Research papers

Variation in the Hatteras Front density and velocity structure Part 2: Historical setting

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A B S T R A C T

On the continental shelf near Cape Hatteras, cool fresh Mid-Atlantic Bight and warm salty South Atlantic Bight shelf waters converge alongshelf 90% of the time, causing strong alongshelf gradients in temperature and salinity known as the ‘Hatteras Front’. The resulting density gradient supports strong shoreward velocities in the cross-shelf oriented ‘nose’, of the Front in wintertime. To investigate further, the Frontal Interactions near Cape Hatteras (FINCH) project used shipboard ADCP and a towed undulating CTD to examine Hatteras Front property, density and velocity fields in August 2004, January 2005, and July 2005. Strong property gradients were encountered across the nose of the Hatteras Front in all cases, but the density gradient, dynamic height gradient, and observed along-front cross-shelf velocities evolved in time. FINCH along-Front velocities were strong and shoreward in fall and winter, and weakly mixed shoreward and seaward in July. Several archived data sets were examined, and demonstrate that the density evolution and wind forcing seen in FINCH are characteristic of other years. Evidence suggests the width of the Hatteras Front does not vary dramatically in time, so that consistently large fall and winter density contrast across the Front implies consistently large shoreward velocities along it in winter. Weak density contrasts across the Hatteras Front in spring suggest the magnitude and sign of springtime density gradients and along-Front velocities could vary interannually. Recruitment success of commercially important stocks on the shelf that depend on cross-shelf transport may thus be affected year to year.

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1. Background

Strong year-round alongshelf convergence on the continental shelf and slope near Cape Hatteras, documented by Savidge and Bane (2001) brings cool fresh Mid-Atlantic Bight (MAB) and warm salty South Atlantic Bight (SAB) shelf waters together, resulting in strong alongshelf gradients in temperature (T), salinity (S), and density known as the ‘Hatteras Front’ (Stefansson et al., 1971; Pietrafesa et al., 1994; Berger et al., 1995; Savidge, 2002). Using mooring records, Savidge (2002) found strong shoreward alongfront velocities, especially in winter, associated with the southern cross-shelf oriented ‘nose’ of the Hatteras Front (Fig. 1).

Mechanisms of shoreward transport in this region are a topic of interest, due to their potential importance to shelf-edge spawning, estuarine dependent commercial fisheries stocks, and the question of whether potential oil industry exploration at the shelf edge could pollute the ecologically and economically important sounds and beaches of North Carolina (Checkley et al., 1988; Shanks, 1988; Stegmann and Yoder, 1996; Quinlan et al., 1999). Because of these concerns, the Frontal Interactions near Cape Hatteras (FINCH) project was designed to examine the circulation and density fields associated with the nose of the Hatteras Front at high horizontal and vertical resolution using shipboard ADCP and towed undulating CTD. The Front was intensively sampled in three field seasons: in August 2004, January 2005, and July 2005. From this work, strong property gradients were verified in all three sampling seasons across a very narrow (several km) Front. T and S gradients did not completely compensate, so that density and dynamic height gradients also existed, driving shoreward geostrophic velocities along the cross-shelf oriented nose of the Hatteras Front.

August results were examined in detail in Savidge and Austin (2007). A plan view of 3.2 m depth velocities from several sections taken on August 9 (Fig. 2) defines strong along-Front shoreward velocities wrapping cyclonically around the boundary between cool MAB and warm SAB shelf waters at the nose of the Hatteras Front. Vertical sections from the shoreward-most ship track illustrate that despite MAB water being cooler, the strong S
contrast between fresher MAB and saltier SAB shelf waters controls the sign of the density gradient across the Hatteras Front. The resulting dynamic height gradient at the surface relative to 20 m depth drives strong surface intensified shoreward velocities, with diminishing magnitude with depth due to sloping isopycnals in the Hatteras Front. Measured velocities (shown) agreed with geostrophic estimates from the dynamic height and density field.

Results from all three FINCH sampling seasons (August 2004, January and July 2005) are compared in Savidge et al. (this issue), also referred to as ‘Part 1’ of a pair of contributions, of which the present paper is ‘Part 2’. As in August, January MAB shelf water was less dense than SAB shelf water, supporting density and dynamic height gradients across the nose of the Front and geostrophic shoreward velocities along it. In the following July, the strong property gradients were also not completely compensated, but in this case, the density gradient had reversed: MAB shelf water was now the slightly denser component. Predicted along-front velocities were weak and seaward in the nose of the Hatteras Front, but measured velocities were weak and shoreward throughout much of the lower water column, with weak seaward velocities in the upper layer. This structure was qualitatively consistent with northward alongshelf winds at the time.

