Contiguous Flow of Upper Labrador Sea Water along the Boundary Rounding Cape Hatteras: Continuous in Time or Intermittent?

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Background

The Deep Western Boundary Current (DWBC) comprises Upper- and Classical-Labrador Sea Water (ULSW and CLSW)—formed by deep convection in the Labrador Sea—and the denser (and deeper) Overflow Waters formed as Nordic Sea waters spill over the Greenland-Iceland-Scotland sill into the North Atlantic. Variability in pathways and strength of these "cold limb" components of the Atlantic Meridional Overturning Circulation (AMOC) is the focus of ongoing study. At Line W, the DWBC flows equatorward, onshore of the Gulf Stream (**Figure 1**).

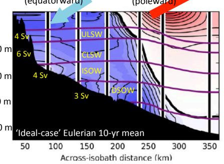

Figure 1. 10-year mean velocity structure and transports of DWBC components measured with moorings (yellow dots in Figure 2) along Line W. Purple lines are isopycnals; heavy black line is the 0 cm/s; positive (poleward) flow is contoured at 10 cm/s increments and negative at 1 cm/s increments. Vertical lines indicate mooring locations. Figure adapted from [Toole et al., 2017].

At Cape Hatteras, some DWBC water passes under the separating Gulf Stream in the "crossover region" (**Figure 2**) and is thought to move to deeper isobaths, conserving its potential vorticity as it continues equatorward along the boundary. Some water is detrained from the DWBC here and flows into the abyssal interior. Different models and observational techniques have led to different conclusions about how susceptible each DWBC layer is to the detrainment and exchange processes within the crossover region [*Pickart and Smethie*, 1993; *Bower and Hunt*, 2000a &b].

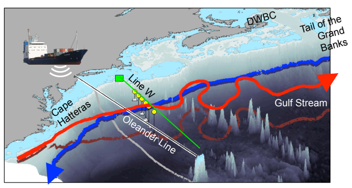

Figure 2. Schematic of the Gulf Stream separating at Cape Hatteras and meandering its way through the New England Seamount Chain (red curve, based on an SSH contour from mapped satellite altimetry, with the path's "shadow" on the seafloor shown in dark red). The DWBC flows along the boundary (i.e., the blue contour highlighting the 2000-m isobath) until Cape Hatteras where is crosses under the separating Gulf Stream. Bathymetry shallower than 200 m is shaded blue.

The PEACH Project:

Collaborative Research: An Observational and Modeling Study of the Physical Processes Driving Exchanges between the Shelf and the Deep Ocean At Cape Hatteras. PEACH aims to identify processes that control the exchange of waters between the shelves along the eastern U.S. seaboard (the Middle Atlantic Bight and Southern Atlantic Bight) and the open ocean where the Gulf Stream leaves the boundary and crosses over the DWBC (**Figure 3**). This multi-institution project (Skidaway, UNC Chapel Hill, NC State, and WHOI with support from the Coastal Studies Institute and URI), funded by the National Science Foundation, has moorings in the water for ~18 months (**Figure 4**). As part of the deployment cruise, extensive shipboard data were collected in April 2017 from the *R/V Neil Armstrong*. These data suggest a contiguous path along the boundary for ULSW at the Hatteras crossover region.

How does the DWBC cross under the Gulf Stream? Is the flow in the ULSW layer contiguous or disrupted? There is evidence of contiguous flow from:

(1) shipboard ADCPs

The *R/V Neil Armstrong's* shipboard acoustic Doppler current profilers (ADCPs) operating at 300, 150, and 38 kHz were used to measure velocities at six tightly-spaced Gulf Stream sections near Cape Hatteras (**Figure 6**) where the Gulf Stream transitions from an attached western boundary current to a separated flow and where it encounters the DWBC. The 38 kHz unit (OS38) provides velocity measures to about 1500-m depth. Each ADCP section shows equatorward flow wedged between the Gulf Stream and the continental slope (**Figure 7**). These velocity data (together with the property data, below) suggest that this counterflow is ULSW rounding Cape Hatteras within a DWBC.

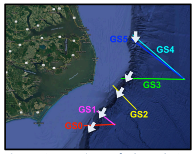

Figure 6. Locations of the velocity sections. Arrows indicate the direction of the counterflow observed beneath the Gulf Stream. Figure courtesy of T. Taylor, CSI.

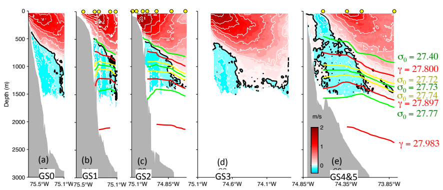

Figure 7. Velocities measured by the OS38 (shaded) rotated to highlight equatorward flow across each section. The 0 m/s isotach is black, positive velocities (towards 30° for a-d and northward for e) and negative (equatorward) velocities are contoured at 0.25 m/s and 0.10 m/s intervals, respectively (white). Green, red and yellow curves highlight isopycnals (kg/m³) determined from the full-water column CTD casts (locations indicated with yellow dots) taken during the respective ADCP sections. (At GS4 the isopycnals are calculated from casts taken along the same track over the previous 24 hours during crossing GS5.) . A similar counterflow was also observed on one of the R/V Armstrong Science Verification Cruises (SVC1 in 2016, see the green line in ***Figure 8a****). Figure from Andres et al. [2018].*

