

## FLOW PATTERNS AT THE CHESAPEAKE BAY ENTRANCE

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### ABSTRACT

The spatial and temporal variability of water entering and leaving the Chesapeake Bay estuary was determined with a spatial resolution of 75 m. The four cruises during which the observations were made took place under different conditions of freshwater discharge, tidal phase, and wind forcing. The tidal variability of the flows was dominated by the semidiurnal constituents that displayed greatest amplitudes and phase lags near the surface and in the channels that lie at the north and south sides of the entrance. The subtidal variability of the flows was classified into two general scenarios. The first scenario occurred during variable or persistently non-southwesterly winds. Under these conditions there was surface outflow and bottom inflow in the two channels, inflow over the shoal between the two channels, and possible anticyclonic gyre formation over the shoal. The flow pattern in the channels was produced by gravitational circulation and wind forcing. Over the shoal it was caused by tidal rectification and wind forcing. The second scenario occurred during persistently southwesterly winds. The anticyclonic gyre over the shoal vanished suggesting that wind forcing dominated the tidal rectification mechanism over the shoal, while gravitational circulation and wind forcing continued to cause the flows in the channels. In both scenarios, most of the volume exchange took place in the channels.

### INTRODUCTION

The study of flows that enter and leave an estuary is essential to assess the fluxes of materials transported into and out of the estuary. Because these transports affect estuarine living resources and water quality we must understand the processes that determine the water exchange between estuaries and their adjacent ocean. The Chesapeake Bay entrance is and has been the focus of several studies because the bay is a habitat for species of commercial and ecological importance that depend on the oceanographic processes at the entrance of the estuary for their

recruitment and development. Research activities also are focused in this area because of the interaction of strong density gradients, tidal currents and variable winds that affects the large buoyant plume and generates complicated frontal features and flow patterns. Until very recently, the flows that enter/leave the Chesapeake Bay at its entrance had only been studied with scattered moored instruments (Boicourt, 1981; Goodrich, 1987), but did not have the spatial resolution required to elucidate relevant processes with scales on the order of 100 meters as presented here.

This study is part of an on-going effort that has the goal of understanding exchange processes between estuaries and the adjacent coastal ocean. The objective of this study is to describe the spatial structure of the subtidal and tidal flows at the entrance of the Chesapeake Bay under different conditions of wind velocity, tidal phase, and river discharge. This is the first effort in this region that describes the spatial distribution of inflows/outflows at resolutions consistent with the coherence length scales. This was accomplished by measurements of current velocities using a towed acoustic Doppler current profiler (ADCP).

## **STUDY AREA**

The Chesapeake Bay entrance is representative of many wide, partially mixed coastal plain estuaries with a characteristic channel and shoals cross-sectional bathymetry (Fig. 1). The relatively wide (~4 km) and deep (28 m) Chesapeake Channel is located off Cape Henry near the southern entrance to the bay. In the central part of the entrance lies the eastward extension of Middle Ground, which is about 10 m deep. To the north-northeast of Middle Ground, depths are about 6 m and we will call this area the Six-Meters Shoal. Between Six-Meters Shoal and Fishermans Island lies the North Channel. North Channel is 13 m deep: roughly one half the depth of Chesapeake Channel and twice the depth of Six-Meters Shoal.

Chesapeake Bay is influenced by seasonal wind forcing that is predominantly from the northeast and the southwest (Paraso and Valle-Levinson, 1996). Northeasterly winds prevail from late summer to early spring, while southwesterly winds dominate during the summer. However, during any season, strong winds can occur from either direction. The most energetic wind events are usually from the northeast or northwest during late fall and winter, although southwesterly winds can occasionally be very energetic. Wind speeds tend to be between 4 and 6 m/s throughout the year, except during the summer months, when they are weaker. Due to the orientation of the bay entrance, northeasterly and southwesterly winds cause the greatest effects on the subtidal sea level and current variability in the area (Valle-Levinson, 1995; Paraso and Valle-Levinson, 1996). The response time of the flow to wind forcing from those two directions in the lower bay is less than 10 hours. A northeasterly wind tends to cause net barotropic inflow and an increase in subtidal sea surface elevation at the entrance. Conversely, a southwesterly wind causes net barotropic outflow through the entrance and sea level drop at the lower bay.

River discharge variability can cause significant variability in exchange processes in the Chesapeake Bay entrance. The Chesapeake Bay receives a mean annual freshwater discharge of approximately 2,500 m<sup>3</sup>/s from a large number of rivers (Goodrich, 1988). Of these rivers, the Susquehanna contributes 50% of the discharge, followed by the Potomac (18%) and the James (14%) (Hargis, 1981). The discharge of the rivers peaks during the months of March and April and is least during August and September. As a result, the mean surface salinity is lowest

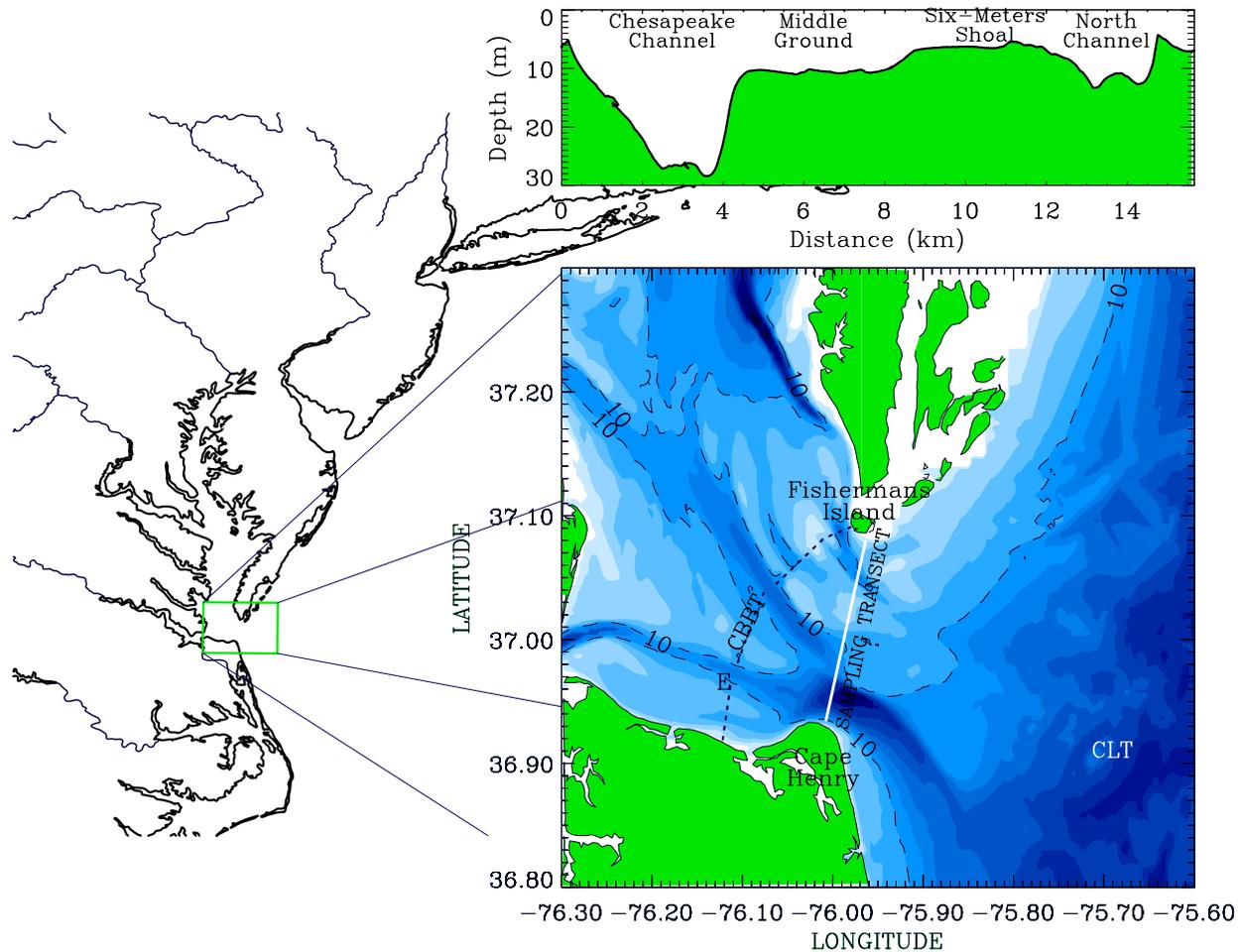


Figure 1. Mid-Atlantic Bight on the eastern coast of the United States showing the area of the lower Chesapeake Bay (lower panel), and a bathymetric profile at the entrance, looking into the estuary (upper panel). The lower panel shows the location of the transect sampled during the four cruises and the outline of the 10-m isobath (dashed contours). Dark tones represent deep areas. The Chesapeake Bay Bridge-Tunnel (CBBT) is presented as a dotted line for reference. The meteorological station at the Chesapeake Light Tower (CLT) and the sea level station at CBBT (E) provided the ancillary data. The upper panel shows Chesapeake Channel to the left and North Channel to the right. Middle Ground and the Six-Meters Shoal are located 4.5 to 8.5 km and 8.5 to 12 km. from Cape Henry. Middle Ground has an averaged depth of about 10 m while Six-Meters Shoal has a depth of about 6 m.

