Three-Dimensional Flow in a Shallow Coastal Upwelling Zone: Alongshore Convergence and Divergence on the New Jersey Shelf

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(Manuscript received 17 July 2002, in final form 8 April 2003)

ABSTRACT

Alongshore flow field divergence is investigated on the inner shelf off the coast of New Jersey during the summer upwelling season of 1996. Velocities obtained from an array of moorings are used to examine the flow field. Empirical orthogonal function (EOF) analyses are employed to extract those features of the flow field that are resolved by the moorings and to construct a measure of alongshore divergence. Multi-input single-output linear systems analysis is used to examine the role of buoyancy intrusions and wind stress in determining alongshore divergence or convergence of the flow field and to construct a proxy for divergence derived from a time series of stratification gradients and wind stress. Alongshore divergence on this shallow shelf (<25-m depth) is shown to be a function of both wind stress and buoyancy intrusions. The latter originate in the Hudson River outflow and produce downshelf flow (i.e., in the direction of Kelvin wave propagation). Examination of the first EOF mode (containing 67% of the variance) reveals that the largest resolved fluctuations are oriented alongshore and are characterized by strong counterclockwise veering with depth. Momentum balances demonstrate that the depth-averaged flow fields are governed by wind stress, bottom stress, and the across-shore pressure gradient. The second EOF mode describes significantly less variance (8%); however, it represents the alongshore and across-shore variations of the flow field, composing the bulk of the alongshore divergence. The production of alongshore divergence by a combination of wind stress and buoyancy intrusions is a likely outcome in upwelling regimes downshelf of a major buoyancy source.

1. Introduction

Flow associated with coastal upwelling is often described as a result of a two-dimensional balance between wind-driven offshore flow within a surface boundary layer and a compensating onshore subsurface flow. The resulting across-shore pressure gradient then drives an alongshore flow parallel to the wind. For the simple case of an unstratified shelf forced by an alongshore wind stress, Ekman (1905) showed that in deep water the steady wind-driven surface transport $U_s$ should be perpendicular to the applied surface stress $\tau^A$, with a magnitude $\tau^A/(\rho_o f)$, where $\rho_o$ is a reference density and $f$ is the Coriolis parameter. This wind-driven transport is confined to a boundary layer of thickness $\delta_p$ equal to $\sqrt{2A/f}$ for a constant eddy viscosity $A$ (Ekman 1905). For stratified conditions, the surface transport is confined to a thickness of $1.3u_*/(N\alpha)^{1/2}$ (Weatherly and Martin 1978; Lentz 1992) where $u_*$ = $\sqrt{\tau^A/\rho_o}$ is the shear velocity and $N$ is the buoyancy frequency just below the boundary layer.

Studies have shown that this two-dimensional description of upwelling is incomplete. Smith (1981) reviewed observations from coastal upwelling studies off Oregon, Peru, and northwest Africa. In all three regions, he found that the offshore, surface layer flow correlated well with the across-shore Ekman transport $\tau^A/(\rho_o f)$ but the onshore, subsurface flow did not fully compensate the offshore flow on the synoptic scale. He concluded that mass balance was influenced by alongshelf bathymetric variations. Others (e.g., Kundu and Allen 1976; Smith and Brink 1994) noted that short alongshore correlation scales have been observed for across-shore flow and called for renewed effort to understand the fully three-dimensional flow field.

The studies reviewed by Smith (1981) concentrated on shelves with steep bottom slopes (bottom slope $\alpha \approx 10^{-2}$). On gently sloping continental shelves such as in the Mid-Atlantic Bight ($\alpha \approx 10^{-3}$), bathymetric and buoyancy effects may assume added importance in the alongshore variation of the flow field. Yankovsky and Chapman (1995, 1996, 1997) demonstrated that variations in the bottom topography along shallow continental shelves can affect the propagation of coastal trapped waves through the modification of the background potential vorticity field, greatly influencing the alongshore velocities. Examining velocities from three moorings off New Jersey, Yankovsky and Garvine...
FIG. 1. Map of the study site showing bottom topography (m) as well as positions of current meter moorings (open circles), ADCP moorings (closed circles), bottom stress tripod (closed diamond), wind observation towers (closed squares), and ship transects (gray lines).

(1998) showed that periods of enhanced buoyancy on the continental shelf coincided with amplified responses to transient wind events. They found that the flow field response to wind events was not strictly governed by Ekman dynamics but instead contained larger than expected alongshore velocities that extended to the bottom. Yankovsky et al. (2000) found that the buoyancy intrusions on the New Jersey shelf were accompanied by large, geostrophically balanced across-shore velocities. Lentz et al. (2003), in an examination of the flow field downshelf of the Chesapeake Bay, found that alongshore velocities abruptly increase near the nose of a buoyant gravity current from the Chesapeake Bay.

In this paper, we show that while alongshore bathymetric variations along our study site are rather small (see Fig. 1), buoyancy intrusions with alongshore spatial scales of approximately 10–20 km can produce alongshore variations in the velocity field resulting in strong alongshore divergence and convergence. The effect of the buoyancy intrusions and wind stress on the overall divergence of the flow field is examined using multi-input systems cross-spectral analysis of observations collected from moored instruments on the inner shelf off the coast of New Jersey during the upwelling season of 1996.

The study site and observations used in this investigation are described in section 2. Section 3 contains a brief discussion of the dynamics responsible for variations in the alongshore velocity due to buoyancy intrusions and alongshore wind events. The characteristics of the observed flow field and the calculation of a mass budget are described in section 4. The use of EOF and multi-input single-output linear systems analyses to examine the physical mechanisms responsible for flow and to calculate divergence is discussed in section 5, and the summary and conclusions are contained in section 6.

