Seasonal characteristics of bottom boundary layer detachment at the shelfbreak front in the Middle Atlantic Bight

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[1] The seasonality of various characteristics of the detached bottom boundary layer of the Middle Atlantic Bight shelfbreak front is examined using a collection of high-resolution transects across the front. The analysis follows previous methodology in which accumulated temperature change along isopycnals within the front is used to infer the location of the detached layer. The seasonal mean isopycnal at which detachment occurs (approximately 26.0 kg m^{-3}) is fairly constant throughout the year. However, the vertical scale of the detached layer varies significantly with season, extending 60–80 m above the bottom in winter and spring, but only 20–40 m above the bottom in summer. The vertical scale is controlled by the strength and depth of the seasonal pycnocline. The observations suggest that the detached layer is capable of extending into the euphotic zone during winter and spring. *INDEX TERMS:* 4528 Oceanography: Physical: Fronts and jets; 4211 Oceanography: General: Benthic boundary layers; 4219 Oceanography: General: Continental shelf processes; 4279 Oceanography: General: Upwelling and convergences; *KEYWORDS:* bottom boundary layer, shelfbreak front, Middle Atlantic Bight

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1. Introduction

[2] Modeling studies of shelfbreak fronts have consistently shown the continuity of flow from the bottom boundary layer (BBL) on the shelf into the interior of the frontal zone. *Gawarkiewicz and Chapman* [1992] identified this as the detachment of the BBL, and suggested this was a possible mechanism for pumping regenerated nutrients from the benthos into the euphotic zone along frontal isopycnals. *Chapman and Lentz* [1994] extended this work and showed that BBL detachment was a fundamental feature of buoyancy driven flows in which cross-shelf density gradients extend to the bottom. This process is intimately related to the so-called shutdown of the BBL, previously identified by *MacCready and Rhines* [1993]. Figure 1 illustrates this process, showing how bottom Ekman layer flows may converge and lead to detachment of the BBL through continuity. In this example, the deep thermal wind shear reverses the flow of the frontal jet near the bottom [see *Chapman and Lentz*, 1994].

[3] Recent observational work has confirmed that there is indeed an upwelling circulation that extends from the BBL on the shelf, along isopycnals, seaward over the continental slope at the shelfbreak front in the Middle Atlantic Bight (MAB). In a series of field experiments, *Houghton* [1997] and *Houghton and Visbeck* [1998] showed that dye, originally released shoreward (and seaward) of the front several meters above the bottom, was carried along frontal isopycnals with vertical velocities on the order of 10 m per day. *Barth et al.* [1998] presented evidence of BBL detachment from distributions of suspended sediments. Most recently, *Pickart* [2000] developed a method to identify the detached BBL within the front using hydrographic data. The basic idea is that pumping along the isopycnal or isopycnal layer in which the detachment is occurring should result in a weaker temperature gradient along that isopycnal (i.e., weaker than on adjacent isopycnals). Hence a plot of accumulated temperature change (ATC) along all of the isopycnals in a vertical section across the front reveals a tongue of low values extending upwards along the specific detachment isopycnal(s). *Pickart* [2000] verified this method by comparing it to an independent measure of the detachment based on the weakened vertical stratification of the detached isopycnal layer (which is an implied signature of a relic bottom mixed layer).

[4] Any such observational measure of the detachment process is especially useful, because, while the frontal secondary circulation in models is dependent on mixing parameterizations [*Chapman*, 2002], the detachment process itself is robust. A particular advantage of the ATC method is that it can be readily applied to any standard conductivity-temperature-depth (CTD) section across the shelfbreak front, provided the section has sufficient horizontal resolution. Using a CTD section from the MAB obtained in May 1996, *Pickart* [2000] found that the detached layer, as revealed by the ATC tongue, extended approximately 80 m above the bottom, reaching within 20 m of the surface. This suggests that at times, the secondary circulation within the front may be capable of transporting

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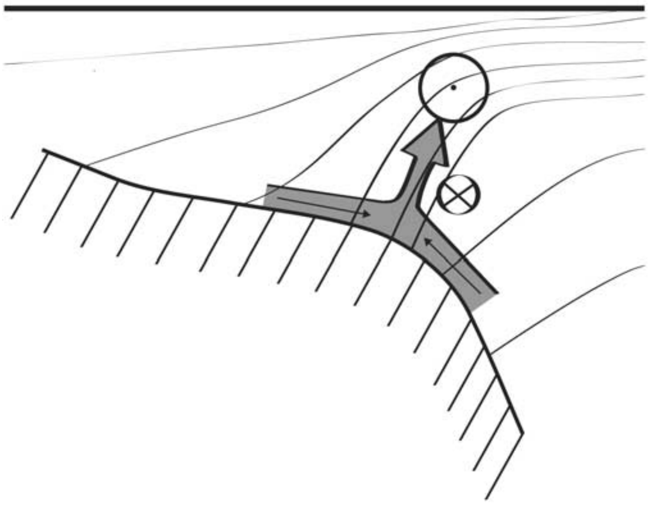

Figure 1. Schematic of the shelfbreak front and bottom boundary layer (shaded region) in a stratified regime. Geostrophic shear within the front reverses the flow near the bottom such that there is a double-sided convergence. This in turn leads to the detachment of the bottom boundary layer into the frontal zone.

regenerated nutrients from the bottom over the shelf into the euphotic zone within the offshore edge of the front, as hypothesized by *Gawarkiewicz and Chapman* [1992] in their modeling study. This could be expected to boost primary productivity within the frontal zone (order 10–15 km wide) as well as influence the spatial distribution of various zooplankton species in the vicinity of the shelfbreak.

[5] A natural question to consider is, how do the characteristics of the detached BBL vary with season? The density stratification changes significantly throughout the year within the front, and so one would expect that the structural changes of the front would affect the characteristics of the detached BBL. In this paper we apply the ATC method to a collection of hydrographic sections from the MAB to investigate the seasonal differences in BBL detachment. We briefly review the method of *Pickart* [2000] for identifying the detached BBL, and describe minor changes to the method that simplify the analysis. Next we describe the seasonal evolution of the shelfbreak front using a new MAB climatological database. The temporal evolution of the detached BBL throughout the year is then investigated using a collection of synoptic sections from winter, spring, and summer. Finally, implications of the seasonal differences in vertical scale of the detached BBL and the effect on the shelfbreak pigment distribution are discussed.

