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# Recent changes in the Greenland–Scotland overflow-derived water transport inferred from hydrographic observations in the southern Irminger Sea

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[1] Recent decadal changes (1955–2007) in the baroclinic transport ($T_{BC}$) of the Deep Western Boundary Current (DWBC) carrying the Greenland–Scotland overflow-derived waters along the East Greenland slope are quantified from a set of hydrographic sections in vicinity of Cape Farewell. The updated historical record of $T_{BC}$ shows clear decadal variability (±2–2.5 Sv) with the transport minima in the 1950s and mid-1990s, maximum in the early 1980s and moderate-to-high transport in the 2000s. Since the mid-1990s, the DWBC $T_{BC}$ has increased by ~2 Sv (significant at the 99.9% level), which constitute ~20% of the mean absolute transport (9.0 Sv) as obtained from three cruises in 2002–2006. The DWBC $T_{BC}$ anomalies negatively correlate (R = –0.80) with thickness anomalies of the Labrador Sea Water (LSW) at its origin implying a close association, albeit not necessarily causative, between the DWBC transport east of Greenland and the LSW production. **Citation:** Sarafanov, A., A. Falina, H. Mercier, P. Lherminier, and A. Sokov (2009), Recent changes in the Greenland–Scotland overflow-derived water transport inferred from hydrographic observations in the southern Irminger Sea, *Geophys. Res. Lett.*, *36*, L13606, doi:10.1029/2009GL038385.

## 1. Introduction

[2] Convective overturning in the Nordic Seas produces cold dense waters that overflow the Greenland–Scotland Ridge and, while descending into the deep subpolar basins, entrain lighter Atlantic waters and form the Denmark Strait Overflow Water (DSOW) and Iceland–Scotland Overflow Water (ISOW). At the East Greenland slope in the Irminger Sea, the DSOW and ISOW flows join in the Deep Western Boundary Current (DWBC) (Figure 1a) constituting the lower limb of the Atlantic meridional overturning circulation.

[3] At the exit from the Irminger Sea, the DWBC accounts for most of the overflow-derived water flux to lower latitudes [e.g., *Kieke and Rhein*, 2006] (hereinafter referred to as KR06), and this makes the southern part of the Irminger Sea one of the best sites for monitoring temporal changes in transport of the deep waters in vicinity to their source regions.

[4] In the absence of sufficient long-term direct current measurements, the basic way to assess the deep water transport variability is to infer it from changes in geostrophic transports derived from repeated hydrographic sections across the flow. This approach based on calculation of relative baroclinic velocities in the water column has been repeatedly applied to estimate deep water transport variability in the North Atlantic in the 1950s–1990s, and the advantages and restrictions of the approach have been discussed [*Bacon*, 1998, hereinafter referred to as B98; KR06].

[5] The DWBC baroclinic transport in the southern Irminger Sea has undergone substantial decadal variability with stronger DWBC in the late 1970s–1980s and weaker DWBC in the 1950s–1960s and early–mid-1990s (B98). Similar decadal signal has been inferred by *Koltermann et al.* [1999] from the set of the transatlantic sections (late 1950s, early 1980s and early 1990s) and by *Marsh* [2000] from the surface heat and freshwater fluxes (1980–1997), and southward transport of the overflow-derived deep waters has been suggested to be negatively correlated with production and transport of the Labrador Sea Water (LSW) [*Koltermann et al.*, 1999; *Marsh*, 2000].

[6] In this study, we assess changes in the baroclinic transport ($T_{BC}$) of the DWBC and its two components, ISOW and DSOW flows, between the 1990s and 2000s using the data from nearly collocated hydrographic sections in the southern Irminger Sea (Figure 1a and Table 1) (section 3). We compare the DWBC $T_{BC}$ with the absolute transport values when available to estimate to what extent the $T_{BC}$ variability may account for that of the absolute transport (section 4). We reconstruct the DWBC $T_{BC}$ time series for 1955–2007 by extending the historical record (B98) with the newly obtained estimates and examine robustness of the earlier suggested link between the deep water transport and LSW production (section 5).

