Interannual variability of newly formed Labrador Sea Water from 1994 to 2005

Tom Avsic,[1] Johannes Karstensen,[1] Uwe Send,[2] and Jürgen Fischer[1]

Received 16 May 2006; revised 30 August 2006; accepted 12 September 2006; published 19 October 2006.

[1] Mooring records collected in the central Labrador Sea are evaluated regarding the variability of the hydrographic properties of newly formed Labrador Sea Water (LSW) between 1994 and 2005. This time series is longer and of significantly higher temporal resolution than any discussed before in the context of decreasing convection activity. For the upper 1500 m depth range two distinct warming periods are identified from 1997 to 1999 and from 2003 to 2005 leading to a substantial temperature increase of 0.6°C over the recent decade. The time series of LSW source water properties suggest that ocean transport of heat and freshwater anomalies play a significant role in determining the ultimate convection depth. In 2005 the LSW temperature and salinity had reached high values comparable to those from the early 1970's, shortly after the passage of the Great Salinity Anomaly. **Citation:** Avsic, T., J. Karstensen, U. Send, and J. Fischer (2006), Interannual variability of newly formed Labrador Sea Water from 1994 to 2005, *Geophys. Res. Lett.*, *33*, L21S02, doi:10.1029/2006GL026913.

1. Introduction

[2] The Labrador Sea is one of the major deep water formation sites that contribute to the initial composition of North Atlantic Deep Water. Intensive air/sea interaction generates winter mixed layers that occasionally reach deeper than 2000 m [*Lazier et al.*, 2002]. Although convection in the Labrador Sea is dominated by surface heat loss, the preconditioning of the water column with respect to temperature and salinity stratification is important in defining the ultimate late winter mixed layer depth and properties [*Schmidt and Send*, 2006].

[3] Based on historical data and in particular on annual occupations of a hydrographic section crossing the Labrador Sea (WOCE AR7W section, see Figure 1, top right), *Dickson et al.* [2002] reported strong variations in the LSW production over the last 4 decades. Since 1996 convection in the Labrador Sea has been reported to be relatively shallow [*Lilly et al.*, 2003; *Pickart et al.*, 2002], while the first half of the 1990's revealed rather high ventilation [*Lazier et al.*, 2002]. During the less intense convection of the late 90'ies a lighter variant of LSW was formed.

[4] It is this variability in convection depth and formation of Labrador Sea Water that motivated the installation of a 'convection-mooring' in the center of the Labrador Sea (mooring K1 (Figure 1, top right)) near the former OWS BRAVO site. This mooring is located in the area of intense open ocean convection and is equipped with high quality sensors for water mass properties and currents. Here we report on the evolution of the convection depth and the hydrographic properties for the time period from 1994 to 2005. After a presentation of the temperature time series, their interannual variability is described, and annual formation depths are estimated. Source properties of the newly ventilated LSW are estimated directly from winter observations rather than being projected backwards from summer data. The observed variability is then discussed in relation to surface heat fluxes and heat and freshwater anomalies, and is put into the context of long term variability.

2. Data

[5] In summer 1994 an observational program was begun to study convection and its variability in the central Labrador Sea. During the first year instruments were added to the Canadian BRAVO mooring, but in the following years a full convection mooring was deployed near the former BRAVO station (about 25 km distance). The mooring, called K1, is part of a large mooring initiative in the Labrador Sea with also boundary current and tomographic elements. Its location was chosen to be in the center of the convective area which is well illustrated by the float data of *Lavender et al.* [2002] (Figure 1, top right), and is located on the regularly occupied WOCE line AR7W. The mooring was equipped with a variety of sensors for precise temperature and salinity measurements (e.g., Seabird SeaCats and MicroCats), plus other temperature and pressure probes and a number of current meters including ADCP's for measuring vertical motions during convective events.

[6] Temporal resolution of the measurements was between 15 minutes and two hours, and there were up to 15 instruments in the vertical for temperature measurements, with fewer (typically 6) salinity points.