2. Data and Methods

2.1. Accumulated Temperature Change

[6] The method we employ to reveal the presence of the detached BBL is described by *Pickart* [2000]. Since the detached layer is transporting water both offshore and upward along density surfaces, the essential idea is that these isopycnals should be characterized by relatively small lateral changes in temperature (weak accumulated temperature change, or ATC). While such a signature in ATC could theoretically result from other processes besides detachment, *Pickart* [2000] analyzed the raw (non-pressure averaged) CTD scan data for a cross-slope transect and found complete agreement between detachment deduced from the anomalously weak vertical stratification of the layer and that resulting from the ATC method (the latter using the 2-dbar averaged data). This implies that at least for the MAB frontal system, the ATC technique accurately detects the presence (or absence) of the detached BBL. We now briefly review the steps necessary to compute vertical sections of ATC, describe minor changes we made to the method, and list the sources of the high-resolution transects used for this analysis.

[7] The ATC sections were computed via a multistep process. First, the potential density (σ_θ) was gridded at high resolution in the cross-stream plane using Laplacian-spline interpolation. We typically used a grid spacing of 2 km in x (cross-stream distance, positive offshore) and 5 m in y (vertical distance, positive upward). The section was then contoured at a small density interval, and the (x, y) coordinates of each contour level were computed. Only those isopycnals that intersected the bottom were considered. This leaves a set of (x, y) coordinates representing the location of each isopycnal that originates from the bottom (or more precisely the deepest local depth of the CTD section) and terminates at either the surface or the offshore boundary of the section. Next we calculated the potential temperature (θ) along each of the isopycnals using the gridded θ section to interpolate along the (x, y) values. The accumulated temperature change was then determined by integrating the absolute value of the θ-gradient along each isopycnal, starting with a value of zero at the bottom. In the final step, these irregularly spaced values of ATC in the cross-stream plane were regridded and contoured like any other property such as temperature or density. We note that the method employed here is somewhat simpler than that used by *Pickart* [2000]. Furthermore, all of the above steps are accomplished in a single computer program.

2.2. Hydrographic Sections

[8] The method of computing ATC requires hydrographic sections that are well resolved laterally across the front in order to ensure the accurate depiction of the isopycnals throughout the section. Coarse resolution means that the contouring interpolation would provide much of the structure between stations so that the subsequent integration along isopycnals would be questionable at best. In general, we sought out cross-shelf transects at the shelfbreak south of New England in which the station spacing was 10 km or less (Figure 2). Fortunately, several recent experiments provided enough high-resolution sections to examine.

[9] The 1995–1997 Shelfbreak PRIMER Experiment [*Gawarkiewicz et al.*, 2004] contained a set of cruises with SeaSoar sampling, as well as high-resolution CTD measurements. Numerous cross-shelf SeaSoar sections were obtained during the summer, winter, and spring [*Gawarkiewicz et al.*, 2001, 2004]. Details of the processing of these data are described in the two cited papers. The SeaSoar sections were located in the vicinity of 71°W, with a cross-shelf spacing of profiles on the order of 1 km. Additionally, cross-shelf transects in different seasons were

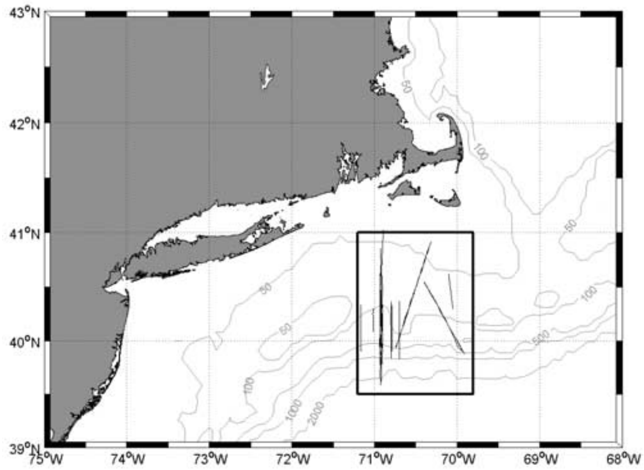

Figure 2. Study area of the Middle Atlantic Bight (denoted by the box), and the vertical sections used in the study (thin lines). Bottom topography contours are in meters.

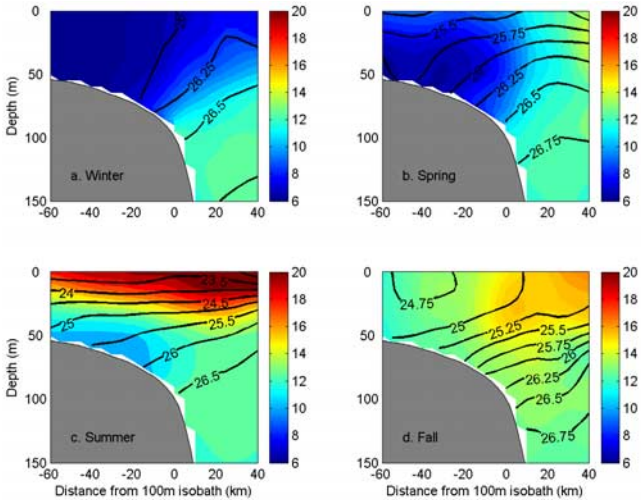

Figure 3. Seasonal composite vertical sections of potential temperature (°C, color) and density (kg m^{-3}, contours) from the new climatology of the MAB shelfbreak front.

occupied during PRIMER using a standard CTD, with a lateral resolution of 2–5 km [*Fratantoni et al.*, 2001]. The CTD line coincided with a TOPEX altimetric subtrack located roughly 40 km east of the SeaSoar sections.

[10] Other CTD sections used in this study came from the Coastal Mixing and Optics Experiment [*Lentz et al.*, 2003] taken at roughly the same time and in the same vicinity as the PRIMER CTD sections, all with 5-km station spacing [e.g., *Rehmann and Duda*, 2000]. Finally, a number of CTD sections from the Shelf Edge Exchange Processes (SEEP-I) experiment were used, kindly provided by C. Flagg. SEEP-I took place in the vicinity of 71°W, and station spacing varied from 7 to 20 km. A typical section from this experiment is described by *Houghton et al.* [1988].