## 2. Data and Method

[7] The $T_{BC}$ for the DWBC (the $\sigma_0 \geq 27.80$ density class, e.g., B98) and its two components – ISOW and DSOW ($27.80 \leq \sigma_0 \leq 27.88$ and $\sigma_0 \geq 27.88$, respectively, e.g., KR06) – were calculated using CTD data from 19 sections across the Irminger Sea in 1991–2007 (Figure 1a and Table 1). The $T_{BC}$ calculation was carried out in exact accordance with the method applied by B98 to the 1955–1997 dataset at the same location (see the method section therein) in order to make our estimates thoroughly compatible with those reported by B98. The 1991–2007 zonally-

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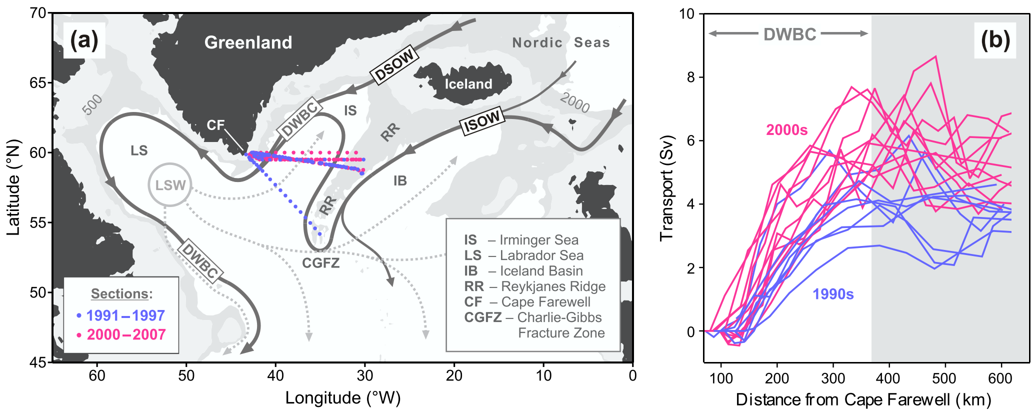


**Figure 1.** (a) Hydrographic section locations and circulation scheme for the Greenland–Scotland overflow-derived waters and Labrador Sea Water. (b) Zonally-accumulated baroclinic transports (Sv) for $\sigma_0 \geq 27.80$ in the Irminger Sea (1991–2007).

accumulated DWBC baroclinic transports are shown in Figure 1b. The $T_{BC}$ time series for DWBC, ISOW and DSOW are shown in Figure 2 in anomalies about the 1991–2007 mean.

[8] During the cruises on board R/V Thalassa in 2002 and 2004 and R/V Maria S. Merian in 2006, direct current velocity measurements were carried out with Acoustic Doppler Current Profiler equipments allowing the DWBC absolute transport to be estimated with the inverse method described by *Lherminier et al.* [2007]. These estimates are used to compare the absolute and baroclinic transport variability.

[9] The 1955–2007 DWBC $T_{BC}$ time series (Figure 3) is obtained by merging our results with B98 estimates. While thoroughly relying on B98, we omitted the 2 transport estimates (of total 21) derived from sections carried out from R/V Hudson (February 1967) and R/V Tyro (April 1991) that did not fully sample the DWBC. When more than one section was available for a given year we plotted the mean transport value.

## 3. Transport Increase Between the Mid-1990s and 2000s

[10] In the mid-1990s, the DWBC $T_{BC}$ in the Irminger Sea was the lowest since the 1960s (B98; KR06). Since the mid-1990s onwards, the transport increased (Figure 2a). Though the transport increase between the mid-1990s and 2000s is evident by the fact that all transport values in the 2000s are higher than in 1994–1997, its quantification as a linear trend varies considerably from +2.1 ± 0.7 to +3.4 ± 0.9 Sv/decade depending on the arbitrary choice of the trend endpoint (2007 or 2004). The difference between the mean $T_{BC}$ values for the 2000s (2000–2007, 11 sections) and the mid-1990s (1994–1997, 5 sections) is +2.04 Sv ($p < 0.001$). Thus, we conclude that the baroclinic transport of the DWBC southeast of Cape Farewell has increased since the mid-1990s by at least 2 Sv, i.e., by 54% relative to the 1994–1997 mean (3.7 Sv).

