Hydrographic and velocity data collected during 11 surveys at the Chesapeake Bay entrance were used to assess fortnightly variations in the lateral structure of the subtidal water exchange and density stratification. The bay entrance extends from Cape Henry to Fishermans Island and features two channels, Chesapeake Channel and North Channel. The channels are separated by Middle Ground (≤ 10 m deep) and Six-Meters shoal. Water density data were available in 8 of the 11 surveys, but current velocity data were available for all surveys. The structure of density and velocity were analyzed by comparing river discharge and wind forcing. Seasonal river input modified the eddy viscosity coefficient, through stratification changes, and became the main factor determining the velocity structure. Bathymetry, wind forcing and fortnightly tidal variations were the other modifiers. Scenarios with similar river input and wind forcing conditions showed consistent structures and they were clearly influenced by neap and spring tidal conditions. Stronger vertical stratification occurred during springs rather than during neaps in the Chesapeake Channel, in contrast to what is observed in the North Channel and to what typically would be expected elsewhere from fortnightly variability. Consistent with the vertical stratification pattern, increased transverse density gradients and two-layer circulation developed over Middle Ground and Six-Meters Shoal during spring tides. Confined to the Chesapeake Channel longitudinal velocity seems to result in larger and closer to the channel transverse density gradient during springs than during neaps and consequently larger transverse velocities.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

The lateral structure of tidal and subtidal velocities in different estuaries indicates a strong dependence on bathymetry. Lateral shear in the longitudinal flow, differential advection of density by tidal flows, lateral differences in tidal mixing energy, tidal velocity phase differences from channel to shoals, transverse velocities and axial convergence are all a result of lateral variations in bathymetry (Fischer, 1972; Lewis, 1979; Nunez and Simpson, 1985; Huzzey, 1988; Valle-Levinson et al., 2000a; Lerczak and Geyer, 2004). Because the strength of the estuarine density-driven longitudinal flow is sensitive to depth, a net transverse circulation must be generated in estuaries with cross section of variable depth (Fischer, 1972). In well-mixed estuaries, the contrasting flow speed between the deep and shallow channel can produce transverse density gradients, transverse flows and transverse turbulent mixing that reduces contaminant concentration across the channel (Smith, 1976). In the partially-mixed York River, lateral homogeneity is achieved at times of maximum flood and ebb and density gradients between channel and shoal waters develop at other times (Huzzey, 1988). The lateral gradients thus generated could be of sufficient strength to drive lateral flows during portions of the tidal cycle (e.g. Lerczak and Geyer, 2004).

Temporal variations in tidal velocity due to fortnightly variability (Le Blond, 1979; Haas (1977); Nunez and Lennon 1987) could also drive or modulate lateral flows. Spring tidal currents can increase the available tidal mixing energy, reducing stratification and the dispersive potential of estuaries (Bowden, 1977). Conversely, the decrease of turbulence during neap tides allows the development of stratification accompanied by increased gravitational circulation (e.g. Nunez and Lennon, 1987). Although there has been progress in understanding the lateral structure of velocity fields in estuaries as well as the fortnightly variability at one location, more information relative to the lateral structure of velocity in response to fortnightly variability is still required in order to understand the consequences of such variability in the dynamics of estuaries.

Although gravitational circulation in the lower Chesapeake Bay can be affected by fortnightly modulation (Valle-Levinson and
Lwiza, 1997), it can also be modified by wind forcing (Wang, 1979a,b; Goodrich and Blumberg, 1990). The individual effect of each forcing cannot be easily separated because of the coincidence in time scales (Goodrich and Blumberg, 1990). Despite those difficulties, several observations within Chesapeake Bay tributaries have indeed distinguished the tidal fortnightly variability and suggest a possible influence in the Chesapeake Bay itself. In the James, York and Rappahannock rivers, Haas (1977) observed a shift from stratified to vertically mixed conditions in correspondence with the shift from neaps to springs. This mechanism was proposed to be the primary factor controlling the hydrography along those estuaries, rather than the annual variation of river flow. Sharples et al. (1994), found that in addition to fortnightly variability in stratification in the Upper York River, it is possible to observe superimposed irregular mixing events related to wind stress. In the James River, Valle-Levinson et al., 2000b observed that lateral advective accelerations increase during spring tides and that the transverse pressure gradient is balanced by advection, friction and Coriolis accelerations, but during neap tides, the transverse pressure gradient is balanced mainly by friction and Coriolis accelerations.

The objective of this work is to describe the transverse structure of the density and the flow fields in an estuary under similar buoyancy and wind forcing conditions, and to relate those transverse structures to fortnightly variability in tidal forcing. This objective is pursued with velocity and hydrographic data obtained from 11 surveys at the Chesapeake Bay entrance, under different buoyancy input and wind forcing conditions. From those surveys, three neap–spring scenarios with similar buoyancy and wind forcing conditions were identified. In the following sections the area of study is presented; the data acquisition procedures are described; the freshwater input, wind and subtidal sea level conditions around the sampling periods are examined; the neap and spring subtidal density and velocity fields are analyzed; and the main findings are summarized.

2. Area of study

The bathymetry of the nearly 16 km-long transect at the entrance to Chesapeake Bay, from Cape Henry to Fishermans Island (Fig. 1), consists of the Chesapeake Channel (≈30 m depth), Middle Ground Shoal (≈10 m depth), the Six-Meters Shoal (6 m depth), and the North Channel (≈14 m depth). The tidal circulation in the entire Chesapeake Bay consists of a superposition of incident and reflected Kelvin and Poincaré waves damped by friction, being the $M_2$ and $K_1$ the main constituents of the wave propagation in order of importance (Fisher, 1986). Spring and neap tidal current amplitudes are about 30%–40% higher and lower than the average values, respectively (Carter and Pritchard, 1998). The Susquehanna River, the Potomac River and the James River contribute ≈82% of the total water discharge into the Chesapeake Bay (Schubel and Pritchard, 1986). The average seasonal discharge, 1992–1998, indicates that the maximum discharge occurs around March–April (≈5000 m³ s⁻¹), and the minimum around July–October (≈1000 m³ s⁻¹, Locarnini et al., 1999). Monthly hydrographic observations in the lower Chesapeake Bay (Valle-Levinson et al., 1995; a,b,c; Reyes-Hernandez and Valle-Levinson, 1997 a,b) suggest that the lower estuary varies from vertically stratified around April to vertically homogeneous (Pritchard, 1965) around October. A partially mixed situation occurs between those two conditions.