[11] All of the sections were examined for the presence of the detached BBL. However, roughly half of the transects showed no clear evidence of detachment. This is partly due to strong mesoscale variability associated with nearby Gulf Stream rings, local winds, or other perturbations to the front. The other reason is that many of the SeaSoar sections did not extend close enough to the bottom to resolve the foot of the front, thereby making it impossible to perform the ATC calculation properly. In the analysis that follows we use only those sections in which the detached BBL can be clearly identified as a minimum in ATC. There are 21 sections in all: ten in summer, five in winter, and six in spring (Figure 2). Owing to the scarcity of well-resolved autumn sections in the study region, we exclude autumn from the analysis.

3. Seasonal Characteristics of the Shelfbreak Front

3.1. MAB Climatology

[12] Before examining the individual synoptic sections for BBL detachment, we first describe some of the general features of the frontal region in the MAB using a new climatology. It is important to consider the overall seasonal evolution of the front as a baseline reference for comparing our synoptic sections. The basic approach and data sources

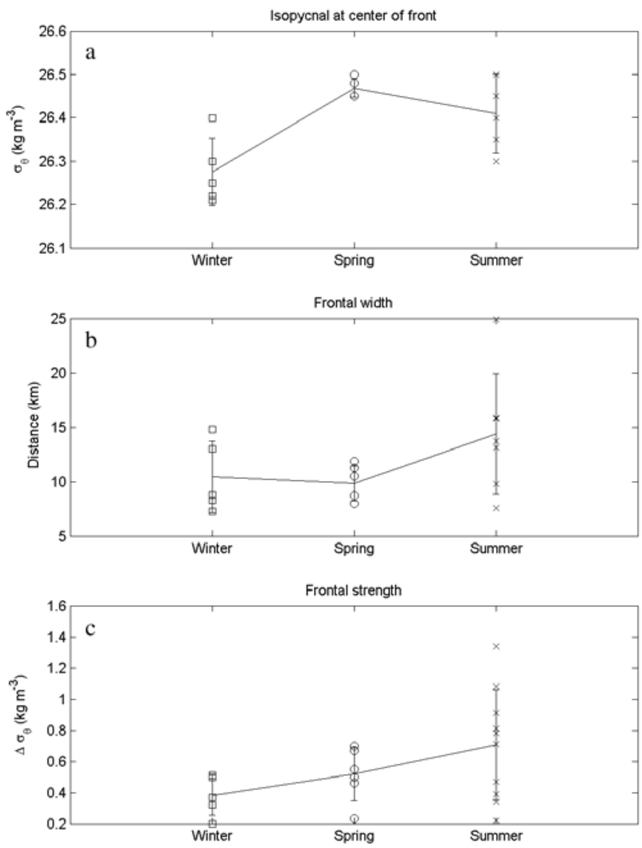

Figure 4. Seasonal characteristics of the near-bottom portion of the shelfbreak front, from the collection of synoptic sections. Mean and standard deviations are shown, along with the spread of individual points. (a) Isopycnal at the center of the front. (b) Frontal width. (c) Frontal strength.

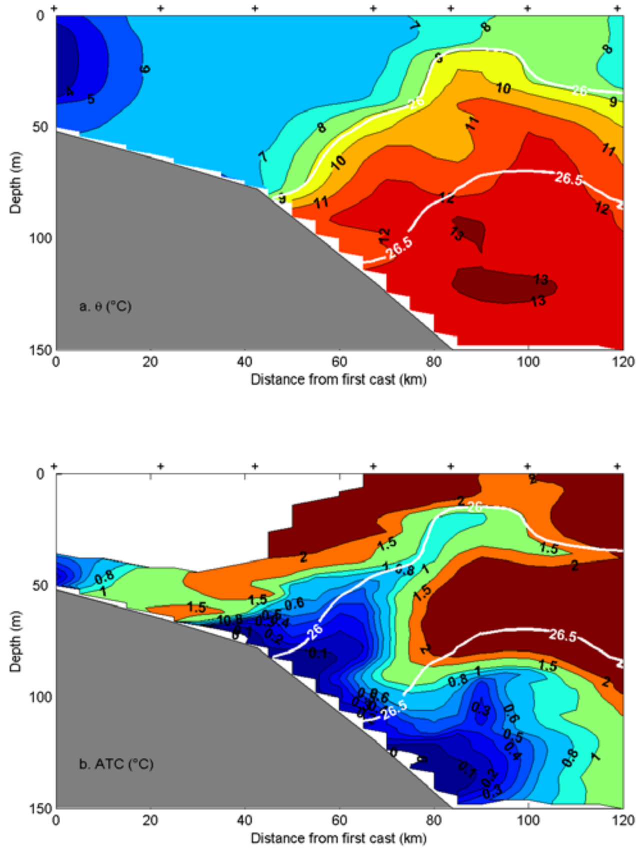

Figure 5. A winter section from February 1984. (a) Potential temperature (°C, color) with isopycnals (kg m^{-3}) contoured in white. (b) Accumulated temperature change (°C, color) with isopycnals contoured in white. Station locations are marked by pluses.

for the climatology are the same as those of *Linder and Gawarkiewicz* [1998]; however, a number of improvements have been made to the earlier method that we briefly highlight.

[13] *Linder and Gawarkiewicz* [1998] employed a depth-bin averaging method to collapse individual station profiles, located within a specified longitude band, onto a single cross-shelf section. While this method is satisfactory for regions of moderately varying bottom slope, it tends to group together profiles in somewhat unrealistic fashion for areas of weak bottom slope (i.e., on the shelf). The climatological sections presented here use a different mapping. Instead of using depth-bin averaging, all the profiles are remapped according to cross-shelf distance from the 100-m isobath (which corresponds to the mean position of the foot of the shelfbreak front in the MAB). The horizontal bins are 5 km in cross-shelf distance. This improvement doubled our cross-shelf resolution on the shelf. In addition, roughly 40% more data was present in the National Ocean Data Center (NODC) archive than was available for *Linder and Gawarkiewicz* [1998]. Furthermore, the 2-min resolution Sandwell-Smith bathymetry [*Smith and Sandwell*, 1994] was used rather than the 5-min DBDB-V. This leads to some significant differences in the averaged bathymetry. The new climatology uses four 3-month seasons (starting with winter, defined as January–February–March).

