Variability of the shelf break jet in the Middle Atlantic Bight: Internally or externally forced?

P. S. Fratantoni and R. S. Pickart
Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

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[1] Velocity records from two bottom-mounted acoustic Doppler current profilers, deployed at the shelf break south of New England are used to characterize the mesoscale variability of the shelf break frontal jet in the Middle Atlantic Bight. While on average the jet is equatorward, energetic current fluctuations dominate the 18-month record at a period near 13 days. The fluctuations are characterized by a deceleration in the equatorward flow over the full water column and are strong enough to reverse the jet near the bottom. The origin of the observed variability is explored with the help of local wind records, concurrent velocity measurements from three tall current meter moorings deployed over the continental slope, and Gulf Stream frontal position information. While we are unable to attribute definitively the observed variability to a single forcing mechanism, we are able to discount several of the traditional possibilities. These include local effects, such as wind driving and tidal rectification, as well as offshore forcing due to Gulf Stream rings, topographic Rossby waves, and the meandering of the Gulf Stream. It is most probable that the fluctuations are caused by baroclinic instability of the shelf break jet. However, we are not able to determine this unequivocally, as our records differ from historical observations of instabilities, and stability models tend to oversimplify the salient features of the jet.


KEYWORDS: shelfbreak, variability, Middle Atlantic Bight, shelfbreak jet, shelfbreak front


1. Introduction

[2] A narrow, equatorward flowing baroclinic jet dominates the circulation near the shelf break in the Middle Atlantic Bight (MAB). To first order the jet is in geostrophic balance, supported by a hydrographic front which separates relatively cold, fresh shelf water from warmer, saltier water over the continental slope. This frontal jet, which transports less than 1 Sv equatorward, is the downstream remnant of a large-scale coastal current system, which originates as the East Greenland Current with a transport of roughly 5 Sv [Loder et al., 1998]. (More recent estimates, using high-resolution direct velocity sections occupied by R. Pickart, indicate that the transport of the East Greenland Current can be as high as 10 Sv.) Along its path the current is modified by various factors, including coastal freshwater discharge and offshore recirculations, and steadily declines in transport. Finally, near Cape Hatteras, North Carolina, the shelf break current is completely entrained into the separating Gulf Stream.

[3] Over this large expanse the current exerts a strong influence on the coastal environment, impacting the heat and salt budgets of the shelf, the dispersion of coastal contaminants, and the migrations and feeding sources of various species of fish. While to first order the shelf break front and jet act as a barrier between the shelf and the open ocean, observations and models suggest that perturbations of this frontal system can lead to significant exchange between the shelf and slope regions. Hence it is of primary importance to characterize the variability of the jet and understand the associated dynamics which result in exchange. Previous studies have implicated wind-driving, baroclinic instability, and open ocean forcing as causes of jet perturbations. However, the dominance of a single forcing mechanism has not been established.

[4] The cross-shelf position and structure of the shelf break front and jet vary on a wide variety of timescales and in response to both internal and external forcing mechanisms. For instance, numerical models [Gawarkiewicz, 1991; Lozier et al., 2003] and observations [Linder and Gawarkiewicz, 1998] show that the structure of the jet is inherently baroclinically unstable. Such internal instabilities lead to meanders that propagate along the axis of the jet at periods ranging from 1–7 days. Occasionally the meanders grow rapidly and develop into frontal eddies [Houghton et al., 1988; Garvine et al., 1988]. The shelf break front is also sensitive to external forcing such as fluctuations in the local winds, typically occurring at periods between 2–10 days. Houghton et al. [1988] demonstrated that both the surface
and bottom "foot of the front" are subject to advection by wind-driven Ekman transport in the surface and bottom Ekman layers, respectively.

Another significant external influence on the shelf break frontal system comes from the adjacent slope water. The close proximity of the Gulf Stream south of New England results in a large number of anticyclonic Gulf Stream rings impinging on the continental slope in the MAB. The rings can temporarily reverse the flow at the shelf break [e.g., Beardsley et al., 1985], and pull streamers of shelf water into the interior [e.g., Joyce et al., 1992]. They can also excite shear instabilities due to enhanced horizontal velocity gradients in the vicinity of the shelf break jet [Ramp et al., 1983]. Smaller submesoscale eddies are also present in the slope water and have been observed to impact the jet over short timescales and space scales [Gawarkiewicz et al., 2001]. Finally, the slope water is characterized by an energetic topographic Rossby wave field due to nearby rings [Ramp, 1989; Aikman et al., 1988] as well as the presence of the meandering Gulf Stream [Pickart, 1995].

The shelf and slope region in the MAB have been the focus of several long-term mooring and hydrographic programs. The Shelf Edge Exchange Program (SEEP, Aikman et al., 1988; Houghton et al., 1988) and the Nantucket Shoals Flux Experiment (NSFE) [Beardsley et al., 1985] separately maintained moored arrays crossing the shelf break south of New England. These programs provided important insights about the circulation in the vicinity of the shelf break. Both studies demonstrated the sensitivity of the regional circulation to seasonal variations in local wind forcing and to seasonal changes in the stratification at the shelf break. For instance, Houghton et al. [1988] inferred that the formation of a seasonal pycnocline during the summer facilitates the formation of frontal eddies at the shelf break. Results from SEEP and NSFE also demonstrated that the continental shelf and slope constitute distinct forcing regimes, with the transition occurring at the shelf break. They concluded that the shelf circulation responds primarily to changes in high-frequency local wind forcing, while the slope circulation is dominated by relatively low-frequency processes originating in the open ocean (e.g., Gulf Stream warm core rings or topographic Rossby waves). Of note is the fact that neither of these moored arrays had the horizontal or vertical resolution to carefully examine the transition region at the shelf break.