throughout the bay in the April-May period and highest in September-November (roughly one month after the river discharge extremes). The low-discharge period is coincident with increased wind-induced vertical mixing associated with cold air outbreaks and extra-tropical storms. However tropical and extra-tropical storms may produce anomalously high runoff during seasons of normally low runoff and cause extremely reduced salinities throughout the bay. The combination of wind forcing and river discharge results in strongly stratified (top to bottom differences in salinity of order 10) conditions in April-May, and nearly homogeneous (maximum top to bottom salinity difference of less than 2) conditions in October-November (Valle-Levinson and Lwiza, 1997).

The tidal forcing affecting the lower Chesapeake Bay is predominantly semidiurnal (Browne and Fisher, 1988). The interaction among the three semidiurnal tidal constituents ( $M_2$ ,  $N_2$  and  $S_2$ ) generates fortnightly and monthly variability in the tidal currents. Owing to the fact that the  $N_2$  constituent dominates over the  $S_2$  in the lower bay, there is a marked asymmetry between consecutive spring (or neap) tides thus causing a primary and a secondary spring (or neap) tide during one month. During spring tides, the currents in the lower bay may exceed 1 m/s, resulting in reduced stratification and weaker subtidal flows than during neap tides (Valle-Levinson, 1995). Thus, bathymetric variations, wind velocity, freshwater discharge, and tidal forcing are expected to influence the volume exchange between the Chesapeake Bay and its adjacent coastal ocean.

Our understanding of the mean flow in this area comes from studies using sparsely moored current meters during the summer (Boicourt, 1981; Goodrich, 1987). The mean flow showed marked bathymetric influences with mean inflow restricted to Chesapeake Channel and mean outflow elsewhere. The tendency for net inflow in channels and outflow over shoals has also been observed a few kilometers upstream of the bay entrance during early October 1993 (Valle-Levinson and Lwiza, 1995). This pattern is different from the classical view of estuarine circulation modified by the earth's rotation, which consists of net inflow appearing to the right and net outflow to the left (looking into the estuary in the northern hemisphere). The present study investigates whether the bathymetric partition of inflows/outflows as found by Boicourt (1981), Goodrich (1987), and Valle-Levinson and Lwiza (1995) is persistent under different forcing conditions.

## **DATA COLLECTION AND PROCESSING**

Current velocity data were collected from the NOAA ship *Ferrel* with an RD Instruments broadband 600 kHz ADCP along the transect between Cape Henry and Fishermans Island, at the entrance to the Chesapeake Bay (Fig. 1). The ADCP was mounted looking downward on a small catamaran (1.2 m long). The catamaran was towed mid-ship with a three-point bridle so the catamaran traveled off the starboard side in water undisturbed by the ship's wake. The instrument was towed at a speed of approximately 2.5 m/s and recorded velocity profiles averaged over 30 seconds. This gave a horizontal spatial resolution of about 75 m. The bin size for vertical resolution was 0.5 m. The ADCP specifications are shown in Table 1. Compass calibration and data correction were performed following Joyce (1989).

The Cape Henry-Fishermans Island transect was sampled repeatedly throughout two tidal cycles on four different cruises: September 24-25, 1996, November 14-15, 1996, February 20-21, 1997 and May 12-13, 1997 (hereafter Sep96, Nov 96, Feb97, and May97, respectively). This data set represents the most comprehensive high-spatial resolution current velocity measurements yet at the entrance to Chesapeake Bay. The transect sampling coincided with expected seasonally variable conditions of weak river discharge in September, strong wind forcing in November and February, and strong freshwater input in May. However, 1996 was the wettest year on record for the Chesapeake Bay and Sep96 and Nov96 actually took place during anomalously high river discharges for those months (more than 3000 m<sup>3</sup>/s). The observations in Feb97 and May97 were during river discharges close to the annual mean of 2500 m<sup>3</sup>/s. In addition, the Sep96 cruise took place one day before spring tides with offshore winds (southwesterly to northwesterly). The Nov 96 cruise was carried out 3 days after spring tides with onshore winds (northeasterly). The Feb97 cruise also had northeasterly winds and took place two days before secondary spring tides (the weaker spring tides of the month). Finally, the May97 transect was sampled two days before neap tides under southwesterly winds (directed offshore).

The length of the transect was roughly 16 km so that it took slightly less than two hours to sample along the complete transect. A total of 14, 11, 13, and 12 transects were made during the two semidiurnal tidal cycles sampled in Sep96, Nov96, Feb97, and May97, respectively. The current velocity values obtained from each transect were interpolated to a uniform grid with a horizontal spacing of 200 m (78 grid points) and a vertical spacing of 0.5 m (60 grid points). This grid had roughly 1500 active (useful) grid points as most of the grid points were at the bottom or within side lobe effects of the ADCP signal. The velocity values were rotated 11° clockwise from true north to obtain transverse (along the estuary entrance) and longitudinal (into and out of the estuary) components.

The time series of current velocity components for each separate cruise was fitted, using a least-squares technique, to a periodic function with semidiurnal (period of 12.42 hrs) and diurnal (period of 23.93 hrs) constituents (Lwiza *et al.*, 1991). This procedure yielded five parameters related to the flow at the entrance to Chesapeake Bay: the subtidal flow during the period of observation, the amplitude and phase of the semidiurnal constituent, and the amplitude and phase of the diurnal constituent. The least-squares fit with only the semidiurnal constituent consistently explained more than 70% (mean of 85%) of the variability observed in the longitudinal component of the flow at every grid point. The addition of the diurnal constituent to the fit improved the longitudinal flow variability explained to an average of 92%. The improved fit yielded root-mean-squared errors between the fit and the observations that in general remained below 0.05 m/s. The percent of variability explained by the fits for the transverse flow component were slightly less (average of 82%), which indicated reduced tidal influences on this component.

Table 1

Acoustic Frequency	600 kHz
Beam Angle	20°
Pings per Ensemble	8
Profiling Mode	4
Sampling Interval	30 s
Blanking Interval	0.5 m
Center of First Bin	1.5 m
Beam Length	0.5 m
Bottom Track	Yes, all the time
Data Acquisition	RD Instruments Software = Transect
Navigation	Differential Global Positioning System (DGPS)

ADCP Specifications

**TIDAL PROPERTIES OF FLOW IN THE BAY ENTRANCE**

In this section the semi-diurnal and diurnal properties of flow in the bay entrance are described.

**a) Semidiurnal**

The amplitude of the semidiurnal tidal flow (Fig. 2) showed similarities and differences from cruise to cruise. The consistent features were the persistent location of the greatest near-surface amplitudes in North Channel and to the south of Six-Meters Shoal. North of Chesapeake Channel, over Middle Ground and Six-Meters Shoal, isopleths paralleled the bathymetry indicating frictional effects on the tidal flows. These frictional effects became less evident in the Chesapeake Channel, where differences appeared from cruise to cruise. The amplitude of the semidiurnal tidal flow in Chesapeake Channel increased with depth in Sep96 and May97, and showed a mid-water minimum in Nov96 and Feb97. The increase of amplitude with depth was probably due to the strong pycnocline associated with the low salinity plume that hindered the upward transmission of the tidal phase as a consequence of low eddy viscosities at the pycnocline. This effect of plume outflow on tidal currents has been shown with a mixed layer model by Haskell *et al.* (1997). The semidiurnal amplitude over the transect also varied from cruise to cruise depending on the tidal phase within the month. Greater amplitudes were near spring tides (Sep96 and Feb97) as the dominant semidiurnal constituents ( $M_2$ ,  $N_2$ , and  $S_2$ ) were close to being

