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Upper Labrador Sea Water in the Irminger Sea during a weak convection period (2002–2006)

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Abstract

Four cruises between 2002 and 2006 sampled physical and chemical tracers in the southern Irminger Sea during the period of weak convection in the North Atlantic Subpolar Gyre. The upper Labrador Sea Water (uLSW) shows complex and time variable patterns reflecting different formation sites: Irminger Sea, South Greenland and Labrador Sea.

1 Introduction

The Labrador Sea Water (LSW) is formed at the center of the Labrador Sea cyclonic gyre where high wind stress and buoyancy loss during winter result in overturning reaching the underlying weakly stratified waters (Lab Sea Group, 1998). After formation in the Labrador Sea, the new LSW vintage follows three main routes in the North Atlantic (Talley and McCartney, 1982; Lavender et al., 2000; Rhein et al., 2002; Bower et al., 2009): southward to the subtropics in the western North Atlantic basin, eastward to the North Atlantic eastern basin and northeastward towards the Irminger Sea.

The LSW is observed in the North Atlantic as a young (high CFC and oxygen concentrations) and fresh water typically found between 1000 and 1700 m depth. Its characteristics are not steady over time; their variability is correlated to the North Atlantic Oscillation index (NAO). In the early 1990's, the NAO was in a strongly positive phase; the convection was deep and exceeded 2000 m in the winter 1993–1994 (Lazier et al., 2002; Azetsu-Scott et al., 2003; Yashayaev et al., 2003; Avsic et al., 2006). That deep convection formed deep LSW (dLSW) and reached the high densities layers 27.74 to 27.80 $kg\,m^{-3}$. In winter 1996, the NAO index switched to a negative phase, and stayed weakly positive or negative until mid-2000. The convection depth declined to reach a 15-year-low in 2004 at 700 m (Avsic et al., 2006), while the LSW became warmer and saltier, forming the so-called upper LSW (uLSW). The uLSW is lighter than the deep convection product; it renews the 27.68–27.74 $kg\,m^{-3}$ density layer (Stramma et al.,

OSD

6, 2085–2113, 2009

ULSW during weak convection in 2002–2006

E. Louarn et al.

2004; Kieke et al., 2006).

During the uLSW formation years, only two events were particularly deep: the 2000 event forming the LSW_{2000} class (Yashayaev, 2007a), and the recently observed 2008 event (Yashayaev and Loder, 2009; Vage et al., 2009) that showed the return of deep convection in the Labrador Sea down to 1800 m.

The main LSW formation site is the Labrador Sea, however other different sites have been highlighted: Pickart et al. (2003b) proposed the Irminger Sea as a formation zone. It is influenced by the number and the strength of wintertime high westerly wind events called Greenland Tip Jets (GTJ) (Pickart et al., 2003a) that are more frequent in positive NAO phase (Moore, 2003). Observations in the Irminger Sea showed locally convected water: at dLSW densities in 1991 (Pickart et al., 2003b) and in 1994 (Falina et al., 2007), at uLSW densities in 1997 (Bacon et al., 2003) and in 2008 to 1000 m (Vage et al., 2009). Model studies by Vage et al. (2008) and Schott et al. (2009) recognize the Irminger Sea as an intermittent formation site for the uLSW. In the 1990's, Lavender et al. (2002) and Pickart et al. (1997) observed respectively uLSW and dLSW formation south west of Greenland and in the eastern Labrador Sea, respectively. Moreover, in 2008, Vage et al. (2009) observed winter mixed layers at a maximum of 1600 m South of Greenland. The northeastern Irminger Sea has also been proposed as a convection site (Reverdin et al., 1999; Vage et al., 2009).

Many sites of LSW formation may be found in the North Atlantic subpolar gyre. During years of limited depth convection in the Labrador Sea, such as those comprised between the 2000 and 2008 events, it is not obvious however that all the sites highlighted previously contribute to the uLSW layer renewal.

This study aims at describing the uLSW in the Irminger Sea during the years when no deep convection was observed, i.e. between the two major uLSW formation events in 2000 and 2008. Biogeochemical data are collected to study the presence of the uLSW in the Irminger Sea between 2002 and 2006, its properties and how it correlates to the different formation sites outlined before.

2 Dataset and methods

This work compiles data of four hydrographic cruises that sampled the Irminger Sea: Ovide02 (Billant et al., 2004), Ovide04 (Lherminier et al., in preparation), D298 (Holliday et al., 2009) and Ovide06 (cf. Table 1). The station locations are presented in Fig. 1. At each station temperature (T), salinity (S), oxygen (O_2) were measured by a CTD-O_2 probe. The accuracy was better than, respectively for temperature, salinity and oxygen, 0.002°C, 0.002 and 0.7 μmol kg^{-1}. Oxygen saturation accuracy is then better than 0.5%. CFC-11 was sampled in 2002 and 2006 cruises from bottles and measured as described by Bullister and Weiss (1988) and modified by Forner (2005). The repeatability in standard air samples was better than 5.4%.

In the following, water mass core characteristics are estimated by first suggesting the property extremum that defines the core. Then the five data points the closest in location and absolute value to the property extremum are taken into account. The mean value of the five points gives the characteristics of the core studied. The standard deviation to the mean is used to evaluate the uncertainty in the core characteristics. All uncertainties presented in this work were computed following this method. It allows to consider cores with limited extension (horizontally and vertically). Five data are taken into account because, on one hand, it allows us to have an evaluation of the uncertainty due to the dispersion of data points and due to the repeatability of the measurements. On the other hand, given the high resolution of our dataset (15 samples per station between 0 to 1000 m and a station spacing of 25–30 km), it allows not to spread the chosen points to a large area. Finally, this method allows to define small structure spread over a maximum of 2 stations and 200 m depth.