The shift in density space occupied by MAB and SAB shelf waters from August to January and from January to July depended primarily upon the evolution of T through strong fall and winter cooling followed by warming in spring and early summer. The density contrast between MAB and SAB shelf waters across the Hatteras Front in August persisted through fall cooling and the sequence of storms that punctuated the January FINCH sampling. By July, SAB waters had warmed to summertime values, while lower layer MAB water retained very cool T. Meanwhile upper layer MAB shelf water had not yet acquired the strong T contrast to the lower layer that is typical of late summer in the MAB. It is conceivable that SAB warming routinely precedes or exceeds MAB warming for some undefined period in spring, due to the SAB’s more southern exposure. If so, the wintertime S-based density discrepancy between SAB and MAB shelf waters may erode somewhat or even reverse, as it apparently had in 2005.

Whether the velocity evolution observed during FINCH represents repeatable variability in this location depends on whether the densities and density contrasts between MAB and SAB shelf waters measured during FINCH were within normal ranges, and whether the width of the Hatteras Front measured during FINCH, and thus the magnitude of the density gradient across it, was also within a normal range. An additional important consideration is that the August and January FINCH transects were each accomplished in the immediate aftermath of strong wind forcing, so FINCH outcomes may represent storm responses. If so, the further question is whether such storms are relatively infrequent and unimportant when their effects are integrated through a season, or whether frequent responses to storms actually define the effective circulation environment at Cape Hatteras.

Therefore, to address whether cross-shelf velocity evolution along the Hatteras Front observed during FINCH represents typical seasonal evolution, several archived data sets are examined to assess whether the density evolution within MAB and SAB shelf waters seen in FINCH is representative of a repeatable seasonal progression. Long term wind records are also examined to explore whether FINCH wind forcing was unusual. Finally, possible changes in the width of the Front separating those shelf waters are discussed.

2. Data and methods

In the following, data from several national archives are examined. Densities in the MAB and SAB shelf waters as a function of month of the year have been examined using the National Oceanographic Data Center (NODC) archived shipboard CTD and bottle cast data. These data have been pre-processed using the methods described in Blanton et al. (2003). These archives extend from 1976–1996 and from 1914–1987 respectively for this region. Data from years 1992–1994 (a Minerals Management Service (MMS) sponsored project described below) have been excluded from the present analysis, and the archive end-date automatically excludes data from FINCH in 2004–2005. The object is to see how density and velocity evolution described for FINCH and MMS years (Savidge, 2002; Savidge and Austin, 2007; Savidge et al., this issue) compares to other years. If the MMS and FINCH years were anomalous, including them in the datasets to which they are being compared might skew the results to imply more agreement than actually exists. If the MMS and FINCH data were not anomalous, then their inclusion would not alter the results discussed herein.

Subsets of the data from the SAB and MAB shelves were extracted by month and used to construct composite Temperature–Salinity (T–S) diagrams. SAB and MAB shelf water T–S characteristics are significantly different from one another, such that the contrast between them should be demonstrable without fine-tuning the selection of latitude and depth boundaries within which to extract samples. Samples from locations where the bottom depths were shallower than 10 m have been excluded to eliminate undue influence from new riverine input, while samples from outer shelf locations seaward of the 35 m isobath were eliminated to minimize the signature of transient Gulf Stream water. Data between 36 and 38 N latitude sampled MAB shelf water both north and south of the Chesapeake Bay, and data

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between 32 and 35°N latitude sampled SAB shelf water. Data availability in the SAB is much more limited than in the MAB, but S and density ranges there are less variable by degree latitude, so a slightly wider (3°) latitude range for SAB waters has been subsampled than for the MAB (2°). Data from the area immediately adjacent to Cape Hatteras have been excluded (35°–36°N). Within this region, particular samples may have been collected either north or south of the Hatteras Front, due to its motion through the region, so samples from regions where the distinction is clear are preferred. These limits were also not fine-tuned, though had they not provided the necessary separation, the color-coded-by-latitude data would overlap into the density space occupied by the shelf water they presumably did not sample. Such instances do not occur using the ranges defined. The T–S diagrams discussed in Section 3.1 were repeated with other latitude limits, with equivalent results.