Typical winds near the bay entrance are northeasterly from August to November and southwesterly from April to July. At the bay entrance, northeasterly winds cause barotropic inflow and set-up after ≈6 h, while southwesterly winds cause barotropic outflow and set-down after ≈2 days (Paraso and Valle-Levinson, 1996). Additionally, southerly winds can enhance a bi-directional exchange between the estuary and the ocean (Valle-Levinson et al., 2001).

3. Data acquisition and processing

3.1. Density and velocity

The purpose of the data collection was to obtain subtidal density and velocity fields around neap and spring tides at times of the year of high and low river discharge in the Chesapeake Bay entrance. Data collection was carried out onboard the RV Holton, the RV Ferrel and the RV Cape Henlopen, under different meteorological and buoyancy forcing conditions. A total of eleven different 25-hour long data sets were analyzed (Table 1). Eight surveys were performed in successive neap-spring tidal conditions. The intent was for all to be consecutive neap-spring surveys, however, weather conditions hindered their execution as planned.

Velocity data were collected by towing a 614.4 kHz Broad Band RD Instruments acoustic Doppler current profiler (ADCP) during ≈25 h of sampling. The ADCP was mounted on a catamaran and towed from the ship’s starboard side. Transducers were about 0.30 m below the water surface, the first usable bin was at a depth of 1.4 m, and the bin size of the velocity profile was 0.5 m. The separation between the catamaran and the boat was about 4 m, which reduced the effect of the wake produced by the boat. The speed of the ship was about 2.5 ms⁻¹, which gave a spatial resolution for the velocity field of 75 m with about 5-second pings averaged over 30 s.

Conductivity, Temperature, and Depth (CTD) casts were repeatedly performed with a Sea Bird SBE-19 instrument at seven different locations along the transect in an attempt to capture the effect of the main bathymetric features. Therefore, separation between CTD stations was irregular (Fig. 1). The boat stopped for
Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Rep.</th>
<th>Buoyancy input (m$^3$ s$^{-1}$)</th>
<th>Wind direction (degrees)</th>
<th>Wind speed (ms$^{-1}$)</th>
<th>$\Delta$ (Gloucester-CBBT/Lewisetta-CBBT) (m/Km)</th>
<th>Transport of volume $\times 10^4$ (m$^3$ s$^{-1}$)</th>
<th>Tidal conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb/20–21/97W1</td>
<td>14</td>
<td>3820</td>
<td>118 (SE)</td>
<td>1.0</td>
<td>-0.02/-0.24</td>
<td>1.940</td>
<td>Springs</td>
</tr>
<tr>
<td>Sep/5–10/97T1,W1,B1</td>
<td>14</td>
<td>650</td>
<td>60 (NE)</td>
<td>5.2</td>
<td>0.17/-0.07</td>
<td>0.920</td>
<td>Neaps</td>
</tr>
<tr>
<td>Sep/17–18/97T2,W1,B2</td>
<td>13</td>
<td>650</td>
<td>194 (SW)</td>
<td>1.8</td>
<td>0.00/0.10</td>
<td>1.310</td>
<td>Neaps</td>
</tr>
<tr>
<td>Jun/25–26/98W1</td>
<td>11</td>
<td>3800</td>
<td>167 (SE)</td>
<td>1.2</td>
<td>0.13/0.04</td>
<td>-0.336</td>
<td>Springs</td>
</tr>
<tr>
<td>Jul/6–7/98T1,W1</td>
<td>9</td>
<td>2360</td>
<td>72 (NE)</td>
<td>4.6</td>
<td>0.17/-0.03</td>
<td>1.147</td>
<td>Neaps</td>
</tr>
<tr>
<td>May/30–Oct/1/98T2,W1</td>
<td>10</td>
<td>800</td>
<td>189 (SW)</td>
<td>3.4</td>
<td>0.70/0.96</td>
<td>-0.750</td>
<td>Neaps</td>
</tr>
<tr>
<td>May/07–08/99T1,W4</td>
<td>9</td>
<td>2400</td>
<td>205 (SW)</td>
<td>3.8</td>
<td>0.55/0.55</td>
<td>0.000</td>
<td>Neaps</td>
</tr>
<tr>
<td>May/22–23/99T1,W4</td>
<td>14</td>
<td>2400</td>
<td>213 (SW)</td>
<td>3.1</td>
<td>0.44/0.06</td>
<td>0.625</td>
<td>Neaps</td>
</tr>
<tr>
<td>May/30–31/99T1,W1,B2</td>
<td>12</td>
<td>2400</td>
<td>224 (SW)</td>
<td>3.1</td>
<td>0.18/0.53</td>
<td>-0.215</td>
<td>Springs</td>
</tr>
<tr>
<td>Sep/26–27/99T1,W2</td>
<td>9</td>
<td>700</td>
<td>85 (NE)</td>
<td>2.1</td>
<td>-0.02/0.08</td>
<td>0.716</td>
<td>Springs</td>
</tr>
<tr>
<td>Oct/2–3/99W1</td>
<td>12</td>
<td>1000</td>
<td>166 (SE)</td>
<td>3.7</td>
<td>0.58/0.39</td>
<td>-0.696</td>
<td>Neaps</td>
</tr>
</tbody>
</table>

Each CTD cast and the velocity data recorded during each CTD cast were discarded because of frequent change of orientation of the ADCP. Each transect line was completed in about two hours, and the average time between CTD stations was about 23 min. Table 1 shows the number of times the transect line was repeated in each cruise, which also corresponds to the number of CTD casts for each station except the end stations 1 and 7, which usually was the number of repetitions minus 4.