[11] The $T_{BC}$ has clearly increased in both the ISOW and DSOW layers (Figures 2b and 2c) and the ISOW, DSOW and DWBC $T_{BC}$ anomalies are well correlated ($0.96 > R > 0.79$, Figures 2d–2f). The ISOW (+1.2 Sv, $p < 0.001$) and DSOW (+0.8 Sv, $p < 0.001$) transport increases, defined as the differences between the means for the 2000s and mid-1990s, constitute respectively 60% and 40% of the net DWBC $T_{BC}$ increase (+2 Sv).

## 4. Comparison With the Absolute Transport in 2002, 2004 and 2006

[12] One of the issues related to interpretation of the baroclinic transport changes is how well do these changes account for those in the absolute ('actual') transport derived using the current measurement data. The absolute transport estimates for the DWBC carried out for the OVIDE section repeats of 2002, 2004 (R/V Thalassa) and 2006 (R/V Maria S. Merian) allow comparison of the DWBC baroclinic and absolute transports and their changes between the 3 observations.

[13] The DWBC baroclinic transport (5.3 Sv in 2002, 7.2 Sv in 2004 and 4.6 Sv in 2006) constitutes on average 63% of the absolute one (8.4, 11.1 and 7.6 Sv, respectively); the mean absolute transport is 9.0 Sv. If we take the latter value as a tentative estimate of the DWBC absolute transport in the 2000s then the ~2-Sv increase in the DWBC $T_{BC}$ between the mid-1990s and the 2000s constitutes 22% of the absolute transport.

[14] The 2002–2004–2006 variability of the $T_{BC}$ is qualitatively consistent with the absolute transport variability: the DWBC baroclinic and absolute transports both increased between 2002 and 2004 (+1.85 Sv and +2.7 Sv, respectively) and decreased between 2004 and 2006 (−2.6 Sv and −3.5 Sv, respectively). Quantitatively, the $T_{BC}$ changes account on average for about 70% of the absolute transport changes between the 2002, 2004 and 2006 observations.

## 5. Long-Term Variability of Baroclinic Transport, 1955–2007

[15] A (multi-) decadal signal with a magnitude of ±2–2.5 Sv (±35–45% of the long-term mean, 5.5 Sv) is evident in the 1955–2007 record for the DWBC $T_{BC}$ anomalies (Figure 3a). The transport increased by 4–5 Sv between the 1950s and the early 1980s, decreased by 4–5 Sv between

**Table 1.** Hydrographic Cruises

| Month/Year | Research Vessel | Cruise Number |
|---|---|---|
| 08/1991 | Charles Darwin | 62 |
| 09/1991 | Meteor | 18 |
| 09/1992 | Valdivia | 129 |
| 11/1994 | Meteor | 30 |
| 06/1995 | Valdivia | 152 |
| 09/1996 | Valdivia | 162/2 |
| 08/1997 | Discovery | 230 |
| 10/1997 | Professor Shtokman | 36 |
| 10/2000 | Pelagia | 169 |
| 06/2002 | Thalassa | Ovide-02 |
| 08/2002 | Akademik Mstislav Keldysh | 48 |
| 09/2003 | Pelagia | 216 |
| 06/2004 | Akademik Ioffe | 15 |
| 06/2004 | Thalassa | Ovide-04 |
| 06/2005 | Akademik Ioffe | 18 |
| 09/2005 | Pelagia | 240 |
| 06/2006 | Maria S. Merian | Ovide-06 |
| 07/2006 | Akademik Ioffe | 21 |
| 07/2007 | Akademik Ioffe | 23 |

the mid-1980s and mid-1990s and then restored to a moderate-to-high state: the mean transport in 2004–2007 is 0.6 Sv higher than the long-term mean. The 1955–2007 trend is close to zero (+0.02 ± 0.3 Sv/decade).

