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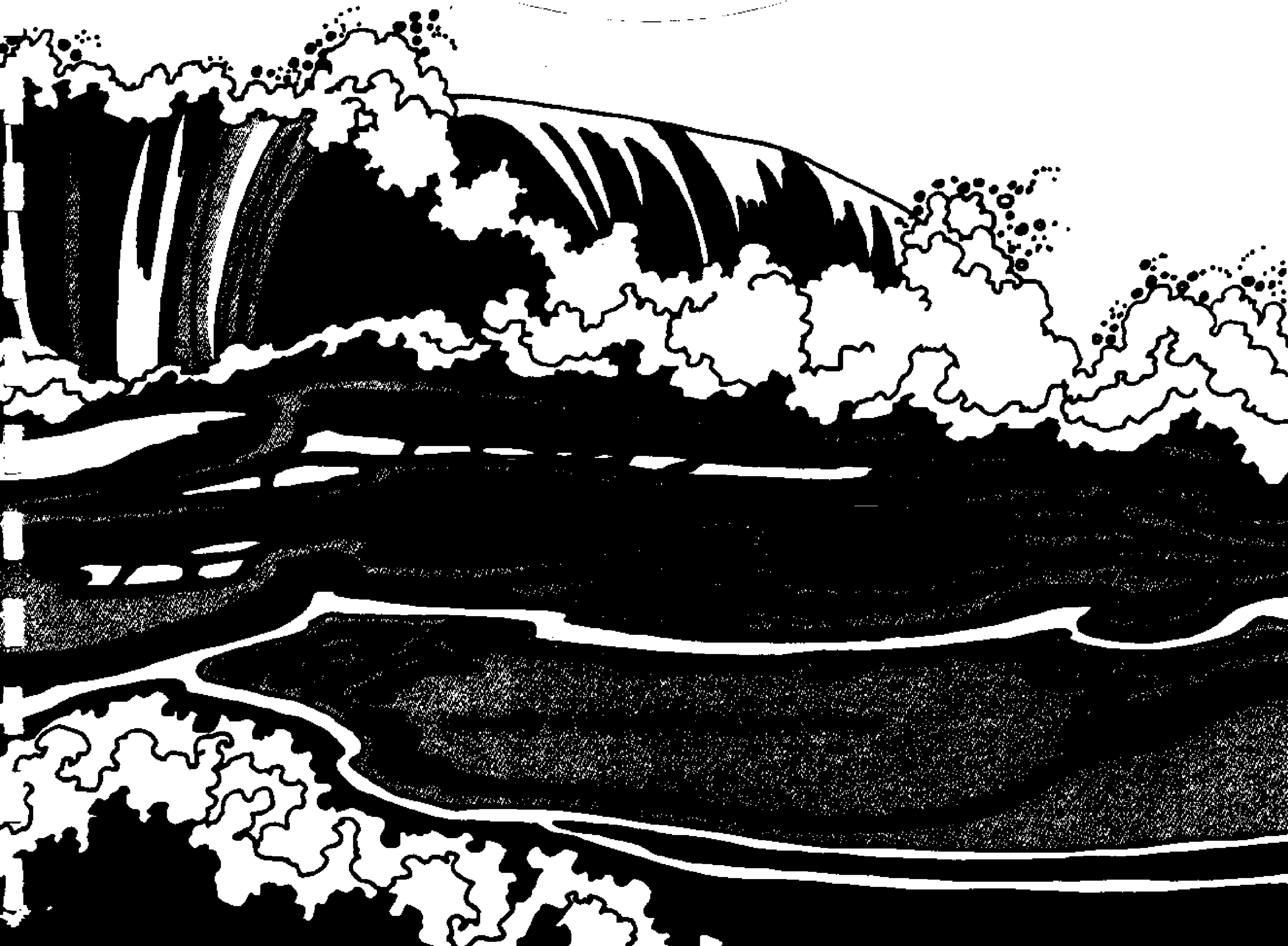

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A DRIFTER STUDY
OF THE LAGRANGIAN MEAN CIRCULATION
OF DELAWARE BAY AND ADJACENT SHELF WATERS

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by

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ABSTRACT

To document the Lagrangian mean circulation of Delaware Bay and adjacent shelf waters a series of nine deployments of surface and seabed current drifters was made. The study area, roughly 50 km up the Bay to 50 km offshore, was chosen to examine the exchange of water between estuary and shelf. Each deployment involved 28 stations and about 1000 drifters. Use of aircraft provided a synoptic release.

The presence of classical estuarine circulation in Delaware Bay can be inferred from maps of the apparent drifter trajectories. The seaward surface residual flow in the Bay is directed towards the Delaware shore, consistent with Coriolis effects, while the bottom residual flow moves upstream in the deep channels of the Bay and then spreads laterally onto the adjacent shallower areas on both sides. The estuarine circulation extends onto the adjacent shelf. The surface residual motion on the shelf is generally toward the south, although it can reverse and flow northward, while the bottom residual currents converge on the Bay mouth.

Vector maps of mean speed and direction of the residual circulation, with 95% confidence intervals, show a coherent flow pattern over the study area during the period studied. The speed of the residual currents on the shelf is consistently faster than that in the Bay. However, over the entire study area, the surface residual circulation is an order of magnitude faster than the bottom circulation. Both surface and bottom current speeds in the Bay are slower than those observed in other estuaries, and currents on the shelf are slower than previously reported for the Middle Atlantic Bight.

Wind and river conditions during the study were not characteristic of their long-term means. Consequently, it was not practical to present residual circulation patterns corresponding to seasonal periods in wind and river runoff. However, the return percentages suggest that offshore surface flow and onshore bottom flow intensify in the second half of the calendar year.

Although river flow shows little correlation with the residual circulation, the wind record explains much of the variance in drifter movement. In general, offshore winds drive surface water downstream/offshore and bottom water upstream/onshore in a simple two layer flow. This pattern reverses for onshore wind. Enough of the variance in drifter movements is left unexplained, however, that other forcing, such as tidal rectification, should be considered.

INTRODUCTION

A residual current in an estuary is defined as the net movement of water averaged over a period of time much longer than a tidal period. These currents are responsible for the exchange of water between estuary and ocean. Concurrent with the exchange of water is the exchange of physical properties, pollutants, biological organisms, and sediments. One reason for studying residual currents in an estuary is to understand the distribution of these. The flushing time and the tolerable load of pollution for an estuary are related to residual currents, as is the extent of saltwater intrusion and shoaling.

An example of the effect of residual currents is the movement of blue crab larvae. (*Callinectes sapidus* Rathbun) at the mouth and offshore of Delaware Bay. After hatching in the estuary, the larvae are planktonic and their distribution thus is directly related to the residual currents of the Bay and offshore waters. The adults are concentrated in the estuaries of the Atlantic coast of North and South America, but there is evidence that some larvae are found in shelf waters (Nichols and Keney, 1963; Sandifer, 1973; Smyth, 1980). An important question is whether these larvae are lost to the estuarine population. Understanding of the local residual circulation will contribute to the answer.

It is valuable to document the residual flow in an estuary, not only to provide a basis for predicting the movements of sediments, organisms, properties, and pollutants, but also to provide data with which theoretical models may be tested. The residual currents of Delaware Bay have not been documented in detail and it was the objective of this study to do so.

In estuaries, the residual currents arise from three known sources: gravitationally induced circulation, atmospheric forcing, and tidal rectification. Gravitational circulation occurs as a result of the density difference between fresh and saltwater, while wind stress and pressure differences provide atmospheric forcing. Tidal rectification occurs as a result of the inertia of the fluid. Consequently, the distance a water particle travels on the flood current is not necessarily the same as it travels on the ebb current. The relationships between these driving mechanisms and the presumed or observed residual flow patterns in an estuary are not completely understood if, in fact, all the relationships are realized. However, the end result is normally a seaward flow of lighter, less saline water near the surface and a landward flow of heavier, more saline water near the bottom.

In considering residual currents, mean velocities may be computed by two different methods. One, the Eulerian residual velocity, is the mean velocity computed at a fixed point. The other, the Lagrangian residual velocity, is the mean velocity following a specific water particle. Since fluid particles move through a velocity field which contains spatial variations, the fluid velocity averaged at a fixed point is generally not the same as that averaged for the same time period for a fixed particle; hence, the Eulerian and Lagrangian residual currents are, in general, quite different. Since the distribution of passive materials and biota is directly related to the Lagrangian mean, it is the current field of interest here.

STUDIES INVOLVING EXPENDABLE LAGRANGIAN DRIFTERS

To study residual currents from a Lagrangian frame, expendable drifters have been successfully employed and this was the technique used for this study. Drifter studies have been conducted extensively in European waters (Phillips, 1970) and Bumpus (1973) conducted a ten year drifter study of circulation on the continental shelf of the east coast of the United States. More abbreviated studies were performed in the near-bottom waters on the shelf of the northwestern United States (Gross et al., 1969; Morse et al., 1968). Expendable drifters have also performed satisfactorily in estuarine work on both the east and west coasts of the United States and in Australia (Bumpus, 1965; Conomos et al., 1970; Gross and Bumpus, 1972; Hollman and Sandberg, 1972; Larkin and Riley, 1967; Marsden, 1979; Norcross and Stanley, 1967; Paskausky and Murphy, 1976; Prytherch, 1929; Squire, 1969).

Surface drifter returns in these studies ranged from 10% to 84%, while the range for bottom returns was 7% to 92%. Phillips (1970) indicated that for inshore seabed studies, a recovery rate of at least 30% is probable. The ranges of velocities calculated for surface and bottom drifters were 5.2 to 27.8 km/day and 0.1 to 3.2 km/day, respectively. Seaward surface currents and landward bottom currents were demonstrated in the majority of estuaries studied.

PHYSICAL PROPERTIES OF DELAWARE BAY

A physical description of Delaware Bay is contained in the Delaware Bay Report Series (Polis and Kupferman, 1973). The Bay is about 75 km long. Its width varies from 18 km at the mouth to about 45 km at the widest point, above which it gradually decreases again. Maximum depth for the Bay is about 45 m and the mean depth is about 10 m, while 90% of the Bay is less than 18 m deep (Polis and Kupferman, 1973). The bathymetry of the Bay is shown in Figure 1.

The major source of freshwater to the Bay is the Delaware River which has an average flow of about 340 m^3/s (Polis and Kupferman, 1973). The tide is predominately semidiurnal and has a flow at the Bay mouth of roughly 1×10^5 m^3/s (Ketchum, 1951), which produces a mean tidal range at the mouth of about 1.5 m (Polis and Kupferman, 1973). The winds over the Bay have a strong seasonal cycle (Polis and Kupferman, 1973). During the

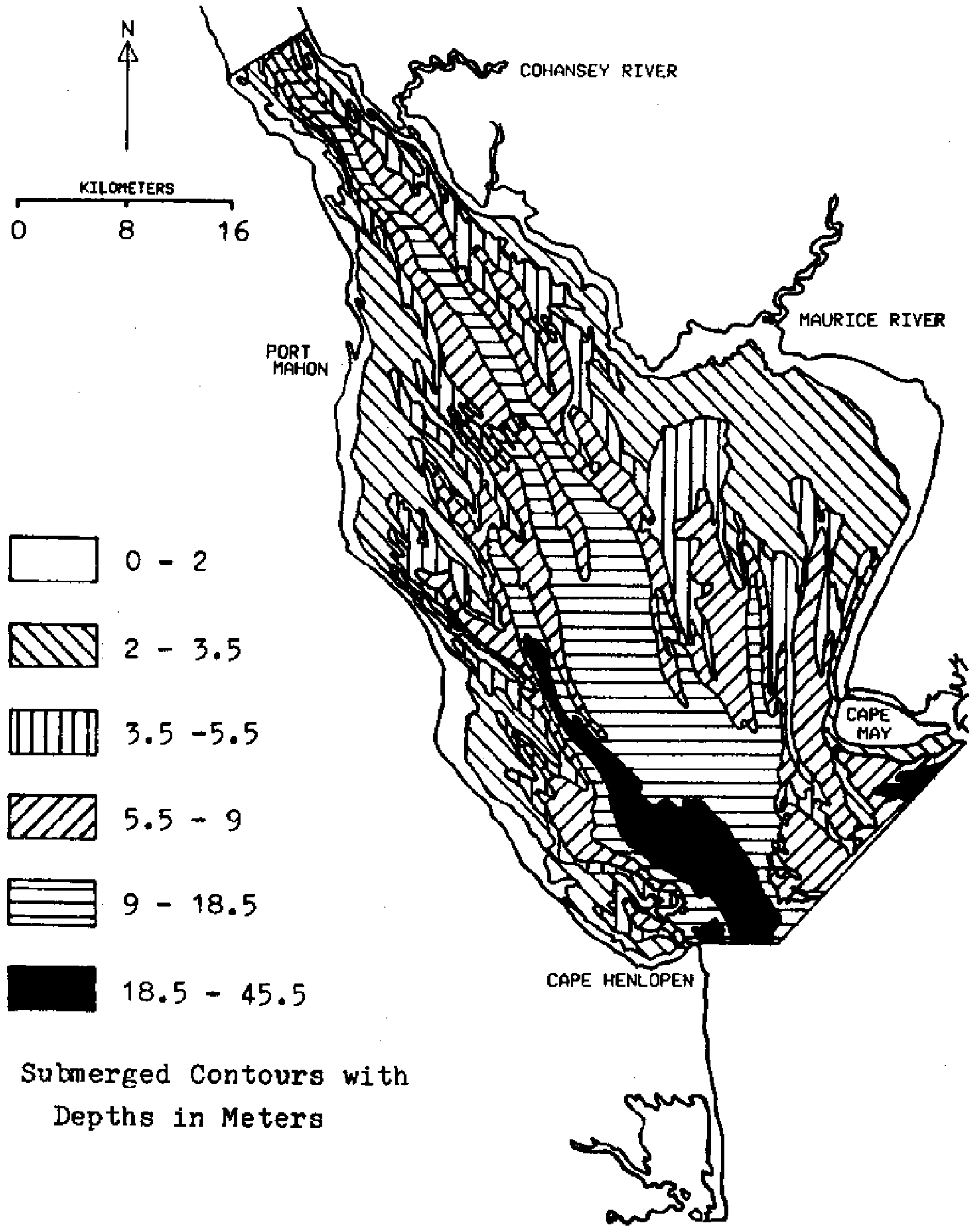

Figure 1. Bathymetry of Delaware Bay (adapted from Polis and Kupferman, 1973)

winter, winds are typically from the west-northwest with a mean speed of 6 m/s. The summer winds, in contrast, are mostly from the south-southwest with a mean speed of 4 m/s.

The strength of the expected tidal rectified current in the Bay can be estimated from Ianniello (1977) as

$$\frac{\eta}{h} \cdot u ,$$

where η is a typical amplitude of the tidal height, h is a typical water depth, and u is a typical amplitude of the tidal current. With $\eta = 2$ m, h = 10 m, and u = 0.5 m/s, the expected current is on the order of 10 cm/s (8.6 km/day), i.e., of the same order as the residual current speed expected.