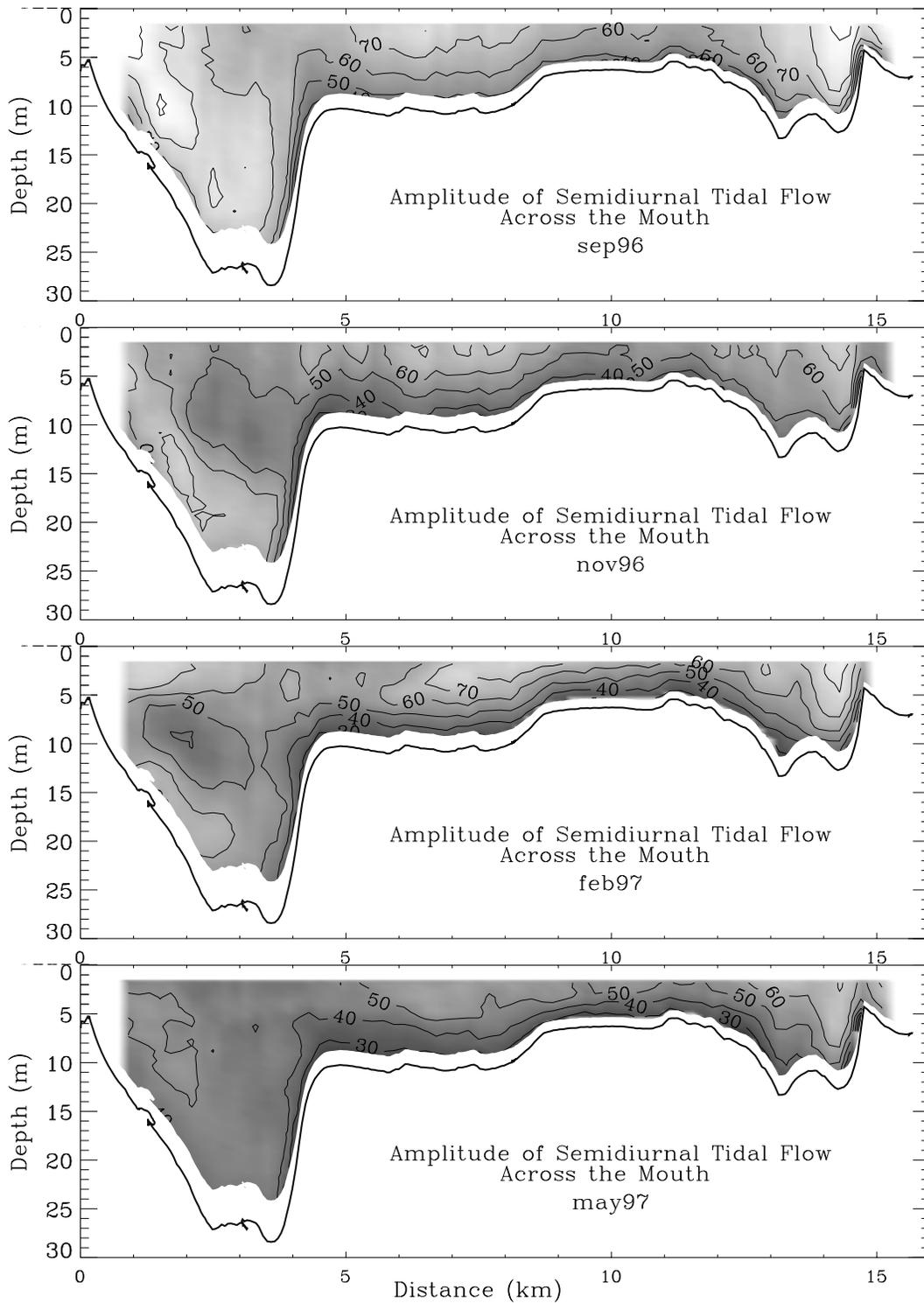


Figure 2. Amplitude of semidiurnal tidal flow (cm/s) perpendicular to the sampling transect during the four cruises. Contour interval is 10 cm/s. Lighter tones represent larger amplitudes.

in phase. Similarly, the amplitudes were lowest in May97, two days before neap tides as the constituents were out of phase. Although the fit was made to the period of the  $M_2$  constituent, the 25-hr long record of each cruise was not long enough to isolate the contributions of the  $N_2$  and the  $S_2$  from the  $M_2$ . That is why Figure 2 reflected the combined effect of all semidiurnal constituents and not the individual effect of  $M_2$ .

The phase of the semidiurnal tidal currents also showed similarities and discrepancies from cruise to cruise (Fig. 3). Low phase values (in degrees) indicated that the tidal currents turned first. During every cruise, lower phases appeared near the bottom compared to the surface, which indicated the expected upward transmission of the tidal phase. Also during every cruise, the tidal currents over Six-Meters Shoal, the shallowest portion of the section, lead those from the rest of the section. This region of phase lead coincided with the area of lowest tidal current amplitudes, which indicated that the weak currents responded more quickly to tidal forcing due to their low inertia. The near-surface portion in Chesapeake Channel showed the greatest lags, up to  $100^\circ$  behind ( $\sim 3.3$  hrs later than) Six-Meters Shoal. The area of large lags appeared at the expected region of the outflowing plume from the Chesapeake Bay. This area of large lags was of different size from cruise to cruise, probably related to the strength of the plume. The area in North Channel also showed phase lags up to  $30^\circ$  (or one hour) relative to Six-Meters Shoal. This again was caused by the stronger tidal currents in the channel than those over the nearby shoals, as they responded more slowly to changes in tidal forcing. Beneath the near-surface area of large lags off Cape Henry, the phases occurred approximately  $30^\circ$  before in Sep96 and Nov96, but were farther ahead by  $60$  to  $70^\circ$  (up to 2 hrs) in Feb97 and May97. The cause of this increased near-surface lag relative to the bottom in 1997 is unknown but will be explored in conjunction with the subtidal flow description. The features of the amplitude and phase of the semidiurnal tidal currents, both in the transverse and vertical directions, were similar to those described by Valle-Levinson and Lwiza (1995) except in Chesapeake Channel. These features should be expected to be general characteristics of the tidal flows in the area.

### **b) Diurnal**

The amplitude of the diurnal tidal flow was in general lower than 0.10 m/s (Fig. 4). Although it was smaller than the subtidal flow, inclusion of this constituent in the analysis improved the fit, by explaining an additional 7% of the variability observed. The improvement to the fit, however, was restricted mainly to the Chesapeake Channel, where the diurnal amplitudes were greatest. These greatest amplitudes (higher than 0.10) were related to the position of the plume. In Nov96 the diurnal amplitudes were particularly large and also could have been the result of the atmospheric forcing with diurnal periodicity.

## **SUBTIDAL FLOWS**

The calculated subtidal flows contained all those motions with periods greater than the diurnal including the different effects of gravitational circulation (or density gradients), wind forcing, and tidal rectification. The 25-hour time series observed during this study covered two semidiurnal tidal cycles and thus was not long enough to reliably separate the contribution of each subtidal flow component. Nevertheless, analysis of even this short records yields information on the general features of the subtidal flow. The following subsections discuss the net volumes

