A Shelf Water Cascading Event near Cape Hatteras

LU HAN,^a HARVEY SEIM,^a JOHN BANE,^a ROBERT E. TODD,^b AND MIKE MUGLIA^c

^a *Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina*

^b *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts*

^c *Coastal Studies Institute, East Carolina University, Wanchese, North Carolina*

(Manuscript received 18 July 2020, in final form 23 March 2021)

ABSTRACT: Carbon-rich Middle Atlantic Bight (MAB) and South Atlantic Bight (SAB) shelf waters typically converge on the continental shelf near Cape Hatteras. Both are often exported to the adjacent open ocean in this region. During a survey of the region in mid-January 2018, there was no sign of shelf water export at the surface. Instead, a subsurface layer of shelf water with high chlorophyll and dissolved oxygen was observed at the edge of the Gulf Stream east of Cape Hatteras. Strong cooling over the MAB and SAB shelves in early January led to shelf waters being denser than offshore surface waters. Driven by the density gradient, the denser shelf waters cascaded beneath the Gulf Stream and were subsequently entrained into the Gulf Stream, as they were advected northeastward. Underwater glider observations 80 km downstream of the export location captured 0.44 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) of shelf waters transported along the edge of the Gulf Stream in January 2018. In total, as much as $7 \times 10^6 \text{ kg}$ of carbon was exported from the continental shelf to a greater depth in the open ocean during this 5-day-long cascading event. Earlier observations of near-bottom temperature and salinity at a depth of 230 m captured several multiday episodes of shelf water at a location that was otherwise dominated by Gulf Stream water, indicating that the January 2018 cascading event was not unique. Cascading is an important, yet little-studied pathway of carbon export and sequestration at Cape Hatteras.

KEYWORDS: Continental shelf/slope; Fronts; In situ oceanic observations

1. Introduction

Shelf–open ocean exchanges play important roles in the global carbon budget (Walsh 1991; Bauer et al. 2013), the transport of nutrients, pollutants, heat and biomass, as well as the modulation of storm tracks and intensity, with significant environmental, economic, and societal implications (Lentz and Fewings 2012; Todd et al. 2019). Cape Hatteras, North Carolina, the dividing point between the Middle Atlantic Bight (MAB) and South Atlantic Bight (SAB) along the U.S. East Coast, is an active region for shelf–open ocean exchanges because of the confluent western boundary currents and convergence of the adjacent shelf and slope waters (Verity et al. 2002; Jahnke 2010). It has long been recognized that a large amount of carbon-rich shelf water is exported from the shelf near Cape Hatteras (Fisher 1972; Churchill and Berger 1998; Savidge and Bane 2001; Churchill and Gawarkiewicz 2012, 2014; Savidge and Savidge 2014). Exported shelf waters that have been entrained along the northern edge of the Gulf Stream have been observed hundreds of kilometers downstream of Cape Hatteras and are commonly referred to as “Ford Waters” (Church 1937; Ford et al. 1952; Kupferman and Garfield 1977; Lillibridge et al. 1990). On the continental shelf, an average of about 0.12 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) of warm and saline SAB water (Savidge and Savidge 2014) and about 0.13 Sv of relatively cold and fresh MAB water flow toward and

converge near Cape Hatteras (Churchill and Berger 1998; Churchill and Gawarkiewicz 2012, 2014). The baroclinic front between these two distinct water masses is known as the “Hatteras Front” (HF; Stefánsson et al. 1971; Pietrafesa et al. 1994; Savidge 2002). Export pathways for shelf water at the front are highly variable and not yet well defined (Churchill and Gawarkiewicz 2012; Savidge and Savidge 2014).

Dense shelf water cascading down the continental slope is an important mechanism for shelf water export, leading to both carbon export from the continental shelf and carbon sinking to deeper layers in the open ocean where it is sequestered from surface exchange (Stefánsson et al. 1971; Yoder and Ishimaru 1989; Shapiro and Hill 1997; Shapiro et al. 2003; Ivanov et al. 2004; Ulses et al. 2008; Sanchez-Vidal et al. 2009). However, among an extensive inventory of observed cases of dense water cascades globally (Ivanov et al. 2004), no such event was reported near Cape Hatteras, possibly due to the intermittency, subsurface nature, and limited spatial extent of shelf water cascades. The closest sites were on the SAB shelf along the Georgia coast (Stefánsson et al. 1971; Yoder and Ishimaru 1989). However, subsurface MAB shelf waters have been observed being carried along the edge of the Gulf Stream (GS) over 200 km downstream of Cape Hatteras as part of the Ford Water (Churchill et al. 1989; Lillibridge et al. 1990). These instances of subsurface shelf waters were observed below GS surface waters, but after the GS detached from the continental slope and thus have not been previously identified as cascading events. However, they might have been first entrained below the GS water by the cascading process near Cape Hatteras and then advected downstream with the Gulf Stream.

The life cycle of a cascading event can be divided into several stages (Gawarkiewicz and Chapman 1995; Shapiro et al. 2003;

Denotes content that is immediately available upon publication as open access.

Corresponding author: Lu Han, luhan@unc.edu

FIG. 1. (a) Sea surface salinity along the ship track of Cruise AR-26, the locations of three NDBC buoys (44014, 41025, 41064), four PEACH buoys/moorings (B1, B2, A4, A7), the NCROEP mooring, and the Spray glider's track during 13–27 Jan 2018. Exported shelf water was observed along the magenta portion of the glider track. The red line marks the location of repeated cross-shelf transects shown in Fig. 2. (b) SST image from 0912 UTC 19 Jan 2018, the day on which cast 77 was taken.

Ivanov et al. 2004). The Gulf Stream has significant impact on the complex dynamic processes near Cape Hatteras (Churchill and Berger 1998; Savidge and Bane 2001; Savidge 2002; Churchill and Gawarkiewicz 2014; Savidge and Savidge 2014). We propose the following four-stage dynamic framework for the cascading of shelf waters at the HF and subsequent entrainment by the Gulf Stream: 1) the preconditioning stage, during which the shelf water becomes denser than the adjacent GS water; 2) the falling stage, during which the shelf water flows down the sloping bathymetry in the form of a gravity current; 3) the turning stage, during which the shelf water reaches a depth where it is neutrally buoyant within the GS and

turns left due to its entrainment into the Stream; and 4) the final stage, during which the shelf water flows with the GS.

Here we document for the first time a shelf water cascading event at the HF, which occurred during January 2018, with detailed observations over and immediately adjacent to the continental shelf. Together these observations reveal the characteristics and dynamics of shelf water cascading at the HF.

