Chlorophyll distributions and nutrient transport in relation to physical processes off Long Bay, South Carolina, USA, in the winter of 2012

PhD Dissertation Proposal

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1. Introduction

Looking along the outer continental shelf of the South Atlantic Bight (SAB), Ryan and Yoder (1996) examined seven years of satellite data. From images of surface chlorophyll and sea-surface temperature (SST), they found anomalously high wintertime productivity on the outer shelf around Long Bay, South Carolina, between Cape Fear and Cape Romain.

These observations motivated the Skidaway Institute of Oceanography and the University of North Carolina Department of Marine Sciences to conduct a field program at Long Bay in the winter of 2012, funded by the National Science Foundation (NSF). The goal of the field program was to determine the physical processes that contribute to the high wintertime productivity in this region.

This dissertation will focus on a subset of the questions that were posed by the 2012 field program, specifically the following:

1) Describe the blooms.
    a. What was the distribution of chlorophyll (in space and time) on the shelf and slope in Long Bay?
    b. Estimate the export of chlorophyll from the shelf to the slope.
2) What caused the blooms?
    a. What was the distribution of nitrate (in space and time) on the shelf and slope in Long Bay?
    b. What physical processes contributed to the observed distribution of nitrate?

2. Background

2.1 Atmospheric forcing

In this region, the mean winds shift in the fall towards the southwest, along the shelf (Blanton et al., 2003). Then, from November to February, the prevailing winds are towards the southeast in the Northern SAB (Blanton et al., 2003).

In the winter, cold air outbreaks (CAO) meet the Gulf Stream, causing intense exchanges of heat and momentum (Bane and Osgood, 1989). Driven by strong atmospheric forcing, “deep mixing” could bring nutrient-rich slope water closer to the surface (Atkinson et al., 1996).

2.2 Stratification

As described by Ryan and Yoder (1996), the wintertime is the “typically unstratified” period in the SAB. The shallow water cools more quickly than the deeper water, resulting in a horizontal temperature gradient across the shelf in the winter (Oey, 1987).

Nevertheless, stratification events do occur in this region in the winter. For example, during the Genesis of Atlantic Lows Experiment (GALE), Atkinson et al. (1989) observed several strong stratification events in January on the shelf off Cape Romain. These were caused by wind-driven Ekman flow and/or surface intrusions of buoyant water from Gulf Stream meanders (Atkinson et al., 1989).

Stratification here may also be a result of density-driven cascading, which could be driven by localized heat loss to the atmosphere (Atkinson et al., 1996; Yoder and Ishimaru, 1989; Shapiro et al., 2003).

2.3 Influence of the Gulf Stream

Gulf Stream meanders and filaments can bring nutrients to the outer shelf and slope (Condie, 1995). The circulation at the western edge of a Gulf Stream meander is such that the nutrient-bearing strata are lifted into the photic zone even without forcing from the wind (Hitchcock, 1993; Martins and Pelegri, 1996; Osgood and Bane, 1987). In water from 22 to 18 degrees C, these nutrient-bearing strata may have nitrate concentrations from 1 to 10 μM, respectively (Atkinson et al., 1996).

Downstream of the topographical feature known as the "Charleston bump", the SAB off of Long Bay is a region where Gulf Stream meanders can grow (Bane and Dewar, 1988; Ryan and Yoder, 1996). Here, the Gulf Stream position is bimodal, either strongly[1] or weakly deflected (Bane, 1983; Bane and Dewar, 1988). When in the strongly deflected mode, the Gulf Stream meanders are larger in amplitude (Bane and Dewar, 1988). The period between meanders is approximately 16 days for the large-amplitude meanders (Bane and Dewar, 1988). For the smaller-amplitude meanders, associated with the weakly deflected stream, the period is shorter, about one week (Bane and Dewar, 1988).

As a Gulf Stream meander grows, the crest may spawn a long filament that wraps around the shoreward edge of a cyclonic gyre. The filament extends in the along-shore direction as the meander propagates downstream. The filament itself may or may not have a net equatorward velocity[2].

We will consider several filament-related processes that may bring nutrients onto the shelf, including the following observations from previous studies:

- Between a Gulf Stream filament and the Gulf Stream itself, cyclonic circulation may cause upwelling of nutrient-rich water onto the outer shelf (Lee et. al., 1991; Bane, Brooks, and Lorenson, 1981). This cyclonic circulation in Long Bay is known as the "Charleston gyre" (Bane, 1983).
- Interestingly, Govoni et al. (2013) looked at transects of the "Charleston gyre" over three consecutive winters and found more surface chlorophyll in the "wrap-around" filaments than in the core of the gyre. The region studied by Govoni et al. included Long Bay.
- Ryan and Yoder (1996) studied five high-chlorophyll events in detail. Two of the five were related to Gulf Stream filaments.

[1] The Gulf Stream is considered strongly deflected when its shoreward front is "offshore of the 600m isobath for several tens of kilometers along the continental slope downstream of the [Charleston] bump" (Bane and Dewar, 1988). The strongly deflected mode is the preferred mode in the winter (Bane and Dewar, 1988).
[2] When describing the velocity of a filament, Glenn and Ebbesmeyer (1994) said, "Depending on the relative magnitudes of the swirl and propagation velocities, the total velocity may either reverse or approach zero."

- Savidge et al. (1992) looked at mooring data off Long Bay from 1986 and found a period when the Gulf Stream became strongly deflected and a filament appeared on the outer shelf. As a result, both pressure and stratification increased on the outer shelf.
- Lee et al. (1981) observed cool, nutrient-rich water moving shoreward in a bottom layer *under* a Gulf Stream filament.

Eventually, if the filament is not advected away before it breaks up, it dissipates on the shelf, mixing with the shelf water and leaving its nutrients there.