[16] The half-a-century long DWBC $T_{BC}$ time series allowed us to examine the suggestion that the deep water transport negatively correlates with the LSW production on a decadal time scale [*Koltermann et al.*, 1999; *Marsh*, 2000]. In the absence of a time series for the LSW production rate, we use the thickness of LSW in its formation region [*Curry et al.*, 1998] as a measure of the LSW production: strong convection produces large volumes of LSW, weak convection leads to a decrease in the LSW layer thickness [e.g., *Bersch et al.*, 2007].

[17] The DWBC $T_{BC}$ and LSW thickness in the Labrador Sea are closely negatively correlated (Figure 3) supporting the earlier suggested relationship. The lagged correlation shows two close maxima at 1-year ($R^2$ = 0.63) and 3-year ($R^2$ = 0.60) lags (Figure 3c), implying that the DWBC $T_{BC}$ changes are delayed by 1–3 years relative to changes in the LSW thickness.

## 6. Summary and Discussion

[18] Based on CTD data from the 19 sections (1991–2007) southeast of Cape Farewell we report that the DWBC baroclinic transport increased since the mid-1990s by about 50%, ~2 Sv, that makes ~35% of the long-term (1955–2007) mean $T_{BC}$ (5.5 Sv) and about 20% of the 2002–2006 mean absolute transport (9.0 Sv, the 3 section-based estimate). The $T_{BC}$ increased in both the ISOW and DSOW layers accounting for 60% and 40% of the DWBC $T_{BC}$

