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Biochemical implications of the Bottom Boundary Layer Detachment at the Mid-Atlantic Bight shelf-break front

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ABSTRACT

The Mid-Atlantic Bight frontal system along the U.S. northeast shelf is rich in biodiversity. In this region, primary production is influenced by a variety of upwelling processes, including internal instabilities of the front, off-shore forcing from Gulf Stream rings, and wind-driven flows. It is noteworthy that the concentrations of chlorophyll-*a* (Chl-*a*) in the shelf-break region are not consistently enhanced throughout the year, although local increases of phytoplankton biomass have been observed in some circumstances. In this work, we investigate the frontal dynamics of one of the possible mechanisms affecting primary production: upwelling via detachment of the Bottom Boundary Layer (BBL). The annual variability of the surface Chl-*a* in the shelf-break region reveals a 5- to 20-day period, which is potentially consistent with nutrient upwelling associated with the BBL detachment. Details of the process are examined using *in situ* data by quantifying along-isopycnal changes in properties. As frontal isopycnals rise in the water column, nitrate tends to decrease and Chl-*a* tends to increase, suggesting utilization of upwelled nutrients by phytoplankton. However, significant fluctuations can be attributed to sample size, intrinsic data variability, and the assumption of homogeneity in the along-shelf dimension.

1. Introduction

Shelf-break fronts are important from a biological point of view (K.H. Mann, 2006), and the Mid-Atlantic Bight (MAB) frontal system is a well-studied example. It is part of the U.S. northeast shelf and its ecosystem is nourished by high concentrations of phytoplankton that undergo substantial variations over broad spatial and temporal scales (Zhang et al., 2013). Current paradigms suggest that this productivity is driven by several upwelling mechanisms located within the shelf-break front (He et al., 2011; Oliver et al., 2022; Zhang et al., 2023). Upwelling supplies nutrients that stimulate primary production by phytoplankton, which in turn leads to enhanced production at higher trophic levels. Although local enhancement of phytoplankton biomass has been observed (Fig. 1) in synoptic measurements within the region (Ryan et al., 1999), such a feature is not prominent in time-averaged measurements, both remotely sensed and *in situ* (Zhang et al., 2013; Oliver et al., 2022).

The MAB shelf-break front is a sharp transition from cooler, fresher shelf waters to warmer, saltier slope waters, with isopycnals (σ) sloping upward and off-shore. The slope of the isopycnals is in the opposite

direction of the slope of the bathymetry (Gawarkiewicz et al., 2018), and the presence of both the topographic shelf-break and the horizontal density gradient typically traps the front between 100–200 m isobath. However, its structure is susceptible to changes in seasonal stratification, strong interactions with the Gulf Stream warm-core rings that impinge on the continental slope, and non-linear instabilities, such as front meanders of ~15 km amplitude and 4-day period (Gawarkiewicz et al., 2004).

Shelf-break frontal processes are inherently non-linear and exhibit variations over a broad range of spatial and temporal scales. In particular, there are several upwelling mechanisms associated with the front, which may significantly influence the circulation and the ecosystem dynamics of the region. Although the processes regulating the shelf-break upwelling are complex, some simple models have been used to understand different dynamical aspects: a secondary mean cross-shelf and vertical circulation driven by the wind (Zhang et al., 2011); convergence of the cross-shelf bottom flows near the sea floor at the shelf-break front, leading to a detachment of the bottom bound-ary layer (BBL) and then upwelling into the interior (Pickart, 2000)

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Shelfbreak Chlorophyll- \ddot{a} enhancement, April 22th 2019

Fig. 1. Map of the northern region of the Mid-Atlantic Bight (MAB), overlaid with an example snapshot of enhanced chlorophyll at the shelf-break. Depth contours of 75, 100, 500, 1000, 2000 and 3000 m are shown in gray. The bold black contour represents the shelf break corresponding to 200 m isobaths. The blue polygon indicates the boundaries of the exact area of interest. The blue dots represent the SPIROPA geographic sampling station locations. Note the log color axis scale. *Source:* Ocean color snapshot from NOAA (2024).

and instability-driven meandering of the shelf-break front (Zhang and Gawarkiewicz, 2015). The overall strength of these different types of upwelling and the relative importance of the vertical nutrient fluxes associated with each are not well constrained.

The primary aim of this study is to evaluate one of these mechanisms, specifically investigating the hypothesis of frontal upwelling linked to the detachment of the BBL. We seek to determine whether this process correlates with nutrient transport, potentially enhancing phytoplankton biomass in the euphotic zone. Context for analysis of *in situ* data is provided by quantification of variability in surface Chlorophyll-*a* (Chl-*a*) from satellite observations. In the next section (Section 2) we present the theoretical bases related to the physics of the BBL frontal upwelling. The material and methods employed for these investigations are detailed in Section 3. Results and discussions are presented in Sections 4 and 5, respectively, and summarized in Section 6.

2. Bottom boundary layer detachment theory

Formation of the shelf-break front involves low salinity water flowing into the MAB from upstream and driving a horizontal density gradient. This leads to the creation of a plume (Chapman and Lentz, 1994) that is influenced by bottom topography because a significant portion is in direct contact with the seabed. By consequence, the along-shelf flow generates off-shore transport in the BBL, establishing a cross-shelf density gradient, proportional to the bottom slope, that increases toward the shelf-break (Gawarkiewicz and Chapman, 1992). This gradient inhibits off-shore transport along the bottom, causing convergence in the BBL near the shelf-break. Thus, that convergence accumulates buoyancy, further enhancing the cross-shelf density gradient and creating a positive feedback loop that can detach the BBL near the shelf-break, forming and maintaining the shelf-break front (Fig. 2a).

This cross-shelf circulation transports less dense water off-shore beneath the denser, saltier water, leading to static instability to within the BBL thickness adjust (Chapman and Lentz, 1994). Consequently, a surface-intensified along-shelf jet with a strong vertical shear is generated, thus reducing the along-shelf velocity to small values at the base of the front. The same happens on the other side of the front with the poleward flow that induces an upslope flow in the BBL that counteracts the downslope flow. The interior density front reaches an equilibrium position at the shelf-break (Fig. 2b); convergence of the two flows in the BBL leads to detachment, and water parcels are forced to move upward following density contours. Upwelling at the front has been verified by Houghton and Visbeck (1998), who performed a dye-release experiment at the bottom of the MAB shelf-break front near 70°W, demonstrating that the water parcels detached from the BBL and moved toward the surface following the isopycnals.