Dyer (1973) includes Delaware Bay in the group of coastal plain estuaries or drowned river valleys using the topographic classification of Pritchard (1952). Based on the salinity structure classification of Pritchard (1955) and Cameron and Pritchard (1963), Dyer labels the lower Delaware Bay as vertically homogeneous but laterally inhomogeneous. For such estuaries, circulation in the horizontal plane is affected by Coriolis force with the seaward flow being concentrated on the right hand side, facing seaward in the Northern Hemisphere, and the landward flow concentrated on the left. Knauss (1978), however, includes Delaware Bay in the partially mixed category wherein there is a clear vertical salinity gradient and a circulation primarily in the vertical plane.

Longitudinal salinity sections of the Bay (Cronin et al., 1962) indicate that there is marked stratification in winter and spring, while summer and fall conditions are more nearly vertically homogeneous (Figure 2). Salinity data from the JD cruises of the University of Delaware and the New Jersey Oyster Research Laboratory (Kupferman, 1971) show that there is some stratification throughout the year. Surface salinities from these cruises mapped by Polis and Kupferman (1973) do not support the hypothesis of a primarily horizontal circulation at any time of the year.

Hansen and Rattray (1966) have developed stratification and circulation parameters to classify estuaries. Application of this system to Delaware Bay has resulted in some ambiguity, however. The Bay is

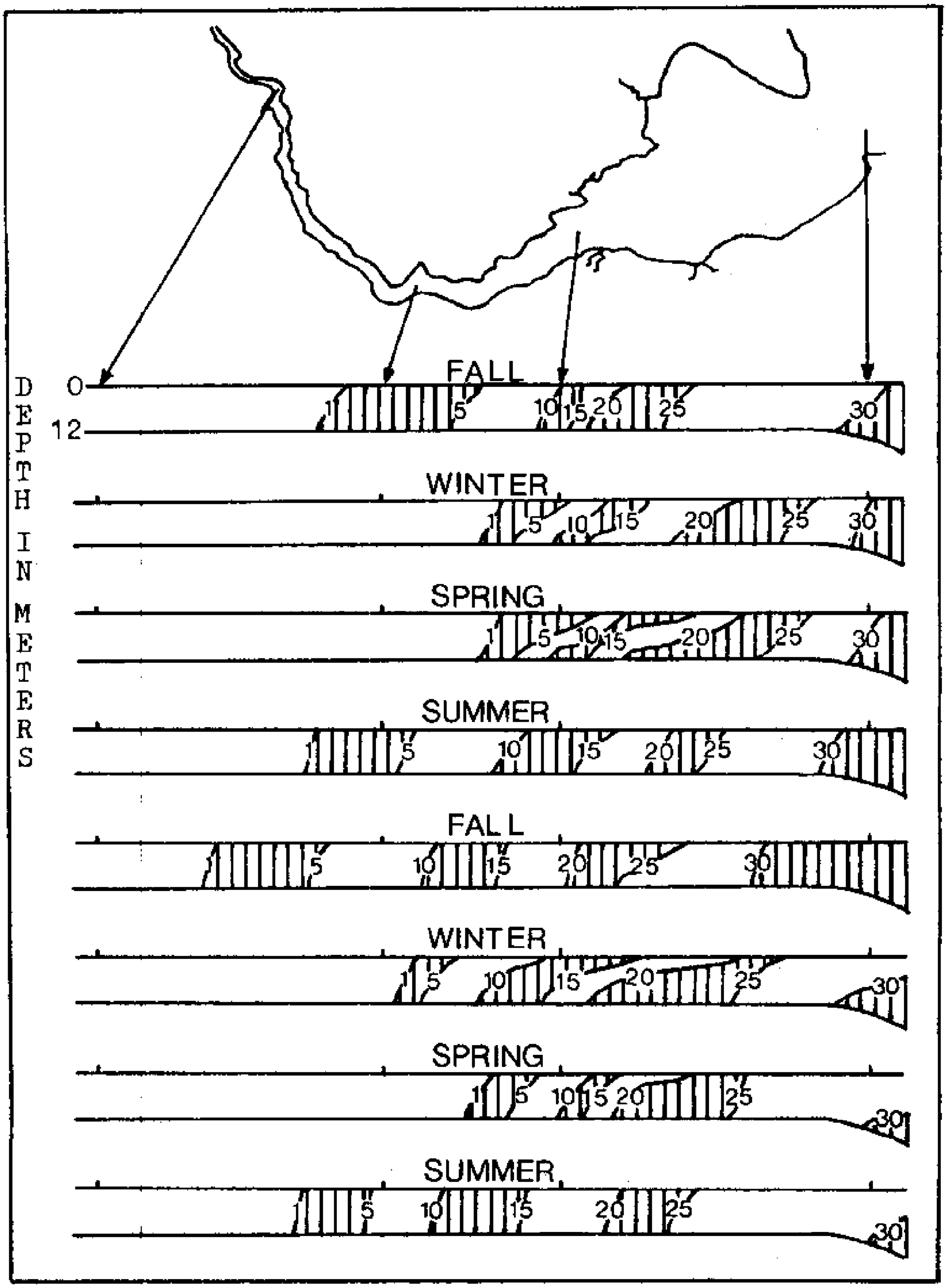

Figure 2. Longitudinal salinity sections of Delaware Bay (from Cronin, Daiber, and Hulbert, 1962)

classified in this system as fjord-like with advection dominating over diffusion (mixing by tidally induced turbulence) in mixing salt upstream. Fjord-like is certainly an improper description of Delaware Bay, however, and the small ratio of river flow to tidal flow in the Bay further implies that diffusion should dominate over advection. Hansen and Rattray have attempted to go one step beyond the simpler classification by stratification and consider circulation, but the scheme seems impractical for Delaware Bay.

From available hydrographic data, one would classify Delaware Bay as a coastal plain estuary of the partially mixed type with a small ratio of river flow to tidal flow.

DESCRIPTION OF ADJACENT SHELF WATERS

The coastal waters over the continental shelf adjacent to Delaware Bay are within the area known as the Middle Atlantic Bight. The Middle Atlantic Bight is that portion of the continental shelf extending from Nantucket Shoals on the east, just south of Cape Cod, to Cape Hatteras on the west (Bumpus, 1973), a distance of approximately 800 km. The width of the shelf is about 100 km, except approaching Cape Hatteras where it narrows to about 50 km and where the New Jersey and Long Island coasts form a curve in the shoreline and the shelf widens to about 150 km (Beardsley and Boicourt, 1981). The shelf break, marking the outer edge of the shelf, is where the slope of the shelf increases sharply. The depth of water there varies from about 150 m near Nantucket Shoals to about 50 m off Cape Hatteras (Beardsley and Boicourt, 1981). Based on these dimensions, a typical slope for the shelf in the Middle Atlantic Bight is about 10^{-3}.

With the use of drifters, Bumpus (1973) found the surface flow over the Middle Atlantic Bight to be directed towards the south, usually at less than about 20 km/day. This flow was reversed occasionally when strong northward winds were persistent and river runoff was low (Bumpus, 1969, 1973). In support of earlier findings (Bumpus, 1965), Bumpus (1973) observed an offshore bottom flow over the outer parts of the shelf, while in depths less than 60 m the bottom flow was onshore. The bottom flow was generally on the order of 1 km/day. The bottom current also tended to move towards the mouths of estuaries (Bumpus, 1965, 1973).

Beardsley, Boicourt, and Hansen (1976) summarized Bumpus's (1973) results, stating that there was an alongshore flow from Cape Cod to Cape Hatteras on the order of 10 km/day. Their study employed current meter records of at least one month duration from various points over the Middle Atlantic Bight. These measurements showed that flow throughout the water column was alongshore towards the southwest. At most of the stations, the deeper currents had greater onshore mean components. Beardsley and Boicourt (1981) also concluded that there was a long-term flow alongshore towards the southwest throughout the water column.

Saunders (1977) reported the mean wind stress in the Middle Atlantic Bight to be directed towards the east and southeast, except in the summer when the wind stress was relatively weaker and towards the northeast. Beardsley and Boicourt (1981) found that the alongshore and cross-shelf current components were significantly coherent with the local alongshore wind stress, while the local cross-shelf wind stress was not coherent with either current component. An exception, perhaps, occurs near the surface (Csanady, 1980) where cross-shelf winds may be coherent with alongshore currents.

In general, only the response of the shelf waters in the Middle Atlantic Bight to alongshore wind forcing has been studied. In their summary paper, Beardsley and Boicourt (1981) reported that alongshore winds towards the northeast (southwest) drive a northeastward (southwestward) barotropic current. The same northeastward (southwestward) winds drive surface water offshore (onshore) and bottom water onshore (offshore). The depth at which the velocities reverse is relatively deep in the unstratified, winter, season and shallower in the stratified, summer, season.

Boicourt and Hacker (1976) reported similar results. Using wind data and cross-shelf profiles of temperature and salinity, they were able to infer that winds from the south drove surface water offshore, requiring a return flow at depth. The return flow was along the bottom in winter and along the thermocline in the summer. Current meter data from periods during winds from the north were consistent with onshore flow in the surface layer and offshore flow in the bottom layer. The same data set showed that mean alongshore velocities during strong southward winds were about 10-30 km/day in a southward direction. Preliminary analysis of the current meter data during northward winds supported the argument for offshore surface flow and onshore bottom flow in the cross-shelf direction, but the longshore currents were not then extractable from the data.

EXPERIMENTAL METHODS

The major means for data collection was the release of surface and seabed Woodhead type drifters in Delaware Bay and offshore waters (Figure 3). The surface drifter, which consists of a plastic disk and stem, has just slightly positive buoyancy and is mostly submerged, lying horizontally as it moves with the surface currents. The seabed drifter has a brass weight attached to the stem which is sufficient to keep the drifter just negatively buoyant so that it remains nearly upright while gliding along the bottom except under conditions of strong turbulence.

The drifters eventually beached themselves or were picked up by fishermen. A message on the disk requested that the finder mail a record of the serial number, time, date, and location that the drifter was found. From this information, a direction and speed of movement could be calculated for each drifter returned.

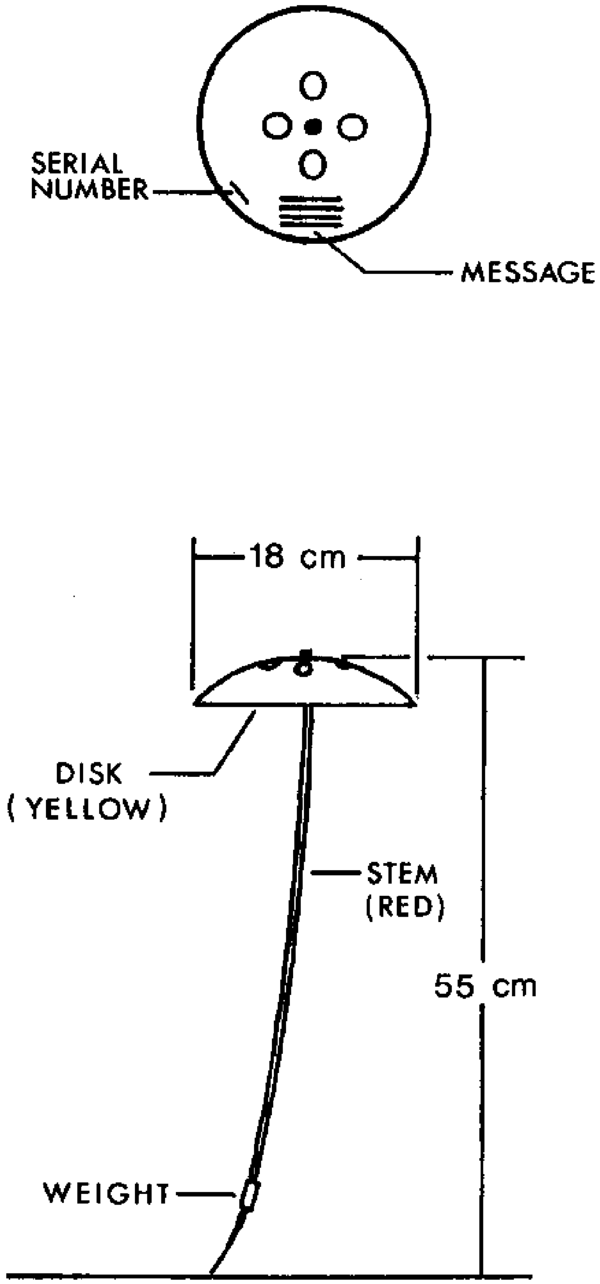

Figure 3. Side and bottom view of seabed drifter (from Conomos, et al., 1970)

Twenty-eight deployment stations were selected (Figure 4). Stations 1-19 covered most of the Bay. The width of the Bay seemed great enough that lateral variation in the residual drift could be important. The offshore stations were included to document the exchange of Bay and shelf water. Since the Bay mouth is the focus of this exchange, there was a concentration of stations there.

A total of eight releases was planned, four in each of two "seasons", a winter-spring season when winds normally are more intense and river flow is high, and a summer-fall season when winds are calmer and river flow is low. The intent was to document any seasonal variability in the residual drift. Due to logistical problems or poor weather conditions the entire study area was not covered on each release date. Table 1 shows which stations were deleted, if any, on each date. As stations near the head of the Bay were frequently deleted, a ninth deployment was made on March 7, 1980, to include most of these stations.

