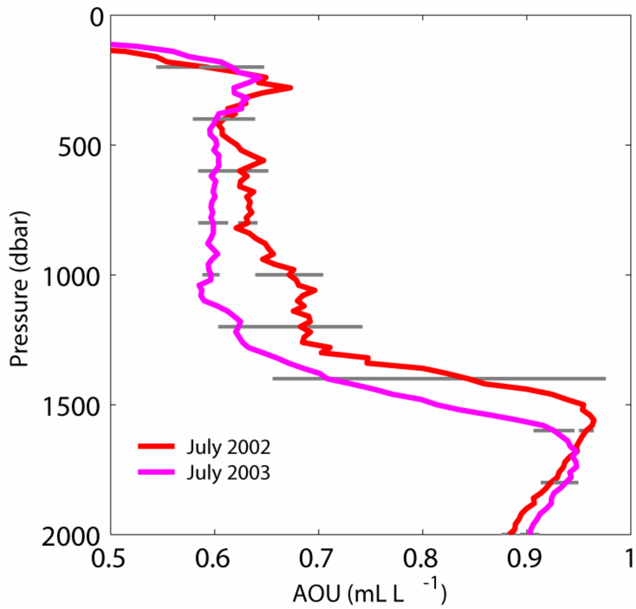

Fig. 5. Average profiles of apparent oxygen utilization in the upper 2 000 m for the four stations in the 320-520 km distance range for the July 2002 and July 2003 AR7W surveys. Selected standard deviations are also shown.

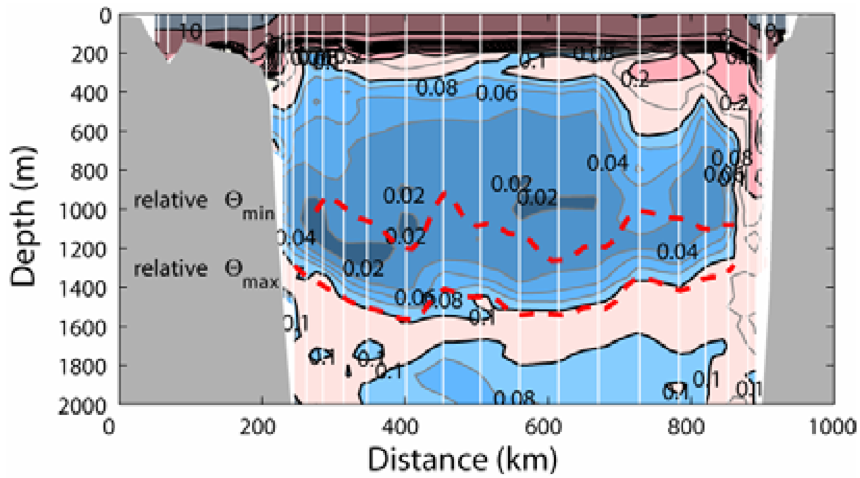

Fig. 6(a). July 2002 potential vorticity (10^{10} $m^{-1}s^{-1}$).

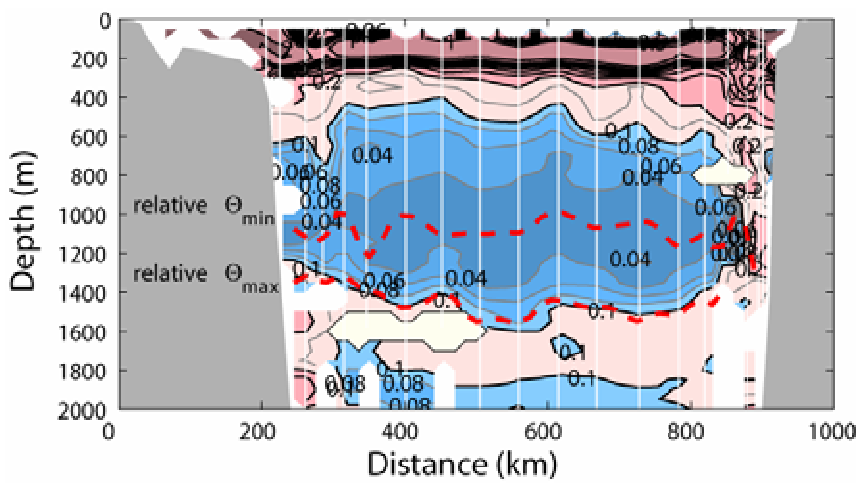

Fig. 6(b). December 2002 potential vorticity (10^{10} $m^{-1}s^{-1}$).