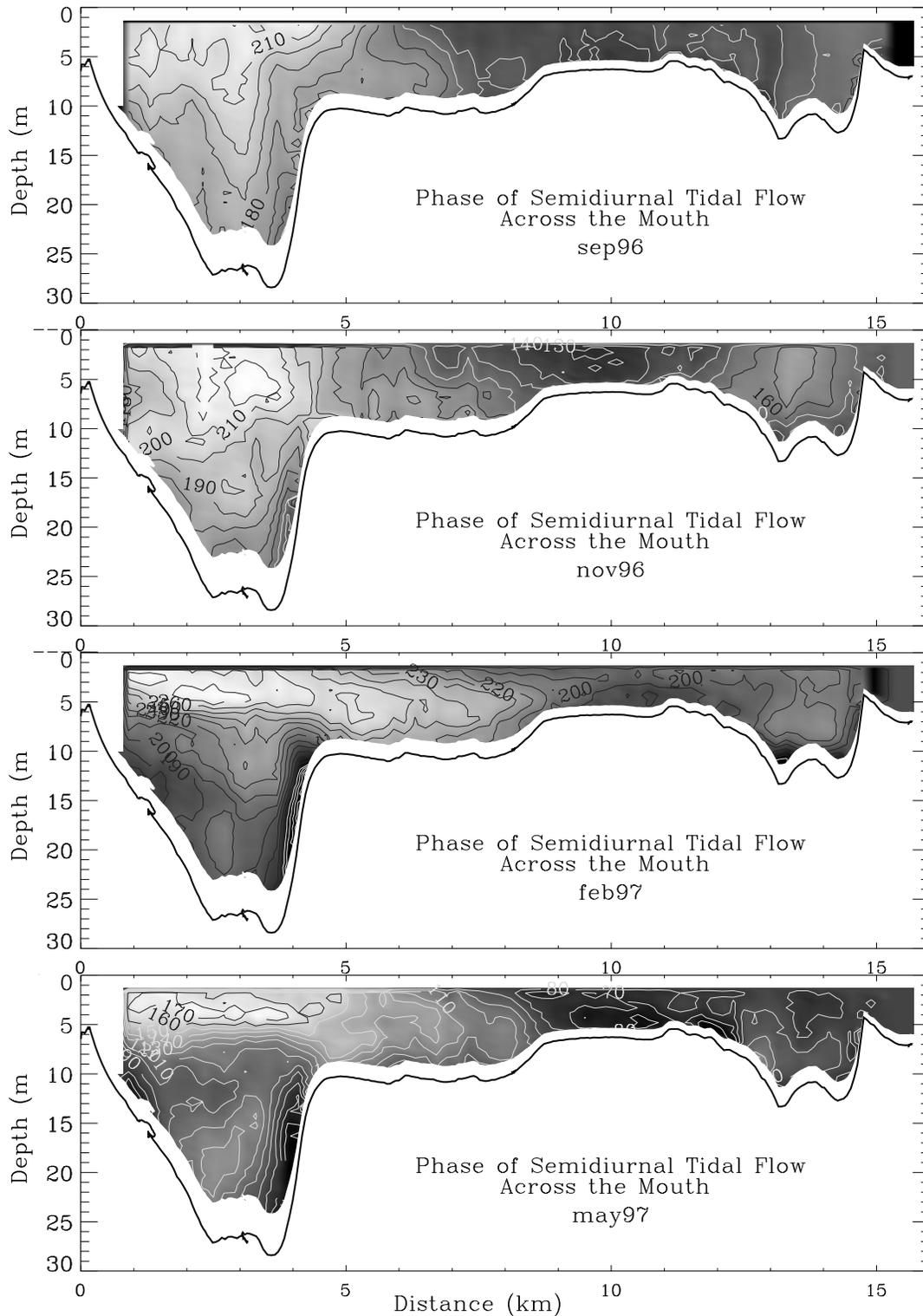


Figure 3. Phase of semidiurnal tidal flow (in degrees) perpendicular to the sampling transect during the four cruises. Contour interval is 10 degrees. Lighter tones represent larger phase lags, *i.e.* tidal changes occur first at the areas denoted by dark tones.

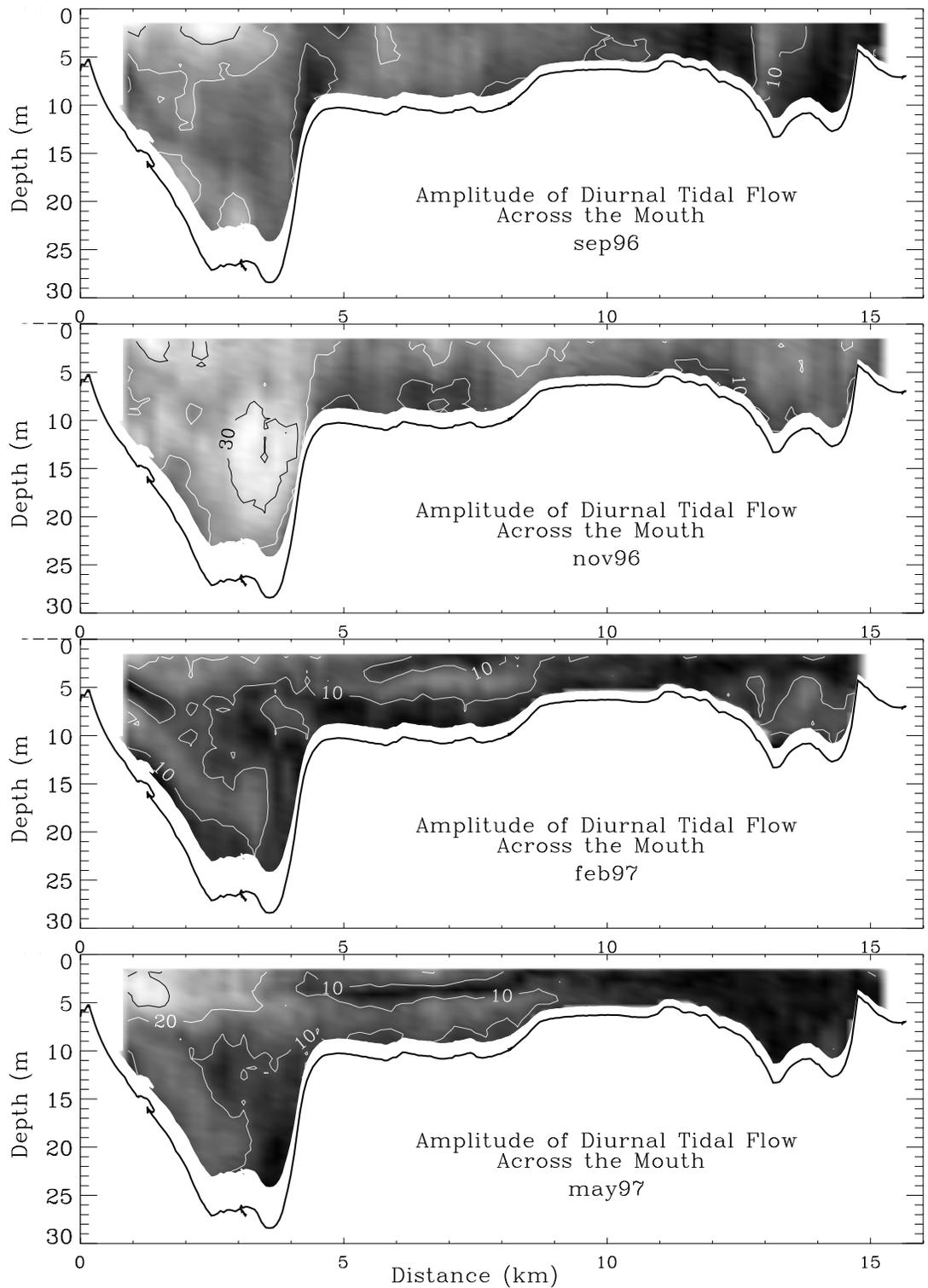


Figure 4. Amplitude of diurnal tidal flow (cm/s) perpendicular to the sampling transect during the four cruises. Contour interval is 10 cm/s. Lighter tones represent larger amplitudes.

transported into and out of the bay, followed by discussions of the variability in the along-estuary and transverse flows.

### **a) Volume Transport**

Appreciable differences occurred in the volumes of water that entered and left the estuary during the four cruises (Table 2). The cruises in Sep96 and Nov96 were associated with high river discharge of about 3000 to 4000 m<sup>3</sup>/s. In contrast, the river discharge for Feb97 and May97 was about 2000 m<sup>3</sup>/s. Furthermore, the cruises in Sep96 (one day prior to spring tides) and May97 (two days before neap tides) were influenced predominantly by offshore winds (southwesterly) that in general caused the subtidal sea level to drop (Fig. 5). The sea level drop produced greater volume outflows (net outflow integrated over the section) than inflows (net inflow integrated over the section) during both cruises (Table 2). In May97 there was a net volume export of approximately  $8 \times 10^3$  m<sup>3</sup>/s which was accounted for by the river discharge and the barotropic transport induced by the sea level set-down as follows. On the basis of mass conservation, the barotropic transport can be estimated from the flow induced by the subtidal change in sea level ( $\partial\eta/\partial t$ ), according to the relationship  $0.75 (A/W) \partial\eta/\partial t$  (e.g. Wong, 1994), where  $A$  is the surface area being influenced by the set-up/set-down, *i.e.*, the area of the main stem of the Chesapeake Bay ( $8 \times 10^9$  m<sup>2</sup>), and  $W$  is the cross-sectional area at the entrance to the estuary ( $2 \times 10^5$  m<sup>2</sup>). Thus, in May97 the sea level set-down (0.08 m in 24 hrs) accounted for  $6 \times 10^3$  m<sup>3</sup>/s (or 75%) of the volume exported by the estuary and the river discharge accounted for the other  $2 \times 10^3$  m<sup>3</sup>/s. Similarly, in Sep96 the net volume exported by the estuary was  $1.2 \times 10^4$  m<sup>3</sup>/s, of which,  $7 \times 10^3$  m<sup>3</sup>/s were accounted for by the set-down (0.08 m in 20 hrs) and close to  $4 \times 10^3$  m<sup>3</sup>/s were attributed to the river discharge. Approximately  $1 \times 10^3$  m<sup>3</sup>/s remained unaccounted for, which was within the accuracy of the estimates.