It is now evident that the BBL plays a fundamental role in the establishment of the shelf-break front. In both of the frontogenesis processes described (Fig. 2), the detachment of the BBL is expected. In the present work we will follow the definition of BBL given by Pickart (2000): it is the weakly stratified near-bottom layer (resulting from mixing), which is separated by a distinct interface of temperature, salinity, and density in the above water column. Its structure can be significantly influenced by the changes of the interior flow above, related to the bottom local topography or the ambient slope water.

3. Material and methods

3.1. In situ data

In situ measurements were collected during three different oceanographic cruises carried out in the northern region of the MAB, in the context of the *Shelfbreak Productivity Interdisciplinary Research Operation at the Pioneer Array* (SPIROPA):

- AR29 (R/V Neil Armostrong) from the 16th to the 28th April 2018;
- RB1904 (*R/V Ronald H. Brown*) from the 12th to the 25th May 2019;
- TN368 (*R/V Thomas G. Thompson*) from the 5th to the 19th July 2019;

North-south oriented transects along 70.8° W were repeatedly sampled across the shelf-break with 14 stations ~ 7 km apart (Fig. 1) to capture the mean state and the variability of the front.

At each station, vertical CTD profiles were taken to measure temperature, pressure, salinity, and density. The system was equipped with a SeaBird 911 CTD system, a WetLabs FLNTURTD fluorometer, a BioSpherical Instruments sensor for photosynthetically active radiation (PAR), and a WetLabs C-Star beam transmissometer. Discrete seawater samples were collected at 10-m intervals, using 24 10-L Niskin bottles mounted on the CTD rosette. The concentration of nutrients (nitrate,



Fig. 2. Schematic of the shelf-break front and detached BBL in two model studies. (a) In the Gawarkiewicz and Chapman (1992) model, convergent flow in the BBL (short arrows) detaches at the shelf-break due to the on-shore pressure gradient resulting from the concentration of frontal isopycnals. The large shaded arrow denotes the trajectories of fluid parcels as they advect into the interior. (b) In the Chapman and Lentz (1994) model, geostrophic adjustment of the front leads to a flow reversal in the jet at depth (O: equatorward flow, S: poleward flow), which leads to opposing upslope and downslope flow in the BBL; the associated collision leads to detachment.

Table 1

CTD fluorometer vs Chl-a calibration coefficients and regression statistic.

Cruise	Slope [m]	Intercept [q]	\mathbb{R}^2	RMSE
AR29	0.99	0.03	0.94	0.83
RB1905	1.14	-0.11	0.90	0.64
TN368	1.09	-0.04	0.89	0.70

phosphate, silicate), Chl-*a*, and particulate organic nitrogen (PON) were measured in each sample. Nutrient concentrations were determined by filtering samples through 0.4 μ m polycarbonate filters, which were frozen in acid-washed polyethylene bottles, and analyzed post-cruise at the Woods Hole Oceanographic Institution Nutrient Analytical Facility. Chlorophyll concentrations were obtained by filtering duplicate water sampling through GF/F Whatman filters under low vacuum (0.45 atm) and immediately frozen in liquid nitrogen. Samples were thawed post-cruise in 90% acetone and analyzed by standard fluorometric methods. PON concentrations were determined by filtering 0.25–2.0 L of seawater under low vacuum through precombusted (450 °C for 2 h) Whatman GF/F filters, stored in precombusted glass vials, dried at 60 °C, and analyzed on a Costech ECS 4010 elemental analyzer.

CTD fluorescence (F_{CTD}) is an indirect measure of chlorophyll pigmentation and, thereby can be a proxy for phytoplankton biomass. To obtain a more precise estimation, F_{CTD} was converted into chlorophylla (Chl_{CTD}) concentration using a regression between CTD fluorescence measurements and chlorophyll-a + phaeopigment concentration from Niskin bottle samples:

$$\operatorname{Chl}_{CTD} = m \operatorname{F}_{CTD} + q \tag{1}$$

The regression coefficients for each cruise are reported in Table 1.

CTD and bottle profiles were linearly interpolated over a regular two-dimensional grid: 7 km in the cross-shelf direction (y) and 1 m in the vertical direction (z).

3.1.1. Identifying the detached BBL: Accumulated property changes

The change of properties along an isopycnal as it extends from the bottom layer upward and off-shore can be used to quantitatively determine the detached BBL (Accumulated Property Change, APC). Because the BBL is well-mixed, the gradient of a given property calculated in the cross-shelf direction should have a minimum close to the bottom. Pickart (2000) and Linder et al. (2004) have applied this technique to the temperature field (Accumulated Temperature Change, ATC), demonstrating that it accurately detects the presence (or absence) of the detached BBL extending toward the surface in a tongue shape. We look at both ATC and AS(Salinity)C minima because temperature changes could result from other processes besides detachment (i.e. heating/cooling), whereas salinity is a more conservative variable, whose changes have a longer timescale compared to temperature.

The novelty of this work is to apply the same method to a biogeochemical variable (nitrate concentration) to link the physical process with the biological activity. If the detached layer is transporting water both off-shore and upward along the density surfaces, then the isopycnals should be characterized by relatively small lateral changes not only in temperature and salinity but also in nitrate (Accumulated Nitrate Change, ANC) below the euphotic zone. Thus, for those days where a significant signal of BBL detachment was found in both temperature and salinity tracers, the same calculation was done for the high-resolution nitrate sections. We use the algorithm developed by Linder (2005) and that is fully described in Linder et al. (2004).