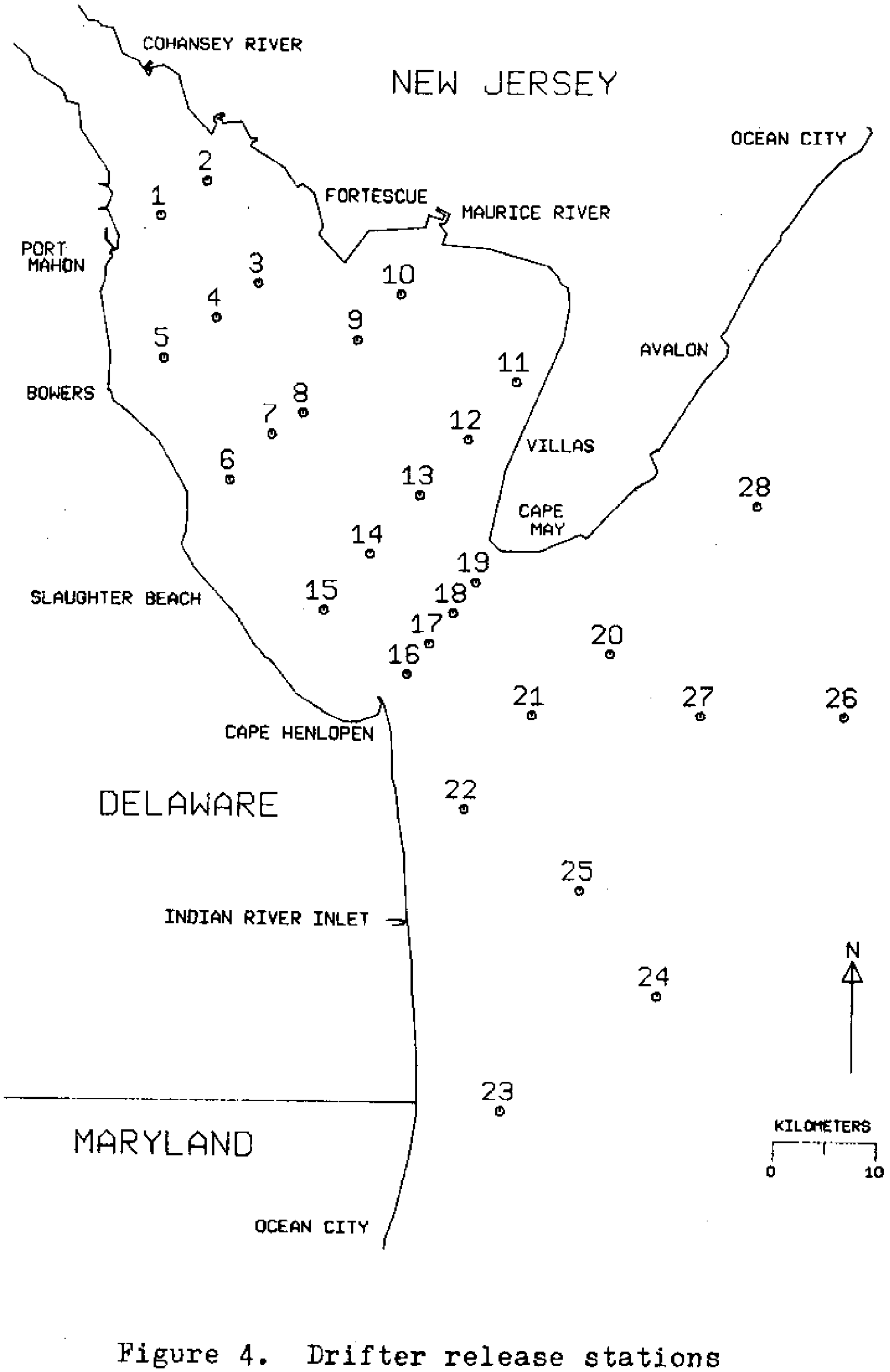

Figure 4. Drifter release stations

Table 1. Stations not sampled on each release date

Release date	Stations not sampled
19 April 1979	10, 11, 23, 24, 26
16 May 1979	1, 2
17 May 1979	----
31 July 1979	1-5
28 September 1979	1, 2
15 November 1979	----
29 November 1979	1-5
13 December 1979	1-10
7 March 1980	6, 10-28

The drifters were deployed from a United States Coast Guard helicopter. Flying time from Station 1 to Station 28 was approximately two and one half hours, a small portion of a tidal cycle, making it for all practical purposes, a synoptic release. Navigation during the release flight was by Tactical Air Navigation (TACAN). This provides a range and bearing from a transmitting station and was presumed accurate to within about 1 km, although this depends somewhat on the distance from the station. For accuracy of position, the offshore stations were chosen at conveniently located navigation buoys. The drifters deployed at each station were thrown from the helicopter as one bundle, the surface drifters in two groups of ten each, or one group of fifteen, depending on the release date, and the bottom drifters in two or three groups of five each. To facilitate release from the aircraft and to provide extra weight to sink the bottom drifters at a faster rate, each group, both surface and bottom, was held together with a rubber band fastened to an 85 g salt lick. The fastening was done in such a way that when the salt lick dissolved (about 55 min in a static test) the drifters separated. Assuming a sinking rate of 3 m/min (Paskausky and Murphy, 1976), a group of bottom drifters should have reached the bottom within navigational error (about 1 km).

In an attempt to release the drifters at each station at nearly the same point in the tidal cycle, the flights were scheduled to follow the point of low slack water up the Bay. Low slack water travels from the mouth to the area of Stations 1 and 2 in about the same time as the flight from Station 19 to Station 1 (about 1 hr). Due to scheduling and logistical problems, the takeoff times were not always optimal. However, it was possible to release all the drifters at some time during a flood current.

The use of drifters to measure residual currents is a relatively inexpensive method but has several limitations. Information on the movement of the drifter is restricted to the point of release and the point of return; nothing is known of the actual path of the drifter otherwise. There is a bias in the distribution of return points brought about, on the one hand, by the concentrated use of specific shoreline and fishing areas by people and, on the other hand, by the relative scarcity of such recovery points offshore.

The velocities determined from drifter returns have inherent uncertainties. The time that the drifter may have been on the shore before discovery or caught previously on some obstruction produces a bias in the estimated velocities toward low values. In addition, in the case of the bottom drifters, the velocity of the drifter is not consistently that of the currents. In current speeds lower than 10 cm/s (8.6 km/day) the drifter velocity is appreciably less than that of the water (Phillips, 1970). The result is that the return point may reveal more the effect of the stronger part of the tidal current cycle than the actual residual currents. The weight attached to the bottom drifter, necessary to overcome the buoyancy of the stem and disk, can also affect the response to current speed. In freshwater, Woodhead and Lee (1960) found that drifters with weights between 5 and 8 g moved with a velocity less than that of the water when the water velocity was below 17 cm/s (14.7 km/day). They recommended a 5 g weight in freshwater and 7 g in seawater. However, several studies (Conomos et al., 1970; Gross and Bumpus, 1972; Gross et al., 1969; Morse et al., 1968) report the use of 5 g weights in seawater. The weights used in the present study weighed between 5 and 6 g. The lighter weight may have made the drifter fully responsive to lower water velocities, but may also have allowed it to rise off the seafloor too often.

EXPERIMENTAL DESIGN

Drifter studies conducted in other waters (Bumpus, 1973; Conomos et al., 1970; Gross and Bumpus, 1972; Gross et al., 1969; Hollman and Sandberg, 1972; Larkin and Riley, 1967; Marsden, 1979; Norcross and Stanley, 1967; Paskausky and Murphy, 1976; Phillips, 1970; Squire, 1969) have not reported statistical justification for the number of drifters released at a station. In order to design a better experiment, some statistical calculations were made based on residual velocities taken from the literature, despite the general scarcity of such reports. The procedures used follow Probability and Statistics for Engineers (Miller and Freund, 1965).

Assuming a normal distribution, the equation,

$$n = \frac{Z_{\alpha/2}^{2} \cdot \sigma^{2}}{E^{2}} , \qquad (1)$$

gives the number of sample observations from the population of residual velocities at a station necessary to obtain a mean velocity for the sample which is, for a desired probability of $1-\alpha$, within a desired error, E, of the true population mean. The statistic Z was obtained from the normal distribution function tables (Miller and Freund, 1965) and σ is the true standard deviation of the population. However, σ is not determinable, since computing it requires mean residual velocities for the entire population. In its absence, one may estimate it from a known sample standard deviation.

Since there was no prior knowledge of the population of residual velocities at a station, it was assumed that this population is similar to that of the mean residual velocities of all estuaries. Each of these means is the average of residual velocities found in the estuary. The population of residual velocities at a station that is to be sampled is therefore taken, for statistical purposes, to be the population of mean residual velocities of all estuaries. The group of mean residual velocities measured for some estuaries, mostly Long Island Sound, is taken to be the known sample observations of the population at a station. From k given sample observations, x_i (where i = 1 through k), the sample standard deviation, s, can be computed from the following equation:

$$s = \sqrt{\frac{k \cdot \sum_{i=1}^{k} x_i^2 - \left(\sum_{i=1}^{k} x_i\right)^2}{k(k-1)}} ,$$

and can be used in place of σ in equation (1).

The n from equation (1) is the number of drifter returns required per station to obtain the desired sample mean using the chosen constraints. Using an estimate of percentage return values given in the literature, the appropriate number of drifters to release at a given station may be computed.

Table 2 gives the sources, mean surface residual velocities, and percentage of drifter returns from the literature used to determine the required number of surface drifters for the first releases. From these figures, it was determined that about 6 returns were necessary to obtain, with 85% probability, a sample mean within 2 km/day of the true mean. This is an error of 22% of the average of the mean velocities given in Table 2. Assuming a 36% return rate, about 17 surface drifters

Source	Mean velocity (km/day)	Percent returned
Prytherch, 1929 Long Island Sound	9.53	----
Larkin and Riley, 1967 Long Island Sound	12.96	46.7
Hollman and Sandberg, 1972 Long Island Sound, Block Island Sound	5.18	23.8
Paskausky and Murphy, 1976 Long Island Sound, Block Island Sound	8.53	37.7

Table 2. Mean surface residual velocities and percentage of drifters returned from previous estuarine drifter studies

should have been released from each station.

Table 3 summarizes results from drifter studies of bottom currents. Using these data, it was found that about 4 returns are required for an error of 0.2 km/day with an 85% probability. This error is 22% of the averaged mean velocities presented in Table 3. The mean return of 34% thus implies a release of about 12 bottom drifters at each station.

These calculations yielded only rough estimates; hence, 20 surface and 10 bottom drifters were released at each station for the first three experiments. There was sufficient time between the third and fourth releases to reconsider these numbers based on the actual return rates of the first three releases. The bottom returns for the first three releases averaged about 9%, far lower than anticipated; the average for surface returns was 30%, nearly that expected. In an effort to insure a sufficient number of bottom returns for statistical purposes, the number of bottom releases was increased to 25 per station for the remaining 6 releases. A corresponding reduction to 15 in the number of drifters released at each surface station was less than optimal, but sufficient. Over the entire study period, 3470 surface and 3940 bottom drifters were released.

Source	Mean velocity (km/day)	Percent returned
Bumpus, 1965 Mid-Atlantic Bight	0.75	24.0
Gross and Bumpus, 1972 Long Island Sound	0.70	33.3
Hollman and Sandberg, 1972 Long Island Sound, Block Island Sound	0.87	42.3
Paskausky and Murphy, 1976 Long Island Sound, Block Island Sound	1.29	36.1

Table 3. Mean bottom residual velocities and percentage of drifters returned from previous drifter studies

SUPPORTING DATA

The movement of the drifters gives an indication of the nature of the near-surface and near-bottom residual currents. Although the cause and effect relationships between the residual circulation and the quantities that drive it are not well understood, some of the mechanisms are apparent. Therefore, some of the measurable quantities associated with the known driving forces of residual currents were recorded for Delaware Bay.

The measurable quantities that served as supporting data sets were wind and river flow. Wind data relevant to Delaware Bay and the adjacent continental shelf were obtained for the study period from the National Oceanic and Atmospheric Administration (NOAA). Atlantic City, New Jersey, is the station closest to Delaware Bay. The wind record at Atlantic City is a reliable record of offshore winds. Halliwell and Mooers

(1980) showed that there was little difference in direction between Atlantic City wind and offshore wind but a constant proportionality factor of about two for speed. This conclusion, along with the similarity of the NOAA Atlantic City data to that at Wilmington, Delaware and Norfolk, Virginia, demonstrates the large scale of the wind forcing compared to the scale of Delaware Bay. Thus, the Atlantic City wind data are applicable to Delaware Bay for present purposes, especially since the level of noise in the drifter return data was appreciable. Figure 5 gives the daily mean wind speed and direction for the study period. The vectors point away from the baseline toward the direction of the wind. The cycle of summer winds from the south-southwest and winter winds from the west-northwest, typical of most years, is not evident for the period when most drifter data were collected, April to December, 1979.

Freshwater flow into the Bay contributes directly to the gravitational circulation. The flow of the Delaware River, the major source of freshwater to the Bay, is recorded daily at Trenton, New Jersey by the United States Geological Survey and this information has been routinely sent to the University of Delaware since

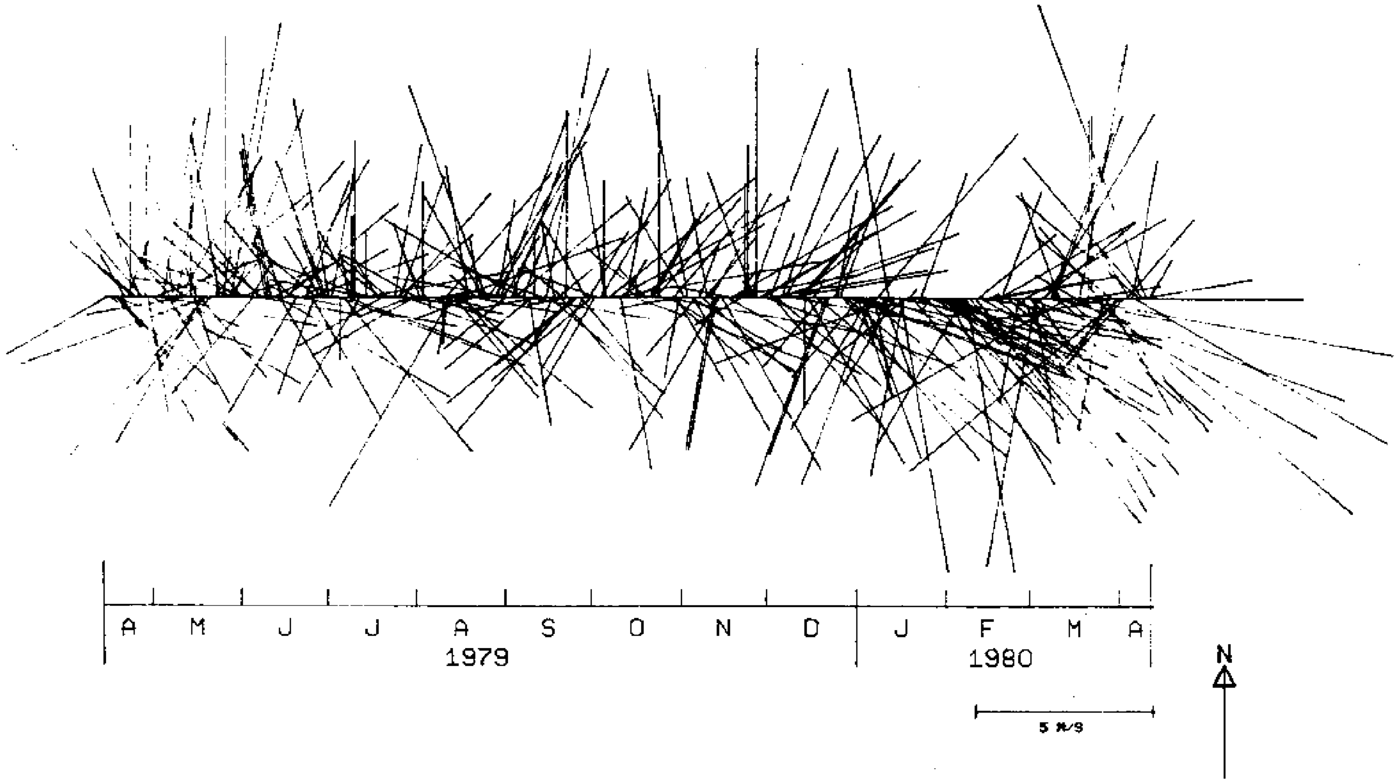

Figure 5. Wind speed and direction at Atlantic City, New Jersey for the study period. Vectors point from the baseline in the direction towards which the wind blew.

1972. These data for the study period are shown in Figure 6. River flow is typically quite high in winter and spring but low in summer and fall; however, no such large variation occurred during the study period (Figure 6). The two records of river flow and wind were correlated with the drifter movements as discussed later.

