Velocity structure along Line W from a decade of shipboard measurements and satellite data

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Introduction

Regular observations along Line W have provided one component of a long-term AMOC observing system in the Atlantic under the umbrella of the US CLIVAR program. Line W stretches from the continental shelf south of New England towards Bermuda across the Deep Western Boundary Current (DWBC), which flows equatorward along the continental slope between the 2500 and 4000 m isobaths, and across the vigorously meandering Gulf Stream down-stream of its separation point by Cape Hatteras (**Figure 1**).

The sustained 10-year Line W program, completed in spring 2014, comprised moorings across the DWBC (**Figure 2**) and repeated shipboard measurements collected once or twice per year at 26 regular stations. Shipboard observations include temperature, salinity, and dissolved oxygen profiles as well as lowered acoustic Doppler current profiler (LADCP) and tracer measurements.

The Line W moorings show tremendous variability in transports of the DWBC water classes (**Figure 3**). Here we examine the LADCP sections from 13 Line W occupations and use tracer measurements and satellite altimetry to investigate the flow at Line W.

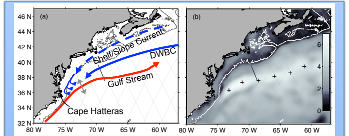
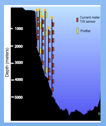


Figure 1. Panel (a): schematic of the circulation in the northwestern North Atlantic. Panel (b): log of the variance in annually-averaged SSH anomalies. Jason-2 tracks (grey lines) and location of Line W mooring array (black line) are shown; crosses represent the Gulf Stream mean path (Peña-Molino and Joyce, GRL, 35, 2008).



Water mass	average depth
ULSW	2095 m
CLSW	1958 m
ISOW	2771 m
DSOW	3575 m

Figure 2. Typical Line W mooring array (this varied somewhat for each setting).

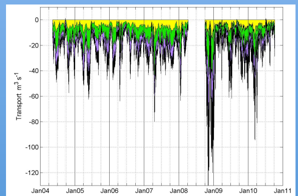


Figure 3. DWBC transports calculated from velocities measured by the moorings. Flow is integrated from the shelfbreak seaward to the (time-varying) location of maximum southward transport stream-function. Water masses are: Upper- and Classical- Labrador Sea Waters (yellow and green), Iceland-Scotland and Denmark Strait Overflow Waters (purple and black). Figure based on Figure 4 of Toole et al., DSR 58, 2011.

The Gulf Stream…

Variability in Gulf Stream path downstream of Cape Hatteras is evident in satellite SSH measurements. Altimetry suggests that the meander envelope of the Gulf Stream where it crosses Line W is 350 km wide when the most extreme paths are included; 98% of the paths fall within an envelope that is 200 km wide (**Figure 4**). The mean position of the Gulf Stream at Line W – taken as the location of the 40-cm SSH contour from maps of the deseasoned, monthly-averaged absolute dynamic topography – lies 260 km offshore of the shelfbreak.

The 13 LADCP sections along Line W also indicate strong variability in Gulf Stream position. The positions – defined by the distance from the shelfbreak to the maximum in the near-surface cross-track velocity component – range from 170 km (Station 12) to 460 km (Station 21). While this range is consistent with the meander envelope suggested by altimetry, an offshore-shifted Gulf Stream is more common in the LADCP sections than in the altimetry data (**Figure 5**). This suggests that large offshore meanders are relatively short-lived and may get smeared out by the monthly-averaged altimetry maps.

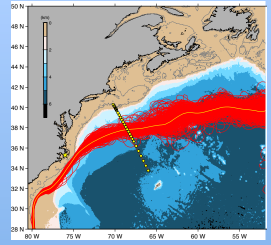


Figure 4. Map of Gulf Stream paths determined from the 40-cm contour from 20 years (1993-2012) of monthly maps of the Aviso absolute dynamic topography (red). The mean path (yellow contour), Line W repeat stations (yellow circles), and Cape Hatteras (yellow star) are also shown. Shading shows the bathymetry with the 200 m isobath contoured.

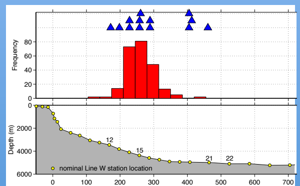


Figure 5. Histogram of distances between the shelfbreak (39.90°N 69.92°W) and the satellite-derived Gulf Stream paths at Line W (red). Also shown are Gulf Stream positions determined from the near-surface velocity maxima from the 13 Line W LADCP sections (blue triangles) and the locations of the nominal Line W stations (yellow circles) superimposed on a bathymetric section.

The subsurface flow…

The LADCP sections along Line W reveal strong temporal and spatial variability in the subsurface velocity structure of the DWBC, the deep Gulf Stream and in the interior (see, for example, **Figure 6** to compare the cross-track velocities from the two LADCP sections with the most extreme Gulf Stream positions).

The Gulf Stream

Previous studies of the Gulf Stream have noted that the location of maximum velocity is progressively farther offshore with increasing depth, resulting in a "tilted" Gulf Stream structure. Line W LADCP sections are consistent with these studies. The position of maximum cross-track velocity at 200 m depth is usually aligned with the near-surface Gulf Stream (**Figure 7**, left), but the position of velocity maximum at 1000 m depth is almost always offset seaward from the upper-ocean Gulf Stream (**Figure 7**, center). This is an important consideration when launching Argo floats to "seed" the Gulf Stream: floats launched where the surface velocity is maximum will be north of the deep Gulf Stream when they descend to their parking depth at 1000 m.