3.1.2. Along isopycnal changes in properties

We hypothesize that BBL detachment will carry nutrients toward the surface, where they can be used by phytoplankton to produce organic matter. For this purpose the difference ($\Delta_{surface} - \Delta_{bottom}$) between the concentrations of nitrate (NO_3^-), Chl-*a*, and PON has been calculated along the isopycnals associated with the detaching of the BBL and with the isopycnals at the center of the frontal surface, identified by the 34.5 isohaline (Houghton et al., 1988; Linder and Gawarkiewicz, 1998). We performed the analysis by looking at the process on a 2-dimensional (2D) plane (cross-shelf and off-shore direction vs depth), thus any contribution of lateral transport has been neglected. With this approximation, the relations among the biogeochemical tracers are straightforward: if NO_3^- decreases (it is consumed by phytoplankton to perform photosynthesis), PON should theoretically increase the same amount assuming all else equal:

$$-\Delta NO_2^- \approx \Delta PON$$
 (2)

However, PON is not exclusively associated with phytoplankton: it contains contributions not only from other trophic levels but also from non-living detritus. As a consequence, the observed PON values can be influenced by bottom resuspension and by any other kind of nitrogen-containing particles throughout the water column. Given all these constituents of PON, the response of this pool of nitrogen to BBL upwelling is accompanied by other factors operating at different time scales. There is no practical way to separate the various constituents in these measurements. As a result, it is necessary to consider the potential influence of the non-phytoplankton components when interpreting the results.

If nitrate is utilized, more Chl-*a* will be produced, hence we hypothesize:

$$-\Delta NO_3^- \sim \Delta Chl-a$$
 (3)

We expect considerable variation in this proportionality, given the N:Chl ratio can be strongly affected by the differences among phytoplankton species as well as photoadaptation (Cullen, 2015).

The key aspects of this methodology are:

- 1. Choice of the target isopycnals along with calculating the differences (*As*);
- 2. Defining the isopycnal coordinates representing the bottom and top end members used in estimating the Δs .

We choose the target isopycnals as follows: the isopycnal intersecting the foot of the front where S=34.5 PSU, and the isopycnals found within the ANC minima. We found that the range of these isopycnals depended on the stratification, and was [26.4–26.6] σ in April and [26.0–26.3] σ in July.

The selection of coordinates for the bottom end of the target isopycnals was based on their intersection with the seabed (closest point available). For the top end, two different criteria were applied depending on the strength of the stratification. During less stratified conditions (early spring), the isopycnals were steep, outcropping at the surface. In these conditions, we chose to select the location where the isopycnal outcropped into the euphotic zone (Fig. 3a). The euphotic zone was estimated as the depth corresponding with the 1% of surface irradiance, following the methodology used by Oliver et al. (2021). In contrast, when the stratification was greater in summer, the target isopycnals tended to flatten in the seasonal pycnocline. For these sections we chose the location where the isopycnal crossed the 34.75 PSU isohaline, therefore extending the Δ calculations toward the off-shore side of the front (Fig. 3b). In the following sections, we will refer to this latter criterion as the isohaline criterion and to the former as the light criterion. To be consistent with the hypothesis, we ensured that the selected data points fell within the region of influence of the BBL detachment. However, employing this methodology resulted in the extraction of only two data points per isopycnal. To increase the sample size and facilitate a more robust statistical analysis, we also incorporated the adjacent data points on the isopycnal within $\Delta z = 5$ m shallower. Consequently, we ensured a minimum of four data points per isopycnal.

Following this method, we chose three target isopycnals for each cruise, along with linearly interpolating the observed concentrations of nutrients and Chl-*a*. We delineate two distinct regions, namely a bottom box and a surface box that encompass the three target isopycnals to facilitate the extraction of pertinent data points along these isopycnals. The bottom box corresponds to the region intersecting the foot of the front, while the criteria used for the surface box is contingent upon the prevailing environmental conditions, either based on *light* or *isohaline criterion*. When the surface box ended up being deeper than the 1% light depth (primarily in July), we also calculated the depth of the 0.1% surface light using the same method as described by Oliver et al. (2021) to verify that photosynthetic organisms had sufficient light to carry out photosynthesis.

3.2. Satellite data

To better understand the Chl-a variability in the MAB shelf-break region, we investigated satellite ocean color data for the period 2003-2020, with particular interest in the annual cycle. We used remote sensing measurements of surface Chl-a concentrations (Ocean Color Index (OCI) algorithm), provided by the Level 3 data product derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS) mounted on NASA's Aqua satellite (EOS PM). This product is available on the NASA Ocean Color Website (NASA, Goddard Space Flight Center Ocean Ecology Laboratory, Ocean Biology Processing Group, 2022), on a daily basis, mapped on a uniform grid with a 4 km resolution. The main issue related to this product is the presence of clouds, resulting in data coverage not being uniform over the selected area. Consequently, we applied a linear gap-filling interpolation to the spatially averaged data. We acknowledge that linear interpolation may not be the most effective method for creating a continuous time series. In order to test the sensitivity of our results to this approach, we also tried using a 3-day moving average, and that yielded similar results.

3.2.1. Space-time analysis method and spatial binned average

Any physical signal can be decomposed into a number of finite frequencies *f* and periods $\tau = \frac{1}{f}$. How the power of the signal (or the time series) is distributed into frequency components can be described with a *Power Spectral Density* (PSD). We applied this method to the linearly interpolated continuous time series of the spatially averaged concentration of surface Chl-*a* in order to identify dominant frequencies within the signal between the 50 and 3000 m isobaths. We did so by dividing the bathymetric distribution into 3 km intervals, resulting in 51 bins (Fig. 4), following the procedure pursued by Oliver et al. (2022). For each day and each depth bin, surface averaged Chl-*a* value was calculated to generate a mean cross-shore distribution.

To calculate the PSD, Welch's method (Welch, 1967) was used, which involves dividing the signal into overlapping segments, applying a window function to each segment, computing the spectral density (or periodogram) in the frequency domain of each segment, and finally averaging the periodograms to obtain an estimate of the PSD. This method has been implemented using the function welch from Python's statistical module scipy.signal (Virtanen et al., 2020).

4. Results

4.1. Satellite chlorophyll-a annual variability

The 2D spectrum of depth-binned mean Chl-*a* (Fig. 5) shows the relationship between the temporal and spatial variability of the signal. As expected the absolute maximum corresponds to the seasonal cycle (yearly frequency), which has the greatest magnitude across the whole area. Two other local maxima were found corresponding to 120 days and 180 days. It is interesting to note that both of them exhibit temporal persistence that is longer on the shelf than it is off-shore. However, as they approach the shelf break (1000 m depth), their persistence contracts before expanding once more, with a secondary local maximum centered on the 1000 m isobath.

