

## The Fortnightly Mean Circulation of Chesapeake Bay

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Data from several current measurement programmes were used to examine the temporal and spatial variability of Chesapeake Bay circulation at time scales of 15 days and longer. First, year-long current records from two stations were analysed for response to runoff, wind stress and gravitational forcing. A strong spring freshet in April resulted in an annual maximum in the longitudinal density gradient, yet the surface current at mid-bay actually declined at the time of this maximum. The reason for this response lies in a prolonged period of northward wind which effectively reduced the strength of the two-layer gravitational flow. This shows that seasonal changes in the wind field can modulate the gravitational flow and that these annual wind shifts are a significant factor in the circulation of this estuary. Statistical analysis also indicates correlation between surface current and longitudinal wind at time scales of 15 days and longer, implying that meteorological effects cannot be completely filtered out at these frequencies.

These data demonstrate that Chesapeake Bay circulation, unlike runoff, does not change by orders of magnitude between seasons, indicating that an examination of spatial patterns of circulation can be made using data collected during different deployment periods. A total of 168 current records from 1977 to 1983, averaged over periods of at least 15 days, were used to examine the spatial structure of the mean bay-wide circulation. Surface velocity, while predominantly down-bay, shows considerable longitudinal structure. This is to be expected considering the different meteorological conditions under which the data was collected. However, bottom observations show remarkably coherent up-bay flow regardless of the measurement period, illustrating the dominant role of topography and the importance of the gravitational mode in bay circulation.

### Introduction

The mean circulation of estuaries has been a subject of interest since at least the early 19th century, when Fleming (1818) noted the presence of brackish subsurface water in the Firth of Tay and inferred the presence of an 'inferior current of salt water' at the bottom, superimposed on the tidal flow. Our modern paradigm is largely that of Pritchard (1956), who described the tidally averaged circulation of a partially mixed estuary in terms of a

longitudinal momentum balance between the pressure gradient, set up by the density difference between fresh- and saltwater, and vertical turbulent diffusion. Studies of variability in estuaries on time scales longer than a week have focused on the effects of changing runoff on this pressure gradient and the gravitational circulation it induces, using both observational (Schubel & Pritchard, 1986) and modelling (Blumberg, 1975; Wang & Kravitz, 1980) approaches. The significance of runoff-induced variability in the gravitational circulation is demonstrated by the marked seasonal changes in estuarine property distributions, especially salinity.

By contrast, examinations of the meteorologically forced estuarine circulation have concentrated on 2–10-day time scales since the late 1970s, when long-term current measurements revealed a rich spectrum of wind-driven variability (Elliott, 1978; Wang & Elliott, 1978). While there is clearly a strong signal at these periods, it has been concluded that the effect on the mean circulation is limited. Pritchard (1989) suggested that meteorologically forced motions have significant energy only below periods of about 10 days, implying that increasing the period of averaging tends to separate gravitational and wind-forced modes.

A critical examination of the response of estuarine circulation to runoff and wind variability on these longer time scales requires correspondingly long time series of current measurements during periods when this variability is occurring. The year 1983 provided such a natural experiment for Chesapeake Bay. Record April discharge was followed by a dry summer (USGS, 1983), and three current moorings were maintained throughout this period in the upper, middle and lower reaches of the bay. More specifically, the questions of whether variability in the longitudinal pressure gradient induced by such changes in runoff dominates current variability at seasonal time scales, or whether meteorological forcing plays a role as well were addressed.

The spatial distribution of the mean velocity, as well as its time variability, is another important aspect of estuarine circulation. The development of numerical models of estuarine circulation with small time and space steps (e.g. Blumberg & Goodrich, 1990) has permitted a relatively detailed look at circulation patterns. Such models often suggest the presence of large-scale flow features generated by interactions with topography. The spatial structure is a feature which a successful model must be capable of reproducing and relating to external forcing functions.

