

# Observations and processes of persistent near-bottom offshore flow at the shelfbreak off South Carolina, USA

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## Abstract

A 3-month field campaign during winter 2012 observed persistent near-bottom offshore flow in current profiles collected with a mooring near the shelfbreak. The study site lies just inshore of the deflection site of the Gulf Stream, known as the Charleston Bump, and is strongly influenced by the current system. Mechanisms that may contribute to the cross-shelf export at this location include wind-forcing, an Ekman drain associated with alongshore flow, and cascading. Downwelling-favorable winds are poorly correlated with transport at the shelfbreak. Strong (up to 0.8 m/s) equatorward currents over the upper slope near the 200 m isobaths, not related to wind forcing, strongly influence export and likely explain the bulk of it. Cascading at this location is promoted by the strong thermal gradients set up by wintertime cooling over the shelf and poleward advection over the upper slope of warm waters in the Gulf Stream. It appears that the density-driven export is greatest during spring tides, consistent with friction breaking a geostrophic balance of the shelf mass field.

## 1 Introduction

We examine possible explanations for persistent near-bottom offshore flow during winter at a shelfbreak location adjacent to the Gulf Stream. The mean cross-shelf profile of horizontal currents exhibits strong offshore flow in the lower 20 m (Figure 1). We consider three mechanisms that may promote near-bottom offshore flow: downwelling-favorable wind forcing; an Ekman drain associated with equatorward flow; and cascading due to dense water formation on the shelf.

A 3 month long field program was conducted in winter 2012 to study persistent phytoplankton blooms in Long Bay, off the coast of South Carolina, USA. This shelf area lies inshore of the Charleston Bump, a region where the Gulf Stream deflects offshore where bottom topography on the upper slope shoals (Figure 2). The Gulf Stream exhibits a bimodal response at the Bump, being either weakly or strongly deflected (Bane and Dewar, 1988). In the strongly deflected state, a cyclonic circulation feature has been observed on the upper slope inshore of the Stream, which may impact the adjoining shelf (Bane et al., 2001). Previous studies have noted dense water formation on the shelf during winter and the

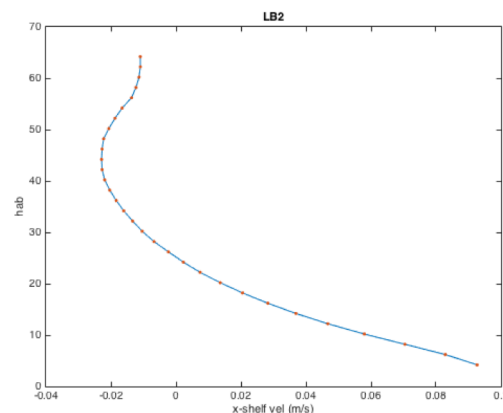


Figure 1 - profile of mean cross-shelf currents at the shelfbreak; positive is off-shelf.

potential for the southeast shelf region to promote shelf-slope exchange (Atkinson et al., 1989). However, these previous studies were upstream of the Gulf Stream deflection and more directly influenced by the Gulf Stream.

## 2 Methods

The field program utilized a cross-shelf line of moored ADCP profiles, a mid-shelf thermistor chain, and glider data, from along the mooring line and from over the upper slope ADCP, to observe conditions over the 3 month period (Figure 2). Wind observations are taken from NDBC buoys on the shelf. The moorings were located at mid-shelf (30 m depth, designated LB1), near the shelfbreak (75 m depth, designated LB2), and on the upper slope (185 m depth, designated LB3).

The processed observations are of good quality but required some corrections. The thermistor chain at LB1 was blown over by strong currents at times and corrected heights were formed assuming a linearly varying tilt with height. Glider CTDs were unpumped and calculated salinities were prone to spiking; the thermal mass correction of Garau et al. (2011) was used to adjust the salinities and improved data quality except at bottom turning points for one of the gliders. Remaining bad data were removed.

