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Seasonal differences in wind-driven across-shelf forcing and response relationships in the shelf surface layer of the central Mid-Atlantic Bight

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[1] Observations of surface currents, wind stress, and adjusted sea level from August 2002 to January 2004 were used to study across-shelf forcing and response relationships in the central Mid-Atlantic Bight (MAB). A commonly observed shelf wide offshore flow pattern was associated with distinctly different wind stress magnitudes and directions during mixed and stratified seasons. During the stratified period, the offshore current flow pattern was associated with relatively weak winds out of the Southwest (upwelling favorable), while the mixed period events were associated with relatively strong across-shelf winds from the Northwest. To quantify these observations, time series of the spatial mean surface current, wind stress, and coastal sea level were analyzed using several types of correlation analyses. Seasonal vector correlations between the surface current and wind stress revealed very high correlations but distinctly different phase angles and transfer coefficients. The stratified (mixed) period current veered to the right of the wind by 30–40° (6–8°) and had a higher (lower) transfer coefficient. Scalar correlations between across-shelf wind stress and across-shelf current showed higher *r* values than with the along-shelf wind stress during the mixed period. While this pattern did not hold between wind stress and sea level, the correlations did show a stronger (weaker) relationship with across-shelf (along-shelf) wind stress than what was observed in the stratified season. However, conditional sampling of shelf wide events during the weaker stratified periods did show stronger relationships between both across-shelf wind/across-shelf current and across-shelf wind/sea level than with the along-shelf wind stress.

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1. Introduction

[2] While there is a sophisticated understanding of several aspects of shelf processes, many questions still remain related to across-shelf transport. As *Lentz* [2001] states, wind-driven across-shelf circulation and its dependence on stratification, bathymetry, and forcing are poorly understood, partly due to a lack of observations. Typically, across-shelf currents have weaker magnitudes and smaller spatial scales than along-shelf flows [*Lentz*, 1994]. However, the tendency for across-shelf gradients of mass properties (temperature and salinity), nutrients, sediments, pollutants, and other constituent components to be stronger than along-shelf gradients can lead to significant exchanges of these properties and material via across-shelf flows [*Lentz*, 1995a; *Austin and Lentz*, 2002]. The most basic explanation typically assumes along-shelf invariance and appeals to Ekman dynamics, in which along-shelf wind drives across-shelf advection of surface waters. As surface waters are advected offshore, bottom water moves onshore and up-wells to replace the surface waters. This explanation works very well in many cases as previous studies have shown [*Winant et al.*, 1987; *Lentz*, 1992; *Wang*, 1997]. In response to changes in the mean across-shelf flow in the surface layer, coastal sea level will fluctuate resulting in coastal setup or set down, depending whether the wind is upwelling favorable or downwelling favorable. Thus changes in coastal sea level are linked to along-shelf wind stress, which can be seen from several previous studies on the response of adjusted sea level to wind-forcing in the MAB [*Noble and Butman*, 1979; *Wang*, 1979].

[3] This simple description of wind driven circulation neglects many important processes that contribution and complicate across-shelf transport. As discussed by *Yankovsky* [2003], the across-shelf flow structure can be affected by many factors, such as along-shelf invariance, lack of steady state, presence of buoyancy forcing/

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stratification, and/or strong bottom friction. In particular, much work has been done on the influence of stratification on wind driven across-shelf circulation. Work by *Mitchum and Clarke* [1986], *Lentz* [1995b], and *Tilburg* [2003] have discussed a view of shelf dynamics in which the surface and bottom boundary layers thicken and potential overlap as the coast is approached. However, this notion of merging surface and bottom boundary layers can be arrested in the presence of stratification. *Weisberg et al.* [2001] found that under stratified conditions, the inner shelf supports well separated surface and bottom Ekman layers which are linked through across-shelf divergence. *Garvine* [2004] also found that strong stratification, resulting from buoyant coastal discharges, allows boundary layer separation in water as shallow as 12 m.

[4] Not unrelated, numerous studies [*Allen et al.*, 1995; *Allen and Newberger*, 1996; *Lentz*, 2001; *Weisberg et al.*, 2001; *Austin and Lentz*, 2002; *Tilburg*, 2003; *Kirincich et al.*, 2005, etc.] have noted the influence of stratification on across-shelf transport. While some of the details and conclusions of these studies vary, which is not surprising given the individualized features and processes impacting inner shelf regions [*Weisberg et al.*, 2001], the general link between stratification and across-shelf transport is consistent with reductions in transport being associated with decreases in stratification. Basically, stratification reduces the nearshore turbulence field which retards the growth of the boundary layers as the coast is approached [*Weisberg et al.*, 2001; *Garvine*, 2004]. As pointed out by *Weisberg et al.* [2001] and *Kirincich et al.* [2005], this suppression of the boundary layers allows for increased veering of the velocity vectors which increases across-shelf transport. These results are consistent with the earlier findings of *Li and Weisberg* [1999a, 1999b], who noted that changes in the eddy viscosity and implied turbulence level (via changes in wind stress) in a barotropic model of the West Florida Shelf directly affected interaction between the surface and bottom Ekman boundary layers. The interconnected nature of the inner shelf presents a situation such that the impediment or facilitation of surface pressure gradient setup by surface Ekman layer divergence, the geostrophic interior flow adjustment to the pressure gradient and/or the bottom Ekman layer reaction to the interior flow can alter the system response to wind-forcing [*Weisberg et al.*, 2001] and consequently transport. As a result, stratification also generates asymmetric responses in the flow field [*Weisberg et al.*, 2001]. The details of asymmetric responses have been reported and studied in a number of works [*Weatherly and Martin*, 1978; *Lentz and Trowbridge*, 1991; *Trowbridge and Lentz*, 1991; *MacCready and Rhines*, 1991; *Garrett et al.*, 1993; *Weisberg et al.*, 2001; *Garvine*, 2004; *Liu and Weisberg*, 2005a, 2005b, 2007, etc.].

[5] As many as previous studies have noted, along-shelf wind is not the only mechanism that can drive across-shelf circulation. The ability of across-shelf wind to drive across-shelf flow in shallow water was shown by Ekman as early as 1905. More recently, modeling studies by *Li and Weisberg* [1999a, 1999b] showed that across-shelf wind stress can be an important factor in driving across-shelf circulation on the West Florida shelf using a barotropic three-dimensional numerical model. Similarly, *in situ* observations on the West Florida shelf by *Liu and Weisberg* [2005a, 2007] have also found that although the across-shelf momentum balance on the inner shelf is primarily geostrophic, across-shelf wind stress plays a secondary role. *Yankovsky and Garvine* [1998] concluded that transient wind-driven events, not associated with upwelling favorable winds, are at least partial responsibly for enhancing across-shelf transport of buoyant waters. Bathymetric features have been shown to contribute to the formation of upwelling centers along the NJ coast [*Song et al.*, 2001]. *Pringle and Riser* [2003] have shown evidence of remotely forced coastal trapped waves causing across-shelf transport on the west coast of the US. However, most of these studies were largely focused on the nearshore region of the coastal zone. *Tilburg* [2003] used a numerical model to show that across-shelf winds can account for significant amounts of on and offshore transport in the surface layer within a stratified outer shelf, away from the frictionally dominated inner shelf. In addition, coastal sea level fluctuations, estimated using time series of the across-shelf flow structures, hydrographic transects, and across-shelf wind stress, have been related to other factors including the offshore sea surface height and the dynamical responses of the inner shelf circulation to meteorological forcing [*Liu and Weisberg*, 2007]. As these studies show, along-shelf wind stress may not always be the dominating force that drives across-shelf transport and the resulting coastal sea level, and that other means of driving across-shelf surface flow may play a role advecting material across the shelf.