In this paper we analyze data from two bottom-mounted acoustic Doppler current profilers (ADCPs), deployed at the shelf break south of New England to characterize the mesoscale variability of the shelf break frontal jet over an 18-month period. The ultimate goal of the study was to identify the dominant forcing mechanisms at work in the MAB shelf break region. After a brief description of the moored array and mean flow, we describe the observed variability of the jet, and consider in turn the various possible causes, both internal and external. The high vertical resolution provided by the shelf break ADCPs details the changing character of the current as one crosses the shelf break, revealing energetic velocity fluctuations at the outer shelf break that are distinct from the variability on the shoreward side of the jet. We demonstrate that none of the traditional forcing mechanisms can definitively explain the strong fluctuations observed at the shelf break. We surmise, however, that baroclinic instability of the jet is the most viable cause, and that present models are likely too rudimentary in their depiction of the salient jet features to accurately capture such variability.

2. Moored Array

A moored array was deployed south of New England as part of the Shelf break PRIMER experiment, funded by the Office of Naval Research, to investigate the shelf/slope circulation in the Middle Atlantic Bight (MAB) and its effect on the propagation of sound. The array was deployed along a TOPEX altimeter subtrack and consisted of two bottom-mounted, upward facing ADCPs situated at the shelf break, and three tall current meter moorings containing vector averaging current meters (VACMs), deployed over the continental slope and rise (Figure 1). The ADCPs were approximately 15 km apart, positioned at the 125 m and 170 m isobaths, while the slope water moorings were located between the 1000 m and 3000 m isobaths. The moored array was deployed along the TOPEX subtrack in order to complement the remote sensing component of the PRIMER experiment, with the hope that in situ observations could be used to ground truth the altimetric data. However, the sea surface height data at the shelf break has proven elusive to interpret and will not be addressed in this paper.

The shelf break ADCPs were in the water for 18 months (December 1995 to February 1997), recording velocities at 10-min intervals from approximately 12 m above the bottom to 25 m below the surface, with a vertical resolution of 8 m. The two instruments were equipped with thermostors measuring near-bottom temperature in the vicinity of the front. Velocity and temperature data were lost at the inshore ADCP for a period of 5 months, between February and July 1996, because of instrument failure (Figure 2). The slope water moorings were deployed for 2 years (December 1995 to November 1997) and contained VACMs at nominal depths of 100 m, 400 m, 800 m, 1400 m, 2000 m, 2500 m and 2800 m (Figure 1). The current meters collected velocity and temperature measurements at 30-min intervals. With the exception of the near-bottom instrument (2000 m) on the middle slope mooring, the data return was complete (Figure 2). There were no VACM failures over the slope during the 18-month period overlapping the shelf break deployment.

Wind data were provided by a nearby surface meteorological buoy that was deployed on the shelf as part of a concurrent experiment, Coastal Mixing and Optics (CMO) [Lentz et al., 2003]. All of the velocity, wind, and temperature records were filtered with a 40-hour low-pass second-order Butterworth filter and subsampled at 12 hour intervals. For the remainder of the paper we will refer to the moorings, proceeding off shelf, as the inshore and offshore shelf break ADCPs, and the inshore, middle, and offshore slope moorings.

3. Mean Structure and Seasonal Cycle

During the PRIMER experiment the mean flow was greatest at the shelf break (the shelf break jet), directed equatorward (Figure 1). The flow was oriented largely along...
the local isobaths, with the exception of the inshore shelf break ADCP which had a significant upslope component. This is possibly due to the presence of a submarine canyon, whose head is located just downstream of this mooring (Figure 1). During the 2-year study period, 6 anticyclonic warm-core Gulf Stream rings passed over the continental slope, resulting in periods of significant eastward flow at the slope moorings. As a result, the record length mean flow is weak or eastward over the upper and middle slope, and westward over the continental rise (Figure 1). However, in the absence of rings, the mean flow is uniformly westward over the entire continental slope (Figure 1).

Figure 1. Configuration of the shelf break PRIMER moored array in the Middle Atlantic Bight. The record length mean velocity vector is shown for the uppermost instrument on each mooring (25 m depth bin for the ADCPs and 100 m over the slope). The gray vectors indicate the full record mean velocity on the slope, and the black vectors indicate the mean velocity for the period when rings were not present over the slope. The shelf break is located at roughly the 200 m isobath and is marked by the heavy contour.

[12] Principle axis ellipses define the direction in which the velocity variance is maximized at each mooring site [Fofonoff and Hendry, 1985] and can be used to determine the statistical significance of the mean velocity vectors, after normalizing by the standard error [Hogg et al., 1999]. At all of the instrument sites the standard error ellipses demonstrate that the mean vectors are significantly different than zero, even near the bottom where the velocity is greatly diminished. At the shelf break the average principle axis is oriented 322T, while over the slope it is oriented 270T. In general, the principle axis ellipses are aligned with the mean flow vectors. Therefore, in the analysis that follows we have
rotated our shelf break and slope timeseries according to these two coordinate axes, where \( x, u \) is along-stream distance and velocity (positive equatorward), and \( y, v \) is cross-stream distance and velocity (positive downslope). Since there is potential ambiguity in interpreting the weak cross-stream velocities defined as such, the details of the cross-stream component of the flow at the shelf break are not examined here.

[13] The vertical structure of the mean velocity at each of the moorings in the rotated framework is shown in Figure 3. The shelf break jet velocity profiles are more baroclinic than those over the continental slope owing to the presence of the lateral density front. During the PRIMER experiment, a vessel-mounted ADCP was used to survey absolute velocity along the mooring line at high lateral resolution, crossing the shelf break on ten separate occasions. Frantantoni et al. [2001] combined the nonsummer occupations (a total of seven) into a stream coordinate mean velocity section, which effectively removed any smoothing due to lateral meanders of the current. The position of the two ADCP moorings relative to this stream coordinate mean indicates that, even though the ADCPs were positioned only 15 km apart, on average they sampled opposite sides of the core of the shelf break jet (Figure 4). This notion is strengthened further in the analysis of the variability in the following section. We note that the along-stream mean velocity profile at the offshore shelf break ADCP has a subsurface maximum that is inconsistent with the mean vessel-mounted ADCP section. However, this may be reconciled with a larger collection of shipboard ADCP occupations.