Argo float data are used to access wintertime conditions. They are drifting probes that measure salinity and temperature down to a maximum depth of 2000 m every 10 days. The Argo data used here are downloaded from CODAC, the Coriolis data center (http://www.coriolis.eu.org), which is a gateway to the global Argo data. Two levels of quality control are performed to the Argo data. First, a series of standard automatic real-time quality control (QC) is applied. Then, a delayed-mode procedure is followed in order to generate a qualified Argo data set (Wong et al., 2003; Boehme and Send, 2005; Wong et al., 2008). Six floats are used in this paper. The delayed-mode profiles are available over the entire float series for pf-6900157, pf-6900239, pf-6900386, pf-4900298 and pf-4900534 for the period considered in this paper. None of those data were corrected during the delayed-mode process. Only real-time data are available for pf-4900609. We performed our own quality control to pf-4900609 and to pf-4900534, following the delayed-mode process referenced here above. No evidence of drift or bias of the sensors was detected. Finally, the temperature accuracy is 0.01°C. The salinity accuracy varies from one float to the other but is generally better than 0.025.

3 Changes in uLSW in the Irminger Sea

The potential temperature/salinity diagram (θ/S) for the four cruises is presented Fig. 2. The uLSW layer is defined between σ_θ=27.68–27.74 (Stramma et al., 2004). In that layer, a minimum of salinity is observed; it represents the central core of the uLSW water. It is situated each year at a density of σ_θ=27.73. Between 2002 and 2004, the salinity minimum value decreases from 34.854±0.002 in 2002 to 34.847±0.003 in 2004. Then the salinity minimum increases to 34.865±0.002 in 2005 and shows no variation in 2006 to 34.868±0.004. The potential temperature is at 3.51±0.09°C in 2002 and reaches a minimum in 2004 (3.33±0.05°C) when the salinity is minimum. The temperature increases afterward to nearly the same value as 2002 and stay constant: 3.45±0.04°C in 2005 and 3.52±0.05°C in 2006. Thus, the temperature and salinity values observed in that core are both minimum in 2004.

It has to be noted that, in the dLSW layer (between 27.74 and 27.80), a salinity minimum is observed at a density of σ_θ=27.79–27.80. During the period considered in that work, a trend in the characteristic values of the dLSW is observed: the salinity and temperature are minimum in 2002 at respectively 34.883±0.004 and 3.00±0.04°C and both increase during the period studied, due to the depletion of the dLSW layer as the deep layer is not renewed in the 2000's (Yashayaev, 2007b). In 2005 and 2006, however, the increase in those characteristics slows down, which is consistent with Sarafanov et al. (2007).

The spatial distributions of potential temperature and salinity during the four cruises in the Irminger sea are presented Fig. 3. The uLSW layer is found between 400 and 1000 m. The salinity minimum in the uLSW described earlier from the θ/S plot are situated at σ_θ=27.72–27.73, corresponding to 700 m in 2002 and to circa 950–1000 m in 2004, 2005 and 2006. In 2002, three lenses of minimum salinity water are visible in the uLSW. The lens to the west (stations 13–15) is wider and has a lower salinity and higher CFC-11 concentration than the two other lenses at station 18 and station 20. Therefore the lenses at stations 18 and 20 are from an older vintage than the salinity minimum. In 2004, two lenses are observed: the central one (stations 22–28) is much wider than the eastern one (station 29), the former is also deeper (1200 m). The first lens, situated in the center of the basin, has a lower salinity content than the eastern one. However the other properties are quite similar leading to the conclusion that the two lenses must share the same origin. In 2005, only one salinity minimum lens is observed in the uLSW layer; it is centered on stations 8–9. In 2006, three salinity minimum water lenses are observed at stations 89–92, 86 and 81–82. The first two are probably from the same vintage of uLSW as they have similar properties. The eastern lens at stations 81–82 is more saline and has lower CFC concentration (cf. Fig. 4), it should be from an older vintage.

The vanishing of the dLSW signal is clearly highlighted also on these sections: the extent of the deeper salinity minimum observed in 2002 at 1500 m decreased between 2002 and 2006. On the other hand, the extent of the salinity signal due to the presence of NEADW in the eastern Irminger Sea at 2000–2500 m (Pérez et al., 2008) is maximum in 2005 and 2006. The fact that the section in 2005 is situated more south than the other years may explain the difference between 2002–2004 and 2005. The 2002, 2004 and 2006 sections are situated at the same location, the presence of a salinity maximum at NEADW level in 2006 shows the change in salinity of the water mass at the Iceland-Scotland sills (Dickson et al., 2002) and the spreading of that change to the western basin of the North Atlantic as observed by Sarafanov et al. (2007) in the Irminger Sea.

The oxygen saturation and CFC-11 concentration sections (cf. Fig. 4) show different patterns to the salinity sections. In 2002, above the salinity minimum, at stations 13–14, lies a core of elevated oxygen saturation and CFC concentration that extends near to the surface. The CFC concentration in that core is maximum at 500 m (CFC-11=5.18±0.07 pmol L^{-1}) where the density is σ_θ=27.71. The oxygen saturation percentage O_2^{sat}=92% isoline deepens to nearly 600 m at those stations. The oxygen saturation percentage is then higher in the CFC-11 maximum water than in the salinity minimum where it hardly reaches 90%. The 1% difference between oxygen saturation percentage are representative as the standard deviation for the five nearest points is evaluated to less than 1%.

The salinity (34.880±0.012) and temperature (3.79±0.16°C) of the CFC maximum water are higher than the one in the salinity minimum. The higher CFC values and oxygen saturation percentage there than at the salinity minimum water indicates a younger water vintage of the uLSW. In addition, a doming of the isopycnals is noticed at the same location.

In 2004, an oxygen saturation maximum is observed along the 27.73 isopycnal where lies the salinity minimum. At station 23, a local salinity minimum corresponding to an oxygen saturation maximum is observed at 400 m. This feature is distinct from the oxygen maximum situated at the surface, it is however situated at a density level not included in the uLSW layer. Therefore, between 27.68 and 27.74 isopycnals, i.e. in the uLSW layer, no other local oxygen saturation maximum is observed except the one corresponding to the salinity minimum at σ_θ=27.73. In 2004, contrary to 2002, there is only one core observed, corresponding to both salinity minimum and oxygen saturation maximum at σ_θ=27.73.