[6] This paper will examine the wind driven forcing that affects across-shelf surface flows in the central MAB, with a particular emphasis on across-shelf wind. In addition, a previous study on the midshelf off the coast of NJ identified two dominate across-shelf surface flow patterns, shelf wide and point flows [*Dzwonkowski*, 2009]. While this previous study characterizes the temporal and spatial variability of these across-shelf flow events, this study investigates their forcing and response relationships with wind stress and adjusted sea level. The focus of this study is to examine the extent to which wind-forcing is responsible for the observed surface flows and to determine their impact on coastal sea level. In addition, this study attempts to provide observational evidence for *Tilburg*'s [2003] recent model results suggesting that across-shelf wind can drive offshore transport in the surface layer on a stratified outer shelf. The remainder of this manuscript is presented as follows. The data used in this investigation are described in section 2. Section 3 presents the spatial and temporal characteristics of the dominant offshore flow events. The effects of wind-forcing over the study region and the response of sea level are contained in section 4. While a discussion and summary of the results are presented in sections 5 and 6.

2. Data

2.1. High Frequency Radar Data

[7] This study uses HF-radar based surface velocity data derived from four long range mode radar sites in New Jersey (Figure 1). The radars, operating at a frequency of 4.55 MHz, provide continuous radial vectors at an effective depth of 2.4m [*Stewart and Joy*, 1974]. The radial vectors collected by the HF radar array are averaged and geometrically combined into a grid of uv velocity vectors every

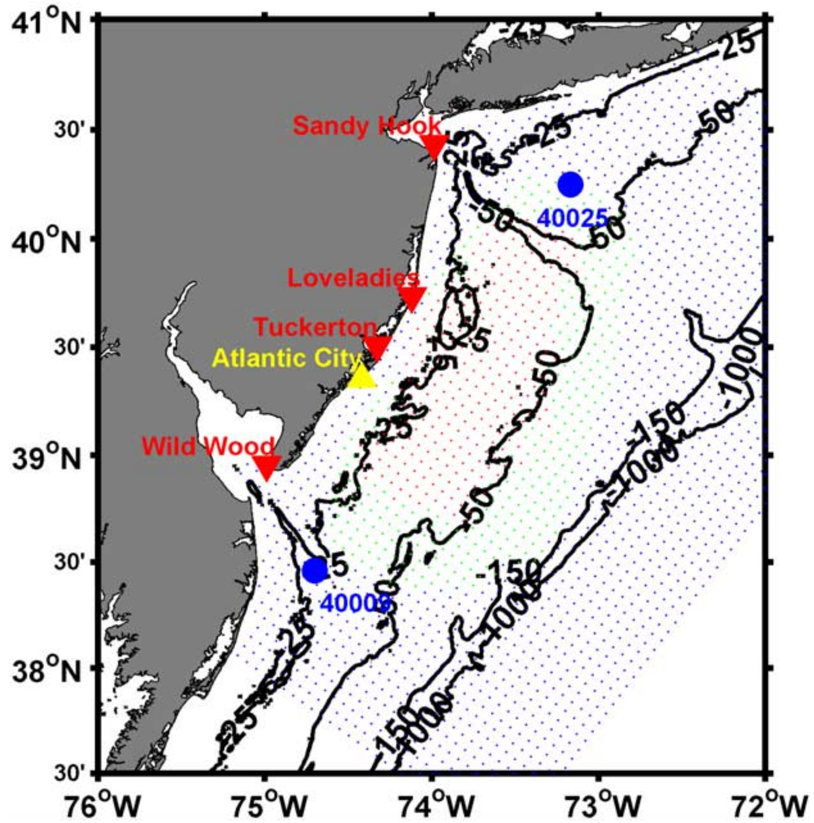

Figure 1. Map of the study site showing bathymetry (black lines), HF radar locations (red triangles), HF radar grid (colored dots), coastal tide gauge at Atlantic City, and NOAA buoys (blue circles). The coloration of the dot indicate the grouping bin of the temporal percentage coverage of the data (magenta 94–100%, red 86–93%, green 80–86%, and blue <80%). The temporal percentage coverage is the percentage of good data at a given grid point over the course of the study.

three hours following *Kohut et al.* [2006]. The collection grid (colored dots in Figure 1) covers an area approximately 240km by 115km, with the distance between grid points on the order of 6km. An 18 month period (15 August 2002 to 6 February 2004) was used in this study, as this time period was subjectively determined to have the maximum spatial coverage with minimal temporal gaps. Only grid points with 80% coverage or greater (temporal percent coverage) were used in the study. The spatial distribution of temporal percent coverage is shown in Figure 1 with dot coloration representing a percent bin (magenta 93–100%, red 86–93%, green 80–86%, and blue <80%).

[8] As this study is focused on low frequency events, the temporal gaps in the velocity time series at the individual grid points were linearly interpolated through as the majority of gaps were less than 12 hours. The resulting time series were low-pass filtered with a 40 hour Lanczos filter to remove any tidal effects and other high frequency components from the velocity data. Furthermore, the velocity vectors were rotated into along and across-shelf components with an along-shore angle of 54° counterclockwise from east determined by the orientation of the coastline [*Chant et al.*, 2004]. This analysis focuses on the spatial times series generated by computing a mean vector over the CODAR footprint at each time step.

2.2. Wind Data

[9] Wind data from a number of regional sources were collected over the same time period as the current data. The primary wind data used in this study were collected from NOAA buoy #44025 (Long Island (LI)) and NOAA buoy #44009 (Delaware Bay (DB)), at the northern and southern regions of the HF radar footprint. In general, the data were continuous over the 18 month period; however, the LI wind had a considerable gap during May/June of 2003. As several analysis methods used required a gap free data set, the gaps in these records were filled using linear interpolation when gap lengths were less then 12 hours. For the large gap in May/June in LI wind, data from NOAA buoy #40017 (Montauk Point) was used. The replacement data were lagged at the highest correlation value (correlation determine over 9 months of data) and its amplitudes adjusted by an appropriate coefficient determined from linear regression. The lag time was only a few hours and exhibited very high correlations ($r > .9$). The wind data used in this study can be found at the (http://www.ndbc.noaa.gov/).

[10] As the NOAA buoys border the north and south boundaries of the study region, a mean wind velocity time series for the study was created by vector averaging the LI and DE buoy wind data. In general, the wind data at the two sites were very similar, particularly after applying the 40 hour low-pass filter, therefore the mean wind data has

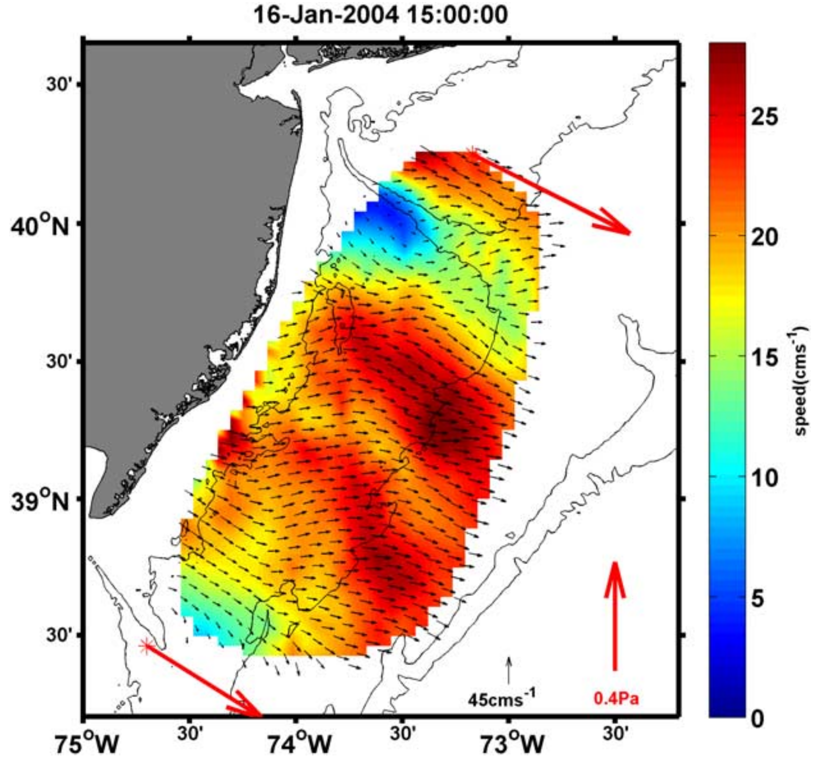

Figure 2a. Snapshots of the two most prominent episodic across-shelf flow patterns that were most commonly seen during the course of the study. The black arrows are HF surface velocity measurements (cm/s), the red arrows are wind stress at the NOAA buoys (Pa), and the coloration under the current vector is the magnitude of the current (cm/s). The snapshot is from well-developed stage of the event a shelf wide flow.

only minor deviations from the original two time series. From this wind data, surface wind stress was estimated following *Large and Pond* [1981].