[14] Previous observations [Houghton et al., 1988; Linder and Gawarkiewicz, 1998] and numerical model results [Gawarkiewicz, 1991] suggest that changes in the stratification at the shelf break due to the formation of a seasonal pycnocline, or seasonal changes in freshwater runoff to the shelf, may significantly alter the basic structure and variability of the shelf break jet. Seasonal variation in the wind field also causes structural changes in the shelf break jet and front [Beardsley et al., 1985; Aikman et al., 1988]. Because our velocity observations only span 1.5 years, spectral methods could not be employed to estimate the annual signal. To test if an annual cycle exists in the PRIMER data, we followed Beardsley et al. [1985] who used multiple regression analysis to fit moored velocity data to a seasonal model. The regression indicates that a statistically significant seasonal cycle exists at all depths at the offshore ADCP, characterized by maximum equatorward flow in fall and minimum equatorward flow in spring, with an amplitude of 2–3 cm/s near the surface. A similar analysis could not be performed on the inshore shelf break ADCP because of the significant gap in the time series at this site.

[15] Linder and Gawarkiewicz [1998] constructed a climatolgy from historical hydrographic data to investigate seasonal changes in the structure and strength of the shelf break front and geostrophically balanced jet. By comparison, they found no significant seasonal cycle in the transport of the climatological shelf break jet. In fact, they report that the maximum jet velocity occurs during spring, in contrast with our findings. It should be noted that their results depict only the baroclinic component of the flow, while ours represent the total, absolute velocity. Over the slope the seasonal cycle was generally the same as the offshore shelf break ADCP, strengthened flow in the fall and winter, with maximum amplitudes near the surface of 7–12 cm/s. This agrees with TOPEX altimetry observations that suggest an increase in equatorward flow of slope water in fall, over the entire MAB (S. Dong, personal communication, 2002).

4. Mesoscale Variability at the Shelf Break

[16] A 3-month portion of the along-stream velocity is shown in Figure 5, to illustrate the dominant variability observed at the shelf break (this variability is reminiscent of the entire record). While the flow is predominantly equatorward at both ADCPs, the current is regularly interrupted by bursts of poleward flow. These are manifestations of a periodic full water column weakening of the shelf break current. It is the origin of these fluctuations which is the focus of our analysis. To compare the extent of weakening of the current at each site, we defined a significant deceleration as one in which the observed velocity at a given depth, \( v(z) \), exceeds \( v(z)/e \), where the mean is taken over the record length. In Figure 6 we contour the magnitude of the decelerations meeting this criterion. Viewed this way it is clear that, throughout most of the record, significant decel-

![Figure 2. Time line of data coverage at the shelf break (inshore/offshore ADCPs) and on the slope (VACMs). The data coverage from the overlapping Coastal Mixing and Optics Experiment (CMO) is also shown.](image)
erations occur more frequently and with greater intensity at the offshore site. Furthermore, the decelerations penetrate higher into the water column at this mooring than at the inshore ADCP. Recall that the mean along-stream velocity at both shelf break moorings is largest in the upper 40 m where it can be 3–4 times as large as the near-bottom velocity (Figure 3). Therefore, defined this way, significant decelerations (and actual flow reversals) occur most often in the middle to lower portion of the water column where the perturbation velocity need not be as large.

[17] Late in the record, a shift occurs whereby the frequency and vertical penetration of the fluctuations dramatically increase (at both of the shelf break ADCPs). Observations collected on the shelf during the PRIMER deployment (CMO experiment) [Lentz et al., 2003], indicate that important changes occurred in the physical environment at the shelf break during this period. Among the changes was an observed deep temperature inversion and corresponding near-bottom increase in salinity at the CMO moorings (Figure 7), which together indicate that the foot of the shelf break front had moved inshore of the 70 m isobath. This suggests that the frequency and magnitude of current fluctuations at the shelf break may be related to the position of the frontal jet.

[18] Clearly, the oscillation in question is more evident at the outer shelf break. It is perhaps not surprising then that, statistically, the variability at the inshore site is most energetic at a shorter period than that observed offshore. Total kinetic energy spectra were computed from the velocity time series at both shelf break ADCPs using the Thomson multitaper method [Thomson, 1982]. The spectra show that energy at the offshore shelf break ADCP is sharply peaked at 13 days (Figure 8). The energy in this band decreases with depth (although there is still significant energy near the bottom). By contrast, a majority of the energy at the inshore ADCP is concentrated at shorter periods.

**Figure 3.** The record length mean vertical profile of velocity at each of the PRIMER moorings. The circles represent the along-stream component of velocity ($u$), while the squares represent the cross-stream component of velocity ($v$). The along-stream coordinate is oriented parallel to the axis of maximum variance.
periods (8–11 days), and is more uniformly distributed over the depth of the water column. These two spectra suggest that different processes may be contributing to the variability at the inshore and offshore sites. We provide further support of this below.

5. Local Shelf Break Forcing

[19] The origin of the current fluctuations shown in Figure 5 is not immediately obvious. One possibility is wind forcing, since observations indicate that the shelf break jet does respond to variations in the local wind [Houghton et al., 1988]. However, it is also possible that the fluctuations are caused by a rectification of the tides, since the spring-neap modulation of the semidiurnal tide occurs at a period of roughly two weeks. Observations have also shown that the position of the shelf break jet is often convoluted by meanders and frontal eddies, presumably resulting from internal instabilities of the current [e.g., Garvine et al., 1988]. Therefore finite disturbances that grow from instabilities in the shelf break jet may be another cause for the variability observed here. In this section we investigate such local forcing mechanisms. It was demonstrated above, however, that the current fluctuations at the inshore and offshore ADCPs become more similar in character when the base of the shelf break front propagates significantly inshore of the shelf break, and hence inshore of our two ADCPs (Figure 7). This suggests that the mechanism driving the velocity fluctuations may originate from the open ocean. In section 6 we consider remote forcing via the adjacent slope water offshore of the jet.