In 2005, the salinity minimum water (stations 8–10) is overlaid at stations 8-9-10 by high oxygen saturation percentage layers. In those layers, two maxima slightly above 88% are observed: one at an intermediate density situated stations 8–9 that lies at σ_θ=27.71, and the second, above and west to the previous one, at stations 9–10 at an upper density corresponding to an oxygen saturation maximum at σ_θ=27.69. The oxygen saturation percentage at the salinity minimum at 27.73 is lower than the two maxima observed above, it is then older than the two others. The difference between both maxima lies in the location (west and central), the density (27.69 and 27.71) and the presence or not of the isopycnal doming that appears stations 8–9, at the level of the upper maximum.

In 2006, a CFC maximum is observed in the western part of the basin at the edge of the salinity minimum. The 2006 salinity minimum corresponds to CFC-11 concentration of 4.49±0.31 pmol L^{-1}. The CFC second maxima observed in the salinity minimum core correspond to the oxygen saturation maxima between 27.73 and 27.69.

In 2002 and 2005, the CFC-11 and oxygen saturation concentration maxima and the S minimum are not situated at the same density, while in 2004 and 2006 they do overlap. Based on a comparison with CFC concentration history from Yashayaev (2007b) and Azetsu-Scott et al. (2003) in the uLSW, we conclude that the CFC-11 concentration at the 2002 salinity minimum (σ_θ=27.73) is not significantly different from the one found in the LSW formation area in the Labrador Sea two to three years earlier. Moreover, the density of the 2002 salinity minimum corresponds to the uLSW formed in the Labrador Sea since 1999, as the water formed earlier was denser. Then, the salinity minimum is likely older than one year and younger than 3 years. On the contrary, CFC-11 concentration in the CFC-11 and oxygen saturation maxima (σ_θ=27.71) in 2002 is higher than the 2002 Labrador Sea value and consequently to concentrations observed previously. Therefore, as the characteristics differ, the Irminger Sea CFC-11 maximum water is probably not formed in the Labrador Sea. From CFC data, we estimate the 2006 salinity minimum age to 3±2 years. This estimate shows clearly that the water is older than a year. The age estimated for the 2002 salinity minimum is situated in the same range.

In summary, we observed the uLSW salinity minimum every year situated at σ_θ=27.73. Thanks to the CFC concentrations, we can conclude that this salinity minimum is bound to be older than a year. We identified during the period two particular years in terms of structural distribution of CFC-11 and oxygen saturation concentration: 2002 and 2005. In those years, one or more CFC/oxygen saturation maxima are overlying the salinity minimum in the uLSW layer. On the contrary, in 2004 and 2006, all characteristic extrema are at the uLSW salinity minimum density.

4 Winter mixed layers in the North Atlantic Subpolar Gyre

Particular structures corresponding to different property extrema have been observed in the uLSW layer thanks to the property sections. Those structures may result of the presence of different vintage of uLSW formed different years at different locations. A few convection sites may be involved in uLSW layer renewal: the Labrador Sea, the Irminger Sea and the area South of Greeland. This sites are studied thanks to Argo floats in the North atlantic Subpolar Gyre.

During the period studied, uLSW formation is observed every year in the central Labrador Sea. In 2000–2005, the core formed is situated at densities between σ_θ=27.725–27.745 (Avsic et al., 2006; Yashayaev, 2007b; Rhein et al., 2007). In winter 2005–2006, the deepest winter mixed layers in the Labrador Sea were found by floats at σ_θ=27.73. During the period 2002–2006, the winter mixed layers reached the lowest depth in 2004 at 700 m, also a all-time-low (Avsic et al., 2006), and the deepest in 2002, 2003 and 2005 at a depth of 1200–1400 m.

In the Irminger Sea, an Argo float crossed each year the potential vorticity minimum region identified by Pickart et al. (2003b) as the LSW formation region in the central Irminger Sea (cf. Fig. 5). The winter mixed layer as observed by the floats never deepened more than 275 m in that region. However, in winter 2000–2001, Vage et al. (2008) noticed the presence of a local overturning to 400 m at the density of σ_θ=27.69, thus included in the uLSW upper layer. Local overturning leading to the ventilation of the upper densities of the uLSW layer is a phenomenon restricted in space and time. The Argo floats did not sample extensively the central Irminger Sea as their number was not sufficient for this purpose particularly in the early 2000's. Then they allow us to highlight the area where local overturning did not happen, yet we cannot exclude an occurence of local overturning in the other areas, such as the west central Irminger Sea. Local overturning would preferentially occur in the area where isopycnals form a dome. Contrary to deep convection, it would reach limited depth and density, but as observed in winter 2000–2001, it could reach the upmost level of the uLSW layer.

On the climatological data presented by (Pickart et al., 2003b, see his Fig. 13) in the subpolar Gyre, the area situated South of Greenland (SG) is a low potential vorticity zone similar to the central Irminger Sea. In 2008, Vage et al. (2009) observed a deep convection in SG down to 1600 m depth. SG has then to be taken into account for the winter mixed layer analysis in the north atlantic subpolar Gyre. Before 2004, no float data are available in SG in wintertime. In winter 2003–2004, the only float crossing the area sampled a mixed layer down to 500 m at the end of March 2004. The water reached a maximum density of 27.69. The convection is not deep and is similar to a local overturning phenomenon as observed in the Irminger Sea in 2001 by Vage et al. (2008). The salinity (S=34.85) and potential temperature (θ=3.7°C) of the mixed layer are higher than in the uLSW formed that winter.

In winter 2004–2005, two floats crossed SG (cf. Fig. 6). The first float (pf-4900609) showed a mixed layer of 480 m deep at σ_θ=27.70. The second float (pf-4900534) sampled an episode of deep convection at 1200 m depth near 56.51° N, corresponding to water at σ_θ=27.71, θ=3.55°C and S=34.85 (cf. Fig. 7).

In winter 2005–2006, one float only was present in that area in late winter: the float pf-4900534, that sampled the convection to 1200 m depth in winter 2004–2005, stayed one more year in SG before leaving the area. Then in winter 2005–2006, it shows a low stratified layer between 700 and 1200 m. The upper layers, however, are highly stratified and do not show any evidence of convection or local overturning in that area.