2.3. Sea Level Data

[11] Sea level data were collected from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) which provides hourly tidal gauge data at Atlantic City, NJ (http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Historic+Tide+Data). Prior to 40 hour low-pass filtering the tide gage data, the predicted tide at Atlantic City for the study period (also obtained from CO-OPS) was removed to eliminate any long term tidal effects. To remove changes in sea level resulting from atmospheric pressure, an inverse barometer correction (IBC) was calculated using atmospheric pressure from the NOAA environmental buoy #44009. The correction was calculated as follows, $IBC = -9.948 * (\textit{atmospheric pressure} - \textit{mean atmospheric pressure})$, which was obtained from the Physical Oceanography Distributed Active Archive Center (http://podaac.jpl.nasa.gov/tpssa/doc/ssa_manula.html#INV_BAR).

3. Offshore Flows

[12] As this study examines the forcing mechanisms associated with across-shelf flow, the results from a companion study [*Dzwonkowski.*, 2009], in which two predominate flow structures, shelf wide and "point" flows were identified (Figures 2a, 2b), has direct bearing on this work. Shelf wide flows were characterized as times in which the surface velocity vectors were generally directed in the offshore direction and had similar magnitudes over most of the HF radar footprint, with occasional exceptions around the Hudson and Delaware Bay canyon regions. While point flows were characterized as times in which there was along-shelf flow near the 25 m isobath that veered offshore where the orientation of the NJ coastline shifts near Barnegat Inlet (~39.6 N). The veering flow can extend across the entire HF footprint and have a relatively wide velocity core (approximately 12–24 km). The study found that the magnitude and duration of shelf wide flows were stronger and shorter during nonsummer months of the year. As this study is primarily focused on the potential forcing mechanisms of these types of events, Figure 3 shows the temporal distribution of the shelf wide (blue and red circles in the top plot) and point flow (green circles in bottom plot) events with the wind vector (black arrows) at the onset of these events. The red circles distinguish the summer events from the nonsummer events in the top plot, as the events appear to be associated with different wind conditions. During the nonsummer (summer) period, the wind vector appears to be much stronger (weaker) and out of the northwest (south or southwest) during the shelf wide events. As southwest wind is approximately upwelling favorable in this region, the summer shelf wide events fit the typical Ekman dynamical explanation of offshore flow. However, during the nonsummer months the shelf wide events appear to be associated with across-shelf wind. For point flow events, there does not appear to be any strong seasonal wind patterns. The wind conditions during these events tended to be out of

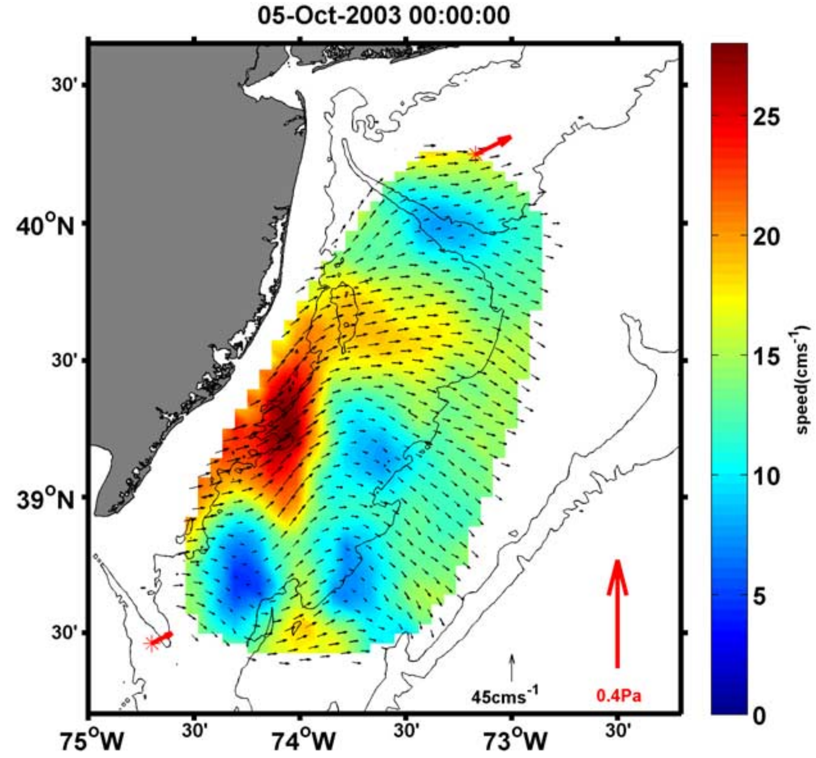

Figure 2b. Same as in Figure 2a, except for a point flow.

the south or southwest (upwelling favorable) with varying levels of magnitude.

[13] As these observations suggest, there appears to be a seasonal difference in the wind current relationship during shelf wide flow events. To address this issue, the data were divided into time periods reflecting the approximate time period of the stratified (June, July, August, September) and mixed (December, January, February, March) regimes. This

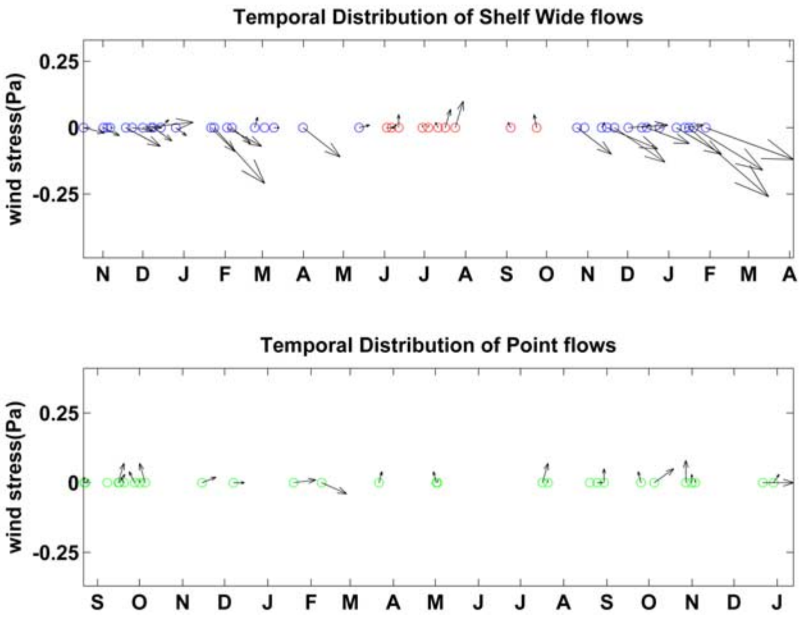

Figure 3. The temporal distribution of the two predominate across-shelf offshore flow events: (top) shelf wide and (bottom) point. Circles represent the onset of an across-shelf flow event with the coloration indicating the type of across-shelf flow event, wherein the blue (red) are weakly stratified/mixed (stratified) shelf wide events and the green are point flow events. The black arrows are wind stress vectors (Pa) at the onset of the across-shelf flow event.

