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Variability and renewal of Labrador Sea Water in the Irminger Basin in 1991–2004

Anastasia Falina,[1] Artem Sarafanov,[1] and Alexey Sokov[1]

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[1] Labrador Sea Water (LSW) property variations are analyzed using the data from six hydrographic sections occupied in 1991–2004 in the southern Irminger Basin between Cape Farewell and the Reykjanes Ridge. From 1991 to 1996, the LSW layer became steadily colder and fresher. The decrease in salinity of the LSW detected in 1994 was caused by the local convection, reaching into the weakly stratified layer of LSW advected from the Labrador Sea. Another indication of local deep convection is in the lateral distribution of dissolved oxygen concentrations in the LSW layer (~1000–2000 m) obtained in 1997 from the section across the Labrador Sea and four sections running ~100, 135 and 180° (true azimuth) from Cape Farewell. A separate lateral maximum of oxygen content in the LSW layer is revealed in the southern Irminger Sea: the concentrations increased from the Labrador Sea eastern edge toward the Irminger Sea rather than the reverse, as would be expected if there was no local modification of LSW via deep convection. Since 1996, the two-modal structure of LSW has been observed in the Irminger Basin. The upper mode of LSW detected in 1996 was formed in situ; during the winter of 1996/1997, the upper mode was locally renewed. From 1997 to 2004, the temperature and salinity signatures of the deeper mode considerably eroded due to the lack of the renewal of the deeper LSW reservoir in the Labrador Sea, while the annually renewed upper mode, on the contrary, became more pronounced in the property patterns.

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1. Introduction

[2] According to the contemporary notion, Labrador Sea Water (LSW [e.g., *Lazier*, 1973]) is formed both in the Labrador Sea and in the Irminger Sea [*Pickart et al.*, 2003a, 2003b].

[3] Formation of LSW in the Labrador Sea occurs due to a strong wintertime cooling of the surface waters, which is caused by the transport of cold polar air from the Canadian landmass toward Greenland [*Bumpke et al.*, 2002]. The cold dense surface water loses buoyancy and overturns forming a weakly stratified cool, fresh, nutrient-poor and oxygen-rich intermediate water mass. Intensity of the deep open-ocean convection and thus the LSW formation rate depend on the severity of the winter [*Curry et al.*, 1998; *Pickart et al.*, 2002]; the depth of the convectively mixed layer varies from less than 1000 m to 2300 m [*Lazier et al.*, 2002]. The LSW formation rates estimated in a number of studies [*Worthington*, 1976; *Clarke and Gascard*, 1983; *McCartney and Talley*, 1984; *McCartney*, 1992; *Speer and Tziperman*, 1992; *Rhein et al.*, 2002] are from 2 to 11 Sv.

[4] Properties of LSW in its source region are as well subject to interannual and decadal variability [*Curry et al.*, 1998]. During the last three decades (1973–2000), potential temperature and salinity of LSW in the central Labrador Sea varied in the ranges 2.7–3.4°C and 34.82–34.90, respectively (Figure 1a, adopted from *Yashayaev et al.* [2000]). The most intense production of LSW in the Labrador Sea occurred in the mid-1970s and in the early 1990s; LSW formed in 1990–1994 was the coldest and densest for the last century [*Rhein et al.*, 2002].

[5] LSW spreads from the Labrador Sea by the following major routes: (1) northeastward into the Irminger Sea, (2) equatorward as a component of the Deep Western Boundary Current and along the western slope of the Mid–Atlantic Ridge, and (3) into the eastern North Atlantic at ~48–54°N over the Charlie-Gibbs Fracture Zone [*Talley and McCartney*, 1982; *Cunningham and Haine*, 1995]. According to the recent estimates [*Sy et al.*, 1997; *Koltermann et al.*, 1999] based on the notion that the Labrador Sea is the only source of LSW, it takes the latter only 6 months to reach the Irminger Basin.

[6] In the first half of 20th century, the deep open-ocean convection was also thought to take place east of the southern extremity of Greenland [*Nansen*, 1912; *Nielsen*, 1928; *Sverdrup et al.*, 1942]. Since then, despite of the evidence supporting this standpoint, southwestern part of the Irminger Basin has been commonly ignored as a convection site.

[7] Recently, the hypothesis of LSW formation in the Irminger Basin was put forward again [*Pickart et al.*, 2003a, 2003b]. The assumption that the additional source of

[1]P. P. Shirshov Institute of Oceanology, Moscow, Russia.

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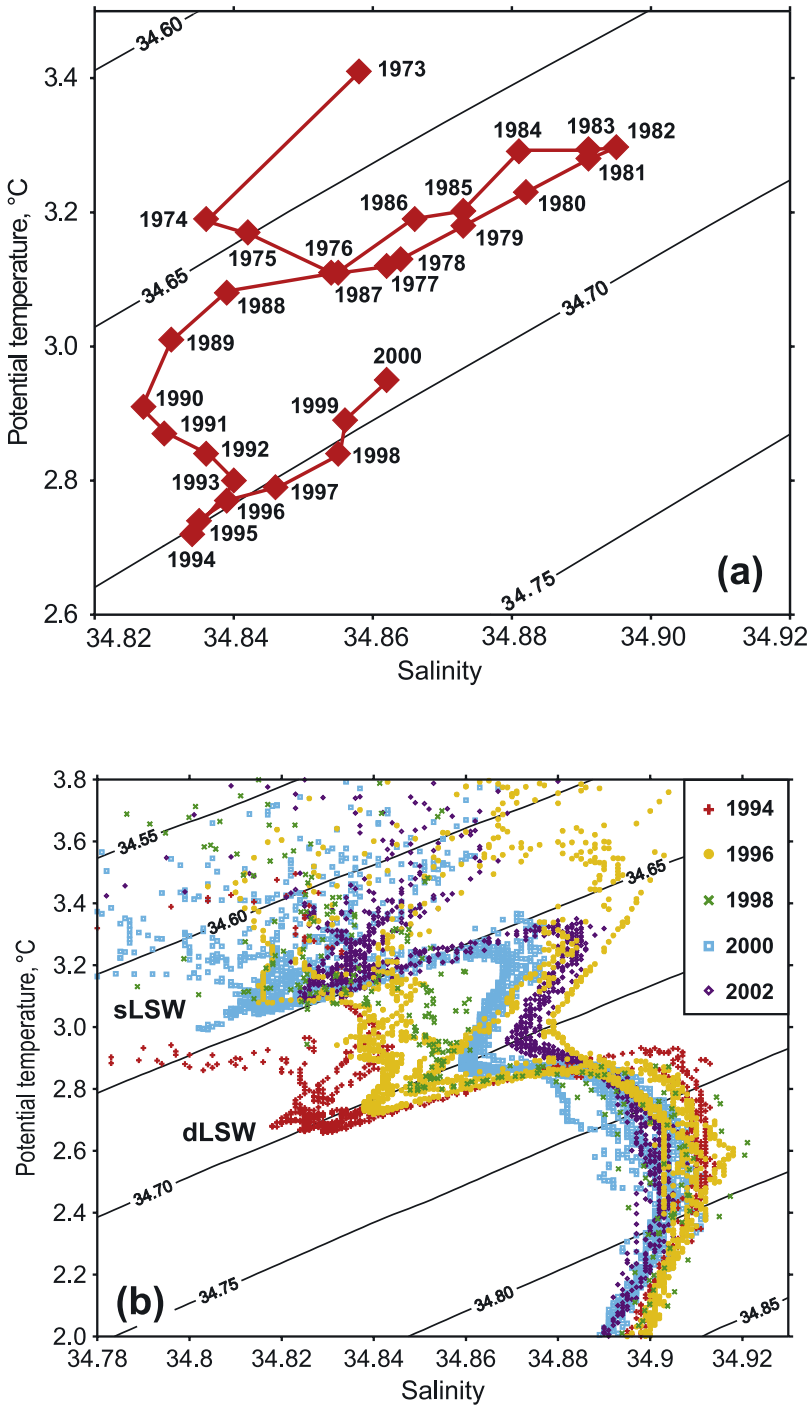

Figure 1. (a) Potential temperature (θ, °C)-salinity (S) properties of the LSW core in the Labrador Sea for the 1973–2000 time period. (b) θ–S diagram for the data from hydrographic sections occupied in 1994–2002 in the Labrador Sea along the WOCE AR7W line, adopted from *Yashayaev et al.* [2000]. sLSW, the upper (shallow) mode of LSW; dLSW, the deeper mode of LSW. Isolines of potential density referenced to 1500 dbar ($\sigma_{1.5}$) are shown.