Velocity data were interpolated to a uniform grid with spacing of 200 m in the horizontal and 0.5 m in the vertical. The velocity components were rotated 11° clockwise to align them along and across the main channel; this coincided with the overall direction of maximum variability in the tidal current across the bay entrance. Semidiurnal and diurnal harmonics plus a residual or subtidal flow were fitted to the observed flow at each grid point by means of least squares (e.g. Lwiza et al., 1991). The reason for the use of two tidal frequencies was based on the knowledge of the main tidal constituents (Fisher, 1986), and the time for the ship to pass over the same transect points, which varied from 0.66 to 4 h. The vertical CTD profiles of each station were bin-averaged to one-meter intervals. A density time series that equaled the number of repetitions was constructed for each depth and station and also a harmonic function was fitted to it in order to relate the subtidal density and velocity fields, which is the focus of this work. The subtidal variables were compared from survey to survey to point out similarities and differences that might have resulted from the different conditions present during the surveys. Although buoyancy and wind forcing contributed to the observed variability of the density and velocity sectional structures, it will be shown that most of the variability corresponded to neap and spring tidal conditions.

3.2. Ancillary data.

The surveys were performed in February, May, June, July, September and October to capture high and low buoyancy input conditions and assess fortnightly variability under such conditions. It has been estimated that salinities of the lower bay respond to the integrated 90 days that precede them (Locarnini et al., 1999). Therefore, a three-month running average of the freshwater inflow to the bay was used as an indicator of the freshwater conditions around the dates of data collection (Fig. 2, Table 1). Typically, the freshwater discharge in September is the lowest of the year. This was consistent for the surveys performed around that month in 1997, 1998 and 1999, where freshwater discharge was about 700 m$^3$ s$^{-1}$. The survey performed in October, 1999, had freshwater input of 1000 m$^3$ s$^{-1}$. Though typically April and May are months with maximum freshwater discharge, February 1997 and June 1998 exhibited anomalously high freshwater discharge conditions about 50% greater than May 1999.
filter with a cut-off frequency of 0.03 h$^{-1}$ to remove diurnal, semi-diurnal, and higher frequency fluctuations. Because sea level data at CBBT were consistently higher than at Gloucester and Lewisetta during the months of each sampling, which would imply a permanent setup towards CBBT, the sea level at Gloucester and Lewisetta were shifted up by adding the mean sea level difference between each station and CBBT. It will be seen ahead that this procedure produced consistent results with wind direction and independent numerical experiments. The horizontal sea level gradient was then estimated as follows:

$$\eta_i = \frac{\eta_i \text{(Gloucester-Lewisetta)} - \eta_i \text{(CBBT)}}{\text{dist (Gloucester-Lewisetta-CBBT)}}$$

where $\eta_i$ is the hourly sea level value at each of the stations. Values of $\eta_i < 0$ imply higher sea level at CBBT and therefore a pressure gradient acceleration towards Gloucester or Lewisetta. The denominator indicates the distance between CBBT and the other 2 stations.

4. Results

The average conditions around each survey are summarized in Table 1. Six surveys occurred in high buoyancy input conditions: three during neaps and three during springs; five surveys occurred under low buoyancy conditions: three during neaps and two during springs. Wind speeds varied around 5.1 ms$^{-1}$ throughout each experiment, but wind direction varied from SW, NE and SE. No preferential wind direction can be assigned to any of the buoyancy input or tidal conditions.

Hourly wind and the estimated sea level gradients $\eta_i$ Gloucester-CBBT and $\eta_i$ Lewisetta-CBBT correspondent to the 25-hour survey and the three previous days (Fig. 3), shows a rapid and consistent response to wind forcing. In consequence, the sea level gradient sign as well as the net volume transport estimated for each survey (Table 1), were, in general, consistent with the respective mean direction of wind and with wind-driven numerical experiments at the Chesapeake Bay by Guo and Valle-Levinson (2008), except on February/20–21/1997, July/6–7/1998 and Sept/26–27/1999 when evolving or oscillatory sea level occurred. The differences in magnitude $\eta_i$ Gloucester-CBBT and $\eta_i$ Lewisetta-CBBT (Fig. 3), larger for NE and SW winds than for SE wind, are explained from slopes alignment relative to the wind direction and distance between stations: NE and SW wind produced a smaller $\eta_i$ Gloucester-CBBT than $\eta_i$ Lewisetta-CBBT. NW wind produced set-up away from the bay and SE wind caused set-up over the northwestern side of the bay. Therefore, these winds drove positive and negative sea level gradients of relatively larger magnitude between Lewisetta and CBBT than between Gloucester and CBBT.

There were five parameters to consider in describing the hydrographic and velocity fields: buoyancy input, wind direction, tidal conditions, sea level gradient and net transport of volume. The approach was to focus in the first three, selecting

---

Fig. 3. Hourly wind arrows observed at the Chesapeake Bay Bridge Tunnel (NOAA) and sea level gradient Lewisetta-CBBT (solid line) and Gloucester-CBBT (dashed line) during the different cruises. Arrows indicate downstream direction. (a) Sept/09–10/97, neap tides; (b) sept/26–27/99, spring tides; (c) sept/30-Oct/01/98, neap tides; (d) sept/17–18/97, spring tides; (e) may/07–08/99, neap tides; (f) june/25–26/98, spring tides.
density and velocity structures with relative similarity in two of the conditions but contrasting in the third. In this way, it was possible to form two groups of similar wind and tidal conditions but contrasting buoyancy input conditions (superscript B1 and B2); four groups of similar buoyancy and tidal conditions but contrasting wind direction (superscript W1, W2, W3 and W4) and three groups of neap and spring tides conditions with similar buoyancy input and wind direction conditions (superscript T1, T2 and T3). The sea level gradient and the net transport of volume, generally consistent with the wind direction, will be mentioned in each case. It is useful to keep in mind that the surveys performed during Feb/20–21/1997 and May/22–23/1999 had no CTD data.