Finally, the winter conditions in the North Atlantic Subpolar Gyre clearly showed at least two convection zones: the Labrador Sea and South of Greenland. The former corresponds to the area where the LSW is observed every year. The density of the newly formed water between 2002 and 2006 was situated at σ_θ=27.732–27.74. Deep convection South of Greenland was osberved in winter 2004–2005. In the Irminger Sea, local overturning is a possible process of uLSW upper layer ventilation as observed in winter 2000–2001 (Vage et al., 2008).

5 Discussion

5.1 Origin of the different structures observed

Different structures were observed in the Irminger Sea in the uLSW layer. They are separated vertically and horizontally and are characterized by different salinity or CFC-11 and oxygen saturation percentage values. The lower level is characterized by the salinity minimum. That structure is present every year in the Irminger Sea. Its density (σ_θ=27.73) corresponds to the density observed in the newly formed uLSW in the Labrador Sea (σ_θ=27.72–27.74). The age has been estimated to 3±2 years in 2006, corresponding to the transit time from Labrador Sea to Irminger Sea obtained by Yashayaev et al. (2007). The newly formed uLSW in the Labrador Sea and the salinity minimum observed in the Irminger Sea lie at the same density, it is then likely to originate from the Labrador Sea a few years earlier.

The other two structures observed, at intermediate and upper levels, correspond to the CFC-11 and oxygen saturation maxima observed in 2002 and 2005. Two separated maxima have been described in 2005 and one only in 2002. The upper maximum in the 2005 section and the 2002 maximum, corresponding then to the upper level of the structures, have in common to lie at the isopycnal doming location. In 2002, the doming is observed at stations 13–14, west of the basin, where the CFC maximum and oxygen saturation maximum are present. In 2005, the isopycnal doming is osberved at stations 9–10, at the center of the basin. The presence of the isopycnal doming at the location of the CFC/oxygen saturation maximum strongly suggests that this structure is the product of local overturning in the Irminger Sea. Besides the density and depth of the 2005 upper oxygen saturation maximum (σ_θ=27.69) is similar to the local overturning phenomenon observed by the southwest Irminger Sea mooring (Vage et al., 2008). The density layer reached by the local overturning phenomenon was higher in 2002 than 2005. As no floats sampled the phenomenon, the local overturning process is bound to be restricted to a small area of the Irminger Sea. Those two years, the ventilation of the uLSW in the Irminger Sea did not reach deeper than 500 m.

The intermediate level of the structures correspond to the deeper oxygen saturation maximum (σ_θ=27.71) observed in 2005. The oxygen saturation value in the intermediate level is similar to the one in the upper level, they are then bound to be the same age. Then the water observed in the intermediate level may have been formed a few months earlier during the winter 2004–2005. Though the two maxima are separated vertically (two different densities) and horizontally (stations 8–9 for the intermediate and stations 9–10 for the upper level), casting doubt on a common origin. That intermediate level is likely to have a non-local but nearby origin.

The winter mixed layer study showed that the 27.71 density has been observed South of Greenland in the deep winter mixed layer earlier sampled by the float pf-4900534 that year. The float (pf-4900609), that was in the vicinity of the convection observed, joined the Irminger Sea in 6 months and crossed the D298 section during the period of the D298-2005 cruise; the float pf-4900534, that sampled the convection event, reached the central Irminger Sea 6 months after leaving the area one year later. Hence, as suggested by Lavender et al. (2005), the transit time between the area South of Greenland to the Irminger Sea may be 6 months. The water that convected South of Greenland in late-winter 2005 may then reach the central Irminger Sea at the level of the cruise in late-summer 2005. The rapid transit allowed the water mass to keep a high oxygen saturation compared to the older Labrador Sea origin water. In conclusion, the deeper oxygen saturation concentration maximum found in the Irminger Sea in 2005 at 27.71, corresponding to the intermediate level of the structures observed, is probably originating from the area South of Greenland.

Finally, the different properties highlighted allowed us to differentiate the origin of the layered structure observed in the uLSW: the lower density corresponding to the salinity minimum originate from the Labrador Sea, the intermediate density may be ventilated in the area South of Greenland in 2005, and the upper density of the uLSW in 2002 and 2005 is probably formed by local overturning in the Irminger Sea.

5.2 Structure variability

The uLSW observed in the Irminger Sea between 2002 and 2006 have a highly structural variability. During the 2002 and 2005 cruises, density water layers were observed originating from different areas of the Subpolar Gyre: Irminger Sea, South of Greenland and Labrador Sea. No evidence of convection in the first two formation sites was found in 2004 and 2006. The uLSW layers observed in 2002 and 2005 showed complex structures: a two layer structure in 2002 and a three layer one in 2005. The 2004 and 2006 observations present only a salinity minimum water originating from the Labrador Sea.

The air-sea flux interannual variability over the 2000–2008 period (cf. Fig. 8) showed two particularly positive years in the period studied in that work: the winters 2001–2002 and 2004–2005. Interestingly, the pattern and intensity of the air-sea fluxes over the subpolar gyre during those two winters are different. The air-sea flux anomaly in winter 2001–2002 is generally lower than the 2004–2005 winter. In winter 2001–2002, a positive anomaly is observed all over the central subpolar gyre but in the southwest Labrador Sea where it is negative. The positive anomaly extends to the north of the Irminger Sea, favoring the formation a local overturning down to the density σ_θ=27.71 in 2002.

In winter 2004–2005, the air-sea flux anomaly is the highest over the period 2002–2006. It is then the most favorable year for a deeper convection. The highest positive anomalies are concentrated in the north-western part of the Labrador Sea and extend to South Greenland and enter slightly the Irminger Basin. A highly positive anomaly is observed in the area South of Greenland (SG) contrary to the other year. It has to be noted that the extent of the exceptionally high anomaly in 2008 covers the SG area also. During the two years (2005 and 2008) deep convection in SG was observed, the depth reached being higher in 2008 than 2005 conforming to the higher air-sea flux anomaly observed in 2008 than 2005. Hence the presence of deep convection in the SG area in 2005 and 2008 may be correlated to the high air-sea flux anomaly over the area.

