



Changes in the pool of Labrador Sea Water in the subpolar North Atlantic

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[1] Measurements of chlorofluorocarbon inventories during 1997–2003 allow the detection and quantification of significant changes in the formation rates of two modes of Labrador Sea Water (LSW): Upper (ULSW) and deep LSW, both here defined in fixed density intervals. Both modes contribute to the cold limb of the Meridional Overturning Circulation. Results reveal that the lighter ULSW formed since the mid-1990s has started to replace the large pool of the deep LSW stored in the western North Atlantic. Formation of deep LSW was absent in 1997–2003. Formation of ULSW compensated for this absence during 1998/99 (7.9 Sv), but afterwards significantly declined to 2.5 Sv. The decrease of the overall LSW formation throughout 1997–2003 correlates with a declining eastward baroclinic mass transport between the centers of the subpolar and subtropical gyres since 1997, a warming of LSW, and a gradually decreasing North Atlantic Oscillation index after 1999. **Citation:** Kieke, D., M. Rhein, L. Stramma, W. M. Smethie, J. L. Bullister, and D. A. LeBel (2007), Changes in the pool of Labrador Sea Water in the subpolar North Atlantic, *Geophys. Res. Lett.*, 34, L06605, doi:10.1029/2006GL028959.

1. Introduction

[2] Evidence from sedimentary records suggests that the Atlantic Meridional Overturning Circulation (MOC) had almost ceased at various times in the geological past. These shut-downs were linked to abrupt climate changes [McManus *et al.*, 2004]. Numerical simulations indicate a link between the formation rate of Labrador Sea Water (LSW) and the strength of the MOC [e.g., Getzlaff *et al.*, 2005; Marsh *et al.*, 2005; Böning *et al.*, 2006]. As a response to global warming, climate models predict a declining MOC caused by decreasing LSW formation. These connections between LSW formation and climate changes make it highly desirable to monitor changes in the formation rate of dense water produced in the Labrador Sea. Two modes of LSW exist, deep (sometimes called ‘classical’) LSW and the less dense upper LSW (ULSW) [Pickart *et al.*, 1996, 1997; Stramma *et al.*, 2004; Kieke *et al.*, 2006]. The formation of both occurs by wintertime oceanic convection in the Labrador Sea, where an

increase in the density of near-surface waters leads to vertical homogenisation of the water column to depths of 200–2000 m. The intensity and extent of the convective process is strongly related to the background density stratification in the water column and to the strength of the atmospheric forcing [Dickson *et al.*, 1996; Curry *et al.*, 1998; Lazier *et al.*, 2002]. Throughout the last decades, the atmospheric forcing in the subpolar North Atlantic (SPNA) showed strong fluctuations, reflected by the North Atlantic Oscillation (NAO) [e.g., Dickson *et al.*, 1996]. During the early 1990s an anomalous high heat loss to the atmosphere occurred in the central Labrador Sea, and the convective overturning penetrated through the water column down to more than 2000 m [Lazier *et al.*, 2002]. This initiated the formation of the thickest layer of the deep LSW observed in the past 60 years [Curry *et al.*, 1998]. In the subsequent years, the formation of this mode was shut down [Lazier *et al.*, 2002]. First evidence that - although deep LSW formation had ceased - convection did continue in the central Labrador Sea and produced the lighter ULSW was found in the western Labrador Sea during the second half of the 1990s [Azetsu-Scott *et al.*, 2003; Stramma *et al.*, 2004]. Decadal time series of layer thicknesses of both LSW types indicated that ULSW is a quite prominent product of the convection activity in the Labrador Sea [Kieke *et al.*, 2006] and, as several studies have shown before, the formation of deep LSW as observed in the early 1990s is rather the ‘unusual’ than the ‘usual’ condition.