Finally, we observed some "filaments" to extend all the way to the bottom on the slope, so we categorize these as "jets" instead of filaments. Since the equatorward-flowing jets extend to the bottom, we would expect to see a seaward Ekman flow in the bottom boundary layer when these are present.

2.4 Nutrient transport from the slope to the shelf

In previous sections, we discussed several mechanisms for bringing nutrient-rich slope water closer to the surface, including a) upwelling inside the cyclonic "Charleston gyre" or b) "deep mixing" on the slope due to atmospheric forcing. In this section, we look at how these nutrients might be transported laterally, from the slope to the shelf.

We know from Checkley et al. (1988) that menhaden and other species of fish spawn along the western edge of the Gulf Stream in this region during the winter; the larvae benefit from the nutrient-rich water and are somehow transported shoreward.

In Ryan and Yoder (1996), the largest blooms were long bands up to 700km in length along sea-surface temperature fronts, inshore of the Gulf Stream. Since this scale is larger than that of a frontal eddy, the authors suggested that nutrients were being transported shoreward via processes that act at a larger scale, either wind or tidal forcing. In this section, we will review evidence from the literature for a) wind-driven, shoreward Ekman flow and b) shoreward transport due to internal waves.

2.4.1 Wind-driven upwelling at the shelf break

According to previous studies (Oey et al, 1987; Ryan and Yoder, 1996; Martins and Pelegri, 1996), a likely mechanism is for promoting cross-shelf transport is a wind-driven, shoreward Ekman flow. This flow may transport nutrients from the western edge of Gulf Stream meanders, filaments, or jets.

Combining model results with observations from GALE, Oey et al. (1987) suggested that southward flowing wind events can cause "transient upwelling" at the shelf break. In this scenario, the nutrient-rich water at the western edge of the Gulf Stream upwells and then flows shoreward in a wind-driven surface Ekman layer (Oey at al., 1987). After losing heat, this water sinks at a mid-shelf front and flows seaward in a bottom layer (Oey at al., 1987). Figure 1 depicts the flow for this scenario (copied from Figure 4 in Oey at al., 1987).

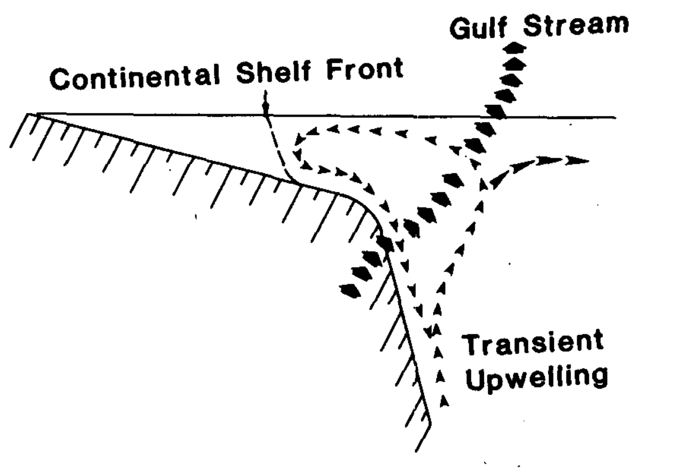

Figure 1: This figure was copied from Oey et al., 1987, their Figure 4. It depicts wind-driven “transient upwelling” at the western edge of the Gulf Stream.

Although Oey et al. (1987) did not provide observational evidence of increased nitrate in the shoreward Ekman flow, another GALE-related study (Atkinson et al., 1996) did find a “weak relation between amounts or concentrations of nitrate and wind stress.”

2.4.2 Internal waves

Internal waves could provide a mechanism for transporting nutrient-rich slope water onto the shelf (Leichter, 2003). For example, Shroyer et al. (2010) observed nonlinear internal waves (NLIW) off the coast of New Jersey. They found that the shoreward transport distance per packet was usually 1-2km, but in one case was nearly 10km. They estimated the net shoreward transport due to the observed NLIW was equivalent to a weak but sustained Ekman flow (Shroyer et al., 2010).

The configuration of the mass field along the shelf break has an impact upon the propagation of internal waves (Chen et al., 2003). Equatorward-flowing Gulf Stream filaments/jets near the shelf break change the mass field such that isopycnal surfaces intersect the bottom of the continental slope, a configuration that Chen et al. (2003) called the “summer front”. They developed a model that showed that this “summer front” at mid-latitudes favors the propagation of internal waves, forced by the semidiurnal tides (Chen et al., 2003). Shoreward of the “summer front”, internal waves are trapped and amplified, causing intense mixing there. Seaward of the “summer front”, internal waves can propagate (Chen et al., 2003). Using the same “summer front” scenario, Vlasenko (2012) describes a similar result from a modeling study, showing an intensification of internal waves across the shelf break and onto the shelf. (See Vlasenko’s Figure 3.19.)

Given these findings, we may expect enhanced mixing due to internal waves near the shelf break when equatorward-flowing Gulf Stream filaments or jets are present, as they bring about the more favorable “summer front” configuration even in the winter.

2.5 Distribution of chlorophyll

The distribution of chlorophyll in space and time is determined by many factors. Fundamentally, phytoplankton requires light and nutrients to grow and multiply, so the availability of these resources impacts the distribution. Other factors include grazing by zooplankton, the phytoplankton's fall rate through the water column, and advection (Miller, 2004).

When analyzing the distribution of chlorophyll, we must also keep in mind the possibility that storms can cause resuspension of not only the sediment but also the settled phytoplankton. This was observed during the GALE study (Checkley et al., 1988), off Cape Romain. It is interesting that the mid shelf of the SAB has a large percentage of the primary production occurring in the sediment—at least in the summer; this was observed off Georgia at depths of 14-40m deep from late spring to early fall (Nelson et al., 1999) and in Onslow Bay at depths of 16-41m (Cahoon and Cooke, 1992).