Table 1. Summary of the Vector Correlation Results Between the Spatial Mean of the HF Radar Surface Currents and the Wind Stress[a]

	r	Lag	Phase	Transfer Coefficient
Total	0.72	3	8	0.75
strat1 (August 2002–September 2002)	0.84	0	32	1.21
strat2 (June 2003–September 2003)	0.82	0	39	1.33
mixed1 (December 2002–March 2003)	0.75	3	4	0.75
mixed2 (December 2003–January 2004)	0.7	3	6	0.65

[a] The result of the entire 18-month time period (Total) and the individual seasonal periods (Mixed1, Mixed2, Strat1, and Strat2). The correlation coefficient is given by the *r* value, the lag is in hours, the phase is in degrees wherein positive values are to the right of the wind, and the transfer coefficient is in (m/s)/(N/m^2).

division is based on previous studies in and near this region [*Lentz et al.*, 2003; *Kohut et al.*, 2004; *Rasmussen et al.*, 2005; *Castelao et al.*, 2008], and AUV measured across-shelf sections of temperature and salinity (October 2003–October 2004).

4. Force-Response Observations

[14] Many previous studies have shown that wind is a primary forcing mechanism in the MAB region [*Beardsley et al.*, 1976; *Ou et al.*, 1981; *Noble et al.*, 1983, etc.], so it is not surprising that there is a relationship between wind stress and the observed surface velocities and coastal sea level. However, the wind/current and wind/sea level analysis did reveal some interesting results in regards to the strength of its influence, the dominant forcing direction, and its spatial variability. Throughout the following section a number of correlation analyses are conducted whose results are significant at the 95% confidence level unless stated otherwise.

4.1. Wind/Current Relationship

[15] As a first order estimate of the relationship between wind stress and current, the spatial mean current vector was correlated to the wind stress using a lagged vector correlation. The lagged vector correlation, put forth by *Kundu* [1976], was used to quantify the differences. This correlation provided a correlation coefficient (*r* value), a phase difference (veering angle between vectors), and a transfer function coefficient (magnitude difference between vectors expressed as (m/s)/(N/m^2) in this study). The correlations were also computed over approximate seasonal periods as stratification can affect the water column dynamics. The temporal breakdown of the data follows the seasonal periods stated above, with the total period being all 18 months, stratified period 1(strat1) being 19 August 2002–September 2002, mixed period 1 (mixed1) being December 2002–March 2003, stratified period 2 (strat2) being June 2003–September 2003, and mixed period 2 (mixed2) being December 2003–January 2004. The results are shown in Table 1. These temporal divisions impact the correlation analysis by affecting the degrees of freedom (DOF) used in determining the significance of the correlation coefficient. A decorrelation timescale of two days was used to determine the DOF for each period. This is an overly conservative value as most of the time series in the HF radar grid have decorrelation timescales of 1–1.25 days. Consequently, the DOF for each time period are 265 for the total, 22 and 61 for strat1 and strat2, and 60 and 30 for mixed1 and mixed 2. As all the lagged correlations occur at timescales shorter than a day, no adjustments to the DOFs were made for calculations.

[16] In general, the correlations are very high with *r* values equal to 0.72 for the total data set, and three of the seasonal periods being higher with values of 0.84, 0.82, and 0.75 for strat1, strat2, and mixed1, respectively. The phase difference of 8° during the total time period reflects a blending of the seasonal phase differences where the stratified season which veers to the right of the wind stress to a greater degree (32° and 39° for strat1 and strat2 versus 4° and 6° for mixed1 and mixed2). The fact that the total period results are similar to the mixed suggests that the weakly stratified periods of October–November and April–May behave more like the mixed period. This was confirmed by vector correlations for these time periods. In addition, the lag time is minimal, with lags ranging from 0 to 3 hours. From the seasonal separation, it can be seen that the mixed period has a slower wind response time than the stratified period. The zero lag during the stratified period indicates that the response time of the surface layer currents is less than the three hour sample interval of the HF radar. This near immediate response of the surface currents to wind-forcing was similar to that found during the summer stratified season on the inner shelf of LEO-15 region by *Münchow and Chant* [2000]. There is also a notable difference in the transfer coefficient between seasons with the mixed period being less than one and the stratified period being greater than one. Since momentum is more easily transferred vertically during mixed conditions it is likely that a given wind stress will produce a smaller surface current, but a deeper overall current, than under stratified conditions. This is consistent with the observations that for a given wind stress, smaller surface currents are produced per unit of wind stress during periods of mixed conditions.

[17] The vector correlations show that the surface current was highly correlated to wind stress, but that there was a seasonal difference in the response. To further explore the seasonal difference, the across-shelf currents are plotted along with across-shelf and along-shelf components of the wind stress, which are shown in Figure 4 for the stratified period (strat2) and Figure 5 for the mixed period (mixed1). In both figures, the spatial mean across-shelf current (red dashed line) is plotted against the along-shelf and across-shelf wind stress (blue) in the top and bottom plots, respectively. Note that in the case of the along-shelf component, the negative of the component is plotted and correlated for visually comparison purposes (i.e. negative along-shelf stress in Figures 4 and 5 corresponded to up-shelf or upwelling favorable wind stress). Figures 4 and 5 also contain the maximum correlation coefficient between

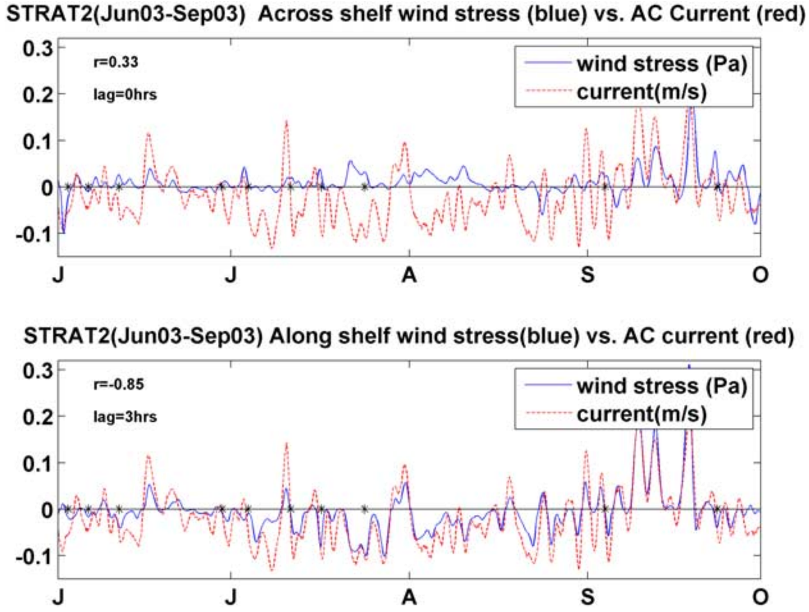

Figure 4. Comparison of the (top) across-shelf (blue line) and (bottom) along-shelf (blue line) components of MAB wind vector with the across-shelf (AC) component of the spatial mean current vector (red dashed line) during the stratified period (June–September). The black stars along the zero line (black line) represent the shelf wide. In the top left corner of each plot are the correlation coefficient (*r*) and its lag, wherein any lag indicates the current follows the wind. In the top plot, positive values indicate the onshore direction and negative values indicate the offshore direction. This is the same for the current in the bottom plot, but for the wind stress, the positive values indicate the down shelf direction and the negative direction indicates the up shelf direction.

the wind component and the across-shelf current, its associated lag, and the starting point of shelf wide events (black stars along the zero line) in the given period. During the stratified period, the top plot of Figure 4 shows that the across-shelf current is not well correlated with across-shelf wind as shown by the low correlation coefficient of 0.33, whereas there is a high correlation between the along-shelf wind stress and across-shelf current with an r value of −0.85 at a 3 hour lag. A similar relationship occurs during the stat1 period with the along-shelf wind stress and across-

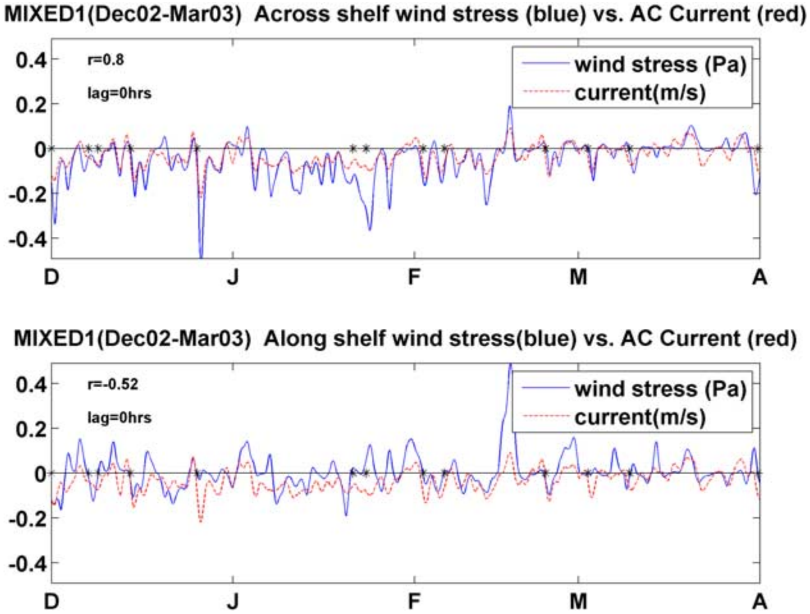

Figure 5. Similar to Figure 4, except the comparison is during the mixed period (mixed1 December 2002–March 2004).