[3] Chlorofluorocarbon (CFC) components like CFC-11 and CFC-12 enter the surface ocean by air-sea gas exchange. The transformation of CFC-tagged surface water into deeper water during the convective processes produces a CFC maximum in mid-depths. The more intense the convection, the more CFCs are imported, leading to an increase in the CFC inventory of the respective water mass. Since the mid-1990s several research groups have collaborated in a major initiative to demonstrate the use of repeated measurements of CFC inventories to infer time series of water mass formation rates [e.g., Smethie and Fine, 2001; Rhein *et al.*, 2002]. Kieke *et al.* [2006] applied this method successfully to CFC-11 inventories of ULSW in the period 1997–2001. In this study we use CFC-12 inventories of ULSW and deep LSW to estimate changes in the formation rates of both water masses in the period 1997–2003 and compare the decline in the pool of deep LSW to changes in the upper circulation of the subpolar North Atlantic during this period.

2. Data and Methods

2.1. CFC-12 Inventories

[4] In the present study, we follow Stramma *et al.* [2004] and define ULSW and the deeper LSW as water layers in the

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density range $\sigma_\theta = 27.68\text{--}27.74\text{ kg/m}^3$ (ULSW) and $\sigma_\theta = 27.74\text{--}27.80\text{ kg/m}^3$ (LSW). A number of studies have pointed to interannual changes in the core properties of LSW in recent years [e.g., *Avsic et al.*, 2006] (hereinafter referred to as AV06). Based on T/S values given by AV06, the mean density of water in the water column from 400 m down to the convection depth (typically 1000–1400 m during 1997–2003) ranged from $\sigma_\theta = 27.764\text{ kg/m}^3$ to $\sigma_\theta = 27.727\text{ kg/m}^3$. The fixed densities chosen in our study thus encompass the deep LSW, but take a larger part of the upper water column into account.

[5] The methodology applied to map and extrapolate the inventories and to estimate the uncertainties closely follows the works of *Rhein et al.* [2002] and *Kieke et al.* [2006]. We mapped the large-scale CFC-12 inventories of both water masses in the subpolar North Atlantic in 1997, 1999, 2001, and 2003 by extrapolating the data on a 0.5° longitude by 0.25° latitude grid using a topography-following mapping scheme. The chosen correlation length scale is 224 km to make certain that regional data gaps are closed and the total inventory is not significantly underestimated. In this sense, the CFC-12 inventory of a water mass is the average CFC-12 concentration C_{ij} in each water mass at a particular location $lat(i)$, $lon(j)$, multiplied by the respective layer thickness D_{ij} and the area of a grid cell A (see equation (1)). During some cruises carried out in 2003, there were analytical errors related to the measurement of CFC-11, while in 1997 some CFC-12 measurements suffered from contamination during particular cruises. In order to avoid switching between the CFC components, the CFC-12 distribution of 1997 was constructed by assuming a fixed CFC-11/CFC-12 ratio of 1.95. This ratio was inferred from those profiles for which both components were analysed successfully. Tests with tracer data from 1999 and 2001 were made when both components were available. They showed only small deviations in the original and reconstructed CFC-12 distributions and the calculated formation rates. Using 1999 data, inventories calculated either from the measured CFC-12 concentrations or derived from assuming a fixed CFC-11/CFC-12 ratio differed by less than 1%. This holds for both water masses. A similar comparison for data from 2001 showed an inventory difference of 1.2% for ULSW and 6.6% for deep LSW. The larger differences determined from the 2001 inventories might point to changing trends in the atmospheric history of both components which may affect the ULSW layer. For the years 1999–2003 the formation rates were calculated from the measured CFC-12 inventories.

[6] Uncertainties in the inventories were estimated using a jackknifing-procedure. We randomly removed 50% of the samples and calculated 100 different inventory distributions for each year and LSW mode. The greatest observed uncertainties are in the order of $\pm 0.3\text{--}0.6$ million moles.