2. The observations

Our study site is located off the coast of New Jersey (Fig. 1). During the summer months, the winds are primarily from the southwest, resulting in upwelling conditions along the coast. Although the shelf is gently sloping and rather shallow (<25 m deep in the study site), it is highly stratified during upwelling events (Fig. 2a). The slope Burger number, $S = \alpha N/\bar{f}$, is a key mea-

![Fig. 2. (a) Density (sigma t) section along a transect from S1 to S3, during an upwelling event (yearday 183). Note the strong stratification at even extremely shallow depths. The dotted lines represent locations of CTD casts. (b) Density section along a transect from C1 to C3, during a buoyancy intrusion (yearday 180). Note the lack of stratification nearshore.](image-url)
sure of the relative influences of stratification and bottom slope (Clarke and Brink 1985). For the Oregon shelf during the upwelling season, \( N \approx 8 \times 10^{-3} \text{ s}^{-1} \), resulting in a slope Burger number \( S = 0.8 \). Although the bottom slope off New Jersey is much less than that off Oregon \( (10^{-2} \text{ vs. } 10^{-3}) \), the water column is much more stratified \( (N \approx 5 \times 10^{-2} \text{ s}^{-1}) \), resulting in a slope Burger number \( S = 0.5 \), very similar to that off the Oregon shelf.

Buoyancy intrusions originating in the Hudson River outflow interact with the shallow bottom of the shelf and result in vertically well-mixed, weakly stratified \((\text{low } N^2)\) conditions onshore of the 15-m isobath (Fig. 2b). During calm or downwelling conditions, these buoyancy intrusions propagate downshelf. During upwelling events, they are advected offshore resulting in patches of stratified and unstratified water on the inner shelf with spatial scales of 10–20 km. The combination of upwelling conditions and buoyancy intrusions in relatively shallow water provide an ideal site for the examination of buoyancy effects on alongshore divergence over the inner shelf.

The observations used in this study consist of current and hydrographic measurements collected from shipboard and moored instruments. These have been previously discussed in detail by Yankovsky and Garvine (1998), Münchow and Chant (2000), and Yankovsky et al. (2000). Here we provide a brief summary of only those observations directly used within this study. Three shipboard surveys were conducted during the summer of 1996. Each survey acquired three or four repeated hydrographic mappings of the region (e.g., gray line Fig. 1) using a Scanfish (undulating towed CTD) and collected velocity measurements from a narrowband \((1228\text{-KHz})\) acoustic Doppler current profiler (ADCP).

Moorings deployed along three across-shore lines at water depths of 12 and 25 m obtained velocity, temperature, and pressure measurements from 19 May to 15 August 1996. Salinity measurements were collected from 19 May to 4 July 1996. InterOcean S4 electromagnetic current meters (open circles in Fig. 1) were installed at moorings S1, S3, and N1, while bottom-mounted RDI ADCPs (closed circles in Fig. 1) were installed at moorings C1, C3, and N3. Thermistor chains complemented these velocity observations at all moorings. Bottom pressure was measured at all moorings by Paroscientific Digiquartz transducers with a quoted accuracy of 0.003 dbar. The moorings enclosed a box with along- and across-shore dimensions of approximately 50 and 20 km, respectively. We use a modification of this box to calculate the mass budget in sections 4 and 5. A Benthic Acoustic Stress Sensor (BASS) attached to a bottom tripod on the central line (closed diamond in Fig. 1) used acoustic current meters at four levels within 2 m of the bottom to provide reliable estimates of the bottom stress (Williams et al. 1987).

Wind measurements used in this study were obtained from the National Oceanic and Atmospheric Administration (NOAA) environmental buoy EB44009. Although the buoy is located south of the study site \((38.5^\circ \text{N}, 74.7^\circ \text{W})\), a comparison of wind measurements at the buoy and land-based observation towers (closed squares in Fig. 1) at Tuckerton Field Station \((39.5^\circ \text{N}, 74.33^\circ \text{W})\) and Atlantic City \((39.3^\circ \text{N}, 74.6^\circ \text{W})\) reveal vector correlations of 0.86 (at 5° lag) and 0.87 (at 2.5° lead), respectively. The high degree of correlation suggests that the same atmospheric processes dominate the region. Although this correlation does not eliminate all spatial variability, the NOAA buoy was used to determine the wind conditions over the study site since its wind measurements, unlike those of the land-based towers, were temporally complete over the time period of interest. Since we are interested in subtidal processes as they affect horizontal divergence, the water velocity, temperature, density, pressure, and wind velocity measurements were processed using a Lanczos low-pass filter with a cut-off frequency of 36 h to remove tidal, inertial, and other high-frequency variations.

3. Buoyancy, wind stress, and divergence on the inner shelf

The inner shelf off the coast of New Jersey is subject to frequent buoyancy intrusions originating within the Hudson River, which can lead to significant variations in both stratification and the across-shore velocity structure (Yankovsky et al. 2000). The three shipboard surveys on the shelf allowed the examination of the spatial and temporal scales of these intrusions. The evolution of one such intrusion is shown in Fig. 3. On 29 June (yearday 180) 1996, light winds allowed the intrusion of buoyancy into the region (Fig. 3a). Since the shelf is extremely shallow, the buoyancy intrusion did not form a lens at the surface but instead reached the bottom, producing less-stratified, freshwater onshore of denser, saltier ambient water (Fig. 2b). The intrusion was characterized by alongshore scales of approximately 20 km and rather short \((\approx 3–5 \text{ km})\) across-shore scales. On 30 June (yearday 181), the region experienced upwelling winds and the buoyancy intrusion was displaced offshore and mixed with the denser ambient water (Fig. 3b). By 2 July (yearday 183), remnants of the intrusion appeared offshore and denser water had replaced the lighter water onshore (Fig. 3c).