4.1. Buoyancy input comparison

The seasonal freshwater discharge was evident in the structure of density (Fig. 4, pairs B1 and B2). During low buoyancy input, buoyant water usually occupied the surface in the Chesapeake Channel while denser water occupied the North Channel from surface to bottom as well as the deep Chesapeake Channel (Fig. 4a, b, e, 4h and Table 2). Consequently, lateral density differences, throughout the bay entrance, could be as large as vertical density differences within the Chesapeake Channel. During high buoyancy conditions, buoyant water usually occupied the surface throughout the wide entrance, such that lateral density differences across the entrance were comparatively smaller than the vertically density differences at the Chesapeake Channel (Fig. 4c, d, f, g and Table 2). On the other hand, vertical density differences in the North Channel were smaller than the vertical density differences in the Chesapeake Channel. Consistently, values of potential energy anomaly (Simpson et al., 1978) indicated stronger stratification for high buoyancy input compared to low buoyancy input conditions (Fig. 5; Table 2, pairs B1 and B2). Stratification existed in the Chesapeake Channel, regardless of the buoyancy input conditions; however, over Middle Ground Shoal, Six-Meters Shoal and North Channel, all <14 m, stratification was variable. The lateral and vertical distribution of density and of the stratification along the bay entrance, remarks the role of buoyancy input and bathymetry on mixing. Wind and neaps–springs forcing should occur around a laterally inhomogeneous estuary for low buoyancy input and around a vertically stratified estuary for high buoyancy input conditions.

Lateral variations from low to high buoyancy input conditions were also evident in the along-estuary velocity component, pairs B1 and B2 (Table 1; Fig. 6). During low buoyancy input the structure of longitudinal velocity was mainly laterally sheared, resembling that of a frictional estuary of triangular section...
(Wong, 1994; Fig. 6b, c, f, j and k). However here, outflow occurred in the shallow areas of the Chesapeake Channel and the North Channel and inflow occurred at the boundary between Middle Ground Shoal and Six-Meters Shoal. During high buoyancy input conditions the structure of longitudinal velocity resembled the classical vertically sheared gravitational circulation (Pritchard, 1956; Fig. 6a, d, e, g, h, i). Two-layer flow occupied the transverse section from the Chesapeake Channel to the North Channel, with outflow by the surface and inflow by the bottom. It will be shown later, that this vertically sheared velocity structure, also approached the form given by Wong (1994) during spring tides with unidirectional landward flow between Middle Ground Shoal and Six-Meters Shoal (Fig. 6c and i). Regardless of buoyancy conditions the magnitude of the longitudinal component of velocity was larger than the transverse component. Also, the magnitudes of each of the two components, longitudinal and transversal, were larger during high than during low buoyancy conditions. Faster transverse velocities for high buoyancy input

<table>
<thead>
<tr>
<th>Survey</th>
<th>Tidal conditions</th>
<th>Vertical density diff.</th>
<th>Lateral density diff.</th>
<th>Long. vel. range CC</th>
<th>Long. vel. range NC</th>
<th>Trans. vel. range CC</th>
<th>Trans. vel. range NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb/20–21/97W3</td>
<td>Springs</td>
<td>—</td>
<td>—</td>
<td>27.2 (+)</td>
<td>13.1 (+)</td>
<td>6.1 (+)</td>
<td>6.4 (+)</td>
</tr>
<tr>
<td>Sept/09–10/97W1,W2</td>
<td>Neaps</td>
<td>2.0</td>
<td>2.5</td>
<td>13.0 (+)</td>
<td>6.9 (+)</td>
<td>5.0 (+)</td>
<td>4.7 (+)</td>
</tr>
<tr>
<td>Sept/17–18/97W2,W3</td>
<td>Springs</td>
<td>2.5</td>
<td>3.5</td>
<td>19.7 (+)</td>
<td>4.4 (+)</td>
<td>5.8 (-)</td>
<td>5.6 (-)</td>
</tr>
<tr>
<td>June/25–26/98W3</td>
<td>Springs</td>
<td>8.5</td>
<td>2.0</td>
<td>30.2 (-)</td>
<td>9.5 (-)</td>
<td>14.3 (-)</td>
<td>12.7 (-)</td>
</tr>
<tr>
<td>Jul/06–07/98W4,W1</td>
<td>Neaps</td>
<td>9.0</td>
<td>2.0</td>
<td>19.0 (+)</td>
<td>7.2 (+)</td>
<td>6.7 (-)</td>
<td>3.3 (+)</td>
</tr>
<tr>
<td>Sept/30–Oct/01/98W1</td>
<td>Neaps</td>
<td>1.5</td>
<td>3.5</td>
<td>15.9 (-)</td>
<td>5.0 (-)</td>
<td>8.0 (-)</td>
<td>4.2 (-)</td>
</tr>
<tr>
<td>May/07–08/99W4</td>
<td>Neaps</td>
<td>6.3</td>
<td>2.0</td>
<td>27.5 (-)</td>
<td>17.1 (+)</td>
<td>10.5 (-)</td>
<td>13.4 (-)</td>
</tr>
<tr>
<td>May/22–23/99W4</td>
<td>Neaps</td>
<td>—</td>
<td>2.0</td>
<td>23.0 (+)</td>
<td>12.7 (-)</td>
<td>6.6 (-)</td>
<td>6.5 (-)</td>
</tr>
<tr>
<td>May/30–31/99W3,W2</td>
<td>Springs</td>
<td>6.0</td>
<td>3.0</td>
<td>28.0 (-)</td>
<td>24.9 (-)</td>
<td>9.4 (-)</td>
<td>9.5 (-)</td>
</tr>
<tr>
<td>Sept/26–27/99W1,W2</td>
<td>Springs</td>
<td>3.0</td>
<td>5.5</td>
<td>19.9 (+)</td>
<td>5.1 (+)</td>
<td>6.2 (-)</td>
<td>2.4 (+)</td>
</tr>
<tr>
<td>Oct/2–3/99W1</td>
<td>Neaps</td>
<td>4.5</td>
<td>3.0</td>
<td>21.0 (-)</td>
<td>9.4 (-)</td>
<td>7.6 (-)</td>
<td>10.1 (-)</td>
</tr>
</tbody>
</table>

Fig. 5. Magnitude of the estimated potential energy anomaly (Wm⁻²) for each of the CTD stations across the Chesapeake Bay Entrance during each sampling cruise. Top panel low buoyancy input conditions; bottom panel high buoyancy input conditions.
conditions were not consistent with the larger lateral density differences found; therefore, other mechanisms in addition to the lateral pressure gradient should explain that behavior. Again, wind and neaps-springs driven velocities should occur around a laterally sheared estuary for low buoyancy input and around a vertically sheared estuary for high buoyancy input conditions.