[14] The MAB is a dynamically complex region where cool, fresh continental shelf water interacts with warmer, more saline continental slope water. The sharp transition in both properties, which occurs near the shelfbreak, is known as the shelfbreak front. The seasonal temperature fields from the new climatology appear in Figure 3, with the isopycnals overlaid. In winter, mixing from storms homogenizes the shelf water, causing isopycnals to slope steeply in the shelfbreak region (and on the shelf). As insolation increases in spring, the seasonal thermocline (and pycnocline) begins to develop. The cold shelf waters that are bounded by the shelfbreak front and the seasonal thermocline during this time of year are known as the ‘‘cold pool.’’ As the thermocline deepens through the summer, the slope of the frontal isopycnals decreases. Autumn, like spring, is a transition season; synoptic sections from this time tend to resemble either a ‘‘summer’’ regime or a ‘‘winter’’ regime depending on storm activity.

[15] Owing to the high degree of smoothing inherent in the climatology, the detached BBL does not appear in the climatological sections. To determine the seasonal characteristics of the detached BBL, high-resolution synoptic sections are required.

3.2. Frontal Analysis

[16] Before analyzing the detached BBL characteristics, we first examined the properties of the shelfbreak front using our collection of 21 high-resolution synoptic sections.

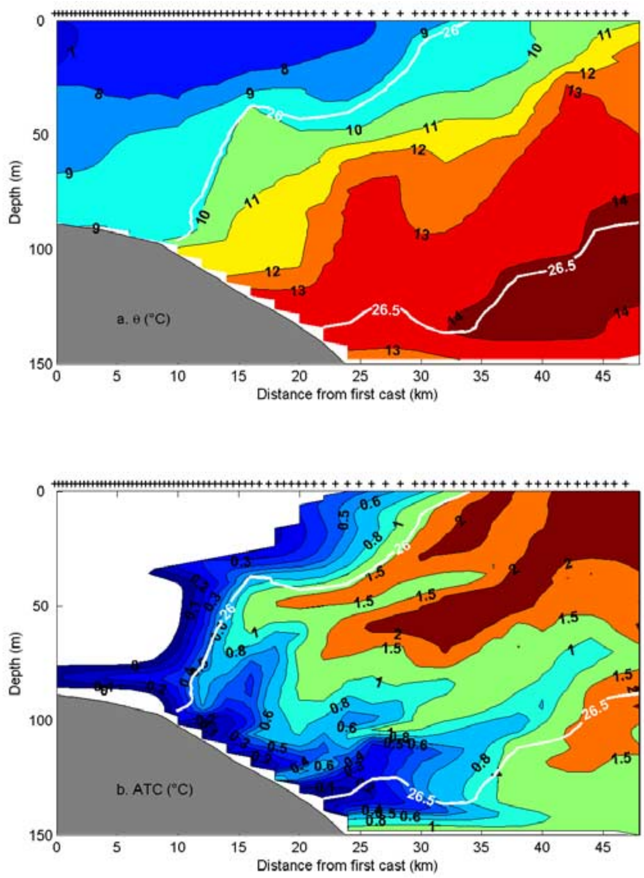

Figure 6. A winter section of (a) potential temperature and (b) accumulated temperature change from February 1997.

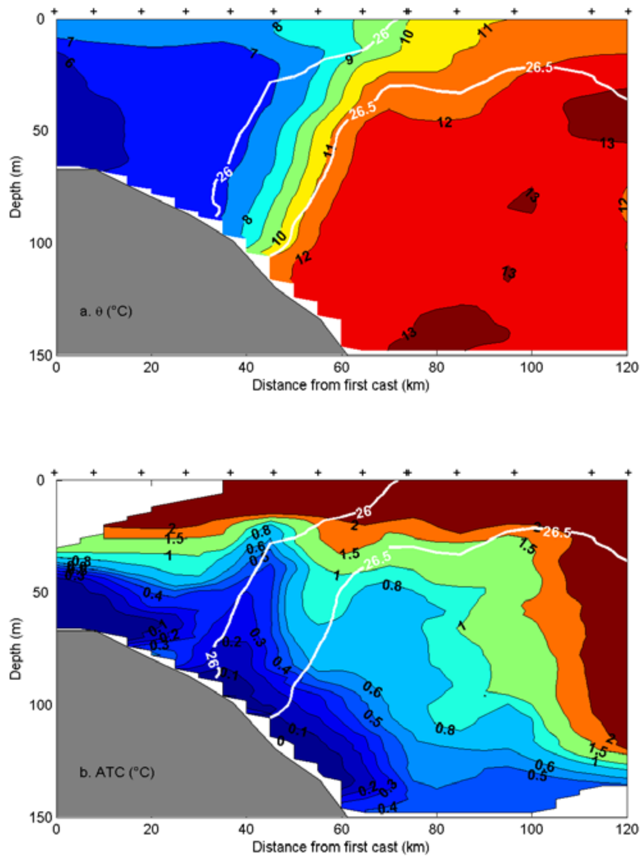

Figure 7. A spring section of (a) potential temperature and (b) accumulated temperature change from May 1984.

The location, width, and strength of the front vary by season (Figure 4). Since defining the front mathematically can be difficult in many cases, we chose the frontal parameters subjectively based on careful consideration of the salinity and density fields. The isopycnal that corresponds to the center of the front (Figure 4a) varies between 25.8 and 26.45 kg m^{-3}. Note that the front is centered on lighter isopycnals in the winter compared to spring and summer. The width of the shelfbreak front, measured along the bottom (Figure 4b), is a minimum during the winter and spring, at 12 and 11 km, respectively, and increases slightly to 14 km during the summer. The density difference across the front, also measured along the bottom (Figure 4c), has a minimum in winter and spring (0.3 and 0.4 kg m^{-3}) and a maximum in the summer (0.7 kg m^{-3}). Overall, then, the front is denser, wider, and stronger in summer, although there is more variability during this time of year. It is interesting to note that the frontal width in general is comparable to, though larger than, the two-layer baroclinic Rossby radius based on the density difference across the front. For our collection of sections the frontal width ranged from about 1.4 to 1.9 times the baroclinic Rossby radius.

