Moored observations of the Deep Western Boundary Current in the NW Atlantic: 2004-2014

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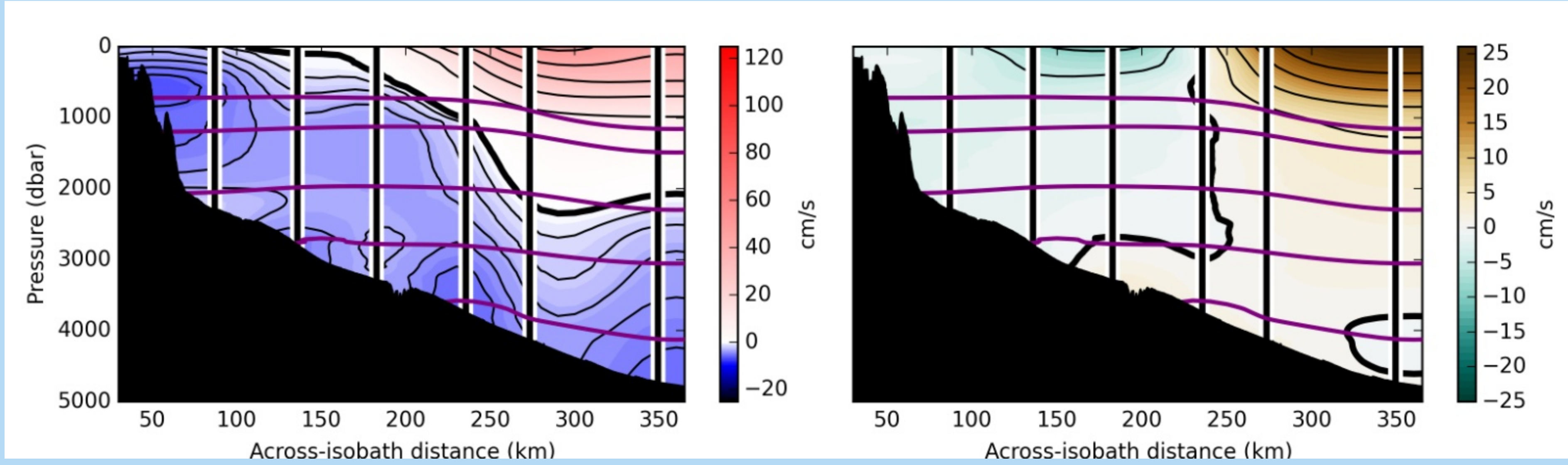
Abstract

A moored array spanning the continental slope southeast of Cape Cod sampled the equatorward-flowing Deep Western Boundary Current (DWBC) for a 10-year period: May 2004 - May 2014. Daily profiles of subinertial velocity, temperature, salinity and neutral density are constructed for each mooring site and cross-line DWBC transport time series are derived for specified water mass layers. Time-averaged transports based on daily estimates of the flow and density fields in stream coordinates are contrasted with those derived from the Eulerian-mean flow field, modes of DWBC transport variability are investigated through compositing, and comparisons are made to transport estimates for other latitudes. Integrating the daily velocity estimates over the neutral density range of 27.8 - 28.125 kg/m^3 (encompassing Labrador Sea and Overflow Water layers), a mean equatorward DWBC transport of 22.8 x 10^6 m^3/s ± 1.9 x 10^6 m^3/s is obtained. Notably, a statistically-significant trend of decreasing equatorward transport is observed in several of the DWBC components as well as the current as a whole. The largest linear change (a 4% decrease per year) is seen in the layer of Labrador Sea Waters renewed in the early 1990s whose transport fell from 9.0 x 10^6 m^3/s at the beginning of the field program to 5.8 x 10^6 m^3/s at its end. The corresponding linear fit to the combined Labrador Sea and Overflow Water DWBC transport decreases from 26.4 x 10^6 m^3/s to 19.1 x 10^6 m^3/s. In contrast, no long-term trend is observed in upper-ocean Slope Water transport. These trends are discussed in the context of decadal observations of the North Atlantic circulation, and subpolar air-sea interaction/water mass transformation.

Eulerian-Mean Velocity

Contour plot of the Line W Eulerian-mean across-line (left) and along-line (right) velocity based on the 2004-2014 Line W moored observations and surface geostrophic velocity estimates derived from altimeter data. The mean depths of the neutral density surfaces chosen to partition the water column and location of the moorings are also indicated. In the left panel, the contour interval for the across-line component is 1 cm/s for equatorward-directed currents (negative values) and 10 cm/s for poleward (positive values). The zero isotachs are marked with thick black lines. C.I. for the right panel is 5 cm/s. Meandering of the Gulf Stream results in a broadening of the upper ocean poleward flow and the deep equatorward flow at W6.