LSW probably exists in the Irminger Basin [*Pickart et al.*, 2003a] was made partly on the basis of the analysis of the chlorofluorocarbon (CFC-11) lateral distribution in the subpolar North Atlantic [see *Rhein et al.*, 2002]. The separated CFC maxima in the LSW density range ($27.74 < \sigma_0 < 27.80$ kg m^{-3}) were revealed from 1997 dataset within the mid-depth cyclonic gyres [see *Lavender et al.*, 2000; *Spall and Pickart*, 2003] in both the Labrador and Irminger Seas [*Rhein et al.*, 2002]. It was suggested that the lateral maximum of the CFC content in the interior Irminger Sea might be produced by the local deep convection, as the latter is the only source of CFC in the LSW layer. The analogous argument was made on the basis of the analysis of the average (for the period 1989–1997) potential vorticity lateral distribution in the

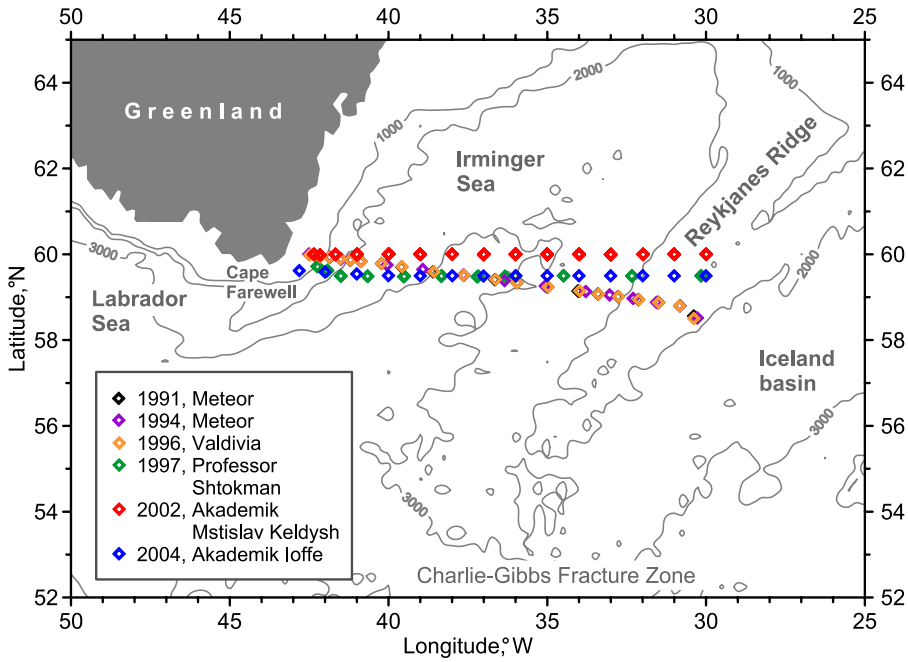

Figure 2. Locations of the hydrographic sections used in the study.

subpolar region at 1000 m, which showed a separate minimum in the southern Irminger Sea [see *Pickart et al.*, 2003a].

[8] As was shown in a number of studies [*Pickart et al.*, 2003a, 2003b; *Bacon et al.*, 2003; *Centurioni and Gould*, 2004], the deep overturning in the Irminger Sea east of Cape Farewell periodically arise due to the cooling of the surface water by the strong and very cold wintertime westerly winds blowing off Greenland over the ocean. During the periods of high North Atlantic Oscillation (NAO) index [*Hurrell*, 1995], this phenomenon also known as the Greenland tip jet [*Doyle and Shapiro*, 1999] is most intense, and the heat loss in the southern Irminger Sea can be comparable to the one in the western part of the Labrador Sea [*Pickart et al.*, 2003b]. The mixed-layer model calculations showed that the deep convection can occur in the Irminger Sea to a depth of 1500–2000 m; the water mass formed this way is characterized by the potential temperature, salinity and potential vorticity values, which are similar to those of LSW formed in the Labrador Sea [*Pickart et al.*, 2003a].

[9] The latest estimate of the time for LSW of Labrador Sea origin to reach the edge of the Irminger cyclonic gyre is approximately 2 years during the intense convection (high-NAO) periods and about 2.5 years during the weak convection periods [*Pickart et al.*, 2003a]. These transit-time values seem to be the most realistic as they were obtained in accordance with the concept of two sources of LSW.

[10] This study of variability of LSW properties in the southern Irminger Sea is based mainly on the hydrographic data collected during three cruises of Russian research vessels in 1997–2004 and during the earlier cruises of R/V *Meteor* (in 1991, 1994) and R/V *Valdivia* (in 1996) across the southern portion of the Irminger Basin at 59–60°N (Figure 2). Revealed LSW property variations were compared with interannual changes in properties of the LSW core in the Labrador Sea in order to detect the possible events of LSW renewal directly in the Irminger Basin.

2. Data

[11] Part of the data used in the study was obtained during the cruises along the nominal latitude 60°N from the southern extremity of Greenland to the European shelf. Three repeated sections were carried out from the R/V *Professor Shtokman* in October–November 1997, from the R/V *Akademik Mstislav Keldysh* in August 2002 and from the R/V *Akademik Ioffe* in June 2004. The 1997 section contributed to the WOCE (World Ocean Circulation Experiment) Hydrographic Program; the 2002 and 2004 sections were made in the framework of the "Meridian" Russian Federal Program. The western parts of the sections (between Greenland and the Reykjanes Ridge, see Figure 2) were selected for the analysis.

[12] The temperature and salinity data were acquired from the sea surface to about 20 m above the bottom with NBIS Mark-III (in 1997, 2002) and SeaBird 911 (in 2004) CTD profilers. Temperature and salinity values were calculated according to the practical scales ITS-90 and PSS-78, respectively.

[13] During the 1997 and 2002 cruises, water samples for oxygen were obtained with General Oceanics Rosette system equipped with the Niskin bottle samplers. The dissolved oxygen concentrations were determined by Winkler potentiometric titration following the indications described in the WOCE Manual of Operations [*Culberson*, 1991]. Precision of oxygen measurements was 0.02 ml l^{-1}.