Several studies have found that the presence of buoyancy intrusions coincide with large fluctuations in velocity and/or strong net downshelf flow. Yankovsky and Garvine (1998), using a subset of this dataset, found that alongshore velocities abruptly increased when buoyant waters entered the region. In their examination of the spatial structure of one particular buoyancy intrusion on the New Jersey shelf, Yankovsky et al. (2000) found that the intrusion supported a geostrophically balanced cyclonic flow that resulted in downshelf velocities nearshore and upshelf velocities offshore. Comparison of velocities with density sections showed that the buoy-
Buoyancy intrusion was characterized by a domelike density structure that supported large velocities and strong shear in the across-shore direction. Lentz and Helfrich (2002) and Lentz et al. (2003) also found large downshelf velocities concentrated near the nose of a buoyancy current.

The downshelf propagation of buoyancy intrusions with strong downshelf velocities near the leading edge of the intrusion can lead to significant alongshore divergence. Since weak stratification (low $N^2$) is indicative of buoyancy intrusions and results in downshelf flow and strong stratification (high $N^2$) is indicative of upwelling or upshelf flow, gradients of buoyancy or stratification ($\partial N^2/\partial y$) will produce gradients in alongshore velocity ($\partial u/\partial y$). Negative stratification gradients ($\partial N^2/\partial y < 0$) indicate a buoyancy intrusion in the upshelf portion of the region. The strong downshelf currents associated with the buoyancy intrusion will result in convergence ($\partial u/\partial y < 0$). Positive stratification gradients ($\partial N^2/\partial y > 0$) indicate a buoyancy intrusion in the downshelf portion. The downshelf currents concentrated near the leading edge will result in alongshore divergence ($\partial u/\partial y > 0$).

The co-occurrence of buoyant waters and amplified currents can be readily seen in a time series of the depth-averaged water kinetic energy (black line in Fig. 4a) and the densities (Fig. 4b) at mooring S1. Periods of high kinetic energy within the water column (i.e., yeardays 145–161 and 167–183) coincide with low surface densities, indicative of a Hudson River buoyancy intrusion. Wind kinetic energy (gray line in Fig. 4a) and the depth-averaged water kinetic energy at mooring S1 (black line) are largely uncorrelated, indicating that local wind stress is not the primary mechanism for energy input into the water column.

As we shall show in this paper, alongshore divergence is governed by two separate mechanisms: flow induced by stratification gradients and by wind stress. We now examine the relationship between wind stress and alongshore divergence. Csanady (1978) showed that, in the absence of bottom friction, alongshore divergence can be directly related to alongshore wind stress. Here we outline this argument with the inclusion of bottom stress.

As we shall see in section 5b, the across-shore transport along the New Jersey shelf is directly related to the vertical difference between alongshore wind stress and bottom stress, that is,

$$\int_{-h}^{0} u \, dz \propto \tau_w - \tau_{by},$$  

where $u$ is the alongshore velocity, $\tau_w$ is the alongshore wind stress, and $\tau_{by}$ is the bottom stress. 

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**Fig. 3.** Surface salinity during (a) 29 Jun 1996 (yearday 180), (b) 30 Jun 1996 (yearday 181), and (c) 2 Jul 1996 (yearday 183). The open circles indicate the mooring locations. Note the alongshore spatial scales of the buoyancy intrusions are similar to the mooring spacing.

**Fig. 4.** (a) Kinetic energy (kg m$^{-1}$ s$^{-2}$) of wind measured at NOAA buoy EB44009 (gray line) and kinetic energy (kg m$^{-1}$ s$^{-2}$) of depth-averaged flow at mooring S1 (black line). (b) Density (kg m$^{-3}$) at depths of 2 and 10 m at mooring S1. The vertical lines bracket two time periods (yeardays 145–161 and 167–183) of enhanced buoyancy and increased kinetic energy characteristic of a buoyancy intrusion. Biofouling of the moored conductivity sensors limited the calculation of densities to yeardays 140–187.
where \( h \) is the water depth, \( u \) is the across-shore velocity, \( \tau_w \) is the alongshore wind stress, and \( \tau_b \) is the bottom stress. Integration of the continuity equation

\[
\frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0
\]  

along an across-shore line from the coastline \((x = 0)\) to a point on the shelf \((x = X)\) (Fig. 5) and substitution into Eq. (1) lead to

\[
\int_0^X \frac{\partial (hu)}{\partial y} \, dx \propto - (\tau_w - \tau_b),
\]

demonstrating that in a coastal region, alongshore divergence \( \partial u/\partial y \) is inversely related to the vertical difference between alongshore surface and bottom stress. As we shall see, this is the dominant mechanism for alongshore divergence. However, in addition to wind-induced divergence, the tendency of buoyancy intrusions to generate downshelf flow in the form of density driven currents (Yankovskiy et al. 2000; Lentz et al. 2003; Lentz and Helfrich 2002) and magnify responses to wind events (Yankovskiy and Garvine 1998) results in alongshelf variations of flow in the presence of stratification gradients, that is, \( \partial u/\partial y \propto - \partial N^2/\partial y \). In section 5, we will examine divergence as a function of surface stress, as well as particular events driven by buoyancy intrusions.