2. Data and methods

Most of the observations used in this study are from the Processes Driving Exchange At Cape Hatteras (PEACH)

FIG. 2. Temperature and salinity along the repeated cross-shelf transect at 35.75°N on (a) 11 Jan, (b) 14 Jan, and (c) 19 Jan 2018. Temperature contours (5°, 10°, 15°, and 20°C) are red, and salinity contours (34, 34.5, 35, and 36) are black. The locations of the numbered CTD casts and B1 are shown along the upper axes. The black dots mark where there were valid measurements.

program. The PEACH field program (April 2017–November 2018) utilized a wide range of observing platforms. During the January 2018 cascading event, we have observations from a research vessel, a Spray glider, surface buoys, subsurface moorings, and satellite remote sensing (Fig. 1a) that complement each other in time and space.

a. Shipboard data

During the second of three PEACH cruises aboard R/V *Neil Armstrong* (Cruise AR-26), hydrographic casts throughout the Hatteras region, underway ADCP data, and surface temperature and salinity measurements along the ship track (Fig. 1a) were collected during 7–19 January 2018. Seventy-seven CTD casts were collected using a multisensor equipped Sea-Bird 911+ CTD rosette. Water mass properties, including in situ temperature, practical salinity, chlorophyll *a*, dissolved oxygen, and turbidity, were measured during each cast. All of these parameters were processed with the SBE CTD data processing software (Sea-Bird Electronics Inc. 2013) and the Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS-10 (McDougall and Barker 2011). Chlorophyll concentration was computed as a standard conversion from the voltage measured directly by the fluorometer with the manufacturer's calibration curve, leading to slight negative values of the lowest chlorophyll concentration. Our results and conclusions are not significantly affected by this since we primarily use the chlorophyll information to infer relative differences between the shelf water and the GS water. Three underway ADCPs operated throughout the cruise: a Teledyne RDI (TRDI) Workhorse 300 kHz (WH300), a TRDI Ocean Surveyor 150 kHz (OS150), and a TRDI Ocean Surveyor 38 kHz (OS38), with vertical resolutions of 2, 5, and 20 m, respectively. Surface temperature and salinity along the ship track were measured by the shipboard Sea-Bird thermosalinograph and were processed and calibrated on board.

During Cruise AR-26, a cross-shelf transect on the MAB shelf at 35.75°N was repeated three times (11, 14, and 19 January; Figs. 1a and 2). The transport of the MAB shelf water was calculated as $T_{\text{MAB}} = \int \int_{x_1}^{x_2} v dx dz$, where v is northward velocity measured by the ship's WH300 ADCP and the integration is over the full water depth z and over the cross-shelf range $[x_1, x_2]$ where the surface salinity measured by the shipboard thermosalinograph was less than or equal to 34.5. This surface isohaline is a common choice to delineate the MAB shelfbreak front (Linder and Gawarkiewicz 1998). The transport calculation assumes vertically well mixed conditions, an assumption supported by CTD casts along the transect (Fig. 2).

b. Glider observations

A Spray autonomous underwater glider (Sherman et al. 2001) collected profiles of temperature, salinity, absolute currents (Todd et al. 2017), chlorophyll fluorescence, and acoustic backscatter along and across the shelfbreak north of Cape Hatteras and within the Slope Sea (Fig. 1a), between 35.5° and 36.9°N during 16 November 2017–10 March 2018 (Todd 2020b). Following Todd (2020b), the shelf water transport through a glider transect was calculated as

$$T_{\text{shelf water}} = \sum_i \sum_j v_{\perp,ij} H(S_0 - S_{ij}) \Delta x_j \Delta z_i,$$

where $v_{\perp,ij}$ is the flow locally perpendicular to the transect (positive offshore), H is the Heaviside function, S_0 is a reference salinity, S_{ij} is local salinity, Δx_j is the distance covered during each glider dive, and $\Delta z_i = 10$ m is the vertical bin size. Here we use $S_0 = 35$ rather than the $S_0 = 34.5$ used by Todd (2020b) because, as we show below, $S_0 = 35$ bounds the exported shelf observed in January 2018. Chlorophyll transport was defined as

$$T_{\text{chl}} = \sum_i \sum_j C_{\text{chl},ij} v_{\perp,ij} H(S_0 - S_{ij}) \Delta x_j \Delta z_i,$$

where $C_{\text{Chl},ij}$ is the measured chlorophyll concentration. The chlorophyll measurements from the glider are calibrated only by applying the factory specified scaling to the measured voltage and are then used for a rough estimation of the carbon export.

c. Buoy and mooring observations

We use meteorological data from three National Data Buoy Center (NDBC) surface buoys (44014, 41025, and 41064) and two PEACH surface buoys (B1 and B2; Fig. 1a). Wind speed and direction were directly measured by the buoys. The net atmosphere-to-ocean heat flux was computed from COARE bulk flux algorithm, version 3.6 (Fairall et al. 2003; Edson et al. 2013):

$$Q_{\text{net}} = \text{SW}_{\text{net}} - Q_{\text{lat}} - Q_{\text{sen}} - \text{LW}_{\text{net}},$$

where SW_{net} is shortwave radiation corrected for albedo into the sea surface, Q_{lat} is latent heat flux, Q_{sen} is sensible heat flux, and LW_{net} is net longwave radiation.

At the two PEACH buoys, temperature and salinity were measured at 5 m depth with Sea-Bird CTDs. In addition, we also use the temperature and depth averaged velocity data from the bottom moored ADCPs at four PEACH shelf moorings (B1, A4, A7, and B2) that were located roughly along the 30-m isobath. We define the along-shelf direction to be the orientation of the major principal axis of the depth-average velocity. The major principal axis direction is roughly parallel to the local isobath at each shelf location. The positive along-shelf direction is poleward.

d. Dissipation estimates

Under the assumption of the proportionality relationship between the Ozmidov scale L_O (Ozmidov 1965) and the Thorpe scale L_T , we estimate the dissipation rate ϵ for a particular CTD cast from the Thorpe scale L_T (Thorpe 1977, 2005) as $\epsilon = c_1 L_T^3 N^3$, where the constant $c_1 = (L_O/L_T)^2 = 0.64$ (Dillon 1982) and N is buoyancy frequency. The Thorpe scale is defined as the root-mean-square (rms) of the vertical displacements between the observed profile and the resorted profile under stable stratification. Standard processing of each CTD cast collected with the SBE 911 CTD results in a density accuracy of $10^{-3} \text{ kg m}^{-3}$ and vertical resolution of 1 m. Thus, the minimum resolvable dissipation rate is $2 \times 10^{-8} \text{ W kg}^{-1}$. Ship heave can significantly degrade performance; however, for the particular cast of interest below, the sea conditions were calm and there were few pressure loops in the raw data.