Chesapeake Bay has been one of the most intensely studied estuaries in terms of current measurements. In this paper we use data from several extensive current meter deployment programs in this estuary to examine both the temporal variability and spatial structure of the circulation, focusing on the fortnightly (or more properly, 15-day) time scale. After a description of the data and the rationale for choice of this averaging period, two synoptic year-long records from the middle and lower reaches of Chesapeake Bay are analysed (see section entitled Temporal variability), along with the corresponding time series of the presumed forcing functions: wind stress, runoff and longitudinal density gradient. We then examine the spatial structure of the velocity field, using current records of more than 15 days taken during a number of different periods, followed by the Discussion and conclusions.

### **Data**

Current meter station locations for this study are shown in Figure 1, with data sources indicated in Table 1. The most comprehensive data set was the NOAA Chesapeake Bay

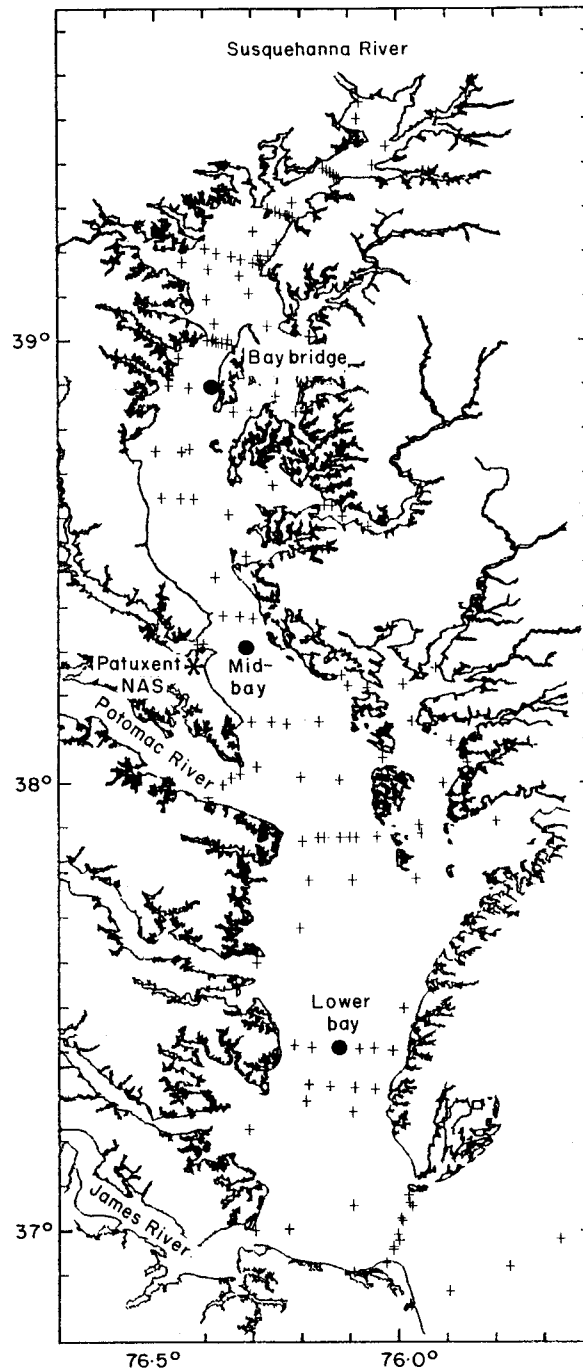


Figure 1. Station locations, Chesapeake Bay. Long-term current moorings (●), conventional current moorings (+) and the meteorological station (\*) are shown. Bay bridge, mid-bay and lower bay stations correspond to NOAA stations 121, 36 and 65, respectively.

Circulation Survey, which was conducted from 1981 to 1983 and included individual moorings deployed over the entire period (Browne & Fisher, 1986). Grundy Model 9021 current meters with temperature and conductivity sensors were used with a 10-min sampling interval and were rotated every 15–30 days. This instrument was equipped with

TABLE 1. Chesapeake Bay current data sources

Institution	Dates	Number of stations <sup>a</sup>	Instrument type	Sampling interval (min)	Reference
Chesapeake Bay Institute	May 1977– May 1978	25	Endeco/ Aanderaa	10/30	Grano and Pritchard (1982)
Chesapeake Bay Institute	June–July 1980	17	Endeco	10/30	Boicourt (1981)
Science Appl. Inc./CBI	July 1981– August 1982	3	Aanderaa	10	Hamilton and Boicourt (1984)
NOAA/National Ocean Service	September 1981– December 1983	103	Grundy	10	Browne and Fisher (1988)

<sup>a</sup>Number used in this study; may not be representative of total deployments.

an impeller-type rotor to reduce 'pumping' by surface gravity waves and was mounted on an A-frame support designed to isolate the instrument from mooring motions.