4. Flow characteristics and the mass budget

Before the effects of buoyancy and stress on the divergence of the flow field can be quantified, we must first examine the general tendencies of the flow field and their relationship with transient wind events, pressure gradients, and bottom stress. Previous studies have shown that the two dominant forcing mechanisms in this region responsible for subtidal temporal fluctuations of the alongshore flow field are wind stress and buoyancy intrusions, which drive flow in opposite directions. Münchow and Chant (2000) examined the flow characteristics at these moorings and demonstrated that the alongshore flow at each mooring is significantly correlated with alongshore wind stress. However, Yankovsky et al. (2000) showed that buoyancy intrusions force significant downshelf and across-shelf currents and often are coincident with downwelling or light winds. The mean alongshore flow (black arrows, Fig. 6) near the 12-m isobath is relatively weak (depth-averaged velocity \( \approx 5 \text{ cm s}^{-1} \)) but oriented downshelf. The depth-averaged velocities along the 25-m isobath are even weaker (\( \approx 2 \text{ cm s}^{-1} \)) and do not follow a consistent pattern from mooring to mooring. Although the average transport is downshelf, the mean alongshore wind velocity is \( 2.0 \text{ m s}^{-1} \text{ upshelf} \), suggesting that the flow associated with buoyancy intrusions balances the wind-forced flow over seasonal timescales.

The principal axes of the transports (gray arrows in Fig. 6) are significantly larger than the means (black arrows) indicating that the two mechanisms do not balance at shorter timescales. Although the variability in the depth-averaged flow field is clearly oriented alongshore, we will see in the following section that the vertical structure of the velocity field at each mooring is characterized by strong veering, which produces significant across-shore flow.

To determine the general pathways of flow throughout the region and examine the flow field’s response to wind events at these shorter timescales, we calculate a mass budget using a control volume (gray lines in Fig. 7) that passes through the moorings. Segments of the control volume form transects that terminate at the moorings, with the exception of the northern transect, whose northeast corner has been moved so that the northern transect extends nearly to the 25-m isobath, similar to the southern transect. To calculate transport through each tran-
FIG. 7. Map of the study site illustrating the control volume used in the mass budget. Note that the control volume has been extended beyond mooring N3 in the northeast corner to include more of the flow along the 20–25-m isobaths. The along- and across-shore transects are approximately 50 and 20 km, respectively. The arrows normal to each transect indicate the std dev of the transports calculated through each transect constructed directly from the observed velocities (gray arrows) and those created using the first two EOF modes (black arrows).

sect, velocities were interpolated throughout each transect. The velocities at the moorings were first interpolated vertically throughout the water column assuming zero velocities at the bottom and uniform flow between the surface and the velocity measurement nearest the surface. The bottom depth along each transect was determined from the National Ocean Service hydrographic survey data (NOAA 2001). The depth of the nearest surface measurement varied from mooring to mooring. The nearest surface velocity measured by ADCPs (C1, C3, and N3) was generally at 4–5 m, while at S1 and N1 the nearest surface velocity measurement was at 2 m (the top current meter at S3 malfunctioned). The flow from N3 to the extended northeast corner was assumed to be uniform in the horizontal. Transports were then calculated by horizontally interpolating the observed velocities between the moorings and integrating the interpolated velocities, that is,

$$ V_i = \int \int_A v_{i \nu} dA, \quad (4) $$

where $v_{i \nu}$ = horizontal velocity normal to transect, $A$ = cross-sectional area of transect, and $i = N$ (north), $E$ (east), $S$ (south), or $W$ (west).

The degree to which the mass budget closes can be determined by calculation of the residual, $V_r = (V_N + V_E - V_S - V_W)$. For satisfactory mass balance, the residual, $V_r$, should be appreciably less than transports through the transects. However, comparison of these transports with the calculated residual (gray lines in Fig. 8) reveals that $V_r$ is of the same order as $V_N$ or $V_S$, demonstrating that the array does not resolve some features in the flow field that contribute significant amounts of transport. Correlations between the alongshore depth-averaged velocities at moorings along the 12- and 25-m isobaths range from 0.75 to 0.89. In contrast, correlations between the across-shore velocities are lower (0.56–0.64), indicating that the across-shore flow features are characterized by smaller-scale fluctuations than that of the array ($\approx 20$ km) and may introduce significant errors into the calculation of $V_E$ and $V_W$. Indeed, density and velocity measurements from shipboard surveys reveal that the across-shore flow and density structure on the New Jersey shelf are characterized by spatial scales on the order of the internal Rossby radius of deformation ($\approx 6$ km) (Yankovsky et al. 2000). The failure of a relatively sparse mooring array to resolve across-shore flow features is not surprising. Others have reached similar conclusions in studies on the North Carolina shelf (Lentz 2001) and the northern California shelf (Dever 1997).
Empirical orthogonal function analysis: Construction of a mass budget

To extract only those flow features whose scales are resolved by the array, we construct empirical orthogonal function (EOF) modes (Davis 1976; Kundu and Allen 1976) from 54 discrete observed across- and alongside current measurements at the six moorings. To prevent variations at moorings equipped with ADCPs (i.e., C1, C3, and N3) from dominating the spatial modes, the measurements are weighted. Each measurement is multiplied by the square root of the effective depth of the measuring instrument before the EOF calculations are performed. This method ensures that variations measured at both the moorings equipped with ADCPs, which contain many velocity measurements (9–15 measurements per mooring) but small effective depths (1–2 m), and the S4 current meters, which contain relatively few measurements (2–4 measurements per mooring) but large effective depths (4–7 m) contribute equally to the formation of EOF modes.