[7] In order to achieve the best possible data quality, Sea/MicroCat's and MiniT's (self-recording temperature/pressure recorder) were calibrated before and after each deployment. For this purpose the instruments are attached to the CTD-rosette and lowered together with the CTD, thereby allowing an accurate calibration of temperature and salinity [*Kanzow et al.*, 2002]. RMS errors of the calibrations are of the order of 5 mK and 0.005, respectively. Differences in pre-deployment and post-deployment calibrations were linearly interpolated over the deployment period, i.e., by assuming a linear drift over the typically one year long deployment. All other temperature sensors (RCM, ADCP, Thermistor Chains and T-sensors on tomography-receivers)

[1] Leibniz-Institut für Meereswissenschaften, Kiel, Germany.
[2] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

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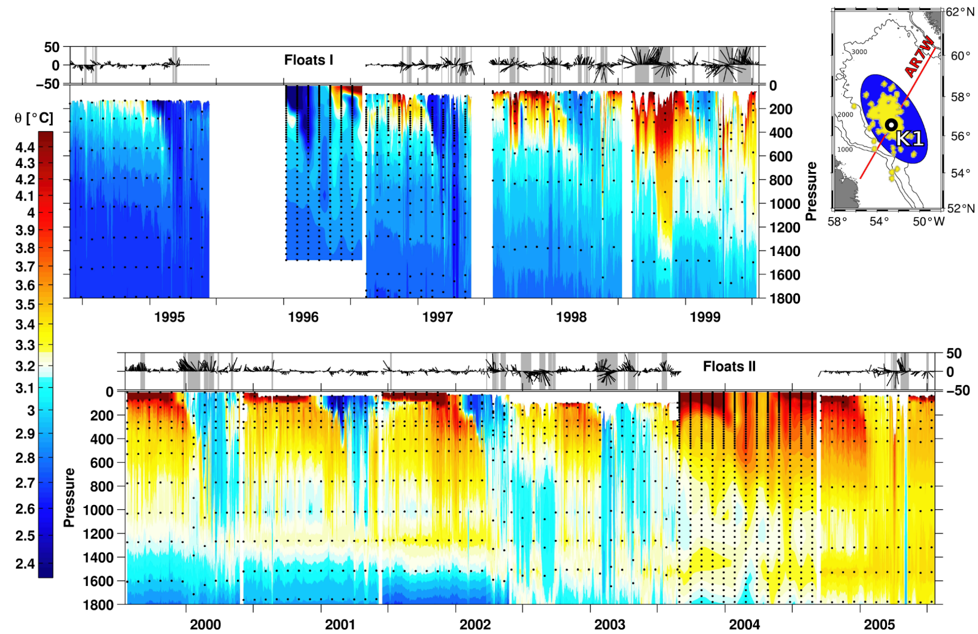

Figure 1. Potential temperature time series (color shading) in the central Labrador Sea based on BRAVO, SFB K1, and float data (Floats I [*Lavender et al.*, 2002], Floats II: ARGO profiling floats). Stickplot of currents at approximately 250 m depth is indicated at top panels, shading indicate periods with current speed larger 20 cm/sec. The black dots in color contour indicate the instruments depth every 30 days. (top right) Map of Labrador Sea with bathymetry (m), mooring position K1 (black and white dot), and AR7W section (red line). Mooring representative float data is indicated by blue ellipse. Yellow dots indicate convection region as given by *Lavender et al.* [2002, Figure 6].

were calibrated against the seacats and microcats, in particular during periods of vertically well mixed water. The K1 mooring was lost from September 2003 to September 2004. This gap was filled by adding data from ARGO floats passing near the mooring position. The region considered for the floats is described by an −40° rotated ellipse with the radii 210 km and 190 km and its center at 56.8°N, 52.4°W (Figure 1, top right). From January 1996 to July 1996 temperature data based on other floats [*Lavender et al.*, 2002] has been added to complete the timeseries. Due to its high vertical resolution, the hydrographic data near the mooring site are used to estimate the final depth of the convectively mixed LSW layer formed in each year.