Hurricane incidence and strength at Cape Hatteras have been examined using the National Hurricane Center’s North Atlantic hurricane archive, which includes 6-hourly timeseries of storm tracks and wind strength (Jarvinen et al., 1984). Data in the hurricane archive since 1984 are examined, as this is when the National Data Buoy Center (NDBC) Coastal Marine Aids to Navigation (CMAN) archive commences for the Diamond Shoals tower (DSLN7). This archive of hurricanes, named and unnamed tropical storms lists location as a function of time, measured winds rounded to the nearest five knots, central pressure, and each storm’s maximum hurricane status on the Saffir Simpson scale, based on miles per hour (MPH) thresholds. Wind speeds associated with these storms are reported here in m/s. For reference, tropical storms have winds ranging from 29 to 69 MPH or 13 to 31 m/s, and category 1, 2, or 3 hurricanes feature sustained winds of 74–95, 96–110, 111–130 MPH, or 33–42, 43–49, 50–58 m/s, respectively.

Jarvinen et al. (1984) remark on the difficulties in ascribing maximum storm wind speeds from sparse stationary measurement locations, due to the likelihood of instrument failure during high winds combined with the fact that storms do not always track directly over existing instrumentation. To further investigate whether winds during FINCH were unusual, several categories of strong winds in fall and winter are examined since 1984 in data from the three nearest NDBC CMAN stations. These are Chesapeake Bay (CHLV2), Diamond Shoals (DSLN7 until 2003 and Buoy 41025 from 2003 to the present), and Cape Lookout (CLKN7) (Fig. 1). Winds measured at these stations at 43.3, 46.6, 5, and 14.4 m, respectively, are converted to winds at 10 m height using the algorithms of Large and Pond (1981) using the Matlab air-sea package implementations of Pawlowicz et al. (2001).

Existing data from two research programs targeted at the Cape Hatteras region are also shown here to illustrate the autumn erosion of summertime stratification within MAB shelf water. The first was a two-year-long (February 1992–February 1994) mooring, drifter, and hydrographic study funded by the Minerals Management Service (designated herein as the ‘MMS-data’) (Berger et al., 1995) (Fig. 1). Temperature time series from within the MAB shelf water at mooring A2 (35 m isobath) will be presented. These data were recorded at 5, 20, and 30 m levels using InterOcean S4 and General Oceanic MkII winged current meters (u,v), with reference, temperature and salinity sensors. Raw data

Fig. 2. August 9 2004 shipboard measurements of Hatteras Front velocity, property, and density fields. The upper left panel shows shipboard ADCP velocity data (3.2 m below the surface, subsampled to every 4th vector of the measured 60 m alongtrack resolution for clarity) superimposed on satellite SST for August 9, 02:13 UTC. SST data were obtained from the Coastwatch archive in Beaufort NC. Clockwise, the other three panels show cross-shelf velocity (positive shoreward), density and salinity along the westernmost transect shown in the upper left panel. Panels are oriented south to north from left to right. Contour intervals are salinity: 0.5 psu; density: 0.25 ρo units; velocity: 0.05 m/s. The bold gray dashed lines are schematic boundaries of the “jet” within the Front, traced roughly along the 15.0 cm/s contour in the velocity panel.
were three-hour low-pass (3-HLP) filtered with a Lanczos kernel and subsampled to hourly values. These hourly data were then processed with a 48-HLP Hanning filter and subsampled to daily noon values.

A second study targeting Cape Hatteras was the Ocean Margins Project (OMP), which deployed a large number of moorings near and north of Cape Hatteras from February to May 1996, and again in July–early October 1996. Project results have been summarized in a dedicated volume of Deep-Sea Research Part II (Verity et al., 2002). Temperatures shown herein from OMP mooring 5 on the 36 m isobath were recorded at 6, 9, 12, 19, 22, and 25 m levels using YSI sensors. These hourly data were processed with a 48-HLP Hanning filter and subsampled to daily noon values.

3. Results

3.1. Density contrast between SAB and MAB shelf waters

To ascertain whether the T–S diagrams derived from the FINCH and MMS shipboard datasets shown in Part 1 are representative of MAB and SAB shelf water density contrasts over time, the NODC shipboard CTD and bottle cast archives were examined. The data are further identified in the T–S diagrams by open circles, which represent data from the upper third of the water column, and filled triangles which represent data from the lower third of the water column. Data from the middle third are excluded for clarity. Both Pietrafesa et al. (1994) and Flagg et al. (2002) have contributed schematic T–S diagrams for the waters impinging on the Cape Hatteras region, with which these monthly maps from the NODC archive are broadly consistent.

During fall and winter (October–March: Fig. 3), SAB and MAB shelf waters cool progressively. In any particular month, upper MAB shelf water is essentially the same T as lower MAB shelf water (black and blue circles and triangles), and both are cooler and fresher than the coolest freshest SAB shelf T (magenta, red and green circles and triangles). MAB shelf waters fall primarily into lighter density space than SAB shelf waters, especially in October–December. By January–March, the density contrast weakens, as MAB shelf water occupies a density range that is less distinct from the SAB shelf water density range. Sample locations are shown on the inset maps in Fig. 3.