Fluctuations at all locations associated with a particular EOF mode are exactly correlated and describe flow features that extend throughout the region. If a few modes contain a majority of the total variance, then the flow features resolved by the array dominate the flow field and EOF analysis is an accurate method of extracting the large-scale flow features, while effectively excluding the smaller-scale fluctuations. Once the energetic modes that govern the flow field are identified, analysis of the spatial structure, as well as the time-dependent amplitude of the EOF modes, can provide insight into the dominant physics of the flow field. Rudnick and Davis (1988) used this method to construct and examine mass and heat budgets along the northern California continental shelf. Although the array is unable to resolve flow features with scales less than the mooring spacing, regardless of the method of analysis, the buoyancy intrusions have spatial scales similar to the spacing (e.g., Fig. 3), indicating that EOF analysis can be effective in resolving fluctuations in the flow field caused by buoyancy intrusions.

Since EOF analysis is a purely statistical technique that distinguishes modes solely by their variance, error estimation procedures are required to determine the significance of the calculated modes before any physical interpretations can be made (North et al. 1982). Only those EOF modes that can be distinguished from noise and have a valid physical explanation should then be used in the dynamical analysis of the flow field. Overland and Preisendorfer (1982) detail a procedure for determining the significance of calculated EOF modes. Using their technique, we are able to determine a significance level based on the percentage of total variance explained for each EOF mode. A comparison between the variance explained by the first 10 EOF modes calculated from the velocities at the mooring array and the 95% significance levels for each mode (Fig. 9a) reveals that only the first 2 EOF modes can be distinguished from random noise and should be used in the analysis of the flow field. However, these two modes explain 75% of the variance of the flow, indicating that a majority of the velocity fluctuations are resolved by the array and described by the first two EOF modes. Examination of the percent of local variance at each mooring described by the first two EOF modes (Fig. 9b) shows that, as expected, the first EOF mode (gray bars in Fig. 9b) dominates the variability at each mooring, consisting of 43%–86% of the local variance. The contributions of the second EOF mode (white bars in Fig. 9b), although measurably less than those of the first mode, are still significant at four of the six mooring locations. Contributions from the second EOF mode increase upshelf from less than 2% of the local variance at the northern moorings (S1 and S3) to 15%–20% at the northern moorings (N1 and N3). Additionally, the contributions of this mode are uniformly greater at the offshore moorings than the onshore moorings.

Both modes describe a readily recognizable physical feature of the flow field. The depth-averaged values of the first EOF mode (explaining 67% of the total variance) are oriented in the same direction, describing a relatively uniform alongshore flow. Values decrease and veer counterclockwise with depth at all moorings (Fig. 9c). The second EOF mode (8% of total variance) describes both across- and alongside variations of the

![Figure 9](http://journals.ametsoc.org/doi/pdf/10.1175/1520-0485(2003)033<2113:TFIASC>2.0.CO;2)
flow field (Fig. 9d) as evident from Fig. 9b. The velocities at the onshore moorings are oriented in the opposite direction as those at the offshore moorings, while the velocities at the upshelf moorings are significantly larger than those at the downshelf moorings. Examination of the vertical structure of the second EOF mode also reveals slight clockwise veering with depth at the offshore moorings but considerably less veering with depth at the onshore moorings.

Since the first two EOF modes are statistically significant and together explain a large percentage of the overall variance, we use them to extract those flow features that are resolved by the array. Transports calculated using velocities constructed from the first two EOF modes (black lines in Fig. 8) are very similar to the original transports for the north and south transects, but are drastically different for the east transect and the calculated residual. The new residual, $V_s \left( \sigma = 7700 \text{ m}^3 \text{s}^{-1} \right)$, varies considerably less than the new alongshore transports, $V_a \left( \sigma = 18000 \text{ m}^3 \text{s}^{-1} \right)$ and $V_e \left( \sigma = 25000 \text{ m}^3 \text{s}^{-1} \right)$, demonstrate that the reconstructed flow field resolves the dominant mechanisms responsible for alongshore variations of the flow field. However, examination of the transports reveals that the first two EOF modes contain less across-shore fluctuations than those calculations made from the observed data (compare the black and gray arrows in Fig. 7), indicating that the mooring array is unable to resolve some significant variations in the across-shore flow field. Although the across-shore transport has been decreased in the EOF analysis, it has not been eliminated. The standard deviations of $V_a \left( \sigma = 10000 \text{ m}^3 \text{s}^{-1} \right)$ or $V_e \left( \sigma = 13000 \text{ m}^3 \text{s}^{-1} \right)$ are only slightly less than those of $V_n$ or $V_s$. However these values are still significantly larger than the mean transports of all transects, which range from $-400$ to $2700 \text{ m}^3 \text{s}^{-1}$. While a large portion of the transport through the eastern and western transects is probably a result of the misalignment between the transects and the alongshore direction, the large standard deviations of the two transects do indicate that some features with spatial scales comparable to the array (and therefore captured within the first two EOF modes) do have significant across-shore components.

b. Description of the EOFs: Momentum balances

Examination of the spatial and temporal structure of the EOF modes allows insight into the dominant mechanisms responsible for the largest variations in flow conditions on the New Jersey shelf. The spatial structure of the first EOF mode describes a relatively uniform alongshore flow that veers counterclockwise and decreases with depth. Münchow and Chant (2000) performed EOF analysis on each of the moorings at this study site separately and found similar veering for the dominant mode. They noted that this veering could not be explained as a response of the flow field to bottom friction and speculated that the veering might instead be due to the fluctuating density gradient through thermal wind balance. Sanders and Garvine (2001) found similar veering in the mean flow of the Delaware Coastal Current south of our study site. They also found that frictional effects were unable to explain the amount of veering and showed that the veering closely followed that predicted by thermal wind balance. They argued that the strong stratification of the inner shelf restricted frictional effects, allowing geostrophic balance even in extremely shallow water. In agreement with Sanders and Garvine (2001), estimates of the Ekman depth (Bowden 1967) for our study site are of the same magnitude as the water depth, resulting in little if any veering due to frictional or wind effects. While a limited number of density measurements suggest that the veering might be due to thermal wind balance, a lack of reliable density measurements prevents any rigorous analysis of the vertical structure.