In this study, we will also try to estimate the rate of export of chlorophyll from the shelf to the slope. As mentioned above, the continental shelf and slope off Long Bay is a region where phytoplankton blooms occur in the winter. The physical processes are such that a significant amount of the phytoplankton gets exported from the shelf to the slope and into deeper water, where it may take much longer for the plankton to be remineralized. Such export of organic carbon to deep water is a process that is therefore of interest to climate change models (Huthnance, 1995).

2.6 Resuspension of sediment

When accounting for nutrients on the shelf, we must also consider resuspension of sediment, as this can bring nutrients back into the water column. It may occur due to storms (Nelson et al., 1999), internal waves (Butman, 2006), or Gulf Stream filaments/jets (Gelfenbaum et al., 1993).

In a study conducted at a depth of 85m on the slope off Cape Romain, Gelfenbaum et al. (1993) found that erosion of the sea bed coincided with the passage of a Gulf Stream filament. The maximum hourly-averaged speed at 1m from the bottom was over 60cm/sec; at this speed, "all but the coarsest material on the bed was put into motion" (Gelfenbaum et al., 1993).

3. Methods

3.1 Deployed instruments

Figure 2 shows the locations of three moorings deployed on the shelf and slope off of Long Bay, at depths of 30m, 75m, and 170m. Each mooring was equipped with an ADCP, a CTD, and an ECO puck.

The moored ADCP measures the velocity as a function of depth over the mooring. The moored CTD measures the conductivity and temperature at the mooring location. The moored ECO puck measures chlorophyll a fluorescence (Chl-a), scatter, and CDOM at the mooring location.

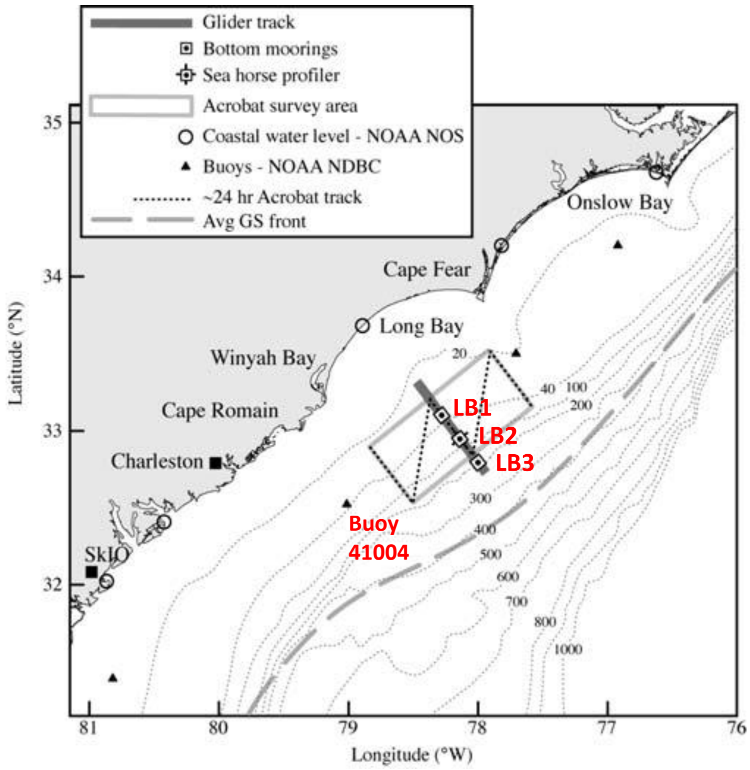

Figure 2: Experiment design, showing instruments deployed off Long Bay in the winter of 2012. The three moorings LB1, LB2, and LB3 were on the middle transect. The dashed line shows the average position of the Gulf Stream front (Miller, 1994).

At mooring LB1, a thermistor chain was also deployed, instrumented at 25 depths. Here, Chl-a, scatter, and CDOM were also measured at depths of 5m and 15m.

Figure 2 also shows the locations of the ship's three transects across the shelf. We shall refer to them as the south, middle, and north transects. The ship performed CTD casts at several stations along the transects. It also had a towed body (Acrobat), which sampled temperature, salinity, Chl-a, turbidity, dissolved oxygen, nitrate concentration, and PAR.

Two gliders were also deployed, ramses and pelagia. The gliders were equipped with a CTD and optical instruments to measure Chl-a, scatter, CDOM, and dissolved oxygen. The gliders accomplished three deployments during the field program, each lasting about one month.

Figure 2 also shows the location of NOAA meteorological buoy, station 41004, maintained by the National Data Buoy Center (NDBC). Data from this buoy were used in this study to estimate heat flux into the ocean as well as wind speed and direction.

3.2 Development of a proxy for nitrate

In this field program, the towed body (Acrobat) measured nitrate concentration, but the gliders did not. Therefore, we would like to develop a proxy for nitrate and apply it to the glider data. Our goal is to use this proxy and current observations to estimate nutrient transport from the slope to the shelf.

For the nutrient-bearing strata of the western edge of the Gulf Stream, previous studies (Atkinson et al., 1996) have shown a relationship between nitrate concentration and temperature. In another region, Palacios et al. (2003) developed a very good proxy for nitrate using not only temperature but also salinity and dissolved oxygen.

For our study, Table 1 below summarizes the availability of relevant observations from the towed body (Acrobat) as well as the two gliders.

	Towed body	Gliders
Temperature	x	x
Salinity	x	x
Dissolved oxygen	x	x
Nitrate	x	N/A

Table 1: Availability of predictor variables per platform

Since the towed body (Acrobat) measured nitrate, temperature, salinity, and dissolved oxygen, we can develop a proxy similar to the one used by Palacios et al. (2003). In other words, the Acrobat's temperature, salinity, and dissolved oxygen will be the predictor variables for our model. Whereas Palacios used a generalized additive model (GAM), we will first try a simpler approach, using multiple linear regression (MLR).