No air-sea flux anomaly is observed in winter 2004–2005 over the Irminger Sea, contrary to the winter 2001–2002, except for a small extension from southwestward. The air-sea flux anomaly pattern in the Irminger Sea is then similar to the one in winter 2000–2001. The absence of any strong anomaly did not allow more than the formation of a locally convected water down to the density 27.69. Finally, the extension of the strong positive anomaly from the Labrador Sea to the north-east observed in winter 2004–2005 reflects itself in the uLSW layer thickness extension observed in 2005 by Rhein et al. (2007) and fits to the maximal convection depth observed in the different formation area: elevated anomaly and deep convection (1400 m) in the Labrador Sea, less high anomaly and less deep convection (1200 m) in SG area and low anomaly and limited overturning in the Irminger Sea.

Contrary to the winters 2001–2002 and 2004–2005, the air-sea flux anomaly was higly negative in winter 2003–2004. That year was then the less favorable year for any convection to happen in the subpolar gyre. Indeed, the actual study did not show any other convection sites than the Labrador Sea. Moreover Avsic et al. (2006) observed a all-time-low for the convection depth in the central Labrador Sea that year. Water transport across the section in the Irminger Sea showed a northward transport in 2004 whereas it was flowing south in 2002 (Lherminier et al., in preparation): no or very little uLSW water is formed north of the Irminger section in 2004, explaining the strong northward transport of the uLSW as no uLSW was formed in the Irminger Sea at the same level that year.

In winter 2005–2006, the air-sea flux anomaly is nor particularly high neither low, it

OSD
6, 2085–2113, 2009

corresponds to the average over the years 2000's. Convection depth in the Labrador Sea, estimated from floats, is not deeper than 1100 m. It is probable that no overturning or convection is present that winter in the Irminger Sea at the latitude of our section, as the presence of convection in that area requires anormally high air-sea fluxes. Yet, the CFC maximum observed to the west of the section at the edge of the East Greenland Current might be related to the higher air-sea flux observed in the northern Irminger Sea. Deep convection South of Greenland may not be favoured that year neither: highly stratified upper layers are observed in that zone by the float pf-4900534. The absence of any convection in the Irminger Sea and deep convection South of Greenland in 2006 explains the lower CFCs concentrations in uLSW in the Irminger Sea in summer 2006: the water is older and more mixed.

A high variability is observed in the uLSW formation zones that is reflected in the structure layer of the water. 2002 is favorable for convection in the Irminger Sea, whereas 2005 is favorable for convection South of Greenland. In 2004 and 2006, the convection is bounded to the central Labrador Sea, in particular in 2004, and is not as deep as the other years (700 m for 2004 and 1100 m for 2006).

6 Conclusions

The study of the Irminger Sea sections between 2002 and 2006 showed that the vertical and horizontal structure differs greatly from one year to another. Three layers may be highlighted: the upper densities of the uLSW layer concentrated in oxygen and CFC (above σ_θ=27.71 in 2002 and σ_θ=27.69 in 2005), the oxygen saturation concentration second maxima at σ_θ=27.71 (in 2005) and the older salinity minima at σ_θ= 27.72–27.73 (the four years).

The salinity minimum is observed every year. This characteristic is due to the presence of water that convected in the central Labrador Sea at least 1 year earlier. In 2006, the age of the water has been estimated to 3±2 years, corresponding to the transit time found by Yashayaev et al. (2007) for the LSW formed in the Labrador Sea to join the Irminger Basin. Thanks to oxygen saturation concentration and CFC-11, additional lenses were highlighted in 2002 and 2005 above the salinity minimum and in the uLSW layer. In 2002, a CFC-11 maximum associated with an oxygen saturation concentration maximum was observed at 500 m at a density of σ_θ=27.71. The presence of the isopycnal doming at the same location points to a local overturning origin. In 2005, the oxygen saturation concentration maximum associated with the doming is situated at a density of σ_θ=27.69, pointing also to a local overturning origin.

Between the salinity minimum and the oxygen saturation concentration maximum at σ_θ=27.69 in 2005 lies the second oxygen saturation concentration maximum at σ_θ=27.71. This water is situated more east than the first oxygen saturation concentration maximum, and the oxygen saturation concentration are similar. Then they should have the same age and a different origin. A convection chimney South of Greenland, that had a density of σ_θ=27.71, was sampled by a float a few months earlier. The area South of Greenland may then be the origin of the second oxygen saturation maximum, as it has the same density.

Hence, our data suggest that the CFC-11 and oxygen saturation concentration maxima and salinity minimum found at different densities are ventilated from different formation sites: Irminger Sea (lightest variety in 2002 and 2005), South Greenland (intermediate variety in 2005) and central Labrador Sea (denser variety).

Finally, the Labrador Sea is the most favourable place for convection to occur. However, convection may occur in other areas in the North Atlantic Subpolar Gyre for particular winter conditions associated with high air-sea fluxes. The winter 2001–2002 enjoyed particularly cold conditions in the Irminger Sea, allowing overturning down to 27.71. The central Irminger Sea convection site is advantaged by the strength and the number of occurence of the Greenland Tip Jet (Pickart et al., 2003a; Vage et al., 2008). Air-sea fluxes were higher in the Labrador Sea and South of Greenland in winter 2004–2005, hence the presence of deep convection in the latter area. Sproson et al. (2008) linked the presence of deep convection South of Greenland to the strong wind that enables convection in the Labrador Sea. The occurrence of convection South of Greenland may then be associated with the strength of that wind and then to the strength of convection in the Labrador Sea.

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OSD
6, 2085–2113, 2009

Table 1. List of the cruises concerned by that study. The acronym N.S. stands for number of stations present in the Irminger Sea and used in the study.

