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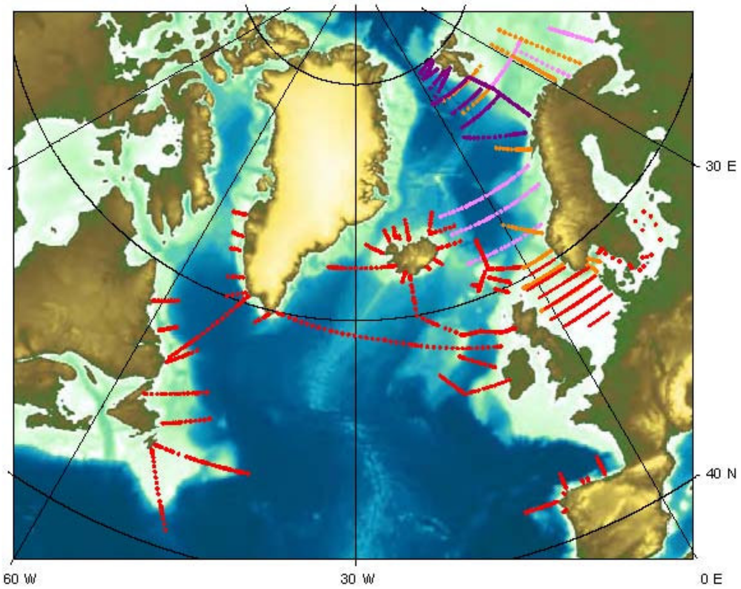

Exchanges

Newsletter of the Climate Variability and Predictability Programme (CLIVAR)

Monitoring the ventilation of the Irminger and Labrador Seas

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Introduction

The Irminger and Labrador Seas in the subpolar North Atlantic are a special part of the "cold water sphere" that makes up the bulk of the world ocean. These areas provide a direct link between the atmosphere and the deep ocean. Winter cooling and wind-mixing create deep surface mixed layers in the sub-polar oceans where vertical stratification is weak, compared to conditions in the subtropics. In episodic severe winters, buoyancy losses give rise to increases in surface density large enough to cause convective overturning that penetrates to depths as great as 2 km. Milder winters lead to lower heat losses, shallower mixed layers, and a decrease in convective activity.

Deep convection in the Labrador and Irminger Seas provides an important pathway for atmospheric gases such as oxygen, carbon dioxide, and chlorofluorocarbons (CFCs) to pass from the surface mixed layer to intermediate depths. Sub-surface flows then distribute the dissolved gases to other regions.

On an annual average, the surface waters in these areas lose heat to the overlying atmosphere and give up a corresponding amount of buoyancy. They gain fresh water (and buoyancy) from the regional excess of precipitation over evaporation, from river run-off, and from ice melt waters of Arctic origin. They gain heat and salt from warm and saline Atlantic Waters carried northward into the Irminger and Labrador Seas. Hydrographic conditions depend on a balance between air-sea heat and fresh water exchanges and advective sources. There is an energetic interannual variability in air-sea heat and momentum fluxes. Associated changes in ocean circulation modulate the inflows of fresh water from northern sources and warm and saline waters from more southerly latitudes. The result is a complex system with strong interannual variability.

