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Pathways of shelf water export from the Hatteras shelf and slope

James H. Churchill[1] and Glen G. Gawarkiewicz[1]

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[1] It has long been recognized that a massive flow of Middle Atlantic Bight (MAB) shelf water is exported to the deep ocean in the region near Cape Hatteras, North Carolina. We examine the details of this export using data from an extensive array of 26 moorings, deployed over the shelf and slope between Cape Hatteras and the Chesapeake Bay mouth (from 35° 27′ to 36° 40′ N) as part of the U.S. Department of Energy's Ocean Margins Program. Our analysis indicates that the flow of the MAB shelf-edge frontal jet, which typically extends over the MAB slope, falls victim to export over the length of the mooring array, essentially vanishing by the southern extreme of the array. By contrast, the flow of MAB shelf water entering the study region over the inner and middle shelf (to roughly the 40-m isobath) tends to experience very little loss over the extent of the OMP array. Based on our findings and those of previous studies, we hypothesize that this inner and middle shelf flow is diverted seaward upon encountering the Hatteras Front, which separates MAB and South Atlantic Bight shelf waters. Some fraction of this flow appears to return to the OMP array, moving northeastward over the upper slope en route to the deep ocean. Our analysis also suggests that the export of MAB shelf water is enhanced as the Gulf Stream approaches the shelf-edge near Diamond Shoals, a process we deem to be a high priority for future study.

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1. Introduction

[2] Situated off the northeast U.S. seaboard, from Cape Cod to Cape Hatteras, is a coastal region known as the Middle Atlantic Bight (MAB). It is occupied by a distinct water mass, with salinity <34, commonly referred to as MAB shelf water (hereafter referred to simply as shelf water). This water is separated from the more saline slope water offshore by a well-defined surface-to-bottom salinity and density front, which often extends well beyond the MAB shelf-edge. Numerous studies have shown that the mean drift of shelf water is toward the south [e.g., *Bumpus*, 1973; *Beardsley et al.*, 1976; *Mayer et al.*, 1979; *Beardsley and Boicourt*, 1981; *Rasmussen et al.*, 2005; *Flagg et al.*, 2006; *Lentz*, 2008]. The mean transport associated with this drift is of order 0.5 Sv and is roughly evenly divided between the transport of the shelf-edge frontal jet, which typically extends over the outer shelf and upper slope, and the transport of water onshore of the jet [*Linder and Gawarkiewicz*, 1998]. That shelf water only episodically appears>50 km south of Cape Hatteras [*Stefansson et al.*, 1971; *Singer et al.*, 1980; *Pietrafesa et al.*, 1994] implies that much of its transport is diverted offshore, to the deep ocean, en route to Cape Hatteras. Such a loss of coastal water is deemed environmentally significant due to the associated seaward transport of constituents such as nutrients introduced to the coastal ocean through runoff and organic carbon produced on the continental shelf. Entrainment of shelf water into the Gulf Stream current near Cape Hatteras has been identified as a principal agent responsible for the export of shelf water to the deep ocean [*Ford et al.*, 1952; *Fisher*, 1972; *Kupferman and Garfield*, 1977; *Churchill et al.*, 1989; *Lillibridge et al.*, 1990; *Churchill and Berger*, 1998].

[3] *Fisher* [1972] reported the first direct observations of shelf water entrainment into the Gulf Stream near Cape Hatteras. From analysis of shipboard CTD data and surface temperature fields obtained from an airborne radiation thermometer, he proposed two means by which shelf water may be conveyed to the Gulf Stream from the region between Cape Hatteras and the Chesapeake Bay mouth. One was entrainment of shelf water into a Gulf Stream meander extending close to the shelf, and the other was movement of water along the northern margin of Gulf Stream water apparently separated from the main current. Later studies have confirmed these two modes of shelf water delivery to the Gulf Stream. Evidence that shelf water may commonly be drawn seaward along the northern boundary of water discharged from the Gulf Stream near Cape Hatteras has been presented by *Churchill and Cornillon* [1991], *Gawarkiewicz et al.* [1996] and *Churchill and Berger* [1998]. Entrainment of shelf water directly into the Gulf Stream current abutting the shelf-edge near Cape Hatteras

[1]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

Corresponding author: J. H. Churchill, Department of Physical Oceanography, Woods Hole Oceanographic Institution, Mail Stop 21, Woods Hole, MA 02543, USA. (jchurchill@whoi.edu)

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has been observed by *Churchill and Berger* [1998] and *Gawarkiewicz et al.* [2008]. *Churchill and Berger* [1998] found that shelf water is often carried to the Gulf Stream along the northern margin of the Hatteras Front, which separates shelf water of the MAB from more saline South Atlantic Bight (SAB) shelf water.

[4] The study of *Churchill and Berger* [1998] made use of data collected over 1992–1994 as part of an intensive investigation, funded by the U.S. Minerals Management Service (MMS), of water properties and flows over the shelf and slope region east of North Carolina [*Berger et al.*, 1995]. As part of this investigation, velocity and water property measurements were acquired from 15 moorings arranged along three across-shore lines and one line coincident with the shelf-edge. *Savidge and Bane* [2001] used these data to examine along-shelf transport in the study region. Notably, they found that convergence of this transport was highly correlated with Gulf Stream position relative to the shelf-edge, which through continuity implies a relationship between Gulf Stream position and across-shelf transport.

[5] Less than two years after the conclusion of the MMS-funded field program, a second intensive investigation of the shelf and slope region near Cape Hatteras was undertaken as part of the U.S. Department of Energy's Ocean Margins Program (OMP) [*Verity et al.*, 2002]. This effort included acquisition of data from a mooring array deployed over the shelf and slope region between Cape Hatteras and the Chesapeake Bay mouth. The velocity and water property data from the array have been used by *Pietrafesa et al.* [2002] to examine the tidal and wind-forced motion over the study region, and by *Kim et al.* [2001] to examine the overall mass and salt budget of the region. However, these data have not been utilized to study the flow and export of shelf water near Cape Hatteras. As will be demonstrated, these data are particularly well suited for such a study, with a high concentration of measurements in the area where a significant off-shelf flow of shelf water tends to occur.

[6] In the work described here, we use the OMP data to examine details of the shelf water transport over the shelf and slope of the OMP study region. Particular attention is given the extent to which the transport entering the northern Hatteras shelf, at the northern boundary of the OMP study region, continues into the SAB. We also examine how the Gulf Stream's position and movement may be related to the export of shelf water. In the Discussion, we put forth a hypothesized scheme of shelf water export from the shelf and slope region north of Cape Hatteras.

2. Measurements

2.1. The U.S. Department of Energy's Ocean Margins Program

[7] The Department of Energy initiated the OMP to investigate various aspects of carbon cycling over the continental margin off the northeastern U. S. seaboard [*Verity et al.*, 2002]. The focus was on the Cape Hatteras shelf and slope region, as this was identified as an area of significant shelf water transport to the deep ocean and as an area where organic carbon produced on the shelf may be deposited over the slope at a significant rate [*DeMaster et al.*, 1994]. The program included collection of data from moored instruments as well as extensive water column and benthic sampling during shipboard surveys [*Verity et al.*, 2002].

2.2. Moored Instrument Data

[8] The OMP mooring array was designed to capture the water transport onto and off of the Hatteras shelf, which extends to roughly the 50-m isobath. It included heavily instrumented mooring lines extending across the northern and southern boundaries of the northern Hatteras shelf, as well as a mooring line extending along the eastern, offshore, boundary (over the upper slope, ~76-m isobath). Additional moorings were deployed over the Hatteras shelf between the northern and southern cross-shelf lines. These included a closely spaced cluster of four moorings, set out near the northern cross-shelf mooring line for the purpose of quantifying fluxes of O_2 and CO_2 within a control volume [*Verity et al.*, 2002].