4. Seasonal Characteristics of the Detached BBL

[17] We now examine two particularly clear cases of BBL detachment during winter, spring, and summer (there is a shortage of well-resolved sections from autumn in this part of the MAB). After discussing these examples, we will summarize the results from all of the sections in order to draw quantitative conclusions about the seasonal characteristics of the detached BBL.

[18] During winter, the seaward edge of the shelfbreak front frequently extends through the entire water column. A good example of a well-defined winter ATC minimum is in a transect from the SEEP program in February 1984 (Figure 5a). This transect shows the 7° and 8°C isotherms extending from the bottom to the surface. The corresponding distribution of ATC shows a well-defined minimum along the 26.0 isopycnal extending from the bottom to within 20 m of the surface (the vertical scale of the tongue is defined by the ATC = 1.0°C contour, Figure 5b). A second example, taken from a winter cruise during the PRIMER experiment, also shows the 26.0 isopycnal extending from the bottom to the surface (Figure 6a). This isopycnal is initially near the 10°C isotherm near the bottom, but is closer to the 9°C isotherm at the surface. In this case, the 25.9 isopycnal has only a 0.5°C change from the bottom to the surface (Figure 6b). Thus, by our definition, the detached layer extends from the bottom to the surface. Note that the shoreward edge of this minimum in ATC is not captured, as the isopycnals do not intersect the bottom within the transect. A confounding factor in the ATC field for winter is thus surface cooling and convection, which homogenizes the temperature field over the shelf by a different process. Another complication in this section is a second distinct

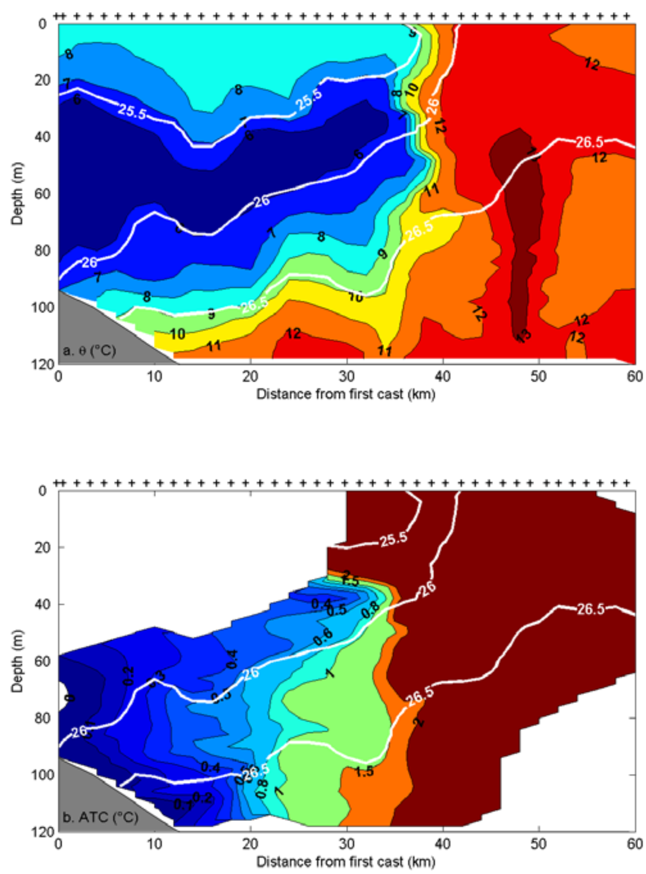

Figure 8. A spring section of (a) potential temperature and (b) accumulated temperature change from May 1996.

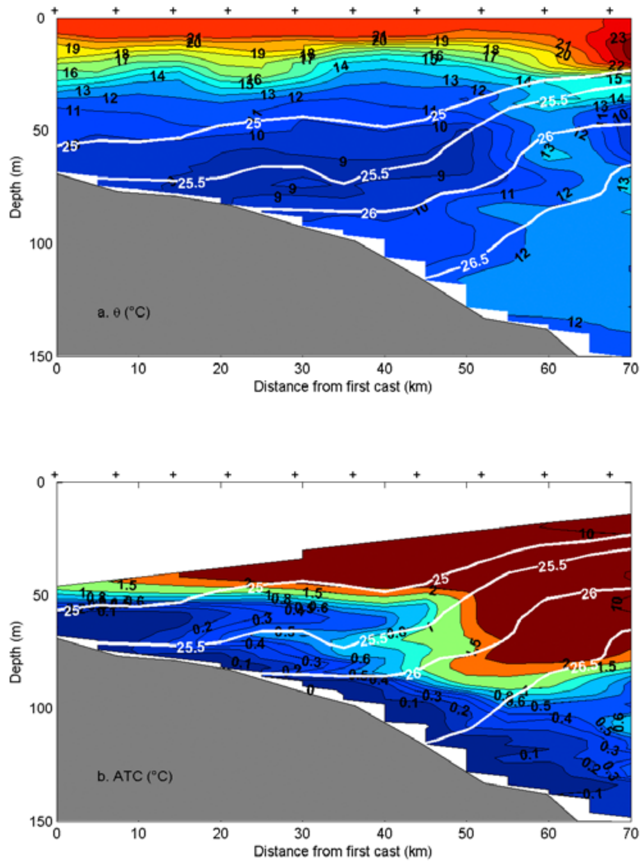

Figure 9. A summer section of (a) potential temperature and (b) accumulated temperature change from September 1983.

ATC minimum located farther offshore. This second minimum is along the 26.4 isopycnal, and extends from the bottom (at 130 m) to within 60 m of the surface. Since this ATC minimum is located in an area of homogeneously mixed slope water, it is impossible to determine if this feature is a real detached BBL or an artifact of the ATC computation. The issue of multiple detachment points will be discussed further in section 5.