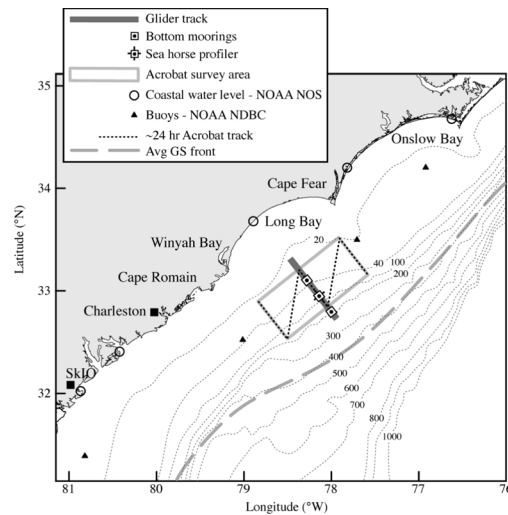


Figure 2 - map of study area and field components. Bottom moorings are LB1 inshore and LB3 offshore.

## 3 Results

We consider the three possible forcings below.

Alongshelf winds are expected to drive cross-shelf Ekman transport, resulting in setup/setdown of water levels and an alongshelf geostrophic current response. There is an obvious relationship between alongshelf wind stress and alongshelf depth-averaged current at midshelf (LB1; see Figure 3). A maximum linear correlation coefficient of around 0.65 was found for a 5 hour lag. At LB2 the correlation coefficient drops to 0.3 and the lag increases to 10 hours, but there is still some evident relationship.

Any connection between cross-shelf transport at LB1 and alongshelf winds (surface Ekman layer) is less obvious. Scaling the wind stress by  $(1/\rho^*f)$ , where  $\rho$  is water density and  $f$  is the Coriolis parameter, and comparing to the transport over 10-26 mab depth (based on the depth of zero-crossings when the fluid is stratified) shows that seldom does the transport reach the theoretical values. Maximum correlation is about 0.5 at zero lag. A comparison of cross-shelf transport at LB2 with the alongshelf wind stress reveals no apparent relationship; no peak in the correlation is apparent. It is likely that the shallowness of the shelf strongly influences the nature of the cross-shelf response to the wind. At LB1, in 30 m depth, surface stress can be expected to

extend to the seafloor when the mass field is well mixed. In this case, cross-shelf transport is less than predicted, as some fraction of the stress input at the surface is lost to the seafloor. In deeper water, the water depth exceeds the Ekman layer depth, the cross-shelf transport will be larger, producing cross-shelf divergence and upwelling/downwelling cells over fractions of the shelf.

The shelfbreak mooring at LB3 revealed the presence of a strong equatorward alongshelf jet, with maximum velocities exceeding 0.8 m/s. Shipboard surveys indicate that the core of the jet nearly coincided with the mooring position near the 185m isobath, so the data from LB3 provides a consistent record of an energetic upper slope process that impacts the shelfbreak. The combination of mooring data, spatial surveys, and SST imagery indicates that the jet was roughly 30 km in width, had depth-averaged speeds in excess of 0.5 m/s, and persisted for at least a week in January and most of February 2012. Importantly, the equatorward flow typically extended to the bottom, though speeds were less than at the surface owing to baroclinic shear. The jet should act to promote offshore flow through a bottom Ekman layer, sometimes referred to as an ‘Ekman drain’ (Simpson and McCandliss, 2013).

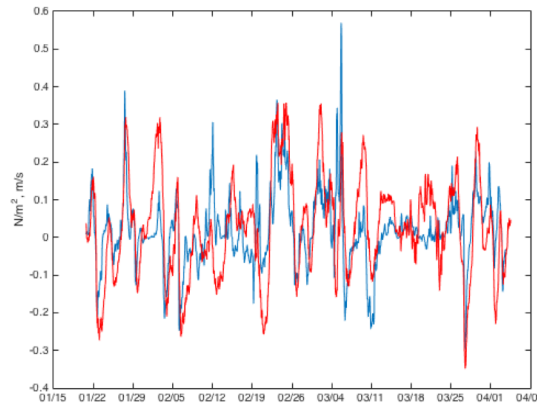


Figure 3 - wind stress (blue) and depth-averaged alongshelf current (red) at LB1.