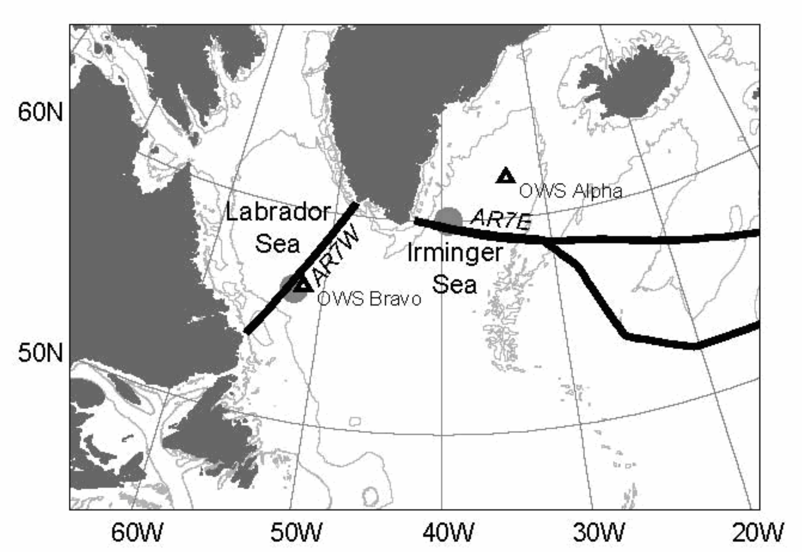

Figure 1. Chart showing the AR7 sections. Marked positions are: OWS Alpha and Bravo (triangles) and NCEP Reanalysis grid points (filled circles).

Historical background

Recent studies have emphasized the role of the Labrador Sea in the ventilation of the sub-polar North Atlantic. Lazier (1980) observed winter mixed layers of Labrador Sea Water (LSW) as shallow as 200 m and as deep as 1500 m in 1963-1974 data from Ocean Weather Station (OWS) Bravo (Figure 1).

Clarke and Gascard (1983) observed convection to 1600 m depths in the same area in early 1976. They pointed out that the 1976 vintage of LSW had temperature and salinity properties quite different from mode waters formed in earlier years.

Convection creates water masses with low or vanishing vertical stratification and correspondingly low values of potential vorticity. The mode water properties set during the formation processes evolve only slowly after the newly-formed water masses are removed from contact with the overlying atmosphere by seasonal restratification. Talley and McCartney (1982) used potential vorticity as a tracer to study the distribution of sub-polar mode waters in the northern North Atlantic. They concluded that LSW formed in the Labrador Sea was exported along several paths, including one leading north-eastward into the Irminger Sea.

Bacon et al. (2003) and Pickart et al. (2003a, 2003b) argue that mode water formation with properties similar to LSW also occurs in the Irminger Sea. Pickard et al. (2003b) review earlier studies suggesting significant formation of sub-polar mode waters occurred in the Irminger Sea; they remark that an historical bias may have been introduced because OWS Alpha (Figure 1) was in an unfavourable location for deep convection. Pickart et al. (2003a) also recognized the importance of LSW exports to the Irminger Sea.

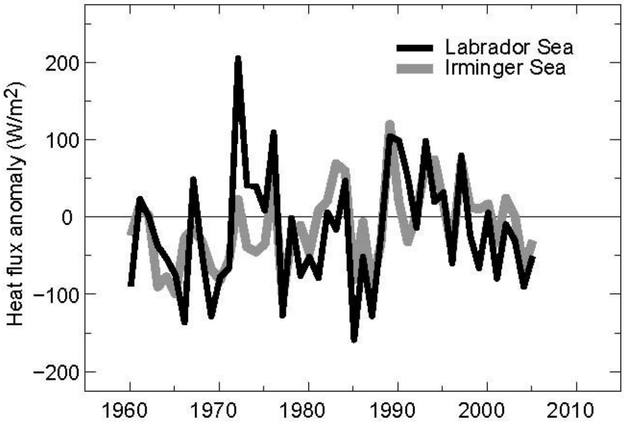

Figure 2. Time series of JFM NCEP Reanalysis sea-air heat flux anomalies relative to 1971-2000 from 1960 to 2005 for the west-central Labrador Sea (black line) and the west-central Irminger Sea (grey line)

The AR7 Section

The AR7 section (Figure 1) subdivided into western (AR7W) and eastern (AR7E) segments was one of the repeat sections occupied during the World Ocean Circulation Experiment (WOCE). The rationale for repeating this section (Needler and Koltermann et al., 1988) included the charge to "Estimate amounts and characteristics of various mode waters transformed during each successive cooling cycle." In 1990, Canada began a series of annual early summer occupations of the AR7W Labrador Sea section as a contribution to WOCE. At the same time, investigators from Germany and the Netherlands began repeated occupations of the AR7E section.