[8] The atmospheric heat fluxes used are based on the NCEP/NCAR reanalysis data. To account for problems in the atmospheric boundary layer approximation [*Renfrew et al.*, 2002; *Bumke et al.*, 2002] only the radiative fluxes were adopted unchanged, whereas sensible and latent heat fluxes were recalculated according to *Bumke et al.* [2002].

3. Results

3.1. Temperature Time Series

[9] Temperatures are contoured for the upper 1800 m which covers the range of deepest winter convection throughout the whole period (Figure 1). Currents, represented by the shallow (250 m) records of the ADCP's, are generally weak, but are interrupted frequently by intense events of up to 50 cm/s. Due to instrument coverage and occasional mooring excursions during the passage of intense mesoscale eddies (gray shaded periods in the current record) the near surface layer was difficult to resolve and some data gaps occurred, for example in spring 1999 and during 2003. The temperature evolution shows a general warming from a rather cold and vertically homogeneous situation in the mid 1990's to an appreciably warmer water column near the end of the record. This general warming appears to be partially interrupted in 2002 and 2003. Apart from the overall trend, we see pronounced variability on seasonal and shorter time scales. Each winter the mixed layer deepening is clearly seen by cold water extending from the surface to large depth. However, there are some cold water anomalies observed at the mooring site which appear after the end of the cooling period (e.g., in summers 1999, 2002, and 2003) and which reach deeper than the locally generated mixed layer. This is water trapped in mesoscale features which are accompanied by strong current events (Figure 1). The cold anomalies are expected to survive for extended periods [*Lilly et al.*, 2003] and may undergo a further local deepening process through buoyancy loss at the surface. Similarly to the cold anomalies, there are warm anomalies passing by the mooring site presumably originating from the West Greenland current [*Lilly et al.*, 2003]; the most intense one is seen in October/November 1998. The convection depth at the mooring location, which already can be roughly estimated from Figure 1, varies between 1000 m to 1400 m and is much shallower than observed in the first half of the 1990's when convection occasionally exceeded 2000 m [*Lazier et al.*, 2002]. A distinct subsurface temperature maximum appears in the late 1990's at 1200 m and is present up to the end of the record but at greater depth of about 1600 m (for discussion, see *Karstensen et al.* [2006]).

[10] The final stage of water mass renewal through convection can be identified every year to occur approximately in late March/April through a deep mixed layer with