The seasonal cycle of Chl-*a* includes two blooms that usually occur every year in April and November (Xu et al., 2011, 2020), lasting about 30 days each (in Supporting Material, Sec. S1, Figs. S1, S2). The spring bloom is related to the increasing light availability that allows phytoplankton to grow in nutrient-replete water. As the spring bloom progresses, the nutrients are utilized leaving a surface water layer depleted. With the beginning of autumn, strengthening of the winds and cooling at the surface increases mixing that replenishes the nutrients at the surface, triggering a second seasonal bloom that is smaller in magnitude. In the summer season, the Chl-*a* is at its minimum (Zhang et al., 2013; Saba et al., 2015).



Fig. 3. Methodology used for estimating Δs . Panel (a): low stratified conditions, target isopycnal (dashed red line) outcropping in the euphotic zone (dotted yellow line). Panel (b): high stratified conditions, target isopycnal crossing the off-shore side of the front (dotted blue line, corresponding to 34.75 PSU). In both panels, the blue line represents the mean location of the front (34.5 PSU). The orange crosses represent the two locations used for the calculation. The BBL is depicted in light blue, and the convergence is shown by the two gray arrows. Green represents the expected positive chlorophyll anomaly associated with the upwelling, which may or may not be superimposed on a broader scale subsurface chlorophyll maxima caused by other processes.



Fig. 4. Distribution of bathymetric bins. The blue polygon indicates the area in which the cross-shore averages were performed. The blue dots represent the station locations of *in-situ* measurements.

The variability at periods lower than 20 days has a much more faint signal that would be completely masked and erroneously neglected if not isolated from lower frequencies. Distinct features emerge, revealing the expected shelf-confined maxima, and also a discernible rise in Chla variance in the shelf-break region (Fig. 5, lower panel). Particularly noteworthy are the secondary maxima straddling the 1000 m isobath, possibly coinciding with the offshore extent of the surface outcrop of the front (Linder and Gawarkiewicz, 1998; Linder et al., 2006). These maxima are present for most of the frequency range of the spectrum, down to about 5-day period. These structures likely result from a combination of several upwelling mechanisms present at the shelf-break (including BBL detachment), subject to the influences of frontal instability (e.g., due to wind, warm core rings, streamers, frontal meanders) (Ryan et al., 1999; Zhang et al., 2013, 2023). However, we hypothesize that the persistent variability at the shelf break reflects a consistently topographic-constrained process, such as nutrient influx originating from the subsurface, specifically within the BBL detachment zone, to be investigated below.

4.2. Shipboard-measured frontal variability

The weakest stratification of the three cruises was found during April 2018 (Fig. 6; also see Supporting Material, Sec. S2, Fig. S3 for a complete view), with a steep front and coincident isohalines and isopycnals outcropping at the surface. In May 2019 (in Supporting



Fig. 5. 2D Welch's power spectrum of depth-binned mean Chl-*a* concentration in the MAB region. Note the log scale for the x- and y-axes. The two white vertical lines delimit the shelf-break area ([100, 1000] m isobaths). Lower panel: zoom in enhancing the high-frequency variability. Note that the different order of magnitude of the color bars. Data presented focus only on the [75–2500] m depth range for consistency with the *in-situ* measurements.

Material, Sec. S2, Fig. S5) the vertical stratification increased compared to April. In contrast, July 2019 (Fig. 7; also see in Supporting Material, Sec. S2, Fig. S7 for a complete view) showed the greatest vertical stratification due to the formation of the thermocline; the front was shallower, and the frontal isopycnals were no longer outcropping at the surface but bending below the shallower mixed layer. The observed stratification reflected the stability of the water column, as evaluated



Fig. 6. Cross-shelf sections of a typical unperturbed (top row, April 19) and perturbed (bottom row, April 27) MAB shelf-break front during April 2018. The black line represents the mean location of the front, corresponding to 34.5 PSU. The red line is the target isopycnal intersecting the foot of the front in the bottom boundary layer (26.6 σ).



Fig. 7. Cross-shelf sections of a typical perturbed (top row, July 6) and unperturbed (bottom row, July 9) MAB shelf-break front during July 2019. The black line represents the mean location of the front, corresponding to 34.5 PSU. The red line is the target isopycnal intersecting the foot of the front in the bottom boundary layer (26.3 σ).

by N^2 , which showed an overall increase from April to July (see Fig. S18, Supporting Material Sec. S5).

Different vertical stratification conditions were also reflected in the identification of the isopycnal corresponding to the 34.5 PSU isohaline which identifies the center of the front. In particular, the density for April was 26.6 σ , for May 26.45 σ , and 26.3 σ for July, thus becoming more buoyant from spring to summer. These results agree with the climatology described by Gawarkiewicz et al. (2018), except for April which was outside the range of variability [25.8–26.45] σ . In general, the front is denser and steeper during spring; less dense and wider during summer.

During all the cruises there were significant influences of off-shore structures impinging on the continental shelf. For example, on the 27th of April 2018, the intrusion of warmer, saltier water from off-shore extending all the way to the front (Fig. 6, bottom row, at 39.7° – 40.1° N) was associated with a Gulf Stream warm-core ring. This caused a divergence between the front and the target isopycnal around 50 m (Hirzel et al., 2023). This interaction flattened the isopycnal and displaced the head of the front farther inshore.

The frontal structure in May was dominated by the passage of two shelf-break eddies with the front in a more on-shore position than normal (in Supporting Material, Sec. S2, Fig. S5). This steepened the frontal isopycnals which normally inhibits shelf-break exchange. That condition was relieved during the last day of the cruise when the frontal surface flattened.

July 2019 had the greatest change in the frontal surface among the three cruises, which was also reflected in the highest salinity variability. The reduced vertical stratification observed on the 6th of July (Fig. 7) was related to a streamer associated with a Gulf Stream warm-core ring (Zhang et al., 2023). The streamer caused the off-shore advection of the shelf water, diverting the shelf-break front more than 35 km to the south of its mean position. After the streamer passed, the shelf-break front was restored.