2.2. Water Mass Formation Rates

[7] Water mass formation rates R (Sv) for the subpolar North Atlantic are derived from changes in the CFC-12 inventories between two particular years t_1 and t_2 :

$$R = \frac{\rho \sum_{ij} (C_{ij} A D_{ij})(t_2) - \rho \sum_{ij} (C_{ij} A D_{ij})(t_1)}{\rho \int_{t_1}^{t_2} [C_{eq}(t) \times sat] dt} \quad (1)$$

where ρ is the density of water, $C_{eq}(t)$ is the CFC-12 concentration that is in equilibrium with the atmosphere, sat is the degree of saturation of newly formed LSW, and C_{ij} , A , D_{ij} are as defined previously. Basic assumptions made are: (1) Convection is the only formation process, introducing all CFCs observed in this water mass. (2) The CFC export out of the subpolar North Atlantic within 2 years (the time period between two repeated surveys) is reasonably small, and the loss of CFCs by vertical mixing is negligible. (3) The CFC saturation between surface water and atmosphere, before convection starts, is 85% [*Kieke et al.*, 2006]. The CFC distributions in the subpolar North Atlantic were measured in two year intervals (Figures 1 and 2), so this is the shortest time scale for which we can infer changes in water mass formation. Uncertainties of formation rates were estimated by considering the inventory uncertainties derived from the jackknifing procedure (Figure 2). Changing the assumed saturation sat by $\pm 10\%$ yielded an additional uncertainty of $\pm 13\%$. Given error bars related to formation rates take these two effects into account.

2.3. Baroclinic Mass Transport Index

[8] *Curry and McCartney* [2001] (hereinafter referred to as CM01) derived an index for the eastward baroclinic mass transport (BMT) in the upper 2000dbar range between Station “S” at Bermuda and the central Labrador Sea. The index is calculated as the difference in the potential energy anomaly derived from respective hydrographic profiles at these locations. It can be considered as an oceanic analogue to the atmospheric NAO index which is derived from sea level pressures. The original time series provided by CM01 ended in 1997 and was extended here to 2003 by recent data from Station “S” and the Labrador Basin.

3. Results

[9] CFC-12 inventories of ULSW and deep LSW for the period 1997–2003 (Figure 1) clearly indicate that the tracer inventory of ULSW increased with time, while the respective inventory of deep LSW significantly decreased. In 1997 (Figure 1a), the highest inventory of the ULSW layer was found in the boundary current region of the Labrador Sea. The maximum was subsequently shifted into the central Labrador Sea and increased with time (Figures 1b–1d). The inventory increase was mostly limited to the western subpolar North Atlantic, but some had also reached the eastern Atlantic west of 20°W . In 2003 (Figure 1d), the CFC-12 inventory maximum in the ULSW layer extended from the Labrador Sea along the western boundary to 45°N .

[10] The 1997 inventory of the deeper LSW was more than three times higher than the 1997 inventory of ULSW (cf. Figures 1a and 1e) and had its maximum in the central Labrador Sea. This large difference is caused by the phase of intense production of deep LSW in the early 1990s, with presumably minor ULSW formation [*Pickart et al.*, 1996, 1997]. There was enough time for deep LSW formed during the intense convection periods to carry its CFC signal across the entire subpolar North Atlantic north of 45°N (Figure 1e) by 1997. The evolution of the tracer inventory in the subsequent years (Figures 1f–1h) is consistent with a shut-down of deep LSW production since 1994, and the well-known spreading of LSW out of its formation region