On the other hand, the cruises in Nov96 (3 days after spring tides) and Feb97 (2 days before secondary spring tides) reflected onshore winds (northeasterly and southeasterly) (Fig. 6) that caused greater volume inflows than outflows (Table 2). In Feb97 the net volume inflow of  $1.1 \times 10^4$  m<sup>3</sup>/s gained by the estuary was accounted for by the sea level set-up during the observation period (0.16 m in 25 hrs). In Nov96 the wind velocities were relatively low compared to the other cruises and there was no apparent sea level set-up. Consequently, the net volume inflow of  $1 \times 10^3$  m<sup>3</sup>/s was relatively small and within the error of the estimates. Still, the subtidal volume inflows and outflows were large, which indicates that even if there is no sea level set-up/set-down, the volume exchanged through the entrance of an estuary may be quite large. The results above agreed qualitatively with the findings of Paraso and Valle-Levinson (1996) and Valle-Levinson (1995) that winds with westerly component cause volume loss in the lower bay and easterly winds produce volume gain, *i.e.*, the volume exchange in the lower bay is sensitive to the easterly component of the wind. The results were also consistent with the modeling results of Valle-Levinson *et al.* (1996) that showed that increased wind-induced coastal flow towards the south favored net inflow into the bay.

### **b) Along-estuary Flow**

The common features of the longitudinal (or along-estuary) subtidal flow component were that in general, two-way exchange with flow reversal with depth was observed in the channels and

Table 2

	Sept 96	Nov 96	Feb 97	May 97
Transport In ( $\times 10^4$ m <sup>3</sup> /s)	0.3	0.8	1.4	0.4
Transport Out ( $\times 10^4$ m <sup>3</sup> /s)	1.5	0.7	0.3	1.2
Net Transport ( $\times 10^4$ m <sup>3</sup> /s)	1.2 Out	0.1 In	1.1 In	0.8 Out
River Flow	Hi	Hi	Low	Low
Tide (days)	1 - spring	3 + spring	2 - sec. spring	2 - Neap
Winds	SW	NE weak	NE & SE	SW
Sea Level	Dropping	Neutral	Rising	Dropping

Subtidal volume transports into and out of Chesapeake Bay after each 25-hr period of observations, typical forcing agents, and resulting subtidal sea level.

circulation modified by rotation with near-surface outflow shifted to the left and the near-bottom inflow shifted to the right (looking into the estuary).

Appreciable distinctions from cruise to cruise were also noted in the spatial structure of the subtidal flow (Fig. 6). Throughout the cruises, the subtidal outflows were concentrated near the surface in both Chesapeake and North channels with maximum speeds of between 0.3 and 0.5 m/s in the Chesapeake Channel. In fact, most of the volume exchanged through the entrance of the Chesapeake Bay occurred in the two channels (Fig. 7). Except for Sep96, when 60% of the volume inflow developed between Chesapeake and North channels, more than 72% of the volume outflow or inflow to the estuary developed in the channels, and most of that volume exchanged in channels occurred over Chesapeake Channel. The proportion of volume inflow through the channels increased from Sep96 to May97, *i.e.*, volume inflows became more concentrated in the channels. For instance, 99% of the volume inflow in May97 was found in the channels, as compared to only 40% in Sep96. Inversely, the proportion of volume outflow through the channels decreased from Sep96 to May97 so that net outflow also appeared over Middle Ground and Six-Meters Shoal. In Sep96, 93% of the subtidal outflow appeared in the channels and by May97 this proportion was reduced to 73%. This shift in location of the subtidal flows throughout the entrance of the estuary was reflected in the tilt of the interface between outflows and inflows in the Chesapeake channel. The tilt was similar between both 1996 and between the 1997 cruises, but was different from 1996 to 1997. The common forcing in 1996, as well as in 1997, was the river discharge. It seems that increased river discharge caused the outflow to be concentrated near the surface in the channels and the inflow to appear near the bottom throughout the section. The reason for this shift of outflow in channels/inflow over shoal to inflow in channel/outflow over shoals is not obvious but could be attributed to a shift from a baroclinic-dominated exchange, related to high river discharge, to a barotropic-dominated exchange, with

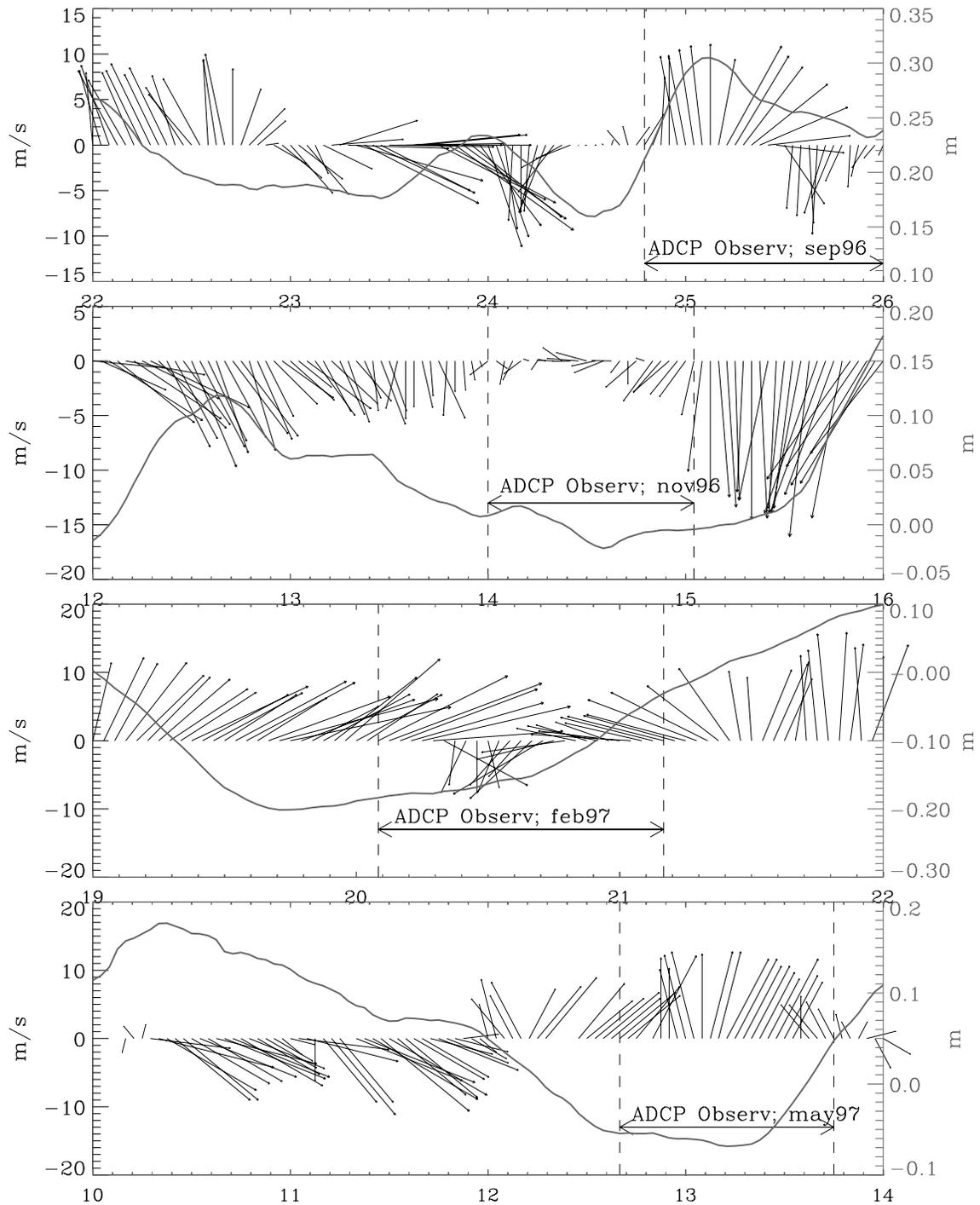


Figure 5. Wind velocity (vectors in oceanographic convention) from the Chesapeake Light Tower (CLT on Fig. 1) and subtidal sea level variations (solid line) from the Chesapeake Bay Bridge-Tunnel (E on Fig. 1) recorded around the period studied (delimited by dashed lines) during each one of the four cruises. The scale for the wind vectors appears on the left and the scale for sea level appears on the right. The abscissa indicates the day of the month when the cruise took place.