[14] Another part of the data that we use was obtained during two cruises of R/V *Meteor* in September 1991 and November 1994 and during the cruise of R/V *Valdivia* in August 1996. All three sections were carried out along the WOCE A1E line from the southern extremity of Greenland

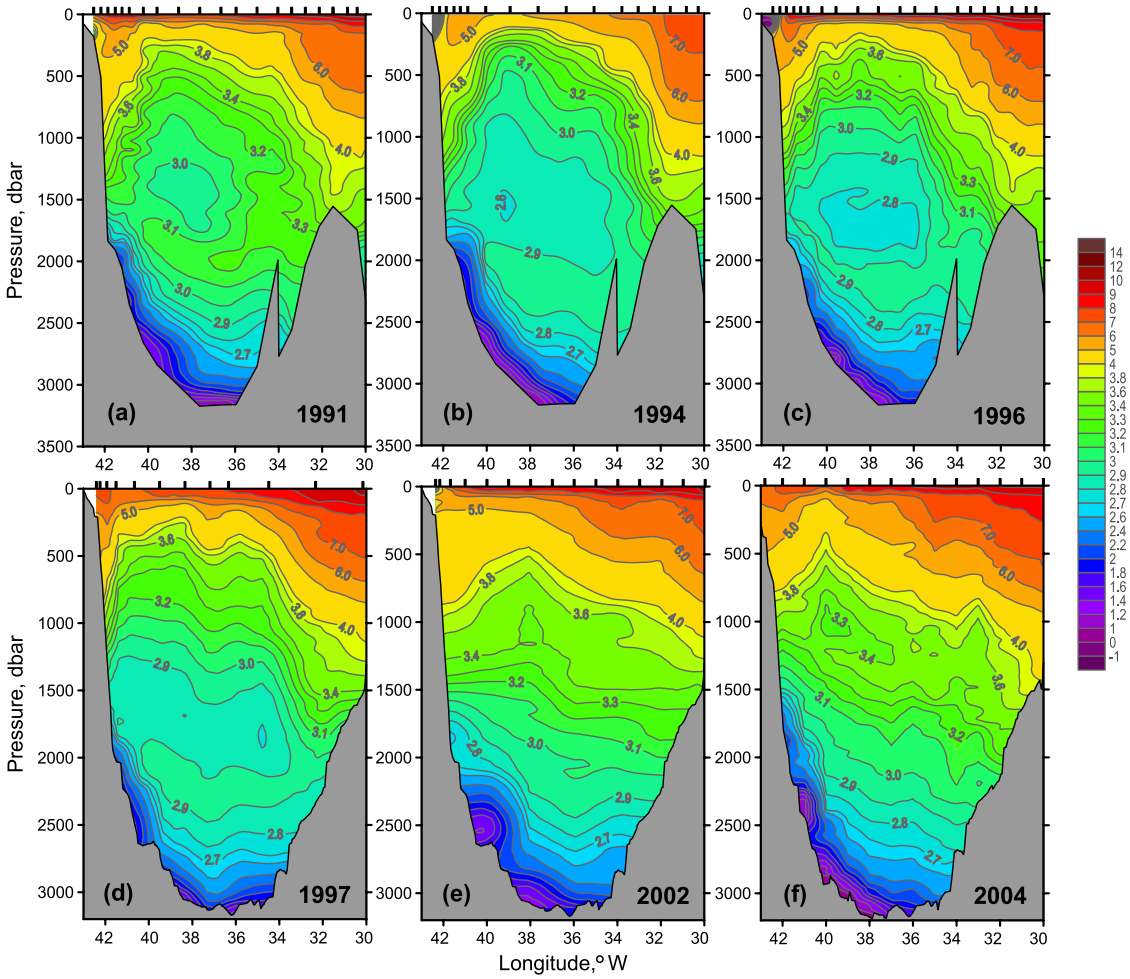

Figure 3. Vertical distributions of potential temperature (°C) in the southern Irminger Basin along the sections occupied in (a) 1991, (b) 1994, (c) 1996, (d) 1997, (e) 2002, and (f) 2004. Station positions are marked with ticks on the top axis of each plot.

to the Porcupine Bank. The western parts of the sections within the Irminger Basin (in the latitude range ~59–60°N, Figure 2) were taken to prolong the analyzed period of observations to the beginning of 1990s.

[15] Distributions of potential temperature, salinity and dissolved oxygen concentrations along the Irminger Sea sections are shown in Figures 3, 4, and 5, respectively.

[16] Additionally, we use the bottle oxygen data from five WOCE sections carried out in the central Labrador Sea – southern Irminger Sea region in 1997 (cruises of R/V *Knorr* 147/5, AR7W line; *Hudson* 97009/1, 44°W; *Knorr* 151/2, A24N; *Discovery* 230, A25; and *Meteor* 39/5, A1E). These data were included in order to examine the lateral distribution of the oxygen content in the LSW core between the Labrador and Irminger Seas. Locations of these sections and vertical distributions of oxygen along them are shown in Figure 8. The total list of the cruises is presented in Table 1.

3. Irminger Data Analysis and Results

3.1. 1991–1996: Cooling and Freshening of LSW

[17] In the sections occupied in 1991–1996, the LSW with potential temperature (hereinafter referred to as temperature) $2.7 < \theta < 3.6$°C, salinity S < 34.9 and oxygen content >6.7 ml l^{-1} is clearly seen in the depth range ~250–2000 m (see Figures 3–5).

[18] From 1991 to 1994, temperature in the LSW core decreased by ~0.2°C (from ~3.0°C to ~2.8°C). Salinity in the core (<34.85) decreased only slightly (by ~0.004, see Figure 6), but the low salinity domain (<34.86) significantly enlarged (by ~800 m in thickness, by ~160 km in east–west extent, see Figures 4a and 4b), and hence the LSW volume increased. Oxygen content in the LSW layer increased by 0.05–0.08 ml l^{-1}.

[19] The aforementioned decrease in LSW temperature in the Irminger Basin between the 1991 and 1994 observations corresponds to the LSW temperature decrease that occurred in the Labrador Sea in 1989–1993. From 1989 to 1993, temperature in the weakly stratified convective layer in the Labrador Sea decreased from 3°C to ~2.8°C (Figure 1a). Figure 1a also shows that in 1990–1993 cooling of LSW in the Labrador Sea was accompanied by the noticeable salinity increase of 0.01–0.02. However, in 1991–1994, salinity in the LSW core did not increase in the Irminger Basin; moreover, the 500–2000 m layer became fresher. Therefore, significant increase in LSW volume observed in 1994 was likely a result of not only the LSW spreading