For the Acrobat data, we will quantify the performance of the MLR approach to see how well it estimates nitrate concentrations on the slope or near the shelf break. We note that the Acrobat's nitrate sensor, the Satlantic ISUS Nitrate sensor, has an accuracy of 2μM (Satlantic Inc., 2010).

For the glider data, we did not measure nitrate, but we did measure the other predictor variables: temperature, salinity, and dissolved oxygen. Therefore, our approach for glider data will be to estimate nitrate using the proxy we develop from the Acrobat data.

4. Observations

4.1 Influence of the Gulf Stream

A view of Gulf Stream related features is provided by the ADCP deployed on the LB2 mooring. The top two panels of Figure 3a show the 36-hr lowpass-filtered velocity at the shelf break from this instrument.

During the period of observation, filaments, jets, and meanders were observed crossing the middle transect on the mid- to outer-shelf. The first jet (J1) can be seen in satellite images (not shown) as early as January 25. It broke up on the shelf by February 1. A second jet (J2) can be seen around February 8 and didn't break up on the shelf until after February 25. Although the SST images are cloudy, the ADCP data suggest the presence of meanders in early to mid-March. Finally, the period from March 10 to late March is a confusing set of filaments, meanders, and sub-mesoscale features in the satellite imagery. A filament (F1) can be seen in the satellite image (not shown) for March 14.

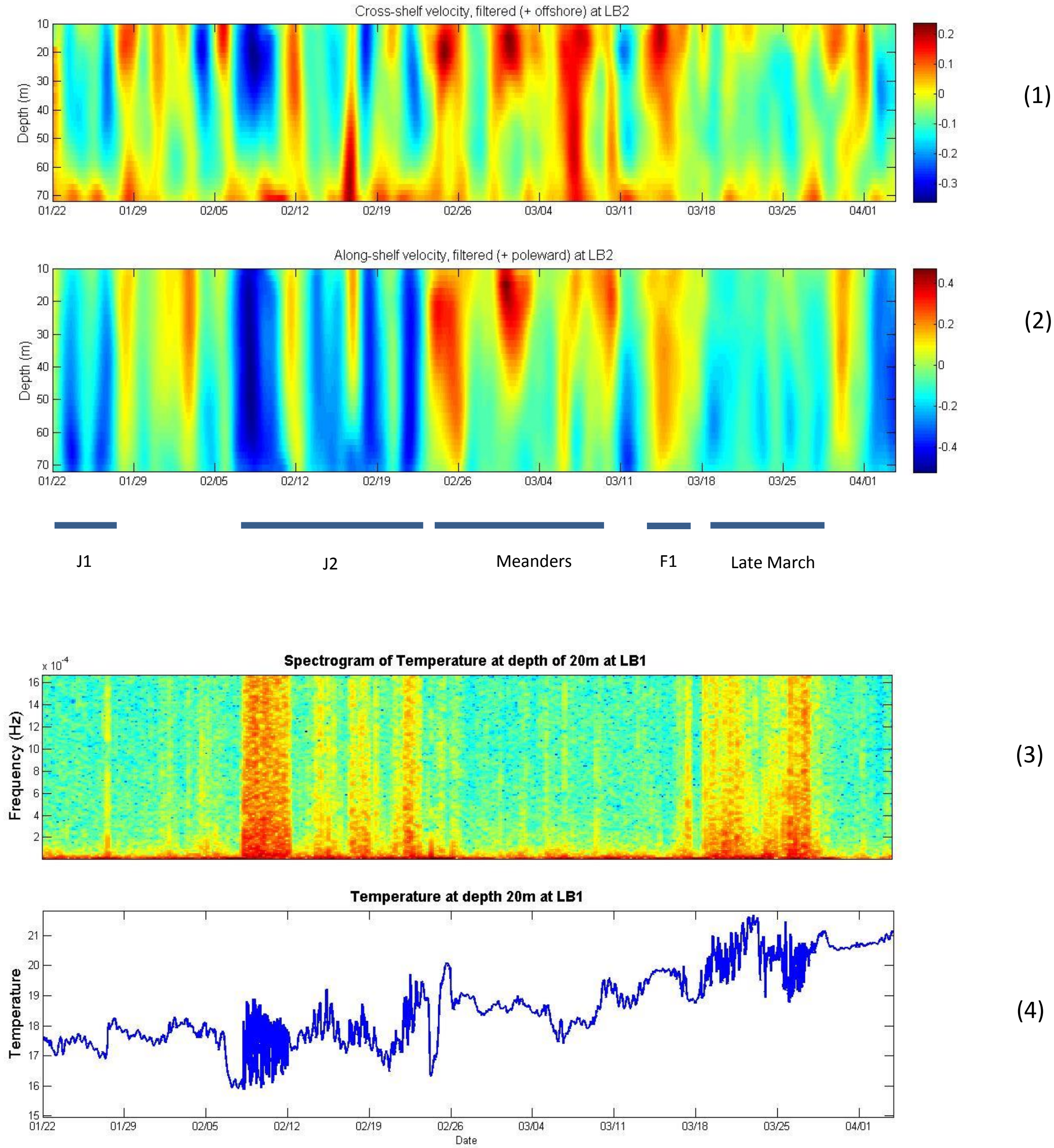

Figure 3a: A 36-hour lowpass-filtered velocity over mooring LB2 on the slope, rotated to be 1) across-shelf (positive seaward) and 2) along-shelf (positive poleward). The across-shelf direction is parallel to the transect lines. Several features are highlighted below the x-axis. Panel 3 shows a spectrogram of the time series in Panel 4, the temperature recorded at a depth of 20m on the shelf, over LB1.

For most of the period of observation, a time-averaged vertical profile of the detided cross-shelf velocity at LB2 shows a shoreward flow in a top layer and a seaward flow in a bottom layer. For example, Figure 3b shows a time averaged profile from 2/2/2012 to 2/22/2012 (during the J2 interval).