[19] During spring, the seasonal thermocline (and pycnocline) begin to form. Thus there is normally a near-surface warm layer capping the winter-chilled cold pool waters. A transect from SEEP from May 1984 shows a slight (1°C) warming near the surface (Figure 7a). The seaward edge of the cold pool, in this case coincident with the 7°C isotherm, does not extend to the surface (although the 26.0 isopycnal does, due to near-surface freshening). The ATC minimum (Figure 7b) is again centered on the 26.0 isopycnal. In this case, the 1.0 contour in ATC extends to within 20 m of the surface after rising 70 m off the bottom. A second example from spring, taken from a PRIMER cruise, shows a similarly weak seasonal pycnocline at 20–30 m depth, with surface warming of 2°–3°C relative to the minimum temperatures of the cold pool (Figure 8a). In this case, there is a particularly sharp thermal front (near x = 40 km), due to the presence of a slope eddy seaward of the front [*Gawarkiewicz et al.*, 2001]. The ATC minimum (at the 25.9 isopycnal) extends 60 m off the bottom, extending to within 35 m of the surface (Figure 8b). In general, the spring sections are qualitatively similar to the winter conditions with the addition of relatively weak surface warming.

[20] During summer the seasonal pycnocline becomes fully developed, which inhibits the vertical penetration of the ATC minimum. A good example of this is the transect collected in September 1983 during the SEEP program (Figures 9a and 9b). There is a minimum in ATC, coincident with the 25.4 isopycnal, which extends 20 m above the bottom intersection point of the isopycnal, and reaches only within 50 m of the surface. A second summer example again shows the limited vertical extent of the ATC minimum (Figures 10a and 10b). This transect was sampled during the PRIMER experiment, when the front was distorted by a large-amplitude frontal meander [*Gawarkiewicz et al.*, 2004]. This is evident in the temperature field, where there is an offshore minimum in temperature (at x = 40 km) as part of a backward breaking frontal wave [e.g., *Garvine et al.*, 1988]. Even in this complex field, there is a distinct ATC minimum near the 26.5 isopycnal. It rises only 30 m above the bottom (75 m from the surface), again substantially deeper in the water column than observed during the spring and winter sections. This isopycnal is more dense than the typical winter and spring case. Unfortunately, the bottom intersection point of the 25.5 and 26.0 isopycnals are not resolved in the section; however, there is suggestion of another ATC minimum at the 25.8 isopycnal (we are not able to integrate from a point near the bottom).

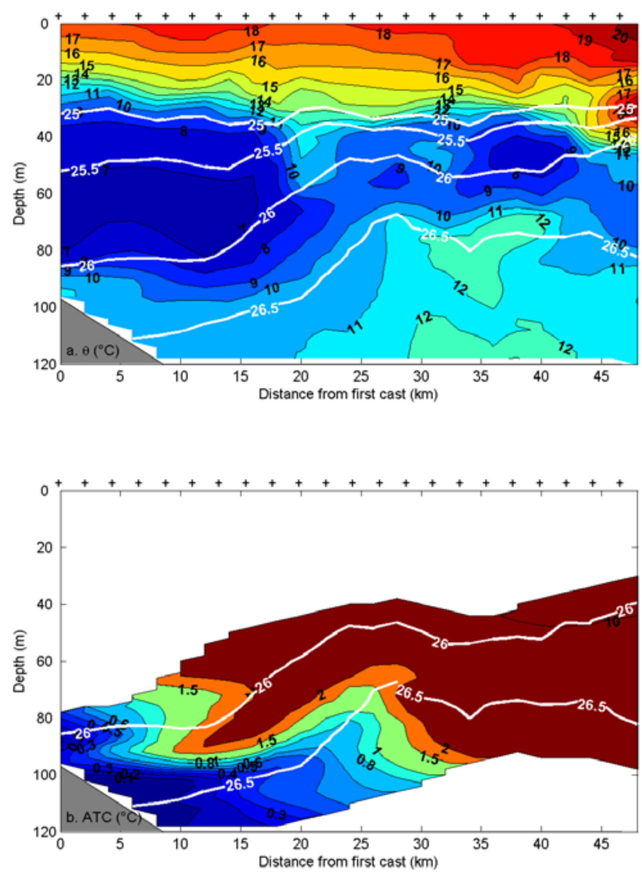

Figure 10. A summer section of (a) potential temperature and (b) accumulated temperature change from July 1996.

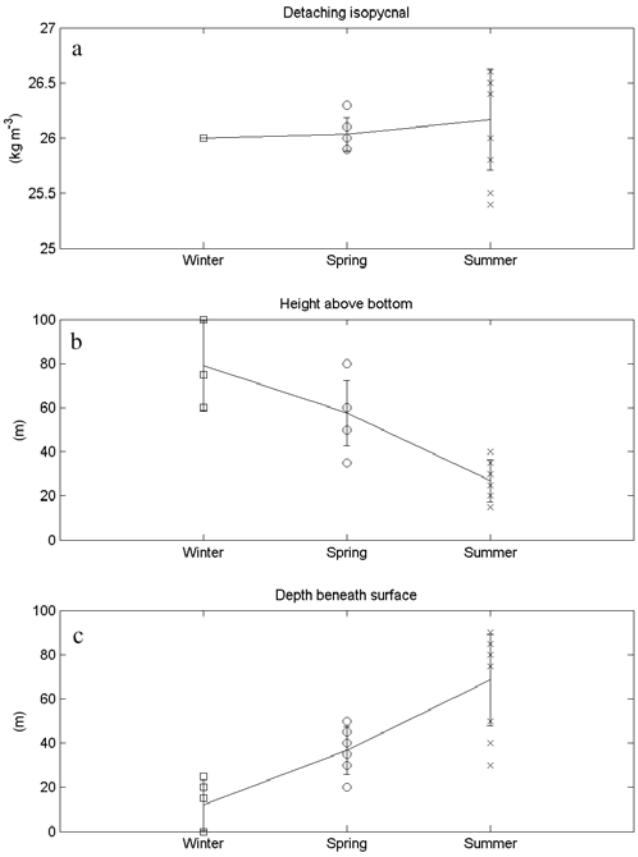

Figure 11. Seasonal characteristics of the detached bottom boundary layer from the synoptic sections. Mean and standard deviations are shown, along with the spread of individual points. (a) The isopycnal that corresponds to the core of the most evident accumulated temperature change (ATC) minimum. (b) Maximum height above the bottom for the most evident detached layer, relative to the bottom intersection point of the corresponding isopycnal. The termination of the detached layer is defined by the ATC = 1.0°C contour. (c) Minimum depth beneath the surface of the detached layer.