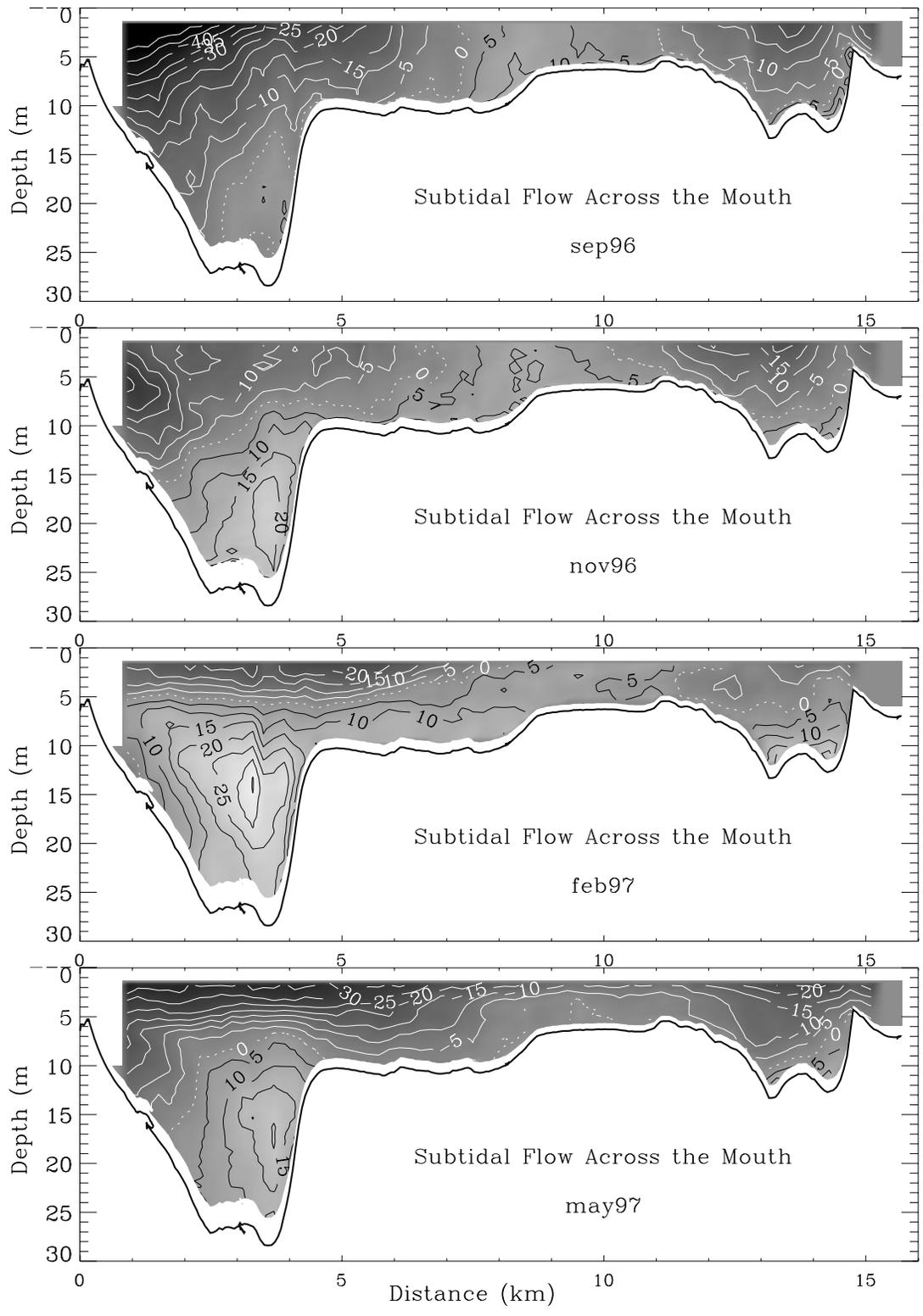


Figure 6. Subtidal flow (cm/s) perpendicular to the sampling transect during the four cruises. Contour interval is 5 cm/s. Light tones and dark (positive) contours represent net inflows.

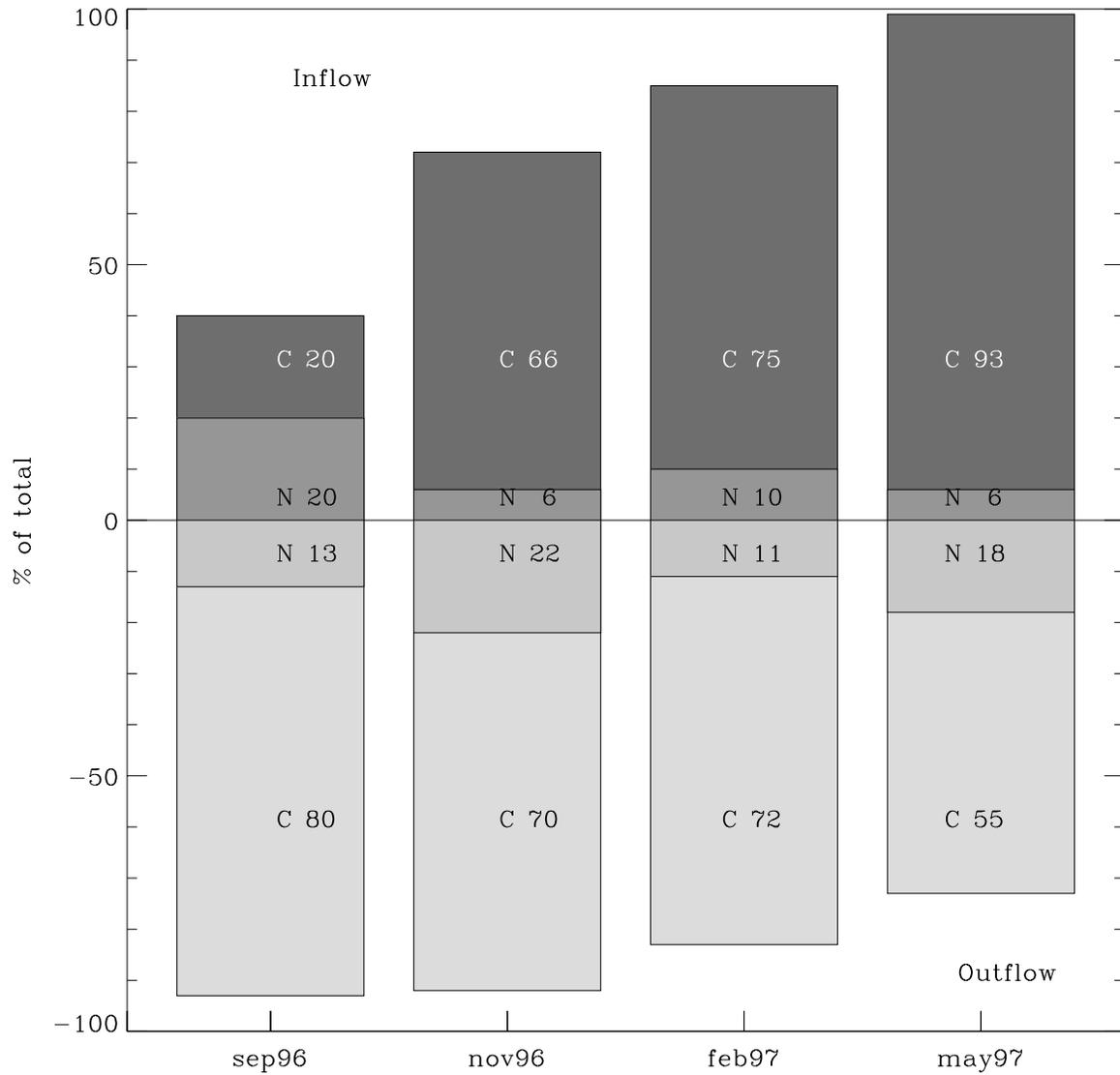


Figure 7. Percent of subtidal volume exchanged in the channels during each one of the four cruises. The percent of the total appearing in each of the two channels (Chesapeake channel- C, and North channel - N) is denoted by the numbers. For instance, in Sep96 40% of all the inflow through the entrance of the bay occurred in the channels, 20% over Chesapeake channel and 20% over North channel; 93% of all the outflow appeared in the channels, 80% in Chesapeake and 13% in North.

unidirectional flow was observed over the shoal (Fig. 6). This suggested that density-induced (gravitational) circulation was prevalent in the channels at the entrance to the bay. It appeared that both channels acted as separate, independent estuaries subject to the classical gravitational weaker river discharge, as suggested by Li *et al.* (submitted). Nonetheless, the proportion of the volume exchanged in the channels indicated their importance as conduits of material from and into the estuary.