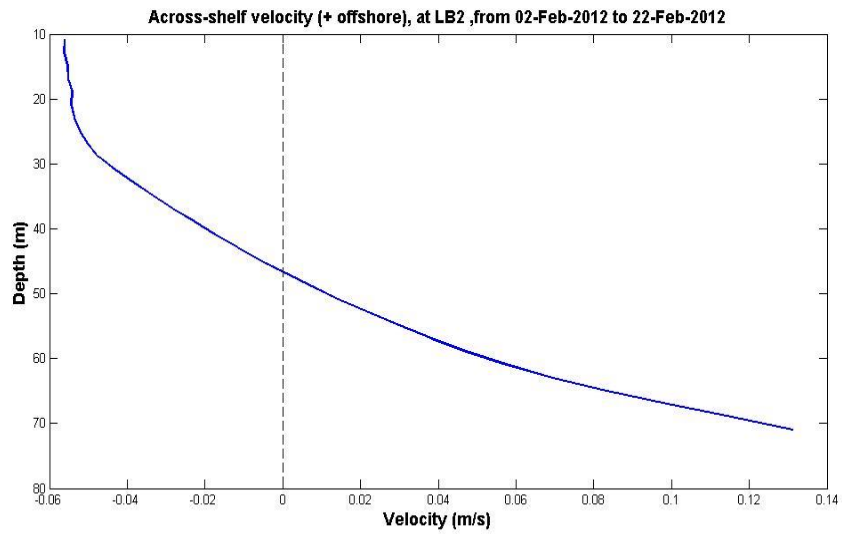

Figure 3b: Time-averaged vertical profile of cross-shelf velocity at LB2 (from 2/2/2012 to 2/22/2012).

4.2 Evidence of Internal Waves

Throughout the entire period of observation (late January 2012 to early April 2012), we see fluctuations in the vertical velocity up to +/-10cm/sec at the top of the bottom boundary layer (BBL) over LB2. An example is provided in Figure 3c.

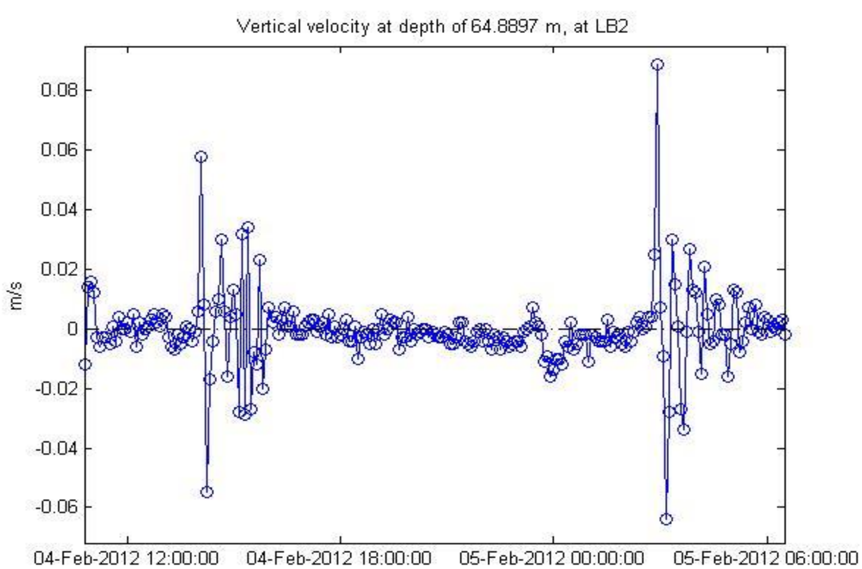

Figure 3c: Vertical velocity at 65m over LB2. Sample interval is 5 minutes.

Figure 3c zooms in on the vertical velocity at a depth of 65m at LB2 for a couple days in February. The wave packet starts positive, peaks at almost 9 cm/s, and the waves have a period of about 30 minutes. The packets occur at the slack before the semidiurnal flood tide.

During the time intervals marked J2 and “Late March” in Figure 3a, we also see high-frequency fluctuations in the temperature field near the pycnocline (19m deep) over LB1, as shown in Figure 3a (4th panel). These fluctuations could be due to internal waves that travel shoreward and break near LB1. The sampling interval for the thermistor chain is 5 minutes. The spectrogram in panel 3 of Figure 3a shows that there is a significant amount of energy at or near the Nyquist frequency (1 cycle per 600 seconds); therefore, we may be seeing aliasing of the signal.

Having one or more equatorward flowing jets or filaments, the time periods J2 and “Late March” are characterized by the “summer front” mass configuration. Therefore, it is possible that the “summer front” mass configuration allows the internal waves prevalent at LB2 to propagate shoreward to LB1. This would be consistent with the model results discussed above from Vlasenko (2012) and Chen et al. (2003).

4.3 Distribution of chlorophyll

We shall document the observed distribution of chlorophyll a fluorescence (Chl-a) in space and time on the shelf and slope during the winter 2012 field program. Chl-a was sampled by moorings, gliders, towed body (Acrobat), satellite, and the R/V Savannah.

At a large scale, the satellite images of surface Chl-a (e.g. for January 28, not shown) have bands along the shoreward edge of the jet J1, consistent with the observations of Ryan and Yoder (1996). We see less surface chlorophyll on the shoreward edge of the mid-February jet J2 and even less along the March filament F1 in satellite images.

Figure 4 provides a representative transect view of the Chl-a distribution in late March from one of the gliders. It shows chlorophyll throughout the water column in a well-mixed region on the shelf near LB1. (This could be the mid-shelf front, depicted in Figure 1.) Farther seaward, we see a layer of chlorophyll traveling along the bottom and exiting the shelf (also consistent with Figure 1).

Analysis of water samples reveal that the blooms observed off Long Bay in the winter of 2012 consisted of *Phaeocystis globosa*. This species thrives on nitrate, forming large colonies in temperate and tropical waters (Schoemann, 2005). Colonies as large as 3 cm in diameter have been observed (Schoemann, 2005). Off Long Bay in 2012, the largest colonies were several mm in diameter.