4.2.1. Chlorophyll and nutrient variability

The distributions of nutrients and chlorophyll reflected the seasonal and submesocale variability characteristic of the region. On 17 April 2018, nitrate, phosphate, and silicate were all relatively abundant throughout the water column (Fig. 6, top row; see in Supporting Material, Sec. S2, Fig. S4 for a complete view). Surface nitrate concentrations were well in excess of that which typically limits phytoplankton growth. The local maximum of PON at the front on April 17th was associated with Ekman restratification, which is a driving mechanism for surface chlorophyll enhancements (Oliver et al., 2022). Surface chlorophyll was enhanced by $\sim 1.5 \text{ mg m}^{-3}$, and persisted until April 23rd (Fig. 6, bottom row; in Supporting Material, Sec. S2, Fig. S3). Offshore of the front, conditions were influenced by a warm core ring, (described in Section 4.2) as observed by the flattening of the isopycnals with increased surface stratification and depletion of nitrate (Fig. 6, bottom row). Note that nitrate was also depleted in the inshore region around 40.5°N, above the local maximum of chlorophyll (> 20 mg m⁻³), corresponding to a regional bloom of *P. pouchetii* (Smith Jr. et al., 2021; Hirzel et al., 2023) adveced on the shelf from upstream. The P. pouchetii bloom signal was also evident in the patchiness of PON. Nevertheless, this event is unrelated to the specific frontal dynamics investigated in this study.

In May 2019, vertical stratification increased the surface nutrient depletion to around 25 m depth (in Supporting Material, Sec. S2, Fig.

Table 2

Summary of the central isopycnals found within the detached BBL in the accumulated temperature, (hence also salinity) and nitrate change sections.

Day of April	Central isopycnal [kg m ⁻³]				
	ATC	ANC			
17	26.6	26.3			
19	[26.4–26.6]	[26.3-26.5]			
21	[26.4–26.6]	26.6			
23	[26.5–26.6]	[26.3-26.5]			
25	[26.5–26.6]	[26.5-26.6]			
27	no significant signal	26.3			
Day of July					
6	no significant signal	26.3			
9	[26.0–26.2]	26.1			
11	26.0	[26.0-26.1]			
14	[26.3–26.4]	[26.0-26.1]			
16	26.3	26.4			
17	26.0	26.0			

S6). Strong frontal eddy interactions led to patchiness in all nutrients, and surface chlorophyll was enhanced up to $\sim 3.0~mg~m^{-3}.$

In July 2019, nutrients were all depleted at the surface, in particular, nitrate was fully depleted above 30 m depth (Fig. 7, and in Supporting Material, Sec. S2, Fig. S8). A subsurface chlorophyll maximum (> 3 mg m⁻³) was located below the warm surface layer (19 °C < *T* < 24 °C). This broad feature is present throughout the section and likely reflects photoadaptation in the stratified layers just below the nutricline. Any Chl-*a* enhancements driven by BBL upwelling would be superimposed on this signal (Fig. 3). As the streamer passed the frontal structure was fully restored (Fig. 7, bottom row). At the offshore end of the front, both the warmer surface layer and the euphotic zone extended deeper, resulting in a deeper chlorophyll maximum and deeper nutrient depletion. The highest PON concentrations (> 2.8 µmol L⁻¹) were found to match the chlorophyll maxima patches.

4.3. BBL detachment identification through APC

To identify the layer of weak stratification characterizing the detached BBL, we employ the criteria defined by Linder et al. (2004): the ATC = 1.0 °C contour, with tongue-shaped structures pointing upward and off-shore. Similarly, we apply the same criteria to the nitrate, selecting the ANC = 1.0 μ mol L⁻¹. This value is an order of magnitude higher than the characteristic limiting value of 0.1 μ mol L⁻¹ for phytoplankton uptake. Hence, we aim to ensure that we are well above this limit to confidently identify the layer where nitrate uptake occurs, subsequently leading to an increase in Chl-*a* concentration. However, both of these values have been chosen to be large enough to overcome small-scale variability that would lead to erroneous layers being tracked but small enough to follow the accumulated change as it rises in the water column. A summary of the isopycnals identifying the BBL detachment based on this method is in Table 2.

For those days where the signal of detachment was found, the central isopycnals of ATC (and also ASC) were in between σ = [26.4–26.6] in April and σ = [26.0–26.3] in July. The position of ANC ranged between σ = [26.3–26.6] in April and σ = [26.0–26.4] in July, matching those of ATCs in both seasons.

4.3.1. April 2019

In general, during April the tongue-shape detached BBL extended from the bottom, penetrating upwards in the water column. This observation is consistent with the early spring conditions described by Linder et al. (2004). A good example of well-defined ATC, ASC, and ANC minima is the transect from 19th April 2018 (Fig. 8, left column). The isopycnals centering the ATC and ASC minima in the BBL were within σ = [26.4–26.6] and the maximum extension of the tongue stretched within ~ 30 m of the surface. Almost the same structure was present



Fig. 8. Accumulated change in salinity (ASC), temperature (ATC), and nitrate (ANC) on 19th (left column, unperturbed fields) and 27th of April (right column, off-shore perturbed fields). The white contours represent isopycnals [kg m⁻³]. ATC = 1.0 °C, ASC = 1.0 PSU, and ANC = 1.0 μ mol L⁻¹ contour is emphasized in black. Note that for the 19th of April, the ASC = 1.0 PSU contour is outside of the displayed range. Refer to Fig. 6 for the temperature, salinity, and nitrate fields from which these were computed.

in the ANC even though this minimum was centered on slightly lighter isopycnals compared to the one of the ATC: σ = [26.3–26.5], extending from the bottom to within 40 m of the surface.

Later in the cruise, off-shore water masses interfered at the surface (see the increased vertical stratification closer to the surface in the last two rows in Fig. S3, Sec. S2 of Supporting Material) flattening the isopycnals and also affecting the BBL structure. One example of that is the section from the 27th of April (Fig. 8, right column). A clear signal of the detachment of the BBL cannot be identified using ATC minima criteria; neither does that layer give an indication of upward detachment in the ASC field. Nevertheless, it is interesting to note that the ANC showed a structure resembling a detachment but without any indication in the ATC or ASC fields, and thus may reflect along-shore variability of nitrate concentration not related to the BBL.