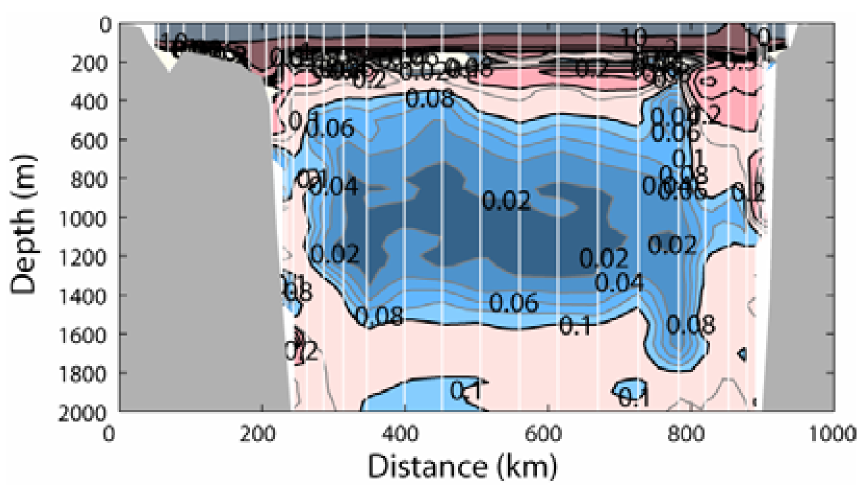

Fig. 6(c). July 2003 potential vorticity (10^{10} $m^{-1}s^{-1}$).

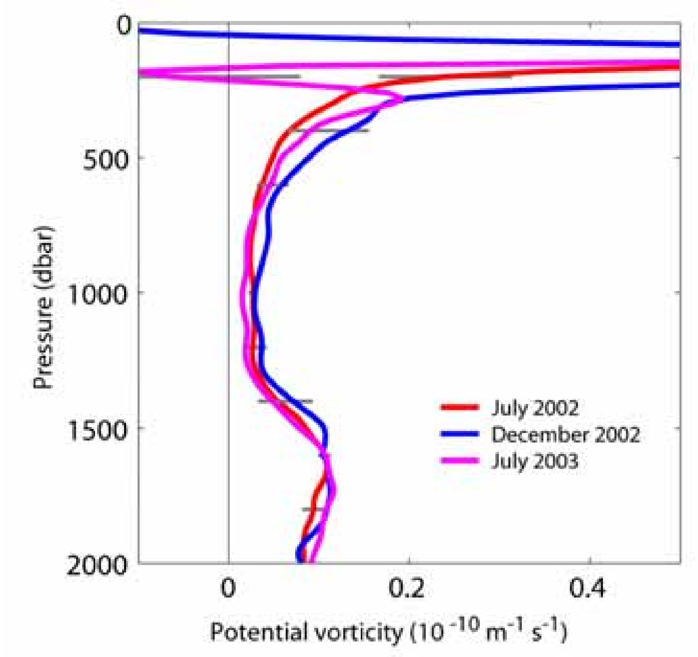

Fig. 7. Average profiles of potential vorticity in the upper 2000 m for the four stations in the 320-520 km distance range for the July 2002, December 2002, and July 2003 AR7W surveys. Selected standard deviations are also shown.

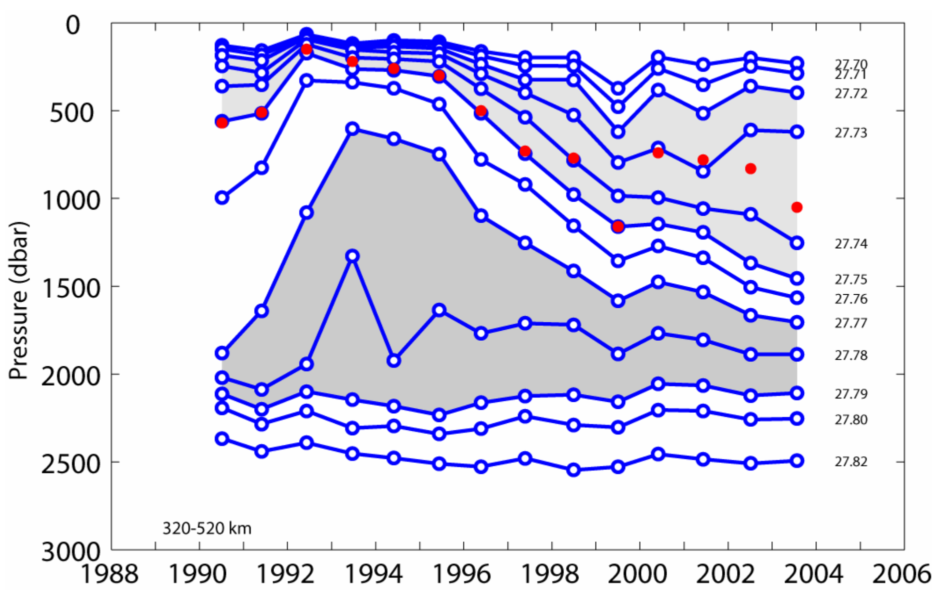

Fig. 8. Average pressure on selected potential density anomaly surfaces for stations in the 320-520 km distance range for 1990-2003 AR7W surveys. The labels to the right of each curve give the values of potential density anomaly in kg/m^3. The filled red circles mark the depth of the minimum potential temperature in the 27.72-27.75 kg/m^3 potential density anomaly range associated with the recent LSW production. This range and the 27.77-27.82 kg/m^3 potential density anomaly range associated with the denser LSW produced in the early-1990s are filled for emphasis.