[9] The array was set out in two deployments. In the first (OMP-A), from early February through mid-May 1996, instruments were distributed over 26 moorings. Because of instrument loss, the mooring count of the second deployment (OMP-B), from early July through early October 1996, was reduced to 23. A description of the velocity, temperature and salinity sensors on the array is given by *Kim et al.* [2001]. The techniques employed to calibrate the moored salinity data, using shipboard CTD measurements and comparison of salinity records from the same mooring during times of a vertically uniform water column, are presented by *Kim et al.* [2001] and *Flagg et al.* [2002]. Data required for our study were spatially coincident, or nearly coincident, records of velocity and salinity that extended over most of a deployment. These requirements were met for 44 paired velocity/salinity records from 19 moorings of OMP-A, and for 24 such records from 14 moorings of OMP-B (Figure 1 and Tables 1a and 1b).

[10] The spatial coverage of these paired records was best over the inner and middle shelf portions (to roughly the 30-m isobath) of the northern and southern cross-shelf moorings lines. The coverage was, however, sparse over the outer shelf and upper slope portion of these lines. In particular, data from the outer portion (>40-m depth) of the southern cross-shelf line included only one paired velocity/salinity record from OMP-A (from 7-m depth on mooring 26) and no such records from OMP-B. As detailed further below, this paucity of velocity/salinity records from the outer moorings of southern mooring line is unfortunate as these moorings appear to have been in a region of enhanced shelf water export to the Gulf Stream.

2.3. Hydrographic Data

[11] The OMP field effort included eight hydrographic surveys conducted from 1993 to 1996. The CTD data acquired were used by *Flagg et al.* [2002] to examine the springtime evolution of the water mass distribution in the OMP region. Two surveys were conducted when the OMP array was in place: the first over early March 1996 (OMP-A) and the second from late July through early August 1996 (OMP-B). The area of the mooring array was intensively sampled during both surveys, with stations occupied along four across-shore lines: one roughly coincident with the northern mooring line, two in the vicinity of the southern mooring line and a fourth near the center of the array

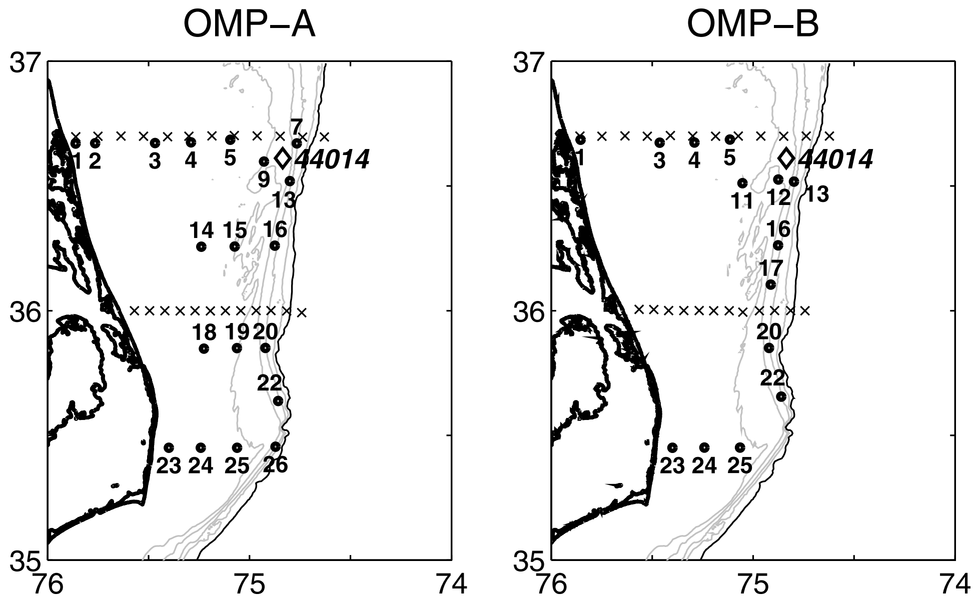

Figure 1. The OMP study region. The bathymetry is represented by the 40, 60, 80 and 100-m isobaths (gray lines) and the 200-m isobath (black line). The dots show the locations of moorings of the OMP-A (winter-spring 1996) and OMP-B (summer-autumn 1996) arrays, from which data used in our study were taken. See Tables 1a and 1b for a listing of depths and times of the records used. Also shown is the site of the NOAA meteorological buoy 44014 (diamond) and the locations of CTD measurements (crosses) used to generate the salinity fields shown in Figure 2.

roughly along 36°N (Figure 1). Both surveys also extended further to the north, essentially encompassing the entire MAB [*Verity et al.*, 2002].

2.4. Meteorological Data

[12] During the time of the OMP mooring deployments, wind and other meteorological data were acquired in the vicinity of the mooring array from NOAA buoy 44014, located at the outer shelf near the northern OMP mooring line (Figure 1), and from NOAA's Diamond Shoals Light C-MAN station (DSLN7), located at the outer shelf roughly 33 km south of the southern OMP mooring line. We computed wind stress from the wind velocity data using the method of *Large and Pond* [1981]. As noted by *Pietrafesa et al.* [2002], the wind records from buoy 44014 and DSLN7 indicate a trend of increasing wind magnitude approaching Cape Hatteras from the north. For 1996, the root mean square (RMS) of the computed wind stress magnitude

Table 1a. Locations of Paired Salinity and Velocity Records Used to Calculate Mean Shelf Water Velocities: OMP-A, Record Duration: 16:00 17 Feb–9:00 8 May 1996

Mooring Number	Latitude	Longitude	Water Depth (m)	Instrument Depths[a] (m)
1	36 40.187	75 51.651	13	7, 10
2	36 40.274	75 45.844	21	8, 18
3	36 40.303	75 28.050	28	11, 20
4	36 40.463	75 17.396	23	6, 9, 15, 20
5	36 41.816	75 5.555	29	10, 18, 24
7	36 40.231	74 45.917	75	7, [35 37], [61 72]
9	36 35.879	74 55.719	39	7
13	36 31.145	74 48.039	76	23, 37, 71
14	36 15.398	75 14.328	30	7
15	36 15.432	75 4.422	40	22, 37
16	36 15.655	74 52.485	76	7, 37,
18	35 50.874	75 13.564	31	8, 22, 28
19	35 51.010	75 3.759	41	8, 23
20	35 51.039	74 55.259	76	9, [36 38], 71
22	35 38.285	74 51.495	76	10, 24, 38, 73
23	35 27.029	75 23.954	20	7, 16
24	35 27.035	75 14.470	30	[8 17], 27
25	35 27.031	75 3.664	40	17, 33
26	35 27.273	74 52.294	75	7

[a]Single depths give the approximate center location of the velocity and salinity records; where these depths are different, depths listed in brackets give the velocity and salinity level respectively.

Table 1b. Locations of Paired Salinity and Velocity Records Used to Calculate Mean Shelf Water Velocities: OMP-B, Record Duration: 5:00 29 Jun–18:00 5 Oct 1996

Mooring Number	Latitude	Longitude	Water Depth (m)	Instrument Depths[a] (m)
1	36 41.112	75 51.264	13	7, 10
3	36 40.419	75 27.747	28	11, 20
4	36 40.447	75 17.409	23	6, 9, 15
5	36 41.14	75 6.892	29	10, 18, [24 22]
11	36 30.675	75 3.178	37	8
12	36 31.527	74 52.524	40	7
13	36 31.052	74 47.834	76	71
16	36 15.730	74 52.591	76	72
17	36 6.293	74 54.756	75	7, [61 72]
20	35 51.045	74 55.264	76	9
22	35 39.347	74 51.655	77	9, 39
23	35 27.048	75 23.949	20	16
24	35 27.052	75 14.473	30	8, 27
25	35 27.065	75 3.895	38	7, 17

[a]Single depths give the approximate center location of the velocity and salinity records; where these depths are different, depths listed in brackets give the velocity and salinity level respectively.