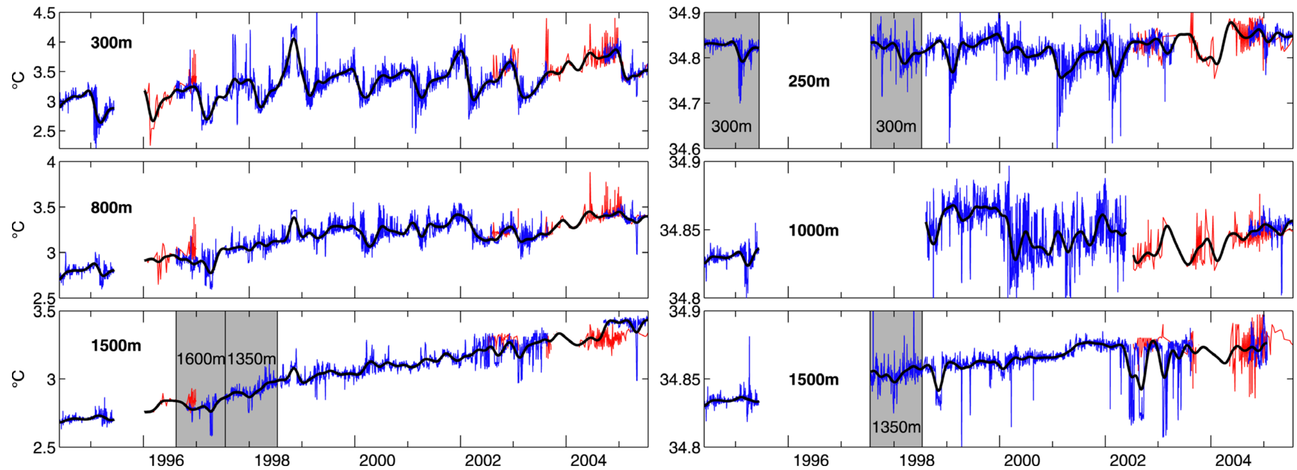

Figure 2. (left) Potential temperature observations in nominal (top) 300 m, (middle) 800 m, and (bottom) 1500 m depth (blue line). (right) Salinity observations in nominal (top) 250 m, (middle) 1000 m, and (bottom) 1500 m depth (blue line). Bold black line indicates the 100 day low pass filtered time series. Data gaps have been filled with either the instrument nearest to the nominal depth (see shaded areas for depth of this inserted instrument and time interval). In addition float data close to the mooring were used (red lines).

rather homogeneous cold waters from the surface to intermediate depth. After this phase, the spring restratification occurs quickly and warm and saline waters enter the gyre occupying the upper 600 m of the water column, in some cases reaching even deeper.

3.2. Interannual Temperature and Salinity Variability

[11] The interannual temperature variability of the central Labrador Sea can roughly be divided in three regimes: the upper 500 m, an intermediate region extending to 1200 m, and the deep layer beneath that. The upper regime shows strong seasonal variations due to gradually deepening convection phases and subsequent rapid restratification (Figure 2, top left). Superimposed on the seasonal saw-tooth like behaviour is a temperature trend. For the instrument at nominally 300 m depth this trend is about 0.05°C yr^{-1}. The salinity at 250 m (Figure 2, top right) reveals a pulse like salinity decrease at the beginning of each year but its amplitude, timing and the background salinities show large interannual variability. In the intermediate regime, the temperature evolution (Figure 2, middle left) reveals a warming trend from 1997 to 1999 from about 3.0°C to 3.3°C. The following years (until 2003) were rather stable in temperature while at the end of the record (2003 to 2005) again the temperature starts to increase further by about 0.1°C. The salinity time series at nominally 1000 m depth (Figure 2, middle right) shows periods of gradually increasing values, that are, however, interrupted and 'reset' by an abrupt decrease in early 2000.

[12] In 1500 m depth, an intense and rather constant warming (0.06°C yr^{-1}) and salinity increase (0.005 yr^{-1}) is observed (Figure 2, bottom left and right). These records are made in the depth range of the classical LSW which have not been ventilated after 1994. The observed warming is part of a large scale warming and is also found in the Labrador boundary current at the exit of the Labrador Sea near 53°N [*Dengler et al.*, 2006] and at the tail of the Grand Banks near 42°N [*Schott et al.*, 2006].

3.3. LSW Formation Depth and Source Properties

[13] The depth of annual LSW formation and the source properties of the convectively renewed waters are derived based on hydrographic survey data and on the moored observations, in order to quantify the interannual variability and provide a reference for other studies of this water mass further downstream. Estimates of the depth penetration of the LSW are guided by the 'classical indicator', a minimum in potential vorticity (PV) [*Talley and McCartney*, 1982]. PV is calculated using CTD data from $PV = f/\rho \, d\rho/dz$, with f the planetary vorticity and ρ the sea water density. For the maximum depth of the LSW layer it is justified to use summer hydrographic data since the homogeneity of the water is preserved through the re-stratification and modifications of the convectively renewed water through lateral mixing. In contrast, the LSW source *properties* need to be derived at the end of the convection season and just before modifications through lateral mixing. Here the high temporal resolution of the mooring data is of benefit. The homogeneity of the water column at the end of the convection season compensates for the rather coarse vertical resolution of the moored measurements. Care is necessary in dealing with the appearance of cold and warm core eddies at the mooring site (as indicated in Figure 1). The eddies carry properties which are not representative for the gyre as a whole (which is what we define as LSW) and have been excluded from our analysis. In particular in 1997 and 2003 the convection time series were perturbed by the appearance of cold core eddies at the site which could lead to an overestimate of the convection depth (and underestimate of the temperature) of the newly formed LSW volume.