Through spring (April–June: Fig. 4), both MAB and SAB shelf waters warm. In the MAB, this warming is primarily confined to surface layers, consistent with the evolution described by Flagg et al. (2002), and MAB shelf waters span larger T ranges than in any particular fall and winter month. Sprtime SAB and MAB shelf waters occupy similar density ranges, especially prior to the development of the warm low-density surface layer in the MAB waters. This suggests the possibility of years when MAB shelf waters are denser than SAB shelf water, and years when the converse is true. Sample locations are shown on the inset maps in Fig. 4.

Summer hydrography (July–September: Fig. 5) is characterized by strong stratification in the MAB shelf waters. MAB upper layer waters are both fresher and warmer than lower layer water (left panel of Fig. 5). SAB upper and lower layer shelf waters cover narrower S, T, and density ranges than MAB shelf waters, and are

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**Fig. 3.** Fall and Winter shelf water densities: T–S diagrams for shelf waters between the 10 and 35 m isobaths on the SAB and MAB shelves from NODC CTD archive data for October–March. The bottom six panels are maps showing where data were collected. Data in both the T–S diagrams and the maps are color coded by latitude. Black and blue represent samples from north of Cape Hatteras, and magenta, red, and green represent samples from the SAB. Data from the years of the MMS, OMP, and FINCH experiments are excluded. Samples from the upper third (open circles) and lower third (solid triangles) of the water columns are plotted.

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denser by several $\sigma$ units than the range covered by upper MAB shelf waters. Lower MAB shelf waters cover nearly the same range of density as the SAB shelf waters. As in spring, this implies the possibility of interannual variability in density contrast between SAB and MAB shelf waters, at least in the lower water column. Upper MAB waters are consistently less dense than SAB surface and bottom shelf waters. In August and September the distribution of MAB data points appears to shift slightly toward the center of the MAB $T$ range, which may reflect occasional early fall transitions in those months. Variability in the timing of the fall transition should be expected. Inset maps in Fig. 5.

By October, $T$ distributions have collapsed to a narrow range encompassing both upper and lower MAB waters (Fig. 3). Once mixed completely in the Fall, MAB shelf waters do not strongly restratify until late Spring.

3.2. Wind setting

Wind strength distributions are often skewed to low wind ranges, even in relatively windy locations like Cape Hatteras in fall and winter, as illustrated by histograms of hourly wind data for the region (Fig. 6A). In this figure, August–February wind speeds adjusted to 10 m from the Coastal CMAN stations off the Chesapeake Bay (CHLV2), Diamond Shoals (DSLN7 and Buoy 41025), and Cape Lookout (CLKN7) for the years 1984–2010 are binned by 2.5 m/s increments. Percentage of data from each year within each wind speed bin are plotted as histograms, using symbols where the tops of stacked histogram bars would be, instead of as bars as in normal histograms. In this way all years can be superimposed within each bin. The distribution of symbols in the vertical defines the interannual variability in percentage of wind speeds within that bin. Further, data from each of the three CMAN locations are presented within each speed bin to adequately represent the wind climate for the entire region. In the lower wind ranges (up to 15 m/s), winds from the years when MMS, OMP, and FINCH oceanographic instrumentation were in place (color symbols) were not unusually skewed to higher wind bins than other years (black circles).

The August 2004 FINCH measurements were conducted immediately after a hurricane, and the January 2005 FINCH measurements were interspersed between several strong wintertime wind events. The generality of the FINCH results will depend on

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whether they represent either the mean or processes of ubiquitous importance at Cape Hatteras, or are storm responses to extreme and anomalous wind forcing. To better examine the distributions at higher wind ranges, two categories of strong fall and winter winds are further examined: the occurrence of tropical force or hurricane strength winds at Cape Hatteras during

Fig. 6. Wind speed histograms from the NDBC archives for the years 1984–2010. For each wind-speed bin, data from the three CMAN stations nearest Cape Hatteras are shown: near Chesapeake Bay (CHLV2); on Diamond Shoals (Tower DSLN7 and Buoy 41025, both denoted by DSLN7 label in the histogram bins); and at Cape Lookout (CLKN7). Panel A includes all fall and winter winds (August–February). The bars under Panel A show the wind speed ranges represented in Panels B and C, which show histograms for subsets of the data in Panel A. Panel B: Tropical to hurricane force winds during hurricane season (August–November). Panel C: High winds during winter (December–February). Blue, green, and red plus signs represent data from the MMS, OMP, and FINCH years, while open black circles represent histogram heights for all other years (as in legends). Note that the y-axis in Panel B is logarithmic, as numbers of occurrence drop precipitously with increasing wind speeds.