Following the end of the WOCE field program in 1997, national research and monitoring efforts by Canada (DFO, BIO), Germany (IfM Hamburg), and the Netherlands (NIOZ, Texel) have maintained regular occupations of AR7W and AR7E. The resulting high quality hydrographic measurements contribute to the CLIVAR goal of describing and understanding ocean processes responsible for climate variability and predictability. Annual updates of conditions in the Labrador and Irminger Seas based on the surveys are reported in the annual ICES Report on Ocean Climate.

Recent results

The sub-polar North Atlantic has experienced major atmospheric and oceanic changes in the 17-year period of repeated AR7 surveys. As one example, Figure 2 shows January-February-March (JFM) sea-air heat flux anomalies from the west-central Labrador Sea and the west-central Irminger Sea from

NCEP Reanalysis data. Maximum heat losses occur in winter months, and the interannual variability is dominated by changes in heat loss during these months. The variance in the Irminger Sea is about half that observed in the Labrador Sea, but the forcing is qualitatively similar in the two areas. Both areas show a period of increased wintertime heat flux associated with the severe winters of the early 1990s and a subsequent trend toward milder winters and lower heat losses. The NCEP Reanalysis values provide at least a qualitative overview but probably overestimate the true fluxes (Renfrew et al., 2002).

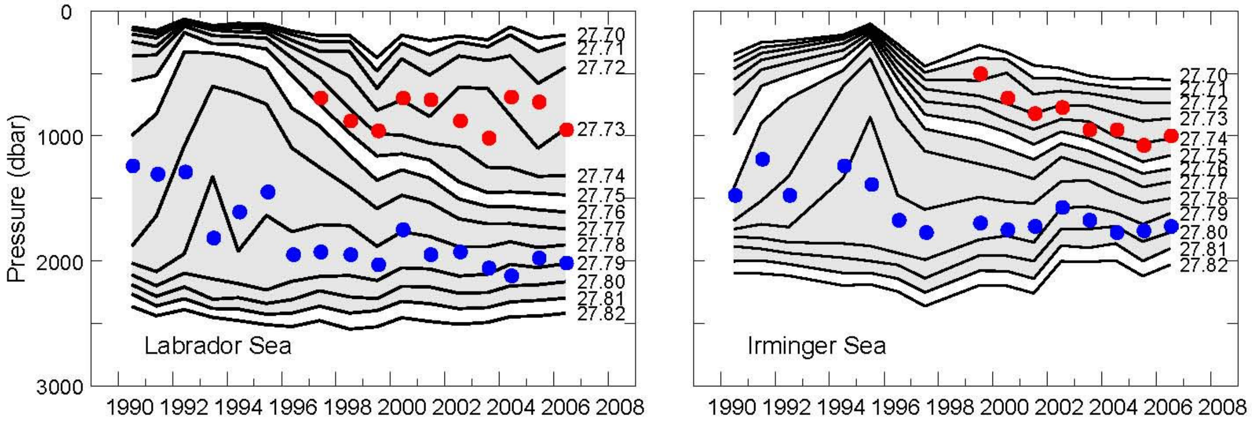

Figure 3. Time series of pressure on selected potential density surfaces averaged over stations in the west-central Labrador Sea (left panel) for spring and early summer AR7W surveys and the central Irminger Sea (right panel) for summer AR7E sections from 1990 to 2006. Filled symbols mark pressures at relative minima in potential vorticity in the two shaded potential density anomaly layers 27.76–27.81 kg/m$_3$ (lower) and 27.71–27.75 kg/m$_3$ (upper).