3. Results

Throughout the winter of 2017/18, glider observations indicated a nearly complete cessation of MAB shelf water ($S \leq 34.5$) export from the continental shelf between the northern edge of the Gulf Stream near 35.5°N and the northern end of the glider survey near 36.9°N (Todd 2020b). Of 12 repeated transects from December 2017 through February 2018, only a single glider transect occupied during 13–19 January, examined below, had seaward MAB shelf water transport close to the long-term average (Todd 2020b). During the winter of

2017/18, a filament of warm and relatively saline waters occupied the outer continental shelf and upper continental slope, extending northward from the northern edge of the Gulf Stream near 35.7°N to near 38°N (Fig. 1b; Todd 2020b). Both glider- and ship-based observations indicated that this water originated in the Gulf Stream and was less dense than the adjacent shelf water, leading to a reversal of the typical cross-shelfbreak density gradient (Todd 2020b) in the MAB where denser slope waters typically abut shelf waters (Gawarkiewicz et al. 2018). This regional-scale setup in the winter of 2017/18 resembled the instances of discharged Gulf Stream water along the edge of the continental shelf that were previously examined by Churchill and Cornillon (1991).

During the AR-26 cruise, no surface signature of MAB shelf water ($S \leq 34.5$ or $T \leq 12^\circ\text{C}$; Savidge et al. 2013) being exported to the adjacent open ocean was evident in either the thermosalinograph data collected along the ship's track or in available sea surface temperature (SST) imagery (Fig. 1). However, as much as 0.21 Sv of MAB shelf water flowed southward toward Cape Hatteras over the southern MAB shelf at 35.75°N on 14 January (Figs. 1a and 2). Throughout the duration of the cruise, no MAB water was observed at B2 (Fig. 3b), the southernmost PEACH mooring, indicating that the MAB water was not flowing very far past Cape Hatteras and onto the SAB shelf. It follows that MAB shelf water was likely exported from the shelf between the latitude of B2 (34.78°N) and the southern end of the glider transect near 35.7°N , where the Gulf Stream flows very near to the edge of the continental shelf.

a. Observations of a subsurface export event in January 2018

The final CTD cast of the AR-26 cruise on 19 January, hereinafter referred to as “cast 77,” captured a layer of relatively low salinity and low temperature water beneath a surface layer of warm and salty GS water at the edge of the GS (Fig. 3). This layer extended vertically for well over 100 m from a depth of about 80 m to the bottom at 220 m with salinity ranging from around 34 to 35 and temperature ranging from about 10° to 13°C , clearly different from the surface GS water directly above and from other GS profiles (Fig. 3). High chlorophyll and dissolved oxygen in the same depth range of cast 77 are characteristic of shelf water (Fig. 3f; Churchill and Gawarkiewicz 2012; Savidge and Savidge 2014). However, no water with these properties was found in any other shipboard CTD casts or the continuously measured thermosalinograph data (Fig. 3b).

Within the high chlorophyll layer, the freshest and coldest point has a salinity of 34 and a temperature of 10°C (herein we refer to this as “34/10 water”), which falls within the climatological T and S ranges of MAB water in January (Fig. 3b, blue ellipse; Savidge et al. 2013). As is clear from Fig. 2, there was a large change in the hydrography on the southern MAB shelf during the cruise, and the MAB shelf water was constrained inshore of the 40-m isobath. The northernmost PEACH mooring, B1, was located at the front between the MAB shelf water and the GS filament water on the outer MAB shelf, where some 34/10 water appeared very briefly on 15 January (Fig. 3b). That 34/10 water possibly formed as a result of mixing

FIG. 3. (a) The locations of CTD casts taken during the AR-26 cruise. Different colors represent casts used in the water mass analysis. (b) A T - S diagram of all of the CTD measurements, with colors as in (a). The gray dots are thermosalinograph data from the cruise. The data at B1 and B2 are also during the cruise (11–19 Jan). (c) Chlorophyll and (d) dissolved oxygen vs salinity at selected shipboard CTD casts, with colors as in (a). (e) Profiles of (e) temperature and salinity and (f) dissolved oxygen and chlorophyll, with cast 77 as solid lines and profiles within the GS as dashed lines.

between the cold and fresh MAB shelf water and the warm and salty GS water in the filament (Fig. 3b). The presence of waters of MAB origin beneath Gulf Stream waters and seaward of the shelf break suggests that these exported waters were subducted as they left the continental shelf.

On the T - S curve for cast 77, mixing signatures are evident from the freshest and coldest point (the 34/10 water) toward higher and lower densities (Fig. 3b). The 34/10 water has the highest values of chlorophyll and dissolved oxygen at cast 77.

The similar two-limb curves in T - S , chlorophyll- S , and dissolved oxygen- S spaces (Figs. 3b-d) suggest that the MAB water is mixing with different water sources at the upper and lower layers. The upper limb suggests mixing between the 34/10 water and the surface GS water. Such mixing may have occurred as the shelf water subducted beneath the GS. The lower limb, at depths between 100 and 220 m, likely indicates mixing between shelf waters with differing properties, which may have already existed before the subduction. In addition to

FIG. 4. (a) The estimated dissipation rate (solid black line) and observed density profile at cast 77 (solid red line). The thin dashed red lines are density at the Gulf Stream profiles, shown in Fig. 3a. (b) The current speed (dashed black lines) and direction (dashed red lines) within a 1-km radius of cast 77, measured by the shipboard ADCP. The solid black line is the speed of the mean current. The solid red line is the direction of the mean current counterclockwise from true east.

the two distinct water masses on the southern MAB shelf already mentioned, there is a third shelf water mass, the waters on the northern SAB shelf. The GS filament water on the MAB outer shelf shared very similar properties with the SAB water, which was warm and salty but with high chlorophyll and dissolved oxygen (Fig. 3). This is supported by both the shipboard CTD casts made on the SAB shelf and MAB outer shelf (Figs. 3c,d), as well as the overlapped temperature and salinity data at B1 and B2 (Fig. 3b). Since the typical GS position along the SAB is immediately adjacent to the continental shelf, both the circulation and hydrography on the outer shelf of the SAB are often dominated by the GS (Atkinson et al. 1983; Castela et al. 2010). SAB water shares some hydrographic properties with GS upper-layer water. However, the relatively long residence time of the water on the SAB shelf (9–11 weeks on average; Savidge and Savidge 2014) allows primary production to increase the chlorophyll and dissolved oxygen concentrations in the water. Likewise, the GS filament water on the MAB outer shelf also had higher chlorophyll and dissolved oxygen relative to the GS water. Accordingly, these two waters will be both categorized as “modified Gulf Stream” (MGS) water. It is possible that the lower limb was due to the mixing between the MAB shelf water with either one of the MGS waters before the subduction. Herein we refer to the exported shelf water as “shelf water mixture” (SWM).