5.1. Wind Forcing

[20] Local winds in the MAB are predominantly northwesterly in the winter months, shifting to southwesterly during summer [Aikman et al., 1988]. This means that throughout the year, the wind opposes the flow at the shelf break. By Ekman dynamics, an eastward wind blowing along a zonally aligned coast draws surface water offshore and near-bottom water onshore within wind-driven Ekman layers. The presence of the coastline causes the sea surface to slope downward toward the coast, resulting in the formation of a cross-shelf pressure gradient that sets up an along-shelf (eastward) current. In the MAB, this is opposite to the sense of the predominant westward flow of the shelf break jet. In order to investigate the relationship between wind forcing and the current variability observed by the PRIMER shelf break moorings, it was necessary to identify the wind direction that is most correlated with currents in this region. R. K. Shearman and S. J. Lentz (Subtidal current variability on the New England shelf during the Coastal Mixing and Optics Experiment, submitted to Journal of Geophysical Research, 2002, hereinafter referred to as Shearman and Lentz, submitted manuscript, 2002) have shown that along-isobath currents on the shelf, inshore of the PRIMER array, are highly sensitive to wind forcing, responding in a manner consistent with the dynamics of coastal set-up outlined above. Further, they demonstrate that along-isobath velocity observed over the shelf (during the PRIMER study period) is most correlated with a wind directed toward 045 °T. This roughly corresponds to the orientation of the coastline in the MAB, estimated from high-resolution coastline data at length scales of 1000 km and more (Shearman and Lentz, submitted manuscript, 2002). Accordingly, the wind observations in our analysis have been rotated relative to a coordinate system in which positive $t_x$ (referred to hereafter as the alongshore component of the wind) is directed along the coast toward the northeast.

[21] Statistically, fluctuations in the local wind during the time period of the PRIMER array occurred on timescales less than 10 days, with energy concentrated within bands centered at 3 days, 4–5 days, and 8–10 days (Figure 9). Comparing the kinetic energy spectrum of the wind stress with the energy distribution at the shelf break (Figure 8), one sees that variations in the winds occur on timescales shorter than the dominant current fluctuations at the outer edge of the shelf break jet (which are peaked at 13 days). In fact,
there is no significant correlation between the winds and the currents at the offshore ADCP, except at periods less than 6 days (Figure 10). By contrast, current fluctuations at the inshore ADCP are energetic on timescales comparable to those associated with the wind, and along-stream currents at the inshore ADCP are significantly correlated throughout the water column with changes in the alongshore wind stress (Figure 10). The fact that the coherence is maximized near 80 m at the inshore site, and near 40 m at the offshore site, might be due to the location of the instruments relative to the shelf break front. On average, the front intersects the inshore ADCP mooring near 80 m and the offshore mooring near 50 m (Figure 4). This suggests that the wind influences the velocity through adjustment of the front, predominantly on a timescale of 4–5 days, although the dynamics of this frontal response are not obvious and require further analysis.

Shearman and Lentz (submitted manuscript, 2002) examined current variability over the shelf inshore of our array and identified periods when the velocity episodically reversed in response to changes in the local winds. Comparing the time series of along-stream velocity at the inshore shelf break ADCP with their results, we find that the wind-related events observed on the shelf are also evident at the inshore shelf break site. Therefore local wind forcing is clearly responsible for some of the high-frequency current variability observed on the inshore side of the shelf break jet. However, wind forcing cannot account for the periodic flow decelerations observed at the outer shelf break, which dominate the record at the offshore ADCP.

5.2. Tidal Forcing

The $M_2$ semi-diurnal tidal current (12.42 hours) is the strongest tidal constituent in the MAB, accounting for up to 80% of the total tidal variance in the region [Moody et al., 1984]. The spring neap tidal cycle is a modulation on the primary semi-diurnal signal that has an amplitude equal to approximately 15–20% of the $M_2$ amplitude and fluctuates at 14.775 days. Because the current fluctuations that we observe at the shelf break occur at a period sufficiently close to that associated with the spring neap variation, it is necessary to investigate the tides as a forcing mechanism. As an example, Butman et al. [1983] proposed that spring neap variations in tidal forcing could cause variations in the subtidal flow around Georges Bank through tidal rectification.

The amplitude of the barotropic semi-diurnal tide was estimated using the unfiltered, vertically averaged, velocity time series from the offshore ADCP. (A similar calculation was applied to the unaveraged velocity time series at several depths to include the effects of the baroclinic tide. However, the results were largely the same.) Complex demodulation was applied to the separate $u$ and $v$ time series and combined to estimate the total amplitude of the velocity fluctuations at the $M_2$ frequency as a function of time. The energy content of the tidal modulation was then determined by computing the power spectrum of the amplitude time series and ultimately used to estimate the energy associated with spring neap modulations of the tide. The largest amplitude fluctuation in the semi-diurnal tide occurs at a period of 27 days, with weaker energy centered near the spring neap frequency. The near-monthly modulation results from the combination of the large lunar elliptic ($N_2$, 12.6583 hr) and $M_2$ tidal constituents, and can be as much as 39% larger than the amplitude of the spring neap modulation in this region [Moody et al., 1984]. The total energy associated with the tidal modulation near 13–15 days is on the order of 4–6 cm$^2$/s$^2$. This is more than an order of magnitude

![Figure 5.](image-url)
smaller than the observed shelf break fluctuations in this same frequency range (Figure 8), indicating that the tides are not strong enough to account for dominant variability observed at the shelf break.