[14] A summary of the LSW layer depth and source properties is given in Table 1. By having access to late winter data, the LSW source properties derived here differ substantially from estimates based on (typically summer) hydrographic survey data [e.g., *Azetsu-Scott et al.*, 2003]. Although we think our analysis is more precise in determining the original LSW properties, a caveat lies in the fixed location of the mooring which may not be exactly in the center of convection.

Table 1. Mean Water Properties Within the Water Column From 400 m to the Convection Depth at LSW Formation Time[a]

Year	Convection Depth	Θ LSW	S LSW
1995	2300	2.68 (±0.05)	34.82_3 ± 0.016
1996	1300		
1997	1400	2.81 (±0.07)	34.82_7 (±0.016)
1998	1000	2.96 (±0.10)	34.82_8 (±0.018)
1999	1000	3.16 (±0.05)	34.83_4 (±0.014)
2000	1100	3.06 (±0.06)	34.81_3 (±0.012)
2001	1100	3.16 (±0.07)	34.82_1 (±0.021)
2002	1200	3.22 (±0.11)	34.83_5 (±0.024)
2003	1400	3.22 (±0.08)	34.83_7 (±0.017)
2004	700		
2005	1300	3.42 (±0.07)	34.85_7 (±0.006)

[a]Formation time is end of March. Numbers in brackets denote the standard deviation. The 1995 to 1996 data is BRAVO mooring data. Note, 1996 and 2004 is based on float data and some CTD stations only. Due to rapid change of the Θ*S* properties with time, it is not possible to give accurate values for the float periods.

[15] Convection depth in the early 1990's had been documented to be of order 2000 m with a maximum of 2300 m in 1993 and 1995 [*Pickart et al.*, 2002; *Lilly et al.*, 2003]. The 1995 to 1999 period is not described consistently in the literature. *Lazier et al.* [2002] found convection depths of ~1000 m for all years, *Yashayaev et al.* [2003] less than 1500 m, whereas *Lilly et al.* [2003] reports depths similar to our results. Not much is documented for the time period 2000 to 2005. In the year 1995 we found the last convection events exceeding 2000 m followed by two years with convection depth to 1300 m and 1400 m. During the period 1998 to 2002 convection depth was shallow (order 1000 m) with a slight increasing trend to 1200 m. The shallowest convection depth was found for 2004 but, as the mooring was lost from September 2003 to September 2004, this is based on ARGO float data and the hydrographic surveys only. 2002 and 2004 convection reached again 1300 m and 1400 m, however with waters more than 0.5°C warmer than 1996/1997.

[16] The LSW source properties underwent a two step increase in temperature: after being coldest (2.68°C) in 1995, a rather linear increase to 3.16°C in 1999 occurred. A period of stable LSW temperatures between 3.06°C to 3.22°C followed from 2000 to 2003 with another dramatic increase in 2005 to 3.42°C (omitting the ARGO float data period). The source water salinity behaved different from temperature: salinity was approximately constant (~34.83) from 1995 to 1998, followed by a decease to 34.81 in 2000, and then slowly increased again to 34.86 (the highest in our record) in 2005. The variability in LSW source water properties carries an integrated signature of advected and entrained temperature and salinity anomalies as well as variability in heat and freshwater flux at the air/sea inter-