[21] The detachment statistics for all the sections are shown in Figure 11. Interestingly, the seasonal mean isopycnal at which detachment occurs remains relatively constant through the year (near σ_θ = 26.0 kg m^{-3}), although there is substantial scatter within the summer season (Figure 11a). When compared to the seasonal mean frontal isopycnal (Figure 4a), this indicates that the detaching layer nearly always originates on the shoreward edge of the frontal region. This is in agreement with numerical models of the detachment process [*Gawarkiewicz and Chapman*, 1992; *Chapman and Lentz*, 1994] and dye release studies [*Houghton and Visbeck*, 1998]. As mentioned above, the major difference between the seasons is that the ATC minimum, and by inference the vertical extent of the detached BBL, rises a greater distance above the bottom during the winter and spring than in summer. During winter the tongue rises on average 80 m above the bottom, and during spring, 60 m above the bottom (Figure 11b). When the stratification is strongest during the summer, the vertical scale of the ATC minimum has a mean of only 25 m.

[22] Conversely, the ATC minimum is closest to the surface in the winter (Figure 11c), with a mean value of 18 m below the surface. During the spring the mean value deepens to 37 m, while in summer it drops significantly to 65 m below the surface. The summer range is large, however: from as little as 30 m to as large as 90 m below the surface. This is primarily due to the wide range of isopycnals associated with ATC minima during the summer (see Figure 11a). The summer sections in which the ATC minimum is closest to the surface are on the lightest isopycnals, which intersect the bottom more shoreward on the shelf, near the 60-m isobath. Hence, even though the ATC minimum does not rise very far off the bottom, because the water depth is so shallow, the ATC minimum is closer to the surface. Thus the broad range of isopycnals over which BBL detachment seems to be occurring in the summer suggests more variability in the potential vertical transport of nutrients into the euphotic zone.

5. Discussion

[23] The analysis presented above has shown a clear variation with season in the height of the ATC minimum above the bottom. The vertical scale of the layer is maximum in winter, when the stratification is weakest, and minimum in the summer, when the stratification is the strongest. During winter, when N^2 (the square of the buoyancy frequency) is small and there is no seasonal pycnocline, the ATC minimum can reach the surface. However, the presence of the seasonal pycnocline limits the penetration of the ATC during the remainder the year. This can be seen by overlaying the ATC tongue on the vertical section of N^2, which is shown for a representative spring section in Figure 12 and representative summer section in Figure 13. In both cases one sees that the detached BBL plume terminates as it encounters the increased stratification associated with the seasonal pycnocline. Furthermore, the value of N^2 where this occurs is similar in each case.

[24] To quantify the relationship between the vertical stratification and the penetration height of the detached BBL, we constructed the vertical section of N^2 for each of the transects, and computed the average value over the local region encompassing the termination of the ATC tongue. This was then compared to the water column vertical profile of N^2 in the vicinity of the BBL tongue. In every instance (excluding winter) the tongue ended near the base of the seasonal pycnocline. The mean value of the "critical N^2" for the collection of spring and summer sections is shown in Figure 14 in relation to the mean of the corresponding vertical profiles of N^2. It is clear from this figure that the vertical stratification, in particular the presence of the seasonal pycnocline, is the primary factor determining the vertical height of the detached layer. The tongue tends to disintegrate when N^2 is in the range of 1.3–1.7 s^{-2} × 10^{-4}.

[25] The vertical scale over which the detached bottom boundary layer rises is significant because this layer is a potential source of nutrients for the euphotic zone. The huge increase in vertical stratification in summer would thus tend to shut off transport to the upper part of the water column during the summer and into the fall. Observations of ocean color suggest that this might be the case. *Ryan et al.* [1999] show that a spring surface pigment maximum develops

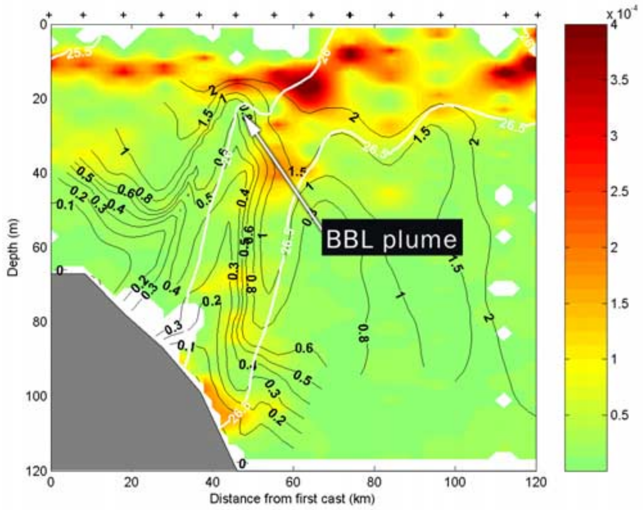

Figure 12. Spring section of N^2 (color, $s^{-2} \times 10^{-4}$), with ATC overlaid (black contours, °C). The tongue of low ATC, indicating the detached BBL, is indicated. The white contours denote the potential density (kg m^{-3}).

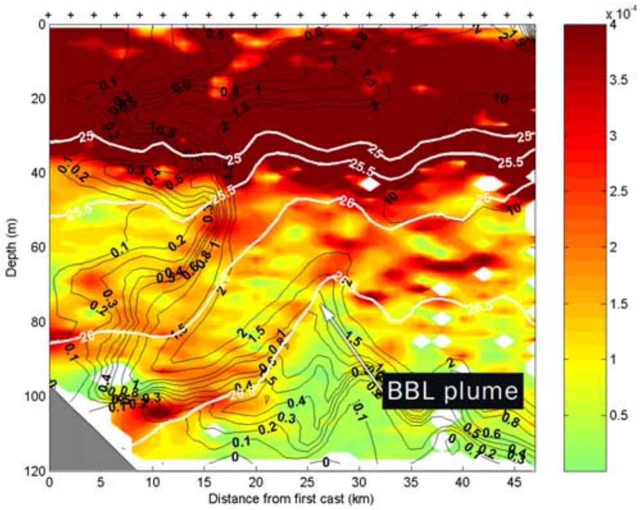

Figure 13. Same as Figure 12, except for a summer section.

along a large portion of the shelfbreak in the Middle Atlantic Bight. The typical duration of this feature is about 6 weeks. It is possible that the development of the seasonal stratification may be a factor in the timing and duration of the pigment signal by limiting the vertical scale of the detached BBL. Specifically, the seasonal pycnocline may cap the frontal upwelling so that the pigment maximum becomes subsurface (or vanishes altogether if the upwelling is confined below the euphotic zone, [*Marra et al.*, 1990]). *Ryan et al.* [1999] also showed that the surface pigment maximum varies interannually in terms of its duration and the date at which the signal is no longer evident in the color imagery. It is possible that this is controlled as well by the BBL detachment process.