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hurricane season; and the occurrence of strong winds in winter. Given the importance of the MAB transition from highly stratified to well-mixed shelf waters in fall, representative winds from the MMS and OMP mooring-documented cases of the fall transition are also compared to archived wind ranges.

3.2.1. Tropical storms and hurricanes
Hurricane Alex, which immediately preceded the August 2004 FINCH measurements, was a category 1 hurricane in the archive, though winds documented in the archive while Alex was within 100 km of Cape Hatteras slightly exceeded the threshold for a category 2 hurricane. Inspection of the National Hurricane Center’s North Atlantic hurricane archive (Jarvinen et al., 1984) indicates that hurricane passage is not unusual at Cape Hatteras. From 1984 to 2010 (27 yr), centers of 24 named storms passed within 100 km of Cape Hatteras, 15 of which were tropical storms, while nine were category 1,2, or 3 hurricanes. Five of the named storms occurred during June or July, seven in August, eight in September, and four in October or November.

To examine high winds less anecdotally, hourly 10 m adjusted wind speeds from CMAN stations CHLV2, DSLN7, Buoy 41025 and CLKN7 data from August–October for the years 1984–2010 were binned into 2.5 m/s wide bins from 12.5 to 32.5 m/s (Fig. 6B). As at lower speeds, tropical and hurricane force winds during MMS, OMP and FINCH years (color symbols) were not unusually skewed to higher wind bins than other years (black circles). Nor do the highest winds from instrumented years occur at abnormally high frequency during those years, as shown by the fraction of high winds in a particular instrumented year relative to the distribution of black circles in any one wind speed bin.

3.2.2. Winter storms
Winds in winter are also routinely strong, though do not typically feature named tropical storm or hurricane force winds. CLKN7 winds

![Fig. 7. Fall winds and the breakdown of summertime stratification in MAB shelf water. Panel A: Temperature from MMS mooring A2 (location in Fig. 1) in 1993, sensors at 5 m (solid line), 20 m (dashed line), and 30 m (dotted line); Panel B: Wind magnitude in fall 1993 at CMAN station DSLN7; Panel C: Temperature from OMP mooring 5 (location in Fig. 1) in 1996, sensors at 6 m (solid line), 19 m (dashed line), and 25 m (dotted line); Panel D: Wind magnitude in fall 1996 at CMAN station DSLN7.](image-url)
for wintertime FINCH sampling are shown in Part 1, and range between 5 and 25 m/s. Histograms for winds in this range (by 2.5 m/s bin) from the December–February CHLV2, DSLN7, Buoy 41025 and CLKN7 records for the 1984/1985–2010/2011 winters are shown in Fig. 6C. Winds from Diamond Shoals (DSLN7 and Buoy 41025) are routinely stronger than at CHLV2 or CLKN7, as routinely higher percentages of winds occur there for bins from 7.5 to 22.5 m/s. Winds from the MMS OMP and FINCH years (color symbols) are not unusually skewed to the stronger range during those years (black circles).

3.2.3. Fall transition

Finally, the evidence from several years of in-situ T time-series suggests that the evolution of well-mixed conditions in MAB shelf water through the fall near Cape Hatteras occurs during a sequence of both strong and weak wind events (Fig. 7). The MMS and OMP years shown each contain at least one named storm that contributes to the mixing, as Hurricane Alex did during FINCH in August 2004. However, weaker winds also contribute. For example, in 1993, August 4, and through September 5–early October in 1993 (Fig. 7) are occasions of relatively lower wind speeds under which stratification is altered at mooring A2 during the MMS study (location in Fig. 1).

Panels A–C of Fig. 6 together indicate that during the documented fall break down in stratification in the MMS, OMP, and FINCH years, wind distributions in weak or strong winds were not skewed towards stronger winds. The density analyses in Section 3.1 show clearly that whatever the necessary wind forcing, strong MAB shelf water stratification is destroyed in fall every year.

4. Discussion

4.1. Density

To illustrate the monthly density progressions in SAB and MAB more clearly, principle component decompositions of the T, S distributions in Figs. 3–5 have been estimated from the data, and plotted as ellipses for each month. Two example months of scatterplot data with estimated ellipses are shown in the top two panels of Fig. 8, while a timeseries of ellipses estimated from the data are shown in the bottom seven panels (Every other month with April repeated as 1st and 7th panels.). This representation shows the seasonal progression of density contrasts between upper and lower MAB and SAB waters, including the points discussed in Section 3.1.