Cruise	Date	Vessel	P.I.	N.S.	CFC-11
Ovide02	10 Jun–11 Jul 2002	N/O Thalassa	H. Mercier	25	yes
Ovide04	5 Jun–6 Jul 2004	N/O Thalassa	T. Huck	26	no
D298	23 Aug–25 Sep 2005	RRS Discovery	S. Bacon	21	no
Ovide06	23 May–27 Jun 2002	FS Maria S. Merian	P. Lherminier	24	yes

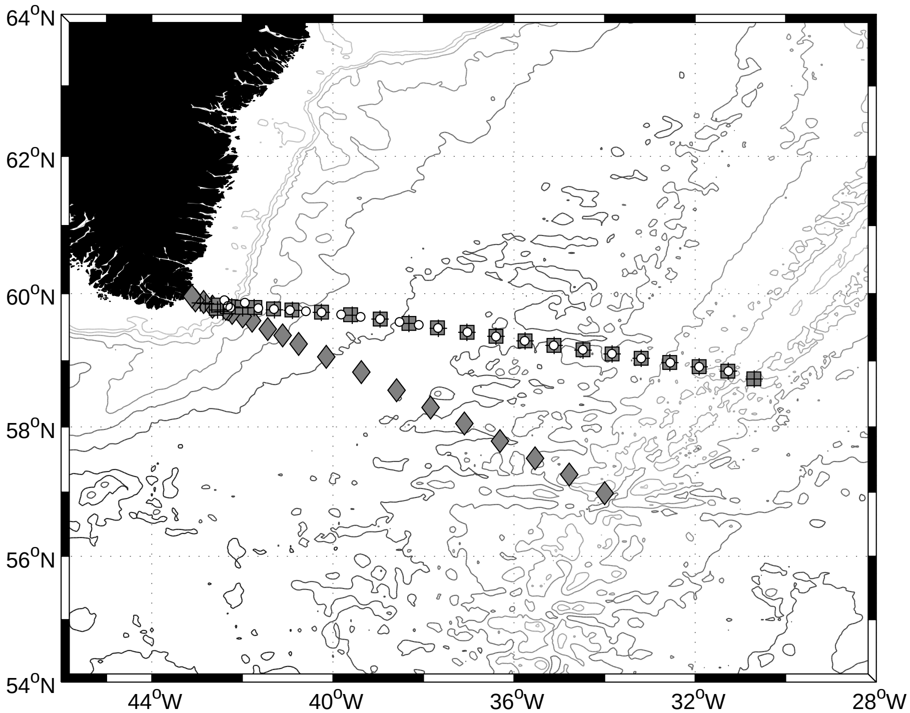

Fig. 1. Locations of the stations in the Irminger Sea of Ovide 2002 (gray square), Ovide 2004 (crosses), D298 (gray diamonds) and Ovide 2006 (white points). The three Ovide cruises are situated along the same line. The D298 cruise took place south of the Ovide line.

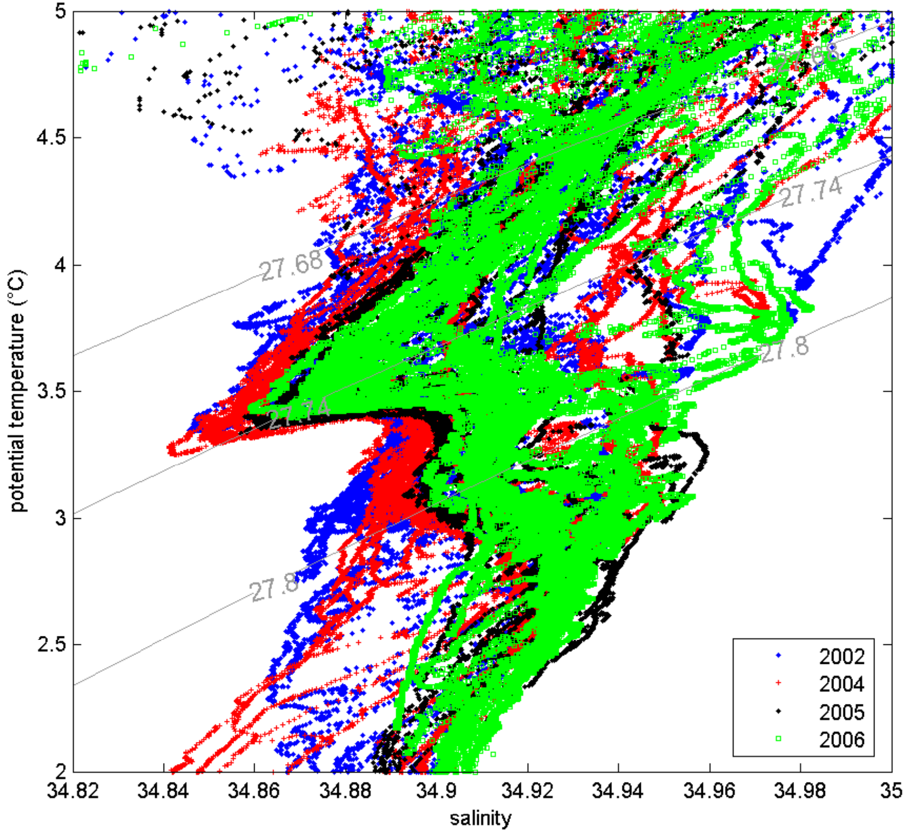

Fig. 2. θ/S diagram for the four cruises in the Irminger Sea. The gray lines represent the isopycnal levels 27.68, 27.74 and 27.80 that bound the uLSW and dLSW layers.