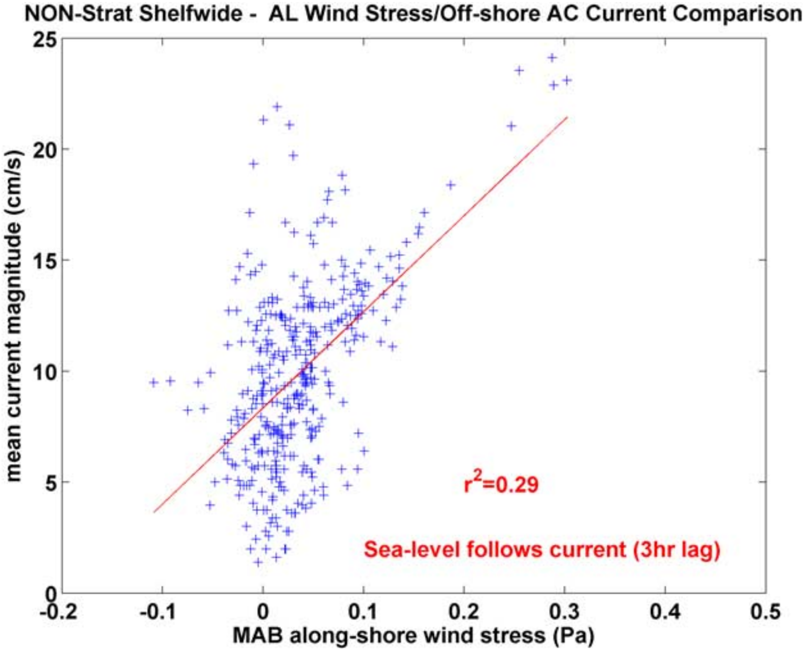

Figure 6a. Scatterplot comparison between the across-shelf component of spatial mean current vector and the directional wind components during the conditionally sampled shelf wide offshore flow events in the nonstratified periods. Comparison of the along-shelf current and along-shelf wind. The blue plus signs are the data points, the red line is the linear regression line, and the r^2 value is shown in red.

shelf current being strongly correlated (r value = 0.83 at 0 hour lag). In addition, nearly all the shelf wide flow events are associated with times of predominately upwelling winds. The one exception occurs in early June where the first event is preceded by a large impulse of across-shelf wind stress (0.1 Pa). However, the along-shelf wind stress begins increasing in strength as the across-shelf component is decreasing just prior to the event.

[18] Figure 5 shows that the current/wind relationship during the mixed period is different from the stratified period. The across-shelf (along-shelf) wind stress appears more (less) in phase with across-shelf current than during the stratified period. This is reflected in the correlation coefficients, where the r value for the across-shelf wind stress and across-shelf current increased to 0.8 at a zero hour lag, and the r value for the along-shelf wind stress and across-shelf current decreased to -0.52 at zero hour lag. This increased correlation between across-shelf wind stress and the across-shelf current shows up even stronger in the mixed2 period, which has an r value of 0.83 with a zero hour lag. This point is further emphasized by examining the fluctuations in across-shelf current and both wind components in conjunction with the shelf wide flow events. There are several shelf wide flow events that occur at times of strong across-shelf wind stress, while the along-shelf wind stress is very weak and/or downwelling favorable (25 December, 22 January, 2 February, 2 March, etc.). This is well illustrated by the 25 December event, in which an extremely strong across-shelf wind stress of approximate 0.5 Pa is well correlated with a 24 cm/s pulse of across-shelf velocity. During the same time, the along-shelf wind stress is only around 0.01 Pa. In contrast, under stratified conditions a similar along-shelf wind stress was observed in conjunction with offshore flow, however, they were not nearly as large in magnitude as this event.

[19] The across-shelf flow events under mixed conditions support the notion that across-shelf wind can drive across-shelf flow under appropriate conditions. For each shelf wide event, the across-shelf current component was compared to the corresponding along and across-shelf wind stresses, with the lag of the best results shown. These data were compared using scatterplots as a way to identify trends with the results shown in (Figures 6a, 6b). The scatterplot of the across-shelf wind compared to the across-shelf current (Figure 6a) shows a strong linear relationship with an r^2 value of 0.68; as compared to the scatterplot with along-shelf shelf wind stress (Figure 6b), which only had an r^2 value of 0.29. There was no similar relationship between stratified shelf wide across-shelf flows and across-shelf wind. Hence the mixed/less stratified conditional events represent a notably different relationship with wind stress than those in stratified periods.

4.2. Wind/Sea Level Relationship

[20] In addition to the association of across-shelf wind and currents, examining the relationship of across-shelf winds on adjusted sea level could provide evidence of their dynamical importance in forcing coastal set down. Similar to the plots above, adjusted sea level was compared to the along and across-shelf components of the wind stress. During the stratified period (not shown), the fluctuations in adjusted sea level were well correlated (r value = -0.81 with 6 hour lag) with along-shelf wind stress where upwelling (downwelling) winds were associated with a decrease (increase) in coastal sea level. The correlation with across-shelf wind stress was much weaker (r value = 0.34 with 0 hour lag). Comparison with the strat1 period was

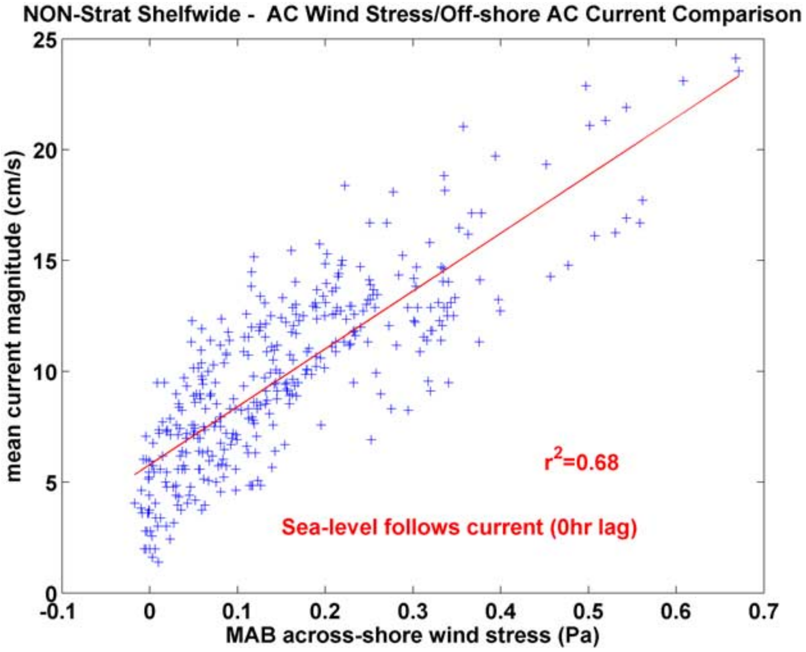

Figure 6b. Same as in Figure 6a, except the comparison is of the across-shelf current and across-shelf wind.

avoided because of gaps in the adjusted sea level data during this time period.