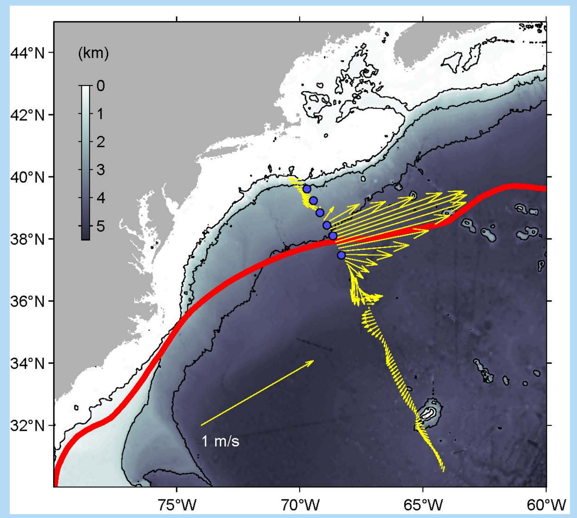
Layer definitions

Layer definitions and bounding neutral density surfaces for transport calculations. Key: SURF: Upper-Ocean Slope Water, ULSW : Upper Labrador Sea Water, CLSW: Classical Labrador Sea Water, ISOW: Iceland-Scotland Overflow Water, DSOW: Denmark-Strait Overflow Water.

Layer name	Neutral Density (kg/m^3)	Average depth (m)
	0.0	0
SURF		
	27.800	678
ULSW		
	27.897	1095
CLSW		
	27.983	1958
ISOW		
	28.066	2771
DSOW		
	28.125	3575

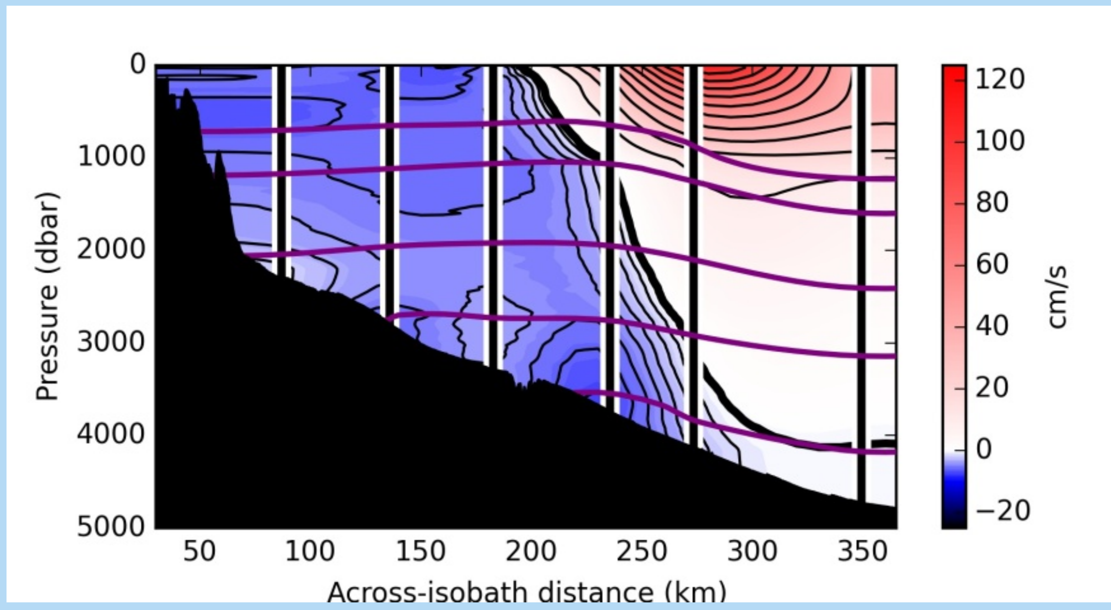
The Study Area

Map of the Northwest Atlantic Ocean bathymetry (shading with color bar over land) showing the location of the Line W moorings (blue dots) and time-average axis of the Gulf Stream (red line - taken as a specified mean sea surface height contour). The yellow arrows depict the mean surface geostrophic velocity on Line W in the 2004-2014 period for the subset of times when the Gulf Stream and its North Wall were near their mean crossing latitudes at the Line and there were no strong surface velocity anomalies in the Slope Water. The 200, 2000 and 4000 m isobaths are highlighted. The surface geostrophic velocity and Gulf Stream axis location are based on altimetric-derived sea surface height estimates