4.3.2. May 2019

During the May cruise, the front was distorted by the presence of frontal eddies. None of the sections show a clear indication of detachment (see Fig. S12 and S13 in Supporting Material, Sec. S3); as a consequence, no ANC was calculated. For almost all the sections the BBL structure arising from ATC was quite flat close to the bottom. The ASC contours were almost horizontal over the slope but became steeper close to the surface following the isopycnal distributions.

4.3.3. July 2019

During July there were two main factors affecting the BBL structure: the seasonal pycnocline becoming fully developed and a streamer originating from a Gulf Stream warm-core ring passing through. Both of them inhibited the vertical penetration of the ATC minima in the water column. A good example of the streamer perturbed conditions was found for the transect of the 6th of July (Fig. 9, left column).



Fig. 9. Accumulated change in salinity (ASC), temperature (ATC), and nitrate (ANC) on 6th (left column, streamer perturbed fields) and 9th of July (right column, unperturbed fields). The white contours represent isopycnals [kg m⁻³]. ATC = 1.0 °C, ASC = 1.0 PSU, and ANC = 1.0 μ mol L⁻¹ contour is emphasized in black. Refer to Fig. 6 for the temperature, salinity, and nitrate fields from which these were computed.

There was no clear indication of detachment in the ATC and ASC: both contours fluctuated without any consistent tendency. Therefore, the ANC minimum found along the 26.3 σ cannot be strictly related to BBL detachment. However, this supports the idea that off-shore water masses can disturb the frontal structure, also affecting the convergence and the upwelling process acting in the BBL.

After the streamer passed, unperturbed summer conditions were found for the transect on 9th July (Fig. 9, right column). There was a distinct minimum, for both ATC and ASC, centered between 26.0 σ and 26.15 σ and extending from the bottom up to ~ 60 m from the surface. An analogous minimum, centered on the same isopycnals, was found for the ANC. That was a clear indication that the BBL detachment is a consistent feature of the MAB shelf-break front when it is not perturbed by external forcing and it is able to be fully restored after such interactions. Furthermore, the signal of the detachment was particularly strong during this time and very well delineated compared to most of the other unperturbed sections (in Supporting Material, Sec. S3, Figs. S15 and S16). The surface stratification was not completely restored (in Supporting Material, Sec. S2, Fig. S7) but the off-shore forcing was no longer intense enough to alter the BBL. On the following day, the front stabilized with the intrusion of denser and saltier water mass over the slope, increasing the upslope flow and reducing the detachment (in Supporting Material, Sec. S3, Fig. S15 left column). The increased stratification limited the vertical rise in the ATC minimum to around 60 m from the surface, a strong contrast to April when it reached 30 m below the surface. The range of isopycnals associated with ATC and ANC minima was wider and centered along lighter density contours compared to April (Table 2).

4.3.4. Summary

Generally, we found that the maximum vertical and horizontal extension of the minima of ASC and ATC were inshore or straddling the frontal isopycnals. Thus, we can conclude that the nutrient transport occurs on the on-shore side of the front (Fig. 2a). In addition, vertical penetration is affected by the off-shore forcing and also the increased strength of the thermocline at the surface. Both reduce the vertical extension of the detached BBL within the water column, which is hypothesized to carry nutrients up to the euphotic zone. To assess if this process can affect the surface and subsurface phytoplankton biomass, along isopycnal changes in properties are investigated in the following section.

4.4. Along isopycnal changes in properties

The main hypothesis of this work is that nutrients are carried upward from the layer detaching from the BBL in association with the front, enriching nutrients in the euphotic zone and increasing phytoplankton biomass. According to the theory of how the detached layer is created (Pickart, 2000) this transport has to occur along isopycnals. Thus we chose target isopycnals to estimate the differences between the concentrations of nitrate, PON, and Chl-*a* in the BBL and closer to the surface/euphotic zone.

4.4.1. Assessment of the applicability of the method in transects

None of the transects from the May 2019 met the criteria described in Section 3.1.2, (Fig. 2) due to strong frontal eddy fields contorting the front. Consequently, only the April and July transects will be considered in the following analysis.

In April 2019, the 26.6 σ isopycnal hit the base of the front in the BBL. The average position of the ATC minima was found along this isopycnal, or 0.1–0.2 kg m⁻³ lighter, and the ANC minima were always within this range of density surfaces. As described above, we can conclude that the detachment of the BBL is occurring on the onshore side of the front. Based on these findings, we have selected two additional target isopycnals: 26.5 σ and 26.4 σ .

Fig. 10 shows two illustrative scenarios, representing conditions of the unperturbed front (April 19th) and front affected by off-shore submesoscale structure (April 27th). In the former scenario, all isopycnals outcrop at the surface, with the 1% light level intersecting around 40.07°N. In the latter, the off-shore forcing displaced the frontal isohaline shoreward and induced a deeper penetration of the isopycnals. Consequently, the criterion for selecting off-shore points is based on isohaline 34.75 PSU outcropping into the euphotic zone (with the exception of the 26.4 σ).

In July, our initial target isopycnal was 26.3 σ . Given the nearbottom patterns in ATC and ANC (Fig. 9), we also chose 26.15 σ and 26.0 σ . The isohaline criterion was applied due to the increased surface stratification (Fig. 11, right column). It is worth noting that during the 6th of July (Fig. 11, left column) the nearly flat isopycnal configuration in the upper ocean was the result of the warm core ring streamer, as described in Sec. 4.2. This caused the surface box from which data points were extracted to be always located below the estimated 1% light level (in Supporting Material, Sec. S4 Fig. S17 third row) but within or straddling the 0.1% light level.

4.4.2. Testing the along isopycnal upwelling hypothesis

The mean extension of the tongue of the detached BBL was within 30 m of the surface during April and up to 60 m for July; thus at the edge of the estimated euphotic zone for both seasons. The Δ s are the variation, linearly interpolated along each isopycnal, of the concentration of NO_3^- , PON, and Chl-*a* within the euphotic zone. The 1% and 0.1% light level depth are a rough estimation of the region in the water column where the incoming light is sufficient for photosynthesis, hence nutrient variations along isopycnals within or nearby these zones can reflect uptake by phytoplankton and associated



Fig. 10. Two examples from April 2018 of the sections used to compute along isopycnal changes in properties. The color map represents the calibrated Chl-*a* from the CTD. The red lines represent the target isopycnals (from shallower to deeper: 26.4, 26.5, 26.6 σ). The black solid line represents the mean location of the MAB shelf-break front (34.5 isohaline); the black dashed line corresponds to the 34.75 isohaline. The area used for the data extraction is shown by the dashed light blue boxes (bottom and surface). The light blue dots are the data points considered. The yellow dotted line represents the estimated 1% light depth.