Since there was no surface signature of shelf water export, the SWM at cast 77 likely resulted from a subsurface shelf water export event due to cascading. The SWM on the shelf

was laterally adjacent to the GS, but was more than 1 kg m^{-3} denser than the GS mixed layer water. Such dense water sitting at the top of the slope would be unstable and tend to flow down the slope. The SWM would cascade down the continental slope until the denser SWM reaches its own isopycnal along the flank of the GS and is then entrained into the GS. It would take some time and distance for the SWM to transform from a gravity current flowing down the continental slope to become part of the GS flow under an approximate geostrophic balance. Propagation of bottom-trapped density driven currents can produce intense turbulent mixing due to entrainment of ambient water and bottom friction (Price et al. 1993). At cast 77, the mean turbulence dissipation rate of the SWM layer (below 100 m) was about $2.85 \times 10^{-6} \text{ W kg}^{-1}$, over 10 times that within the surface mixed layer (upper 30 m; Fig. 4a), which is evidence of active turbulent mixing (Thorpe 2005). Furthermore, the speed of the SWM had much smaller vertical variation than that of the upper layer and the direction of the depth-averaged flow over the SWM layer was about 17° to the right of the overlying GS flow (Fig. 4b). Taken together, these support the hypothesis that the SWM measured at cast 77 was in the turning stage, transforming from a gravity current flowing down the continental slope and turning left to the poleward direction due to the GS entrainment.

b. Observations of the final stage

Glider observations provide evidence of the final stage in the cascade process in the form of a roughly 100-m-thick layer of

FIG. 5. Spray glider observations along successive southbound (13–19 Jan) and northbound (19–26 Jan) transects along the upper continental slope: (a) temperature, (b) salinity, (c) T – S diagram, (d) chlorophyll fluorescence, (e) eastward velocity, and (f) northward velocity along the transect. The black contours are isopycnals, and the gray contours are the 35 isohaline.

relatively cold and freshwater with high chlorophyll approximately 80 km downstream of cast 77 on 17–18 January (Fig. 5). This is the only instance of shelf waters observed along the upper continental slope by the glider from December 2017 through February 2018. This layer of water was bounded by the 35 isohaline, making it distinct from GS water, but it shared similar properties with the SWM sampled at cast 77 (Figs. 5a–d). The similar two-limb mixing feature of the exported shelf water at both cast 77 and along the glider track suggests that the water observed by the glider could have been produced during the same event as the SWM at cast 77, or at least through the same process of SWM cascading from the shelf. The glider-observed layer of SWM lay between the 26 and 26.75 isopycnals, sloping toward the core of the GS. It was moving with the GS at a speed of about 0.2 – 0.9 m s^{-1} northeastward

(Figs. 5e,f). The total transport for the water with salinity less than or equal to 35 through the glider transect in the Slope Sea was 0.44 Sv , which is almost double the sum of the mean alongshore transport on both the MAB and the SAB shelves (Savidge and Savidge 2014). This implies that the SMW entrained a large amount of the ambient water while cascading along the continental slope, as observed in previous measurements of gravity currents (e.g., Price et al. 1993). No such water was observed after the glider turned back to the north on 19 January, indicating the transient nature of the event (Fig. 5).

c. Time scale of the event

The temporal duration of the export event can be estimated from the combined dataset. The mean velocity of the exported SWM measured by the glider was 0.48 m s^{-1} . At that speed, it

FIG. 6. (a) The net heat flux near Cape Hatteras. The red line is the hourly net heat flux at 41025. The black line is the mean daily net heat flux of the five buoys near Cape Hatteras. The shaded area is 1 standard deviation of the daily estimates. (b) Stick plot (black) and magnitude (red) of wind stress at 41025. (c) The along-shelf velocity and (d) bottom temperature at 4 PEACH moorings (B1, A4, A7, and B2, from north to south). The vertical purple dashed lines mark the beginning and the end of the exported shelf water from glider observation, and the vertical green dashed line marks the time at which cast 77 was made.

would have taken the water about 3 days to move with the GS from the cascading location near cast 77 to where it was encountered by the glider about 80 km downstream. In this case, the glider-observed SWM should have been exported from the shelf on 14–15 January. Southward winds began to increase on 14 January (Fig. 6b) and the waters on both the MAB and SAB shelf off Cape Hatteras were pushed equatorward in the along-shelf direction (Fig. 6c). This southward movement lasted for about 5 days, until 19 January, which was the longest southward shelf water flow episode off Cape Hatteras during the entire winter of 2017/18 (Fig. 6c). The stronger equatorward along-shelf flows and the much lower bottom temperature at the moorings on the MAB shelf (B1 and A4) relative to the ones on the SAB shelf together suggest that the HF stayed in Raleigh Bay between moorings A4 and A7 within this 5-day period (Figs. 1, 6c,d). It is conceivable that either one export event lasted for 5 days or that two separate, but closely spaced in time, episodes of shelf water export were measured, one by the glider and another by cast 77.

d. Preconditioning by atmospheric cooling

The waters on the MAB and SAB shelves near Cape Hatteras lost substantial heat to the atmosphere during the 2017/18 winter. The daily net heat flux measured by surface buoys on the shelf had been from ocean to atmosphere for almost 2 months before the export event (Fig. 6a). During that time, shelf waters were losing heat to the atmosphere at an average rate of 345 W m^{-2} and with maximum heat loss of at least 2217 W m^{-2} during passage of a “bomb cyclone” in early January (Hirata et al. 2019). If we neglect lateral advection and consider only one-dimensional heat transfer, a 30-m-deep column of seawater could cool by as much as 15°C in 2 months, assuming an average net heat flux of 345 W m^{-2} from ocean to atmosphere. For shelf waters with salinities of 34–35, cooling from 20° to 5°C would increase density by about 3 kg m^{-3} . However, warmer SAB water and colder MAB water were advected to the Cape Hatteras region. Based on our mooring observations, the temperature of the MAB water decreased by about 10°C (at B1) and that of SAB water (at B2) decreased by

FIG. 7. (a) The essential features and their relative positioning during the shelf water cascading event. The black circle and white triangle mark the locations of cast 77 and the NCROEP mooring, respectively. (b) Schematic of the cascading event at the transect along the Hatteras Front [white dashed line in (a)]; Q represents spatially variable heat flux.

about 5°C between mid-November and mid-January (Fig. 6d). Considering a salinity increase of 1.5 at B1, the MAB water accordingly became 3 kg m^{-3} denser while the SAB water density increased by 2 kg m^{-3} . During the cruise, the maximum observed density of MAB shelf water was 1026.8 kg m^{-3} while SAB waters had a maximum density of 1026.7 kg m^{-3} (Fig. 3b). The GS surface layer had a density of 1025 kg m^{-3} (Fig. 4a). The excess density of the shelf waters due to the cooling preconditioned the system for the cascading event.