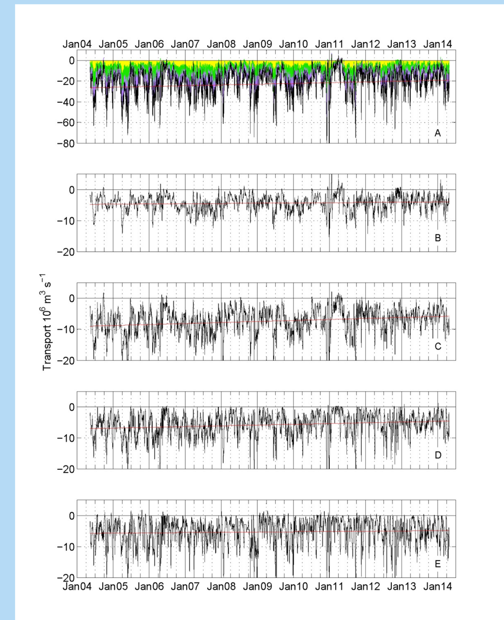
Ideal-State Velocity

"Ideal state" composite across-line velocity section constructed from the subset of observations when the Gulf Stream velocity core and North Wall were near their time-averaged locations and no strong surface velocity anomalies were present in the Slope Water. Contour interval is 1 cm/s for equatorwardward flows and 10 cm/s for poleward velocities; the thick black line marks the zero isotach.



Transport Time Series

Time series of DWBC transport at Line W partitioned by water mass. Negative values correspond to equatorward flow. Total intermediate and deep water transport is given in Panel A with layers identified by color (ULSW=yellow, CLSW=green, ISOW=purple, DSOW=black). Panels B through E show the individual layer transport time series (ULSW, CLSW, ISOW and DSOW respectively). The daily values for each layer represent the most southward value of the transport streamfunction integrated between the shelf break and mooring W5. The red lines are linear least square fits to the transport estimates versus time.



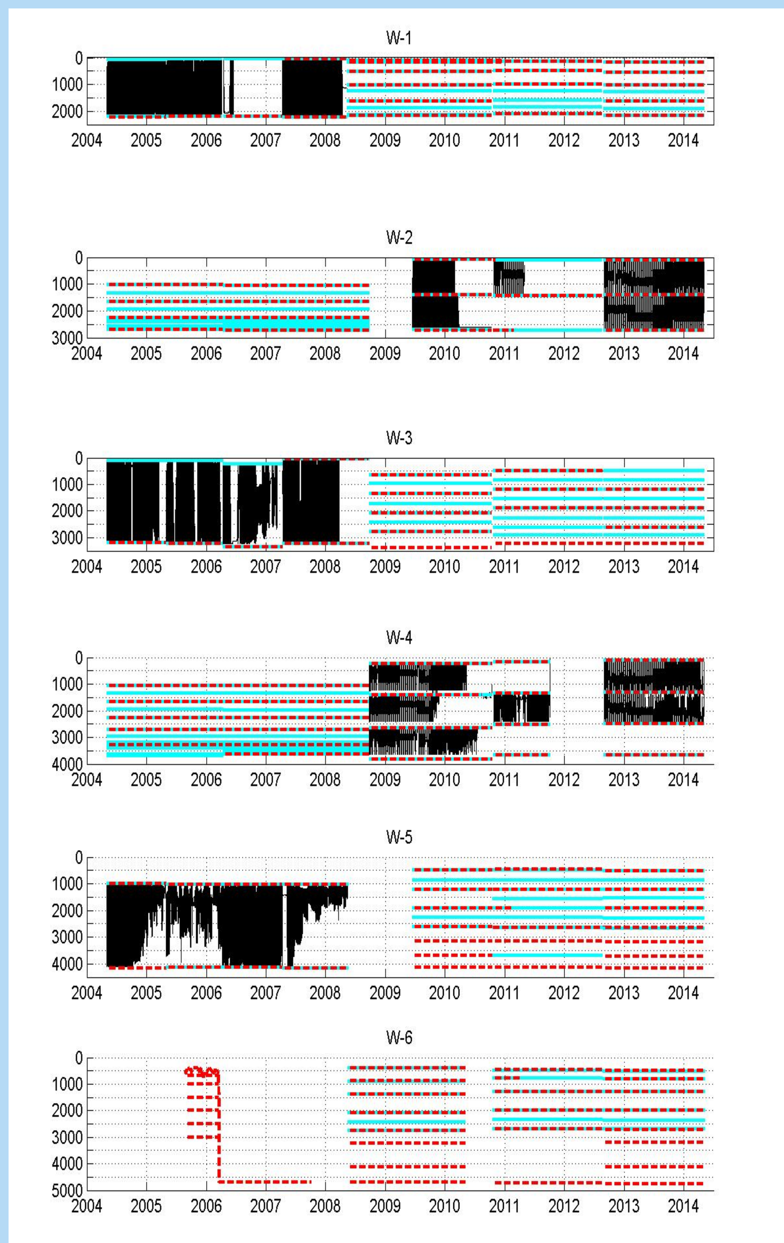
The Line W Moored Array

Observations from these sites between 11 May 2004 and 27 April 2014 are analyzed here. Average mooring locations and corresponding ocean depths are given along with the type of mooring deployed: MMP indicates a mooring that supported a McLane Moored Profiler while a Conventional Mooring supported discrete current meters and T-C/CTD sensors. The shallowest sensor column gives the range of depths for the various settings of each mooring of that style.