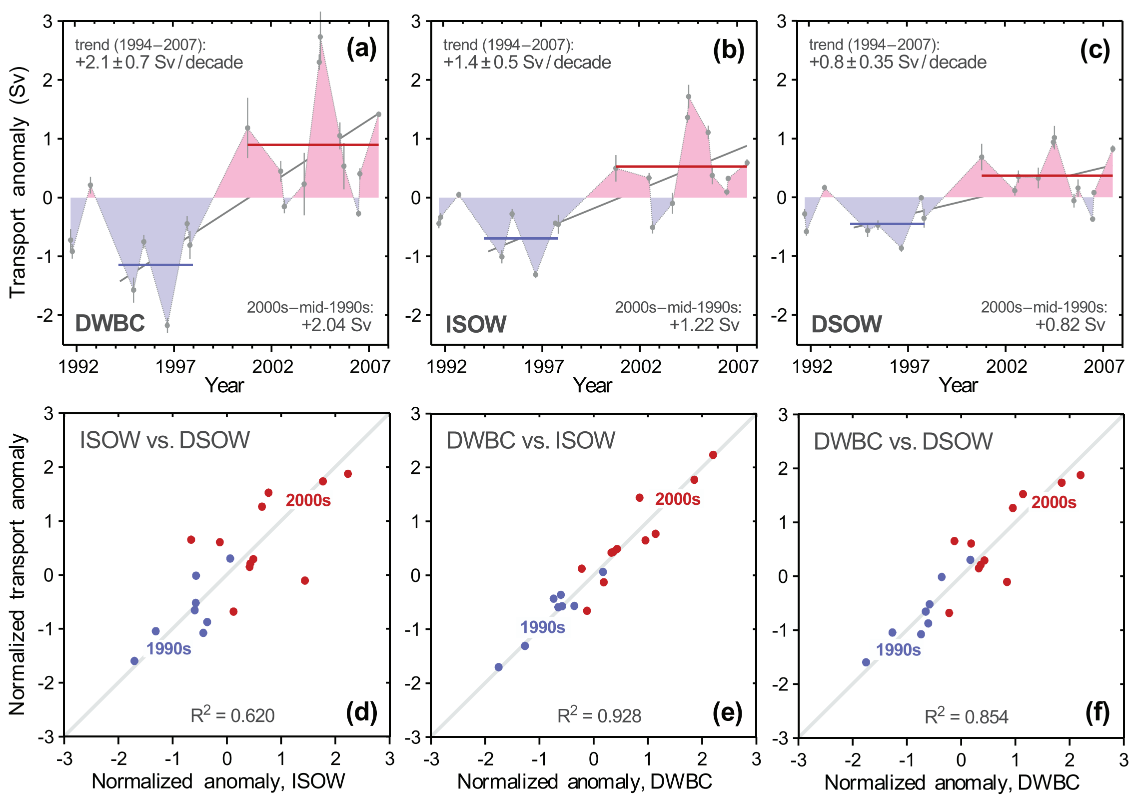


**Figure 2.** The 1991–2007 time series of baroclinic transport anomalies (Sv) for the (a) DWBC and its two components – (b) ISOW and (c) DSOW; the 1991–2007 means are 4.9, 2.7 and 2.2 Sv for DWBC, ISOW and DSOW, respectively. The mean anomalies for the mid-1990s (1994–1997) and 2000s (2000–2007) and the 1994–2007 trends are plotted as continuous blue, red and grey lines respectively. Error bars associated with the two different ways of velocity extrapolation in the 'bottom triangles' (see the method section of *Bacon* [1998]) are indicated. The differences between the 2000s and mid-1990s means are significant at the 99.9% confidence level according to the *t*-test. (d–f) Transport anomalies shown in Figures 2a–2c normalized by their standard deviations and plotted versus each other.