The upper layers of the Labrador Sea re-stratify rapidly (Lazier, 1980) but annual surveys can monitor the interannual evolution of sub-surface signatures of winter convection. Lazier et al. (2002) discuss the development of deep convection in the Labrador Sea in the early 1990s and the restratification phase that followed based on AR7W surveys from 1990-2000

Figure 3 (page 18) shows time series of the pressure on selected potential density anomaly surfaces from average profiles in the west-central Labrador Sea (spring and early summer surveys) and the central Irminger Sea (late-summer surveys) as an overview of inter-annual variability of the ventilation of the Labrador and Irminger Seas based on AR7 surveys since 1990. Pressures within two potential density anomaly intervals shaded in Figure 3 where vertical minima in potential vorticity were encountered are marked with colour-coded filled circles.

Lower layer 27.76 - 27.81 kg/m$_3$

The wide separation during the early 1990s of the potential density anomaly surfaces bounding the deeper shaded layer in the left panel of Figure 3 reflects the deep convection in the Labrador Sea discussed by Lazier et al. (2002). The maximum separation was observed in 1993. Figure 3 shows increasingly thick homogeneous layers in the same density range in the Irminger Sea in the early 1990s, reaching a maximum in 1995. Note that no Irminger Sea observations are available for 1993. The deep layers thinned rapidly after reaching maximum thickness.

Figure 4 shows time series of minimum potential vorticity for each of the two layers in Figure 3. Low values of potential vorticity correspond to widely separated isopycnals.

The deep convection in the Labrador Sea in the early 1990s is reflected in the low values of lower-layer minimum potential vorticity during 1991-1994 (blue symbols in Figure 3). The core of this early 1990s LSW had potential temperature near 2.7 °C, salinity near 34.83, and potential density anomaly near 27.78 kg/m$_3$. The volume of water in this potential density range decreased rapidly from 1995 to 1999, and decreased more slowly in subsequent years. The minimum potential vorticity in this layer has steadily increased since 1994. Figure 4 shows minima in potential vorticity in the lower layer in the Irminger Sea in the summers of 1994 and 1995 that were essentially identical to the extreme minima in the Labrador Sea. From 1996 onwards the minimum potential vorticity in the deeper Irminger Sea layer increased in step with the corresponding Labrador Sea values. The Irminger Sea values appear to have levelled off since about 2004.

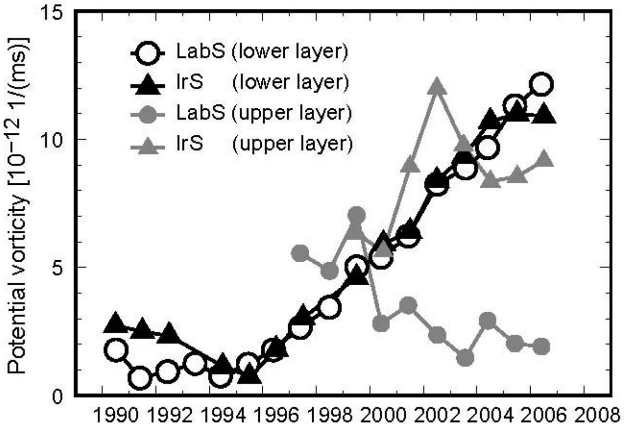

Figure 4. Minimum potential vorticity for the two potential density layers 27.76–27.81 kg/m$_3$ (lower layer) and 27.71–27.75 kg/m$_3$ (upper layer) in the west-central Labrador Sea (LabS) and the central Irminger Sea (IrS).

Upper layer 27.71 - 27.75 kg/m3

The upper shaded layers in Figure 3 with potential density anomalies in the 27.71 - 27.75 kg/m3 range show an increase in thickness beginning in the late 1990s in both the Labrador and Irminger Seas. A low-stratification upper layer marked by a relative minimum in potential vorticity first appeared in the Labrador Sea in 1997 and was well-established by 2000. For the most-recent four-year period the shallower Labrador Sea layer is characterized by potential temperatures near 3.3 □C, salinities near 34.84, and potential density anomalies near 27.73 kg/m3. Figure 3 shows a similar but less prominent increase in thickness of the upper Irminger Sea layer since 1999. The associated values of minimum potential vorticity in Figure 4 are higher than the corresponding Labrador Sea values. In recent years the shallow Irminger Sea layer is characterized by potential density anomalies near 27.74 kg/m3, slightly higher than the corresponding Labrador Sea values. The fact that the AR7W surveys took place in late spring or early summer and most of the AR7E section took place in late summer/early autumn may contribute to the observed differences between the two regions. In any case, the complex but regionally-coherent upper-layer signal suggests renewed mode water formation involving less-dense and shallower winter mixed layers.