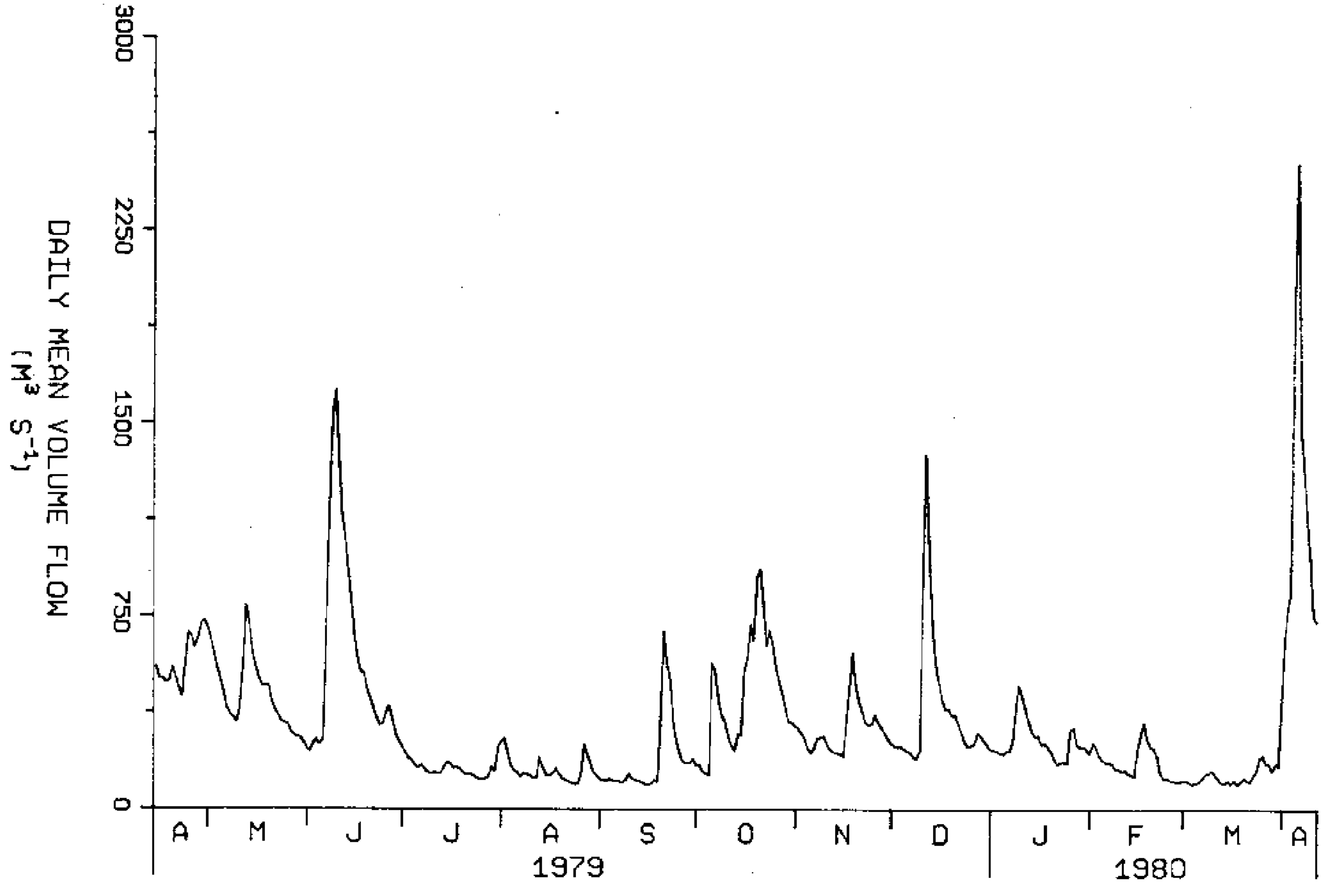

Figure 6. Volume of Delaware River flow, measured at Trenton, New Jersey, for the study period

DATA ANALYSIS TECHNIQUES

Introduction

The major part of the data analysis involved the mapping of the movements of the drifters. From the return data, Lagrangian mean speeds and directions for each drifter were calculated and mapped. An average of these means was calculated for each station, both for each release date and for the study period as a whole. These two series of maps were used to infer a pattern of near-surface and near-bottom residual circulation in Delaware Bay and offshore. Summary statistics were computed for returns from each release date and these were correlated with wind and river conditions in hope of describing the physical processes responsible for residual circulation. The following sections explain those details of data analysis and reduction essential to interpretation of the results.

Mapping Techniques

In the absence of knowledge of the actual trajectory of a drifter, an apparent trajectory was constructed. Where possible, this apparent trajectory was simply represented by a straight line connecting the point of release with the point of recovery. Occasionally, this line coincided with the orientation of the coastline such that the point of recovery was not visually distinct. If this occurred adjacent to the recovery point over a distance of about 2 km (1 nm) or more, the apparent trajectory was adjusted, as demonstrated in Figure 7 (line ABC), to make an angle of approach to the coastline of at least 45°. This adjustment was not always necessary, however, as illustrated by line DE. In many cases, a straight line would have given an apparent trajectory crossing land. A consistent technique was used to alleviate this. An example is given in Figure 7 in which the adjusted apparent trajectory runs along line FGHI. In all cases of adjustment for land crossings, the trajectory was kept at least 2 km offshore and the number of angles was restricted to three where possible. Use of acute angles was avoided because of the small likelihood of their

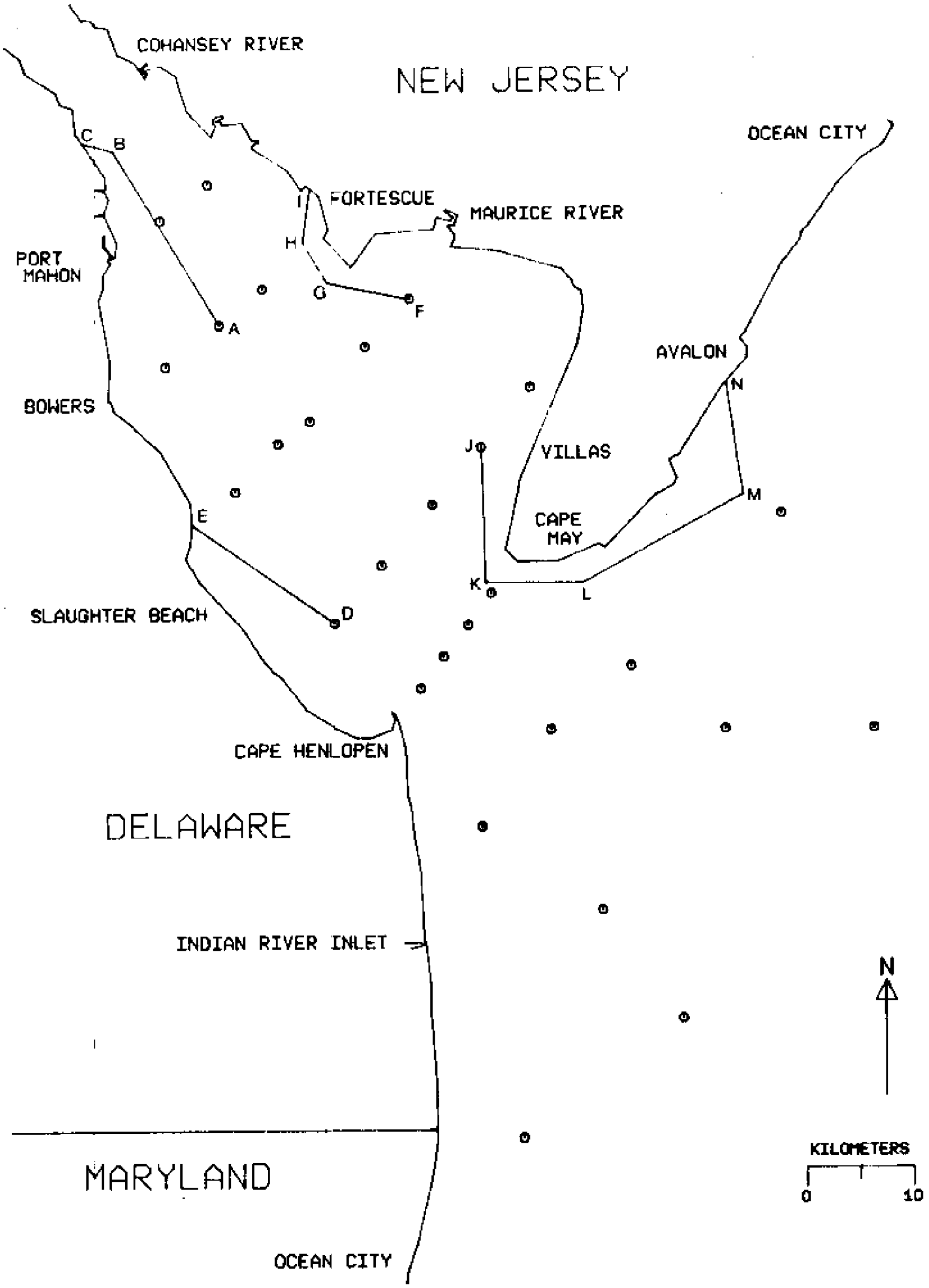

Figure 7. Apparent trajectory examples

occurrence in actual trajectories. Instead, obtuse angles were used, even if this required use of a greater number of such angles. An example of such usage is line JKLMN in Figure 7.

The recovery points of many of the surface drifters showed that some had spent a long time moving in waters outside the vicinity of Delaware Bay and the adjacent shelf. In order for a drifter's estimated velocity to be representative of the residual circulation of the Bay and adjacent shelf, it must have traveled primarily within this area. Two drifters, in particular, illustrate this point in the extreme. Both were returned from Ireland. Obviously, most of their trajectories were outside the area of interest. These and other less extreme examples led to the definition of a limited experimental domain which included Delaware Bay and portions of the adjacent shelf. Limits to the domain were determined by examining the distribution of returns north and south along the coast. A cumulative plot of this distribution is given in Figure 8. The two points at which the slope of the plot changed abruptly (marked with arrows) were chosen as the latitudinal boundaries of the experimental domain. The northern boundary is about

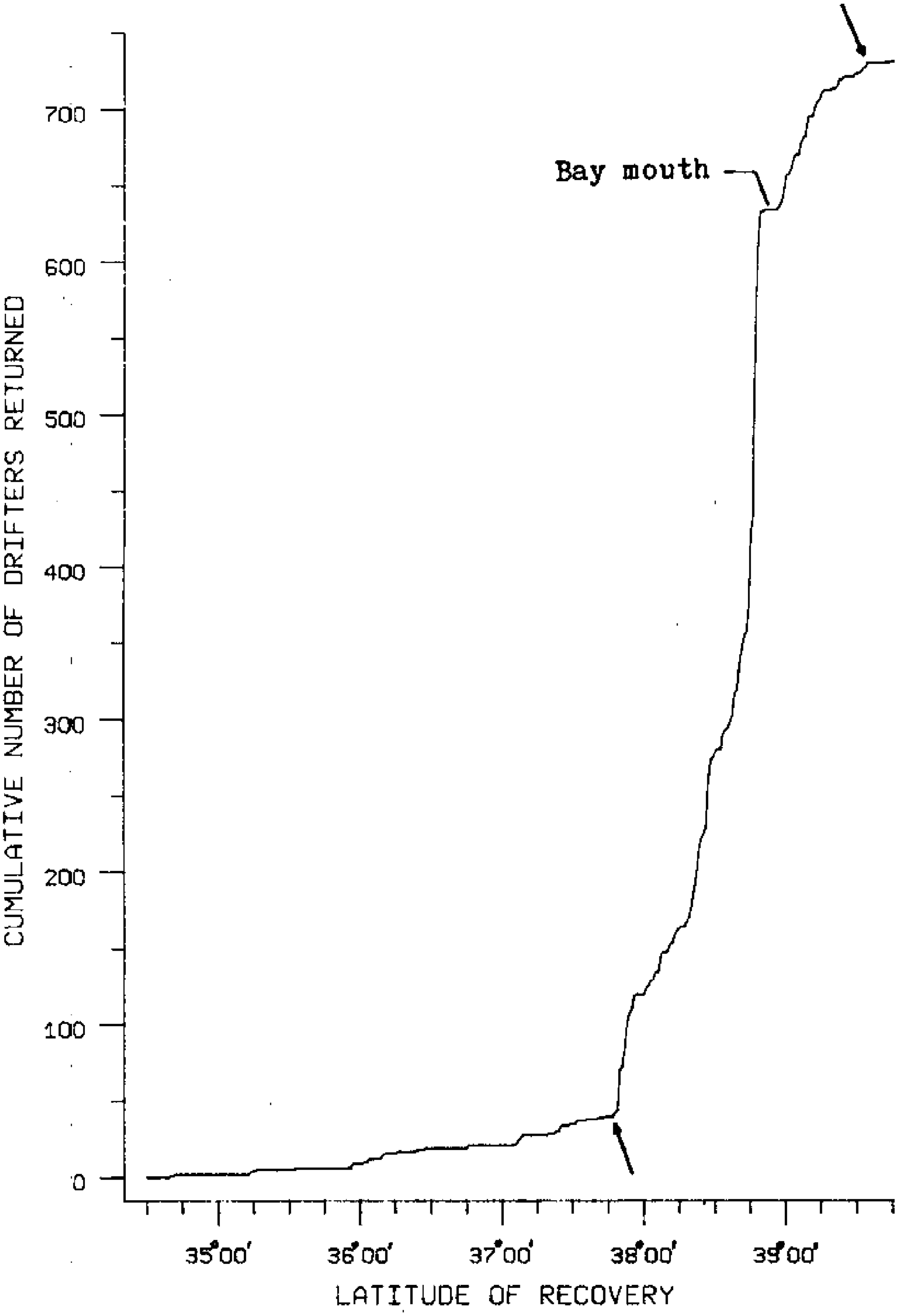

Figure 8. Cumulative number of drifters returned for the study period plotted against latitude of recovery

20 km north of Atlantic City, New Jersey at latitude 39°34'N. It represents the position north of which returns decreased sharply. The southern boundary is about 10 km south of Assateague Island, Virginia at latitude 37°47'N. It represents the position south of which returns decreased sharply. Returns from beyond these bounds were judged to have failed this test of relevance for calculations of both return statistics and mean currents. Of 733 surface returns, 33 failed. However, all bottom returns were within the domain.

Relevant drifters also had to satisfy a time requirement. An upper limit to acceptable durations eliminated those drifters that went so far offshore as to be outside the current field of interest for a long time. It also eliminated drifters with suspiciously long durations, probably due to anomalous delays, including the time that may have passed while a bottom drifter was caught on an object or while a drifter was on the beach prior to discovery. The upper limit was chosen after examining cumulative duration plots for returns from each release date. An example is given in Figure 9. The point at which the slope of the curve decreased sharply was used as an upper limit to durations for that date.