OSD

6, 2085–2113, 2009

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

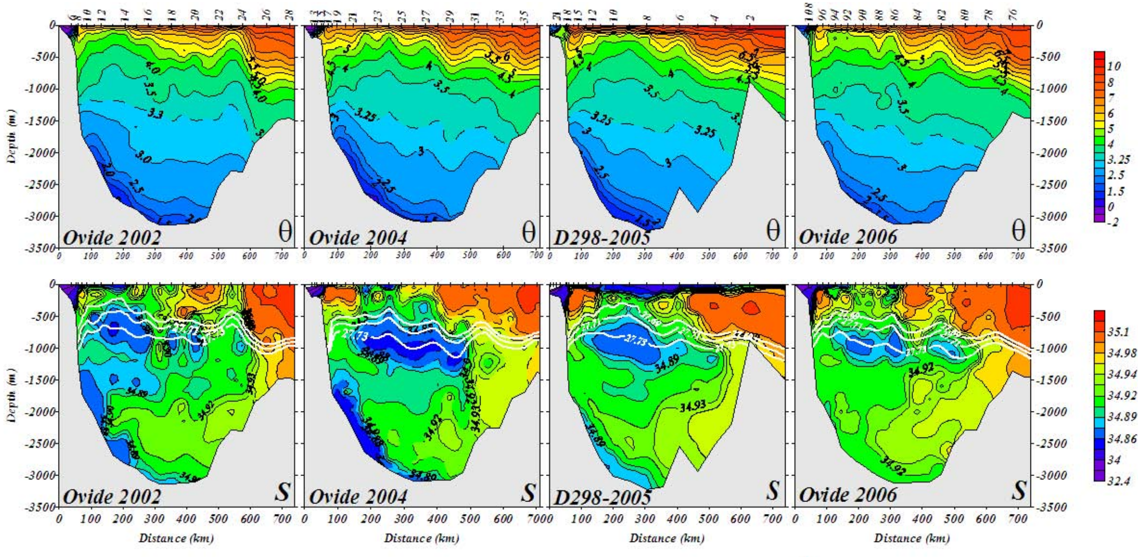

Fig. 3. Water property contour plots in the Irminger Sea for the four cruises Ovide 2002, Ovide 2004, D298 and Ovide 2006: (upper panel) potential temperature θ (in °C); (lower panel) salinity (S). The white lines represent the σ_θ=27.69, 27.71 and 27.73 kg m^{-3} isopycnals.

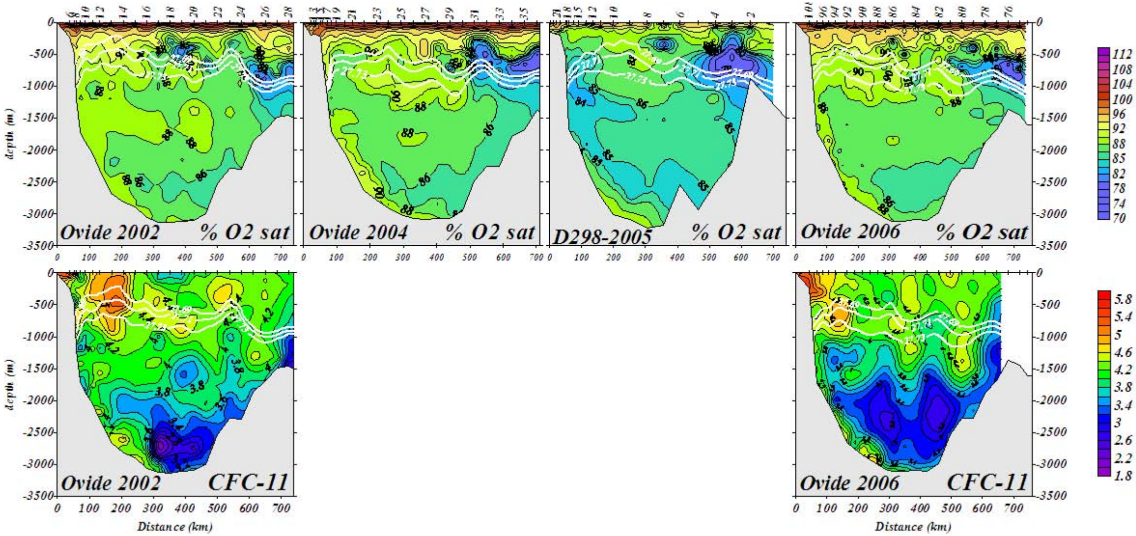

Fig. 4. Water property contour plots in the Irminger Sea for the four cruises Ovide 2002, Ovide 2004, D298 and Ovide 2006: (upper panel) saturation oxygen concentration (O_2^{sat} in %); (lower panel) CFC-11 concentrations (in pmol L^{-1}) in 2002 and 2006. The white lines represent the σ_θ=27.69, 27.71 and 27.73 kg m^{-3} isopycnals.

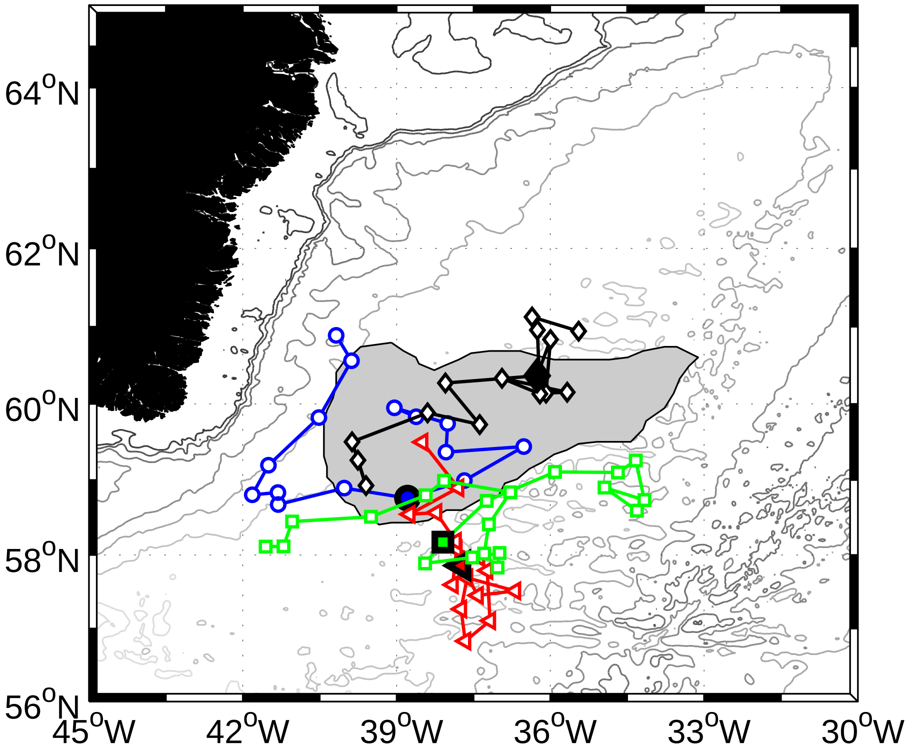

Fig. 5. Trajectory of the floats crossing the central Irminger Sea during winter 2001–2002 (blue circles), 2003–2004 (red triangles), 2004–2005 (black diamonds) and 2005–2006 (green squares). The bigger dark symbols represent the deepest winter mixed layer. The gray area corresponds to the minimum potential vorticity area as described by Pickart et al. (2003a).