### **c) Transverse Flow**

The subtidal transverse flow was consistent with rotational effects acting on the longitudinal flow. During the cruises when net volume outflow developed (Sep96 and May96) the transverse component was predominantly to the south, *i.e.*, from Fishermans Island to Cape Henry (Fig. 8). Similarly, the cruises with net volume inflow reflected transverse flow to the north, more markedly in Feb97 than in Nov96 due to the much greater inflow during the former. A common feature to all cruises was the convergence associated with the southern flank of the North Channel. The southern flank of Chesapeake Channel was not resolved by these cruises, but also is expected to be a zone of convergence in the subtidal transverse flow. The zones of convergence were also appreciable in the near-surface velocity vectors (Fig. 9). During all four cruises convergence zones developed over the same general location that corresponds to observations of foam lines where floating material accumulates.

### **d) Gyre Formation**

An additional interesting feature in the subtidal velocity field was the apparent formation of an anticyclonic gyre around Six-Meters Shoal during three of the four cruises. This is consistent with tidal rectification tendencies over a bump or shoal (*e.g.* Zimmerman, 1978; 1981; Robinson, 1981; and Park, 1990, Li, 1996). Also, in a channel-shoal bathymetry, inflow is expected to develop over the shoals as a consequence of tidal rectification (Li and O'Donnell, 1997). The development of the anticyclonic gyre suggests that tidal rectification dominated over gravitational circulation at the shallow portions of the Chesapeake Bay entrance. This observation was expected as stratification over the shoals tends to be much weaker than in the channels (*e.g.* Valle-Levinson and Lwiza, 1997). The absence of the anticyclonic gyre in the May97 cruise was attributed to the persistent southwesterly wind forcing (Fig. 5) that reversed the inflow over the shoals. Thus, wind forcing had a preponderant influence on the subtidal flows throughout the entrance to the bay. The strength of the pattern of near-surface outflow in channels and inflow over shoals was modulated by the wind speed, direction, and persistence. The strong near-surface outflow and weak inflow of Sep96 was explained by the period of southwesterly winds coincident with the observations. The shift of the wind direction to north-northeasterly favored the inflow over the shoal, in contrast to its suppression in May97. The relatively strong near-surface inflow over shoal and weak near-surface outflow in channels of Nov96 and Feb97 was explained by the onshore winds that prevailed during both cruises.

## **SUMMARY**

A series of four cruises were carried out at the Chesapeake Bay entrance in order to characterize the spatial and temporal variability of the flows in this region. These were the first

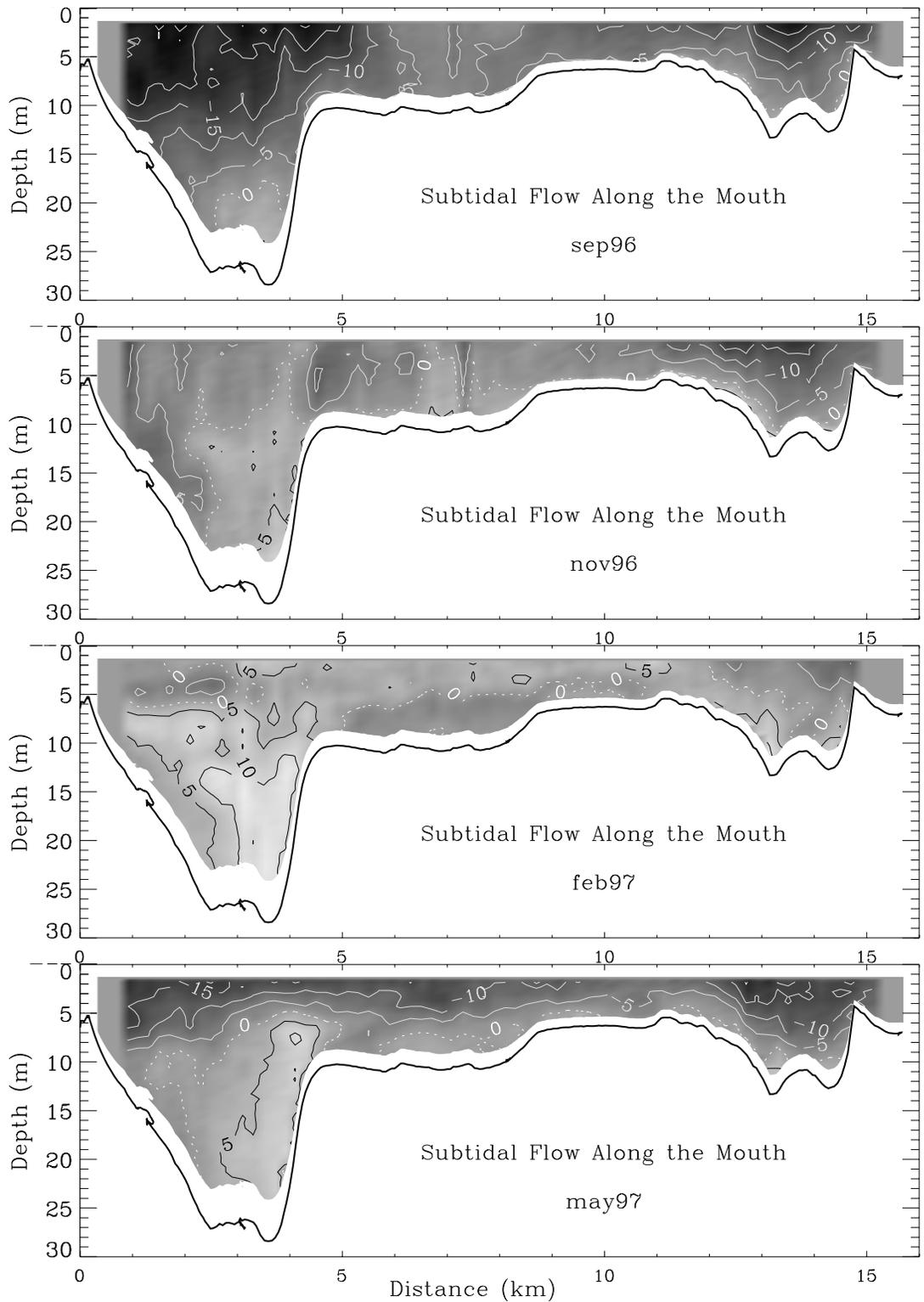


Figure 8. Transverse subtidal flow (cm/s) during the four cruises. Contour interval is 5 cm/s. Light tones and dark (positive) contours represent flows to the north (to the right on the figure).