4. Discussion

The processes and driving dynamics of shelf water export in the Cape Hatteras region are complex, with a wide range of forcing variability (e.g., the GS, atmospheric forcing, shelf water properties, and local bathymetry; Churchill and Berger

1998; Savidge and Bane 2001; Gawarkiewicz and Linder 2006; Churchill and Gawarkiewicz 2012; Savidge et al. 2013; Churchill and Gawarkiewicz 2014; Savidge and Savidge 2014). The export is largely event-driven (e.g., Todd 2020b). Examination of discrete shelf water export events, as we do here, allows for studying the characteristics and dynamics of shelf water export under certain combinations of forcing.

Using a combination of ship, buoy, mooring and glider observations, we have documented a shelf water cascading event in which a 100-m thick layer of SWM was entrained beneath the shoreward edge of the Gulf Stream (Figs. 3 and 5). However, we are unable to conclusively determine the origin of the SWM, since waters with the same properties were not observed anywhere else on the shelf, except for the 34/10 tip appearing at B1 briefly. We can, however, speculate about potential formation mechanisms for SWM based on regional hydrographic observations.

When the HF advanced southwestward past Cape Hatteras into Raleigh Bay on 15 January, four different water types met at the HF: 1) fresh and cold MAB shelf water, 2) GS water, 3) the GS filament water, and 4) SAB shelf water (Fig. 1b). These last two shared very similar properties and abutted the MAB water at the eastern and southwestern sides, respectively (Fig. 1b). The SWM observed at cast 77 and by the glider could have formed through mixing of MAB shelf water with either the GS filament water on the MAB outer shelf or the SAB water. The SWM could be part of the frontal water between the MAB shelf water and the GS filament water on the southern MAB mid and outer shelf, advected to the HF with the MAB shelf water. It is also plausible that the mixing was between the MAB and SAB waters and occurred at the HF. Along the HF, the SWM flowed to the boundary between the MAB shelf water and the GS, where it cascaded.

We now present a hypothesized dynamic framework of the shelf water cascading event in January 2018 (Fig. 7). We focus on the cross-shore structure near the HF when it was south of Cape Hatteras, since ship- and glider-based observations showed no shelf water exported along the southern MAB shelf edge during and prior to this event. In this framework, we divide the process into four stages.

- 1) Preconditioning stage: The extensive cooling on the MAB and SAB shelves near Cape Hatteras in the 2017/18 winter coincided with the preconditioning stage (section 3d). As a result of the surface cooling, the density of the waters on both the MAB and SAB shelf increased. At the time of the cascade event in January 2018, the SWM at the HF front was more than 1 kg m^{-3} denser than the adjacent GS surface mixed layer water.
- 2) Falling stage: The negative buoyancy acquired from the density gradient drove the SWM to cascade down the upper continental slope in the form of a gravity current, until reaching its neutral density along the edge of the GS (Fig. 7). There it could intrude into the GS following the sloping isopycnal. A 5-day time scale for the cascading event (section 3c) falls within the typical GS meandering periodicity of 3–8 days near Cape Hatteras (Savidge 2004).

FIG. 8. Sea surface temperature (SST) imagery during five probable cascading events from (a)–(e) the earlier mooring observations and (f) the January 2018 event, overlaid with the locations of cast 77 and the NCROEP mooring. The gray dots are all data from the bottom CTD on the NCROEP mooring, and the red dots are those during each event. Black squares show observations from cast 77 for comparison.

The passage of a GS meander can also play a role in the falling process. The downward motion of the cascading SWM can be enhanced by the usual downwelling within the trailing portion of a GS meander's frontal eddy (which is along the leading edge of a GS meander crest). Similarly, cascading could be impeded by upwelling within the leading portion of a frontal eddy (at the trailing edge of the previous meander crest; see [Bane et al. 1981](#); [Lee and Atkinson 1983](#); [Osgood et al. 1987](#); [Gula et al. 2016](#)).

- 3) Turning stage: As the SWM flowed down the continental slope, it would tend to turn right (equatorward in this

location) because of the Coriolis effect; however, the large onshore–offshore sea surface slope of the GS provides a shoreward pressure gradient force, which could slow the cascade's downslope flow and thereby reduce its Coriolis effect, allowing for a left-turning tendency. The velocity at cast 77 suggests that the exported SWM was in the stage of turning left to join the poleward-flowing GS ([section 3a](#)). As part of the process of being entrained into the GS, the exported SWM would tend to turn left due to Ekman dynamics from bottom drag ([Ekman 1905](#)), turbulent mixing with the poleward-flowing GS water, and form drag from the GS.

4) Final stage: In the final cascading stage, the SWM reached its neutral density, became part of the GS, and moved downstream. The glider observations 80 km downstream of cast 77 captured a roughly 100-m-thick layer of SWM transported northeastward with the GS (section 3b). Some instances of the subsurface shelf waters observed by Churchill et al. (1989) and Lillibridge et al. (1990) might have been in the final stage of the cascading process, when the exported shelf waters were carried along the edge of the GS over 200 km downstream of Cape Hatteras. The temperature and salinity of these subsurface shelf waters were not as low as 10°C and 34, which might be due to the seasonality of the shelf water properties or a combination of double diffusion and shear-induced turbulence (Churchill et al. 1989; Lillibridge et al. 1990).

To summarize, a variety of external forcing mechanisms, including atmospheric cooling, wind, and interactions with GS frontal eddies, can conspire to generate a cascading event (Fig. 7b).

The cascading event at the cast 77 location in January 2018 is not unique. Prior to the PEACH field program, a bottom-moored ADCP/CTD was maintained from 2014 to 2017 on the upper slope near Cape Hatteras in water depth of about 230 m (Fig. 1a) by the North Carolina Renewable Ocean Energy Program (NCROEP; General Assembly of North Carolina 2010; Muglia 2019). The location of the NCROEP mooring was 4.2 km from the location of cast 77 (Figs. 1 and 7a). Near-bottom salinity and temperature observations at the NCROEP mooring site usually indicated the presence of GS waters, but the record was punctuated by multiple instances of cool, fresh MAB shelf water along the seafloor (Fig. 8, inset *T-S* diagrams). These episodes usually occurred during winter and lasted for several days each (Muglia 2019). During each of these episodes, the SST pattern was very similar to that during the cascading event in January 2018 (Fig. 8). The HF was to the south of Cape Hatteras, and the seaward flank of the HF was the boundary between the MAB shelf water and the leading portion of a Gulf Stream meander crest (trailing portion of a frontal eddy; Fig. 7a). The large temperature gradient between the shelf water and the Gulf Stream suggests strong horizontal convergence, which we believe is a signature of denser shelf water being subducted under the lighter Gulf Stream water, as was seen during the January 2018 event. The multiyear observations from the NCROEP mooring suggest that cascading of shelf waters at this location may occur during most winter/spring seasons, and that conditions favoring subduction of shelf water at this location may be part of the typical seasonal cycle.