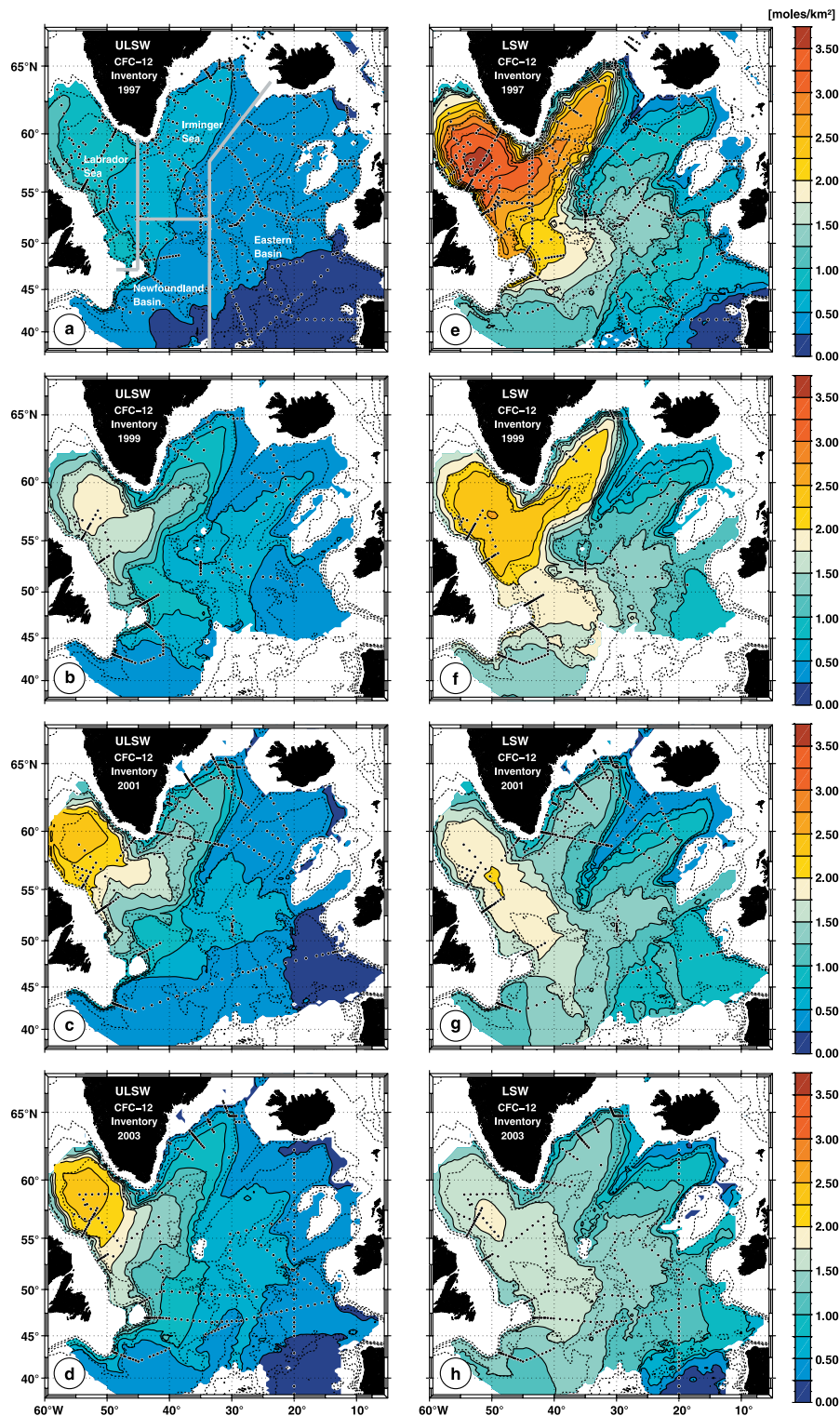


Figure 1. CFC-12 inventories [moles/km^2] of (left) ULSW and (right) deep LSW for (top to bottom) 1997, 1999, 2001, and 2003.

[Talley and McCartney, 1982; Sy *et al.*, 1997]. The subpolar and regional CFC-12 inventories of ULSW (Figure 2a) indicate that the invasion of higher CFC inventories into the Irminger Sea and the Newfoundland Basin and the strong increase in the Labrador Sea can only be explained by recent formation of ULSW in the region of the maximum

and the export of this water mass out of the formation region. The data do not exclude ULSW formation in the southern Irminger Sea [see Pickart *et al.*, 2003], but the Labrador Sea is by far the dominating source region. The total inventory of deep LSW (Figure 2b) did not change much, but the fraction remaining in the Labrador Sea