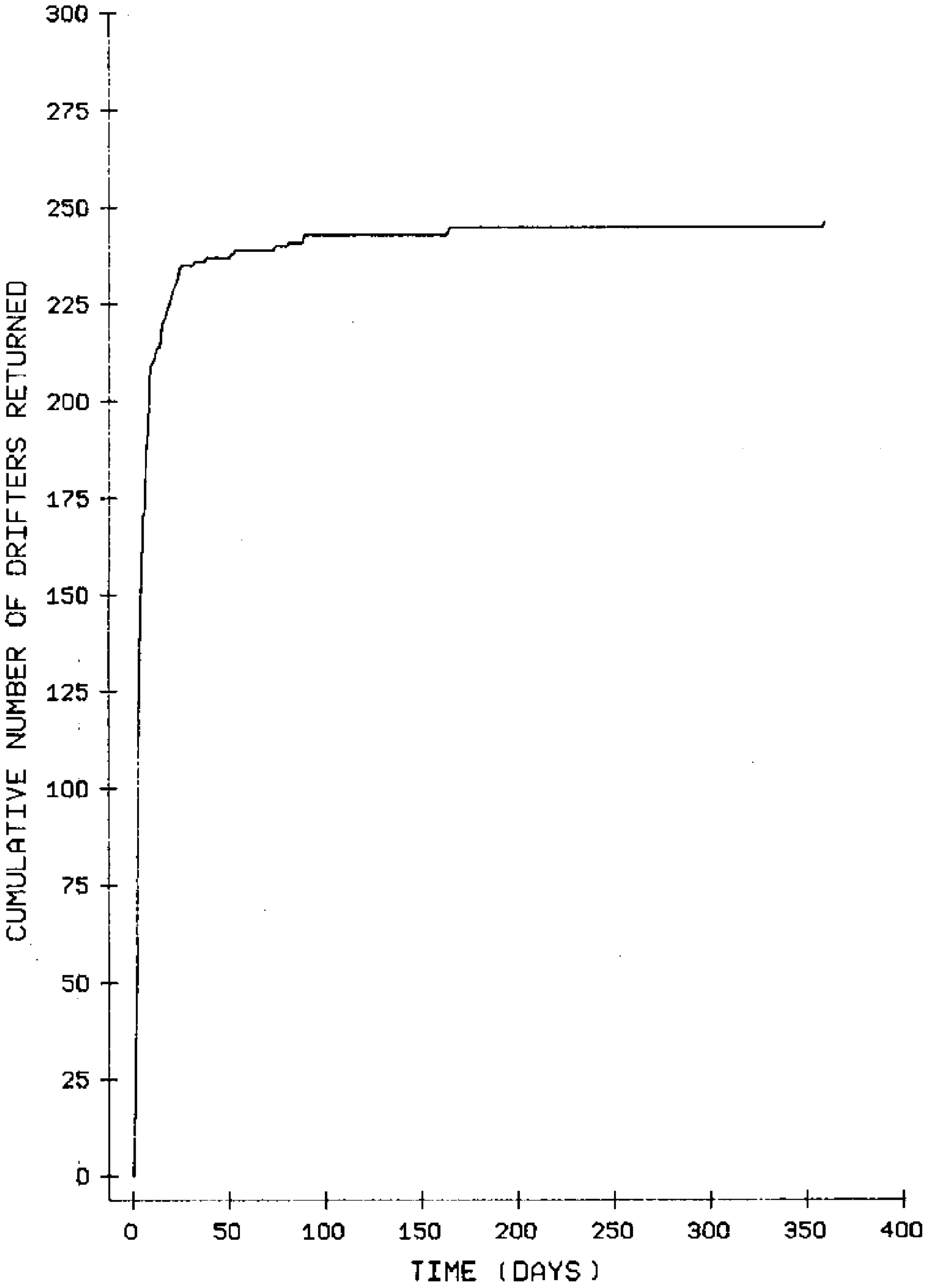

Figure 9. Cumulative number of drifters returned plotted against durations for surface returns from 16 May 1979 release

In addition, a lower limit was also imposed and set at one day, since time of shorter duration would not represent a long-term averaged current.

Calculation of Speed and Direction and Their Means

The speed of each relevant drifter was calculated by dividing the apparent trajectory length by the estimated time. This speed was an estimate of the Lagrangian mean speed. Each drifter, no doubt, traveled a circuitous path at varying speed, but only the apparent trajectory was available. The direction of travel was taken as the orientation of the initial segment of the trajectory from the release point. The mean speed and direction then gave a trajectory mean, the estimated Lagrangian mean velocity vector of each drifter and thus, presumably, of the parcel of water in which it had traveled.

In fact, a distribution of velocities should be expected for a group of drifters deployed at one time from a particular station. Even for drifters released at the same time and place, somewhat different onshore arrival times and places will result from their immersion in a turbulent medium with random motions. Therefore, a station mean speed and direction, an average of the individual trajectory mean speeds and directions from a station, with associated confidence intervals, was determined for each station from the sample of reported recoveries. This is in contrast to the common practice of rejecting all computed velocities, except the fastest, under the assumption that all lower values are associated with anomalous delays. The present method provides a more valid estimate of the Lagrangian mean current for a station.

For the group of relevant drifters at each station, mean directions and associated confidence intervals were determined using directional statistics (Mardia, 1972). This approach alleviated the problems encountered when common linear statistics are applied to directional data; for example, the arithmetic mean of the angles 10° and 350° is 180°, but using appropriate geometrical interpretation, the mean should be 0°. The geometrical approach uses, instead, means of the separate horizontal coordinates for a particular station and release, as in vector averaging.

It had been planned for interpretation of the data to divide the study period into two "seasons" based on wind conditions and river discharge, a windy/wet season (winter and spring) and a calm/dry season (summer and fall), as Paskausky and Murphy (1976) did. Unfortunately, the greater part of the experimental period, April to December 1979, was anomolous in terms of both wind and river flow. The typical seasonal trends described previously were not clear for either wind or river flow (Figures 5 and 6). Consequently, this idea was abandoned. No separate averaging over such a "season", then, was done. Instead, only total means for the entire series of releases were computed in addition to the means at each station for a given release.

Wind and River Data

For interpreting drifter returns, the most important direction of water movement is directly into or out of the Bay mouth. Both river flow and wind stress can induce currents in these directions.

River flow must move seaward and out of the Bay. In principle, as the freshwater flows into the estuary and over the more dense saltwater, saltwater is mixed upward and carried seaward. Thus, mass continuity requires a compensating flow of seawater moving up the Bay. This is the process of gravitational circulation which, presumably, would intensify with greater river flow.

The processes whereby wind stress can force currents into or out of the Bay mouth are more complicated. Well away from a coast, the combined action of Coriolis force and wind stress causes movement of surface water to the right of that of the wind (in the Northern Hemisphere). This is known as surface Ekman transport. In a right-hand coordinate system, wind in the positive (negative) y-direction moves surface water in the positive (negative) x-direction. Therefore, wind blowing parallel to the mouth of Delaware Bay (y-direction) would move surface water into or out of the Bay (x-direction). Winds in this direction, then, should strongly affect drifter returns.

Wind parallel to the Bay mouth is also an alongshore wind. The coast acts as a barrier, preventing the transport of water perpendicular to it. Therefore, due to mass continuity, an alongshore wind to the northeast, which transports surface water offshore to the right, will produce upwelling at the coast supplied by a compensating onshore flow of deeper water. Alternatively, wind to the southwest would cause onshore surface flow, downwelling at the coast, and a compensating offshore flow of deeper water. Where the coast is interrupted by an estuary, such as Delaware Bay, the head of the estuary acts as the coastal barrier. For Delaware Bay, then, a northeastward wind, with its corresponding offshore surface flow and onshore deeper flow extended into the Bay, should intensify the estuarine gravitational circulation. A southwestward wind, alternatively, with its onshore surface flow and offshore deeper flow, should oppose the gravitational circulation.

Ekman transport clearly cannot operate in waters close to shore, since no transport perpendicular to shore is possible. The response of water there, instead tends to be primarily to the alongshore component of the wind with the induced current in the same direction as the alongshore wind component and similar throughout the water column (barotropic). Thus, the alongshore wind component should strongly affect the alongshore movement of both surface and bottom drifters, both those deployed offshore and those deployed in the Bay which reached the adjacent shelf.

Surface Ekman transport itself reflects the average movement of water over the whole depth of frictional influence, typically 5 to 10 m. While the vertically averaged direction is perpendicular to the wind, the current direction in the upper meter or so is more nearly aligned with the wind. Doebler (1966), for example, reported averaged surface wind drift currents at 5° to the right of the wind. Thus, surface drifters should respond also to the local wind direction. This is particularly likely near shore and in the Bay where the proximity of the shore inhibits a response to wind in the form of Ekman transport.

Some surface transport perpendicular to the coast does occur. Bottom flow due to mass continuity does not perfectly compensate for this surface flow and the result of offshore wind is a drop in coastal sea level, while onshore wind causes a rise. A drop in coastal sea level can also occur, again because of the imperfect bottom response, as a result of northward alongshore wind and the offshore surface Ekman transport response away from the coast. Likewise, a southward wind alongshore can force a rise in coastal sea level.

In quantitative terms, surface Ekman transport is given by the following equation (Knauss, 1978):

$$M_x = \frac{\tau_y}{f} , \qquad (2)$$

where M_x is the transport of mass in the x-direction per unit width in the y-direction integrated vertically through the depth of frictional influence, τ_y is the wind stress in the y-direction, and f is the Coriolis parameter. Wind stress in the y-direction was computed from the standard form,

$$\tau_y = \rho \cdot C_d \cdot V_{w_y}^2 ,$$

where ρ is the density of air, C_d is a non-dimensional coefficient representing the drag of the wind on the water's surface, and V_{w_y} is the component of the wind in the y-direction. A value of 1.23×10^{-3} g/cm^3 was used for ρ representing the density of air under average conditions (Petterssen, 1969). A value for C_d of 1×10^{-3} was chosen as representative (Wu, 1969). For simplicity, f was taken as constant and equal to 1×10^{-4} 1/s.

Equation (2) gives a quantitative measure of mass transport in the surface layer 90° to the right of the wind. In addition, since f is constant, it gives a quantitative measure of wind stress itself in the y-direction. Therefore, the values derived from equation (2) will hereafter be referred to as mass transport/wind stress data.

Intuitively, one expects that surface transport out of the Bay mouth would reduce the number of surface drifters returned, while the compensating bottom flow up the Bay would increase both the number and speed of bottom returns. Conversely, surface transport into the mouth would increase surface returns and speed and decrease bottom returns and speeds. It was thus expected that the river and wind data would account for much of the variation in the percentage of drifters returned, as well as their speed. Furthermore, it was expected that their direction of movement alongshore to the north or south could be explained by the speed and direction of alongshore wind.

In order to examine the quantitative relationship between drifter returns and variations in river flow and wind data, correlations (Pearson product moment) were computed between these data and both drifter return percentages and speed; this was done separately for surface and bottom drifters. The river data used were the daily mean volume flow rates of the Delaware River at Trenton, New Jersey (Figure 6). The daily mean volume flow rate was numerically integrated over the median time that drifters were out for each release. Surface and bottom median times for each date were used for separate integrations.

Several wind directions were chosen to test for a relationship between the drifter data and the wind. The mouth of the Bay, as well as the coast from Chesapeake Bay to southern New Jersey, has an orientation of about 30°. The component of the wind in this direction, taken as the positive y-direction, was used in Equation (2) to compute the offshore Ekman mass transport toward 120°, i.e., out of the Bay and perpendicular to the Bay mouth. Negative values, thus, would correspond to Ekman transport toward 300°, i.e., into the Bay, in response to the wind component toward 210°. This wind stress component would also be relevant to longshore current generation. A second series of calculations was made for a direction of 115° for the positive y axis to investigate direct movement out of the Bay and offshore for surface drifters.

Besides computing correlations for these two directions expected to be most important, it was decided to use wind directions in all four quadrants of the compass to test for any unexpected high correlations. Thus, a range of directions covering the first two quadrants (30°, 55°, 75°, 105°, 115°, 145°, 170°) was used. Negative wind stress along these orientations corresponded to positive values in the other two quadrants.

The mass transport/wind stress values resulting from each axis orientation selected were correlated separately with the drifter data, both percentages and mean speeds for surface and bottom on each date. Each mass transport/wind stress curve (an example of which is given in Figure 10) was numerically integrated using the same technique as was applied to the river flow data.

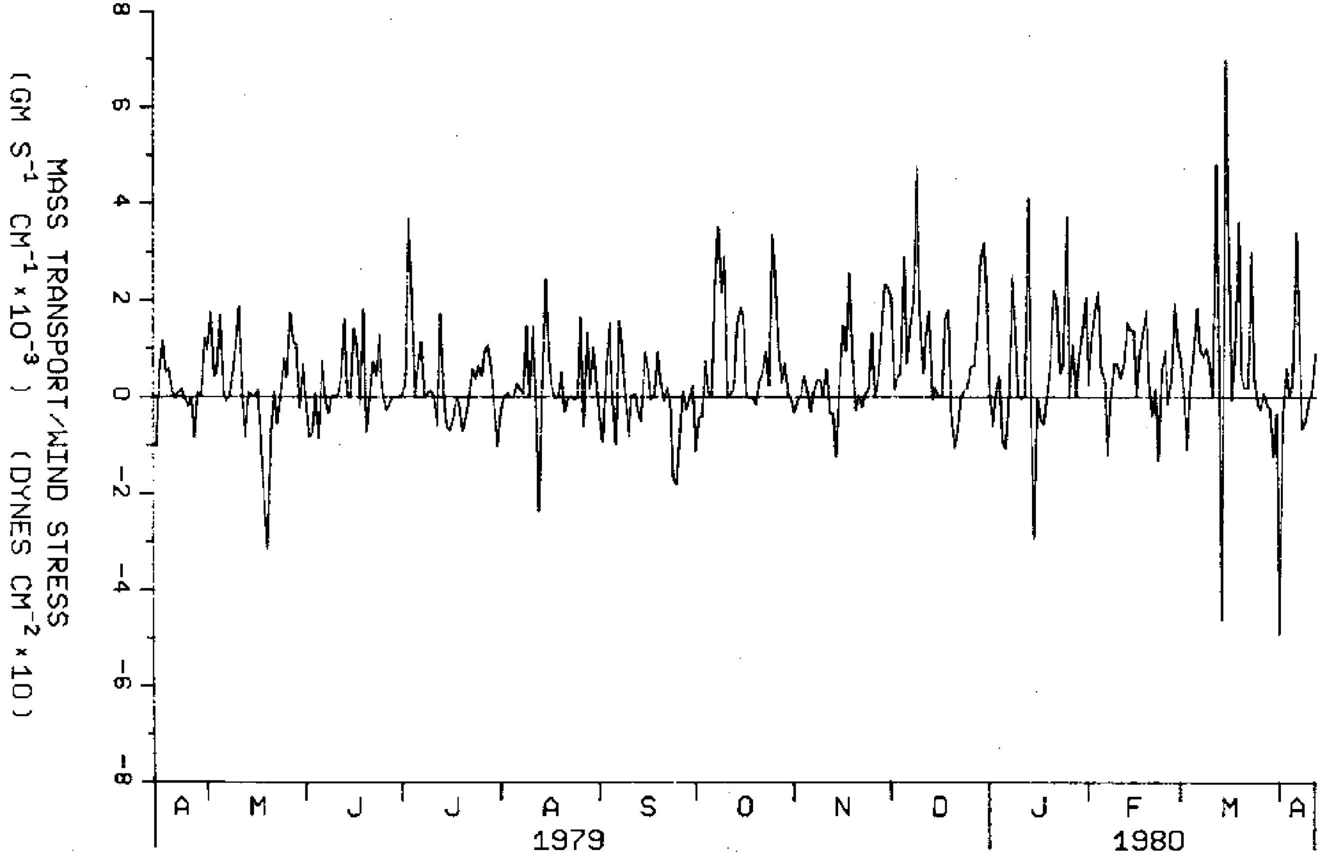

Figure 10. Mass transport/wind stress data for 75° axis for the study period. Positive values indicate wind stress in the 75° direction and negative values indicate wind stress in the 225° direction.