This type of cascading may be an important pathway for carbon export near Cape Hatteras due to the large amount of carbon carried by the chlorophyll-rich shelf waters (Yoder and Ishimaru 1989; Churchill and Gawarkiewicz 2014; Savidge and Savidge 2014). The mean chlorophyll concentration in the cascaded SWM at cast 77 was more than 1 mg m^{-3} and that measured by the glider about 80 km downstream was about 0.7 mg m^{-3} (Fig. 5d). About 0.3 kg s^{-1} of chlorophyll was carried by the 0.44-Sv SWM flow across the glider transect.

Assuming a carbon to chlorophyll ratio of 50 (Yoder and Ishimaru 1989) and steady export, roughly $7 \times 10^6 \text{ kg}$ of carbon would have been exported from the shelf to the open ocean during a 5-day-long cascading event. From a numerical simulation, Fennel and Wilkin (2009) estimated annually averaged carbon export across the MAB shelfbreak of about $50 \times 10^6 \text{ mol C yr}^{-1}$ per kilometer of shelf. The estimated carbon export along the entire length of the MAB shelf over 5 days is nearly equivalent to that during the 5-day cascading event. As with other export events documented in the MAB (e.g., Cenedese et al. 2013; Chen et al. 2014; Todd 2020b), this short-duration event can dominate the annually averaged export, though we note that carbon export near Cape Hatteras may be greater than the MAB-wide average inferred by Fennel and Wilkin (2009) due to the mean along-shelf convergence. Unlike the surface pathways, cascading cannot only export this large amount of carbon in the shelf water offshore to the open ocean, but it can transport the carbon to depths of 200 m or more, beneath the GS surface mixed layer.

5. Conclusions

Carbon-rich MAB and SAB shelf waters converge at the HF off Cape Hatteras, where they can be exported to the open ocean. Episodic shelf water cascading events in the winter constitute one of several different export pathways for MAB and SAB shelf waters near Cape Hatteras. We have used extensive observations collected during the PEACH field program to document a cascading event that occurred in January 2018. We observed 0.44 Sv of SWM transport at the edge of the GS, after being exported from the continental shelf. The estimated total carbon export during the event was $7 \times 10^6 \text{ kg}$, which is comparable to the total carbon export along the entire length of the MAB shelf over 5 days. We divide the cascading event into four stages:

- 1) During the preconditioning stage, SWM became denser than the adjacent GS mixed layer water due to sufficient heat loss to the atmosphere. The seaward flank of the HF became the front between the SWM and the GS, due to the HF being pushed to the south of Cape Hatteras by northerly winds.
- 2) In the falling stage, this large density gradient drove the denser SWM to subduct beneath the GS water and cascade down the continental slope as a gravity current. The falling stage could have been modulated by GS meandering and vertical motions associated with a passing GS frontal eddy.
- 3) During the turning stage, the SWM turned left while being entrained by the GS.
- 4) Last, the SWM flowed downstream as a part of the GS. A number of other likely cascading events observed earlier at the NCROEP mooring indicate that this is a recurring process and not a unique event.

The cascading process could play an important role in the local carbon budget by rapidly transporting carbon-rich shelf water beneath the surface layer in the open ocean.

Acknowledgments. This research was funded by the National Science Foundation (Grants OCE-1558920 to University of North Carolina at Chapel Hill and OCE-1558521 to Woods Hole Oceanographic Institution) as part of PEACH. We acknowledge and thank Sara Haines for the processing and QC of the mooring data, and we thank the PEACH group for helpful discussions and for their support. Additional thanks are given to the crew of R/V *Armstrong* (AR-26). We also acknowledge North Carolina Renewable Ocean Energy Program for providing the CTD data at the NCROEP mooring. We thank two anonymous reviewers for their input and suggestions.

Data availability statement. The cruise data are available online (<https://www.rvdata.us/search/cruise/AR26>). Sea surface temperature (SST) was measured by NOAA's Advanced Very High Resolution Radiometer (AVHRR), with spatial resolution of 1 km and was obtained from the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) THREDDS server (<http://tds.maracoos.org/thredds/ARCHIVE-SST.html>). Spray glider observations from PEACH are available online (<http://spraydata.ucsd.edu>) and should be cited using <https://doi.org/10.21238/S8SPRAY0880> (Todd 2020a). Details of the CTD data at the NCROEP mooring and how to request access are available from mugliam@ecu.edu at East Carolina University Coastal Studies Institute.