- Spring (April–June, Fig. 8 left bottom panels)
  - Both MAB and SAB shelf waters warm through spring.
  - MAB warming is primarily confined to surface layers.
  - MAB vs. SAB shelf waters span larger T ranges than in any particular fall or winter month.
  - SAB and MAB shelf waters occupy similar, relatively wide density ranges.
- Summer (July–August Fig. 8)
  - MAB shelf waters show strong vertical T, S, and density stratification.
  - SAB upper and lower layer shelf waters occupy a narrow density range.
  - Density ordering of shelf water layers is: upper MAB < < upper and lower SAB ~ lower MAB.
  - MAB density spread contracts somewhat in August and September, which may reflect occasional early fall transitions (September ellipses are shown in Fig. 9.).
Fig. 9. T–S diagrams for densities measured during the three FINCH sampling seasons, with archived data principle component analyses overlain. Ellipses are identical to those from Fig. 8 and their corresponding versions for months not shown there. Ellipses are color coded in each panel by month, with all four ellipses for a month in one color: orange for the earlier month, green for the later month. The leftmost pair of each color are ellipses for upper and lower MAB water (upper is the one in lighter density space), while the rightmost pair from each month are ellipses for upper and lower SAB water (upper is the one in lighter density space). FINCH data are shown as grayscale-shaded probability plots, where the darker shades represent the largest quantities of data sampled in the FINCH transects across the Hatteras Front. The probabilities are identical to those presented in Part 1, where their derivation from the data is discussed. Data from SAB and MAB mid-shelf CTD casts in August and November 1993 (MMS project transects) are shown in blue in the two right panels. Leftmost datapoints are from a cast near A2 on the MAB mid-shelf, while rightmost data points are from a cast near C2 on the SAB mid-shelf (locations in Fig. 1). In November especially, multiple data-points from the upper third and lower third of the water column casts overlap one another, due to the small range of T–S values in the well-mixed water columns at mooring locations A2 and C2.

- Variability in the timing of the fall transition should be expected.
- Fall and Winter (October–March, Fig. 8)
  - By October, upper and lower MAB shelf water densities collapse to a narrow range.
  - The density range occupied by mixed MAB shelf water is several \( \sigma_t \) units lighter than that occupied by SAB shelf water, especially in October–December.
  - Both SAB and MAB shelf waters cool progressively through fall and winter.
  - By January–March, the density contrast between SAB and MAB shelf waters weakens.
  - Once mixed completely in the fall, MAB shelf waters do not strongly restratify until late Spring.

A direct comparison between these archive density ranges by month and the FINCH and MMS shelf waters densities illustrates how consistent they are (Fig. 9). For example, in Panel A, January FINCH CTD section data are plotted along with archive ellipses from two relevant consecutive months, December and January. The ellipses show cooling from December (orange) to January (green), with probability density plots from the January FINCH transects falling between archive values for those months. Probability plots are explained thoroughly in Part 1, Fig. 4, where they are presented without ellipses overlain. Densities from the MAB side of the Hatteras Front fall at the left ends of the probability bands, and densities from the SAB side fall at the right end.

July 2005 FINCH transect data in Fig. 9, second panel show warmer MAB and SAB waters than in January. FINCH MAB densities fall near the May archive MAB values (orange ellipses), and FINCH SAB densities are similar to June archive SAB values (green ellipses).

In the third panel of Fig. 9, August data from both the 1993 MMS transect and FINCH are shown. In both cases, SAB shelf water densities are consistent with archived August and September ranges (orange and green ellipses on the right side of the panel). MMS 1993 MAB upper and lower layer densities fall near the archive August densities (orange ellipses on the left side of the third panel) and along a mixing line between them. However, FINCH August 2004 MAB data fall in density space near the September archive values (green ellipses on the left side of the third panel).

November 1993 MMS data from after the fall transition to mixed conditions in the MAB are plotted in the fourth panel of Fig. 9. SAB and MAB shelf waters fall within the archived ranges shown by the October and November ellipses.

4.2. Winds

Wind speeds during the MMS, OMP, or FINCH studies were compared to archived data because both August and January 2005 FINCH measurements were interspersed between strong wind events. Winds are relevant because they affect density and stratification evolution, and may also affect motion of the Front, which in turn may affect the steepness of the Front or velocities along it in unspecified ways.

Any number of studies have examined the evolution of S, T, and density in the MAB, including, Houghton et al. (1982), Chapman and Gawarkiewicz (1993), Flagg et al. (2002), Mountain (2003), Lentz et al. (2003), Lentz (2010). These studies include the importance of numerous influences, including surface heat fluxes, freshwater fluxes, wind speeds and directions, and horizontal advection. It would be quite difficult to estimate each of these components from the MMS and FINCH project years and from all other years for comparison, particularly to the degree of accuracy necessary to reduce the error bars to values lower than the interannual variability of the terms.