A second major data source was the Environmental Protection Agency Chesapeake Region Intensive Modeling Program (CRIMP) deployments from summer 1980. Primary instrumentation was the Endeco Model 105 current meter, which had a similar rotor to the Grundy instrument. It was isolated from the mooring with a rope tether. Additional data sources for this study were the upper bay current measurements of Grano and Pritchard (1982) and those of Hamilton and Boicourt (1984). It should be noted that the data from Grano and Pritchard (1982) were provided as mean along-channel vectors, with across-channel flow assumed to be insignificant. In general, the full database presented here represents a mix of instrumentation and deployment periods; however, the long-term measurements described in the next section are synoptic and use common instrumentation.

Data from all four of the sources shown in Table 1 were combined into a single data set consisting of 699 records, representing 168 locations in and around Chesapeake Bay at various levels in the water column. Surface measurements were considered to be 6 m or less from the surface, and bottom measurements were considered to be 10 m or less from the bottom, provided they were at least 6 m from the surface. Velocity records with a minimum length of 15.01 days (29  $M_2$  tidal cycles) were vector-averaged. For the development of long-term records, vector averages were decomposed to principal axis values.

Time series of forcing parameters were also obtained for the period of the 1983 long-term moorings. Discharge data for the Susquehanna River at Conowingo (Figure 1) were obtained from the U.S. Geological Survey. This represents roughly 85% of the fresh-water discharge to Chesapeake Bay above the mid-bay station (Seitz, 1971). Wind data were acquired from the Patuxent River Naval Air Station. In order to account for the increased amplitude of wind over the bay, north and east components of wind speed were increased by factors of 2.05 and 1.44, respectively (Goodrich, 1985). Speed was converted to stress using the quadratic law with a drag coefficient of  $1.5 \times 10^{-3}$ . A time series of the density gradient between the bay bridge and mid-bay surface current meters was also generated using the temperature and conductivity records from these instruments.

The selection of 15 days as the averaging period clearly will influence the representation of the circulation which emerges from the observations. Weisberg (1976) suggests that

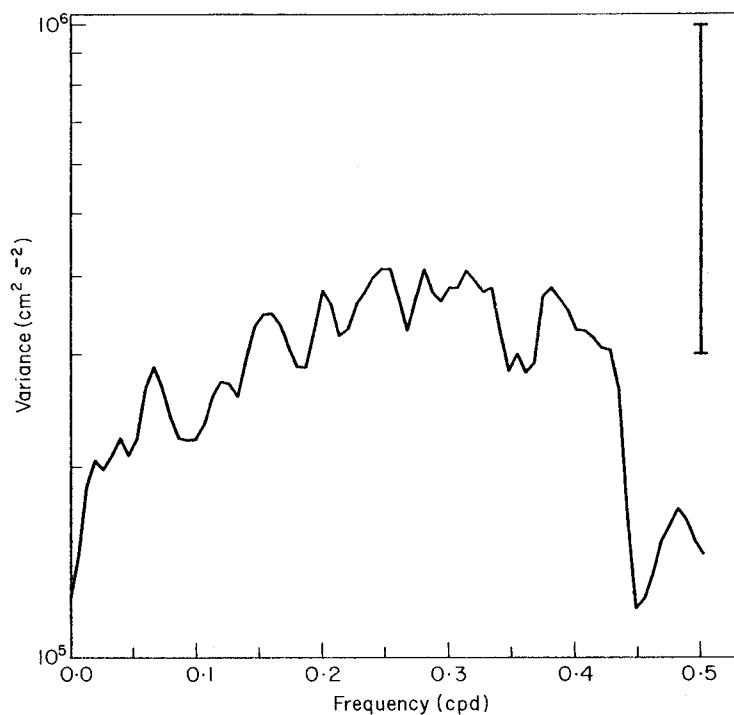


Figure 2. Power spectrum of mid-bay surface current record for 149-day period beginning 13 November 1982. Bar indicates 95% confidence interval.