When the colonies are sampled with a fluorometer, a large “spike” is recorded. In Figure 4, we can see large spikes close to the bottom. With these spikes, the Chl-a data are not normally distributed; therefore, we plot the log of Chl-a in Figure 4. Another approach is to segment the data into “large” and “small” signals.

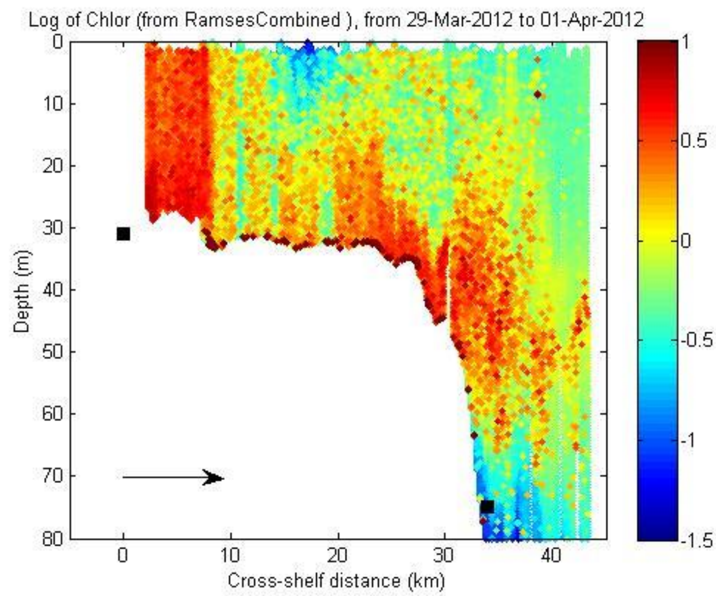

Figure 4: Transect of log of Chl-a, from the glider Ramses, from March 29 to April 1, 2012. The arrow indicates the direction of travel on the transect, and the black squares indicate mooring positions (LB1 on the shelf at 30m and LB2 on the slope at 75m).

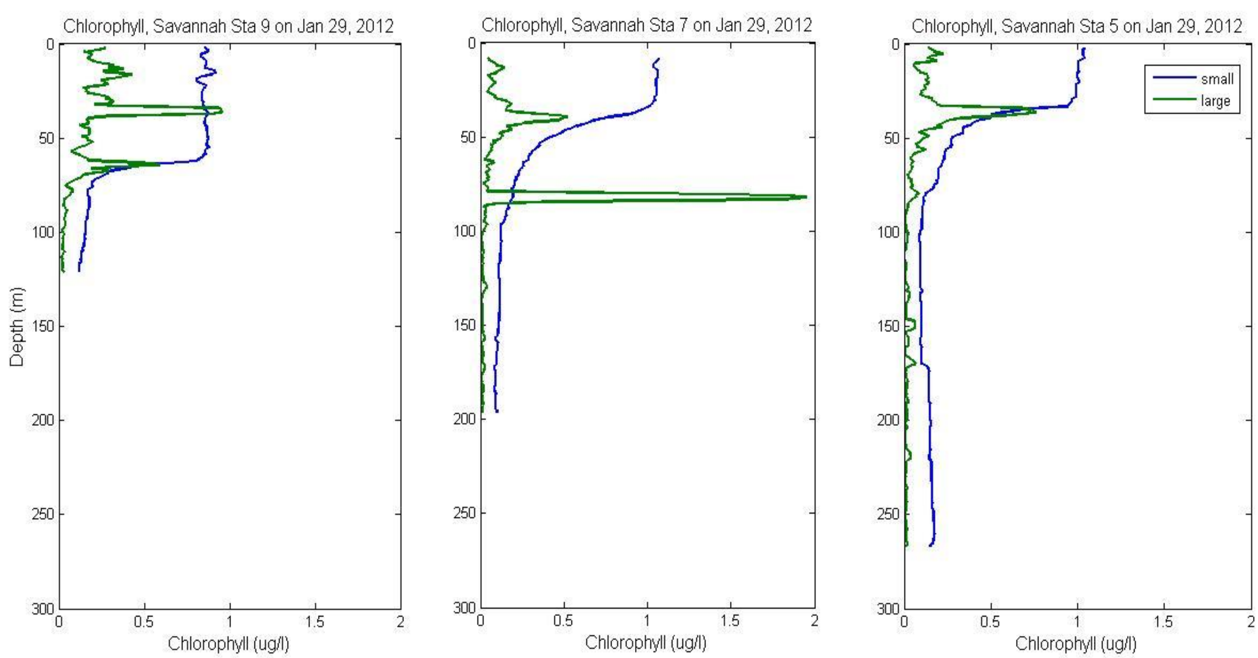

Figure 5: Profiles of Chl-a (small and large) from R/V Savannah. From left to right, the profiles are at Station 9 (40 km from LB1), Station 7 (50 km from LB1), and Station 5 (60 km from LB1).

Figure 5 shows the vertical profiles of the two segments (large and small) for three different casts of the R/V Savannah on January 29. In this figure, we see that the "small" Chl-a is evenly distributed in the mixed layer. In each profile, there is a layer of the "large" Chl-a (representing the clusters) at the pycnocline. (Density profile is not shown.) Interestingly, there are other layers of the "large" Chl-a—at half the depth of the mixed layer at Station 9 and at twice the depth of the mixed layer at Station 7.

Figure 6 shows the time series of Chl-a measured at three depths (5m, 15m, 30m) over mooring LB1. It shows many large spikes (presumably representing colonies) near the bottom at LB1. We have a similar time series at the bottom at LB2 (75m) and LB2 (170m); however, at LB2 the sensor failed in the middle of February. We will be examining many additional transects and profiles to arrive at a more complete picture of the distribution of chlorophyll in space and time.