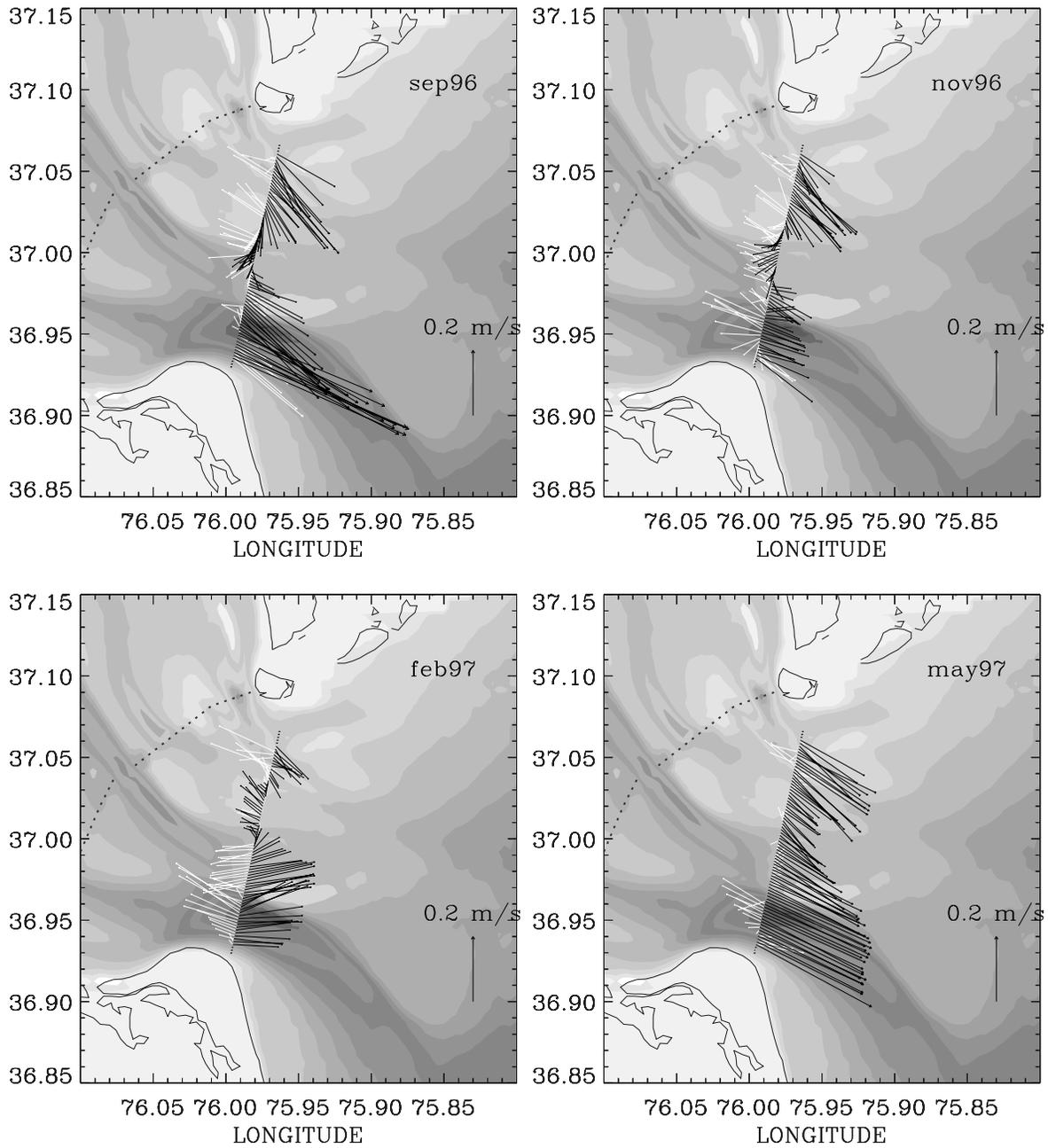


Figure 9. Near-surface (dark vectors) and near-bottom (white vectors) velocity vectors plotted every 200 m over the bathymetry at the entrance to Chesapeake Bay.

high spatial resolution observations of the flow field in this area. An acoustic Doppler current profiler was towed by the NOAA ship *Ferrel* during periods of at least 25 hours on 24-25 September 1996, 14-15 November 1996, 20-21 February 1997, and 12-13 May 1997. The measurements took place along an approximately 16 km-long transect between Cape Henry and Fishermans Island. The transect featured bathymetry consisting of two channels near its ends (Chesapeake to the south and North to the north) separated by a relatively shallower portion, that occupies almost one half of the transect with shoals up to 6 m. The cruises occurred during different conditions related to river discharge, tidal phase, and wind forcing and allowed the description of the variability of tidal and subtidal properties.

The amplitude of the semidiurnal tidal currents was, in general, greatest near the surface and away from the shoals and decreased with depth. The contours of co-amplitude followed the bathymetry thus suggesting frictional effects on the tidal flows. These frictional effects, combined with the inertia of the tidal currents, caused the phases of the semidiurnal tidal flows to occur first over Six-Meters Shoal relative to the rest of the section. The near-surface tidal phases in Chesapeake Channel occurred at least 3 hours later than those over Six-Meters Shoal. The tidal phase propagated in general from bottom to surface.

The subtidal results showed the important role played by wind forcing on the volume exchange between the Chesapeake Bay and the adjacent ocean. This was the first time that the responses to different wind forcing were quantified in terms of volume exchanged at the Chesapeake Bay entrance. The net volume gained and lost by the bay during various forcing events was accounted for by mass conservation through sea level variations and river discharges. Associated with the net volume gained and lost by the bay, there were larger volumes entering and leaving the bay simultaneously, as was the case in Nov96, when  $8 \times 10^3$  m<sup>3</sup>/s entered and  $7 \times 10^3$  m<sup>3</sup>/s left resulting in a net gain of  $1 \times 10^3$  m<sup>3</sup>/s. Therefore, it is important to look at the two-way exchange instead of the unidirectional transport produced only by sea level variations. This two-way exchange at the Chesapeake Bay entrance took place primarily in the two channels in terms of the volume transported. The exchange in the channels appeared to be influenced by the competition between gravitational (or density-induced) circulation and wind-induced flow, and over Six-Meters Shoal it was produced by tidal rectification and wind forcing. The subtidal flows observed in the four cruises drew two main scenarios for the volume exchange at the Chesapeake Bay entrance, which are summarized schematically on Figure 10. The first scenario depicts variable and/or non-southwesterly winds. In this, near-surface outflow is found in the channels and near-surface inflow over the shoals associated with an anticyclonic gyre. Near-bottom inflows develop practically everywhere across the entrance, but are strongest in the channels. The second scenario depicts persistent southwesterly winds. In this scenario, the near-surface anticyclonic gyre is not present due to wind forcing and the near-surface flow is directed seaward everywhere, weakest over Six-Meters Shoal. Near-bottom flow is directed into the estuary only in the channels.

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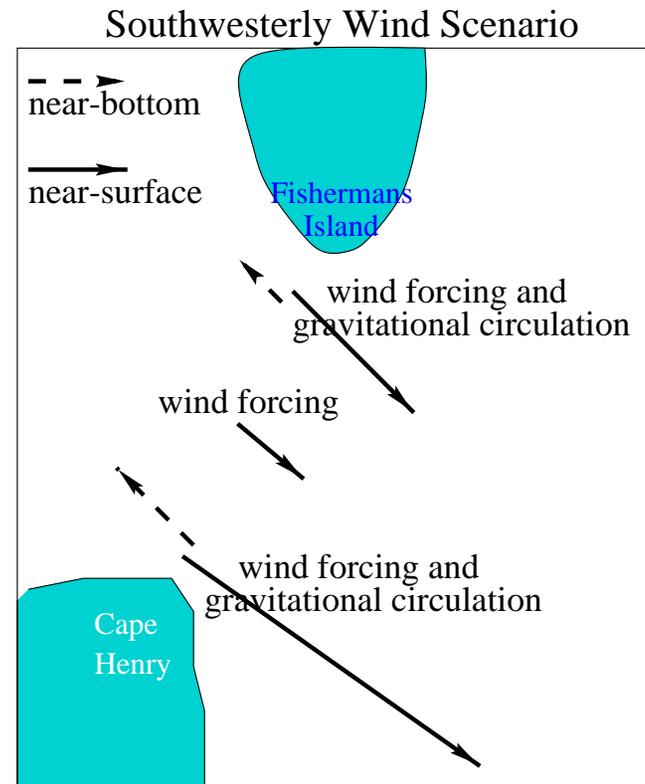
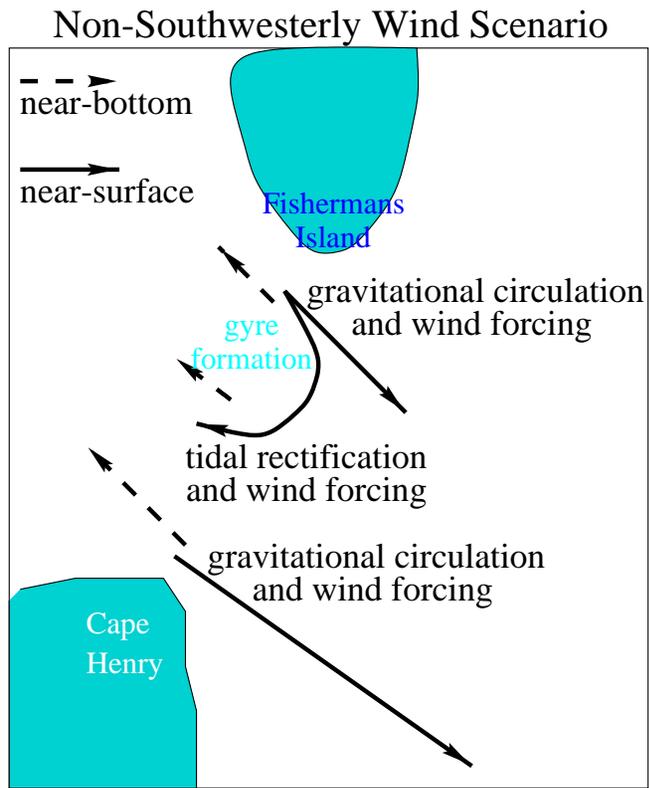


Figure 10. Scenarios derived from the observed subtidal flows. Continuous vectors represent near-surface velocities and dashed vectors represent near-bottom velocities.

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