Although the forcing mechanisms responsible for the vertical structure of the first EOF remains elusive, the time varying, depth-averaged transport of the mode is shown to be a function of wind stress, bottom stress, and the across-shore pressure gradient. The across- and alongshore transports of the first EOF mode can be examined using the vertically integrated horizontal momentum balances:

$$\int_{-h}^{0} (u_t + uu_x + vu_y + wu_z + P_x / \rho_o) \, dz - \int_{-h}^{0} n_v \, dy = \tau \left( \rho_o - \tau^{\nu} / \rho_o \right),$$

(5)

$$\int_{-h}^{0} (v_t + uv_x + vv_y + wv_z + P_y / \rho_o) \, dz + \int_{-h}^{0} n_v \, dy = \tau \left( \rho_o - \tau^{\nu} / \rho_o \right),$$

(6)

where $u$, $v$, and, $w$ are the across-shore, alongshore, and vertical velocity components; subscripts indicate differentiation; $P$ is pressure; $u_{ave}$ and $v_{ave}$ are the depth-averaged velocities; $\tau^{\nu}$ and $\tau^{\nu}$ are the across- and alongshore components of wind stress; $\tau^{\nu}$ and $\tau^{\nu}$ are the components of bottom stress; and $h$ is the water depth.

To determine the primary factors influencing the across- and alongshore flow, each term in Eqs. (5) and (6) was estimated. Rough estimates of the acceleration ($u_t$ and $v_t$) and nonlinear advective (e.g., $uu_x$, $wu_z$) terms revealed that these terms are considerably smaller than the stresses or pressure gradients and probably play a secondary role on flow field fluctuations. The alongshore volumetric transport $h v_{ave}$ was determined by dividing the transport through the northern transect ($V_n$) by its length. The across-shore volumetric transport $h v_{ave}$ was determined by dividing the transport through the eastern transect ($V_e$) by its length. The pressure gradients were calculated from bottom pressure measurements at moorings S1, S3, and N1. Limited measurements of the density variations at the three moorings showed that the baroclinic pressure gradient accounted for less than 8% of...
In a region frequently subjected to buoyancy intrusions and spatially uniform wind stress, one would expect alongshore divergence to be a function of the intrusions and of the wind stress itself (Csanady 1978). Using the two EOF modes to reconstruct the velocity field enables us to include the effects of wind stress, bottom stress, and pressure gradients as well as buoyancy intrusions and spatially uniform wind stress, one would expect alongshore divergence to be a function of the intrusions and of the wind stress itself (Csanady 1978). Using the two EOF modes to reconstruct the velocity field enables us to include the effects of wind stress, bottom stress, and pressure gradients as well as buoyancy intrusions in the flow field, while excluding those small-scale flow features that are not resolved by the array. Using our reconstructed velocity field, we calculate the net divergence (Fig. 12a):

$$\frac{\partial u}{\partial y} \approx \frac{u_x - u_y}{\Delta y},$$

alongshore pressure variations and 15% of across-shore pressure variations. While still a significant contribution to the pressure gradient, these were neglected in the analysis due to the short duration of the density measurements. The bottom stress was calculated following the classical description of upwelling, the spatial structure of the second EOF mode suggests that it is related to buoyancy intrusions. This mode (containing 8% of the variance) describes a flow that varies in both the across- and alongshore directions. The offshore moorings contain clockwise veering with depth, while the onshore moorings do not. While the mechanism responsible for the strong veering of the offshore moorings (Fig. 9d) is unclear, the across-shore variation of the depth-averaged flow is consistent with the geostrophically balanced cyclonic circulation found by Yanovsky et al. (2000). Examination of the across- and alongshore volumetric transports (Fig. 11) reveals that the second EOF mode contributes significantly less transport than the first mode; however, as we will see in the next section, it is highly correlated with the calculated divergence ($r = 0.73$) and alongshore variations of buoyancy ($r = 0.62$).

c. Calculation of alongshore divergence and multi-input linear systems analysis

In a region frequently subjected to buoyancy intrusions and spatially uniform wind stress, one would expect alongshore divergence to be a function of the intrusions and of the wind stress itself (Csanady 1978). Using the two EOF modes to reconstruct the velocity field enables us to include the effects of wind stress, bottom stress, and pressure gradients as well as buoyancy intrusions in the flow field, while excluding those small-scale flow features that are not resolved by the array. Using our reconstructed velocity field, we calculate the net divergence (Fig. 12a):

$$v_{ave} = -\frac{1}{\rho_s f h} (\tau^{xx} - \tau^{hx} - hP_x),$$

However, the highest correlation ($r = 0.83$) and rms agreement between the across-shore flow associated with the first EOF and various combinations of terms in the alongshore momentum balance (equation 6) reveals that $h u_{ave}$ of the first EOF mode represents the portion of the across-shore flow field that is driven by the divergence of the alongshore stress (Fig. 10b); that is, Eq. (6) reduces to

$$u_{ave} = \frac{1}{\rho_s f h} (\tau^{yy} - \tau^{hy}).$$
where $v_N$ is the depth-averaged alongshore velocity through the northern transect, $v_S$ is the depth-averaged alongshore velocity through the southern transect, and $\Delta y$ is the distance between the centers of the two transects. Examination of the calculated net divergence shows that the flow field experiences divergence and convergence, ranging in value from $6.2 \times 10^{-2}$ to $6 \times 10^{-1}$ s$^{-1}$ over the alongshore length ($\approx 50$ km) of the mooring array. Typical values of the depth-averaged alongshore flow are $10 \pm 15$ cm s$^{-1}$, indicating a $60\%-85\%$ change over the mooring array.