4.2. Contrasting wind comparison

Contrasting wind conditions were analyzed through groups with similar buoyancy input and tidal conditions W1, W2, W3 and W4 (Table 1). Group W1 occurred during low buoyancy input, neap tides and NE, SW and SE wind all $\leq 1.8\text{ m s}^{-1}$. Group W2 experienced low buoyancy input, spring tides and NE and SW wind between 1.8–2.1 m s$^{-1}$. Group W3 occurred under high buoyancy input, spring tides and SE and SW wind $< 3.1\text{ m s}^{-1}$ and group W4 occurred under high buoyancy input, neap tides and NE and SW wind $> 3.0\text{ m s}^{-1}$.

No substantial differences in the vertical and lateral density contrast (Fig. 4) nor in potential energy anomaly (Fig. 5) resulted from the comparison of contrasting wind conditions, except on the W1 surveys where stratification from strong to weak corresponded to SE, NE and SW wind. It seems possible, however, that the stronger stratification observed under SE wind, October/2–3/1999, corresponded to the anomalous high fresh water pulse rather than to wind conditions, such pulse was about 42% greater than that of September. These results open the possibility that the observed structures of density in consecutive neap and spring tides (such as those on Sept/9–10/1997, Sept/17–18/1997, and June/25–26/1998, July/6–7/1998) were not in response to the different wind direction forcing, but to tidal modulation.

Under NE wind, the structure of longitudinal velocity showed a lateral partition that was better defined under low buoyancy input (Fig. 6b and j) than under high buoyancy input (Fig. 6e), particularly in the Chesapeake Channel. SW and SE winds and low buoyancy input seemed related to a lateral structure of velocity, mainly between the shoals and the channel (Fig. 6c, f and k). Under SW and SE winds and high buoyancy input, the structure of velocity remained mainly vertical, even over the shoals (Fig. 6a, d, g, h and i). The structure of the transverse velocity component had not definitive patterns: under NE and SW winds, two-layer circulation (Fig. 6b, e, f, g, h and i) or cells of convergence and divergence (Fig. 6c and j) were present. Under weak, SE wind, transverse two-layer exchange occurred. Under moderate SE wind, uniform, down-wind transverse velocity was observed (Fig. 6d and k).
4.3. Neaps-springs comparison

The comparison of the density and velocity structures under similar buoyancy input and wind but contrasting tidal conditions (Table 1, superscripts T1, T2 and T3), had clear dependence on the neaps and springs conditions, as well as on bathymetry.

Under low and high buoyancy input conditions, larger lateral density differences from the Chesapeake Channel to the North Channel occurred for spring tides rather than for neap tides (Fig. 4a and h, b and e and f and g; Table 2). Also, isopycnals indicated that during low buoyancy input conditions, the transverse density gradient during spring tides located mainly at the northern side of the Chesapeake Channel, while during neap tides it located around Six-Meters Shoal. Under high buoyancy input conditions the transverse density gradient located at Six-Meters Shoal for spring tides and at the northern side of the North Channel during neap tides. In all comparisons the transverse density gradient during spring tides was relatively large compared to that during neap tides. Unexpectedly, under low and high buoyancy input conditions, vertical stratification at the Chesapeake Channel, was stronger during spring tides than during neap tides (Fig. 5; 0, 1.6 and 2.8 km), while, as would be expected, from Middle Ground Shoal to the North Channel stratification was comparatively weaker during spring tides than during neap tides (Fig. 5; 6.1 to 15.6 km). Some departures to this pattern occurred in pair T2, possibly associated to the contrasting directions of net transport of volume in those two surveys.

At the Chesapeake Channel, under low buoyancy input conditions, the vertically sheared structure of velocity was sharper for spring tides (Fig. 6c, i and j) than for neap tides (Fig. 6b, f, g and h); in contrast to the Chesapeake Channel, from Middle Ground Shoal to the North Channel, the structure of longitudinal velocity was laterally sheared during spring tides and vertically sheared during neap tides. Under high buoyancy input conditions and neap tides, the longitudinal velocity structure was vertically sheared from the Chesapeake Channel to the North Channel (Fig. 6g and h and e). During high buoyancy input and spring tides, however, vertically sheared velocities constrained to the channels while about Six-Meters Shoal, the structure was laterally sheared, with landward depth independent velocity (Fig. 6i). The transverse velocity component exhibited also structures dependent on buoyancy and tidal conditions. For low buoyancy input conditions and neap tides (Fig. 6b and j), two-layer exchange occurred between the northern half of the Chesapeake Channel and Middle Ground Shoal and between Six-Meters Shoal and the southern half of the North Channel, with northward velocities by the surface and southward velocities by the bottom. During low buoyancy input conditions and spring tides (Fig. 6e and f), the two-layer exchange occurred between Middle Ground Shoal and Six-Meters Shoal, while at the Chesapeake Channel and at the North Channel velocities were convergent and divergent throughout the whole water column. Convergence occurred by the northern and southern sides of the Chesapeake and North channels respectively and divergence occurred by the southern and northern sides of the Chesapeake and North channels respectively. During high buoyancy input conditions and for neap and spring tides, the structure of transverse velocity exhibited three-layer exchange, with surface and bottom northward velocities and mid-depth southward velocities. During neap tides (Fig. 6g, h and i), three-layer exchange existed between Middle Ground Shoal and Six-Meters Shoal, while the Chesapeake Channel and North Channel showed two-layer exchange with northward velocities by the surface and southward velocities by the bottom. During spring tides, the three layer exchange occupied the northern half of the Chesapeake Channel and the southern Middle Ground Shoal. From Middle Ground Shoal to the North Channel two-layer exchange existed, but in contrast to neap tides, with southward velocities by the surface and northward velocities by the bottom.