(2) hydrographic casts

Hydrographic data from the cruise suggest that the equatorward flow sampled by the OS38 is the ULSW layer and top of the CLSW layer. Using water mass definitions based on neutral density, γ, the sections' ULSW (27.800 < γ < 27.897 kg/m³) and CLSW (27.897 < γ < 27.983 kg/m³) are indicated by the red curves in **Figure 7**. These isopycnals slope across the sections and are deeper within the deep-reaching Gulf Stream on the offshore sides of the sections. On the onshore sides—where the counterflow is observed—the OS38 captures the entire ULSW layer and even the upper-most CLSW. *Pickart and Smethie* [1993] considered water masses using potential density referenced to the surface, σ_0 (green curves in **Figure 7** and **8**). They found that none of the lightest Labrador Sea Water (the layer between the widely-spaced green curves on the theta-S plot in **Figure 8b**) and only some of the 'intermediate' Labrador Sea Water (between the tightly spaced green curves in **Figure 8b**) rounds Cape Hatteras along the boundary. In contrast, the shipboard observations from AR-15 show equatorward flow in *both* density classes (blue dots in **Figure 8b**).

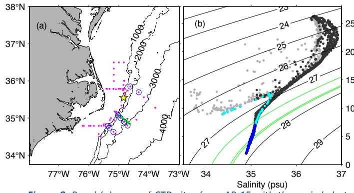

*Figure 8. Panel (a): map of CTD sites from AR-15 with those circled at which equatorward deep flow was observed (blue). Also shown is 'the Point' by Cape Hatteras (star), and location of the SVC1 ADCP section (green), which also sampled a counterflow beneath the Gulf Stream. Panel (b): theta-S curves for casts over isobaths shallower than 500-m (light gray) and exceeding 500-m (black, blue and cyan) where the blue and cyan dots highlight the portions of these casts where equatorward flow was observed (****Figure 7****). Figure from Andres et al. [2018].*

(3) an Argo float

Continuous DWBC flow implied by the closely-spaced velocity sections here is also corroborated by the trajectory of an Argo float deployed on the cruise (**Figure 9**).

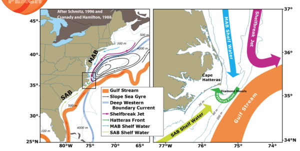

Figure 3. Schematic of the circulation along the U.S. east coast (left) and near Cape Hatteras (right). Image credit: A. Boyette, Skidaway.

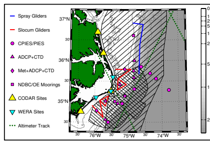

Figure 4. PEACH mooring array deployed April 2017 (recovery in November 2018), radar sites and glider tracks. Patterns indicate area with radar coverage; green dots are altimeter tracks.

Figure 5. R/V Neil Armstrong preparing for the AR-15 cruise, which spanned the 17 to 3500-m isobaths on the Middle and Southern Atlantic Bight shelves and adjacent open ocean. Photo credit: J. McCord, CSI.

Ongoing Work

Though the AR-15 cruise observations from (1) the ADCP sections, (2) hydrographic casts, and (3) the Argo trajectory suggest continuous ULSW flow around Cape Hatteras, these results contrast with previous studies in which the lightest DWBC constituents did not follow the boundary to cross under the Gulf Stream but were detrained from the DWBC and exported into the abyssal interior (e.g., see **Figure 10** adapted from Bower and Hunt [2000a &b] in which all RAFOS floats deployed at ~800 m depth in the BOUNCE program were entrained into the Gulf Stream at the crossover region).

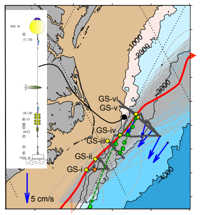

Figure 9. The 6 ADCP sections (dark gray), ensemble of Gulf Stream paths from monthly-mean 25-cm SSH contours (light gray), the path during AR-15 estimated from the daily altimetry product on 20 April 2017 (red), and the trajectory of an Argo float (green) deployed during the cruise that got caught in the ULSW layer. Also shown are locations of near-surface (yellow) and sub-surface (orange) velocity maxima observed on the Gulf Stream crossings. Blue vectors indicate near-bottom DWBC flow observed with SYNOP moorings [Pickart and Watts, 1990]. Inset shows the Articulating Profiler mooring deployed in January 2018 on AR-26 (to be recovered in November 2018 with the other PEACH moorings).

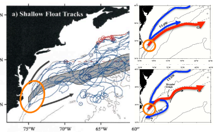

Figure 10. Left: RAFOS float tracks (blue) from the BOUNCE program with launch positions (Xs), tracks shorter than 2-year duration (red), Gulf Stream meander envelope (grey shading), crossover region (orange circle). Right: ULSW fluid parcel trajectories (blue) for two different Gulf Stream configurations (red). In both cases, the ULSW is detrained from the boundary at Cape Hatteras. Figures adapted from Bower and Hunt [2000a&b].

To augment the AR-15 "snapshot" of the ULSW flow around Cape Hatteras, more observations are presently being collected:

Is this contiguous flow of ULSW around the Cape continuous in time, or intermittent? A mooring, deployed on the 1500 m isobath just upstream of Cape Hatteras (**Figure 9**), is equipped with an upward-looking ADCP at 500-m depth, Microcats and an **Articulating Profiler** (to obtain profiles of temperature, salinity and velocity between the fixed point sensors). This is the first deployment of an Articulating Profiler and complements the PEACH mooring array (**Figure 4**).

What is the spatial distribution of ULSW along the boundary in the DWBC? Spray Gliders from an ongoing program to monitor the Gulf Stream (**Figure 11**), are diving to 1000-m depth to measure profiles of water properties and velocity and are able to sample the top of the ULSW layer. This will allow us to generate a map of ULSW distribution.

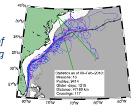

Figure 11. Tracks of Spray gliders crossing the Gulf Stream.

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