Tracers

Many of the AR7 surveys include related chemical measurements. Examples from occupations of AR7E are presented in Figure 5. The left panel of Figure 5 shows dissolved oxygen profiles from the centre of the Irminger Sea from 1991, 1994, 1997, 2000, and 2005. Maxima in dissolved oxygen concentrations near 1200 dbar in the 1994 profile reflect the ventilation of these layers by the deep overturning that occurred in the early 1990s. Oxygen concentration in the upper 1200 dbar decreased significantly by the time of the 1997 survey. In 2000, a shallow oxygen maximum had developed near 650 dbar, corresponding to the shallow convection regime discussed above. The 2005 oxygen profile shows a weaker subsurface maximum near 760 dbar.

The right panel of Figure 5 shows profiles of total dissolved inorganic carbon (total CO2) measured in the Irminger Sea in 1991 and 2005. Between these two surveys total CO2 increased significantly by more than 10 µmol/kg at the intermediate levels (~400 to 1800 dbar) where the mode waters are found. The details of these changes are related partly to changes in the convective formation of the mode waters. The secular trend is related to the anthropogenic increase in atmospheric CO2.

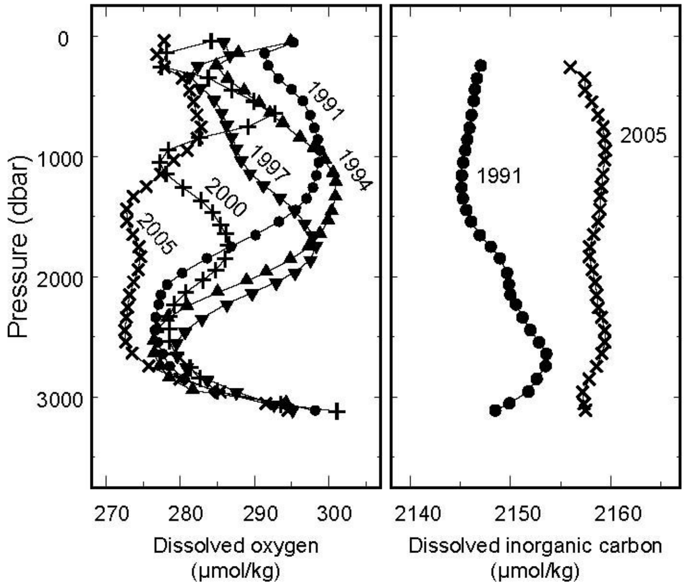

Figure 5. Profiles of dissolved oxygen and total dissolved inorganic carbon (total CO_2) in the centre of the Irminger Sea, measured during different surveys of the AR7E section. Several deep stations from each survey were combined, and some smoothing and interpolation was applied to produce these profiles.

Summary and Outlook

The hydrographic properties of the Labrador and Irminger Seas share the strong inter-annual variability of the larger-scale North Atlantic climate system. AR7 surveys since the early 1990s saw a period of intense deep convection and abundant mode water formation, followed by a period of re-stratification and a present-day trend to warmer and more saline conditions. A shallower convective regime appears to have established itself in recent years.

The historical record suggests that natural variability on decadal time scales will continue to force intermittent deep convection such as observed in the mid-1970s and the early 1990s. The controlling balances are complex and potentially sensitive to shifts in climatic conditions such as could be caused by global warming. Continuing the AR7 surveys is one way of monitoring climate variability in this important region.

Acknowledgements

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