record lengths of at least 18 days' duration are required to remove locally energetic wind fluctuations. On the other hand, Oey *et al.* (1985) argue that an averaging period of at least 30 days is required to define 'equilibrium' (i.e. statistically stationary) salt fluxes in an estuary. To examine the frequency distribution of velocity variance in this data set, a power spectrum of a 149-day record from the mid-bay station is shown in Figure 2. While there is a decrease in energy at frequencies below 0.05 cpd, the spectrum is essentially white, suggesting no clear cut-off period. Thus a 15-day period is chosen here to remove high-frequency tidal and neap-spring influences. As will be demonstrated, meteorological effects are reduced but not eliminated at this period.

### Temporal variability

The year-long series of fortnightly mean velocity for the mid-bay station is shown in Figure 3, together with corresponding series of Patuxent River longitudinal wind stress, Susquehanna River discharge, and density gradient between mid-bay and bay bridge stations. Data points represent means of identical 15-day intervals on all series except discharge, which is a daily average. Mean values of these parameters over the entire record are shown in Table 2. Perhaps the most prominent feature of the velocity series is the constancy of the two-layer circulation regime of seaward surface and landward bottom flow. This flow pattern is reversed only once in mid-summer, during a series of northward wind events at 2–4-day periods (not shown). The stability of the two-layer flow clearly demonstrates the influence of the density field on the long-term circulation of the bay. The role of the averaging period is significant here. In a study of year-long current records at three depths in the Potomac estuary, Elliott (1978) found the pattern of surface outflow and