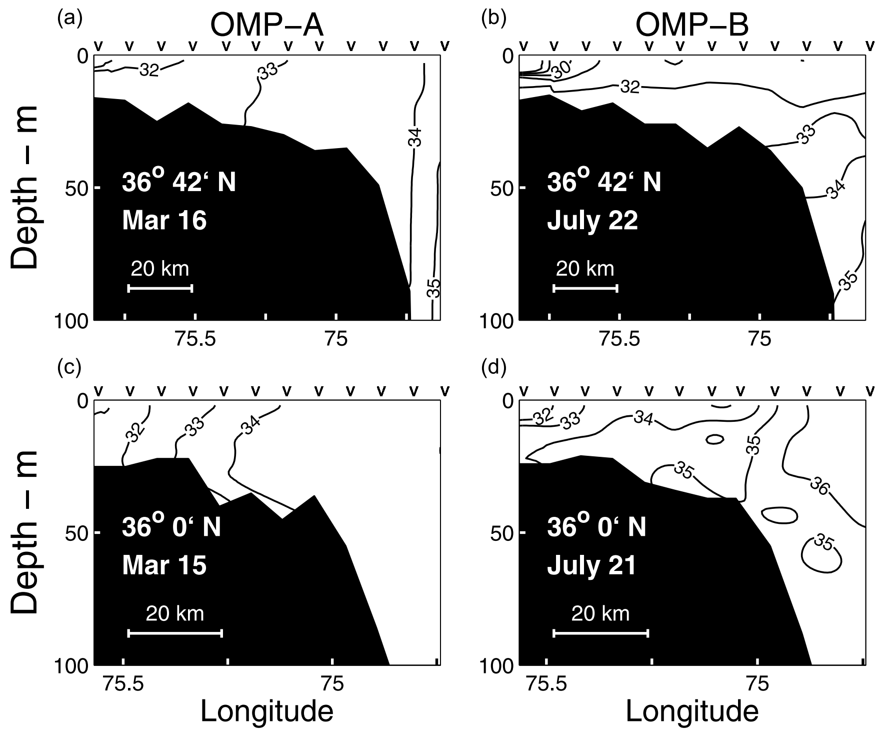

Figure 2. Examples of salinity fields measured by CTD surveys carried out in the (a and c) OMP-A and (b and d) OMP-B mooring deployment periods. Figures 2a and 2b and 2c and 2d, respectively, show the salinity fields along the northern and central portion of the OMP study region (Figure 1).

at DSLN7 is 75% greater than the RMS of the wind stress magnitude at buoy 44014. However, the two wind stress series are highly correlated. The complex correlation coefficient [*Kundu*, 1976] relating the buoy 44014 and DSLN7 stress series of 1996 is 0.73. Here, we present the stress series from buoy 44014 only.

3. Results

3.1. Salinity Fields Over the Hatteras Shelf and Slope

[13] The CTD survey data from 1996 show marked differences between the water mass distributions over the Hatteras shelf and slope during March 1996 (OMP-A) and July 1996 (OMP-B) (Figure 2). The shelf salinity fields of the July survey are much more stratified in the vertical than the salinity fields of the March survey, reflecting the onset of vertical stratification over the Hatteras shelf in spring 1996 as reported by *Flagg et al.* [2002]. Of particular importance to our analysis of the moored salinity and velocity data is the apparent freshening of water over the northern Hatteras shelf between the March and July surveys (Figure 2). This freshening trend is marked by a seaward displacement of the isohalines of the salinity field measured along the northern mooring line. In particular, the position of the 33 isohaline along northern line appears at the mid-shelf in the salinity field of March survey but extends from the outer shelf seaward in the salinity field of the July survey (Figures 2a and 2b). This trend is confirmed by the salinity records from the northern OMP mooring line. Our examination of the CTD data taken further to the north during the OMP surveys indicate the freshening of water over the shelf between March and July 1996 to be a MAB-wide phenomenon, extending to Nantucket Shoals. As will be discussed further below, this freshening of water over the northern Hatteras shelf was a factor in the selection of salinity bands for which fluxes and transports over the OMP-A and OMP-B deployment periods were calculated.

3.2. Patterns of Shelf Water Flow and Export

[14] The OMP mooring data are well suited for examining the transport of shelf water over the Hatteras shelf and slope. To investigate the pathways of shelf water flow, we used the coupled velocity/salinity records (Tables 1a and 1b) to compute mean velocities of water within various salinity bands. Those bands for which mean velocities are shown here are meant to represent relatively low, intermediate and high salinity shelf water. In view of the freshening of water over the MAB shelf, noted above, the salinity limits of these three bands are set at different values for OMP-A and OMP-B. For OMP-A, they are: <32, 32–33, 33–34; whereas <31, 31–32, 32–34 are used for OMP-B. The alteration of the salinity band limits is partially dictated by the quantity of 33–34 salinity water observed over the shelf and slope during the two deployments. Water of 33–34 salinity appears in 36% of the salinity observations of OMP-A, but in only 7% of the OMP-B salinity measurements.

[15] Mean velocities of each deployment are calculated over the same period (see Tables 1a and 1b for limits), chosen to include as many long (>2 months) salinity/velocity records as possible. The averaging period, T, is 80.75 d for OMP-A and 98.6 d for OMP-B.

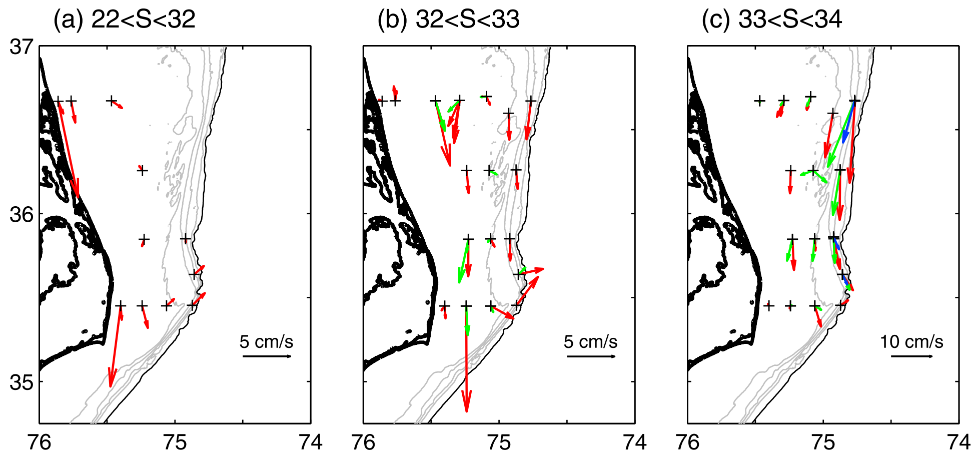

Figure 3. Mean velocities of water within the indicated salinity bands as determined from OMP-A mooring data. All means are for the period 17 February–8 May 1996. Vectors are colored to indicate the depth band of the mean velocity. Means from the depth range of 0–20 m, 20–40 m and >40 m are represented by red, green and blue vectors, respectively. For clarity of viewing, the means from mooring 13 (2nd mooring from the north on the 75-m isobath) are not shown as the vectors intersect those from mooring 7 (to the north) and mooring 16 (to the south). The means from the three current meters on this mooring are of similar magnitude to those of mooring 7, and have cross-isobath components of -0.4, 0.7 and 2.3 cm s^{-1} (with positive directed offshore).

[16] The mean velocity of water within a given salinity band, B, passing a CTD/current meter pair was determined from the pair's salinity/velocity record according to

$$\langle u \rangle_B = \int^T uH_B dt/T,$$

where u is measured velocity vector, and H_B is a function set to 1 for times when the salinity record falls within the limits of B and to 0 when outside these limits. The quantity $\langle u \rangle_B$ may be characterized as a "deployment mean." It reflects both the magnitude and frequency of appearance of velocities measured within the salinity band. The calculation of $\langle u \rangle_B$ was done as a summation

$$\langle u \rangle_B = \sum u_{Bi}/N,$$

where u_{Bi} are those velocities with corresponding salinities within the band, B, and N is the total number of velocity measurements within the period, T.