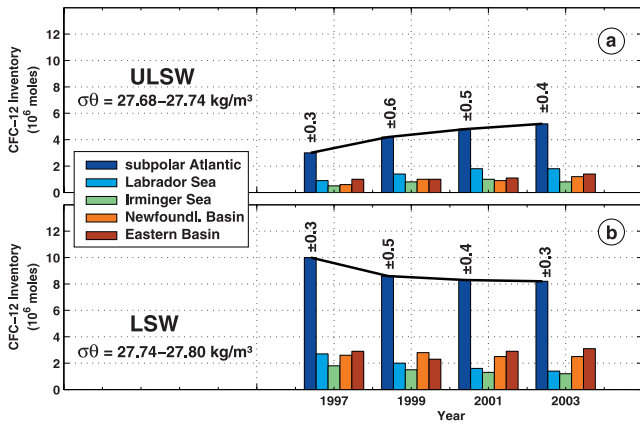


Figure 2. Subpolar and regional CFC-12 inventories of (a) ULSW and (b) deep LSW. Uncertainties were derived using a jackknife-procedure, see text. For geographical regions see Figure 1a.

decreased significantly. The highest fractions of the inventory are now stored in the Newfoundland Basin and in the Northeast Atlantic (Figure 2b). The latter contains the highest values in 2001 and in 2003 (Figures 1g, 1h, and 2b). From Figures 1 and 2 it is evident that there was no significant formation of deep LSW in the period 1997–2003 since the total CFC-12 inventory continuously decreased. In the years 1998–1999, the production of ULSW was high (7.9 ± 1.0 Sv; compare Figure 3), more than twice the decade long ULSW average of 3.2 Sv. The enhanced production of ULSW essentially compensated for the shut-down in formation of deep LSW. Hence, the pool of deep LSW normally present in the western subpolar North Atlantic declined as it was progressively replaced by ULSW. In 2000–2001, the formation of ULSW decreased to 4.0 ± 0.5 Sv, and in 2002–2003, only 2.5 ± 0.3 Sv of ULSW were produced (Figure 3b). The ULSW formation rates for the years 1998/1999 and 2000/2001 derived from CFC-12 inventories are in good agreement with earlier estimates based on the tracer CFC-11 [Kieke *et al.*, 2006]: 1998/99: 6.9–9.2 Sv, 2000/01: 3.3–4.7 Sv.

[11] We further compared our time series of ULSW formation with the NAO index and the extended transport index originally derived by CM01 (Figures 3a and 3b). The latter can be considered as a proxy for the strength of the upper circulation. We also added an LSW temperature time series from AV06 which indicates a gradual warming of LSW in the formation region throughout the last decade. Although the temporal resolution for the respective time series is different, there are similarities in the respective trends of the transport index and the formation rates. The decline of transport from 70 megatons per second (~ 68 Sv) in 1995 to well below 60 megatons per second (~ 58 Sv) in the late 1990s/early 2000s correlates with the decline in the ULSW formation rates, with the caveat that there are few points to compare. The reduced ULSW formation after 1999 also correlates with a general decrease in the strength of the NAO and the warming trend in the LSW temperatures. Though we are aware that our investigation period is quite short, LSW-temperatures and the BMT-index (Figures 3a and 3c) are highly negatively correlated ($r = -0.80$)

during 1997–2003. The highest correlation between the BMT-index and the NAO is $r = -0.83$, with the NAO leading by 1 yr.

4. Discussion

[12] Evidence that the lighter ULSW has started to replace the deep LSW since the mid-1990s suggests a relation to climate-relevant changes in the ocean. With a possible link to global warming, the deep water in the North Atlantic became significantly less saline throughout the last four decades [Dickson *et al.*, 2002], accompanied by a salinity increase in the upper water layers of the lower latitudes [Curry *et al.*, 2003]. Häkkinen and Rhines [2004] (hereinafter referred to as HR04) inferred a decline of the subpolar North Atlantic circulation in the 1990s from long-term changes in the sea surface height which could be confirmed by high-resolution model studies [Hátún *et al.*, 2005; Böning *et al.*, 2006]. From moored instruments recording a deep velocity time series in the Labrador Sea, HR04 concluded that the weakening convective forcing in the Labrador Sea and the observed decline in the strength of the subpolar gyre are connected. The cessation of deep LSW production, the trends of the ULSW formation rate and the transport index (Figure 3) support this view.