REFERENCES

- Atkinson, L. P., T. N. Lee, J. O. Blanton, and W. S. Chandler, 1983: Climatology of the southeastern United States continental shelf waters. *J. Geophys. Res.*, **88**, 4705–4718, <https://doi.org/10.1029/JC088iC08p04705>.
- Bane, J. M., D. A. Brooks, and K. R. Lorenson, 1981: Synoptic observations of the three-dimensional structure and propagation of Gulf Stream meanders along the Carolina continental margin. *J. Geophys. Res.*, **86**, 6411, <https://doi.org/10.1029/JC086iC07p06411>.
- Bauer, J. E., W.-J. Cai, P. A. Raymond, T. S. Bianchi, C. S. Hopkinson, and P. A. G. Regnier, 2013: The changing carbon cycle of the coastal ocean. *Nature*, **504**, 61–70, <https://doi.org/10.1038/nature12857>.
- Castelao, R., S. Glenn, and O. Schofield, 2010: Temperature, salinity, and density variability in the central Middle Atlantic Bight. *J. Geophys. Res.*, **115**, C10005, <https://doi.org/10.1029/2009JC006082>.
- Cenedese, C., R. E. Todd, G. G. Gawarkiewicz, W. B. Owens, and A. Y. Shcherbina, 2013: Offshore transport of shelf waters through interaction of vortices with a shelfbreak current. *J. Phys. Oceanogr.*, **43**, 905–919, <https://doi.org/10.1175/JPO-D-12-0150.1>.
- Chen, K., R. He, B. S. Powell, G. G. Gawarkiewicz, A. M. Moore, and H. G. Arango, 2014: Data assimilative modeling investigation of Gulf Stream warm core ring interaction with continental shelf and slope circulation. *J. Geophys. Res. Oceans*, **119**, 5968–5991, <https://doi.org/10.1002/2014JC009898>.
- Church, P. E., 1937: Temperatures of the western North Atlantic from thermograph records. *Geophys. Int.*, **4**, 1–32.
- Churchill, J. H., and P. C. Cornillon, 1991: Gulf Stream water on the shelf and upper slope north of Cape Hatteras. *Cont. Shelf Res.*, **11**, 409–431, [https://doi.org/10.1016/0278-4343\(91\)90051-7](https://doi.org/10.1016/0278-4343(91)90051-7).
- , and T. J. Berger, 1998: Transport of Middle Atlantic Bight shelf water to the Gulf Stream near Cape Hatteras. *J. Geophys. Res.*, **103**, 30 605–30 621, <https://doi.org/10.1029/98JC01628>.
- , and G. G. Gawarkiewicz, 2012: Pathways of shelf water export from the Hatteras shelf and slope. *J. Geophys. Res.*, **117**, C08023, <https://doi.org/10.1029/2012JC007995>.
- , and —, 2014: Shelf water and chlorophyll export from the Hatteras slope and outer shelf. *J. Geophys. Res. Oceans*, **119**, 4291–4304, <https://doi.org/10.1002/2014JC009809>.
- , P. C. Cornillon, and P. Hamilton, 1989: Velocity and hydrographic structure of subsurface shelf water at the Gulf Stream's edge. *J. Geophys. Res.*, **94**, 10 791–10 800, <https://doi.org/10.1029/JC094iC08p10791>.
- Dillon, T. M., 1982: Vertical overturns: A comparison of Thorpe and Ozmidov length scales. *J. Geophys. Res.*, **87**, 9601, <https://doi.org/10.1029/JC087iC12p09601>.
- Edson, J. B., and Coauthors, 2013: On the exchange of momentum over the open ocean. *J. Phys. Oceanogr.*, **43**, 1589–1610, <https://doi.org/10.1175/JPO-D-12-0173.1>.
- Ekman, V. W., 1905: On the influence of the earth's rotation on ocean-currents. *Ark. Mat., Astron. Fys.*, **2**, 1–52, <https://jscholarship.library.jhu.edu/bitstream/handle/1774.2/33989/31151027498728.pdf?sequence=80&isAllowed=y>.
- Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk parameterization of air–sea fluxes: Updates and verification for the COARE algorithm. *J. Climate*, **16**, 571–591, [https://doi.org/10.1175/1520-0442\(2003\)016<0571:BPOASF>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2).
- Fennel, K., and J. Wilkin, 2009: Quantifying biological carbon export for the northwest North Atlantic continental shelves. *Geophys. Res. Lett.*, **36**, L18605, <https://doi.org/10.1029/2009GL039818>.
- Fisher, A., 1972: Entrainment of shelf water by the Gulf Stream northeast of Cape Hatteras. *J. Geophys. Res.*, **77**, 3248–3255, <https://doi.org/10.1029/JC077i018p03248>.
- Ford, W. L., J. R. Longard, and R. E. Banks, 1952: On the nature, occurrence and origin of cold low salinity water along the edge of the Gulf Stream. *J. Mar. Sci.*, **11**, 281–293.
- Gawarkiewicz, G., and D. C. Chapman, 1995: A numerical study of dense water formation and transport on a shallow, sloping continental shelf. *J. Geophys. Res.*, **100**, 4489, <https://doi.org/10.1029/94JC01742>.
- , and C. A. Linder, 2006: Lagrangian flow patterns north of Cape Hatteras using near-surface drifters. *Prog. Oceanogr.*, **70**, 181–195, <https://doi.org/10.1016/j.pcean.2006.03.020>.
- , and Coauthors, 2018: The changing nature of shelf-break exchange revealed by the OOI pioneer array. *Oceanography*, **31**, 60–70, <https://doi.org/10.5670/oceanogr.2018.110>.
- General Assembly of North Carolina, 2010: An act to modify the Current Operations and Capital Improvements Appropriations Act of 2009 and for other purposes. Session Law 2010-31, Senate Bill 897, <https://www.ncleg.net/EnactedLegislation/SessionLaws/PDF/2009-2010/SL2010-31.pdf>.
- Gula, J., M. J. Molemaker, and J. C. McWilliams, 2016: Submesoscale dynamics of a Gulf Stream frontal eddy in the South Atlantic Bight. *J. Phys. Oceanogr.*, **46**, 305–325, <https://doi.org/10.1175/JPO-D-14-0258.1>.
- Hirata, H., R. Kawamura, M. Nonaka, and K. Tsuboki, 2019: Significant impact of heat supply from the Gulf Stream on a “superbomb” cyclone in January 2018. *Geophys. Res. Lett.*, **46**, 7718–7725, <https://doi.org/10.1029/2019GL082995>.
- Ivanov, V. V., G. I. Shapiro, J. M. Huthnance, D. L. Aleynik, and P. N. Golovin, 2004: Cascades of dense water around the world