5.3. Baroclinic Instability

[25] Meanders and frontal eddies are ubiquitous features of the shelf break front in the MAB, presumably due to baroclinic instability of the jet itself. Hence these features are a likely source for the variability present in the PRIMER data. Over the years the size, shape, and speed of shelf break meanders and frontal eddies have been documented from observations [e.g., Garvine et al., 1988; Ramp et al., 1983] and with increasingly more complex and realistic stability models [e.g., Flagg and Beardsley, 1978; Gawarkiewicz, 1991; Lozier et al., 2003]. With few exceptions, the observations and model results to date suggest that perturbations arising from the instability of the shelf break jet occur on timescales less than 5 days, much shorter than the 13-day timescale observed at the shelf break (Table 1).

[26] Flagg and Beardsley [1978] are the only modeling study to report periods longer than 10 days. Their two-layer model included a front in geostrophic balance over both flat and linearly sloping bottom topography. However, they found that the sloping bottom tended to stabilize the front so that perturbations did not grow to a discernable size in less than 200 days, an unrealistically long timescale in the MAB.

[27] A perusal of sea surface temperature maps from the Advanced Very High Resolution Radiometer (AVHRR) during the PRIMER period reveals that wavelike features were often present near the shelf break. However, the noncontinuous nature of these images makes it difficult to make any quantitative assessment about the evolution of such frontal features. Instead, we can examine the observed current fluctuations to determine whether they have the character of a propagating meander. On average, the shelf break ADCPs are located on opposite sides of the core of the current (Figure 4). Therefore it is expected that the passage of a meander would result in enhanced flow at one...
ADCP and decreased flow at the other. Instead, the along-stream velocity at the two shelf break ADCPs is positively correlated throughout the record (Figure 11). To first order, this suggests that the decelerations and flow reversals exhibited in Figure 5 are not caused by simple cross-shelf meandering of the jet axis. Admittedly, the position of the ADCPs is measured relative to a mean velocity section that was compiled from just 7 synoptic realizations [Fratantoni et al., 2001] and may not be representative of the average jet position for the full PRIMER study period. Unfortunately, on average, the foot of the front was located inshore of both shelf break moorings (Figure 4). Therefore the bottom-temperature records do not reveal the cross-shelf movement of the foot of the front and can not be used to shed light on this. Interestingly, Fratantoni et al. [2001] found a similar result using the collection of shipboard ADCP sections contained in Figure 4. Their analysis indicated that the along-stream velocity varied in phase across the entire section, accelerating and decelerating over the full water

Figure 7. Time series of bottom salinity and top to bottom temperature difference at the 70 m isobath as measured by the central CMO mooring. Negative temperature difference indicates a temperature inversion where bottom temperatures are warmer than temperatures near the surface.

Figure 8. Total kinetic energy spectra (cm²/s²) calculated from the shelf break ADCP time series and shown as a function of depth.

Figure 9. Total energy spectrum ((dynes/cm²)²) for wind stress collected by the nearby CMO wind buoy during the PRIMER experiment.
column, resulting in flow reversals near the bottom. This is consistent with our moored observations.

Finally, there is some suggestion from past results that there is a seasonal dependence to frontal instabilities. For instance, Houghton et al. [1988] argues that perturbations in the shelf break jet (and possibly the occurrence of shelf break frontal eddies) are more prevalent during summer when the seasonal pycnocline is fully established. They note that the perturbations appear to be trapped in the upper water column, bounded by the seasonal pycnocline. Similarly, Gawarkiewicz [1991] has shown that the summer front is more unstable, by up to a factor of two, than the winter front. In particular, the formation of a seasonal pycnocline alters the vertical structure of the most unstable modes, causing them to be more pycnocline-trapped. By contrast, the current fluctuations we have observed at the shelf break are present throughout the year, occupy the full water column, and their magnitude does not appear to exhibit any seasonal dependence.

Overall, the impression one gets after reading the existing literature is that baroclinic instability is not the source of the 13-day fluctuations observed here. Our measurements are dissimilar to the expected timescales, lateral displacements, seasonality, and vertical structure of unstable perturbations. However, we note that observations of frontal meanders have most often sampled just one or two meander events or are based on a single quasi-synoptic section. By contrast, the two PRIMER ADCPs represent the most complete and statistically significant sampling of the MAB shelf break jet to date. Furthermore, even the most recent stability models are based on idealized representations of frontal jets. We revisit this issue at the end of the paper.

6. Remote Slope Water Forcing

Perturbations at the shelf break may also be forced from the seaward side of the jet. On average, the highly energetic Gulf Stream is located just 200 km offshore of the shelf break front in the MAB [Halliwell and Mooers, 1979]. The close proximity of the Gulf Stream causes variability over the slope that may, in turn, influence the shelf break region. In the most common example, anticyclonic warm-core rings (spawned farther to the east) propagate westward along the continental slope, situated between the Gulf Stream and the shelf break. When these rings impinge on the upper slope they can advect shelf water offshore within streamers [Joyce et al., 1992], and force large meanders in

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Table 1. Timescales for Wavelike Instabilities in the Shelf Break Front Inferred From Observations and Models

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Measurement:</th>
<th>Period</th>
</tr>
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<tbody>
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<td>Saunders [1973]</td>
<td>Airborne radiometry</td>
<td>3–5 days</td>
</tr>
<tr>
<td>Voorhis et al. [1976]</td>
<td>floats</td>
<td>3–5 days</td>
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<tr>
<td>Ramp et al. [1983]</td>
<td>SST</td>
<td>1 day</td>
</tr>
<tr>
<td>Garvine et al. [1988]</td>
<td>SST, hydrography, current meters</td>
<td>5 days</td>
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<tr>
<td>Ramp [1989]</td>
<td>Eulerian temperature</td>
<td>5–7 days</td>
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<td>SST</td>
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Figure 10. Coherence between alongshore wind stress and along-stream velocity at both shelf break ADCP sites. The solid contours are statistically significant, and the shaded contours indicate that the wind leads the current.