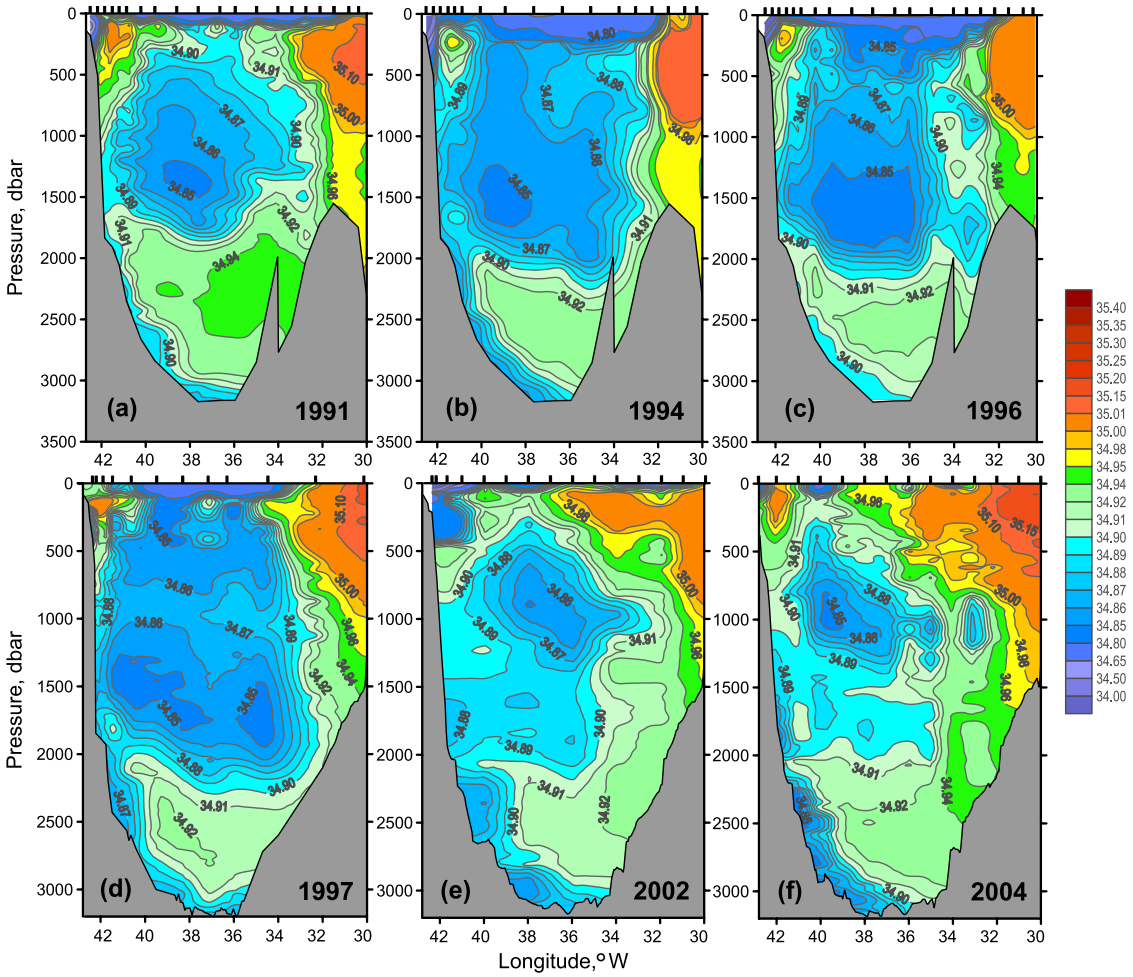

Figure 4. Vertical distributions of salinity in the southern Irminger Basin along the sections occupied in (a) 1991, (b) 1994, (c) 1996, (d) 1997, (e) 2002, and (f) 2004. Station positions are marked with ticks on the top axis of each plot.

from the Labrador Sea but also of the additional influence of convection occurred directly in the southwestern Irminger Sea. The November 1994 salinity and oxygen data (Figures 4b and 5b) do show that the LSW bulk at 38–40°W extends upward to depths of about 250 m, i.e., to the lower boundary of the fresh and oxygen-rich near-surface layer. Thus, the 1994 vertical salinity distribution at specified longitudes could be a result of restratification of previously overturned rather thick water column, actual (wintertime) thickness of which obviously cannot be determined from the November data. Note that on the basis of time series of the winter mean air-sea heat flux, 1993 and 1994 have been recently recognized as "the most likely candidate years for convection in the Irminger Sea" in the first half of the 1990s [see *Bacon et al.*, 2003]. Probably, the event of local deep convection could occur in the Irminger Basin because the layer above ~1500–2000 m was already "preconditioned" by the arrival of weakly stratified LSW from the Labrador Sea, where convection reached ~2000 m in the beginning of the 1990s.

[20] Between the 1994 and 1996 observations, the LSW core domain contoured by the 2.8°C isotherm at depths of ~1500–2000 m became several times larger (Figures 3b and 3c). In 1996, temperature in the LSW core reached its minimum value (2.75°C) for the entire 1991–2004 time period. The specified decrease of temperature in the LSW core was most likely a result of advection of the colder LSW vintage from the Labrador Sea, as no traces of the local deep convection to depths of more than ~600 m are seen from the 1996 salinity pattern in the Irminger Basin (Figure 4c). The latter fact is not surprising since the NAO index was extremely low in winter of 1995/1996 [see *Pickart et al.*, 2003a]. In the Labrador Sea, the coldest LSW (~2.7°C) for the last 30 years was observed in 1994 (Figure 1a). This water was formed during the severe winter of 1993/1994. If the lag time for the LSW signal were about 6 month [*Sy et al.*, 1997; *Koltermann et al.*, 1999], then the coldest LSW should have been found in the southern Irminger Sea in November 1994. The fact that the coldest LSW was observed not in 1994, but in August 1996 better agrees with the notion [*Pickart et al.*, 2003a] that the transit time for LSW from the Labrador Sea to reach the Irminger Basin is at least 2 years.

[21] As well as the low temperature domain (<2.8°C), the low salinity one (<34.85) noticeably enlarged (by ~150 m

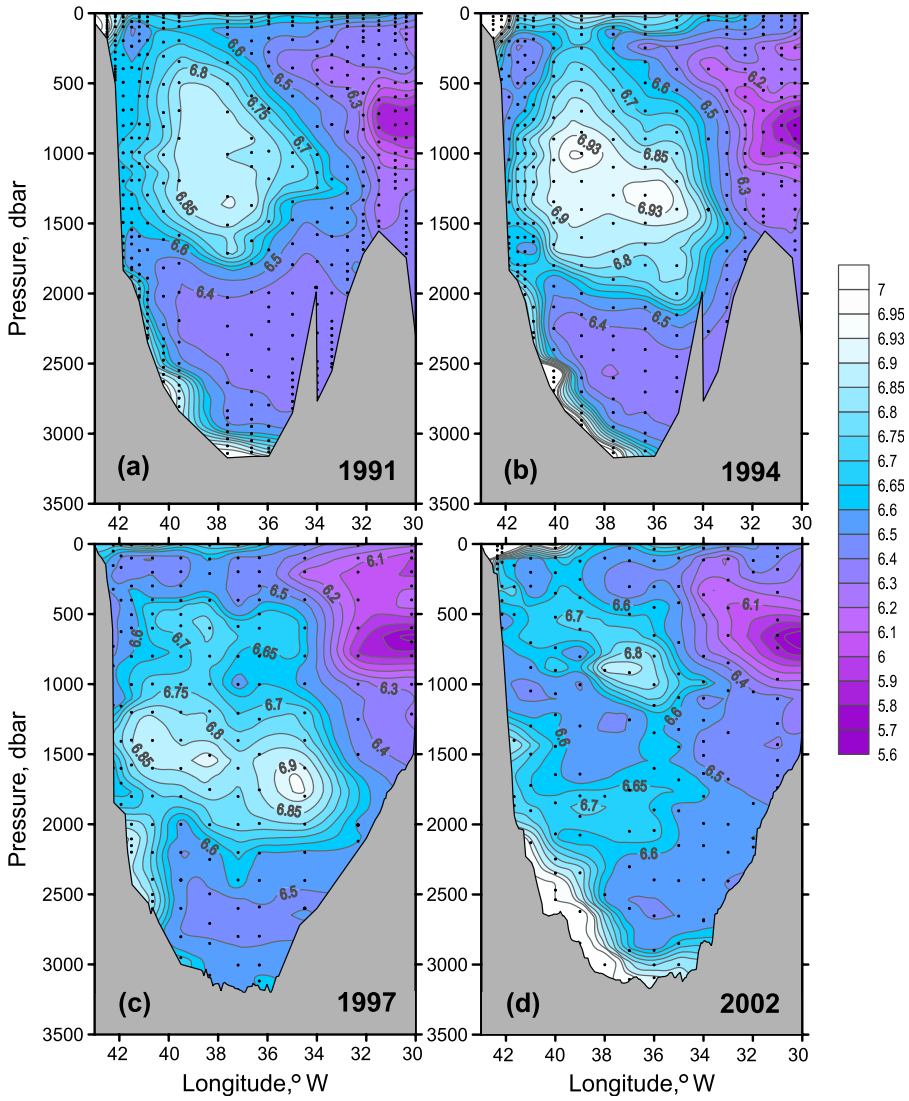

Figure 5. Vertical distributions of dissolved oxygen concentrations (ml l^{-1}) in the southern Irminger Basin along the sections occupied in (a) 1991, (b) 1994, (c) 1997, and (d) 2002. Bottle locations are marked with dots.

in thickness, by ~110 km in zonal extent) during the 1994–1996 time period (Figures 4b and 4c).