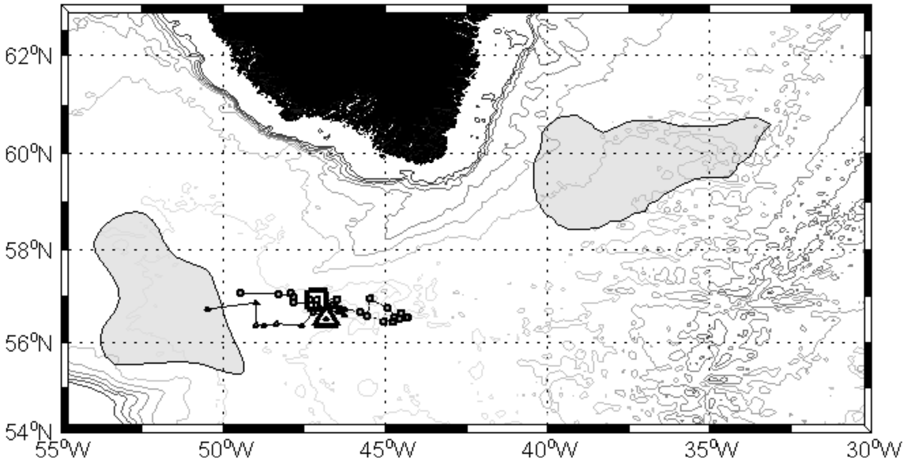

Fig. 6. Trajectory of the floats crossing South of Greenland during winter 2004–2005: pf-4900609 as triangles and pf-4900534 as squares. The bigger symbols are located at the deepest winter mixed layer for each float, the big square corresponds to the observed 1200 m deep winter mixed layer. The areas where potential vorticity are minimum in the Irminger Sea and Labrador Sea (Pickart et al., 2003a) are presented as gray areas.

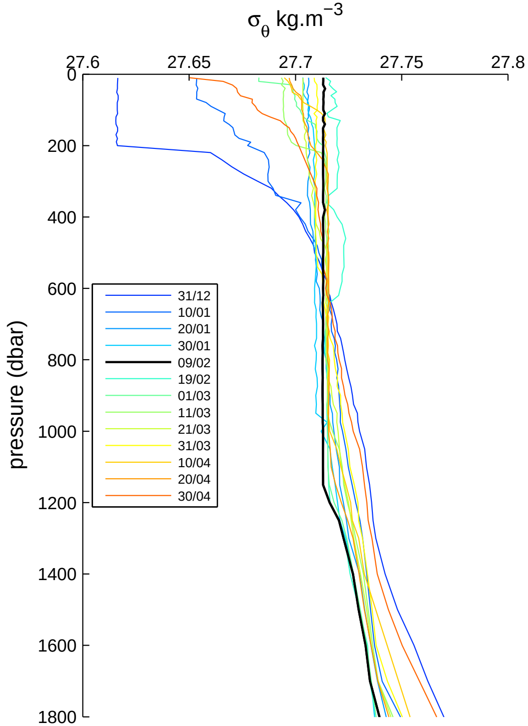

Fig. 7. Vertical density observed by the float pf-4900534 during winter 2004–2005 South of Greenland. The deepest winter mixed layer is highlighted in black.

OSD

6, 2085–2113, 2009

ULSW during weak convection in 2002–2006

E. Louarn et al.

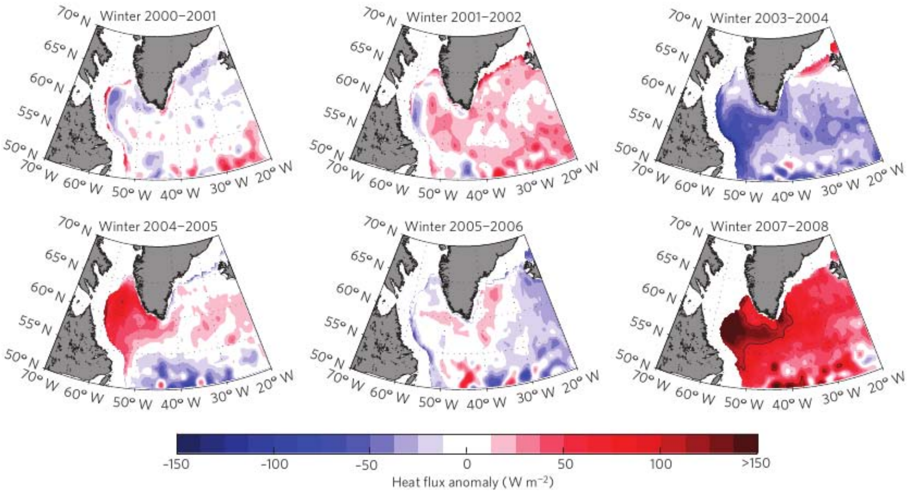

Fig. 8. Interannual variability of wintertime air-sea heat flux. Each panel shows the mean December to February bulk heat flux anomaly field (W m^2) for the given winter relative to the 2000–2007 base period. The 100 W m^2 isoline is contoured. Adapted from Vage et al. (2009), Fig. 3.

OSD
6, 2085–2113, 2009

ULSW during weak convection in 2002–2006

E. Louarn et al.