Variability of the Deep Western Boundary Current east of the Grand Banks

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[1]   The Deep Western Boundary Current east of the Grand Banks has been observed during 1999–2005 by moored current-meter stations and shipboard current profiling sections. These recent observations can be compared with those of a WOCE moored array deployed during 1993–95 at the same location. Overall, the observations of Deep Water currents east of the Grand Banks reported here do not support suggestions of a basin-wide "slowdown" of the Atlantic Meridional Overturning Circulation. **Citation:** Schott, F. A., J. Fischer, M. Dengler, and R. Zantopp (2006), Variability of the Deep Western Boundary Current east of the Grand Banks, *Geophys. Res. Lett.*, *33*, L21S07, doi:10.1029/2006GL026563.

1.   Introduction

[2]   The circulation east of the Grand Banks has been studied by repeat hydrographic ship sections along the WOCE line A2 [*Stramma et al.*, 2004], ending at the western continental slope near 42°N (Figure 1a), and by repeated moored arrays along the western end of that section during 1993–95 [*Clarke et al.*, 1998; *Meinen et al.*, 2000] and again during 1999–2001 [*Schott et al.*, 2004] (hereinafter referred to as S04). The circulation is characterized by southward Deep Water flow directly along the topography, followed by the deep-reaching northward flowing North Atlantic Current (NAC) farther offshore. While the northward flow underneath the NAC more than compensates the DWBC transport, actually yielding net northward transport in the western part of the basin, water mass properties show that the deep NAC cannot just be a recirculation of the DWBC (S04). Shoreward of the DWBC, the shallow part of the Labrador Current flows southward, flowing through Flemish Pass, north of the moored array (Figure 1a).

[3]   While the combined observational and modeling evidence available at present suggests that the bulk of the Deep Water export occurs along the western slope, off the Grand Banks, there is also observational evidence from tracer distributions [*Rhein et al.*, 2002] and float trajectories [*Bower et al.*, 2002] that a fraction is spreading southward along the topography of the mid-Atlantic Ridge. This is also concluded in a new model study using Lagrangian particles [*Getzlaff et al.*, 2006].

[4]   The WOCE 1993–95 moored current-meter observations had been combined by S04 with the Kiel 1999–2001 station data into mean transports for the DWBC in different

density layers of the North Atlantic Deep Water. Toward the surface the array data were expanded, based on geostrophy from shipboard hydrographic sections in that study. We here present a new averaged transport section, based on four shipboard ADCP/LADCP surveys of the western A2 section during 1999–2005, and new time series of moored currents from the DWBC for the time period 2001–2005.

2.   The Observations

2.1.   Shipboard LADCP Sections

[5]   Current profiles were obtained on four ship sections (in July 1999, May 2001 and September 2003 by "Meteor", and in August 2005 by "Thalassa") along the western end of the WOCE A2 line (Figure 1a). The upper layer was measured by shipboard Acoustic Doppler Current Profiler (ADCP) and the deeper layers by lowered ADCP (LADCP). Transports were compiled from the merged and interpolated data sets of both systems for each individual section and for the mean as described by [*Dengler et al.*, 2006] (hereinafter referred to as D06). Then transports were calculated between isopycnals σ_θ = 27.68, 27.74, 27.80 and 27.88 kgm^{-3} (Figure 1b), as used earlier (S04) to mark the boundaries of upper Labrador Sea Water (uLSW), classical Labrador Seawater (LSW), Gibbs Fracture Zone Water (GFZW) and Denmark Strait Overflow Water (DSOW), respectively.

2.2.   Current-Meter Time Series

[6]   Current-meter time series were obtained from the summers of 1999 to 2005 at stations K 101–K 104 east of the Grand Banks, in three consecutive deployments of about two years duration each, along the western end of the WOCE A2 line. The array repeated the western part of the earlier WOCE array of *Clarke et al.* [1998], but only one of the earlier stations, station 1125, was repeated, by K 104, at approximately the same location (Figure 1a). Mooring K 102 was lost for the interim deployment period, 2001–2003. Current-vector plots from the near-bottom instruments of K 101–K 104 (Figure 2a) for the time period 1999–2005 show strong intraseasonal variability but no apparent signs of decadal trends.

3.   DWBC Transports

[7]   The composite mean of the four ADCP/LADCP ship sections is shown in Figure 1b, with DWBC transports in the four NADW layers and total DWBC marked. There is large cruise-to-cruise variability in structure and transport of the DWBC regime among the four individual sections (the first two of which were already presented by S04; see their Figure 14). The mean transport below σ_θ = 27.68 kgm^{-3}, i.e. including the upper-LSW layer, results as 17.5 ± 6.8 Sv.