[17] Prominent in the collection of mean velocities of OMP-A (Figure 3) is the relatively high mean southward flow of 33–34 salinity water over the outer shelf and upper slope along the northern OMP mooring line (note the change of velocity scale from Figures 3a, 3b to 3c). For example, the mean velocity of 33–34 salinity water measured at the near-surface current meter on mooring 7 (at the 75-m isobath) has a magnitude of 16.3 cm s^{-1}, whereas the largest mean velocity of water in any salinity band measured over the northern line's shelf moorings (1–5) is no more than 9 cm s^{-1} in magnitude. As detailed in Section 3.4, the high mean velocity of 33–34 salinity water passing mooring 7 is largely due to the appearance of the shelf-edge frontal jet over the upper slope portion of the northern OMP mooring line.

[18] Notably, the mean southward flow of 33–34 salinity water passing over the upper slope declines appreciably going southward from mooring 7. For example, the near-surface (7–9 m depth) mean velocities of 33–34 salinity water at upper slope moorings 7, 16, 20 and 22 are all directed toward Cape Hatteras but lessen in magnitude from 16.3 cm s^{-1} at mooring 7 to 10.0, 6.2 and 4.1 cm s^{-1} at moorings 16, 20 and 22, respectively. The mean southward flow ceases before reaching mooring 26, at the southeastern extreme of the array, as the mean near-surface velocity of 33–34 salinity water passing the mooring has a northward component.

[19] The mean velocities of OMP-B (Figure 4) also are of highest magnitude at the shelf-edge and upper slope. Unlike the mean velocities of OMP-A, however, these high shelf-edge and upper slope mean velocities are distributed over all salinity bands. This reflects the wide range of salinities seen in the vertically stratified water at the shelf-edge during OMP-B as compared with narrow salinity range of the nearly vertically homogeneous water seen at the shelf-edge during OMP-A (Figure 2). The decline of the magnitude of the southward mean flow over the shelf-edge and upper slope going toward Cape Hatteras is also plainly apparent in the OMP-B mean velocities.

[20] This trend is likely the result of eastward deflection of the shelf-edge/upper slope flow, including the shelf-edge frontal jet, going southward toward Cape Hatteras. As would be expected, this trend is accompanied by an indication of offshore flow over the upper slope moorings. Most, but not all, of the mean velocity vectors along the upper slope mooring line are oriented offshore of the local isobath orientation (Figures 3 and 4). The cross-isobath component of these vectors is small, however, not greater than 2.7 cm s^{-1}.

[21] Also prominent in the OMP-A mean velocities is a region of offshore flow over the outer shelf and upper slope

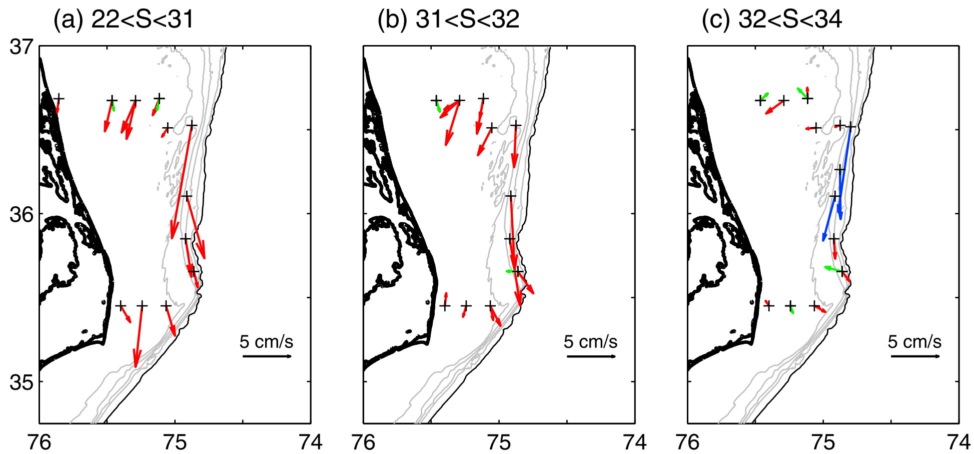

Figure 4. Same as Figure 3 except showing mean velocities in various salinity bands computed from OMP-B mooring data spanning the period of 29 June–5 October 1996.

at the southern end of the array. This is especially apparent in the means of the <32 and 32–33 salinity water. For the <32 salinity band, the offshore flow over the upper slope is particularly noteworthy as water of this salinity appears only over the inner and middle shelf at the northern mooring line (Figure 3). The implication is that this lower salinity water crosses isobaths en route to its export from the shelf at the southern end of the array. Hereafter, this region of export from Hatteras shelf and upper slope, which as identified by the OMP-A mean velocities extends roughly from 35.4 to 35.7°N, will be referred to as the "Hatteras export region." We caution that this designation is based on only 80.75 d of measurements, and so may not be applicable at all times. Evidence of export from this region is not as prominent in the mean velocities of OMP-B (Figure 4). However, these means do not encompass mooring 26, where the strongest offshore shelf water flow is seen in the mean velocities of OMP-A (Figure 3).

3.3. Shelf Water Transport Over the Shelf

[22] Ideally, the OMP data could be used to determine the surface-to-bottom volume transport of shelf water, in various salinity bands, over the three boundary lines of the array. This would allow us to quantify the fate of shelf water flow entering the study domain across the northern mooring line.

[23] As noted in Section 2, however, the limited spatial coverage of paired salinity/velocity records from the array restricts the areas where shelf water volume transport can be reliably estimated. Fortunately, the coverage of these records is most dense over the inner and middle shelf region of both the southern and northern lines of the array.

[24] To compute the volume transport over the relatively well covered portion of these mooring lines (moorings 1–5 of the northern line and 23–25 of the southern line), the cross-sectional area of each portion was divided into rectangular sections (Figure 5). Most sections encompassed a CTD/current meter pair. For those few sections lacking either a velocity or salinity record, the missing record was supplied by the nearest record on the same mooring (see Figure 5). Transport of water in a particular salinity band through each section was taken as the product of velocity of this water, perpendicular to the section, times the section area. The north-south component of velocity was used to compute the volume transport through all sections except for those encompassing mooring 1. Transports for the mooring 1 sections were computing using the velocity component along 336.5° T, roughly parallel to the shore and to the direction of the mean flow at mooring 1.

[25] The total area encompassed by the sections of both lines extends across roughly 90% of the shelf, reaching to within 10 km of the shelf-edge (50-m isobath) at the northern line and to within 6 km of the shelf-edge on the southern line. The estimated total transport (sum of the section transports) along each line thus very nearly represents the total transport of shelf water over the shelf.

[26] Here we show transports in the same salinity bands (Figures 6 and 7) as those of the mean velocities discussed above (Figures 3 and 4). For both deployments, the transports in all salinity bands are highly correlated (at >99% confidence level) with the northward wind stress at buoy 44014 (Figures 6a and 7a). For example, the squared correlations (R^2) relating the northward wind stress with the transport series of OMP-A (shown in Figure 6) are in the range of 0.28–0.41. This result is consistent with the findings of *Kim et al.* [2001] and *Savidge and Bane* [2001]. Both set of investigators report the estimated total volume transport (for all salinities) over across-shelf mooring lines over the Hatteras shelf to be highly correlated with the alongshore wind stress.

[27] By contrast, the difference in transport across the northern and southern lines, the along-shelf flow convergence, is not highly correlated with the northward wind stress, with $R^2 < 0.03$ for all transport series of OMP-A. *Savidge and Bane* [2001] also report that the convergence of the along-shore flow (again for all salinities) is not significantly correlated with the alongshore wind stress.