[21] The relationship with adjusted sea level and wind stress components becomes more complicated during the mixed season. Figure 7 is similar to Figures 4 and 5 with the exception of the blue line being adjusted sea level in both the top and bottom plots and the red dashed line being the across (along) shelf wind stress in the top (bottom) plot. From Figure 7, both along and across shelf wind components appear to be correlated with sea level variations. While still strong, the along-shelf wind stress correlation with adjusted sea level weakened (r = 0.69 with a 12 hour lag) and the across-shelf correlation coefficient increased (r = 0.42 with a 3 hour lag) from the strat2 period. The pattern gets stronger in the mixed2 period with the across (along)-shelf stress correlation increasing (remained approximately

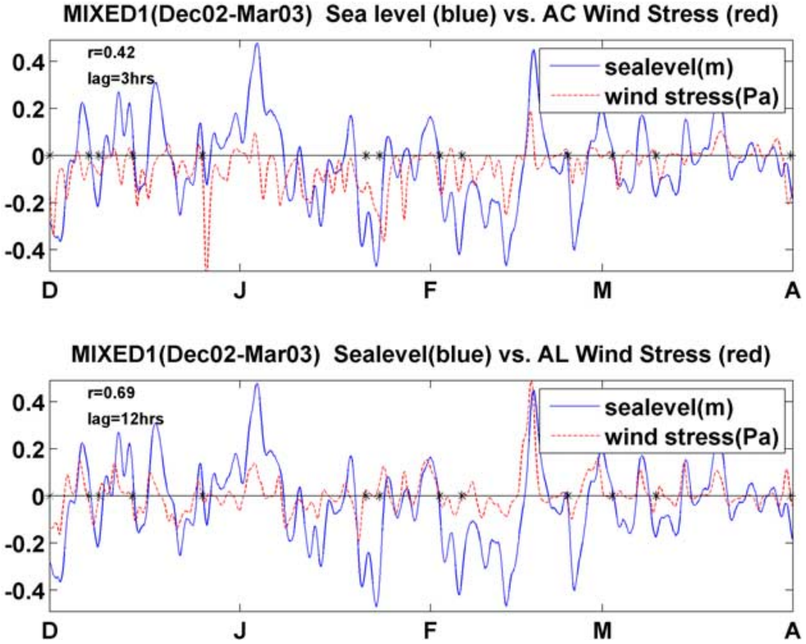

Figure 7. Similar to Figures 4 and 5 with the exception of the blue line being sea level in both the top and bottom plots and the red dashed line being the across (along)-shelf wind stress in the top (bottom) plot.

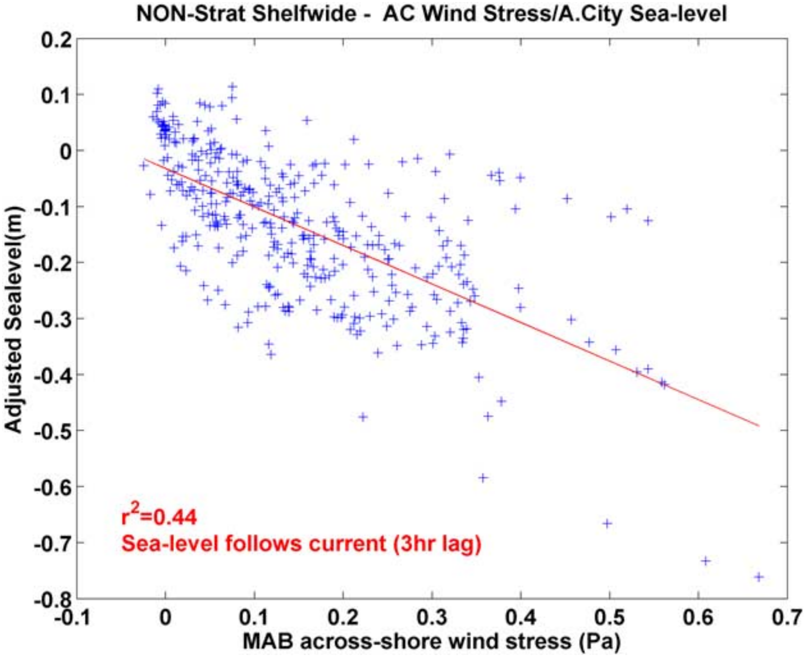

Figure 8. Scatterplot comparison between the across-shelf component of wind stress and adjusted sea level during the conditionally sampled shelf wide offshore flow events in the nonstratified periods. The blue plus signs are the data points, the red line is the linear regression line, and the r^2 value is shown in red.

equal) to 0.57 (0.68). Again, similar to the wind stress/across-shelf current plots, there are several periods of decreasing adjusted sea level when along-shelf wind stress was very small or downwelling favorable, which typically coincided with shelf wide events. Thus the adjusted sea level and wind stress components are conditionally sampled during the shelf wide flows in the nonstratified study period. Scatterplots of along-shelf wind stress showed no significant relationship to adjusted sea level with an r^2 value of 0.09. However, the scatterplot of the across-shelf wind stress and adjusted sea level showed a relationship ($r^2 = -0.44$) with adjusted sea level decreasing with increasing offshore across-shelf wind stress (Figure 8).

4.3. Current/Sea Level Relationship

[22] As a connection between the wind stress/current correlation and the wind stress/sea level correlation, it would be expected that the surface layer across-shelf current should lead to sea level set up and set down. There is generally reasonable agreement between onshore (offshore) flow and adjusted sea level increase (decrease) with an r-value for the stratified (mixed) period of 0.78 (0.56) with a 6(9) hour lag. Furthermore, the mixed period relationship strengthens during the mixed2 period where the *r* value increases to 0.79 at 3 hour lag.

4.4. Spatial Variability of Wind/Current Relationship

[23] As the study area covers a large region of the continental shelf, with depth ranging from less then 25 m to greater then 100 m, the relationship between wind stress and the current would be expected to change as the effects of bottom friction decrease with increasing depth. Here we utilize the spatial times series of the HF radar sampling to describe the variability in the surface current response to wind-forcing over shelf scales. This was done by grouping the lower portion of the study region, where the relative angle of the isobaths do not change significantly, into three subregion; inside (≅23–28 m isobath), middle (≅33–48 m isobath), and outside (≅55–95 m isobath). The HF radar grid points used in the subregions are shown in Figure 9 with the inside region marked by red "+," middle region marked by green, and the outside region marked by blue. Each of the subregions is separated by approximated 12 km with regional grouping limiting the potential effects of gaps and reducing the nosiness typically associated individual points.

[24] The time series of the spatial mean current of these subregions was vector correlated with the wind stress and the results are shown in Table 2. All the subregions and temporal periods showed good correlations between the current and wind stress with mixed (stratified) periods having correlations greater than 0.65 (0.7). The veering angle for the mixed periods did not show a consistent relationship with distance from the coast with the mixed1 (mixed2) period showing little change (an increase) in veering angle with distance from the coast. However, the veering angle in both stratified time periods increased consistently with distance from the coast. For stratified conditions in the inside subregion, currents are approximately 15–20° to the right of the wind, but further offshore in the outside subregion, the current/wind veering angle increases by approximately 25° so that the current is 45–50° to the right of the wind.