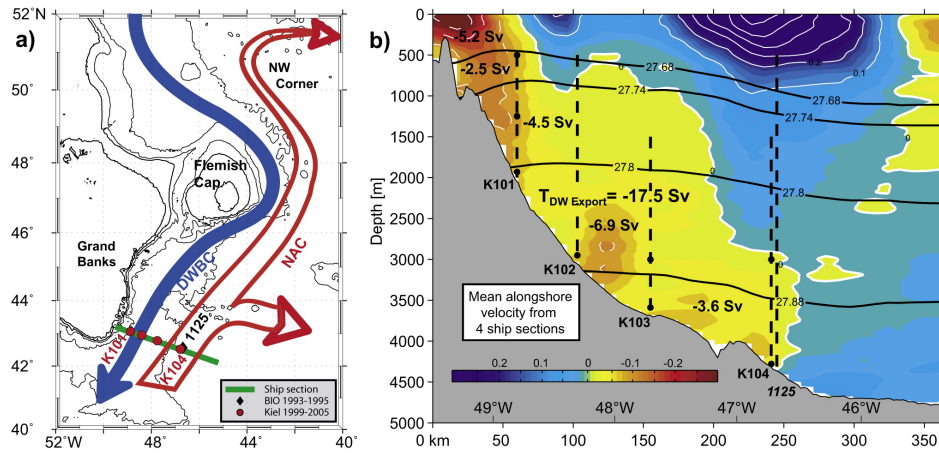[1]Leibniz-Institut für Meereswissenschaften an der Universität Kiel, Kiel, Germany.

Figure 1. (a) Topography of the Grand Banks region and location of the ship section (green line) and moored stations used here, with schematic representations of the Deep Western Boundary Current (DWBC) and North Atlantic Current (NAC) and (b) ship section of averaged ADCP/LADCP currents normal to the section, composed from four cruises in summers of 1999, 2001, 2003 and 2005. The DWBC flows southward along the boundary, the NAC flows northward offshore. DWBC transports (in Sv = $10^6 m^3 s^{-1}$) are given for the total (below $\sigma_\theta = 27.68$ kgm^{-3}) as well as in density layers corresponding to the different NADW water masses. Also shown are locations of moored instruments from station 1125 of WOCE array 1993–95 and IFM-GEOMAR array K 101– K 104 used in the following.

This 4-section average is higher than the mean of 12.9 Sv which S04 obtained from the combined 1993–95 and 1999–2001 moored-array current-meter data, with the difference mostly in the uLSW layer (2.5 Sv in Figure 1b vs. only 0.7 Sv in the work by S04) and in the GFZW layer (6.9 Sv in Figure 1b vs. 4.3 Sv in the work by S04). Besides the large intraseasonal variability affecting the 4-section average, differences in sampling of the DWBC by the moorings and shipboard profiling may also be a factor in this difference. The agreement with the moored section of S04 is better if the DWBC transport of our ship-section mean (Figure 1b) is integrated only within the area of mean southward DWBC flow of S04, i.e. west of the zero-flow contour in their Figure 14. Then the mean from Figure 1b would be 14.4 ± 5.0 Sv, much closer to the 12.9 Sv below $\sigma_\theta = 27.68$ kgm^{-3} of S04.

[8] There is considerable deep northward flow directly east of the DWBC, underneath the NAC (Figure 1b). However, as already mentioned, this deep water flow differs in water mass characteristics from the DWBC (S04), with part of it even having Antarctic Bottom Water characteristics, and it can therefore not be considered a straight DWBC recirculation. Mean transports for the NAC are not shown in Figure 1b because our shipboard-section coverage did not reach far enough out to compare with the transport section of S04. What is also obvious from Figure 1b, and even more so from the individual ADCP/LADCP velocity sections (not shown) is that transport determinations in the Deep Water outflow regime need direct current measurements; applying geostrophy with some pre-selected "level of no motion" can lead to quite erroneous transport numbers in this region.

4. Intraseasonal to Interannual Variability

4.1. For the Observational Period 1999–2005

[9] Here we analyze the moored observations for longer-term changes by calculating averages over the deployment-time periods of the alongshore velocities from the DWBC domain of the array (Table 1). The errors of the approximately two-year long means were calculated by first determining the number of degrees of freedom from the decorrelation time scale of the autocorrelation functions which was typically about 20 days. The mean errors are thus quite small, <1 cms^{-1} typically (Table 1). At the upper two levels of K 101, the mean for the first and the third period are the same within their small error bars, while the southward flow during the intermediate period is higher than before and after; but it has also to be noted that these intermediate records are shorter, due to instrumental failure in the second observational period (Figure 2a).