Fig. 11. Two examples from July 2019 of the sections used to compute along isopycnal changes in properties. The color map represents the calibrated Chl-a from the CTD. The red lines represent the target isopycnals (from shallower to deeper: 26.0, 26.15, 26.3 σ). The black solid line represents the mean location of the MAB shelf-break front (34.5 isohaline); the black dashed line corresponds to the 34.75 isohaline. The area used for the data extraction is shown by the dashed light blue boxes (bottom and surface). The light blue dots are the data points considered. The yellow dotted line represents the estimated 1% light, and the orange is the 0.1% light depth.

Table 3

Statistics of hypothesized relationships between along isopycnal changes in NO_3^- , Chl-*a*, and PON. The inferred C:Chl ratio assumes Redfield stoichiometry of C:N = 6.6.

Cruise	Hypothesis	Num. Obs	Estimated quantities			
			r	r^2	p-value	C:Chl
April 2018	$-\Delta(NO_3^-) \sim \Delta(\text{Chl-}a)$	36	-0.60	0.36	0.0001	82.43
"	$-\Delta(NO_3) \approx \Delta(PON)$	35	-0.54	0.29	0.001	
July 2019	$-\Delta(NO_3^-) \sim \Delta(\text{Chl-}a)$	31	-0.63	0.40	0.0002	52.45
"	$-\Delta(NO_3^-) \approx \Delta(\text{PON})$	30	-0.30	0.09	0.106	

increases in biomass and Chl-a fluorescence.

The interpolated distribution of NO_3^- , Chl-*a*, and PON along the target isopycnals (Fig. 12) generally conforms to the anticipated patterns. Specifically, nitrate exhibits a trend of decreasing concentration from the bottom toward the surface, whereas Chl-*a* and PON concentrations tend to increase in this direction.

The hypotheses that $-\Delta(NO_3^-) \approx \Delta(\text{PON})$ and $-\Delta(NO_3^-) \sim \Delta(\text{Chl} - a)$ are supported by the negative values of *r* (Figs. 13, 14 and Table 3). The statistical reliability of this correlation is robust for the Chl-*a* vs. $\Delta(NO_3^-)$ regression (*p*-value < 0.05), whereas the correlations were not significant for $\Delta(NO_3^-)$ vs PON. The C:Chl ratios inferred from fitting our conceptual model with the data (Table 3) fall within a range of reasonable values (Cullen, 2015).

The BBL detachment can be influenced by various factors that impact front stability, including off-shore forcing. In fact, at most, the

40% of the variation of Chl-a can be accounted for solely by its linear correlation with $\Delta(NO_2^-)$ ($r^2 \sim 0.4$, Table 3). However, this correlation is even less for PON, particularly in July, where $r^2 < 0.1$. Hence, it is necessary to consider non-linear processes to comprehensively explain the entire spectrum of variability in these quantities. For example, the lagged effects of the cross-shelf streamer crossing the transect (Section 4.2) may have led to the positive along isopycnal change in nitrate $(\Delta(NO_2^-) > 0)$ observed on the 11th and 14th of July. Specifically, the shallower penetration of a high nutrient water mass (around 40.0°N in Fig. S8, third row; Supporting Material Sec. S2) might have resulted in the observed increase in concentration with decreasing depth. This phenomenon is potentially driven by an off-shore flux of fixed nitrogen induced by the streamer (Selden et al., 2024). These data points are highlighted in red in Fig. 14 and we excluded them from the linear regression estimation due to their clear lack of association with the BBL detachment phenomena of interest here. On April 27th, the intrusion of



Fig. 12. Along isopycnal distribution of properties for all the sections of April (1st row) and July (2nd row). The black dashed vertical line separates the deep and shallow boxes from which the data were extracted (e.g. Figs. 10 and 11).



Fig. 13. Left panel: $-\Delta(NO_3^-)$ vs $\Delta(Chl - a)$ calculated along the target isopycnals. Right panel: $-\Delta(NO_3^-)$ vs $\Delta(PON)$ calculated along the target isopycnals (26.4, 26.5, and 26.6 σ). Each marker represents a different day of April: • 17th, × 19th, \triangle 21st, \blacksquare 23rd, \blacklozenge 25th, and \bigstar 27th. The days when the off-shore forcing was significant are indicated in light blue. The orange data points ($\Delta(Chl - a) < 0$ or $\Delta(PON) < 0$) were excluded (see text). The blue line represents the regression between the observations and the conceptual model.

nutrient-depleted Gulf Stream water (Section 4.2.1) resulted in reduced Δ (Chl) values highlighted in the left panel of Fig. 13. Other conditions where our conceptual model failed in the prediction of the hypothesized trend were detected in the data as Δ (Chl) < 0 and Δ (PON) < 0. These may be the result of three-dimensional processes not resolved in our two-dimensional cross-shore transect observations. The model's inability to predict such phenomena led to the exclusion of these data points for consistent analysis. This limitation constitutes the principal constraint of the current methodology.

5. Discussion

Phytoplankton concentration at the MAB shelf-break is affected by the upward nutrient transport associated with several upwelling mechanisms acting at the front as well as external forcing (e.g., wind, warm core rings, streamers). Evidence of this kind of variability emerged in the annual 2D surface Chl-*a* spectrum with notable high-frequency peaks in the shelf-break area for periods shorter than 20 days. The fact that these peaks span a range of frequencies supports the idea that multiple processes may be active, including eddy pumping (Hirzel



Fig. 14. Left panel: $-\Delta(NO_3^-)$ vs $\Delta(Chl - a)$ calculated along the target isopycnals. Right panel: $-\Delta(NO_3^-)$ vs $\Delta(PON)$ calculated along the target isopycnals (26.0, 26.15, and 26.3 σ). Each marker represents a different day of July: • 6th, × 9th, \blacktriangle 11th, \blacksquare 14th, \blacklozenge 16th, and \bigstar 17th. The days when the off-shore forcing was significant are indicated in light blue. The orange data points ($\Delta(Chl - a) < 0$ or $\Delta(PON) < 0$) were excluded (see text). The blue line represents the regression between the observations and the conceptual model.

et al., 2024), Ekman restratification (Oliver et al., 2022), as well as wind-driven upwelling (Zhang et al., 2011).