[22] In summary, the monotonic cooling and freshening of the LSW layer in the Irminger Basin occurred from 1991 through 1996 (Figures 3 and 4, upper panels). The cooling of the LSW core corresponds to the decrease of the LSW temperature observed in the Labrador Sea in 1990–1994. However, the 1991–1994 decrease in salinity in the LSW

Table 1. Sections Used in the Study

Research Vessel	Month, Year	Cruise	Program	Principal Investigator
	Irminger Sea Hydrographic Sections Along 59–60°N			
Meteor	September 1991	18	WOCE	Jens Meincke
Meteor	November 1994	30/3	WOCE	Jens Meincke
Valdivia	August 1996	161/2	WOCE	Manfred Bersch
Professor Shtokman	November 1997	36	WOCE	Alexey Sokov
Akademik Mstislav Keldysh	August 2002	48	Meridian	Eugeniy Morozov
Akademik Ioffe	June 2004	15	Meridian	Sergey Pisarev
	1997 Oxygen Sections in the Central Labrador Sea – Southern Irminger Sea Region			
Knorr	March 1997	147/5	WOCE	Robert Pickart
Hudson	May 1997	97009/1	WOCE	Allyn Clarke
Knorr	June 1997	151/2	WOCE	Lynne Talley
Discovery	August 1997	230	WOCE	Sheldon Bacon
Meteor	August 1997	39/5	WOCE	Alexander Sy

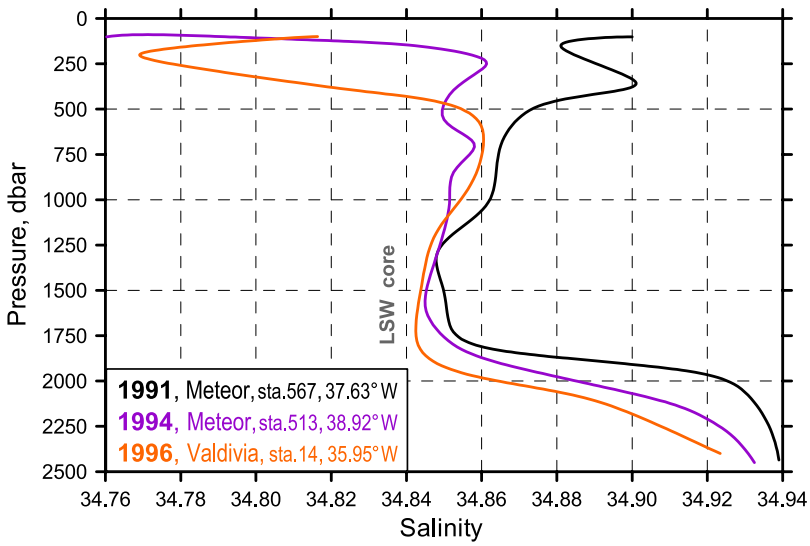

Figure 6. The 1991, 1994, and 1996 smoothed vertical salinity profiles for individual stations (see legend) where the deep salinity minima, associated with the LSW core, are most pronounced. This figure supplements the 1991–1996 salinity patterns (see Figure 4, upper panel) and illustrates the slight decrease in salinity (<0.01) in the LSW core that occurred in the southern Irminger Basin during the 1991–1996 time period.

layer was apparently caused by local deep convection – this decrease cannot be explained by the changes in the Labrador Sea, where salinity of LSW, on the contrary, steadily increased in 1990–1993 (Figure 1a).

3.2. 1996–1997: Local Formation and Renewal of the LSW Upper Mode

[23] In the early 1990s, intense deep convection (>2000 m) in the Labrador Sea produced extremely cold and dense LSW. Shallower convection (<1500 m) that has occurred since the mid-1990s, resulted in the coexistence of two modes of LSW in the Labrador Sea, namely dLSW (deep LSW, after [*Rhein et al.*, 2002]) formed before 1995 and sLSW (shallow LSW) produced after 1995 [see *Lazier et al.*, 2002; *Azetsu-Scott et al.*, 2003]. Figure 1b (adopted from *Yashayaev et al.* [2000]) shows θ–S diagram for the data from five hydrographic sections occupied in 1994–2002 in the Labrador Sea along the WOCE AR7W line. As seen in Figure 1b, the lighter ($34.63 < \sigma_{1.5} < 34.65$ kg m^{-3}) LSW core has been observed in the Labrador Sea above the main denser ($34.69 < \sigma_{1.5} < 34.71$ kg m^{-3}) core since May 1996.

[24] Figure 7 shows θ–S diagram for the data from the 1991–2004 Irminger sections analyzed herein. The sLSW is seen from the August 1996 data in the density range $\sim 34.60 < \sigma_{1.5} < 34.63$ kg m^{-3}, while the 1991 and 1994 data do not allow to distinguish this mode. Hence, the formation of sLSW had to begin directly in the Irminger Sea in winter of either 1994/1995 or 1995/1996, i.e., earlier or simultaneously with the beginning of sLSW formation in the Labrador Sea. The signature of local convection is clearly seen from the 1996 salinity pattern (Figure 4c). The upper 600-m-thick layer represents the weakly stratified water column of low salinity (<34.87), and sLSW is barely distinguished within this column. Comparison of θ–S plots for the Labrador and Irminger Sea data (Figures 1b and 7a) shows that sLSW of Irminger origin was ~0.2°C warmer, 0.02–0.03 saltier and ~0.02 kg m^{-3} lighter than sLSW formed in the Labrador Sea in winter of 1995/1996.

[25] As was recently reported [see *Pickart et al.*, 2003b], the numerous Greenland tip-jet events, which took place in January and February 1997, led to enhanced heat loss in the southern Irminger Sea along a band centered near 60°N. Estimated heat flux in the Irminger Sea was comparable to the one observed in the western Labrador Sea during the same winter. Thus, deep convection in the southern Irminger Basin was possible in winter of 1996/1997. The 1996/1997 wintertime data from profiling float together with the salinity data from a hydrographic section occupied on board the R/V *Meteor* (cruise 39, leg 4) in July 1997 showed that convection south of Cape Farewell reached depths of 900–1000 m [see *Bacon et al.*, 2003].

[26] In the section occupied in November 1997 on the R/V *Professor Shtokman*, the weakly stratified freshened water column extends from the sea surface to a depth of ~2200 at 34–40°W (Figure 4d). Within this bulk, two modes of LSW – sLSW and dLSW – are seen as the low salinity (<34.86) domains at depths of ~400–750 m and 1000–2000 m, respectively. In the salinity pattern, sLSW is almost indistinguishable from the near-surface layer, which penetrated at ~38–40°W into the sLSW one as a tongue of low salinity (<34.85). Therefore, the vertical distribution of salinity in the southern Irminger Basin in 1997 points to the local renewal of sLSW in winter of 1996/1997. This is in fact confirmed by the results of recent study of open-ocean convection in the region [*Bacon et al.*, 2003], according to which the upper 700-m-thick layer in the southern Irminger Sea was formed in situ during the winter of 1996/1997. In θ–S plot (Figure 7b), the upper mode of LSW can be distinguished in the density range $\sim 34.60 < \sigma_{1.5} < 34.66$ kg m^{-3}. From 1996 to 1997, thickness of the sLSW layer increased by ~200 m (see Figures 4c and 4d).