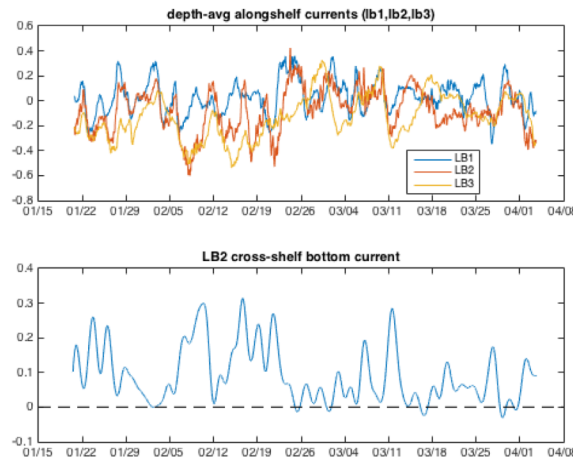


Figure 4 - (top) depth-averaged alongshelf currents at each mooring. (bottom) Low-passed near-bottom cross-shelf flow at LB2.

Alongshelf flow at LB2 is at times clearly correlated with alongshelf flow at LB3 (Figure 4). Bottom Ekman layer dynamics appear to hold at LB2 as there is a strong relationship between the along- and across-shelf flow 4 mab (Figure 4, lower panel). It is worth noting that the (Butterworth 4<sup>th</sup> order 36-hour lowpassed) across-shelf flow is essentially always offshore (positive); during the brief intervals of onshore flows the speed never exceeds 0.03 m/s. Interestingly, a linear fit to the relationship between the two velocity components suggests offshore flow of about 0.04 m/s when the alongshelf flow goes to zero. So while the strongest offshore flow events occur when the jet is strongest, the lack of onshore flow is not explained by the jet, which is at times absent.

A cross-shelf density gradient was observed by the glider transects. Comparing density-averaged over the upper 30 m measured at LB1 with a thermistor chain (converted to density using a temperature-salinity relation) with glider observations of density near the LB2 mooring reveals that the mid-shelf density was always greater than at the shelfbreak (Figure 5, top panel). Density at midshelf is slowly decreasing over the field program, whereas density at the shelfbreak is more consistent, producing a decreasing gradient over time. With the 34 km separation between locations, the gradient varies from  $4.5 \times 10^{-2}$  to  $7.5 \times 10^{-3} \text{ kg m}^{-3}/\text{km}$ .

After subtracting off the component associated with the Ekman drain described above, the residual cross-shelf currents at 4 mab at the shelfbreak exhibit a pattern of off-shelf and on-shelf flow (Figure 5, middle panel). Also plotted is the water level record from mid-shelf, which serves as a proxy for bottom mixing (Figure 5, lower panel). It appears that periods of on-shelf flow tend to occur at neap tides, and that periods of off-shelf flow occur during spring tides.