[10] At the 3000 m level, three long records are available across the Deep Water range, from K 102 – K 104. Even after applying a 50d low-pass filter, they still show intraseasonal anomalies of more than 10 cms^{-1}, but none of them displays variations at longer time scales. The average of the three time series (which for 2001–2003 is only the mean of K 103 and K 104, due to loss of K 102) shows a large reduction of the variability (heavy black curve). The deployment period means of the 3-curve average differs only by a few tenths of a cms^{-1} (Table 1). At 4200 m depth, station K 104, the mean is more strongly southward than at 3000 m and the errors of the mean are larger, still only slightly above 1 cms^{-1}.

[11] Overall, the means of the 1999–2001 deployment period do not differ significantly from the third period, 2003–2005 for any of the records (Table 1). What varies among the deployment periods is the intraseasonal variability. Variance-conserving spectra of the 6-year long records from 3000 m (K 103, K 104) and 4200 m (K 104, Figure 3a) show maximum energy at 15–60 day periods, but drop off sharply toward longer periods. The energy of the near-bottom variability is significantly larger than higher up. A likely cause for this bottom enhancement are topographic
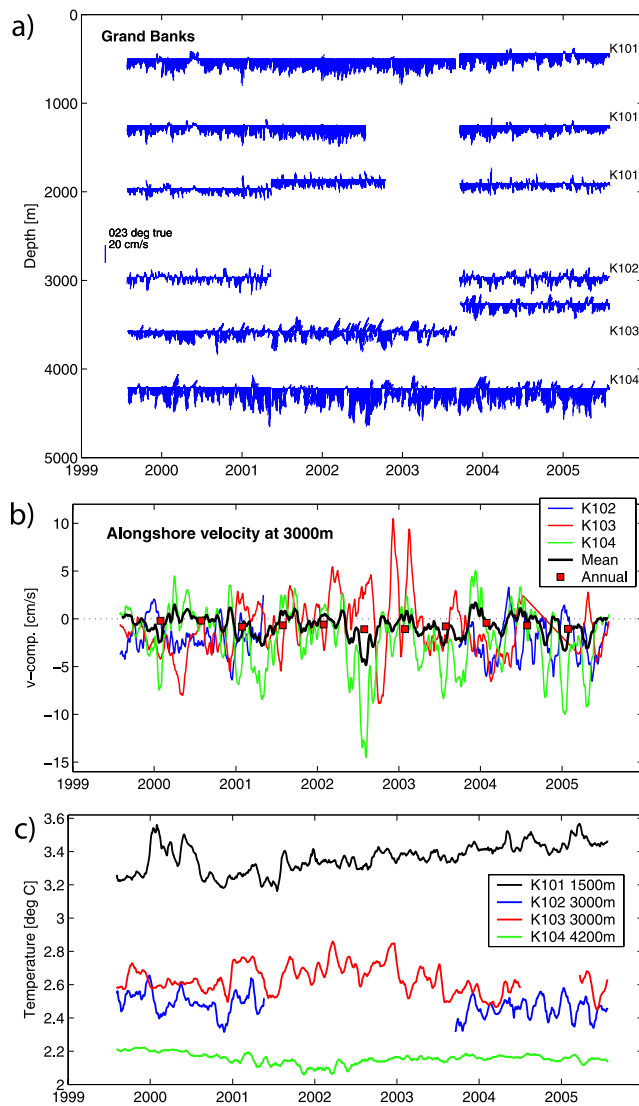
Figure 2. (a) Current-vector plots 1999–2005 from approximately 500 m and 1200 m depth at station K 101 and from near-bottom instruments at moorings K 101–K 104 (velocity scale in upper left) vs. depth; vectors are rotated to 23°T so that outflow parallel to boundary is downward; some depth shifts occurred among different deployments at K 101 and K 103; (b) 50d-low-passed alongshore currents at the 3000 m level of stations K 102 (blue), K 103 (red) and K 104 (green) for 1999–2005; also shown is mean curve (heavy black) and its annual means (magenta squares), shifted every half year; and (c) temperature time series from selected Microcat sensors.

Rossby waves, but this question needs to be pursued in a separate study.