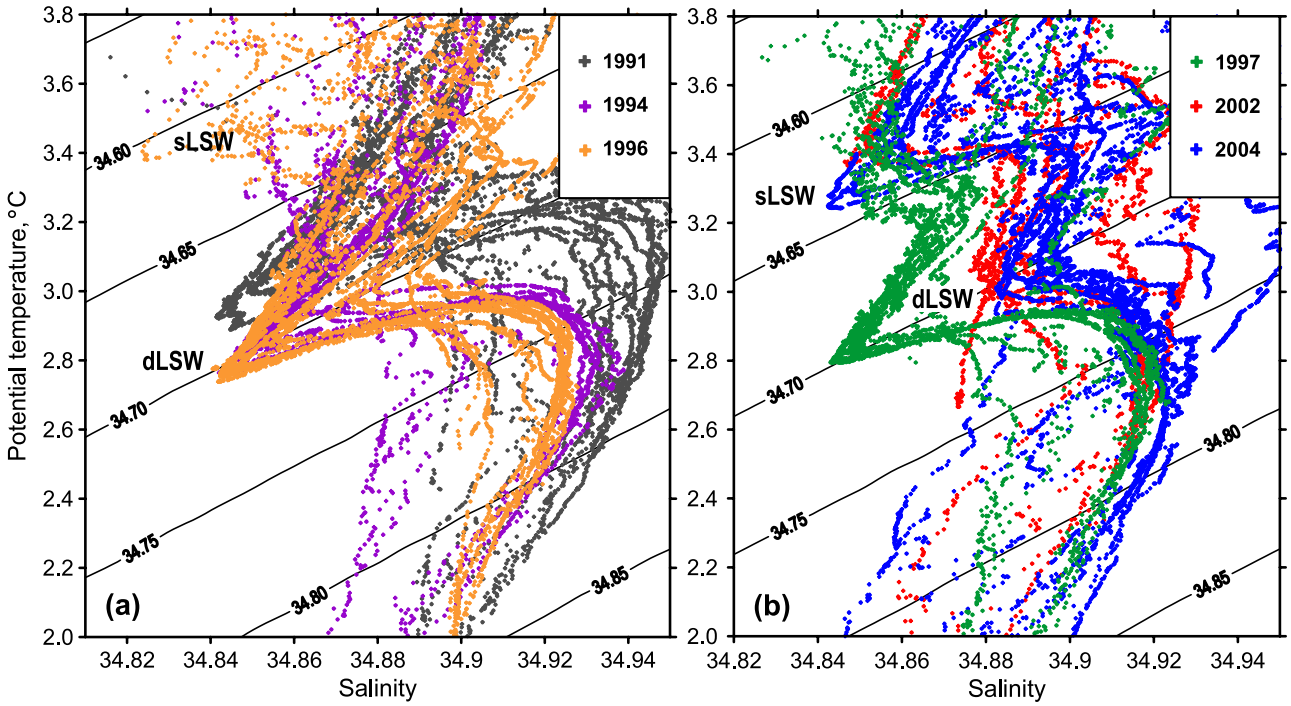

Figure 7. θ–S diagram for the data from hydrographic sections occupied in the southern Irminger Basin (a) in 1994 and 1996; (b) in 1997, 2002, and 2004. sLSW, the upper (shallow) mode of LSW; dLSW, the deeper mode of LSW. Isolines of potential density referenced to 1500 dbar ($\sigma_{1.5}$) are shown.

[27] Strictly speaking, the weakly stratified low-salinity shallow water that was first observed in the Irminger Basin in 1996 and locally renewed in winter of 1996/1997, the analog of the shallow Labrador Sea Water in the Labrador Sea, could be named "shallow Irminger Sea Water" (according to its origin sight). However, following *Pickart et al.* [2003a], we suggest that there is no necessity to give a new name, i.e., to introduce a new water mass. First, this water has the same (convective) origin as the origin of sLSW in the Labrador Sea and it is formed within the region located close to the latter. Second, it occupies almost the same density interval ($\sim 34.60 < \sigma_{1.5} < 34.66$ kg m^{-3}, Figure 7b) as that of sLSW formed west of Greenland ($\sim 34.62 < \sigma_{1.5} < 34.66$ kg m^{-3}, Figure 1b). Third, and the most important, this water contributes to the LSW bulk in the Irminger Basin. Moreover, the "shallow Irminger Sea Water" would probably be confused with the "Irminger Sea Water" of Atlantic origin, which is determined as the "upper water in the northern Irminger Basin" with salinity of 35.05–35.10 and temperature of 5–7°C [see *Fogelqvist et al.*, 2003].

3.3. 1997–2004: Depletion of the Deeper LSW

[28] The changes in temperature and salinity in the deeper LSW core in 1996–1997 corresponded to those in the deep LSW reservoir in the Labrador Sea taking into account the 2–year lag. As well as in the Labrador Sea in 1994–1995, temperature in the dLSW core in the Irminger Basin only slightly increased (by ~0.05°C) in 1996–1997, salinity remained almost constant (see Figures 1a and 7).

[29] In 2002, the minimum salinity values (34.85–34.87) in the LSW bulk were observed in the sLSW layer at depths of ~500–1300 m; the higher salinities (34.88–34.89) were detected within dLSW at ~1400–2100 m (Figure 4e).

[30] From 1997 to 2002, the sLSW layer deepened and became considerably more pronounced in salinity pattern than the dLSW one, volume of which visibly decreased (compare Figures 4d and 4e). The dLSW core became ~0.3°C warmer, salinity in the dLSW layer increased by 0.03–0.04 (Figure 7b), oxygen content decreased by ~0.2 ml l^{-1} (see Figures 5c and 5d).

[31] From 2002 to 2004, temperature and salinity in the sLSW layer decreased by ~0.1°C and less than 0.01, respectively; salinity in the dLSW core increased by ~0.01 (Figure 7b). The low salinity domain (34.86–34.88) against the Greenland slope at depths of 1600–2000 m (Figure 4f) should not be considered as the layer of fresher dLSW, since the minimum temperature values within this domain were about 2.0°C (Figure 3f). Such low temperatures in this near-slope layer point to a high content of the overflow water from the Nordic Seas therein. Thus, during the 2002–2004 time period, the upper mode of LSW in the southern Irminger Basin became slightly colder and fresher, while the deeper mode continued to become less pronounced. No signs of the local renewal of sLSW and dLSW are seen from the 2002 and 2004 data.

[32] Significant change in the LSW structure in the Irminger Basin between the 1997 and 2004 observations was obviously caused by the restratification in the Labrador Sea, which began in the mid-1990s. From 1995 through 2000, after the annual wintertime renewal of dLSW in the Labrador Sea had stopped and the formation of sLSW had started [*Lazier et al.*, 2002], the dLSW core isolated from the convective layer became ~0.3°C warmer and 0.03–0.04 saltier (Figure 1a). Lack of dLSW renewal in the Labrador

Sea together with mixing of dLSW with the surrounding waters along the Labrador Sea–Irminger Sea pathway caused the substantial erosion of the dLSW properties in the Irminger Basin. During the 1997–2004 time period, dLSW became ~0.3°C warmer and 0.04 saltier.

[33] The 1994–1997 patterns show that the LSW layer either is raised toward the near-surface layer (in 1994) or indistinguishable from the latter (in 1996 and 1997) at 38–40°W. This fact corresponds to the recently presented results of the basin-wide analysis of the average (for the period 1989–1997) potential vorticity lateral distribution in the Irminger Sea at 1000 m [*Pickart et al.*, 2003b, Figure 5], according to which the site of the deepest convection is centered east of Cape Farewell at 59–60°N, 38–40°W.

4. Likely Oxygen Signature of Deep Overturning in the Irminger Sea

[34] From the data collected in 1997, a separate lateral maximum of CFC was previously revealed in the density range of LSW within the Irminger Sea mid-depth cyclonic gyre [*Rhein et al.*, 2002]. This maximum was interpreted as a sign of local deep overturning [see *Pickart et al.*, 2003a]. Here we present one more indication that deep convection likely occurred in Irminger Basin before 1997.

[35] Figure 8 shows the oxygen distributions along five WOCE sections carried out in the central Labrador Sea – southern Irminger Sea region in 1997. As seen from Figures 8c–8f, oxygen content in the core of dLSW increases from the Labrador Sea eastern edge toward the southern Irminger Sea. The lowest values (6.82–6.84 ml l^{-1}) in the dLSW core were observed in May 1997 at 44°W. Slightly higher values (6.84–6.86 ml l^{-1}) were observed at A24N and A25 lines in June and August 1997, respectively. And finally, the highest values (6.90–6.95 ml l^{-1}) were detected in the Irminger Sea at 59–60°N in August 1997 (practically the same values were detected at the same latitude during the November cruise of R/V *Professor Shtokman*, see Figure 5c). It should be emphasized that 44°W section was occupied ~3 months earlier than 59–60°N section. Therefore, the less oxygen values in the core at 44°W cannot be explained by the temporal erosion of signal due to oxygen utilization.