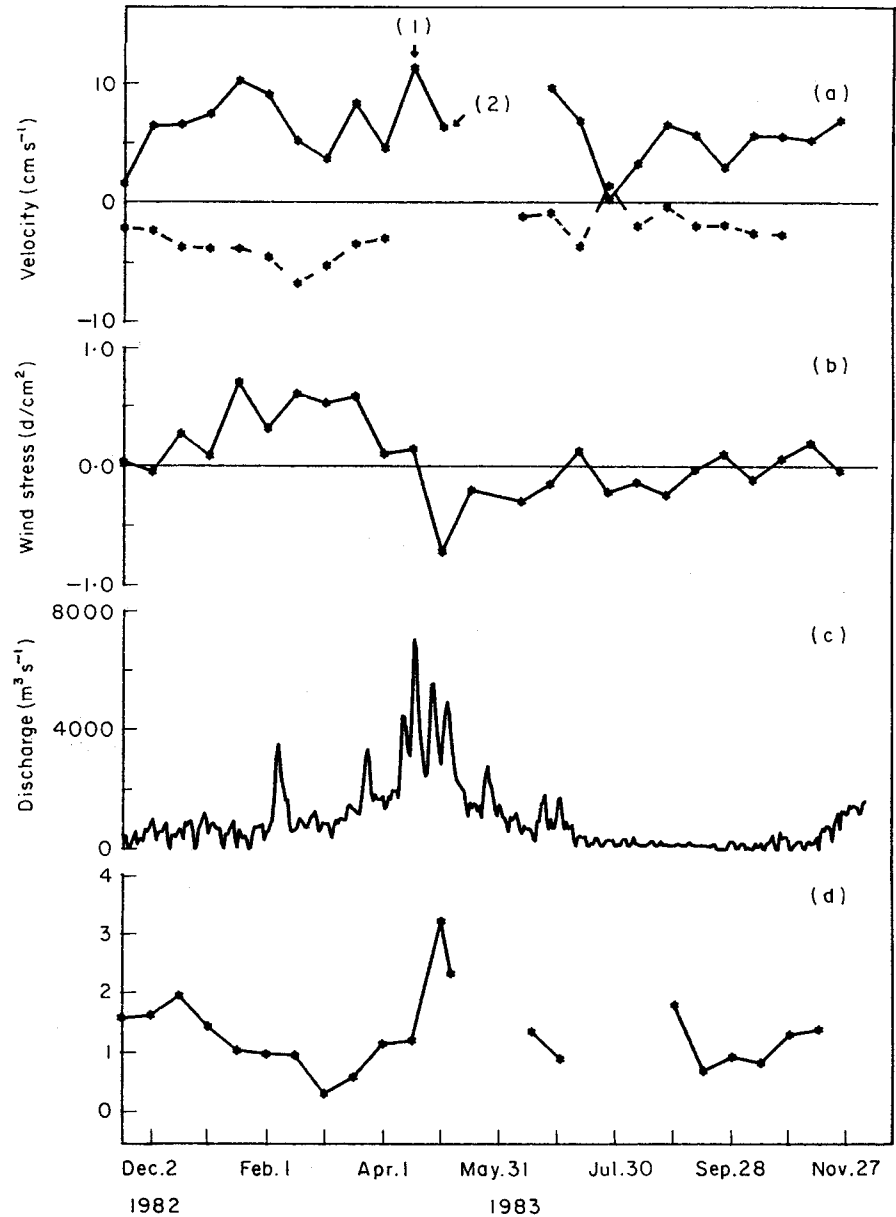


Figure 3. Mid-bay current velocity and forcing parameters. Arrows refer to discussion in the text. Tick marks on abscissa represent 30-day intervals. (a) Surface (—) and bottom (---) 15-day mean longitudinal velocity at the mid-bay station. Positive values indicate flow toward  $159^\circ$  (seaward). (b) Wind stress at Patuxent River. Direction is the same sense as (a). (c) Daily average discharge from Susquehanna River at Conowingo. (d) 15-day mean density difference between mid-bay and bay bridge surface current meters.

inflow at depth, while the most frequent, present only 43% of the time. However, since his data were averaged in 24-h blocks and were thus subject to the effects of meteorological forcing on time scales of a few days, his findings are not inconsistent with Figure 3.

The lower two panels illustrate the response of the density field to increased runoff. In April, peak discharge is followed, after a lag of 0 (15 days), by the annual maximum in density gradient. A significant lag is to be expected, since the northern of the two stations

TABLE 2. Long-term station means, November 1982–December 1983

	Value	Principal axis	Total length of record (days)
Mid-bay surface velocity ( $\text{cm s}^{-1}$ )	6.1	159°	345
Mid-bay bottom velocity ( $\text{cm s}^{-1}$ )	-2.7	159°	300
Wind stress ( $\text{d cm}^{-2}$ )	0.072	159°	390
Susquehanna runoff at Conowingo ( $\text{m}^3 \text{s}^{-1}$ )	990.5	—	394
Density gradient, mid-bay to lower bay ( $\sigma_t$ )	1.323	—	315

Positive values indicate flow toward indicated directions.

from which this difference is obtained is 70 km from the Susquehanna River mouth. The spring freshet has the effect of compressing the bay-wide salinity and density fields, since salinity at the bay mouth is constrained to values near those of the continental shelf. The compression of isopycnals is reflected in the doubling of the density gradient between the mid-bay and bay bridge stations. Lower in the water column the isopycnal compression is not nearly as large. The increase in freshwater discharge thus increases the longitudinal pressure gradient (and the stratification), which drives a stronger surface flow until a new equilibrium state is approached.

According to the model of Hansen and Rattray (1965), this strongly increased density gradient should lead to a strengthened gravitational mode and an increase in the seaward surface mean velocity. This is not shown in the data. The highest velocity of the year (arrow 1) is coincident with the peak in spring runoff. However, the next 15-day mean velocity, corresponding to the annual maximum in density gradient (arrow 2), actually decreases. The reason for this decrease apparently lies with the changes in wind forcing during the interval (arrow 2). During this interval, wind stress is strongly northward (negative), driving water up the bay in opposition to gravitational forcing. Wind forcing of this magnitude evidently is sufficient to mask the combined effect of river discharge and gravitational convection. It should be recognized that gravitational convection is a relatively slow process, and the velocity field will not respond instantaneously to an imposed longitudinal density gradient. On the other hand, Oey (1984) suggested that at equilibrium the surface current is insensitive to changes in freshwater discharge. In his formulation, the increase in the longitudinal salt advection, because of the increased salinity gradient, is balanced by an increase in the longitudinal dispersion of salt through a larger longitudinal dispersion coefficient.