4.2. Comparison With WOCE Array 1993–1995

[12] The sparser array of 1999–2005 repeated only one station, 1125, of the WOCE array of 1993–95 (Figure 1a). Here we compare records from 100 m above the bottom, at 4200 m, and from 3000 m depth of both observational periods (Figure 4a). The deployment period means for 1993–95 and the more recent three deployments at 4200 m depth are the same, within the errors of the mean (Table 1), and at 3000 m the mean of -2.8 ± 0.7 cms^{-1} from 1993–95 is also not different from the -2.1 ± 0.8 cms^{-1} of 2003–2005 (where it has to be noted that for 1993–95 the average of the 2500 m and 3500 m records is taken, since 3000 m was not covered in the WOCE array). The result that only very small changes on periods longer than intraseasonal have occurred is confirmed by the mean profiles of repeat stations 1125/K 104 (Figure 4b). The approximately two-year long means of the four mooring deployments fall pretty much onto the same vertical profile.

[13] There are, however, changes in the shorter-period variance in the time series of the current fluctuations of the four deployments as shown in Figure 3b for the near-bottom records from 1125/K 104. The largest fluctuative kinetic energy occurs during 2001–2003, the deployment period for which inspection of the vector time series (Figure 2a) and alongshore components (Figure 4a) also shows the strongest short term events.

4.3. Temperature Variability Within the DWBC

[14] The Labrador Sea is known for its much reduced convective activity during the time period of our observations, leading to a near-linear warming of about 0.05°C per year since the mid-90's at the 1500 m level (D06, their figure 2). The temperature record from the 1500 m level at station K 101 (Figure 2c), located in the LSW-DWBC core (Figure 1b), shows a warming trend of about this magnitude after 2001. It can, however, not be stated clearly from our observations what the time lag is between the beginning of that warming trend in the LS and at our moored array at 43°N. The K 101 temperature time series shows a large positive anomaly of 0.3°C during 2000 that is not seen in the D06 temperatures at 53°N.

[15] At the DSOW level, at 4200 m depth at station K 104, there is an about 0.1°C cooling during 2001–2003 (Figure 2c), while at the 3000 m level that period is characterized by warming. Overall, an interesting result of comparing the DWBC temperatures (Figure 2c) with

Table 1. Alongshore Current Components

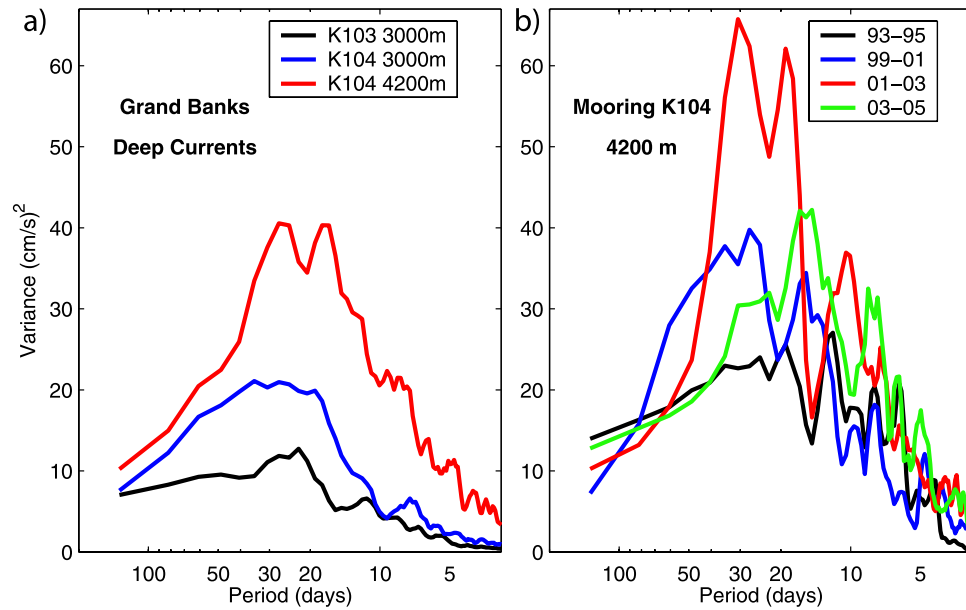|	2-Year Means ± Error of the Means, cm/s			
	1993–1995	1999–2001	2001–2003	2003–2005
K101 - 500 m	–	-7.4 ± 1.2	-10.3 ± 0.5	-8.1 ± 0.9
K101 - 1250 m	–	-6.7 ± 0.7	-11.6 ± 0.5	-7.2 ± 0.8
K101 - 2000 m	–	-3.5 ± 0.4	-3.2 ± 0.4	-3.5 ± 0.4
K102/K103/K104 3000 m	–	-0.5 ± 0.2	-0.8 ± 0.3	-0.7 ± 0.3
K104 – 3000 m	-2.8 ± 0.7	-1.6 ± 0.8	-2.5 ± 0.8	-2.1 ± 0.8
K104 – 4200 m	-8.4 ± 1.1	-8.5 ± 1.1	-9.3 ± 1.0	-8.8 ± 1.1

Figure 3. Variance-conserving spectra of alongshore velocity fluctuations of (a) 6-year long time series at 3000 m at K 103, K 104 and at 4200 m at K 104 and (b) 2-year long time series at the bottom instrument of 1125/K 104, at 4200 m depth.

the current strength (Figure 4) is that, while there are interannual to decadal variations in the temperatures, the currents are surprisingly stable over the time period of a decade.