[36] The total difference of the maximum oxygen content values in the dLSW core between the 44°W section and 59–60°N Irminger section reaches 0.1 ml l^{-1}, which significantly exceeds the precision of the oxygen measurements. If the high-oxygen signal were advected to the Irminger Basin from the Labrador Sea, the lateral distribution of oxygen content in the dLSW core should have been opposite to the observed one. Therefore, it is reasonable to assume that this signal was produced by the deep convection directly in the Irminger Sea before 1997.

[37] In the central Labrador Sea, below the upper ~700–1000-m-thick oxygen rich (>7 ml l^{-1}) newly ventilated layer [*Pickart et al.*, 2002], the oxygen concentrations of more than 6.90 ml l^{-1} were detected in the deep LSW reservoir (~1300–2200 m) in March 1997 (see Figure 8b, adopted from *Pickart et al.* [2002]). Consequently, two separated oxygen maxima, one on each side of Greenland, were observed in the dLSW layer in 1997 that corresponds to the lateral distribution of CFC in the same year [see *Rhein et al.*, 2002]. It should be noted that existence of the separate oxygen maximum in the Irminger Sea at depths of LSW was earlier mentioned (but not shown) by *Pickart et al.* [2003a].

[38] The question is when the deep oxygen maximum could be produced in the Irminger Basin. Values of 6.90–6.95 ml l^{-1} detected in the dLSW core in 1997 are considerably less than those (about 7 ml l^{-1}) typically observed in the newly ventilated LSW layer in the Labrador Sea (see, e.g., Figure 8b, [*Clarke and Coote*, 1988, Figure 2d]). Consequently, this oxygen maximum could not be produced in winter of 1996/1997. It is also unlikely that deep convection took place during the mild winter of 1995/1996. As was mentioned in section 3.1, the most probable years for the deepest convection in the Irminger Sea were 1993 and 1994 [see *Bacon et al.*, 2003].

[39] Probably, since the winter when the overturning occurred, the high-oxygen signal has been preserved in the Irminger Sea recirculation gyre from quick erosion because of mixing. The fact that oxygen concentrations in the deep LSW reservoir in the Labrador Sea remained more than 6.90 ml l^{-1} at least until 1997 confirms that such scenario is possible.

5. Conclusions

[40] Changes in Labrador Sea Water (LSW) structure and properties occurred in the southern Irminger Basin during the 1991–2004 time period were to a large extent determined by the variability of the LSW core properties in the Labrador Sea. Nevertheless, the events of additional local renewal of LSW in the Irminger Sea are revealed.

[41] Convection in the Irminger Sea influenced the LSW salinity signature observed in 1994. From 1991 to 1994, the LSW layer in the southern Irminger Basin became fresher, while in 1990–1993 salinity of the LSW core in the Labrador Sea noticeably increased.

[42] Since 1996, the two-modal structure of LSW has been observed. The lighter mode of LSW (sLSW) detected in 1996 was formed directly in the Irminger Basin. This water was ~0.2°C warmer, 0.02–0.03 saltier and ~0.02 kg m^{-3} lighter than sLSW observed in the Labrador Sea in the same year. During the winter of 1996/1997, sLSW was renewed in situ.

[43] Restratification in the Labrador Sea started in the mid-1990s, caused the radical change in the LSW layer structure in the Irminger Basin. During the 1991–1997 time period, dLSW dominated in the LSW bulk (before 1996, the LSW structure was one-modal). From 1997 through 2004, temperature and salinity of dLSW drastically increased (by ~0.3°C and 0.04, respectively), the deeper mode thus became significantly less pronounced, and fresher sLSW began to prevail in the LSW layer.

[44] Analysis of the oxygen data collected in the Labrador Sea – Irminger Sea region in 1997 showed that the oxygen values in the dLSW core are significantly higher (by ~0.1 ml l^{-1}) in the southern Irminger Sea than at the eastern periphery of the Labrador Sea. This result allows the assumption that the oxygen signal observed in the Irminger Basin in 1997 was not advected from the Labrador Sea but produced directly in the Irminger Sea by the deep over-

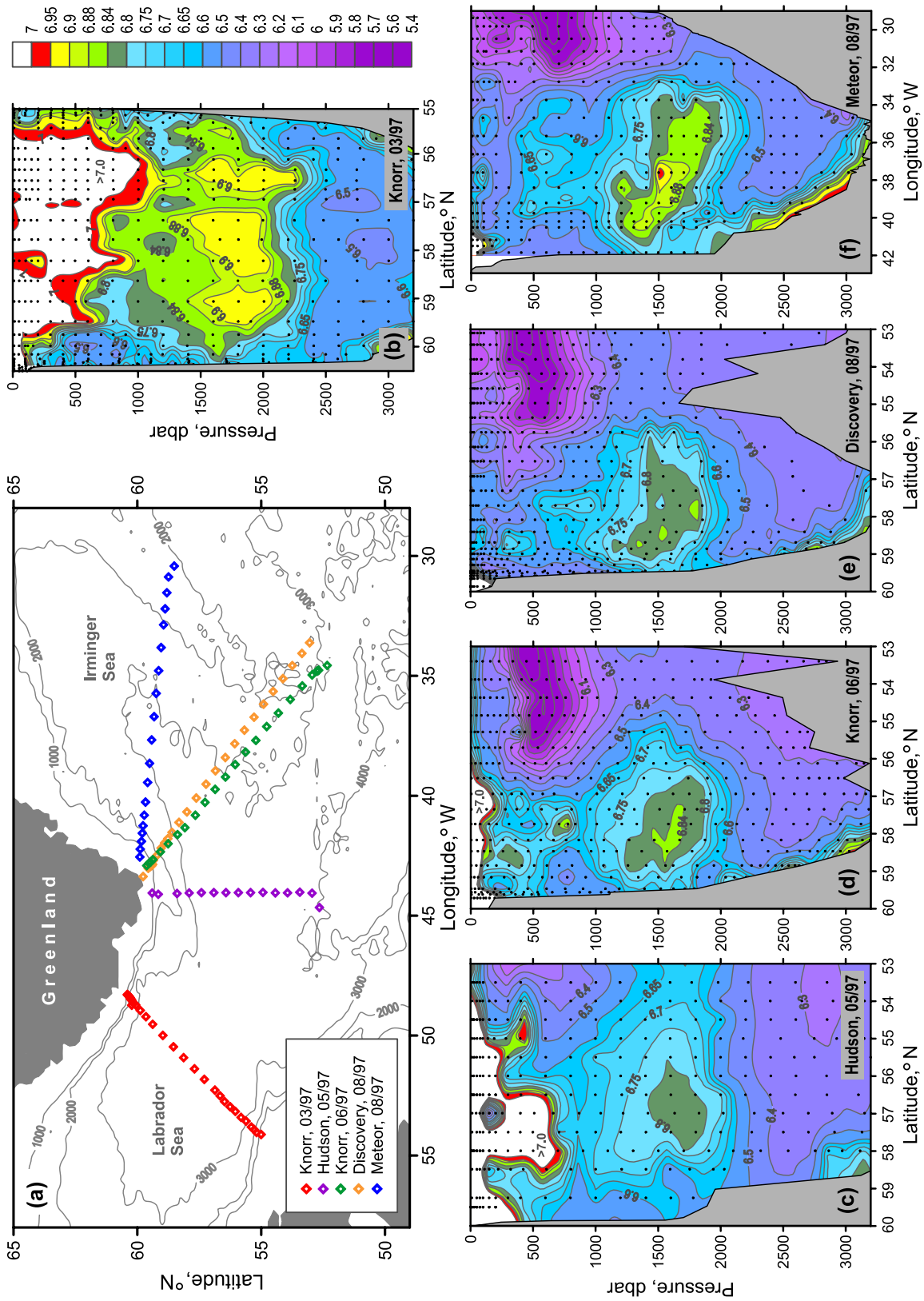

Figure 8. Oxygen content in the deeper LSW core in the Labrador Sea – Irminger Sea region in 1997. (a) Section locations; (b)–(f) vertical distributions of dissolved oxygen concentrations (ml l^{-1}) obtained during the 1997 cruises: *Knorr* 147/5, March (Figure 8b), *Hudson* 97009/1, May (Figure 8c), *Knorr* 151/2, June (Figure 8d), *Discovery* 230, August (Figure 8e) and *Meteor* 39/5, August (Figure 8f); bottle locations are marked with dots. Greenland is on the left in all of the oxygen plots. Figure 8b is adopted from *Pickart et al.* [2002].