Figure 11. Lagged correlation between the along-stream velocity measured by the inshore and offshore shelf break ADCPs. The correlation is contoured as a function of depth and lag. The shaded region highlights correlation values that are statistically significant. The dashed line marks the maximum correlation coefficient at each depth.
the shelf break front [Ramp, 1989; Pickart et al., 1999]. The strong eastward flow associated with Gulf Stream rings has been known to drive shear instabilities in the shelf break front as well [Ramp et al., 1983]. Furthermore, it has been demonstrated that the Gulf Stream [Pickart, 1995] and warm core rings [Ramp, 1989; Aikman et al., 1988] can remotely excite topographic Rossby waves over the continental slope in the MAB. Topographic waves with periods as short as 16 days have been observed on the upper slope near the PRIMER array [Aikman et al., 1988]. In the following section, we investigate possible coupling between the circulation over the slope and variability at the shelf break.

6.1. Warm-Core Rings

[31] Four Gulf Stream rings passed through the PRIMER region during the 18-month deployment. The presence of a ring was easily identified in the slope water V ACM records by an intense burst of eastward flow, accompanied by a significant change in temperature. The presence of each of the rings was independently verified using maps of sea surface temperature from the AVHRR. On average, a ring propagated through the slope water array every 4.5 months, much too infrequently to explain the periodic 13-day perturbations observed at the shelf break. Similarly, the passage of a single ring typically occurs over roughly 30–40 days, also long with respect to the variability at the shelf break.

[32] Recall that a significant increase in the magnitude, frequency, and vertical penetration of shelf break fluctuations occurred late in the record at both shelf break ADCPs (Figure 6). This shift coincided with the onshore movement of the foot of the shelf break front (Figure 7). Approximately 20 days later, AVHRR observations indicate that a large warm-core ring impinged on the slope, influencing temperature and velocity records at all three slope moorings, including the mooring closest to the shelf break. The largest onshore shift in the foot of the front actually occurred after the warm-core ring had begun to influence the slope moorings on January 10 (Figure 7), suggesting that the ring may be partially responsible for the movement of the foot of the front and hence linked to the changes in magnitude and frequency of fluctuations during this period.

[33] In order to investigate the possibility that the amplitude of the shelf break fluctuations is correlated with the passage of nearby Gulf Stream rings throughout the record, complex demodulation, with a period of 13 days, was applied to the velocity time series of the offshore shelf break ADCP (Figure 12). We show the resulting amplitude time series at a depth of 90 m, since this is deep enough to capture the most energetic current fluctuations observed at both shelf break ADCPs (the largest peaks are also present in the amplitude time series calculated at other depths). It is seen that the current fluctuations at the shelf break occasionally intensify, with the largest events occurring at the beginning and end of the record (Figure 12). However, there is no clear correlation between the most energetic events and the passage of Gulf Stream rings. In the remaining analysis, we utilize the 6-month ring-free period from June to December 1996 to investigate other possible forcing mechanisms in the slope water. Note that during this time period two large-amplitude events occurred at the shelf break (Figure 12).

6.2. Topographic Rossby Waves

[34] During the ring-free period, the current fluctuations over the upper slope were predominantly rectilinear (Figure 13). The power spectrum at the slope mooring closest to the shelf break (1000 m isobath) shows that, near the bottom, the energy is maximized at a period of 20–30 days (Figure 14). The variance ellipses at this period are more elongated with depth, and are slightly inclined near the bottom relative to local isobaths (Figure 15). These features are reminiscent of bottom-trapped topographic Rossby
waves (TRWs) [see Pedlosky, 1979], which were likely present over the continental slope during the ring-free period. To confirm this, we first computed the lagged cross-correlation between the along-slope component of velocity at the neighboring, near-bottom slope moorings (Figure 16). The correlation curves are sinusoidal in character, with a period near 30 days. The maximum correlation is such that the inshore slope instrument leads the middle instrument by roughly 2 days, while the middle leads the offshore instrument by 4–5 days. This difference is consistent with the instrument spacing, implying an offshore phase propagation of the 30-day perturbation.

[35] Following Johns and Watts [1986], the phase speed of the wave can be determined by

\[ c_p = \frac{1}{T} \left( \frac{360}{C^2} \right) \]

Figure 13. Time series of vector velocity recorded during the ring-free period, by the inshore slope mooring located at the 1000 m isobath. Westward flow is directed toward the top of the page.

Figure 14. Total kinetic energy spectrum (cm²/s²) computed from velocity collected by the slope mooring closest to the shelf break (1000 m isobath). The instrument depths are denoted by the dashed lines.

Figure 15. Thirty day variance ellipses calculated at each of the near-bottom instruments in the PRIMER array. The depth of the instrument is indicated beside each ellipse.
where $T$ is the wave period, $\bar{f}$ is the average phase offset, $\Delta s$ is the average instrument spacing, and $\Delta \theta$ is the relative angle between the mooring line and wave vector. The variance ellipses in Figure 15 imply that, on average, the wave vector lies along $178^\circ T$ (perpendicular to the average ellipse orientation), so that $\Delta \theta = 2^\circ$. Coherence calculations show that the along-slope velocity at neighboring slope moorings are coherent at periods of 30 days and longer, with an average phase offset $\bar{f} = 6^\circ$. On the basis of these parameters and the average instrument spacing between the slope moorings ($\Delta s = 46$ km), the phase speed of the 30 day waves is approximately 7 km/day, and the wavelength roughly 225 km. The wave energy vector points upslope, indicating an offshore source. The most probable candidate is the meandering Gulf Stream [Hogg, 1981; Schultz, 1987; Pickart, 1995].