5. Summary and Concluding Remarks

[16] The new 4-section ADCP/LADCP average (Figure 1b) yields a deep water outflow, below $\sigma_\theta = 27.68$ kgm^{-3}, of 17.5 Sv, with an error of the mean of 3.9 Sv, based on 3 degrees of freedom. While this new ship section mean is higher than the mean of 12.9 Sv obtained from the moored-array estimate of S04, both are in the range of the "cold-

limb" MOC transport required at this latitude by inverse models. Estimates of 13.8 ± 2.1 Sv and 15 ± 2 Sv were determined from inverse studies by *Lumpkin and Speer* [2003] and *Ganachaud and Wunsch* [2000], respectively, for the entire basinwide MOC transport across the WOCE A2 line.

[17] Recent studies of tracer distributions [*Rhein et al.*, 2002] and float trajectories [*Bower et al.*, 2002] suggest an additional outflow route, along the mid-Atlantic Ridge. This pathway is also resulting from new Lagrangian model studies [*Getzlaff et al.*, 2006]. However, the fraction of mean deep water outflow not following the western topography is still an unresolved issue. If there is no sizeable
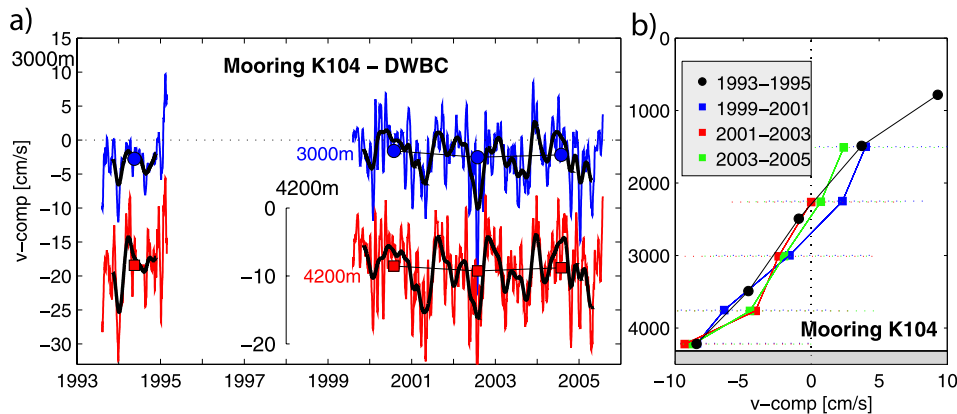

Figure 4. (a) Low-passed alongshore current fluctuations (light = 20d LP; heavy black = 100d LP) from 3000 m (blue) and 4200 m (red) depth of stations 1125 of the WOCE array for 1993–1995 and K 104 for 1999–2005; also shown (squares) are 2-year means and (b) vertical profiles of mean currents from all instruments at mooring K 104, averaged for about 2-year long deployment periods during 1999–2001, 2001–2003 and 2003–2005 at station K 104, and for 1993–95 from station 1125 (black).

northward recirculation of the DWBC (for example, underneath the NAC), this outflow branch should be small given the same magnitude of MOC and DWBC estimates.

[18] The most notable result of our moored-array study is the surprisingly stable characteristic of the DWBC flow east of the Grand Banks (Figure 4) when the approximately two-year long means of our deployments are compared (Table 1). There are, however, changes in the shorter-period variability over the decade of the observations (Figure 3b) which merit further investigation. Although the water mass characteristics show interannual to decadal variations at those locations (Figure 2c), there is no sign of any MOC "slowdown" trend over the past decade, contrary to some recent suggestions [*Bryden et al.*, 2005]. Considering the above-mentioned discovery of mean-outflow pathways in the interior, there is, however, the question whether there might be variability of the meridional exchanges elsewhere along the 43°N section. There also is some redistribution of the constant total DWBC transport among density layers during the past decade, due to the longer-period water mass modifications of the outflow (Figure 2c). These changes will most notably affect the split between the upper LSW and the "classical" LSW (Figure 1b), not the deeper layers.

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