5. Discussion

[25] The results of the correlation analyses identified several important relationships between surface current,

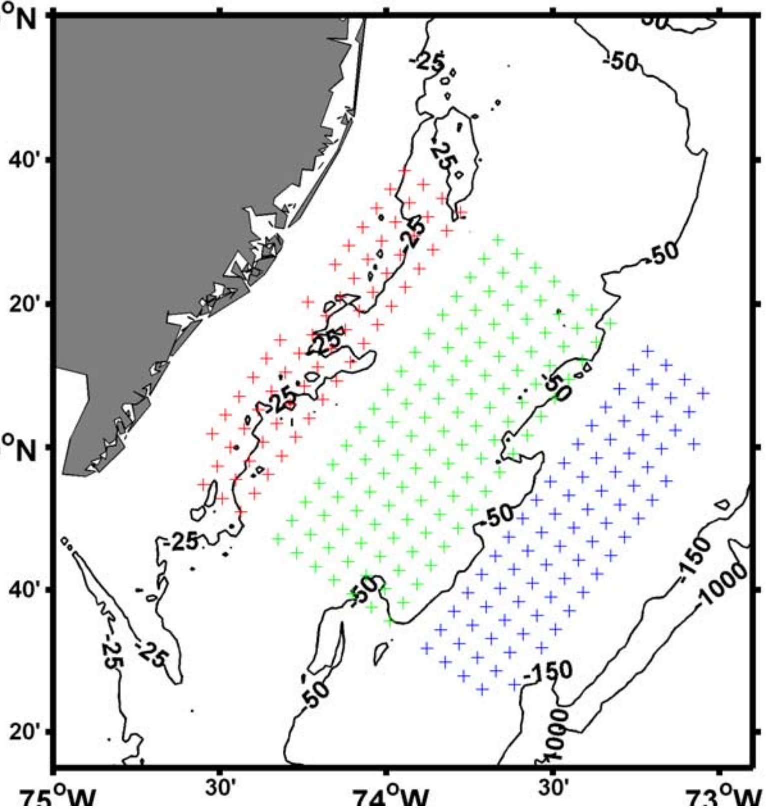

Figure 9. Lower portion of the study region showing the HF radar grid points used in the subregions with the inside region marked by red plus signs, middle region is marked in green, and the outside region is marked in blue.

wind stress, and adjusted sea level. During the stratified period, the current appears to exhibit flow behavior consistent with the development of an Ekman spiral in the surface boundary layer as the vector correlation between the wind stress and current indicates that the two are highly correlated with the current veering between 30° and 40° to the right of the wind. Furthermore, the along-shelf wind stress component is highly correlated with across-shelf current and adjusted sea level variability with down (up) shelf wind causing onshore (offshore) current flow and sea level set up (down). These results are consistent with several other studies inner shelf of the NJ coast [*Yankovsky and Garvine*, 1998; *Kohut et al.*, 2004]. However, *Yankovsky and Garvine* [1998] observed summer time upwelling events that typically lasted 8–10 days on the inner shelf of the LEO-15 region, which is longer than the duration of events in this study. This difference could result from the quick response times of the surface currents to wind-forcing as mentioned in the vector correlation results (virtually 0 hour lag over the HF grid). For example, two separate offshore flow events were observed during 19–28 August (9 days). However, a one day shift in the wind led to a brief break in the offshore flow and thus resulted in the 9 day period to be considered two separate events. Another interesting result stemming from the regional vector correlations is the reduced correlation in the inner and outer regions during the stratified period. These reductions may be associated with baroclinic processes. The lower correlation on the inside region could be effected by buoyancy intrusions which are known to impact the inner shelf along the NJ coast during the stratified period [*Yankovsky and Garvine*, 1998]. While the outside region may be impacted by shelf break processes, such as the shelf break front jet. *Liu and Weisberg* [2005a, 2005b] found that baroclinicity played an increasingly im-

Table 2. Summary of the Subregion Vector Correlation Results Between the Spatial Mean of the HF Radar Surface Currents of Each Subregion (Inside, Middle, Outside) and Wind Stress[a]

	r	Lag	Phase	Transfer Coefficient
		Mixed1		
Inside	0.70	3	7	0.81
Middle	0.73	3	3	0.90
Outside	0.69	6	2	0.89
		Mixed2		
Inside	0.65	3	0	0.74
Middle	0.68	3	3	0.75
Outside	0.69	3	10	0.70
		Stratifed1		
Inside	0.78	0	16	1.68
Middle	0.84	0	26	1.55
Outside	0.73	0	43	1.06
		Stratifed2		
Inside	0.76	0	22	1.47
Middle	0.83	0	34	1.45
Outside	0.70	0	51	1.28

[a] The result of the individual seasonal periods (Mixed1, Mixed2, Strat1, and Strat2). The units are the same as in Table 1.

portant role as the depth and stratification increased on the similarly, gentle sloping West Florida shelf. Using shipboard ADCP transects near the northeast edge of the study region, *Flagg et al.* [2006] has plots of a frontal jet feature impacting near surface currents well within the 150 m isobath. While the climatology of this feature is strongest during fall and winter, there are well illustrated examples of its impact during summer months [*Flagg et al.*, 2006, Figures 4 and 6]. To further explore this possibility, the HF radar data was examined for direct evidence of an offshore jet. However, the approximately 0.1 difference in the correlation coefficient between the outer and middle regions, results in only an approximate 20% difference in the variance explained by the wind/current correlation. Thus the effects of a shelf break jet in the outer region would be expected to be subtle. That being said, surface currents do show some limited evidence of down-shelf flow in the outer region that are counter to what would be expected given the wind-forcing. Whether this is evidence of the shelf break frontal jet can only be speculated as no temperature or salinity data for the water column were available.

[26] The mixed period results suggest a different response to the wind stress, at least at times. While the vector correlation is slightly weaker than the stratified period, it is still high, O(0.70), but the slight phase angle implies that the current follows the direction of the wind. This observation, in conjunction with the climatological predominance of northwest winds during this time period, suggest that there could be significant offshore across-shelf flow attributed to across-shelf winds during the mixed period. Supporting this notion is the analysis of the wind stress components and the across-shelf current, which showed strong correlations with across-shelf wind that were significantly higher than the along-shelf wind stress correlations. In addition, a climatologically study of six years of HF radar data showed that these results are constant with longer timescale observations (D. Gong et al., Seasonal climatology of wind-driven circulation on the New Jersey shelf, submitted to Journal of Geophysical Research, 2009). While the relationship between wind stress and adjusted sea level was less clear, it does suggest that across-shelf wind stress can be a player in adjusted sea level as previous studies have noted [*Li and Weisberg*, 1999a, 1999b, 2007, etc.]. This was especially notable during specific shelf wide offshore flow events, where conditional sampling showed these events were strongly associated with across-shelf wind stress and well correlated with decreased adjusted sea level. Furthermore, as can be seen from the scatterplots and wind stress/current/sea level plots, the shelf wide events during the mixed periods were often associated with very strong wind stress and depressed adjusted sea level, which supports the notion that the importance of across-shelf wind stress increases significantly during severe weather events as noted by *Trasviña et al.* [1995] and *Liu and Weisberg* [2005a].

[27] In addition, the correlations between wind stress and adjusted sea level are lower than the correlations between wind stress and current. While a definitive explanation is difficult to determine with the given data set, there are several potential factors that could contribute to these results. This is a region of complex geography and bathymetry which has been shown to be significantly impacted by remotely forced waves. *Ou et al.* [1981] found that wind-forcing and southward propagating free waves in the MAB are equal in magnitude and accounted for 80% of the total energy in the along-shelf direction [*Noble et al.*, 1983]. Thus these continental shelf waves could reduce the correlation between local wind stress and sea level. Furthermore, as one reviewer pointed out, the correlation between the wind stress and sea level compares a spatial mean wind with a point measurement of sea level. A spatially averaged sea level from additional tide gages around the study area could result in higher correlations between the wind and sea level. This could be important, as the geographic complexity of the regional coastline could allow for local winds, as opposed to a regional mean representation thereof, to have a significant impact on the local sea level changes. Another, possible factor is the known three-dimensional nature of shelf circulation. As stated by *Weisberg et al.* [2001], differences between vertically integrated across-shelf volume transport and the volumetric rate of sea level change can only occur in a three-dimensional flow. Thus inner shelf along-shelf divergence could result in across-shelf current without strong changes in sea level. While no comparison to sea level was made, *Tilburg and Garvine* [2003] did demonstrate that along-shelf divergence does occur at the coastal edge of the study region during the stratified time period and would be expected to affect across-shelf transport.