As a consistency check, we can use the dispersion relation for TRWs in a stratified ocean to predict the orientation of the 30 day wave vector and compare it to what is observed. Following Pickart and Watts [1990], the dispersion relation is

$$T = \frac{2\pi \tanh(2\pi ND/\lambda f)}{Na \sin \theta},$$

(1)

where $T = 30$ days, $\lambda = 225$ km is the wavelength, $N = 3 \times 10^{-3}$ s$^{-1}$ is the subthermocline buoyancy frequency, $D = 2000$ m is the average water depth over the slope array, $f = 9 \times 10^{-4}$ s$^{-1}$ is the Coriolis parameter, $\alpha = .02$ is the bottom slope, and $\theta$ is the angle between the wave vector and the downslope direction. The dispersion relation is not dependent on the planetary vorticity gradient ($\beta$) because topographic $\beta$ is 2 orders of magnitude larger in the vicinity of the PRIMER slope moorings. From (1), the predicted direction of phase propagation is $\theta = 2^\circ$ from downslope. By comparison, the observations indicate that the wave vector is directed toward $178^\circ T$. Therefore, on the basis of the average isobath orientation the observed direction of phase propagation is roughly $7^\circ$ from downslope. Given the uncertainty in estimating the downslope direction, this agrees very well with the predicted value.

It is not surprising to find evidence of TRW activity on the continental slope in the MAB. Such waves have been observed on numerous occasions in the past, with periods ranging from 15–30 days, wavelengths from 80–220 km, and phase speeds on the order of 10 km/day [e.g., Johns and Watts, 1986; Shultz, 1987; Shaw and Csanady, 1988; Ramp, 1989]. The relevant question here is whether any topographic wave energy reaches the shelf break, which in this region is roughly the 200 m isobath. Observations [Ramp, 1989] and numerical modeling studies [Shaw and Peng, 1987] suggest that, unless the source is nearby, wave refraction and bottom friction act to insulate the shelf break and upper slope from waves with periods greater than 10 days. Following Ramp [1989], the frictional parameter governing onshore penetration of a perturbation of frequency $\sigma$ is $q = r(\sigma h)$, where $h$ is the nominal water depth, and $r = 5 \times 10^{-4}$ m/s is the bottom friction coefficient defined for the slope. For a 30 day wave, friction dominates ($q = 1$) at a water depth of approximately 200 m. Thus, for the PRIMER region, while the presence of 30-day TRWs at the 1000 m isobath is feasible, the likelihood of such energy reaching the shelf break is small.

What do our observations suggest? The energy spectrum at the inshore slope mooring implies that the 30 day waves do not penetrate the full water column. According to
linear theory, the vertical structure of a topographic Rossby wave is given by $A(z) = \cosh(H^{-1}z)$, where $H = \lambda f/2 \pi N$ is the vertical trapping scale of the wave when planetary $\beta$ is negligible [Pedlosky, 1979]. Using the observed parameters, the predicted vertical decay scale of the waves is 1100 m, or roughly half the nominal water depth. This is consistent with the observed energy distribution, and confirms that the TRWs are bottom-trapped. Therefore, if the wave energy reaches the shelf break it would be most prevalent at depth. However, the cross-correlation between the near-bottom along-stream velocity at the offshore shelf break ADCP, and that at the bottom of the inshore slope mooring, is insignificant.

[39] Recall that the energy at the shallowest inshore slope water instrument (100 m) shows a peak at shorter periods (13–16 days) than the bottom-trapped TRWs (Figure 14). This is similar to the variability observed at the outer shelf break ADCP. In fact, these two records are coherent at this period. Hence the phenomenon observed at the shelf break is present on the upper slope as well (but decoupled from the deep waves). This raises the possibility of an upper layer slope water source, which we investigate next.

6.3. Direct Forcing by the Gulf Stream

[40] In the region between the Gulf Stream and the shelf break in the MAB, the mean circulation consists of an elongated cyclonic gyre called the Slope Sea Gyre [Csanady and Hamilton, 1988]. This feature, evident in surface dynamic topography, stretches approximately 800 km along the slope, and recirculates slope water within the upper few hundred meters of the water column. The offshore PRIMER moorings sampled the shoreward limb of this gyre (Figure 17). Bane [1988] has demonstrated that changes in the position of the Gulf Stream, on monthly timescales, are correlated with fluctuations in the strength of the northern limb of the gyre northeast of Cape Hatteras. Specifically, his observations show that a shoreward shift in the Gulf Stream position coincides with stronger equatorward flow at the 1000 m isobath. This suggests that the Gulf Stream may be capable of forcing current fluctuations over the upper slope and shelf break from several hundred kilometers away, by “compressing” the Slope Sea Gyre.

[41] In order to investigate the possibility that this type of process may be happening at the PRIMER site, we utilize frontal positions digitized from sea surface temperature data (courtesy of P. Cornillon) to monitor the distance between the Gulf Stream front and the shelf break at 70°W. The frontal data covers 4 years, including the PRIMER study period, at a resolution of 2 days. Following Bane [1988], we examined the relationship between the position of the Gulf Stream and the currents at the onshore slope mooring. However, unlike the earlier study, we find no significant correlation between monthly averaged Gulf Stream positions and monthly averaged currents on the slope. This is perhaps not surprising, since the Gulf Stream is much farther offshore of the shelf break at our site than where Bane [1988] did his study.

[42] By the same token, it is difficult to imagine that the meandering Gulf Stream could cause fluctuations even further inshore at the shelf break, especially at a shorter period of 13 days. The AVHRR data indicate that the most commonly occurring meander period in the Gulf Stream is roughly 40 days [Pickart, 1995; Lee and Cornillon, 1996]. If the 13-day fluctuations observed at the shelf break were forced remotely by the Gulf Stream, the effect should be observable at each of the slope moorings. While such a signal was present at the 1000 m mooring, there is no significant coherence at any of the offshore moorings, nor with the Gulf Stream, at this period. This appears to preclude the notion that the current fluctuations at the shelf break are forced by a mechanism originating in the shallow portion of the adjacent slope water.