So far results indicate that, while from Middle Ground Shoal to the North Channel, the stratification and longitudinal velocity were within the expected neaps and spring patterns; in the Chesapeake Channel intensification of the vertically sheared longitudinal velocity structure coincided with nearer to the Chesapeake Channel and larger transverse density gradient for spring than for neap tides.

To explore further these results, the relative importance of the available accelerations were compared. In the longitudinal direction friction, advection and Coriolis were compared throughout dimensionless analysis. For the transverse direction, the available transverse subtidal terms were compared. This exercise did not intend to work out complete balances as clearly that cannot be achieved; instead, it was performed to provide clues about the relative importance of accelerations as function of neaps and springs across the section. The results shown here on correspond exclusively to similar buoyancy input and wind conditions but contrasting tidal conditions, cases T1, T2 and T3.

The comparison of the advective acceleration against friction in the longitudinal direction was assessed through the estuarine Reynolds number

$$R_e = \frac{R_o}{E_k}$$

where $R_o$, the Rossby number, compares adective and Coriolis accelerations and is given (c.f. Vallis, 2006) as

$$R_o = \frac{U}{fB}$$

$U$ is the magnitude of the sub-tidal longitudinal velocity component, $f$ is the Coriolis parameter and $B=200\text{ m}$ is the horizontal grid space (see Section 3.1). $E_k$ is the Ekman number (Kasai et al., 2000)

$$E_k = \frac{A_z}{fH_{max}}$$

a comparison of friction against Coriolis acceleration. $H_{max}$ is the maximum depth of the water column and $A_z$ is the eddy viscosity coefficient. The magnitude of the eddy viscosity coefficient was estimated as function of stratification and velocity (Munk and Anderson, 1948) as

$$A_z = \frac{A_0}{\sqrt{1+10R_i}}$$

where $A_0 = 2.5 \times 10^{-3}U_sH$ is the eddy viscosity coefficient dependent on the longitudinal tidal current $U_s$ and depth $H$ (Bowden, 1953), and $R_i$ is the subtidal gradient Richardson number

$$R_i = -\frac{g}{\rho} \frac{\partial \rho}{\partial z} \frac{\partial u}{\partial z}^2 + \frac{\partial v}{\partial z}^2$$

In this work, $R_i$ was computed from the vertical density and velocity gradients at each repetition and averaged over the tidal cycle.

The relative importance of friction to Coriolis acceleration, expressed as $\log_{10} E_k$ (Fig. 7) varied from $O(10^{-1.4})$ to $O(10^0)$ during low buoyancy input and from $O(10^{-1.6}$ to $O(10^{-0.6})$ during high buoyancy input. The largest $E_k$ numbers, indicating dominance of friction over Coriolis, occupied Six-Meters Shoal, while relatively small $E_k$ occupied the Chesapeake and North channels, indicating increased importance of Coriolis acceleration. During low buoyancy input and neap tides, the lowest $E_k$ numbers
spanned from the channels to Six-Meters Shoal, forming a laterally sheared distribution over the shoals. During spring tides the lateral distribution restrained even more to Six-Meters Shoal, therefore, $E_k$ distribution was vertically dependent from the channels toward Six-Meters Shoal. During high buoyancy input and neap tides $E_k$ contours were laterally sheared at Six-Meters Shoal. Therefore, Coriolis acceleration was relatively significant within the channels, but over the shoals friction was dominant. Also it seems that from neaps to springs, Coriolis acceleration relative importance spans towards Middle Ground Shoal from the Chesapeake Channel.

The comparison of advective vs. Coriolis acceleration was expressed as $\log_{10} R_o$ (Fig. 8) and ranged from $O(10^0)$ to $O(10^1)$ for both, low and high buoyancy input conditions; the largest $R_o$ numbers indicating dominance of advection over Coriolis. Advective acceleration was dominant in all cases. Large $R_o$ numbers occurred near the surface and bottom as well as over the sides of the channels and at Six-Meters Shoal. Within the Chesapeake Channel large $R_o$ contours corresponded to the position of maximum longitudinal velocity cores, near surface and bottom (cf. Fig. 6). Small $R_o$ numbers therefore formed a strip about mid depth, coincident with the position of the longitudinal velocity shears. $R_o$ contours were nearly constant with depth for low buoyancy input but depth dependent for high buoyancy input. For low buoyancy input, within the Chesapeake Channel and the North Channel, $R_o$ contours distribution was mainly laterally sheared for neap tides and vertically sheared for spring tides, but at Middle Ground Shoal and Six-Meters Shoal, $R_o$ distribution was laterally sheared for both conditions. For high buoyancy input, $R_o$ distribution was about the same for neap and spring tides within the Chesapeake and the North channels, however, at Middle Ground Shoal and Six-Meters Shoal contours distribution was vertically sheared during neaps and laterally sheared during springs. Compared to advection, Coriolis importance was mainly limited to the Channels and Middle Ground Shoal.

The magnitude of $R_e$ expressed as $\log_{10} R_e$ (Fig. 9), was slightly higher for high than for low buoyancy input conditions, however, the range of variation was similar, $O(10^{0.8})$ to $O(10^{1.8})$ indicating predominance of advection over friction as can be expected from the previous result from Ekman and Rossby numbers. Relatively large $R_e$ numbers occupied the upper layers from Middle Ground Shoal to the Chesapeake Channel, where distribution about depth independent, with low $R_e$ toward the northern side slope of the channel. Relatively low numbers, $\log_{10}(R_e) < 1$, distributed from the lower layers at Middle Ground Shoal to the whole column in the North Channel, in a vertically sheared distribution. Although the distribution structure of $R_e$ was similar for low and high buoyancy input, neaps and springs patterns suggest that low $R_e$ numbers reached further south during spring tides than during neap tides for both high and low buoyancy input, as result of increased friction.