RESULTS AND DISCUSSION

Introduction

This section begins with an overview of the movements of the drifters. Then, a more detailed examination of apparent trajectories is given, including a statistical summary of the returns. Inferences are then made from the pattern of residual circulation found. Correlations of some of the return statistics with two of the agents forcing residual circulation, wind and river discharge, are then discussed.

Drifter Movements

The general pattern of surface trajectories will be considered first, followed by the general pattern of bottom trajectories. Figures 11-19 show the apparent surface trajectories resulting from each of the nine

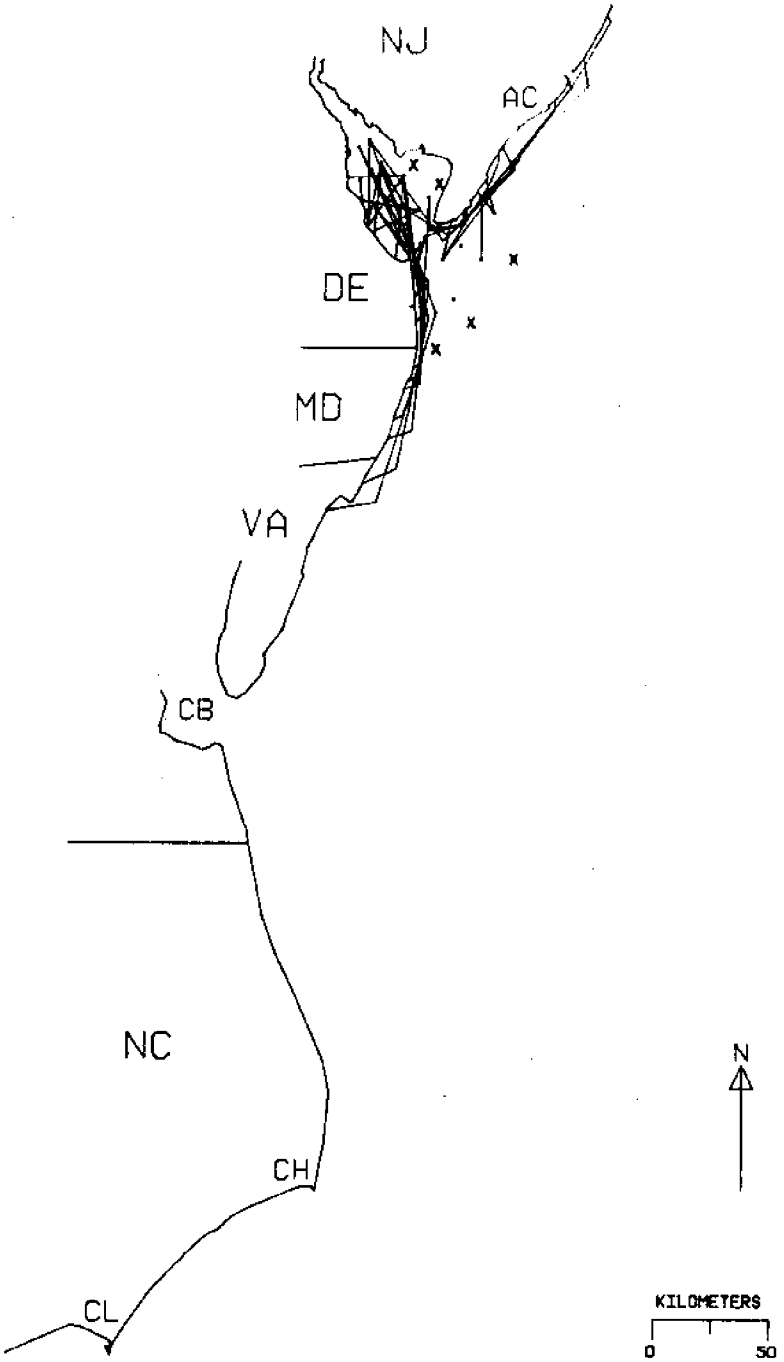

Figure 11. Apparent surface trajectories for 19 April 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

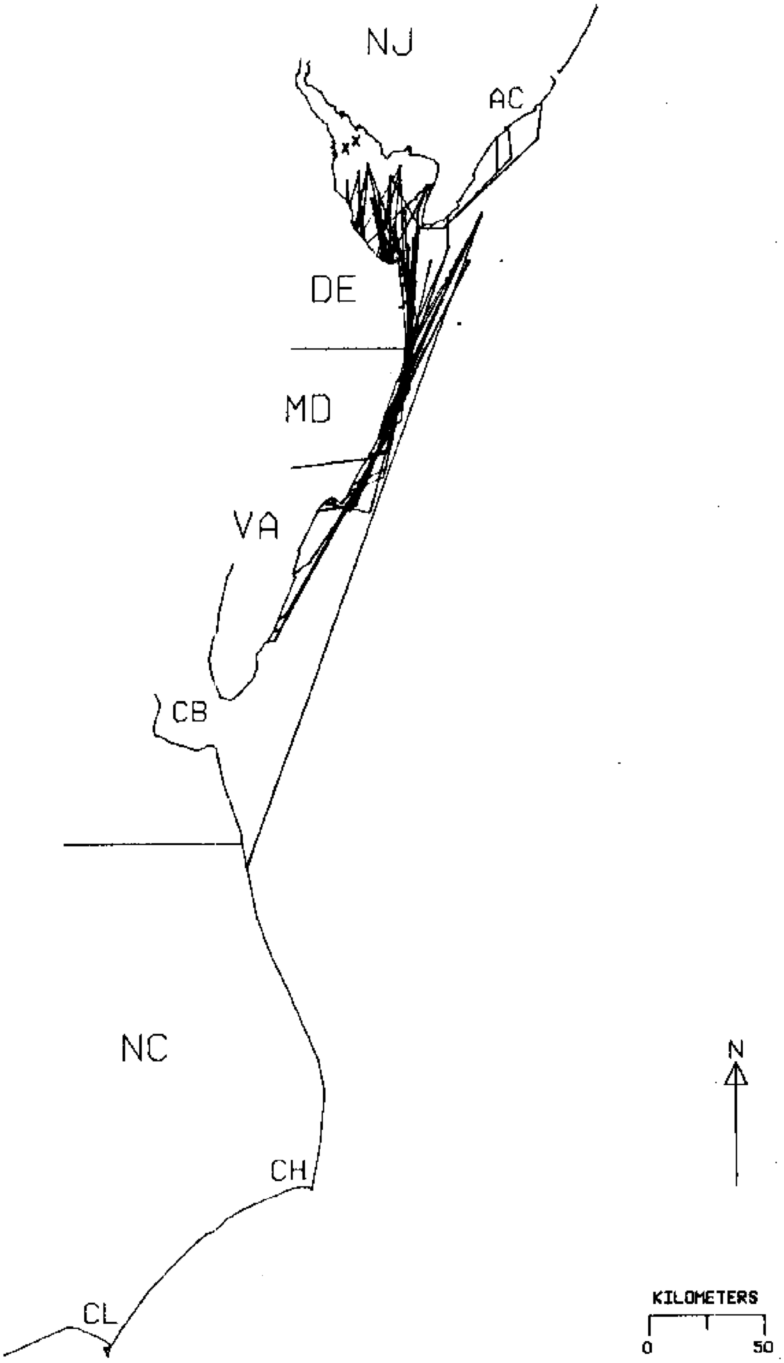

Figure 12. Apparent surface trajectories for 16 May 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

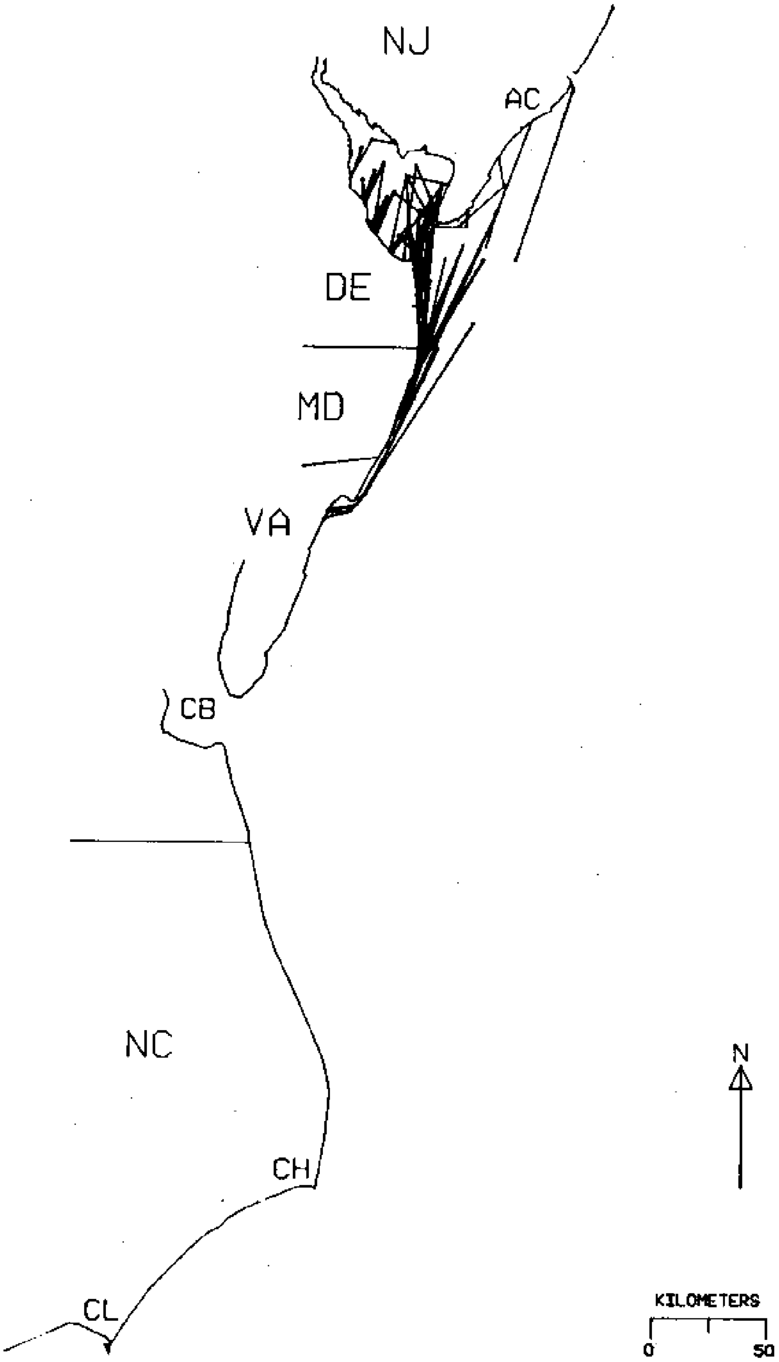

Figure 13. Apparent surface trajectories for 17 May 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

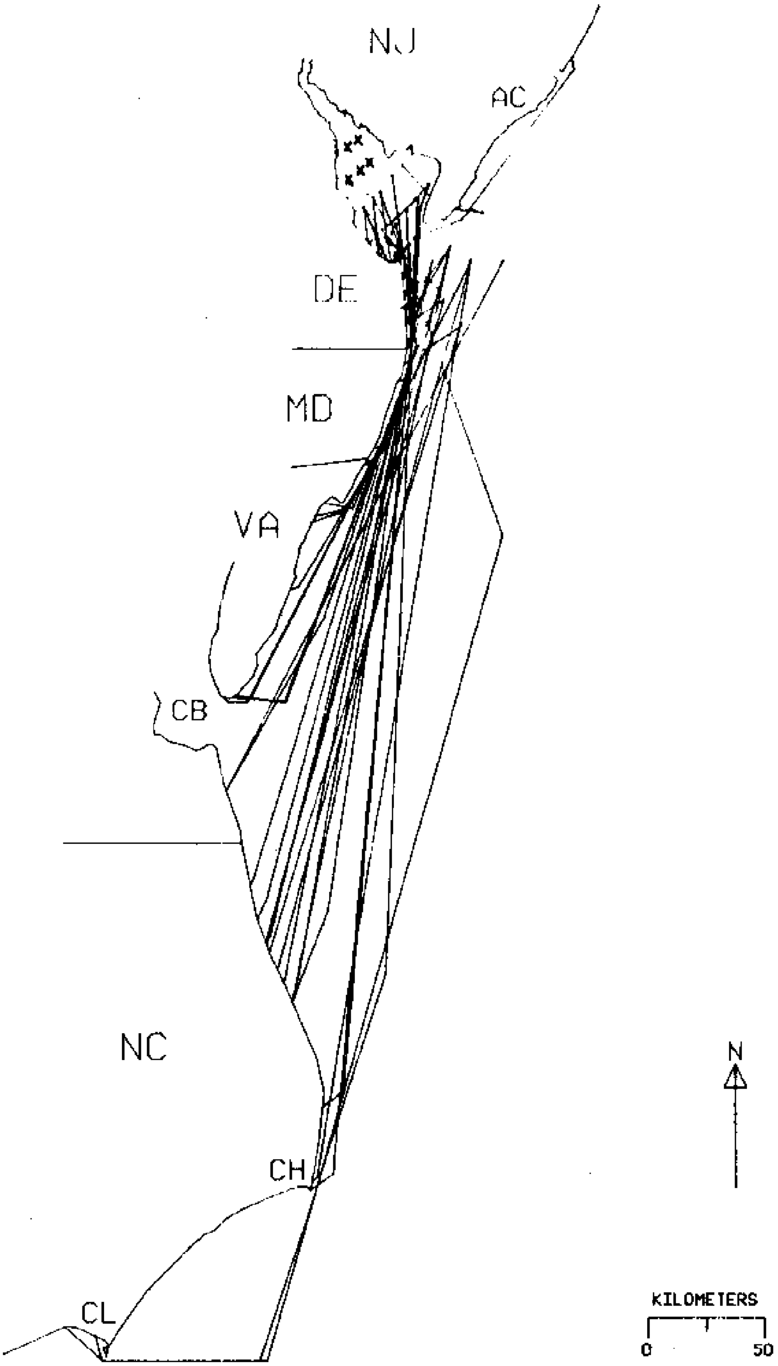

Figure 14. Apparent surface trajectories for 31 July 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