[28] For much of both OMP-A and OMP-B, the computed transports along the northern and southern line are closely matched. Most significant are the events of southward flow over which the transports are nearly equal. Notable examples occur during mid-March, early April (Figure 6), early September and mid-September (Figure 7). On such occasions, nearly all the shelf water transport entering the Hatteras shelf over the northern mooring line continues into the SAB. This

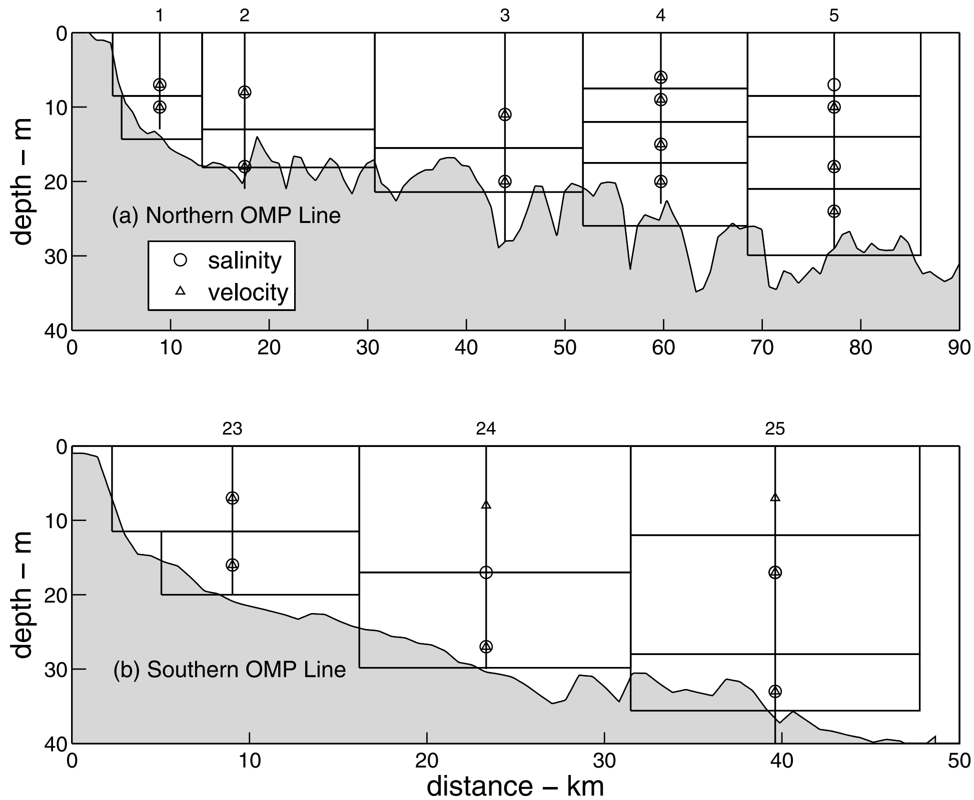

Figure 5. Locations of velocity and salinity records (circles and triangles, respectively) used to compute transports of shelf water across the northern and southern OMP mooring lines. Mooring number is indicated along the top axis of each plot. Transport of water in various salinity bands was computed over each of the rectangular cells shown and summed to give the total transport over the northern and the southern line.

conclusion applies also to the mean transports of both deployments. For all salinity bands, the mean transports across the northern and southern mooring lines are very nearly identical (Figures 8a and 8b), differing by less than their standard error. Given the southward decline in cross-sectional area of the Hatteras shelf (Figures 1, 2 and 5), the near-equality of the southward transport over the northern and southern mooring lines of the OMP array implies a tendency for the along-shelf flow to accelerate approaching Cape Hatteras.

3.4. Shelf Water Properties and Transport Over the Upper Slope

[29] The mean velocities from OMP-A (Figure 3) show two features of the upper slope flow field worthy of closer examination. They are the decline in the along-slope flow of shelf water going southward toward Cape Hatteras (noted in Section 3.2), and the seaward export of low salinity shelf water at the southern end of the OMP array.

[30] The character of the along-slope flow over the upper slope during OMP-A is illustrated here by the low-pass filtered (with a 50-h half-power point filter) northward velocity records from the near-surface (<10-m depth) current meters on mooring 7 (at the northern end of the array) and mooring 22 (near the southern end of the array) (Figure 9). Periods of strong southward flow (>50 cm s^{-1}), marking the presence of the jet associated with the shelf-edge front, appear in both records. On occasions, strong southward flow is seen at both moorings, indicating the extension of the shelf-edge frontal jet to the southern portion of the OMP array. Three notable episodes of this type occur: on 18 February, 30 March and 17 April. The first two coincide with strong southward winds (Figure 9a), whereas the third episode does not.

[31] Very frequently, strong southward flow is seen at mooring 7 and not at mooring 22, indicating a seaward diversion of the shelf-edge frontal jet between the two moorings. A noteworthy event of this type occurs over late April through early May (Figures 9b and 9c). During this event, salinity is in the shelf water range (<34) at mooring 7 but exceeds 35.5 at mooring 22, implying the presence of Gulf Stream or slope water to the south of the area where the shelf-edge frontal jet had been diverted offshore.

[32] Further examination of the salinity records from moorings 7 and 22 (Figure 9c) shows markedly different water mass histories at the two moorings. During the first two months of the deployment, to late April, salinities measured at mooring 7 are predominately in the 33–34 range while salinities at mooring 22 often fluctuate between high (>36) and low (<33) values. The frequent appearance of low salinities (<33) at mooring 22 and not at mooring 7 is further indication that the low salinity water seen at mooring 22 comes not from the upper slope, but rather from the shelf via seaward flow across isobaths. Furthermore, the low salinities seen at mooring 22 very seldom coincide with the presence of the shelf-edge frontal jet at the mooring (as would be indicated by strong southwestward flow in the mooring's

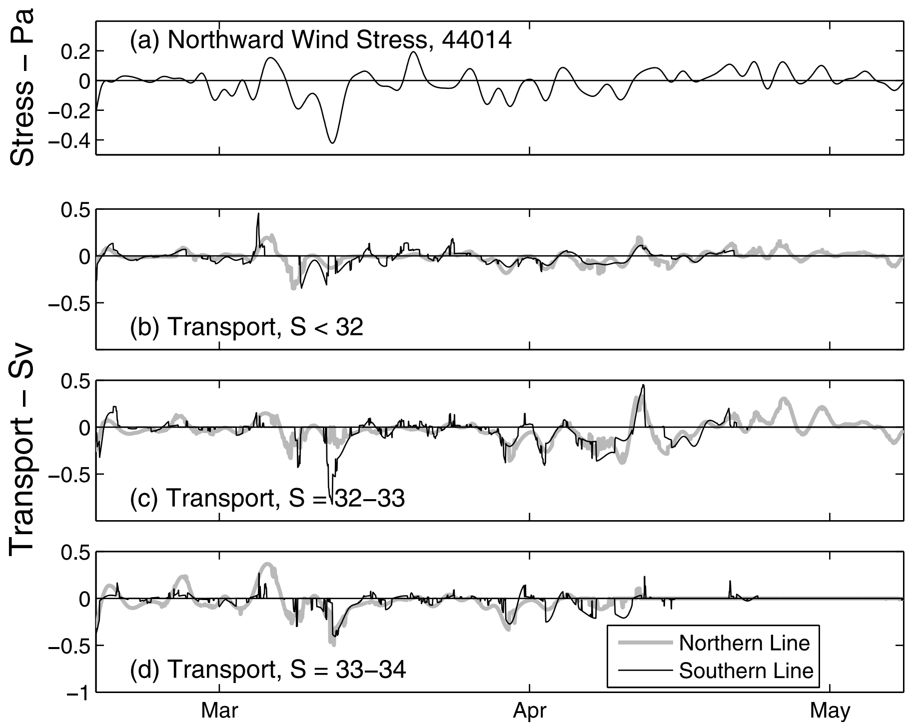

Figure 6. For the OMP-A deployment, a comparison of the (a) northward wind stress at NOAA buoy 44014 (Figure 1) with (b–d) along-shelf transport of water in various salinity bands over the inner and middle shelf (to the ~30-m isobath, see Figure 5) of the northern and southern OMP mooring lines. Positive transport and wind stress is directed to the north.