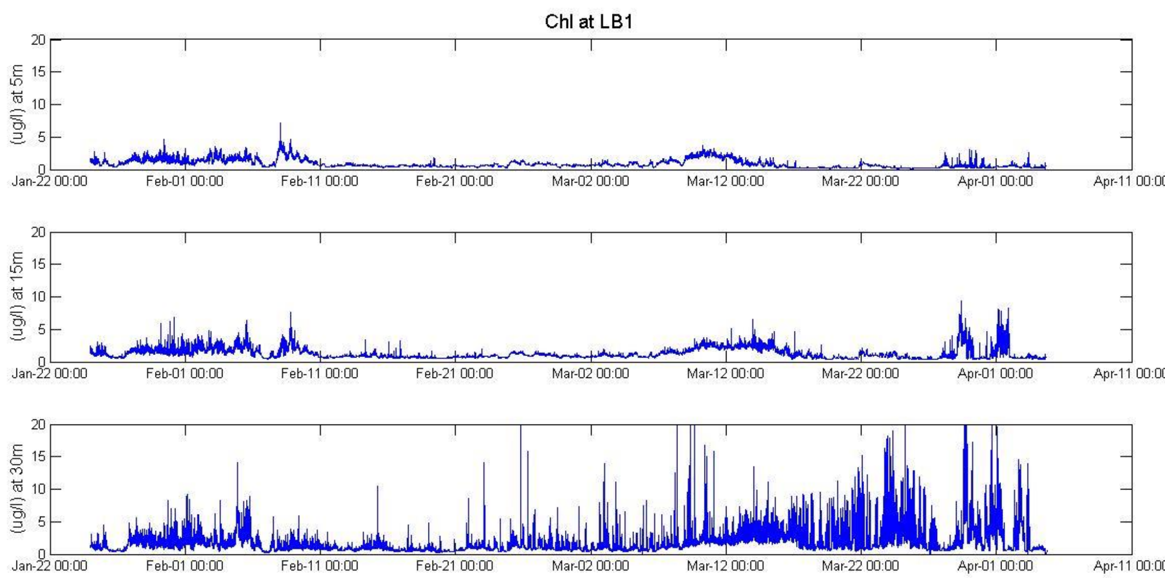

Figure 6: Chl-a at three depths (5m, 15m, 30m) over mooring LB1.

4.4 Nutrient transport

4.4.1 Up-slope transport of nutrients at the shelf break

In several transects, up-slope transport of nitrate was detected at the shelf break. In this section, we focus on Acrobat data. Traveling at about 10 km/hr, the Acrobat takes 2 minutes per yo on the shelf (approximately 0.3 km per yo) and about 3 minutes per yo on the slope (approximately 0.57 km per yo).

Table 2 summarizes each Acrobat transect, indicating whether we saw any up-slope transport of nitrate.

Date(s)	Transect	Description
Jan 28	**Mid**	**~Up-slope transport**
Jan 29	South	~Up-slope transport
Jan 30	North	~Up-slope transport
Feb 17	South	Perturbation further seaward (50-60km from LB1), possibly in the "gyre"
Feb 18	Mid	Perturbation further seaward (45-60km from LB1) , possibly in the "gyre"

Mar 14	North, Mid	Perturbation slightly further seaward (40km from LB1)
Mar 18	**South**	**Up-slope transport**

Table 2: Description of the nutricline per transect. Items in bold will be detailed further.

We will zoom in on several of these events (the items in bold in the table above) using all of the available data, including transects of temperature, salinity, density, nitrate (or estimated nitrate from our proxy), dissolved oxygen, and velocity as well as satellite imagery. For each of these events, we will also look at atmospheric forcing and Gulf Stream influence during the event in an effort to understand the physical mechanism(s) driving the event.

4.4.1.1 Up-slope transport of nutrients at the shelf break on March 18 (South transect)

For example, late in the day on March 18, 2012, while heading seaward along the South transect, the R/V Savannah captured evidence of upwelling of nutrients at the shelf break. Figure 7 shows transects of dissolved oxygen, nitrate concentration, and Chl-a for this event, sampled by the towed body (Acrobat). From shipboard ADCP data, Figure 8 shows not only up-slope shoreward transport but also a strong bottom flow seaward during this event.

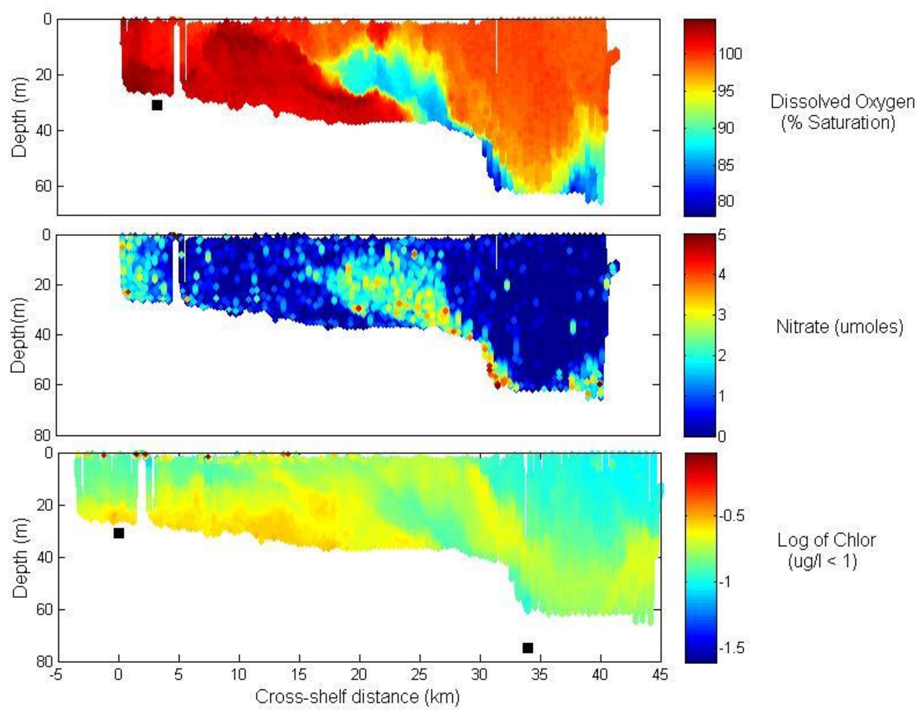

Figure 7: Transects of a) dissolved oxygen, b) nitrate concentration, and c) log of Chl-a on the outer-shelf and slope on March 18, using the towed body (Acrobat) along the South transect. The x-axis is cross-shelf distance from the LB1 mooring. In this plot, Chl-a values above 1 μg/l (at the surface) are capped so that we can highlight the subsurface structure.