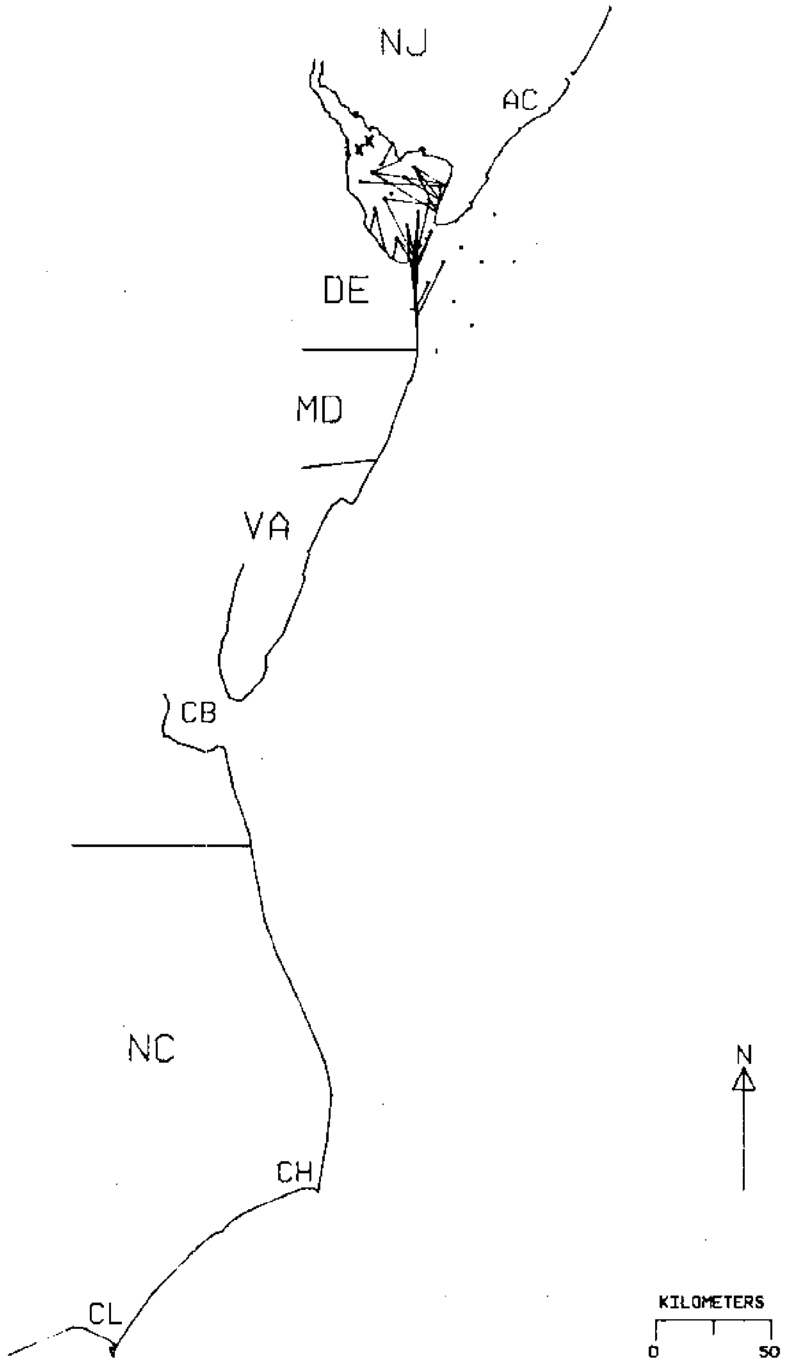

Figure 15. Apparent surface trajectories for 28 September 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

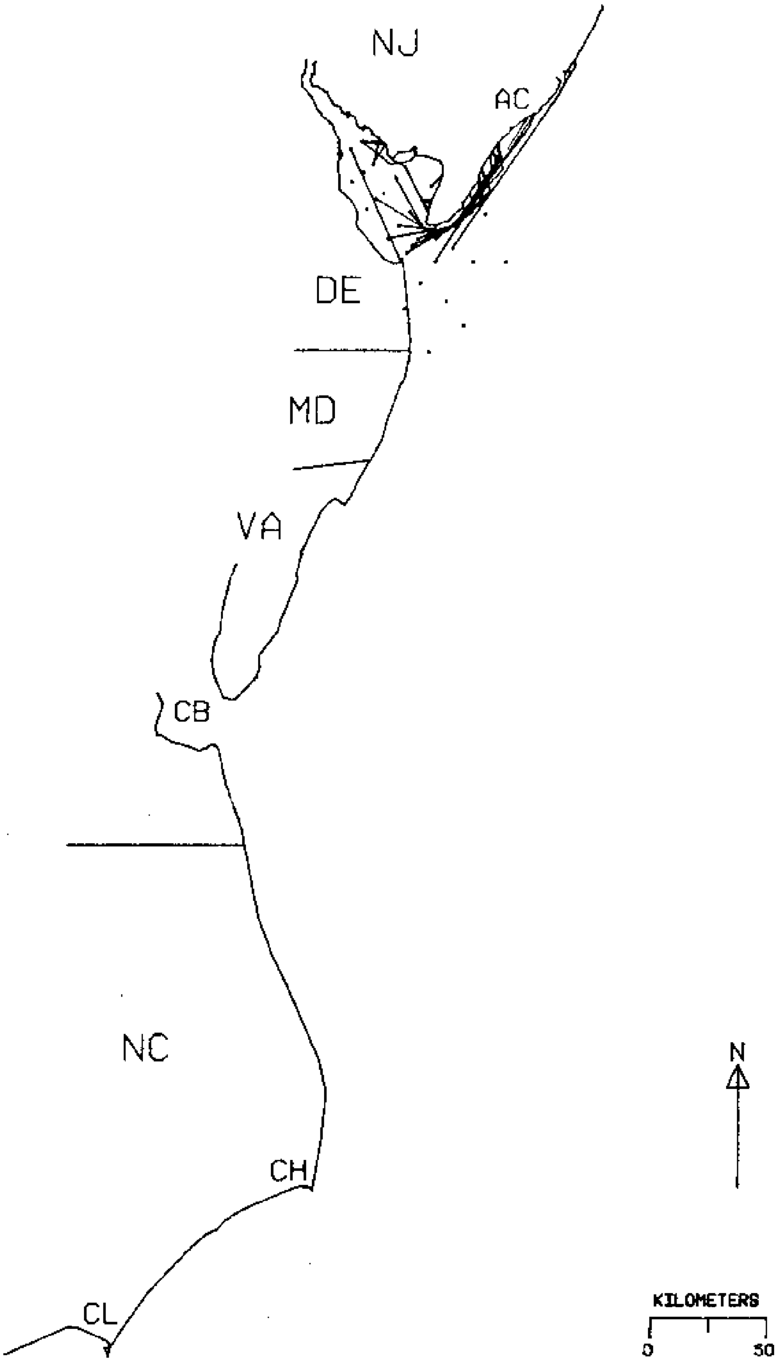

Figure 16. Apparent surface trajectories for 15 November 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

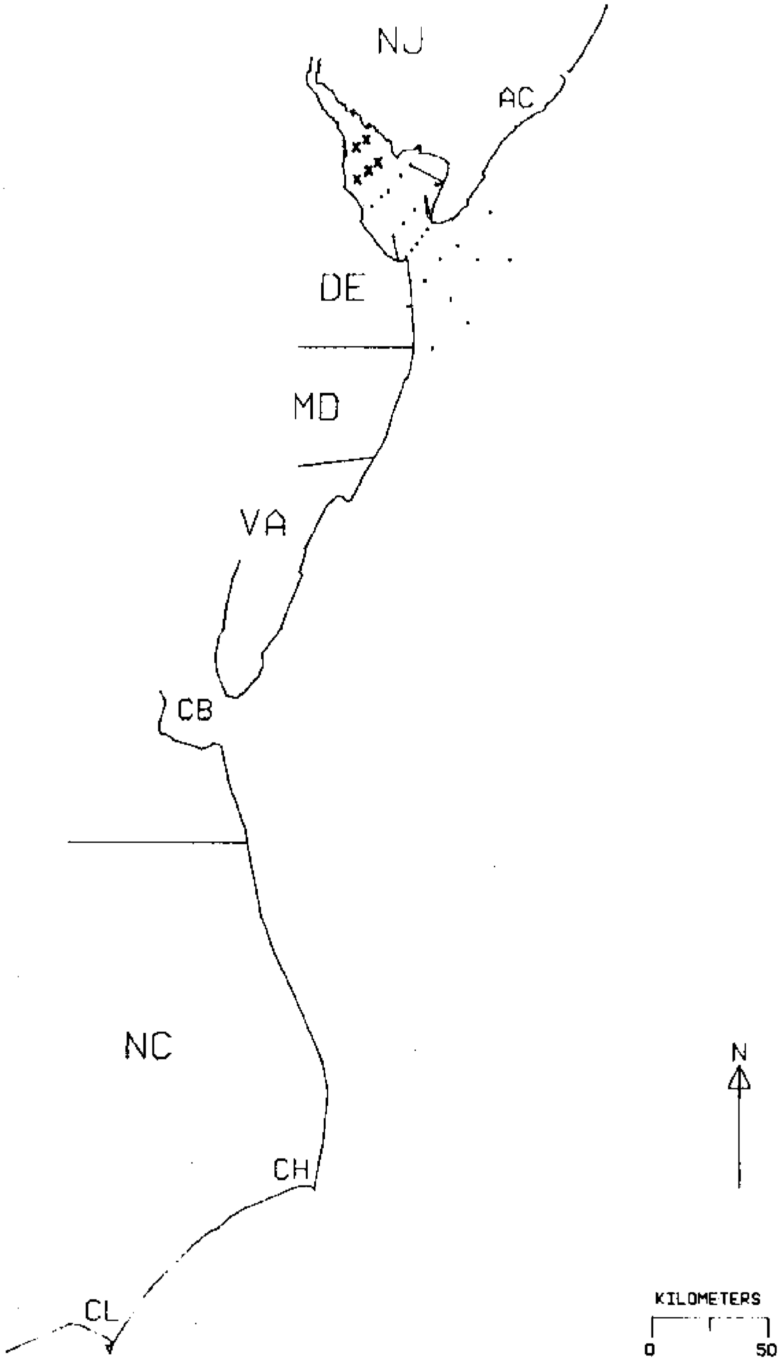

Figure 17. Apparent surface trajectories for 29 November 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

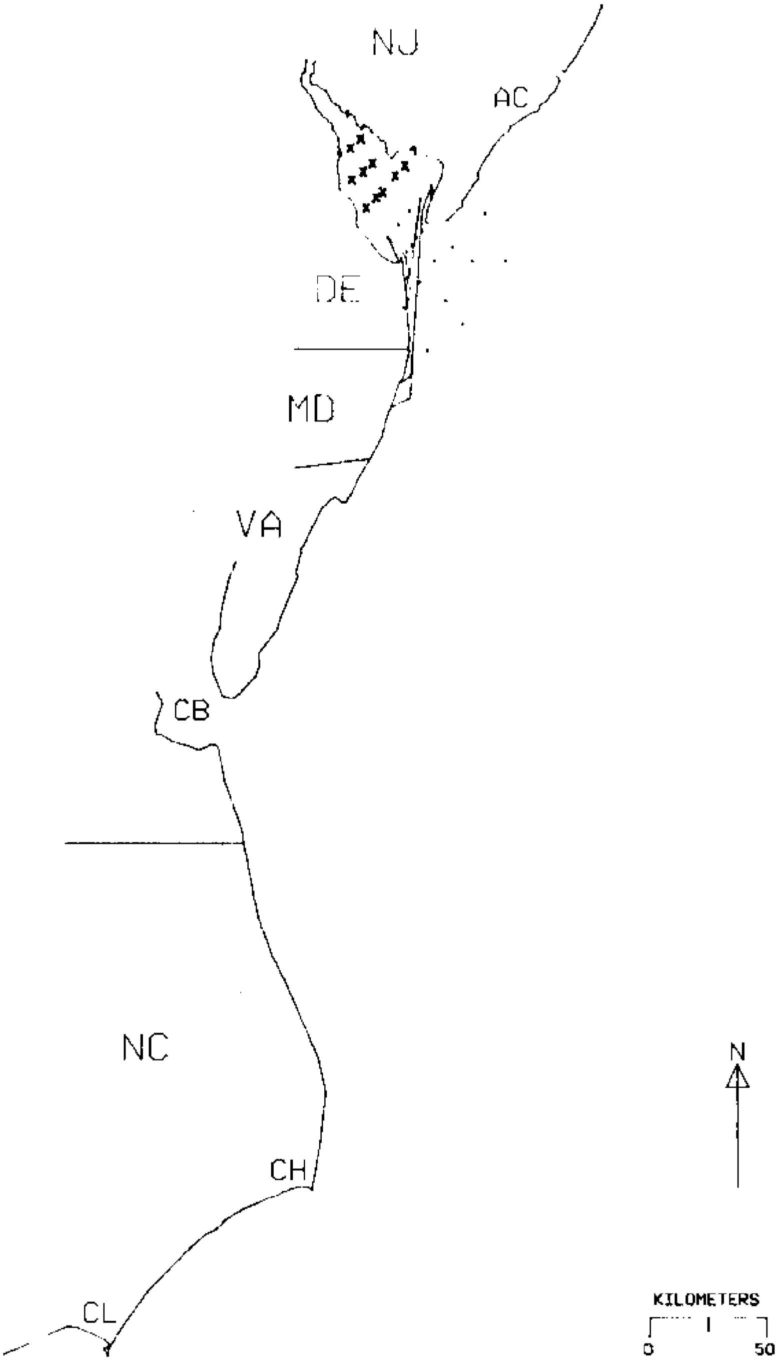

Figure 18. Apparent surface trajectories for 13 December 1979 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

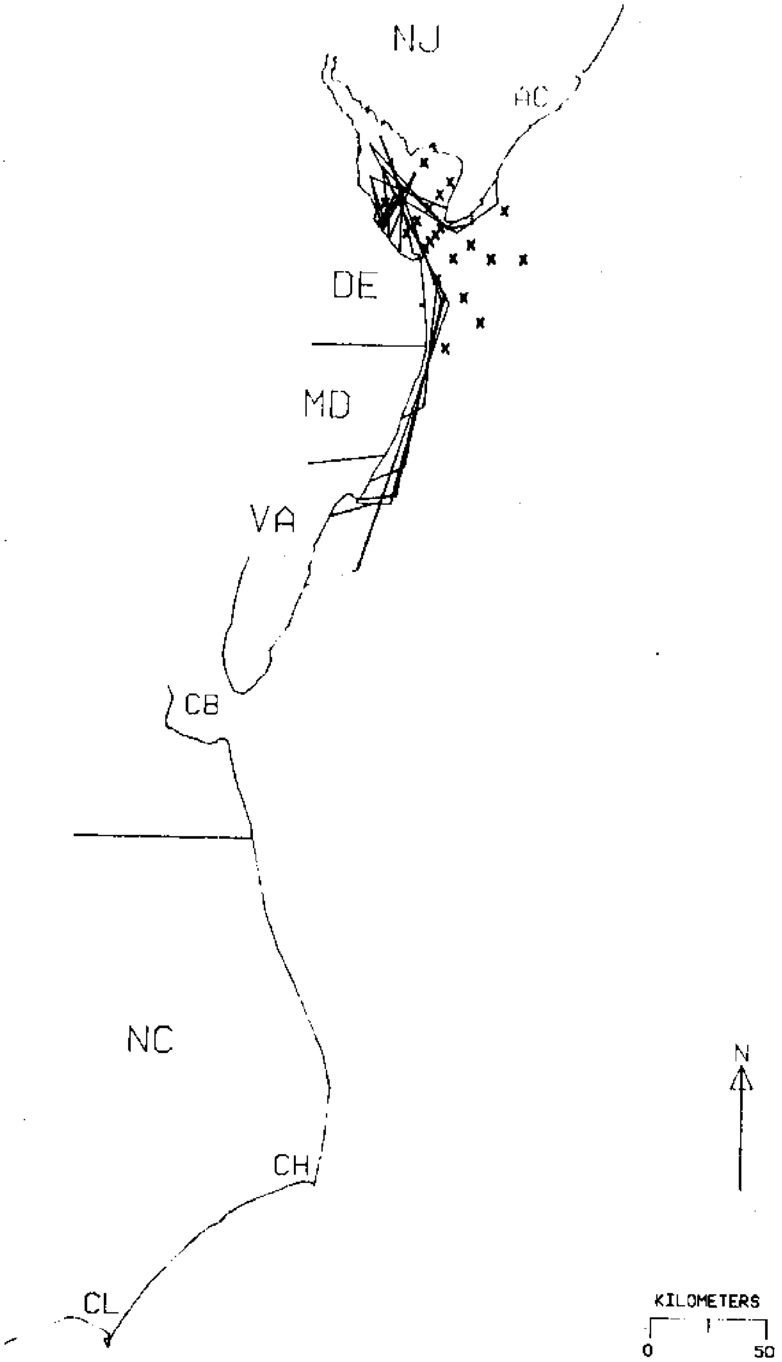

Figure 19. Apparent surface trajectories for 7 March 1980 release. Symbols: NJ - New Jersey, DE - Delaware, MD - Maryland, VA - Virginia, NC - North Carolina, AC - Atlantic City, CB - Chesapeake Bay, CH - Cape Hatteras, CL - Cape Lookout

deployments. This series of maps includes all surface drifters which were returned within the defined period of validity for each date. Returns outside the defined experimental domain were included to show the absolute extent of the return area. An "X" at a station indicates that no release was made there on that date. Trajectories of several drifters released and returned from the same points appear as a single trajectory.