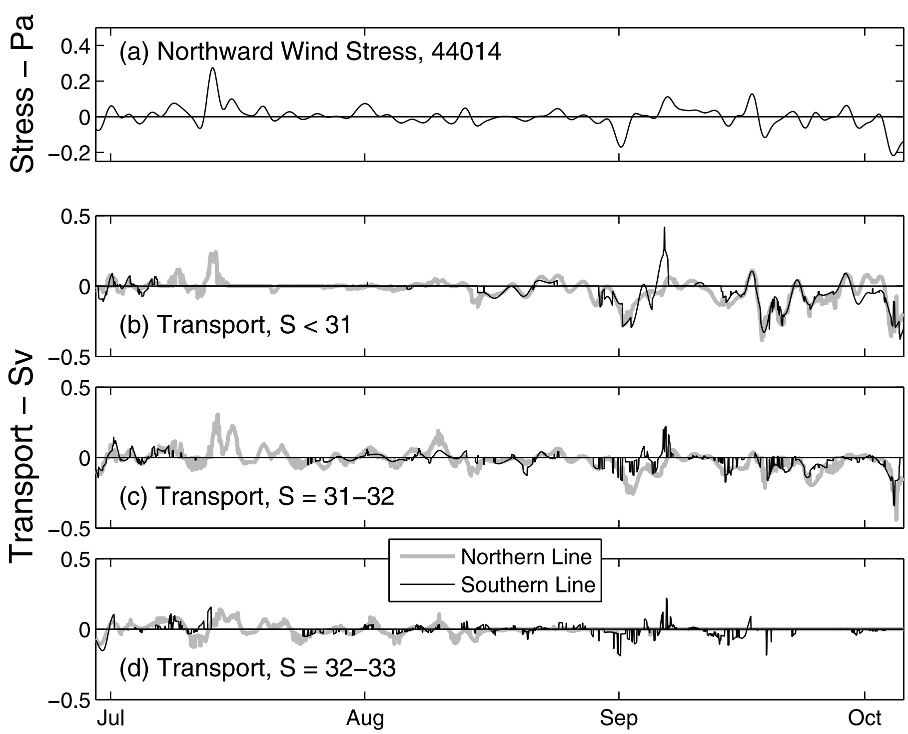

Figure 7. Same as Figure 6 except showing wind stress and shelf water transports of the OMP-B deployment.

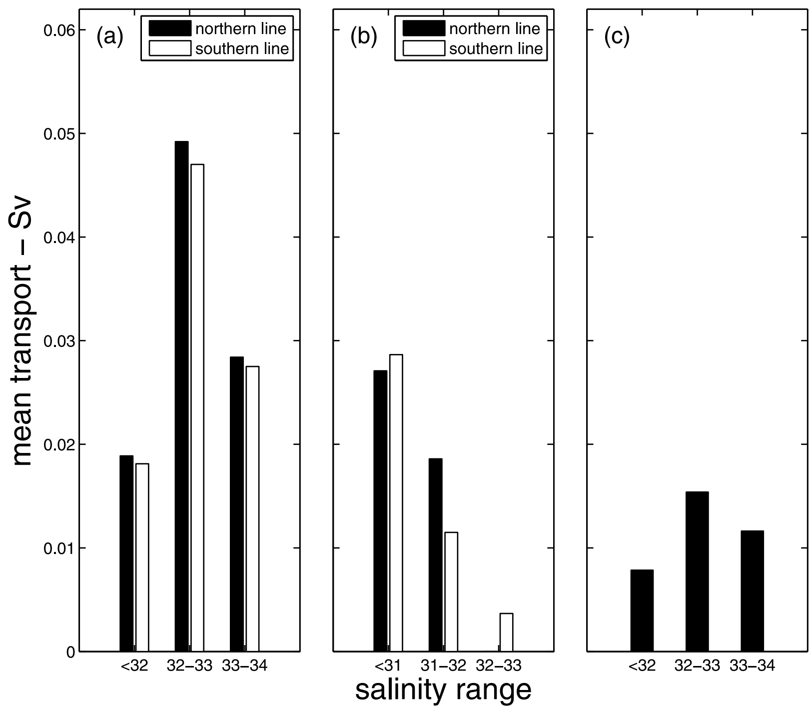

Figure 8. Mean volume transports in the indicated salinity bands. The mean along-shelf transports of water over the inner and middle shelf (to roughly the 30-m isobath) portion of the OMP northern and southern mooring lines as computed from (a) OMP-A and (b) OMP-B data. As opposed to the convention of Figures 6 and 7, positive transports are directed to the south. (c) Estimated mean near-surface (to 15-m depth) water transports over the upper slope across a southern segment of the OMP array (determined from OMP-A data), with positive transport directed offshore.

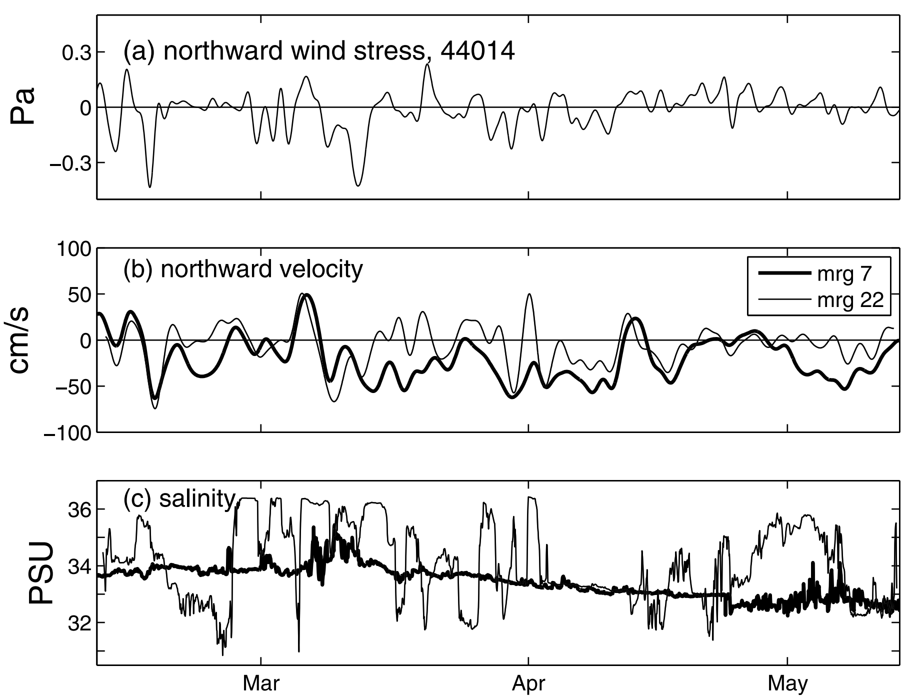

Figure 9. Comparison of (a) northward wind stress at NOAA buoy 44014 with near-surface (7–10 m depth) records of low-passed filtered (b) northward velocity and (c) salinity measured over the upper slope at OMP moorings 7 and 22 (Figure 1).