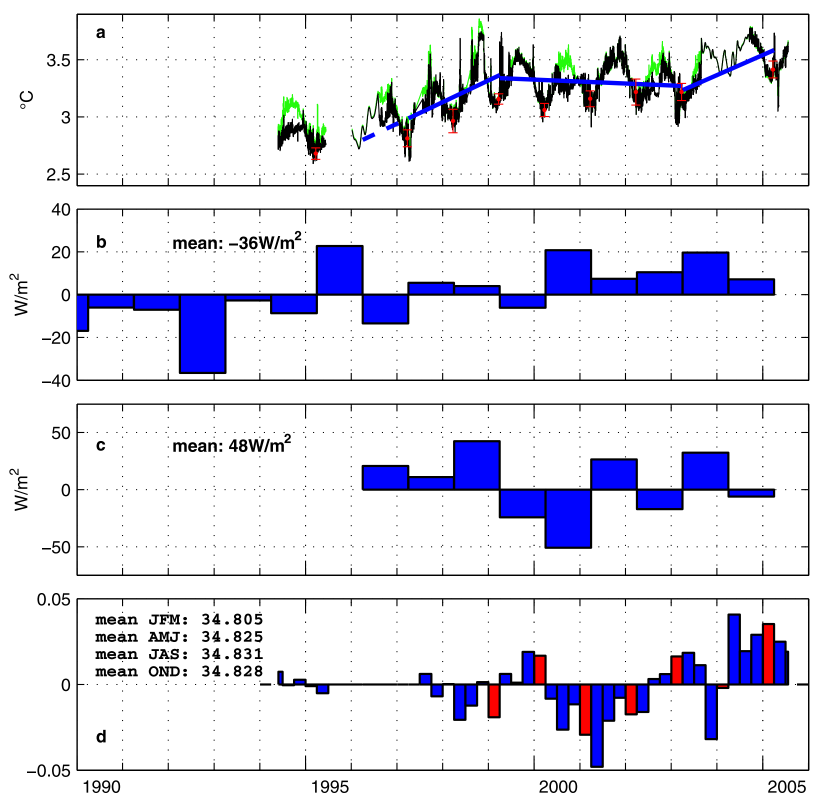

Figure 3. (a) Mean temperature over the upper 1500 m as observed at K1 (black line) and supplemented with upper layer data from floats (green line). In addition, source properties of the LSW (red dots with bars) and trends (blue lines) calculated for the first (04/1997 to 03/1999) and second (04/2003 to 03/2005) warming and the transition period (04/1999 to 03/2003). (b) Heat flux anomaly over the central Labrador Sea based on recalculated [*Bumke et al.*, 2002] NCEP/NCAR reanalysis data. Neighbouring grid points have been linearly interpolated to the mooring position. (c) Heat flux via horizontal advection (see text for details). (d) Salinity anomaly at nominal 250 m depth based on Figure 2 (left, upper). Red bars denote winter (JFM) month.

face. In particular during the period with rather constant temperatures, from 1999 to 2002, the freshening of the source waters documents that anomalously high freshwater content could have hampered deeper convection to occur.

3.4. Discussion

[17] The warming periods as well as its seasonal modulation discussed above are well captured in the vertically averaged temperature of the upper 1500 m (Figure 3a). Most of the warming in late spring and summer occurs in a rather thin surface layer which is often not well resolved by the moored instruments. In order to minimize the errors from not resolving the near surface layer as a result of the mooring configuration, an average seasonal temperature cycle was derived from the ARGO float data and used to fill the surface gaps.

[18] Similar to the temperature time series at individual depths, the vertically averaged temperature shows an overall increase of about 0.6°C for 1996 to 2005. Again this is composed of a warming of about 0.19°C yr^{-1} from 04/1997 to 04/1999 and of about 0.17°C yr^{-1} from 04/2003 to 04/2005. From 04/1999 to 04/2003 the average temperature trend was small and maybe slightly decreasing (order −0.02°C yr^{-1}).