[28] The observed seasonal differences in the vector correlations are supported by a study by *Weisberg et al.* [2001]. The study primarily examined the effects of stratification on upwelling and downwelling events generated by along-shelf wind using a twin model experiment, one model with and without stratification. However, the study did show that current veering in the boundary layer is significantly influenced by stratification. Without stratification very little turning in the surface boundary layer was observed, which is inline with this study's observations.

[29] Both seasonal results can be explained in a manner consistent with Ekman dynamics. During the stratified period, a strong thermocline across the shelf would inhibit the growth of the surface boundary layer, which would consequently extend the timescale for the transfer of momentum from the surface to the bottom. This in effect allows the rotational timescale of 1/f to play a role in the system dynamics [*Lentz*, 2001], which explains the 30–40° veering of the current to the right of the wind. While in the mixed period the surface boundary layer is often of O(h), which causes transport, or in this study's observations, surface flow, to travel in the direction of the wind. As evidence of this, the Ekman surface layer depth was calculate using simple theory, $\delta_{ek} = \kappa u_*/f$ where κ is von Karman's constant (0.4), f is the Coriolis parameter, and u_* is $\sqrt{\tau/\rho_0}$ where τ is the wind stress, and ρ_o is a reference density (assumed 1030 kg/m^3) [*Ekman*, 1905; *Lentz*, 1995b]. During the mixed1 and mixed2 periods of the study, the mean δ_{ek} was 37 m and 46 m, respectively. At these depths, most of the shelf would be considered of the order of δ_{ek}, which is similar to what *Lentz* [2001] suggested from his work off the North Carolina shelf. This expectation is consistent with the observed seasonal differences in the transfer coefficient of the vector correlation. The lower transfer coefficient during the mixed period means that

stronger winds are associated with surface current velocity which suggests that since momentum is more easily transferred vertically during mixed conditions, the additional momentum associated with the stronger wind would be transferred to a larger depth, hence a deeper δ_{ek}. Furthermore, some additional evidence of this can be found in the spatial relationship between wind stress and current. As shallower water would be proportionally more affected by bottom friction, the expectation is that deeper water, in the presence of weak stratification, would be more likely to allow the formation of δ_{ek}. The notion can be indirectly tested in a rather limited way by comparing the veering angle between the wind stress and the current with depth. Unfortunately, the results from the subregion correlations (Table 2) are inconclusive during the mixed periods, with the mixed2 period having only a minor increase in veering angle with depth, while there was actually a decrease, albeit smaller, in the veering angle over subregions during the mixed1 period. However, the stratified period was consistent and had a strong change in the veering angle with distance from the coast. This suggests that water column depth affects coastal dynamics over a large portion of the shelf even during periods associated with strong stratification when the surface boundary layer should be insolated from bottom friction effects.

[30] While the HF radar measures the spatial variability of surface currents as they respond to forcing across the shelf, it only samples near the surface. Attempting to fully describe shelf circulation, an inherently three-dimensional flow field, with only surface currents can lead to interpretation difficulties as pointed out by *Liu et al.* [2007]. As such, it should be re-emphasized that the relationships examined are between *surface* currents, wind stress and sea level. As such, whether there is significant transport associated with the across-shelf flows discussed above is another question that cannot be addressed without further observations and/or modeling. *Lentz* [2001] found that unstratified conditions on the North Carolina coast were associated with transport much lower than that estimated by across-shelf Ekman transport, which lead to the suggestion that strong wind-forcing may not be a very effective mechanism for across-shelf movement of organisms, nutrients, or sediments during the fall and winter. Similarly, the twin model study by *Weisberg et al.* [2001] mentioned above, showed that the constant density case had reduced transports in the boundary layers when compared to the stratified case. The data in this study were similar in that during the mixed period, the along-shelf wind stress was not well correlated with across-shelf flow in the surface layer.

[31] However, the across-shelf surface velocities, and thus possibly surface transport, were episodically quite high (>.15 cm/s at times) and were well correlated with across-shelf wind stress during the mixed period as mentioned above. The notion that offshore wind can in fact drive across-shelf transport under constant density conditions was shown by *Li and Weisberg* [1999a, 1999b] with a three-dimensional numerical model. Their modeling results for the West Florida Shelf showed that offshore wind-forcing results in fully three-dimensional flow with opposing surface and bottom boundary layers which account for the across-shelf transports. Furthermore, the contribution of across-shelf wind stress to the across-shelf momentum balance was confirmed by in situ studies on West Florida Shelf by *Liu and Weisberg* [2005a, 2007], where they showed that across-shelf wind did contribute significantly but in a secondary way to the across-shelf momentum balance on the inner shelf. Thus these studies would suggest that significant across-shelf transport driven by across-shelf wind stress could be occurring during the mixed conditions in the MAB.

[32] On the other hand, the data in this study do not show evidence of across-shelf wind stress driving large amounts of surface transport within a stratified outer shelf as shown in a modeling study by *Tilburg* [2003]. As stated above, this study cannot address the issue of transport, however the surface currents during the stratified period were not correlated with across-shelf wind which would suggest that large amounts of transport in the surface layer were not likely during times of across-shelf wind in the stratified periods observed Thus there remain some unresolved questions as to the importance of across-shelf wind in across-shelf transport during mixed and stratified periods in the MAB.

6. Summary

[33] Seasonal differences in the forcing and response relationships of surface currents, wind stress, and adjusted sea level were observed in 18 months of data in the central MAB. Seasonal vector correlations between the surface current and wind stress revealed very high correlations but distinctly different phase angles and transfer coefficients. The stratified (mixed) period current veered to the right of the wind by 30–40° (6–8°) and had a higher (lower) transfer coefficient. Scalar correlations between across-shelf wind stress and across-shelf current showed higher r values than with the along-shelf wind stress during the mixed period. While this pattern did not hold between wind stress and sea level, the correlations did show a stronger (weaker) relationship with across-shelf (along-shelf) wind stress than what was observed in the stratified season. These relationships were particularly notable during commonly observed surface shelf wide offshore flow patterns which were associated with distinctly different wind stress magnitudes and directions during mixed and stratified seasons. Conditional sampling of shelf wide events during the mixed/weaker stratified periods did show stronger relationships between both across-shelf wind/across-shelf current and across-shelf wind/sea level than with the along-shelf wind stress. Furthermore, regionally comparing subsectional current averages of the HF radar footprint with wind stress showed increased current veering to the right of the wind with increased offshore distance during the stratified periods, while the mixed time periods showed little or no current veering to the right of the wind with increased depth.

[34] It was speculated that these seasonal differences resulted from a larger Ekman surface boundary layer depth during the mixed period which suggests that there is a significant seasonal change in the size of the inner shelf, the area of shelf most sensitive to across-shelf wind stress. Thus during the mixed period across-shelf wind stress could be an important factor in driving across-shelf circulation over a much large portion of the central MAB then presumed. However, additional studies in the central MAB during the

mixed period are needed to confirm this. Furthermore, this study presents additional evidence of the episodic importance of across-shelf wind stress during severe wind events, as well as little evidence of significant across-shelf transport being driven by across-shelf wind over a stratified outer shelf. While the analysis relies on correlations with surface currents, which can be difficult to interpret without vertical water column measurements, the results of this study dovetailed well with previous studies of across-shelf circulation in other locations, reinforcing the results analysis in this study.

[35] **Acknowledgments.** This work would not have been possible without collecting, processing, and archiving the HF radar velocity maps by Coastal Ocean Observation Lab at Rutgers University, including Hugh Roarty and Scott Glenn. We also need to thank Bruce Liphardt, Rich W. Garvine, Kuo Wong, and John T. Reager for advice and technical assistance. In addition, we would like to thank the two anonymous reviewers for their comments, as they significantly improved this work. This work was supported by the National Atmospheric and Oceanographic Administration through grant NA17EC2449 and NASA-Space grant NNG05GO92H and is a part of the lead author's Ph.D. dissertation at the University of Delaware. This work was partially supported by NOAA-SG through grant NA09OAR4170070, and by NASA through grant NNX08AW02A, NNX09AF33G, and NNG05GO92H.

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