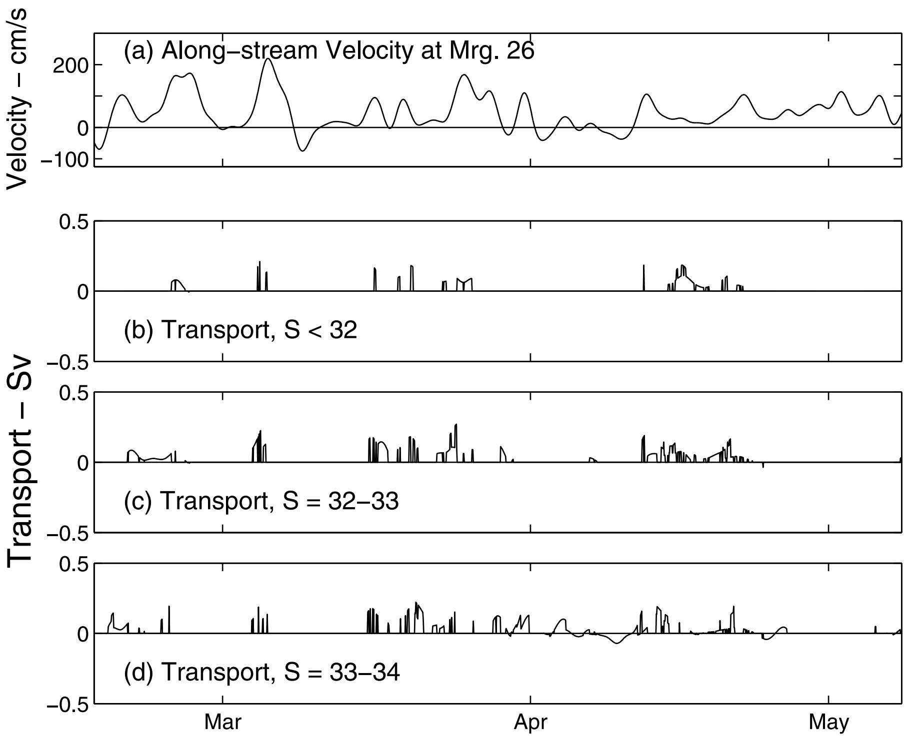

Figure 10. Comparison of the near-surface (7-m depth) (a) along-stream velocity at OMP mooring 26 (Figure 1) with near-surface (upper 15 m) (b–d) off-shelf transports of water in the indicated salinity bands as computed using salinity and velocity data from OMP moorings 22 and 26.

velocity record), implying that the low salinity water had not been carried to mooring 22 within the frontal jet.

[33] To further investigate the seaward export of low salinity shelf water at the southern end of the OMP array, we used the salinity/velocity records from moorings 22 and 26 to estimate the offshore (eastward) transport of shelf water in various salinity bands following the approach outlined in Section 3.3. Because the available salinity/velocity data from mooring 26 was limited to a single near-surface record from OMP-A (Tables 1a and 1b), we computed only a near-surface transport for OMP-A.

[34] The transport estimate was taken as the sum of transports across two sections, oriented along the slope. These sections encompassed the near-surface current meter/CTD pairs on mooring 26 (at 7 m) and mooring 22 (at 9–10 m). The depth of both sections was set to 15 m. Section length was set to 21.3 km for the section containing mooring 26 (the north-south distance between moorings 22 and 26), and to 22 km for the section containing mooring 22 (north-south distance separating the mid-points between moorings 22 and 26 and between moorings 22 and 20). Specifying the orientation of the velocity normal to each section was a bit problematic because of the varying orientation of the bathymetry of the region (Figure 1). The transports shown here (Figures 8 and 10) were computed assuming that the velocity normal to the southern section (containing mooring 26) was oriented perpendicular to the line connecting moorings 22 and 26. The direction normal to the northern section was taken as the perpendicular to the line connecting moorings 22 and 20. Transports computed using other normal velocity orientations (e.g., perpendicular to the local isobaths) were not appreciably different from those shown here (means differing by no more than 35%). The offshore transports were determined over the same salinity bands as those of the along-shelf transports of OMP-A (Figure 6).

[35] Estimated offshore transports in all salinity bands are highly episodic, reflecting the episodic presence of shelf water at moorings 22 and 26 (Figures 9 and 10). With very few exceptions, transports are directed offshore. Over all salinity bands, the mean transports (Figure 8) sum to 35 mSv.

[36] Of particular significance is the estimated 8 mSv mean offshore transport in the <32 salinity band. Based on the discussion above, it may be assumed that this represents the transport of water that had entered the OMP study region principally over the inner shelf (Figure 3a) and crossed isobaths en route to its export from southeastern portion of the OMP array. This 8 mSv mean transport estimate, which accounts for flow in the upper 15 m only, is 42% of the estimated mean southward transport of <32 salinity crossing the shelf over the northern mooring line (Figure 8a). We may conclude that a significant portion of the southward flow of water entering the Hatteras shelf may, at times, be exported from the shelf in the region of OMP moorings 22 and 26 (i.e., in the Hatteras export region defined above).

3.5. Possible Influence of Gulf Stream Motion on Shelf Water Export

[37] With regard to the mechanism affecting the export noted above, we find no causal relationship between the wind stress and the episodes of offshore export shown in Figure 10. Specifically, these episodes of near-surface shelf water export are not clearly associated with periods of upwelling favorable alongshore wind stress (northward) or with offshore directed cross-shelf wind stress (eastward).

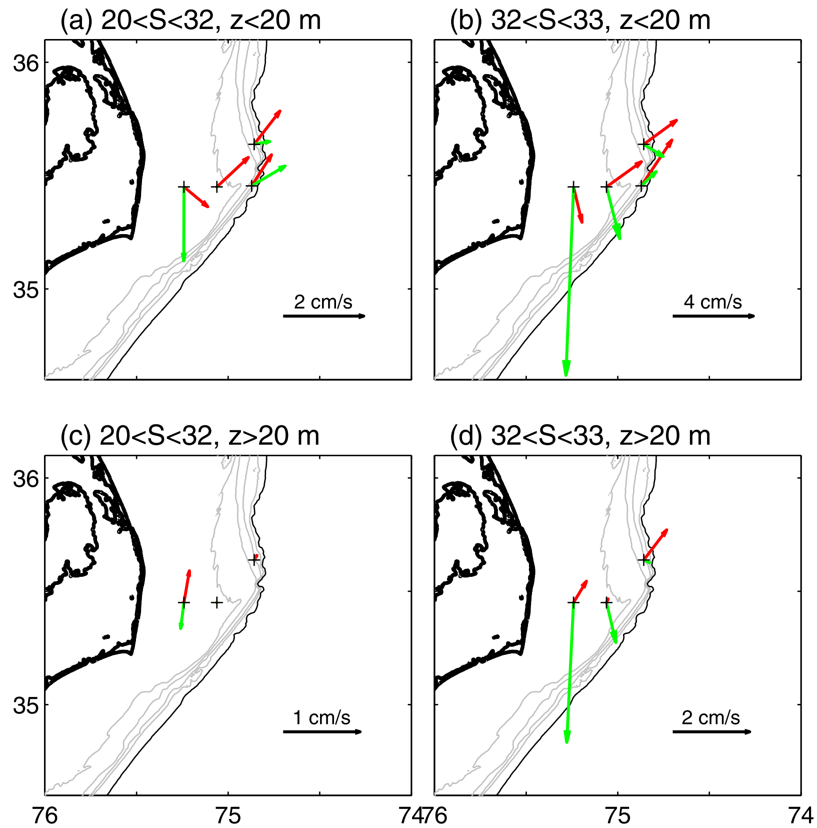

Figure 11. Mean velocities, measured in the "Hatteras export region," of water in the indicated salinity and depth bands under two sets of conditions. Red vectors show mean velocities 36-h before and after the approach of the Gulf Stream to mooring 26 (Figure 1) as indicated by an increase of the along-stream velocity measured at 7-m depth on mooring 26 to over 80 cm s^{-1}. Green vectors show mean velocities for all other times, which comprise roughly 60% of the period considered (17 February–8 May 1996).

[38] To explore a possible relationship between the shelf water export episodes and position of the Gulf Stream relative to the shelf-edge, we show here (Figure 10a) velocities from the near-surface current meter on mooring 26, located at the 75-m isobath at the southeastern corner of the OMP array (Figure 1). These velocities are along an orientation of 26°T, the major principal axis orientation of the low-passed filtered velocity record from the current meter. Note that the velocities along this axis are frequently directed to the NNE with high magnitude (>1 m s^{-1}), indicating the Gulf Stream's proximity to the shelf-edge. Comparison of these velocities with the estimates of off-shelf transport discussed above (Figure 10) indicates that the episodes of off-shelf transport are often associated with the approach of the Gulf Stream front, as indicated by increasing velocity magnitude to the NNE. This trend is consistent with the findings of *Savidge and Bane* [2001], cited above, that the convergence of along-shore transport is correlated with Gulf Stream position relative to the shelf-edge.