7. Summary and Discussion

[43] A mooring array was maintained across the shelf break and slope in the Middle Atlantic Bight, near 70°W, as part of the PRIMER experiment. The variability of the shelf break current over the 18-month record, as revealed by a bottom-mounted ADCP at the outer edge of the jet, was dominated by fluctuations at a period of 13 days. The fluctuations are characterized by decelerations in the equatorward flow, which are large enough to reverse the jet near the bottom. While the variability is evident throughout the water column, the variance is surface intensified. We have explored most of the potential, and often cited, forcing mechanisms that could be responsible for the observed variability, and have not been able to identify unequivocally the cause. We have, however, been able to discount several possibilities. These include local effects, such as wind driving and tidal rectification, as well as offshore forcing due to Gulf Stream rings, topographic Rossby waves, and the meandering of the Gulf Stream.

[44] We also explored the possibility that the fluctuations are caused by baroclinic instability of the shelf break jet. We found differences between the character of the variability observed in the PRIMER array and that traditionally believed to result from instability. The most notable difference is the timescale of the oscillations: 13 days is longer than what is commonly thought to be associated with...
unstable waves. Most of the existing information on the nature of instabilities at the shelf break has been derived from linear stability models. It should be noted, however, that the growth of disturbances at finite amplitude may bear little resemblance to the short-term linear behavior found in these models. For example, linear stability models require small perturbations about the mean background state, capturing primarily the initial growth period of the wave. The shelf break ADCP moorings in the PRIMER array were positioned approximately 15 km apart in a jet with roughly the same width. Perhaps this somewhat wide spacing prohibited us from detecting relatively small amplitude oscillations like those that are simulated in the linear models. Instead, it is possible that the 13 day oscillations observed here represent the timescale for the entire life cycle of a baroclinic disturbance, extending from its growth to an amplitude that is observable by our array, through its spindown. Other recent observations indicate that perturbations in the shelf break front can reach large amplitudes [e.g., Gawarkiewicz et al., 2002]. It has also been demonstrated in models that nonlinear interactions, occurring after the initial growth period, may result in energy cascades to larger scales, and hence longer wavelengths [Flierl et al., 1987]. In a primitive equation model of the shelf break front in the MAB, Sloan [1996] hypothesizes that two frontal waves, interacting nonlinearly, combine to form a single wave with a larger wavelength. These effects can not be captured in linear stability models.

[45] Another unexplained feature of the velocity fluctuations observed during PRIMER is that they do not exhibit the character of a propagating meander. Instead of varying out of phase, as one would expect on the basis of the cross-stream position of the moorings relative to the mean jet, the velocity fluctuations at the shelf break ADCPs are correlated and in phase. A similar type of pulsing fluctuation was observed in repeat shipboard ADCP surveys along the PRIMER mooring line [Fratantoni et al., 2001]. Such variability is reminiscent of varicose oscillations [Pratt et al., 1991], which are characterized by along-stream variations in the width of the current. This is in contrast to sinuous meanders, which are the focus of stability models in the MAB, whereby the position of the current varies. Varicose oscillations have been observed in the Gulf Stream [Cornillon et al., 1986], and it has been shown that they can grow in an unstable manner and lead to the detachment of warm eddies from the current [Pratt et al., 1991]. Perhaps a similar effect is happening in the shelf break jet. However, unlike the sea surface temperature maps of the Gulf Stream, such a phenomenon is not easily observed in the shelf break jet where temperature gradients are not as pronounced along its offshore edge.

[46] While in recent years linear stability models in the MAB have evolved to include more complex dynamics, it is important to note that they still contain major simplifications. For example, Lozier et al. [2003] explore the stability characteristics of the shelf break jet using a linear primitive equation stability model with parameters specifically chosen to represent the conditions within the MAB. They systematically vary the width, depth, and speed of the background jet. While this is the most realistic simulation of its kind to date, the study incorporates two important simplifications: linear vertical stratification and symmetric horizontal velocity shear. The former does not allow for the existence of a sharply defined front, the dominant hydrographic feature of the shelf break, and the latter ignores the fact that the horizontal velocity shear is twice as large on the cyclonic side of the shelf break jet [Fratantoni et al., 2001]. It is not clear how these simplifications might effect the results of the stability analysis; however, it has been shown that significant changes in the background stratification significantly alter the structure and timescales associated with the unstable waves [Gawarkiewicz, 1991].

[47] Lozier et al.’s [2003] analysis indicate that the fastest growing waves have wavelengths on the order of 10–20 km and periods less than 5 days. By comparison, observations suggest that meanders in the shelf break front typically have slightly longer wavelengths, between 20 and 50 km [Voonrhis et al., 1976; Garvine et al., 1988; Pickart et al., 1999; Gawarkiewicz et al., 2002]. A wave with a wavelength of 40 km, propagating at a speed of 3 km/day, will have a period of 13 days (the observed period in the PRIMER array). By comparison, the fastest growing waves in the Lozier model tend to have shorter wavelengths and faster phase speeds. However, in at least one case, perturbations were generated in their model with phase speeds as slow as 5 km/day and wavelengths on the order of 50 km/day. These perturbations were generated in a background jet with a maximum speed of 30 cm/s and a width of 15 km, realistic parameters with respect to observations [see Fratantoni et al., 2001]. Although these waves were not the fastest growing, their growth rates are not significantly smaller than the most unstable ones. In fact, there is a local extremum in the growth rate at these long wavelengths. This suggests that it is at least possible, even in simplified models, for unstable perturbations with longer periods to develop in the shelf break jet.

[48] Clearly we do not yet fully understand the stability characteristics of the shelf break jet in the MAB. Hence, unlike the other forcing mechanisms discussed above, we can not unequivocally rule out baroclinic instability as a cause for the variability observed in the PRIMER array. Our study demonstrates the need for more thorough observations, in particular with better spatial resolution across the shelf break jet, as well as more realistic stability models. Until the nature and dynamics of such shelf break current fluctuations are understood, we will be unable to quantify other important attributes of the shelf break system, such as the shelf-slope exchange of mass and properties.

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