- ocean. *Prog. Oceanogr.*, **60**, 47–98, <https://doi.org/10.1016/j.pocean.2003.12.002>.
- Jahnke, R. A., 2010: Global synthesis. *Carbon and Nutrient Fluxes in Continental Margins*, K.-K. Liu et al., Eds., Springer, 597–615.
- Kupferman, S. L., and N. Garfield, 1977: Transport of low-salinity water at the slope water-Gulf Stream boundary. *J. Geophys. Res.*, **82**, 3481–3486, <https://doi.org/10.1029/JC082i024p03481>.
- Lee, T. N., and L. P. Atkinson, 1983: Low-frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf. *J. Geophys. Res.*, **88**, 4541–4567, <https://doi.org/10.1029/JC088iC08p04541>.
- Lentz, S. J., and M. R. Fewings, 2012: The wind- and wave-driven inner-shelf circulation. *Annu. Rev. Mar. Sci.*, **4**, 317–343, <https://doi.org/10.1146/annurev-marine-120709-142745>.
- Lillibridge, J. L., G. Hitchcock, T. Rossby, E. Lessard, M. Mork, and L. Golmen, 1990: Entrainment and mixing of shelf/slope waters in the near-surface Gulf Stream. *J. Geophys. Res.*, **95**, 13 065–13 087, <https://doi.org/10.1029/JC095iC08p13065>.
- Linder, C. A., and G. Gawarkiewicz, 1998: A climatology of the shelfbreak front in the Middle Atlantic Bight. *J. Geophys. Res.*, **103**, 18 405–18 423, <https://doi.org/10.1029/98JC01438>.
- McDougall, T. J., and P. M. Barker, 2011: Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox. SCOR/IAPSO WG127, 28 pp., http://www.teos-10.org/pubs/Getting_Started.pdf.
- Muglia, M., 2019: An observation-based study of gulf stream position, width, orientation, marine hydrokinetic energy, and meander kinematics off Cape Hatteras, NC. Ph.D. thesis, University of North Carolina at Chapel Hill, 206 pp., <https://doi.org/10.17615/8wyl-mt72>.
- Osgood, K. E., J. M. Bane, and W. K. Dewar, 1987: Vertical velocities and dynamical balances in Gulf Stream meanders. *J. Geophys. Res.*, **92**, 13 029–13 040, <https://doi.org/10.1029/JC092iC12p13029>.
- Ozmidov, R. V., 1965: On the turbulent exchange in a stably stratified ocean. *Atmos. Ocean. Phys.*, **1**, 861–871.
- Pietrafesa, L. J., J. M. Morrison, M. P. McCann, J. Churchill, E. Böhm, and R. W. Houghton, 1994: Water mass linkages between the Middle and South Atlantic bights. *Deep-Sea Res. II*, **41**, 365–389, [https://doi.org/10.1016/0967-0645\(94\)90028-0](https://doi.org/10.1016/0967-0645(94)90028-0).
- Price, J. F., and Coauthors, 1993: Mediterranean outflow mixing and dynamics. *Science*, **259**, 1277–1282, <https://doi.org/10.1126/science.259.5099.1277>.
- Sanchez-Vidal, A., and Coauthors, 2009: Across margin export of organic matter by cascading events traced by stable isotopes, northwestern Mediterranean Sea. *Limnol. Oceanogr.*, **54**, 1488–1500, <https://doi.org/10.4319/lo.2009.54.5.1488>.
- Savidge, D. K., 2002: Wintertime shoreward near-surface currents south of Cape Hatteras. *J. Geophys. Res.*, **107**, 3205, <https://doi.org/10.1029/2001JC001193>.
- , 2004: Gulf Stream meander propagation past Cape Hatteras. *J. Phys. Oceanogr.*, **34**, 2073–2085, [https://doi.org/10.1175/1520-0485\(2004\)034<2073:GSMPPC>2.0.CO;2](https://doi.org/10.1175/1520-0485(2004)034<2073:GSMPPC>2.0.CO;2).
- , and J. M. Bane, 2001: Wind and Gulf Stream influences on along-shelf transport and off-shelf export at Cape Hatteras, North Carolina. *J. Geophys. Res.*, **106**, 11 505–11 527, <https://doi.org/10.1029/2000JC000574>.
- , and W. B. Savidge, 2014: Seasonal export of South Atlantic bight and mid-Atlantic bight shelf waters at Cape Hatteras. *Cont. Shelf Res.*, **74**, 50–59, <https://doi.org/10.1016/j.csr.2013.12.008>.
- , J. A. Austin, and B. O. Blanton, 2013: Variation in the Hatteras Front density and velocity structure Part II: Historical setting. *Cont. Shelf Res.*, **54**, 106–116, <https://doi.org/10.1016/j.csr.2012.11.006>.
- Sea-Bird Electronics Inc., 2013: Seasoft V2: SBE data processing—CTD data processing and plotting software for Windows XP, Windows Vista, or Windows 7. <https://www.seabird.com/software>.
- Shapiro, G. I., and A. E. Hill, 1997: Dynamics of dense water cascades at the shelf edge. *J. Phys. Oceanogr.*, **27**, 2381–2394, [https://doi.org/10.1175/1520-0485\(1997\)027<2381:DODWCA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1997)027<2381:DODWCA>2.0.CO;2).
- , J. M. Huthnance, and V. V. Ivanov, 2003: Dense water cascading off the continental shelf. *J. Geophys. Res.*, **108**, 3390, <https://doi.org/10.1029/2002JC001610>.
- Sherman, J., R. E. Davis, W. B. Owens, and J. Valdes, 2001: The autonomous underwater glider “Spray.” *IEEE J. Oceanic Eng.*, **26**, 437–446, <https://doi.org/10.1109/48.972076>.
- Stefánsson, U., L. P. Atkinson, and D. F. Bumpus, 1971: Hydrographic properties and circulation of the North Carolina shelf and slope waters. *Deep. Res. Oceanogr. Abstr.*, **18**, 383–420, [https://doi.org/10.1016/0011-7471\(71\)90102-1](https://doi.org/10.1016/0011-7471(71)90102-1).
- Thorpe, S. A., 1977: Turbulence and mixing in a Scottish Loch. *Philos. Trans. Roy. Soc.*, **286A**, 125–181, <https://doi.org/10.1098/RSTA.1977.0112>.
- , 2005: *The Turbulent Ocean*. Cambridge University Press, 439 pp.
- Todd, R. E., 2020a: Spray glider observations in support of PEACH [Data set]. Scripps Institution of Oceanography, Instrument Development Group, <https://doi.org/10.21238/S8SPRAY0880>.
- , 2020b: Export of Middle Atlantic Bight shelf waters near Cape Hatteras from two years of underwater glider observations. *J. Geophys. Res. Oceans*, **125**, e2019JC016006, <https://doi.org/10.1029/2019JC016006>.
- , D. L. Rudnick, J. T. Sherman, W. Brechner Owens, and L. George, 2017: Absolute velocity estimates from autonomous underwater gliders equipped with Doppler current profilers. *J. Atmos. Oceanic Technol.*, **34**, 309–333, <https://doi.org/10.1175/JTECH-D-16-0156.1>.
- , and Coauthors, 2019: Global perspectives on observing ocean boundary current systems. *Front. Mar. Sci.*, **6**, 423, <https://doi.org/10.3389/fmars.2019.00423>.
- Ulses, C., C. Estournel, P. Puig, X. Durrieu de Madron, and P. Marsaleix, 2008: Dense shelf water cascading in the northwestern Mediterranean during the cold winter 2005: Quantification of the export through the Gulf of Lion and the Catalan margin. *Geophys. Res. Lett.*, **35**, L07610, <https://doi.org/10.1029/2008GL033257>.
- Verity, P. G., J. E. Bauer, C. N. Flagg, D. J. DeMaster, and D. J. Repeta, 2002: The Ocean Margins Program: An interdisciplinary study of carbon sources, transformations, and sinks in a temperate continental margin system. *Deep. Res. II*, **49**, 4273–4295, [https://doi.org/10.1016/S0967-0645\(02\)00120-0](https://doi.org/10.1016/S0967-0645(02)00120-0).
- Walsh, J. J., 1991: Importance of continental margins in the marine biogeochemical cycling of carbon and nitrogen. *Nature*, **350**, 53–55, <https://doi.org/10.1038/350053a0>.
- Yoder, J. A., and T. Ishimaru, 1989: Phytoplankton advection off the southeastern United States continental shelf. *Cont. Shelf Res.*, **9**, 547–553, [https://doi.org/10.1016/0278-4343\(89\)90020-4](https://doi.org/10.1016/0278-4343(89)90020-4).