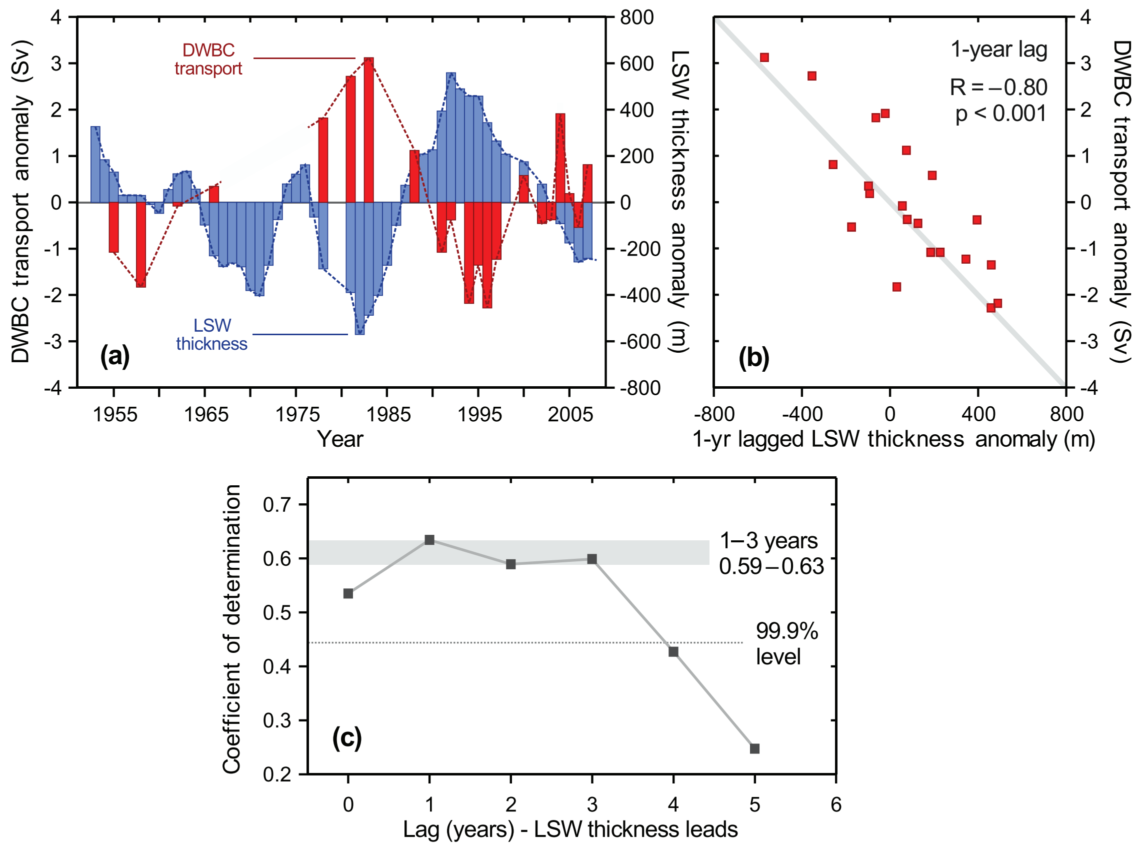


**Figure 3.** (a) The 1955–2007 time series of the DWBC baroclinic transport anomalies (Sv) in the southern Irminger Sea, updated after B98, and the 3-year smoothed LSW thickness anomalies (m) in the Labrador Sea, updated after [*Curry et al.*, 1998]. (b) DWBC transport anomalies plotted versus 1-year lagged LSW thickness anomalies. (c) Coefficient of determination ($R^2$) for the two times series at 0–5-year lags (LSW thickness leads).

increase respectively. The ISOW and DSOW transports are well correlated implying consistency of the ISOW and DSOW $T_{BC}$ changes in the region on a multiyear time scale.

[19] Comparison with the absolute transport changes between 2002, 2004 and 2006 shows that the $T_{BC}$ variability may account for the major part (~70%) of the variability of the DWBC absolute transport on interannual time scale. This result based on 3 repeats does not, however, mean that the agreement between the baroclinic and absolute transport changes is robust. A further examination of the absolute–baroclinic transport relationship is essential, as only the $T_{BC}$ variability can be assessed from historical hydrographic data.

[20] Our estimate of the DWBC $T_{BC}$ increase since the mid-1990s (+22% of the 2002–2006 mean absolute transport) is in general agreement with the increase in the DWBC ($\sigma_0 > 27.80$) absolute transport (+25%) that was observed downstream, in the southwestern Labrador Sea (~53°N), in 1996–2003 [see *Dengler et al.*, 2006, Figure 3]. This implies that decadal changes (trends) in the absolute transport of the DWBC are satisfactorily represented by the $T_{BC}$ changes. Long-term direct monitoring of the DWBC is needed to verify this inference.

[21] On a decadal time scale (1955–2007), the DWBC $T_{BC}$ fluctuates by ±2–2.5 Sv. The transport was low in the 1950s and mid-1990s, high in the early 1980s and moderate-to-high in the mid-2000s. The overall DWBC $T_{BC}$ trend is nearly zero providing no evidence of the DWBC slowdown or acceleration over the past five decades in agreement with the absence of detectable trend in the simulated overflow flux across the Greenland–Scotland Ridge over the 1948–2005 time period [*Olsen et al.*, 2008].

[22] The causes of the decadal changes in the DWBC transport are not well understood at present.

[23] Noteworthy, the DWBC $T_{BC}$ increase since the mid-1990s was not accompanied by any comparable change in the northward recirculation at the DWBC levels east of the DWBC eastern edge (~400–500 km off Cape Farewell, Figure 1b). This suggests that the inferred DWBC transport changes in the southern Irminger Sea have other cause(s) than baroclinic changes in intensity of local cyclonic recirculation cell.

[24] B98 argued that the DWBC transport variability was an oceanic response to the air-sea buoyancy flux variability and suggested a relationship between the DWBC $T_{BC}$ and severity of winters over the Nordic Seas: low winter temperatures favor strengthening of deep convection, and thus may lead to an increase in density and/or production rate of the convectively formed Arctic Intermediate Water thereby increasing the Nordic Seas' outflow to the North Atlantic. This suggestion that followed from previous work by *Dickson et al.* [1996] has been based on a negative correlation between the DWBC baroclinic transport southeast of Cape Farewell and the Jan Mayen (71°N, 8.5°W)

winter mean air temperatures averaged for the 3 winters preceding the hydrographic measurements in the Irminger Sea (B98). To examine whether this correlation is robust, we have assessed it for the updated DWBC transport time series shown in Figure 3a. The correlation is indeed close for the 1955–1997 time period analyzed by B98 (R = –0.8, $p < 0.01$ if the transport in 1966 is excluded as discussed by B98), but is considerably less for the entire 1955–2007 record (R = –0.41, p = 0.07) as the deep water transport increase between the mid-1990s and 2000s was accompanied by increase in winter temperatures. Here we report on this matter, while a more detailed investigation of a probable link between the DWBC transport and the surface forcing over the Nordic Seas will be performed elsewhere.