[26] We can crudely estimate the amount of additional nitrogen (as nitrate) that is carried into the euphotic zone by the detached bottom boundary layer. If we assume a frontal width of 15 km and an upwelling rate of 10 m day^{-1} [*Houghton*, 1997], we get a transport per unit length of 1.75 m^2 s^{-1}. Examination of some of the nutrient profiles from the New England shelf suggests that nitrate levels near the bottom over the shelf are roughly 2 mM m^{-3} higher than levels in the upper 50 m of the water column. If we take the length of the Middle Atlantic Bight shelfbreak front to be 900 km, we get 3.15×10^6 mM s^{-1} of nitrogen as nitrate reaching the euphotic zone. This is equivalent to 1.4×10^6 tons per year, if the pumping were to occur throughout the year. However, since we have found that it is unlikely that the pumping reaches the euphotic zone in summer and at least the early part of autumn, we should reduce this by roughly 50% to 0.7×10^6 tons of nitrogen per year. If this were all converted to carbon, it would be 3.3×10^{11} MC $year^{-1}$, which is equivalent to 5.9×10^6 tons C $year^{-1}$. This is equivalent to 5% of the total carbon in primary production for the entire Gulf of Maine [*Charette et al.*, 2001].

[27] An unanticipated result of the present work was the occurrence of multiple ATC minima in some of the sections. These cells could be associated with other frontal phenomena such as the tidal mixing front over Nantucket shoals, or buoyant inflows from Massachusetts Bay which pass to the west of the Great South Channel. While the primary isopycnal for BBL detachment is near 26.0 kg m^{-3}, sections in the summer have minima on isopycnals as light as 25.4, and as heavy as 26.5. Thus there is a possibility that there are multiple upwelling/downwelling cells at the edge of the shelf. This has important ramifications for sampling the front, as there may be multiple injections into the euphotic zone at different cross-shelf locations. We note that *Gawarkiewicz et al.* [2001] observed bands of upwelling and downwelling from shipboard ADCP measurements during the spring.

[28] A final issue is the relation of the ATC minimum to the cross-shelf location of the shelfbreak frontal jet. While

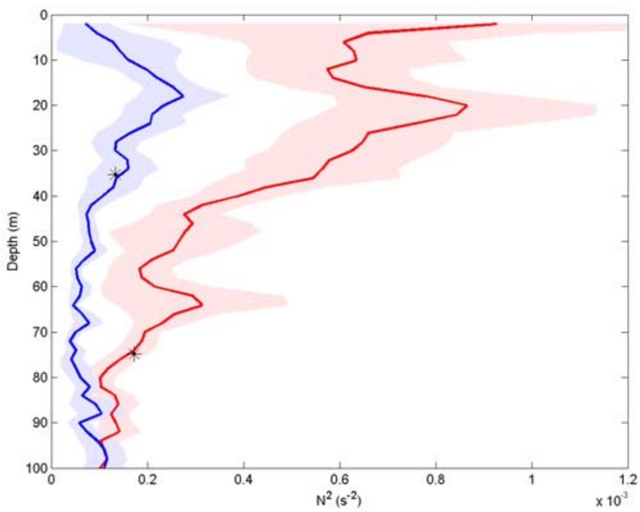

Figure 14. Seasonal mean value of N^2 at the termination point of the detached BBL (asterisk) in relation to the mean vertical profile of N^2 (solid line) for the collection of spring sections (blue) and summer sections (red). See text for details. The shading represents the standard deviation of the vertical profiles.

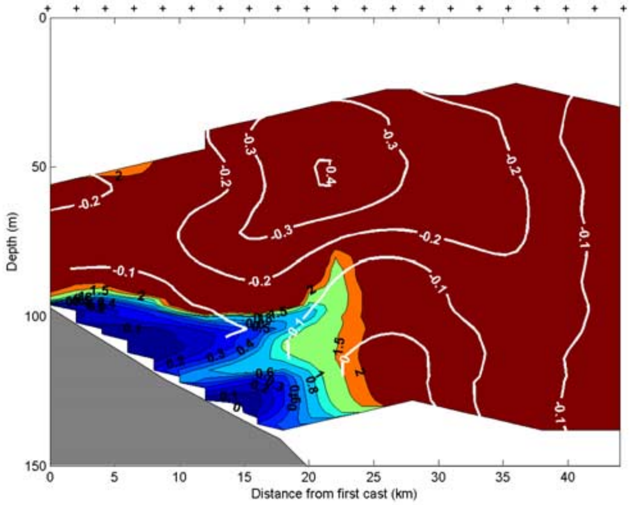

Figure 15. Vertical section from summer 1996 showing the relationship between the ATC tongue (color, °C) and the alongshelf (equatorward) velocity (white contours, m s^{-1}).

most of our sections did not have concurrent shipboard ADCP measurements or did not resolve the jet, other transects suggest that the offshore extent of the ATC minimum is coincident with the cross-shelf location of the frontal jet core (as one would expect from thermal wind shear). A section from the Summer PRIMER experiment shows the ATC minimum coincident with the frontal jet (Figure 15). This serves as a reminder that the detachment process is three-dimensional and involves strong alongshelf advection. Clearly, further work is necessary in both modeling and observations, throughout the seasonal cycle, to learn more about the structure of the detached BBL within the shelfbreak front and its ramifications for the biological processes occurring there.

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