[39] To examine the possible effect that the approach of the Gulf Stream may have on shelf water flow in the Hatteras export region, we computed mean flows of shelf water for two sets of conditions: times when the Gulf Stream front approached and passed mooring 26, and all other times. A time of Gulf Stream frontal passage was taken as a period of 36 h before and after a time at which the low-pass filtered NNE-ward near-surface velocity at mooring 26 rises over 80 cm s^{-1}. Such times sum to roughly 40% of the overall OMP-A period.

[40] The mean velocities (Figure 11) show a strong tendency for offshore shelf water flow in the Hatteras export region during the times of Gulf Stream approach to the shelf-edge. Mean velocities of the Gulf Stream frontal passage times defined above are predominately directed off-shelf. With only one exception (for <32 salinity water at the near-surface current meter on mooring 26), the off-shelf component of these means appreciably exceeds the off-shelf component of the means computed for times other than the Gulf Stream frontal approach times.

[41] Given the relatively small number of shelf water export events and times of Gulf Stream frontal passage, this result must be interpreted with caution. We present it here as a possible subject of future studies.

4. Discussion

[42] A significant finding of our analysis is the indication, from the transport calculations, of relatively minor export of water from the inner and middle shelf region of the OMP array. For all salinity bands considered, the mean transports of shelf water over the shelf portions of the northern and southern OMP mooring lines are nearly matched.

[43] This result prompts the question of exactly where one might expect the flow of shelf water entering the Hatteras

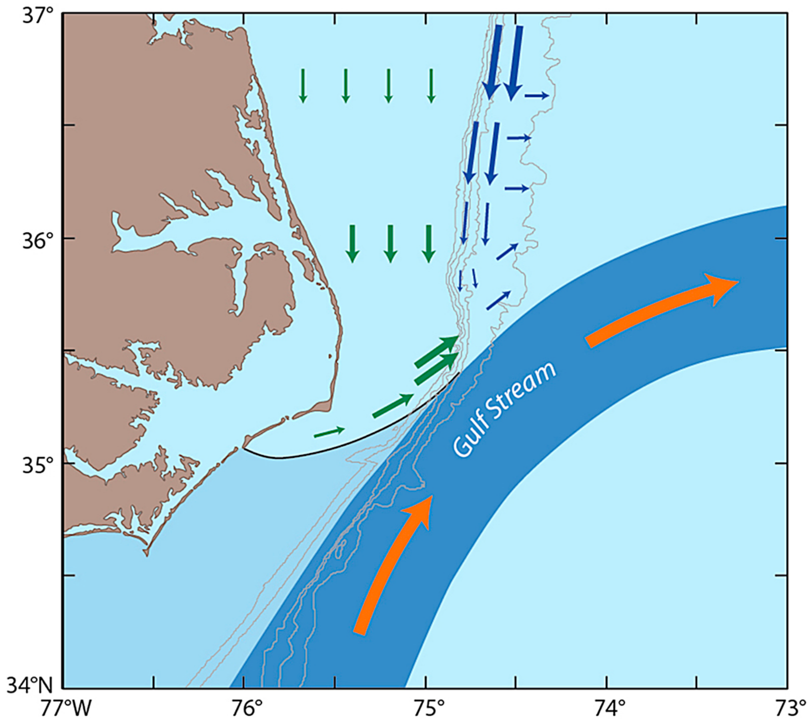

Figure 12. Hypothesized pattern of mean shelf water flow and export from the Hatteras shelf and slope region, based on our analysis and previous work. According to this scheme, the mean flow of shelf water over the inner and middle shelf, represented by the green arrows, experiences little loss going southward toward Cape Hatteras. Because of the decreasing shelf cross-section going southward, the flow tends to accelerate as it approaches the Cape. We hypothesize that most of this flow is transported offshore to the Gulf Stream along the northern edge of the Hatteras Front (the thick black line). Mean transport in the shelf-edge frontal jet, represented by the blue arrows, tends to steadily decline approaching Cape Hatteras, due to offshore export, and essentially vanishes near 35° 20′ N.

shelf to be exported to the deep ocean. *Pietrafesa et al.* [1994] found that shelf water may occasionally reach Frying Pan Shoals, nearly 300 km SSW of Cape Hatteras. However, analysis presented by *Churchill and Berger* [1998] indicates that shelf water entering the SAB may commonly be diverted offshore within a short distance, order 50 km, south of Cape Hatteras. Using CTD data from six cruises, conducted over 1992–1993, they determined the cross-sectional area of shelf water over a cross-shelf line nearly coincident with the southern OMP mooring line and over a cross-shelf line roughly 30 km southwest of Cape Hatteras. No shelf water was detected over the southern, SAB, line during four of the cruises. For the cruise with the maximum shelf water cross-section over the southern line, the estimated shelf water transport across the line was less than one tenth the estimated shelf water transport over the northern, MAB, line.

[44] The complexity of the shelf water flow in the Hatteras region is revealed by the mean offshore flow of <32 salinity water, as calculated from the OMP-A data, that appears over the upper slope at the southern portion of the OMP array. The origin of this flow is uncertain. It does not appear to be linked to a southward flow over the upper slope, as the OMP-A data show no water of salinity <32 over the slope further to the north. It also is unlikely to be the result of seaward flow over the domain of the OMP array, as it is not matched by a difference in the mean alongshore transport of <32 salinity water over the shelf portions of the northern and southern OMP mooring lines. To speculate on a source of this flow, we note that *Churchill and Berger* [1998] found that a significant offshore flow of shelf water is often observed along the northern margin of the Hatteras Front. A surface salinity field presented by *Churchill and Berger* [1998, Figure 3] shows that the Hatteras Front can take a form in which it reaches into the SAB over the inner and middle shelf, but extends northeastward into the MAB over the outer shelf and upper slope. In view of the above observations, we hypothesize that the <32 salinity water transported offshore at the southeastern corner of the OMP array is water that had flowed southward into the SAB over the inner and middle shelf, turned eastward upon encountering the Hatteras Front, and subsequently was carried to the outer shelf/upper slope of the MAB along the margin of the front. Tracks of drifters following such a route are presented by *Churchill and Berger* [1998, Figure 9] and *Gawarkiewicz and Linder* [2006, Figure 12]. We further speculate that the tendency for offshore shelf water flow over the outer shelf and upper slope to be linked with an onshore approach of the Gulf Stream front may be in part due to the influence of the Gulf Stream on the position of the Hatteras Front, with the front extending further northward with the approach of the Stream.

[45] In contrast to the estimated mean southward transport of water over the shelf portion of the OMP array, which is

largely undiminished over the extent of the array, the mean southward flow of shelf water measured over the upper slope steadily declines going toward Cape Hatteras. Mean velocities of OMP-A show the southward flow of shelf water over the upper slope essentially vanishes at the southeastern corner of the array.

[46] This trend is consistent with the tracks of 42 drogued drifters analyzed by *Gawarkiewicz and Linder* [2006]. A large number of drifters entered the northern boundary of their study area (38°N) moving southward over the continental slope [see *Gawarkiewicz and Linder*, 2006, Figure 2]. All but two of these drifted seaward and were entrained into the Gulf Stream over the latitude band of 35.5–38°N.

[47] Based on the discussion above, we propose an overall pattern of MAB shelf water export from the Hatteras shelf and slope region that is consistent with the OMP observations and previous studies (Figure 12). As part of this pattern, southward flow over the slope, which includes the shelf-edge frontal jet, is drawn seaward and entrained by the Gulf Stream over a region extending roughly 40–200 km north of Cape Hatteras. Further shoreward, most of the water entering the inner and middle Hatteras shelf continues into the SAB. After encountering the Hatteras Front, this water is diverted offshore to the northeast, with some portion passing over the outer shelf and upper slope north of Cape Hatteras. Because the OMP data we employed encompasses a total of only 179 days, we cannot be certain if this pattern is representative of shelf water export in the Hatteras region at all times. Further detailed observations are necessary to more fully resolve the pattern and dynamics of export in the Hatteras region, in particular to better understand the roles of shelf bathymetry and Gulf Stream frontal movement in diverting shelf water offshore.

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