turning, likely, during the pre-1995 period of high-NAO conditions.

[45] Comparison of LSW property variations in the Irminger and Labrador Seas showed that the lag time for the LSW signal from the Labrador Sea to reach the Irminger Basin certainly exceeds 6 month and more likely is about 2 years, that agrees with the recent model estimate [*Pickart et al.*, 2003a] based on the "additional source of LSW" concept.

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References

Azetsu-Scott, K., E. P. Jones, I. Yashayaev, and R. M. Gershey (2003), Time series study of CFC concentrations in the Labrador Sea during deep and shallow convection regimes (1991–2000), *J. Geophys. Res.*, *108*(C11), 3354, doi:10.1029/2002JC001317.

Bacon, S., W. J. Gould, and Y. Jia (2003), Open-ocean convection in the Irminger Sea, *Geophys. Res. Lett.*, *30*(C5), 1246, doi:10.1029/2002GL016271.

Bumpke, K., U. Karger, and K. Uhlig (2002), Measurements of turbulent fluxes of momentum and sensible heat over the Labrador Sea, *J. Phys. Oceanogr.*, *32*, 401–410.

Centurioni, L. R., and W. J. Gould (2004), Winter conditions in the Irminger Sea observed with profiling floats, *J. Mar. Res.*, *62*, 313–336.

Clarke, R. A., and A. R. Coote (1988), The formation of Labrador Sea Water. Part III: The evolution of oxygen and nutrient concentration, *J. Phys. Oceanogr.*, *18*, 469–480.

Clarke, R. A., and J. C. Gascard (1983), The formation of Labrador Sea water. Part I: Large-scale processes, *J. Phys. Oceanogr.*, *13*, 1764–1778.

Culberson, C. H. (1991), WOCE operations manual (WHP operations and methods), *WHPO 91/1*, 15 pp., Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Cunningham, S. A., and T. W. N. Haine (1995), Labrador Sea water in the Eastern North Atlantic, Part I: a synoptic circulation inferred from a minimum in potential vorticity, *J. Phys. Oceanogr.*, *25*, 649–665.

Curry, R. G., M. S. McCartney, and T. M. Joyce (1998), Oceanic transport of subpolar climate signals to mid-depth subtropical waters, *Nature*, *391*, 575–577.

Doyle, J. D., and M. A. Shapiro (1999), Flow response to large-scale topography: the Greenland tip jet, *Tellus, Ser. A*, *51*, 728–748.

Fogelqvist, E., J. Blindheim, T. Tanhua, S. Østerhus, E. Buch, and F. Rey (2003), Greenland-Scotland overflow studied by hydro-chemical multivariate analysis, *Deep Sea Res., Part I*, *50*, 73–102.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation, *Science*, *269*, 676–679.

Koltermann, K. P., A. V. Sokov, V. P. Tereschenkov, S. A. Dobroliubov, K. Lorbacher, and A. Sy (1999), Decadal changes in the thermohaline circulation of the North Atlantic, *Deep Sea Res., Part II*, *46*, 109–138.

Lavender, K. L., R. E. Davis, and W. B. Owens (2000), Mid-depth recirculation observed in the interior Labrador and Irminger Seas by direct velocity measurements, *Nature*, *407*, 66–69.

Lazier, J. R. N. (1973), The renewal of Labrador Sea water, *Deep Sea Res.*, *20*, 341–353.

Lazier, J. R. N., R. Hendry, A. Clarke, I. Yashayaev, and P. Rhines (2002), Convection and restratification in the Labrador Sea, 1990–2000, *Deep Sea Res.*, *49*, 1819–1835.

McCartney, M. S. (1992), Recirculating components to the deep boundary current of the Northern North Atlantic, *Prog. Oceanogr.*, *29*, 283–383.

McCartney, M. S., and L. D. Talley (1984), Warm-to-cold conversion in the northern North Atlantic Ocean, *J. Phys. Oceanogr.*, *14*, 922–935.

Nansen, F. (1912), Das bodenwasser und die abkühlung des meeres, *Int. Rev. Gesamten Hydrobiol. Hydrogr.*, *1*, 1–42.

Nielsen, J. (1928), The waters around Greenland, in *Greenland, The Discovery of Greenland, Exploration, and the Nature of the Country*, vol. 1, edited by M. Vahl, pp. 185–230, Oxford Univ. Press, New York.

Pickart, R. S., D. J. Torres, and A. J. Clarke (2002), Hydrography of the Labrador Sea during active convection, *J. Phys. Oceanogr.*, *32*, 428–457.

Pickart, R. S., F. Straneo, and G. W. K. Moore (2003a), Is Labrador Sea Water formed in the Irminger Basin?, *Deep Sea Res., Part I*, *50*, 23–52.

Pickart, R. S., M. Spall, M. H. Ribergaard, G. W. K. Moore, and R. Milliff (2003b), Deep convection in the Irminger Sea forced by the Greenland tip jet, *Nature*, *424*, 152–156.

Rhein, M., J. Fischer, W. M. Smethie, D. Smythe-Wright, R. F. Weiss, C. Mertens, D.-H. Min, U. Fleischmann, and A. Putzka (2002), Labrador Sea water: pathways, CFC inventory, and formation rates, *J. Phys. Oceanogr.*, *32*, 648–665.

Spall, M. A., and R. S. Pickart (2003), Wind-driven recirculations and exchange in the Labrador and Irminger Seas, *J. Phys. Oceanogr.*, *33*, 1829–1845.

Speer, K., and E. Tziperman (1992), Rates of water mass formation in the North Atlantic Ocean, *J. Phys. Oceanogr.*, *22*, 93–104.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming (1942), *The Oceans: Their Physics, Chemistry and General Biology*, 1060 pp., Prentice-Hall, Upper Saddle River, N. J.

Sy, A., M. Rhein, J. R. N. Lazier, K. P. Koltermann, J. Meincke, A. Putzka, and M. Bersch (1997), Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean, *Nature*, *386*, 675–679.

Talley, L. D., and M. S. McCartney (1982), Distribution and circulation of Labrador Sea Water, *J. Phys. Oceanogr.*, *12*, 1189–1205.

Worthington, L. V. (1976), On the Atlantic circulation, *John Hopkins Oceanogr. Stud.*, *6*, 110 pp.

Yashayaev, I. M., R. A. Clarke, and J. R. N. Lazier (2000), Recent decline of the Labrador Sea Water, *CM Doc. 2000/L:18*, 10 pp., Int. Counc. for the Explor. of the Sea, Copenhagen, Denmark.

A. Falina, A. Sarafanov, and A. Sokov, P. P. Shirshov Institute of Oceanology, 36, Nakhimovskiy Prospect, 117997 Moscow, Russia. (sokov@ocean.ru)