In order to examine the contribution of stratification gradients and wind stress on the net alongshore divergence, we use two-input, single-output linear systems analysis (Emery and Thomson 2001), which we briefly outline here. If we assume that the alongshore divergence can be expressed as the summation of a series of responses to inputs, that is,

$$a(t) = a_{N}(t) + a_{\tau}(t) + \varepsilon(t),$$

then the Fourier transform of the output $a(t)$ is

$$A(f) = A_{N}(f) + A_{\tau}(f) + E(f)$$

where $H_{N}(f)$ and $H_{\tau}(f)$ are the transfer functions relating the inputs $X_{N}(f)$ and $X_{\tau}(f)$ to the outputs $A_{N}(f)$ and $A_{\tau}(f)$.

From the transfer functions and the Fourier transforms of the inputs and output, we can construct the two-input cross-spectral plots, which show that wind stress (solid black line in Fig. 13) is highly coherent with alongshore divergence at frequencies ranging from 0.3 to 0.5 cpd. Fluctuations in the alongshore stratification gradients (dashed line), while less coherent than those of wind stress, are still significantly correlated at frequencies of 0.05 to 0.2 cpd. [Comparison of the multi-input cross-spectral plot of the second EOF mode (not shown) is very similar to that of divergence, consistent with the spatial structure of the second mode.] The higher coherence between wind stress and divergence suggests that alongshore divergence is primarily governed by the shelf’s response to the alongshore wind stress. However, as is especially clear during times of light winds, buoyancy intrusions are responsible for significant convergence or divergence within the flow field at lower frequencies. The combination of the two (gray line in Fig. 13) shows high coherence throughout a frequency space of 0.05 to 0.5.

The portion of divergence solely derived from fluc-
tations of the stratification gradient and the wind stress, that is,
\[
\frac{\partial u}{\partial y}(t) = a_{\nu}(t) + a_{\nu^2}(t)
\] (12)
can be generated by taking the inverse Fourier transform of
\[
A(f) = a_{\nu^2}(f) + A_{\nu^2}(f).
\] (13)

From Eq. (12), we can construct a time series of the portion of divergence coherent with the stratification gradient and the wind stress (Fig. 12b). If we neglect \(a_{\nu}(t)\) in Eq. (12), we can construct a time series of the portion of divergence coherent with wind stress alone (Fig. 12c). The wind stress is highly correlated with the alongshore divergence (\(r = 0.61;\) Fig. 12c) as expected from Fig. 13. However, the addition of the effects due to stratification variations results in significantly greater correlation (\(r = 0.80;\) Fig. 12b), indicating that fluctuations of both the stratification gradient and wind stress are responsible for variance in divergence.

Examination of divergence and the negative of the wind stress (Fig. 12c) shows that, in agreement with Eq. (3), during periods of downwelling winds (i.e., yeardays 154–156 and 176–180), when the flow is generally downshelf, the region experiences divergence. During periods of upwelling winds (i.e., yeardays 181–183, 195–203, 214), when the flow is generally upshelf, the region experiences convergence. However, during three time periods (yeardays 167–175, 186–191, and 215–219), bracketed by the vertical lines in Fig. 12c) there is little correlation between wind stress and alongshore divergence. Although we lack density data for yeardays 186–191, we have density measurements from moorings N1 and S1 for yeardays 167–175 and the Scanfish for yeardays 155–175, 186–191, and 215–219. Both of these time periods are characterized by relatively weak winds, but strong divergence or convergence (\(\partial u/\partial y \approx 6.0 \times 10^{-6} \text{ s}^{-1}\) over yeardays 167–175 and \(\partial u/\partial y \approx -5.0 \times 10^{-6} \text{ s}^{-1}\) over yeardays 215–219). During yeardays 155–175, the region experiences strong stratification gradients (Fig. 14). During yeardays 155–167 negative stratification gradients indicate a buoyancy intrusion that enters the region from upshelf. During yeardays 167–175, the stratification gradient is strongly positive, indicating that the buoyancy intrusion has propagated downshelf. While the wind stress from yearday 167 to 175 is weak (Fig. 12c), the proxy for divergence constructed from the wind stress and stratification gradient (gray line in Fig. 12b) transfer functions is large, agreeing with the calculated divergence (black line in Fig. 12b) during this period. This agreement indicates that the buoyancy intrusion in the downshelf portion of the array (i.e., \(\partial N^2/\partial y > 0\)), not the wind, is responsible for the divergence, \(\partial u/\partial y > 0\). During yeardays 215–219, Scanfish density transects (Fig. 15) show a buoyancy intrusion in the upshelf section of the array. The southern (downshelf) transect (Fig. 15b) shows strong stratification (\(N^2 \approx 2 \times 10^{-3} \text{ s}^{-2}\) near mooring S1) onshore, characteristic of upwelling. The northern transect (Fig. 15a), in contrast, shows evidence of weak stratification (\(N^2 \approx 2 \times 10^{-4} \text{ s}^{-2}\) near mooring N1), characteristic of a buoyancy intrusion. During the absence of upwelling winds, this buoyant intrusion entered the region from upshelf, and the downshelf flow associated with the stratification gradient created convergence in the flow field (i.e., \(\partial u/\partial y \approx \partial N^2/\partial y < 0\)). There are also two other periods of strong buoyancy gradients (yeardays 155–157 and 181–182; Fig. 14), but they coincide with strong winds, which mask their impact.