[25] The overflows on both sides of Iceland together provide about 6 Sv of the dense water flux into the Irminger Sea and Iceland basin [e.g., *Olsen et al.*, 2008]. The DWBC variability in response to changes in the atmospheric forcing north of the Greenland–Scotland Ridge implies consistent decadal variability of the overflow water transport across the Ridge. The observations and model simulations show, however, that the overflows are relatively stable on a multiyear and longer time scales; at least, long-term changes in the overflow flux comparable to the DWBC $T_{BC}$ variability have never been observed [e.g., *Dickson et al.*, 2008; *Olsen et al.*, 2008]. However, the initial overflow flux is then enlarged by entrainment resulting in the ~9-Sv deep water flow (2002–2006) southeast of Cape Farewell. Thus, the entrainment-derived waters substantially contribute to the DWBC, and variability of the entrainment flux may potentially be responsible for a great part of the DWBC transport variability.

[26] Can changes in the entrainment flux explain the seeming contradiction between the relative stability of the overflow flux and substantial variability of the DWBC transport? A weak decadal variability in the overflow flux potentially induced by changes in the convection intensity in the Nordic Seas, may be amplified in the subpolar North Atlantic by concurrent changes in the entrainment flux, if one suggests that stronger/weaker overflow entrains more/less water. If the latter relationship is non-linear, then even faint changes in the overflow flux may lead to considerable changes in the deep water transport. This could be tested in models.

[27] Another striking phenomenon that deserves a detailed investigation is the robust relationship between the LSW production and the DWBC $T_{BC}$ anomalies.

[28] First, this relationship may reflect a phase opposition of oceanic responses to the North Atlantic Oscillation-related forcing similar to that evidenced between convective activities in the Labrador Sea and the Nordic Seas [*Dickson et al.*, 1996].

[29] Second, the 'LSW production – DWBC transport' relationship may be causative. Convection in the Labrador Sea is thought to be one of the forcings of the subpolar gyre circulation. Changes in the convective activity (i.e., in the LSW production rates) lead to changes in strength and zonal extension of the subpolar gyre [e.g., *Bersch et al.*, 2007], which cause drastic thermohaline and circulation changes in the region where the overflows entrain Atlantic waters [see *Hátún et al.*, 2005; *Bersch et al.*, 2007]. In models, the gyre circulation reacts to the LSW production changes with a 3-year lag [e.g., *Gulev et al.*, 2003] that corresponds to the maximum lag at which the maximum correlation ($R^2$ = 0.60) between the DWBC transport and the LSW thickness is achieved.

[30] One more mechanism on how changes in the LSW production may influence the DWBC strength can be mentioned. Prior to joining the DWBC in the Irminger Sea, ISOW passes through the Charlie-Gibbs Fracture Zone (CGFZ) where substantial temporal variability of deep water transport and even blocking events have been observed (see KR06 and references therein). Right above the ISOW westward flow, LSW propagates through the CGFZ eastwards (Figure 1a). Therefore, variability of the ISOW flux through the CGFZ may be associated (anticorrelated) with the LSW production variability: in the periods of increased LSW production, the ISOW westward flux in the CGFZ may be diminished by increased LSW transport in the opposite direction leading to a decrease in the ISOW transport in the Irminger Sea. The Labrador Sea – CGFZ spreading time for LSW of about 1.5 yr [*Kieke et al.*, 2006] compares favorably with the 1–3-yr lag between the anomalies of the LSW thickness in the Labrador Sea and the DWBC transport. As a caveat, this potential mechanism does not explain the concurrent changes in the DSOW transport.

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