According to comparisons, advection was the most relevant acceleration, while Coriolis and friction played a secondary role. Advection and Coriolis showed the largest magnitudes within the Chesapeake Channel, friction showed increased importance toward Six-Meters Shoal. While during neap tides advection and Coriolis appeared confined to the Chesapeake Channel in favor of friction. During spring tides the two accelerations spanned toward Six-Meters Shoal confining friction.

For the comparison of accelerations in the transverse direction, the stationary transverse subtidal balance in a right hand
coordinate system was used

\[
\begin{align*}
\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{w}}{\partial y} + \frac{\partial \bar{u}}{\partial z} + f\bar{u} &= -\frac{g}{\rho_0} \int \frac{\partial \bar{\theta}}{\partial y} \, dz \\
&\quad + \frac{g}{\rho_0} \frac{\partial \bar{r}}{\partial y} + \left( \frac{\partial \bar{r}}{\partial z} \right)
\end{align*}
\]

where the brackets represent the tidal-cycle (25 h) average. Here, the first, third and sixth terms of the balance could not be estimated from the collected data; therefore only the transverse advection of velocity, Coriolis, baroclinic pressure gradient and friction were used.

The ratio of friction to the baroclinic pressure gradient (Fig. 10), varied from \(O(10^{-1})\) to \(O(10^{1})\); the largest values indicating dominance by friction. In general friction was dominant throughout the section for both low and high buoyancy input. While friction was comparatively large near the surface from the center in the Chesapeake Channel to North Channel, baroclinic acceleration was dominant within the channels near the southern slope in the Chesapeake Channel and the northern slope in the North Channel. During neap tides friction was dominant across the bay entrance from surface to bottom; during spring tides, however, baroclinic acceleration acquired relevance at the southern slope of the Chesapeake Channel and northern slope of the North Channel.

The ratio of advection to friction, expressed as \(\log_{10}\) (Fig. 11), varied from \(O(10^{-1})\) to \(O(10^{1})\) for low buoyancy input and from \(O(10^{-1})\) to \(O(10^{1})\) for high buoyancy input. While friction was dominant over Middle Ground Shoal and Six-Meters Shoal, advection was important within the Chesapeake and North channels. For low and high buoyancy input and within the channels, the relative importance of advection during spring tides was larger than during neap tides.

The ratio of advective to baroclinic acceleration, expressed as \(\log_{10}\) (Fig. 12), varied from \(O(10^{-1})\) to \(O(10^{1})\) for both low and high buoyancy input. In general advection was dominant near the surface and baroclinic pressure was dominant near bottom. In the Chesapeake Channel, however, the distribution was rather nearly depth independent with relatively important advection and baroclinic accelerations at the southern and northern sides of the channel respectively. For low buoyancy input, the vertically sheared acceleration distribution accentuated and no discernible neaps and springs patterns were evident. For high buoyancy input, advection was relatively important near surface and bottom while baroclinic acceleration importance constrained to mid-depth strip within the Chesapeake Channel during neap tides and from that channel to Six-Meters Shoal during spring tides.

The ratio of Coriolis to friction (Fig. 13), varied from \(O(10^{-1})\) to \(O(10^{1})\) during low buoyancy input and from \(O(10^{-1})\) to \(O(10^{0})\) during high buoyancy input. Friction dominated through most of the bay entrance, Coriolis constrained to the channels. No clear neap and spring tides patterns could be identified for neaps and springs, however, during high buoyancy input, while Coriolis occupied most of the Chesapeake Channel during spring tides, during neap tides it occupied just a narrow vertical band at the center of it.

The ratio Coriolis to baroclinic acceleration, expressed as \(\log_{10}\) (Fig. 14), varied from \(O(10^{-1})\) to \(O(10^{2})\) for low buoyancy input and from \(O(10^{-0.5})\) to \(O(10^{1.5})\) for high buoyancy input, where
largest values indicated relative dominance of Coriolis. Coriolis acceleration was dominant near the surface. The baroclinic acceleration, on the other hand, was dominant at the lower Chesapeake Channel and North Channel. During low and high buoyancy input and neap tides, baroclinic acceleration confined to the low Chesapeake Channel and to Six-Meters Shoal, but during spring tides, the baroclinic acceleration spanned from the low Chesapeake Channel to Middle Ground Shoal and from the North Channel to Six-Meters Shoal.

The ratio of Coriolis to advective acceleration expressed as $\log_{10}$ (Fig. 15), varied from $O(10^{-1})$ to $O(10^1)$ for both low and high buoyancy input. The largest values indicated the relative dominance of Coriolis over advection. Although not clear neap and springs patterns emerged for low and high buoyancy input, it seemed that during neap tides advection constrained to the lower southern side of the Chesapeake Channel, while Coriolis was relatively important near the surface over Middle Ground Shoal and the North Channel. On the other hand, during spring tides advection was relatively important in the channels and Coriolis constrained to a narrow band at mid depth in the Chesapeake Channel and at Six-Meters Shoal.

In summary, transverse accelerations dominance is given by friction, advection, baroclinic gradient and Coriolis. Although in general friction was relevant at the shoals and at the surface and bottom in the channels, it competed with advection at the Chesapeake Channel and North Channel during spring tides. The baroclinic pressure gradient and Coriolis generally were relatively important in the channels and their relative importance also increased during spring tides, expanding toward the shoals.