[13] On the other hand, transport estimates (LSW and deep water) based on moored instruments in the boundary current region of the Newfoundland Basin did not show a

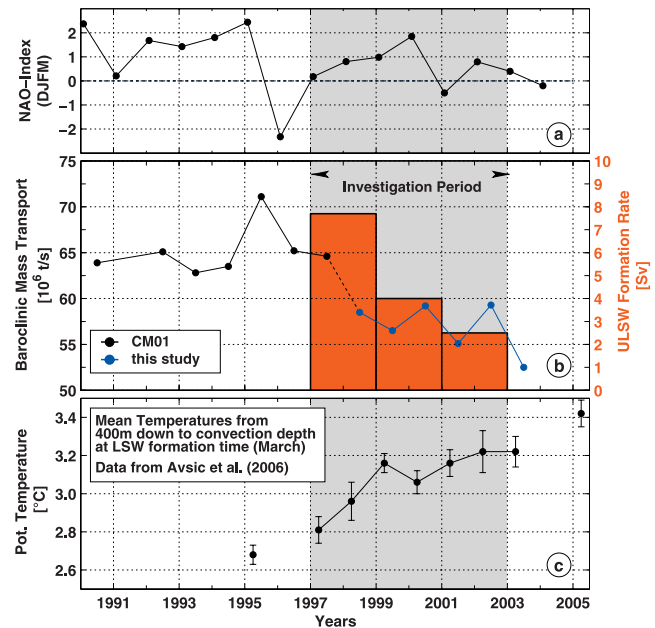


Figure 3. (a) Winter mean NAO index (DJFM) following Jones *et al.* [1997]. (b) Extended mass transport index [Mega tons per second] representing the eastward baroclinic mass transport between the central Labrador Sea and station “S” at Bermuda, pressure range: 0–2000 dbar. Black dots mark estimates from Curry and McCartney [2001], blue dots indicate extensions made in this study. ULSW formation rates (Sv) are included as red bars. (c) Temperature time series of LSW source water properties derived by Avsic *et al.* [2006] from central Labrador Sea hydrographic data.

weakening of the deep circulation, and the deep water transport seemed unaffected by changes in the LSW formation rates [Schott et al., 2004]. Dengler et al. [2006] discuss an index of LSW export at 53°N/56°N for the period 1996–2005, which shows interannual to decadal export variability in the deep Labrador Current at 1500 m of the order of 15% of the mean speed. Furthermore, the results point to an increase of LSW export out of the formation region during the late 1990s to 2001–2005 which the authors found to be in contrast to the results by HR04. From model studies Böning et al. [2006] suggested a correlation between LSW formation and changes in the strength of the Atlantic MOC. They interpreted the decline of the subpolar gyre strength as derived from changes in the SSH as being part of a decadal pattern of natural variability. Though changes in the circulation cannot be resolved here, our findings are consistent with HR04 and an extended BMT-index. Our results confirm a change since 1997 from deep LSW to ULSW formation, followed by a decline in ULSW formation. These formation rates have been calculated in fixed density intervals kept constant throughout the investigation period and do not consider interannual changes of LSW core properties (e.g., AV06).

[14] At present, the ULSW formation rate time series is still short. The continued observation of the temporal evolution of ULSW and deep LSW formation rates is clearly needed to reveal future coherency with changes in the MOC. Atmospheric CFC concentrations peaked during the past decade and have begun to decline slowly [Walker et al., 2000]. In addition, dissolved CFC concentrations in ULSW have almost reached saturation equilibrium with the atmosphere during this period. Thus, changes in ULSW production rates will become more difficult to detect using the CFC inventory technique in future. Starting in 2007 the time series will be continued using sulphur hexafluoride (SF₆) inventories to elude these differences. This tracer has been increasing almost linearly in the atmosphere for the past several decades [Tanhua et al., 2005]. Thus it may have a greater temporal sensitivity to changes in formation rate, making it highly suitable for this task.

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