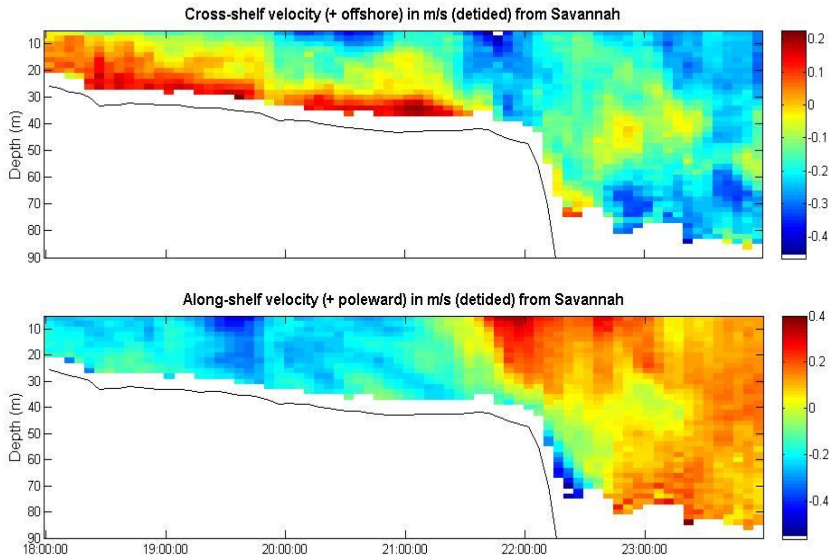

Figure 8: Contour plots of a) cross-shelf velocity and b) along-shelf velocity as a function of depth and time, using the shipboard ADCP from March 18, along the South transect.

Forming the product (not shown) of nitrate concentration and cross-shelf velocity, it is clear that nutrient-rich water is indeed moving up the slope and shoreward.

Around this time, the along-shelf wind at buoy 41004 (not shown) is transitioning from “upwelling-favorable” to “downwelling-favorable”, but this transition does not happen until March 19. (A “downwelling-favorable” wind would generate a cross-shelf surface Ekman flow shoreward.) Therefore, it seems that this instance of upwelling at the shelf break is not related to wind forcing.

The satellite imagery (not shown) is cloudy, but there appears to be a filament on the slope across the mid- and Southern transects at this time.

4.4 Availability of Light

We will analyze the transects of PAR, from the towed body (Acrobat) data. We would like to know the depth of the euphotic zone and how this changes in space and time.

4.5 Resuspension of sediment

In this study, we will use scatter/turbidity as indicators of resuspension of sediment. When scatter/turbidity is high but Chl-a is low, this may indicate resuspended sediment (or dead colonies). We will look at transects of these measurements. We will then try to correlate resuspension events with a) filaments/jets passing nearby (in space and time), or b) storms, or c) strong velocity near the bottom, or d) the presence of internal waves.

5. Synthesis and conclusions

5.1 Distribution of chlorophyll

We will try to relate the observed distributions of chlorophyll to the other observations (e.g. scatter, stratification, velocity, availability of light and nutrients, presence of Gulf Stream filaments/jets/meanders, air-sea interactions).

Examples of questions we hope to address include the following:

a) What is the distribution of chlorophyll in space and time during the period of observation?
b) How are the observed chlorophyll concentrations correlated (in space and time) to oceanographic variables and features?
c) What is the rate of export of chlorophyll from the shelf to the slope?

5.2 Distribution of nitrate

We shall return to the question that initially motivated the Long Bay 2012 field program--what physical processes contribute to the high wintertime productivity there.

In this proposal, I zoomed in on one event of up-slope transport of nitrates, measured by the Acrobat. After developing a proxy for nitrate for the gliders, I will try to relate the observed distribution of nitrate on the slope and shelf to all of the other observations. In general, I will ask: what observations are correlated to nitrate?

Examples of specific questions we hope to address include the following:

a) The Gulf Stream with its meanders, filaments, and jets can bring nutrients into the photic zone via several mechanisms (e.g. upwelling due to the cyclonic circulation between the Gulf Stream and one of its filaments). To what extent is nitrate on the shelf/slope correlated to the presence of each of these Gulf Stream features?
b) Does a wind-driven Ekman flow increase the concentration of nitrate in a surface layer on the shelf? Remember that Atkinson et al. (1996) found a “weak relation”. We will look for correlations between the wind-driven Ekman flow and nitrate concentration a) with and b) without the presence of a Gulf Stream filament or jet on the outer shelf.
c) The propagation of internal waves from the slope to the shelf may be facilitated by the presence of jets/filaments. How much do internal waves contribute to the region’s high wintertime productivity? Can we estimate a shoreward transport of nitrate due to the observed internal waves? The internal waves shown in Figure 3c are not strongly non-linear waves like those discussed by Shroyer et al. (2010); therefore, their associated transport may not be as great. Still, as they propagate into more shallow water, they may become non-linear. If internal waves are indeed propagating from LB2 to LB1, we should be able to detect their impact upon glider trajectories, an approach used by Todd (in press).

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