Wind effects on Frontal motion, Frontal steepness, and velocities within the Front are distinctly speculative, at least as far as FINCH data are concerned. However, since alongshelf transports of shelf waters on both sides of the Front are highly correlated with alongshelf winds (Savidge and Bane, 2001), it seems likely that the boundary between MAB and SAB shelf waters may also move with wind forcing. SST imagery certainly suggests such a relationship, both anecdotally and by averaging according to wind direction (Savidge, 2002). The evidence to date indicates that along-Front velocities in the nose of the Front do not depend on
alongshelf Frontal motion (Savidge and Austin (2007)). The August FINCH along-Front velocities were investigated by Savidge and Austin (2007) in the context of a slope-controlled buoyancy plume, as discussed by Lentz and Helfrich (2002). They found that this framework fit the FINCH data fairly well. It is difficult to see where further progress could be made with existing datasets alone. Detailed modeling of the Front as it translates over realistic bathymetry under realistic forcing is likely necessary to define and quantify actual wind effects.

Instead of diagnosing wind effects on density, stratification, Frontal motion, and along-Front velocities during the MMS and FINCH years relative to other years, the winds forcing whatever those effects might be from MMS, OMP, and FINCH years and other years are examined. The implicit assumption is that, whatever the net wind effects might be, they will be similar from year to year for similar categories of winds. The winds during the MMS, OMP, and FINCH fell well within the expected envelop of wind distributions during fall and winter (Sections 3.2.3 and 3.2.2), and were not affected by strong events to a degree that is unusual at Cape Hatteras (Section 3.2.1).

The archived density scatter and ellipse plots suggest that Hurricane Alex, immediately prior to FINCH August measurements, mixed southernmost MAB waters earlier than is typical. This event is likely to have affected a more limited geographical area than mixing from a series of region-wide strong wind events in August and September typically would have. Nonetheless, the NODC archive demonstrates that the mixing does occur every fall, repeatedly altering the density space occupied by the MAB shelf waters, and therefore its contrast to the density range occupied by SAB shelf water in fall.

4.3. Velocity

Wintertime along-Front velocities measured in FINCH and MMS were geostrophic, consistent with the dynamic height gradients across the nose of the Hatteras Front (Savidge and Austin, 2007 and Part 1). In July FINCH data, the dynamic height gradient estimated from the weak density gradient suggested weak seaward flow. The realized flow was apparently overwhelmed by other processes, resulting in weak shoreward transport. Nonetheless the July FINCH density gradient is consistent with climatology. Since FINCH density evolution is consistent with the demonstrated seasonal progression in the archived density fields, the question is whether FINCH and MMS velocities are also representative of a seasonal progression in velocities. The density and dynamic heights gradients across the Front depend on the order of magnitude width of the Front. However, even fairly large variations in the width of the Front about a presumed equilibrium near the Rossby radius, say from half to twice the width, would still drive substantial geostrophic shoreward velocities in winter. The 10 km width of the Front measured in August and January of FINCH is consistent with the expected Rossby radius of about 6–9 km for the 20–40 m depth of mid-shelf waters for the observed density differences across the Front (Savidge and Austin, 2007; Savidge et al., this issue). The estimated 10 km width of the Front for winter from MMS mooring data is also consistent with the expected Rossby radius (Savidge, 2002).

However, it is reasonable to expect that the Front may alternately steepen and relax in response to storm forcing or motion of the Front across the variable alongshelf bathymetry. Yet for the nose of the Front, Savidge and Austin (2007) found consistent widths and along-Front velocities over 4 days in August, during which the Front translated southwestward alongshelf, stopped, and then reversed its direction. Additionally, Savidge (2002) detected strong shoreward velocities in the nose of the Front throughout the MMS project winters, regardless of whether the Front was translating poleward or equatorward past the mooring, or was stalled over it. This implies that the Front was sufficiently narrow to support strong velocities, regardless of alongshelf motion of the nose of the Front.

Churchill and Berger (1998) determined that the steepness of the alongshelf oriented part of the Hatteras Front (the ‘seaward flank’) depended on whether the flank was translating shoreward or seaward across-shelf. In their study, even the direction of flow along the Front (not just the magnitude) depended on direction of translation of the Front. However, the cross-shelf motion of the seaward flank of the Hatteras Front is likely to be dynamically different than alongshelf motion of the nose of the Front, due to differing dynamical constraints on cross-isobath motion (i.e., Taylor column or Chapman and Lentz, 1994 considerations). Without additional evidence or modeling, the question cannot be resolved further.