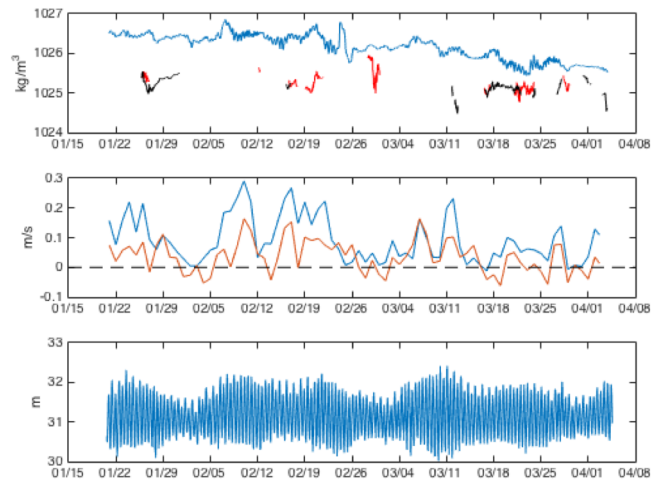


Figure 5 - (top) density over upper 30 m at LB1 (blue) and LB2 (red and black, from 2 gliders). (middle) cross-shelf flow at 4 mab before (blue) and after (orange) removing the Ekman drain component. (bottom) water level at LB1.

#### 4 Discussion

The results above are a cursory examination of possible causes of the persistent near-bottom off-shelf flow observed at the shelfbreak in Long Bay, SC. This discussion will briefly examine the findings and largely consider next steps in further analysis to better understand how each contributes to the flow regime.

The breakdown in correlation of the wind field and cross-shelf transport at the shelfbreak is somewhat surprising. It is likely that wintertime conditions favor weak stratification, such that the Ekman layer depth  $d = (2A_z/f)^{1/2}$  is largely set by the eddy viscosity. Blanton et al. (2002) estimate that the tidally-driven vertical eddy viscosity is  $O(10^{-2}) \text{ m}^2/\text{s}$ , such that the minimum value of  $d$  is about 20 m. Any additional source of turbulent mixing (e.g., wind stress) is likely to increase  $d$ , and should it reach 30 m, suggests that over the inner half of the shelf, bottom stress will reduce Ekman transport. Thus surface divergence is expected over the shelf. How the area of the shelfbreak responds is clearly complex given that no significant linear correlation between the wind and cross-shelf transport was observed in the data. A more careful calculation of the surface transport depth, taking into account the varying stratification, may provide greater insight into locally wind-driven transport processes.

The upper slope jet has a clear influence on shelf export. A description of the jet is the subject of another publication, but the jet was the dominant feature of circulation on the shelfbreak, with significant potential impact to cross-shelf exchange and transport of organic matter. Strong

equatorward flow occurred for more than a week in mid-January and most of the month of February 2012, and explains the strongest off-shelf flows. Future work will characterize the thickness of the bottom boundary layer and the magnitude of the transport. A rough estimate, summing all off-shelf flow, finds the transport to average  $1.7 \text{ m}^2/\text{s}$ , which, in the context of other studies, is quite large (Huthnance, 1995).

There appears to be a background level of bottom export that may result from the negative density gradient that develops on the shelf. In the absence of friction such a gradient would be expected to drive a geostrophic shelf current. Friction will allow ageostrophic, cross-isobath flow, at which point the details of the bottom topography may be important in steering the flow. A more careful examination of the magnitude of turbulent mixing will be instructive, but the suggested visual correlation of greater tidal range with stronger off-shelf flow is consistent with the notion that (with sufficient friction) the density gradient supports a density current.

## 5 Summary

A field study in Long Bay, South Carolina, finds persistent off-shelf flow at the shelfbreak in the lower 20 m of the water column. Wind forcing does not appear to be a major factor in driving the flow. A strong equatorward jet over the upper slope does appear to drive much of the export as a bottom Ekman layer, acting as an Ekman drain. A persistent cross-shelf density gradient that favors off-shelf bottom flow may explain the remainder of the flow. The bottom flow not explained by the Ekman drain may be greatest during spring tides, consistent with friction breaking a geostrophic balance of the shelf mass field and permitting cross-isobath flow.

## 6 Acknowledgements

We thank the crew of the R/V Savannah for their able help during the field program; Trent Moore, Julie Amft, Chris Calloway and Sara Haines for the assistance in preparing equipment for deployment and processing afterwards; and William Stark for implementing the thermal mass corrections to the glider data. The work was funded by National Science Foundation grants OCE-1032285 (SkIO) and OCE-1032276 (UNC-CH).

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