Here we investigated the hypothesis that nutrient transport induced by the BBL detachment can lead to a biological response in the frontal region. Prior research established that a pressure gradient is responsible for sustaining the front at the shelf-break (Gawarkiewicz and Chapman, 1992). The geostrophically adjusted currents drive a convergence in BBL that leads to the uplift and off-shore transport of water masses. While this phenomenon had been previously examined through seasonal analyses of temperature and salinity fields, our study employs the Accumulated Property Change algorithm (Linder, 2005) to identify and characterize the detachment of the BBL in synoptic cross-shelf sections. The novelty in this work is that we were able to apply the APC algorithm also to a biogeochemical variable: NO_3^- concentration. That allowed us to provide a comprehensive description of the variability of the BBL detachment, and to link the physical process with the biological distributions.

We found that the BBL detachment occurs on the on-shore side of the front and can be strongly affected by the off-shore forcing. The signal of the BBL detachment can be completely disrupted during periods of perturbed conditions and the modifications can last a few days after the passage of the perturbation. When no external forcing was present, BBL detachment was always detected with the APC method, suggesting this process is a consistent feature of the MAB frontal system.

The seasonal dynamics of the frontal system are also a key factor in BBL detachment. In the case of spring low surface stratification, the tongue originating from the BBL can extend much closer to the surface. In contrast, summertime stratification compresses the vertical extent of the detached layer. The extent to which the BBL tongue penetrates up into the water column can influence factors such as nutrient distribution, and consequently, the vertical distribution of phytoplankton abundance. We also found that when the BBL detachment signal was detected in ATC and ASC sections, the same signal was also present in ANC, thus supporting our initial hypothesis.

To assess the importance of the BBL detachment for nutrient upwelling, we evaluated the change in properties along some selected isopycnals. That allows us to give an order of magnitude estimation of how much of the observed Chl-*a*, NO_3^- , and PON variability might be associated with the frontal upwelling (Fig. 2). Results show that the relationships between the decline of nitrate along isopycnals and the concurrent increase in phytoplankton biomass did not exhibit a simple pattern. The most robust result was the inverse relationship between NO_3^- decline and Chl-*a* increase. The negative correlation was lower when considering PON. This is not surprising given that PON includes living material other than phytoplankton as well as non-living material and all these constituents vary on different time scales.

The observed variability in nutrient and phytoplankton biomass underscores the complexity of their relationship with frontal dynamics. Instances where the model failed can be attributed to the non-linear nature of the mesoscale and submesoscale processes active in the region, which may cause deviations from the hypothesized linear relationships among variables. In addition, water column stability could also influence the proposed mechanisms. In April, vertical mixing reduced stability, as shown by lower N² values (Fig. S18, first row; Supporting Material Sec. S5). This mixing enhanced nitrate availability throughout the water column but likely led to light limitation, constraining phytoplankton growth. By July, increased stratification led to surface nutrient depletion and formation of a subsurface Chl-*a* maximum, changing the background conditions on which the BBL detachment mechanism was operating.

The primary limitation of our model is the 2D approach, which neglects the variability associated with lateral transport (along-shelf). Photoadaptation of phytoplankton must also be considered to interpret variations in Chl-*a*, given their ability to modulate their pigment content according to light availability. This is particularly evident in the subsurface chlorophyll maximum (in Supporting Material, Sec. S4, Fig. S17, third row) where light is relatively low. Thus, high fluorescence values may not always correspond to high phytoplankton biomass. This might be reflected in the lower correlation estimated in July.

To further investigate these complex processes and enhance our understanding of the specific contributions of the various upwelling mechanisms in the region, it would be interesting to expand the computational model developed in Pickart (2000), which simulated the detachment of the BBL at the shelf-break front. Combination with a biogeochemical model including nutrient cycling and the dynamics of phytoplankton growth and grazing would allow further investigation of the three-dimensional coupled physical-biological processes. Such models, together with synoptic data sets with which they can be validated, could provide valuable insights into the interconnected nature of physical and biogeochemical processes in the MAB shelf-break region and contribute to a more comprehensive understanding of the ecosystem's behavior.

6. Conclusions

This work investigates the role of nutrient transport induced by the BBL detachment in driving biological responses at the MAB shelf-break front. Upwelling mechanisms associated with the front and off-shore forcing contribute to the observed variability in phytoplankton concentrations, which is intricately linked to the complex and highly non-linear dynamics of these processes.

Using the APC algorithm, this study identifies and characterizes the detachment of the BBL in synoptic cross-shelf sections, linking the physical process with biological responses. BBL detachment occurs on the on-shore side of the front and can be affected by external forcing. The seasonal dynamics of the frontal system also play a key role, in particular with the extent of BBL penetration depending on stratification with concomitant influences on the nutrient distribution and biological response. Our analysis reveals that when BBL detachment signal is detected in temperature and salinity fields, it is also present in nutrient concentrations, supporting the hypothesis of nutrient upwelling. We evaluated the relationships between nutrient decline along isopycnals and phytoplankton biomass variability in cross-shore sections. Considerations such as the neglect of lateral transport variability and the photoadaptation of phytoplankton highlight the complexity of interpreting observed trends. Despite scatter in the data, the results show a correlation between nitrate decline and chlorophyll increase, indicating a biological response to nutrient upwelling.

CRediT authorship contribution statement

Serena Negroni: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Dennis J. McGillicuddy: Writing – review & editing, Supervision, Resources, Project administration, Formal analysis, Conceptualization. Glen G. Gawarkiewicz: Writing – review & editing, Supervision, Investigation, Conceptualization. Paolo Oddo: Writing – review & editing, Visualization, Supervision, Conceptualization. Nadia Pinardi: Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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