5. Summary

The August and January FINCH shipboard undulating CTD and ADCP sections across the nose of the Hatteras Front document strong property and density gradients across a relatively narrow front, and strong shoreward velocities along the Front. The density climatology in this paper indicates that the FINCH data are representative, so that by mixing away the significant density difference between upper and lower MAB shelf water that is due to T in fall, the strong S contrast between mixed MAB and mixed SAB shelf waters results in a strong density contrast between them. The density contrast between MAB and SAB shelf waters across the Hatteras Front persists through fall cooling and sequences of winter storms. The climatology indicates that stronger cooling in the MAB through winter does not reduce MAB densities sufficiently to erode the density contrast between MAB and SAB water until possibly late winter (March). This density evolution suggests that after the fall transition, strong shoreward velocities along the nose of the Front can be expected to result throughout fall and winter, driven geostrophically by the relatively large contrast in density between fall and winter SAB and MAB shelf waters.

Shelf-edge winter-spawning species might reliably depend on these shoreward velocities for transport to the nearshore regions, near the adjacent Albemarle or Pamlico Sound nursery grounds. The magnitude of that velocity will change with evolving density through the winter. FINCH measurements show that the cross-shelf velocities in the nose sometimes preferentially carry MAB shelf water, and sometimes preferentially carry SAB water. Therefore, at any given time, MAB or SAB populations might be preferentially transported. Controls on this variability are unknown.

In 2005 FINCH sampling, springtime warming of SAB water resulted in a slight reversal in the density gradient, so that the cold fresh MAB water was the slightly denser component in the lower layer. The climatology indicates that the SAB warming effect on density can precede or exceed that of MAB warming, and reduce the S-based density discrepancy between SAB and MAB shelf waters in spring. Because of the slight mean density contrast between SAB and MAB shelf waters in spring, and the large ranges of density space each occupies, this suggests springtime interannual variability in density contrast between MAB and SAB. This could lead to interannual variability in both magnitude and sign of geostrophic along-Front velocities in the nose of the Hatteras Front. If spawning behaviors of shelf species in spring are temporally tied to lunar cycles (which have low interannual variability in timing), then species that require cross-shelf transport could be affected from year to year, as Hatteras Front related cross-shelf transport would be more variable, both temporally and in magnitude and direction. Recruitment success for such
species might correlate with the magnitude and sign of the developing density contrast across the Hatteras Front.

Summertime velocities along the nose of the Hatteras Front have not been investigated in mooring datasets, and FINCH did not sample the Front in a season of high vertical stratification in MAB shelf waters. The climatology herein shows that in summer, SAB shelf waters and MAB lower layer waters occupy approximately equivalent density space, while strong vertical stratification in the MAB places upper MAB water into significantly lighter density space than either SAB shelf water or lower layer MAB shelf water. This suggests interannual variability in lower layer pressure gradients caused by density differences, and large vertical variability in the pressure gradient and geostrophically forced along-Front currents in the nose. Perhaps summertime spawning species are adapted to deal with this level of uncertainty in cross-shelf transport, or are dependent on other transport mechanisms.

The fall transition apparently ‘switches on’ strong shoreward velocities in the nose of the Front, with the mixing of MAB shelf waters and the establishment of strong density gradients across the nose of the Hatteras Front. The consistency in sign of that gradient with depth after the fall transition results in significant dynamic height gradients across the nose of the Front and strong shoreward transport within it. The timing of the fall transition should be expected to vary interannually, with differing levels of summertime stratification and fall wind and air temperature conditions. Presumably species adapted to tolerate such temporal uncertainty can utilize such currents to their recruitment advantage. It would be very revealing to explore transport implications for species present near Cape Hatteras by season, with fisheries specialists possessing appropriate knowledge of the range of species and early life strategies they employ.

As pointed out by Savidge and Austin (2007), other examples of profound along-shelf convergence and persistent mesoscale cross-shelf oriented fronts do exist. For example, the ‘Subtropical Shelf Front’ off southwestern Brazil studied by Piola et al. (2000) results from convergence on the wide shelf there that is hypothesized to result from convergence of the adjacent western boundary currents. Since the Hatteras Front also coincides with a region of deep ocean convergence seaward of the continental slope (Csanyad and Hamilton, 1988: Flagg et al., 2006), one may reasonably speculate that along-shelf convergence on the shelf could occur shoreward of other western boundary current convergence zones.

Dynamics and variability of cross-shelf oriented fronts like the Hatteras Front may thus be of importance in a variety of locations.

References