Our analysis has shown that alongshore divergence is dominated by alongshore wind stress. Buoyancy in-
Buoyancy intrusions, however, tend to generate downshelf flow at scales similar to the mooring spacing and can also create alongshore divergence, as seen clearly in times of light winds. Calculation of a proxy for divergence using transfer functions derived from multi-input single-output linear systems analysis results in an expression that is highly correlated with calculated divergence ($r = 0.80$) and dependent on both mechanisms, that is,

$$\frac{\partial \nu}{\partial y} \propto F\left(\frac{\partial N^2}{\partial y} - \tau^y\right).$$

While the presence of buoyancy intrusions would be expected to cause alongshore variability in the flow field, the combination of the two relatively straightforward measurements allows for a reliable estimate of alongshore convergence or divergence on the coastal shelf.

### 5. Summary and conclusions

Mass balance calculations are performed on the flow field on the New Jersey shelf using currents from an array of moorings. During the summer season of 1996, upwelling winds created significant stratification within the relatively shallow, straight inner shelf ($<25$ m depth). However, the downshelf intrusion of buoyant waters from the Hudson River nearly 100 km upshelf of the study region created vertically well-mixed conditions characterized by low densities, as well as downshelf flow. The two competing physical mechanisms, upwelling winds and buoyancy intrusions, drive alongshore flow in opposite directions and create a flow field that varies alongshore on scales equal to those of the buoyancy intrusions ($\approx 10$–$20$ km).

Several earlier studies have demonstrated that the buoyancy intrusions can affect the flow. Buoyancy intrusions drive a generally downshelf flow that contains strong across-shore shear (Yankovsky et al. 2000) accompanied by large alongshore velocities (Yankovsky and Garvine 1998; Lentz et al. 2003). The increase in alongshore transport with buoyancy intrusions can result in alongshore divergence or convergence, depending on the direction of the alongshore stratification gradient.

Since the flow field contains numerous small-scale fluctuations that cannot be resolved by the array, we used EOF analysis to extract the large-scale flow features. Analysis of the spatial and temporal structure of the EOF modes allows greater insight into the governing dynamics of the region. The first EOF mode accounts for $67\%$ of the total variance. The depth-averaged values of this mode describe a roughly uniform alongshore flow tightly coupled to across-shore pressure gradient as well as across-shore wind stress and bottom stress ($r = 0.79$). The across-shore flow is driven by alongshore wind stress and bottom stress ($r = 0.83$). Examination of the vertical structure reveals that the first EOF mode veers strongly counterclockwise and decreases with depth. This veering is not caused by Ekman dynamics. While previous authors (e.g., Münchow and Chant 2000; Sanders and Garvine 2001) have suggested that the veering is caused by thermal wind balance, the lack of reliable density measurements prevents any rigorous analysis of the vertical structure. The second EOF mode accounts for $8\%$ of the total variance and describes a flow that varies in both the across- and alongshore directions and is correlated ($r = 0.73$) with calculations of alongshore divergence and the alongshore stratification gradient ($r = 0.62$). The depth-averaged values of this mode increase in amplitude as one goes upshelf. The downshelf direction of the current at the nearshore moorings and the upshelf direction at the offshore moorings is consistent with cyclonic flow in buoyancy intrusions described by Yankovsky et al. (2000).

Error analysis demonstrates that the first two EOF modes are statistically significant and distinct. They are, therefore, used to reconstruct a velocity field composed of fluctuations resolved by the array. A mass budget calculated using these reconstructed velocities results in satisfactory mass balance and shows that the majority of the large-scale flow is alongshore. However, the vertical structure of the EOF modes still results in significant across-shore transport.

The temporal and spatial structures of the two EOF modes suggests that the velocity field constructed from these modes contains those fluctuations due to temporal variations in wind stress, across-shore pressure gradient, and buoyancy intrusions. Multi-input linear systems analysis demonstrates that divergence is coherent with alongshore wind stress, that is, $\partial \nu/\partial y \propto -\tau^y$, at high frequencies (i.e., 0.3–0.5 cpd) and with stratification gradients, that is, $\partial \nu/\partial y \propto \partial N^2/\partial y$, at lower frequencies (i.e., 0.05–0.2 cpd). Comparison of the time series of divergence and the negative of the wind stress shows...
that divergence is primarily governed by alongshore wind stress. However, during two periods of relatively light winds but strong divergence, analysis of mooring-derived densities and Scanfish density transects reveals the presence of buoyancy intrusions in the region and confirms that divergence is related to the stratification gradient, \( \partial u / \partial y \approx \partial N^2 / \partial y \). Although wind stress is highly correlated with divergence \( (r = 0.61) \), a proxy for divergence created from time series of both the stratification gradient and alongshore wind stress results in much greater coherence \( (r = 0.80) \).

While early studies have described coastal upwelling as a two-dimensional mass balance in which subsurface mass transport compensates for surface Ekman transport, recent investigations have revealed that upwelling is characterized by significant alongshore variations which affect both the across- and alongshore transport. Previously, the mechanism for the alongshore variations has been linked to alongshore bathymetric or shoreline variations. We report a less obvious but equally effective mechanism for divergence on the continental shelf: buoyancy intrusions from river outflow. We expect this mechanism to be important in all regions that are influenced by both coastal upwelling and buoyancy intrusions.

Acknowledgments. We thank Andreas Münchow and Alexander Yankovsky for the processing of the mooring and Scanfish data. We greatly appreciate the comments on earlier drafts of this manuscript by G. Avicola, K. Brink, D. Chapman, S. Lentz, A. Münchow, M. Whitney, and A. Yankovsky, as well as two anonymous reviewers. We also thank J. S. Allen and A. D. Kirwan for challenging several of our assumptions, which led to a much improved manuscript! We gratefully acknowledge financial support by the National Science Foundation through Grant OCE-0002375.

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