[19] In order to address the cause of the warming and its variability, it is useful to separate anomalous surface forcing from anomalous ocean heat transport. The NCEP/NCAR reanalysis data based annual average (April to March; to be in phase with convection activity) heat flux over the central Labrador Sea is about −36 Wm^{-2} for the 04/1990 to 03/2005 period. Considering only the period 04/1996 to 03/2005 it reduces to −30 Wm^{-2} and agrees with earlier estimates [e.g., *Lilly et al.*, 2003]. The time-varying component of the heat flux (here shown as the anomaly) (Figure 3b) only partly shows similarities with the evolution of the heat content, in particular with the two warming periods. In the first half of the 1990's above average (more negative) heat loss is found and coincides with the more intense convection activity reported for this period [e.g., *Lazier et al.*, 2002]. Since spring 1997 weaker than average heat loss can be seen, in particular during the 2000's. The heat flux through ocean transport is derived from the difference between the surface heat flux and the change in heat content over the upper 1500 m (Figure 3c). The average ocean heat transport is 48 Wm^{-2} and agrees with earlier estimates, based in part on the same mooring data [*Lilly et al.*, 2003] and based on float data from 1996–2000 [*Straneo*, 2006]. The residual between average ocean heat transport and atmospheric heat loss (−30 Wm^{-2} for the K1 mooring period) is 18 Wm^{-2} and equals the accumulation of heat in the gyre. We attribute this 'accumulation' to the existence of the subsurface temperature maximum which, as a consequence of the stratification, is responsible for an anomalous amount of heat kept in the gyre. In spite of considerable uncertainties in these values, for the warming period from 1996 to 1999 anomalous ocean heat transport was likely the major factor which is also the case for the second warming period from 2003 to 2005. A similar conclusion was arrived at by *Straneo* [2006] for the years 1996 to 1998. However, as she limits her study to the upper 1300 m she misses part of the accumulated heat, in particular after 1999 where a subsurface temperature maximum is located at 1300 m. The instrumentation of the mooring does not allow conducting a comprehensive freshwater budget. However, averaged over 3 months salinity observations at 250 m depth agree rather well with the LSW source water salinity variability (Table 1). Again a period of anomalous freshwater import from 2000 to 2002 can be seen and a strong positive anomaly (saltier water) occurs since mid 2004 to the end of the record. Very likely the salinity decrease from 2000 to 2002 reduced convection while in 2004 to 2005 the salinity anomaly could support convection even with a yet warmer LSW blend.

[20] The average temperature for the depth range 1000 to 1500 m is 3.36°C in 2005 and the warmest on record after a peak in the mid 1960's and the mid 1970's [e.g., *Sy et al.*, 1997]. The average salinity of this depth range (34.86 from the CTD survey data in September 2005) is comparable with the situation after the 'Great Salinity Anomaly' had propagated through the Labrador Sea (mid 1970's) and thus is 0.02 lower compared to the mid 1960's which had a similarly high temperature [*Sy et al.*, 1997]. *Dickson* [1997] suggested the timing of deep convection in the Labrador Sea to be out of phase with the timing of deep convection in the Greenland Sea and intensive Mode Water formation in the Sargasso Sea. As deep convection in the Labrador Sea has been found to be rather sluggish for the last decade one might thus expect an increase in convection activity in the Greenland Sea and Mode Water formation in the Sargasso Sea. At least for the Greenland Sea this has not been observed [e.g., *Karstensen et al.*, 2005]. However, one fundamental difference in the large scale atmospheric state is in the NAO high phase during the 1990's/2000 and NAO low phase during the Great Salinity Anomaly years (1960/1970's). It is thus possible that the timing of convection activity in the tripole (Greenland, Labrador, and Sargasso Sea) is modulated by what is responsible for the interannual variability of the NAO. Very likely the advection of heat and freshwater anomalies play the governing role.

[21] **Acknowledgments.** This study was supported by the Deutsche Forschungsgemeinschaft in the framework of Sonderforschungsbereich 460 Dynamik thermohaliner Zirkulationsschwankungen (TPA2). The NCEP/NCAR reanalysis data was provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/. The ARGO float data were collected and made freely available by the International Argo Project and the national programs that contribute to it. (http://www.argo.ucsd.edu, http://argo.jcommops.org). Argo is a pilot program of the Global Ocean Observing System. We thank Karl Bumke and Ian Renfrew for the support on the surface heat flux calculations. Comments from two anonymous reviewers are acknowledged.

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T. Avsic, J. Fischer, and J. Karstensen, Leibniz-Institut für Meereswissenschaften, Düsternbrooker Weg 20, D-24105 Kiel, Germany. (tavsic@ifm-geomar.de; jfischer@ifm-geomar.de; jkarstensen@ifm-geomar.de)

U. Send, Scripps Institution of Oceanography, Mail Code 0230, University of California, San Diego, La Jolla, CA 92093-0230, USA. (usend@ucsd.edu)