It should be noted that the periods of higher-amplitude mean flow in December through March do not correspond with either high runoff or density gradient but do coincide with periods of strong southward wind stress. This suggests that the southward wind events which characterize winter and early spring seasons have a strong influence on variability in the mean flow during the year. In contrast, the period from June through November of this year is characterized by relatively low-amplitude northward wind stress and lower current velocities. For the 120-day period of continuous current record from 8 January to 8 May, mean down-bay flow was  $7.4 \text{ cm s}^{-1}$  with a mean southward wind stress of  $1.63 \text{ d cm}^{-2}$ . During the 18 June–16 October period, however, mean flow dropped to

TABLE 3. Correlation matrix of 7-day low-pass filtered records from 13 November 1982 to 10 April 1983, and per cent of variance represented in the first empirical orthogonal function

	Correlation matrix				EOF first mode % variance
Surface velocity	1.00	0.03	0.58	0.21	48.7
Bottom velocity	0.03	1.00	-0.39	-0.11	27.9
Axial wind stress	0.58	-0.39	1.00	0.45	16.7
Runoff	0.21	-0.11	0.45	1.00	6.7

$5.2 \text{ cm s}^{-1}$  with winds reversing to a mean northward stress of  $0.48 \text{ d cm}^{-2}$ . Overall, these data suggest that large-scale seasonal changes in the wind field over the bay are reflected as a modulation of the mean current.

To investigate statistically the relationships between surface and bottom velocity, longitudinal wind stress and runoff, an empirical orthogonal function (EOF) analysis was performed on the longest continuous velocity series, a 149-day record beginning 13 November 1982. This period includes the entire winter season but does not include the strong discharge events of late April 1983. The original data were passed through a 7-day low-pass filter prior to analysis, with the results shown in Table 3. The highest correlation in the correlation matrix is between surface current and wind. This is consistent with the notion of direct wind forcing of surface flow at these time scales. The first EOF mode (48% of the total variance) consisted of coherent surface and bottom fluctuations, associated to some degree with wind variance and not at all with runoff. (The second mode, not shown, was made up almost entirely of bottom current fluctuations.) It is evident that during this relatively low-runoff winter period that the wind is a prominent feature in the low-frequency circulation.

We have so far considered the effects of wind stress operating directly on the estuary. However, evidence from numerous studies suggests that non-local forcing by the wind, in the form of sea-level oscillations propagating in from the continental shelf, is prominent in Chesapeake Bay, particularly at time scales of 8 days and longer (Wang, 1979; Vieira, 1986). The order of this effect at the mid-bay station can be examined using sea-level records as follows: the highest-amplitude fluctuation in a 5-month time series of subtidal sea level from the bay entrance was 0.5 m over a 10-day period (Goodrich, 1988). This event was also observed at Newport, Rhode Island, 600 km away, and is thus assumed coherent over Chesapeake Bay. A uniform 0.5-m rise in sea level in the bay landward of the mid-bay section would require  $1.57 \times 10^9 \text{ m}^3$  to pass through this section (the product of the sea-level rise and the surface area landward of this section of the bay). The passage of this water over 5 days would require a sectionally averaged velocity of  $2.2 \text{ cm s}^{-1}$  at the site of the mid-bay mooring. Thus a large but low-frequency sea-level rise can be expected to produce a relatively small signature in the velocity record at this station, even in this extreme case.

### Spatial structure

Inspection of the annual record of the fortnightly mean current shown in Figure 3 indicates that while the mean flow shows significant seasonal variability, it does not vary by