Mooring	Latitude	Longitude	bottom depth (m)	mooring style	shallowest sensor (m)
W1	39° 36.32' N	69° 43.62' W	2238	MMP: 2004-2008 Conventional: 2008-2014	48 - 85 62 - 177
W2	39° 13.54' N	69° 26.73' W	2752	Conventional: 2004-2008 MMP: 2008-2014	1026 - 1033 76 - 98
W3	38° 50.33' N	69° 10.63' W	3248	MMP: 2004-2008 Conventional: 2008-2014	95 - 170 480 - 650
W4	38° 26.27' N	68° 53.87' W	3686	Conventional: 2004-2008 MMP: 2008-2014	1040 100 - 222
W5	38° 5.80 N	68° 38.95' W	4110	MMP: 2004-2008 Conventional: 2008-2014	988 - 1010 479 - 492
W6	37° 28.66' N	68° 18.34' W	4700	Conventional: 2008-2014	268 - 438

Sensor Performance

Graphical presentation of the moored sensor performance during the Line W program. For each of the 6 mooring sites (labeled W1 to W6), the times and depths when good data were obtained from Moored Profilers (black lines), fixed-depth current meters (red broken lines) and fixed-depth Temperature-Conductivity (or Temperature-Conductivity-Pressure sensors - cyan lines) are shown. In each case, the abscissa spans the period of the full Line W moored program and the ordinate is pressure (with axis length scaled according to mooring site depth).



Mean DWBC transport and10-year linear trend estimates

Reported mean transports (negative values denoting equatorward transport in units of 10^6 m^3/s) represent the most equatorward values of the across-line transport streamfunctions evaluated over moorings W1 to W5. Eulerian-mean values given within parentheses consider the transport streamfunctions extended to mooring W6 if different from those truncated at W5. Shown are the estimates for the full 10-year Eulerian-mean fields (W6 only for the 2008-2014 period), the ideal-case Eulerian mean, and the means of the daily DWBC transport estimates in stream coordinates. Statistical uncertainties reported for the latter represent 95% confidence bounds based on degrees of freedom derived from integral time scales (also reported in days). The 4-layer sum encompasses the two Labrador Sea and two Overflow water masses while the 5-layer sum adds the surface layer. For comparison, preliminary estimates of the time-mean net meridional transport across 26.5˚N from the RAPID/MOCHA program are provided (E. Frajke-Williams, personal communication, 2016). The final column in the table give linear trend estimates of the Line W DWBC transports (x 10^6 m^3/s /year) with 95% statistical uncertainties based on a bootstrap procedure.

Layer	Eulerian 10-yr-average	Eulerian ideal-case composite	average of daily profiles	statistical uncertainty	integral T-scale	RAPID/MOCHA preliminary	Line W 10-y trend
SURF	-2.45	-6.62	-6.83	±0.42	12.2	-----	0.004 ± 0.10
ULSW	-2.66	-3.74	-4.33	± 0.46	13.2	-1.8	0.08 ± 0.04
CLSW	-5.06	-6.20	-7.37	± 1.20	14.7	-4.1	0.32 ± 0.06
ISOW	-3.97 (-4.97)	-4.39	-5.77	± 0.93	8.9	-5.5	0.24 ± 0.06
DSOW	-3.74 (-6.14)	-3.31	-5.29	± 0.50	4.7	-5.3	0.09 ± 0.06
4-layer sum	-15.43 (-18.83)	-17.64	-22.76	± 1.38	10.5	-16.7	0.74 ± 0.20
5-layer sum	-17.88 (-21.28)	-24.26	-29.59	± 2.08	11.9	-----	0.74 ± 0.25

Acknowledgements

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Conclusions

A roughly consistent picture is starting to emerge of the time-average AMOC. Some 20-25 x 10^6 m^3/s of intermediate and deep water are carried equatorward by the DWBC in the northern hemisphere, with local recirculations significantly boosting the boundary current flow at 26.5˚ and 16˚ N and to a somewhat lesser extent at 53˚ N and at Line W. One surprising aspect to this analysis is how similar the mean DWBC transport estimates at Line W, 42˚ and 53˚N are to the mean net (boundary to boundary) equatorward deep water transport estimates at 26.5˚ and 16˚ N. While synthesis of these observations into an internally-consistent dynamical description of AMOC variability has not as yet been accomplished, we look forward to a time when this will be possible.