5. Discussion

Although short in number, the patterns of density and velocity from each survey suggest that neaps and springs subtidal variations across the bay entrance depended on buoyancy input, bathymetry and tidal conditions. In spite of consistency among water level slopes, net transport of volume and direction of wind in most of the surveys, the role of wind magnitude, about $5 \text{ ms}^{-1}$, had little relevance on the resulting patterns. The net transport of volume was in the wind direction under developing set-up and in opposite direction ensuing completely developed set-up. Water density and mixing increased from Chesapeake Channel to North Channel. Therefore, during low buoyancy input conditions, water characteristics were closely oceanic and lateral inhomogeneity characterized the density distribution. During high buoyancy input conditions, vertical stratification characterized the density distribution across the section. In consequence, during high buoyancy input conditions, vertical stratification increased relative to low buoyancy input. In concordance with depth, the Chesapeake Channel remained stratified during low and high buoyancy input conditions and the shoals and North Channel had variable stratification. Also consequent, the longitudinal component of velocity approached a laterally sheared structure during low buoyancy input and a vertically sheared structure during high buoyancy input and its magnitude was larger during high than during low buoyancy input, especially at the Chesapeake Channel.

Within the context given by similar buoyancy input conditions and bathymetry, the structures of density and longitudinal and transverse velocities, exhibited variations for neap and spring
Fig. 10. Ratio of friction acceleration to the baroclinic pressure gradient acceleration expressed as $\log_{10}$.

Fig. 11. Ratio advective acceleration to friction accelerations expressed as $\log_{10}$. 
Fig. 12. Ratio advective acceleration to baroclinic acceleration expressed as $\log_{10}$.

Fig. 13. Ratio Coriolis acceleration to friction acceleration expressed as $\log_{10}$. 
tidal conditions, however, some aspects were unexpected. From Middle Ground Shoal to North Channel, stratification was weaker during spring tides than during neap tides but in the Chesapeake Channel the opposite occurred: stratification was stronger during spring than during neap tides. Consistent with stratification, from Six-Meters Shoal to the North Channel longitudinal velocity was nearly depth independent under springs and depth dependent under neaps, however, from the Chesapeake Channel to Middle Ground Shoal the structure of longitudinal velocity was depth dependent under springs and depth independent under neaps.

The gross comparison of longitudinal accelerations suggests that during neap tides, advection and Coriolis were relatively important in the channels while friction dominated at the shoals but during spring tides, advection and Coriolis importance extended northward and southward from the Chesapeake and North channels, and friction was relevant only at Six-Meters Shoal. On the other hand, the comparison of accelerations in the transverse direction suggests that friction and advection had probably a more important role than the baroclinic pressure gradient and Coriolis and, in a similar way to the longitudinal component, advection, baroclinic pressure and Coriolis relative importance spanned from the channels toward the shoals during spring tides.

Although the transverse distribution of density had similar tidal patterns for low and high buoyancy conditions, the location of the transverse density gradient shifted southward from neap to spring tides, in agreement with larger mixing efficiency at larger depths during spring tides. The weak stratification and depth independent structure of longitudinal velocity over the shoals during spring tides, suggests that part of the kinetic energy was used to produce mixing. In consequence, larger transverse density differences and baroclinic accelerations could migrate northward during spring tides. Two and three-layered transverse flows seemed to occur between the Chesapeake Channel and Middle Ground Shoal and between the North Channel and Six-Meters Shoal during neap tides and between Middle Ground Shoals and Six-Meters Shoal during spring tides. This pattern seems consistent with the lateral migration of large baroclinic accelerations from neaps to springs.

During spring tides not just stratification and longitudinal velocity intensification occurred, in the Chesapeake Channel, but also those structures occupied partially Middle Ground Shoal. In consequence the relative importance of advection should increase northward from Chesapeake Channel. Weak vertical stratification and laterally sheared longitudinal velocity structures from Middle Ground Shoal to North Channel during spring compared to neap tides, are indication of intense friction effects. In the Chesapeake Channel, larger vertical density differences and larger longitudinal velocity shear during spring tides than during neap tides suggest that there advection should control the longitudinal estuary-ocean exchange during spring tides. The relative increase of longitudinal velocity and transverse density gradient between the Chesapeake Channel and the shoals, should increase the transverse velocities and consequently the advective and frictional terms in the transverse balance.

6. Conclusions

A set of eleven surveys 25-hour surveys performed along the Chesapeake Bay entrance were analyzed to assess the neaps and springs variability on the subtidal density and velocity transverse structures. The surveys were carried under different buoyancy input, wind and tidal conditions from 1997 to 1999.
Comparisons using similar buoyancy and wind conditions but contrasting tidal conditions showed that density and velocity main lateral distribution patterns were consistent with bathymetry, neap and spring tidal conditions. While the shoals exhibited the expected weaker stratification and closer laterally sheared velocity distribution for spring than for neap tides, the Chesapeake Channel had an unexpected opposite pattern, with sharper stratification and vertically sheared structure of velocity during spring than during neap tides. Results, however, are in agreement with the observed density and velocity structures. In dynamic terms it can be said that while friction was dominant through the shoals, advection and Coriolis in the longitudinal direction and advection, baroclinic pressure gradient and Coriolis in the transverse direction, were the most important accelerations in the Chesapeake Channel and the North Channel. During neap tides those accelerations confined to the channels and friction was relatively important at the shoals, during spring tides, however, the relative importance of those accelerations spanned from the Chesapeake Channel to Middle ground shoal and from the North Channel to Six-Meters Shoal, constraining friction dominance.

Acknowledgments

We thank to the crews of the RV Holton from Old Dominion University, the RV Ferrel from NOAA and the RV Cape Henlopen from the University of Maryland as well as all participating volunteers. Thanks to Sergio Mendoza Vázquez from UMAR for his help with figures edition.

Fig. 15. Ratio Coriolis acceleration to advective acceleration expressed as log₁₀. (a) Sept/09–10/1997, neap tides; (b) sep/26–27/1999, spring tides; (c) sep/30–Oct/01/1998, neap tides; (d) sept/17–18/1997, spring tides; (e) may/07–08/1999, neap tides (f) may/30–31/1999, spring tides, (g) july/6–7/1998, neap tides; (h) june/25–26/1998, spring tides; (i) oct/2–3/1999, neap tides.

References