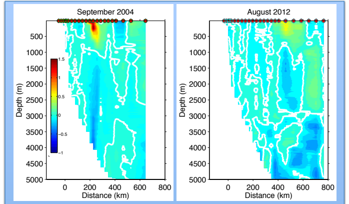


Figure 6. Cross-track velocities (m/s) from two LADCP sections along Line W. Left: the crossing with the onshore-most Gulf Stream position (near Station 12). Right: the crossing with the offshore-most Gulf Stream position (near Station 21).

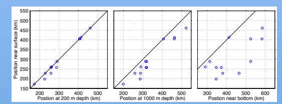


Figure 7. Position of cross-track velocity maxima at depth versus the near-surface maxima for each LADCP section.

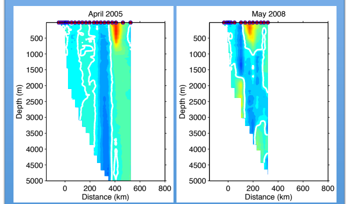


Figure 8. Cross-track velocities (m/s) for LADCP sections showing a Gulf Stream that reaches through the entire water column (left) and one where the maximum bottom velocities are disconnected from the upper-ocean Gulf Stream (right).

The position of maximum (northeastward) cross-track velocity near the seafloor is typically offset even farther offshore (**Figure 7**, right). Though this deep velocity maximum is sometimes clearly an extension of the upper-ocean Gulf Stream (**Figure 8a**), this connection is not always obvious in individual sections (**Figure 8b**).

The Eulerian mean section of the cross-track velocities – generated from LADCP data from all 13 sections – indicates a deep-reaching Gulf Stream with weak (northeastward) flows that extend from the base of the upper-ocean Gulf Stream to the seafloor (**Figure 9**).

The DWBC

A DWBC is evident in the Eulerian mean velocity section as a core of bottom-intensified negative (southwestward) flow over the slope between the 3500 m and 5000 m isobaths (**Figure 9**). This feature is consistent with the the Eulerian mean velocity section previously reported for the 2004-2008 Line W mooring array (**Figure 10**). However, a bottom-intensified southwestward flow over the 2500 m to 3000 m isobaths that is observed in the mooring-mean and in some of the individual LADCP sections is *not* clear in the LADCP Eulerian mean section.

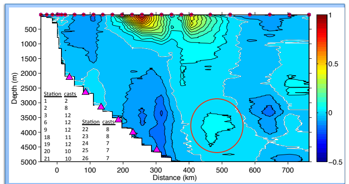


Figure 9. Eulerian mean of the cross-track velocities (m/s) from the 13 LADCP sections. Contour interval is 5 cm/s and grey contour is 0 m/s. Red dots indicate the 26 nominal station locations. Number of realizations at each station is 13 unless indicated otherwise. Magenta trianlges show the Line W mooring locations from the 2004-2008 setting of the array.

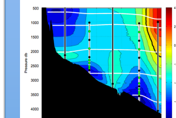


Figure 10. The Eulerian mean of the cross-track velocities (cm/s) reproduced from Figure 4 of Toole et al., DSR, 58, 2011, calcualted from the 2004-2008 Line W mooring array. Instrument locations are indicated.

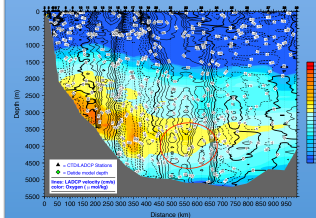


Figure 11. Cross-track velocity (black contours) from LADCP measurements superimposed on the contemporaneous oxygen concentrations for the May 2014 Line W section (29 stations were occupied, extending up the Bermda Rise).

A possible interior pathway

The LADCP section from May 2014 exhibits intensified flow from 3500 m to 4500 m depth in the interior between Stations 18 and 24 (**Figure 11**, red circle), similar to the Eulerian mean here (**Figure 9**, red circle). Furthermore, CFC-12 from the May 2014 section (**Figure 12,** red circle) shows elevated levels in this region of intensified flow.

This elevated CFC-12, which is observed to occur in the same potential density layer as the DSOW component of the DWBC (white contours in **Figure 12**), is indicative of northern source waters contributing to this intensified interior flow. This suggests the deep Gulf Stream carries recirculated DWBC waters.

The average velocity of flow in this potential density layer (calculated from the LADCP and CTD data at each station) shows the strong southwestward flow associated with the DWBC. In addition , the strong northeastward flow of this high CFC-12 water at Stations 21 – 23 is evident (**Figure 13**).

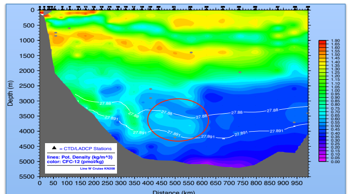


Figure 12. Tracer observations from the May 2014 Line W section showing CFC-12 concentrations. The potential density layer that inlcudes the DSOW is contoured in white.

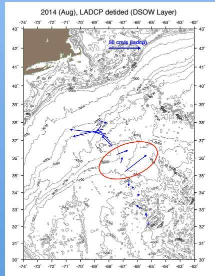


Figure 13. Layer-averaged velocities for May 2014 in the potential density layer indicated with the white contours in Figure 12.

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