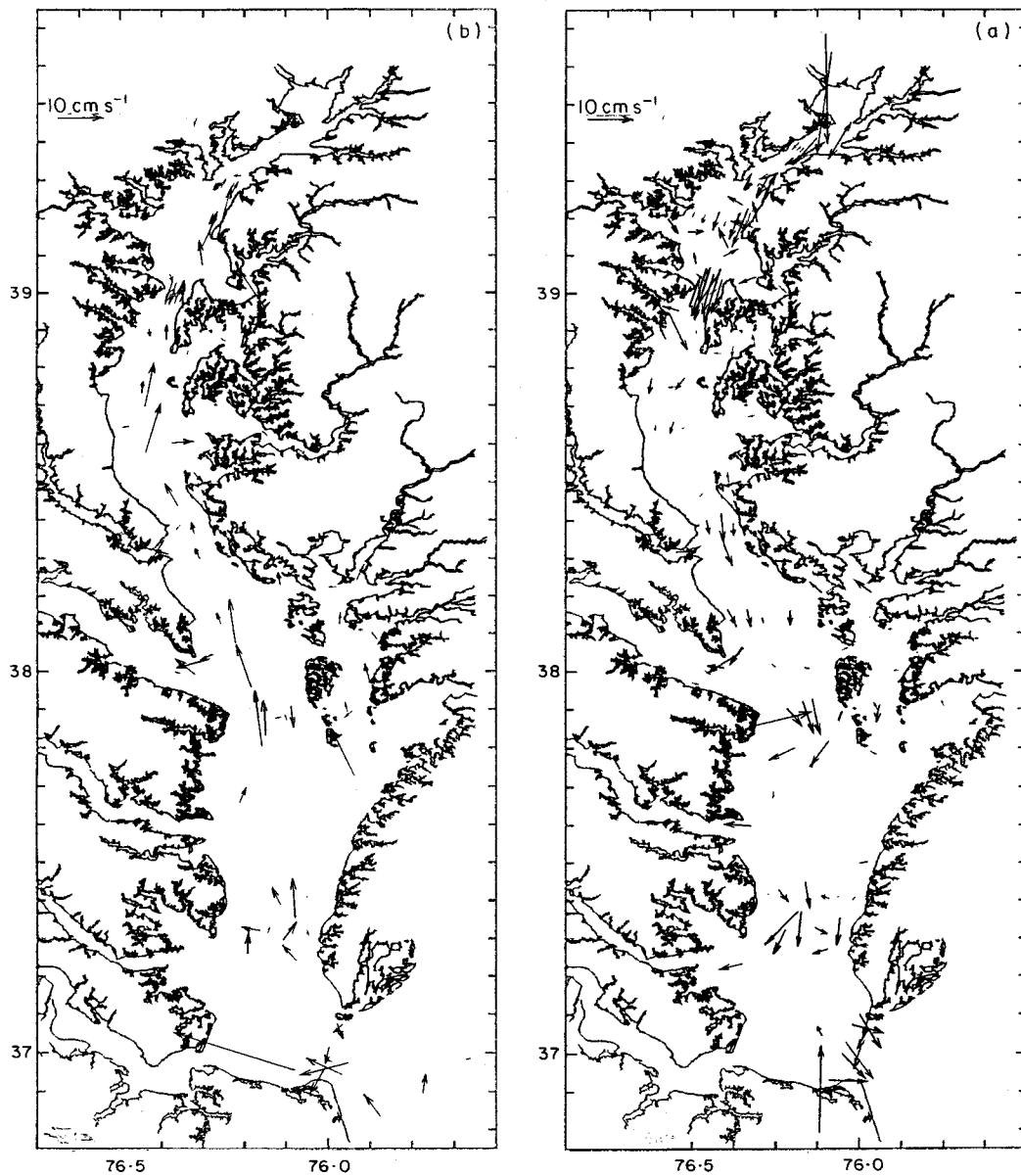


Figure 4. Distribution of mean velocity, 1977–83 data. Each data point represents an instrument record of at least 15 days. Station location is the mid-point of the vector. (a) Surface (0–6 m); (b) bottom (10 m and below).

orders of magnitude, nor does the sign of the surface of bottom flow change. This implies a certain underlying stability, an important assumption for the examination of the spatial structure of the mean flow using asymptotic data. For this analysis, all current time series from the 1977–83 database with record length greater than 15 days were grouped according to depth and shown as vectors. Multiple long records at the same site were weighted by series length and plotted as a single vector. Figure 4(a) shows the vector average of all current records from 0 to 6 m (surface), while current records from 10 m and below (bottom) are displayed in Figure 4(b). There are 134 surface and 80 bottom vectors plotted. Prominent in Figure 4(a) is the seaward surface outflow, present in virtually all of