Within the Bay the surface movement was largely downstream. Over the shelf, it was generally southerly, in agreement with Bumpus (1973) and Beardsley, et al. (1976). This southerly flow was strongest for the July 31 deployment when several drifters passed Cape Hatteras. Reversal of flow over the shelf, as described by Bumpus (1969, 1973), occurred on the November 15 release. A widespread lack of returns, such as from the September 28 and November 29 deployments, implied a relatively large component of offshore surface flow. Three surface trajectories not illustrated, but worthy of note, were one to Block Island from Station 25 on the April 19 release (150 days), and two to Ireland. One of these was from Station 18 on the November 15 release (444 days) and the other was from Station 8 on the September

28 release (617 days).

All bottom returns were within the experimental domain and will be considered in detail in conjunction with maps showing only those surface returns within the domain. In general, however, there was a strong convergence on the Bay mouth of bottom drifters released offshore. This is in agreement with Bumpus (1965, 1973). Bottom drifters released within the Bay moved laterally but often with an up-Bay component. The three drifters that traveled farthest up the estuary were eliminated because their durations were too great. Two were recovered at the Salem Nuclear Plant in New Jersey, about 85 km from the mouth of the Bay. One of these was released from Station 6 on May 16 (192 days) and the other was from Station 4 on September 28 (216 days). The other drifter was found on Pea Patch Island, about 100 km from the mouth. It was released on November 29 from Station 8 (420 days).

Next, apparent trajectory maps will be presented, surface and bottom, for those drifters recovered within the experimental domain. The surface trajectories for each date are shown in Figures 20-28. All bottom recoveries were made within the defined boundaries of the

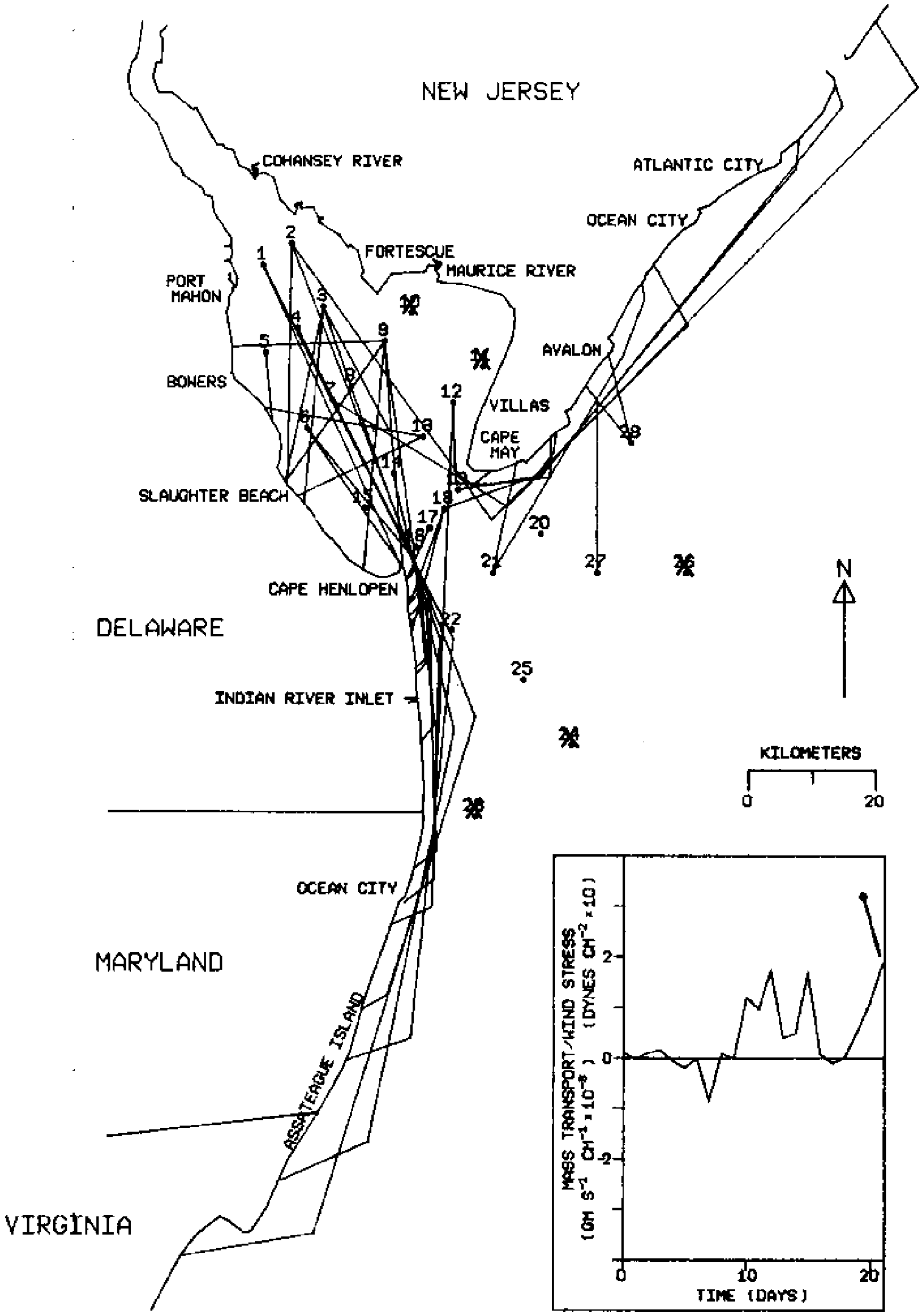

Figure 20. Apparent surface trajectories within the experimental domain for the 19 April 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

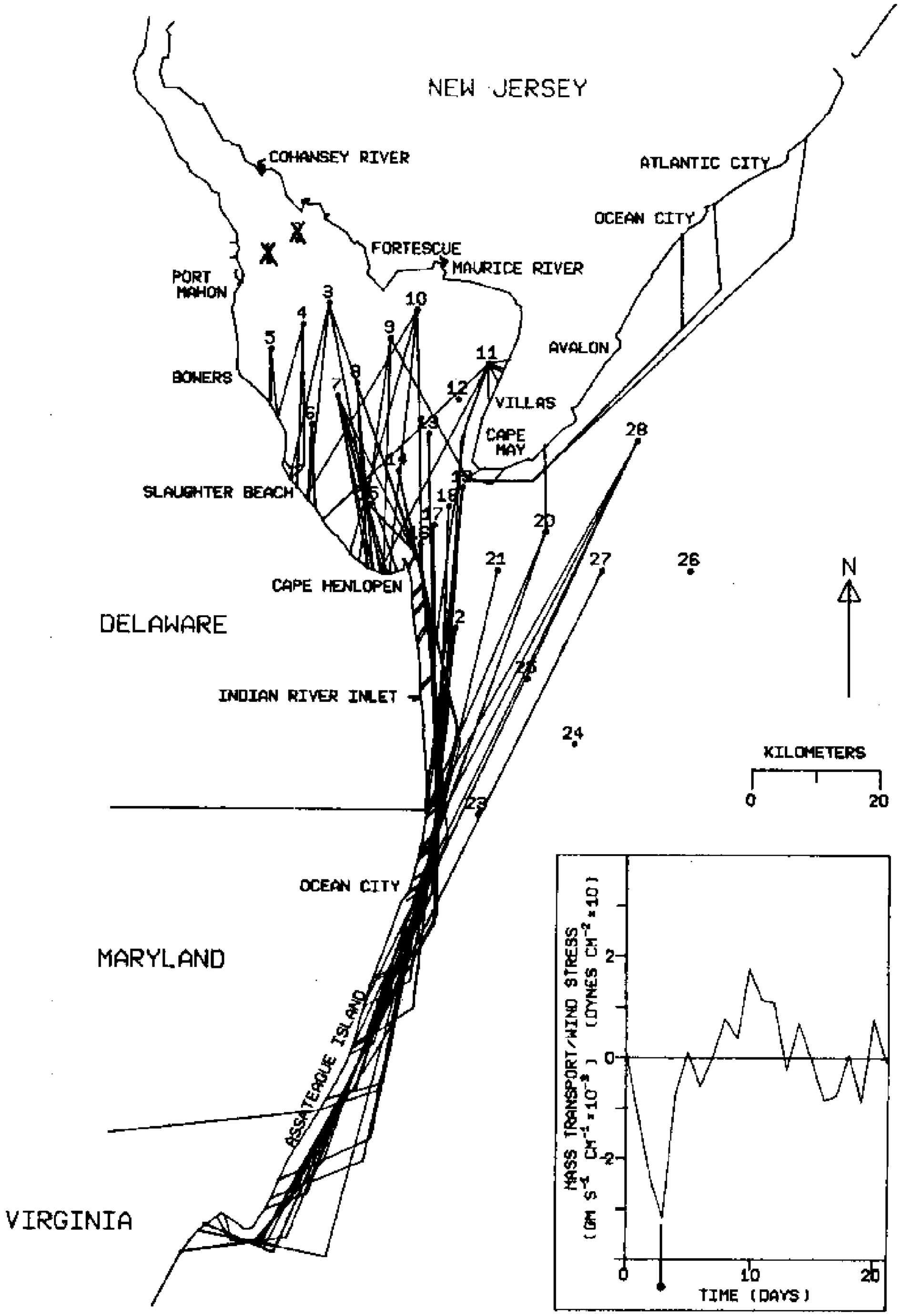

Figure 21. Apparent surface trajectories within the experimental domain for the 16 May 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

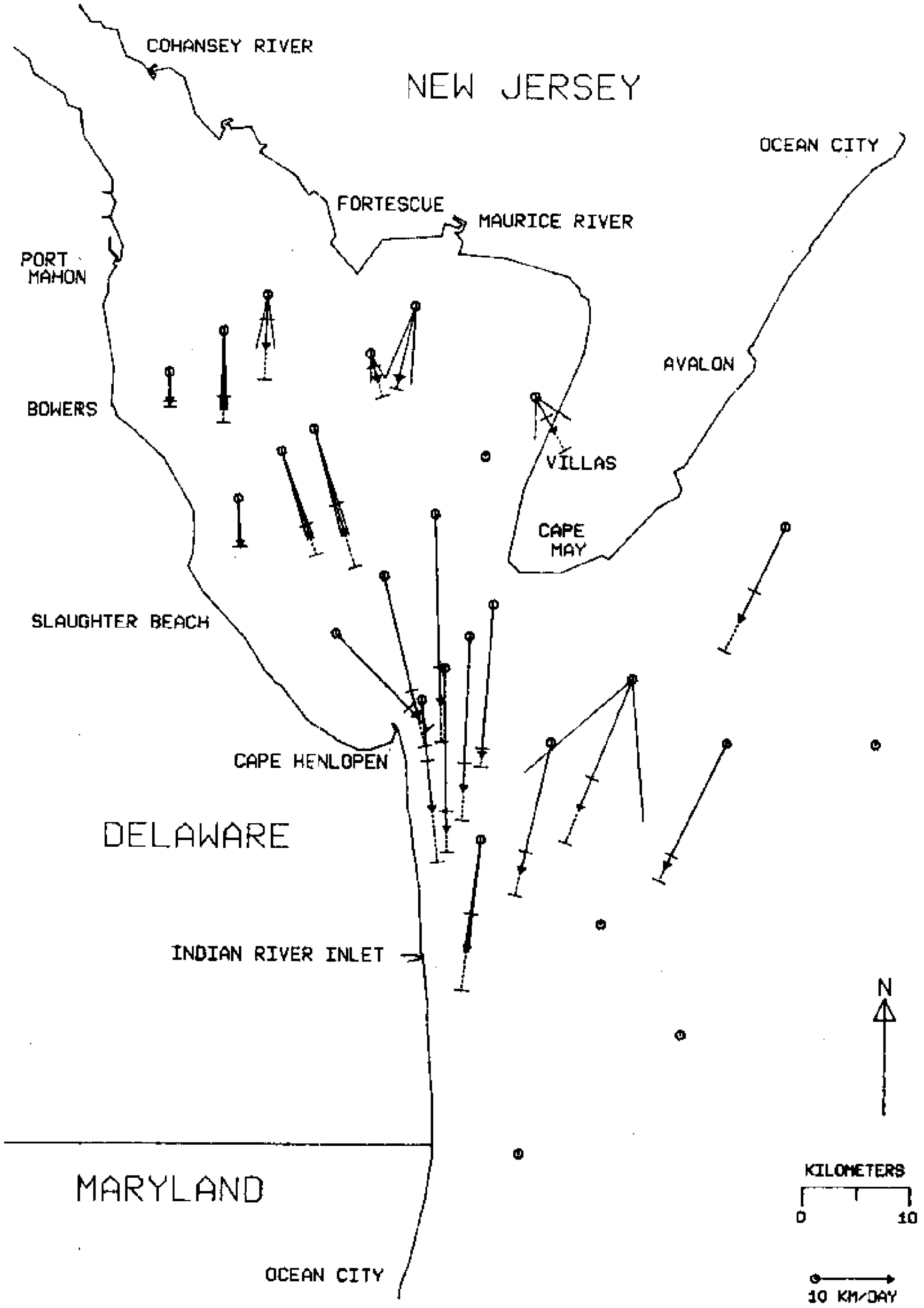

Figure 21a. Vector map of surface mean speeds and directions and associated 95% confidence intervals for the 16 May 1979 release

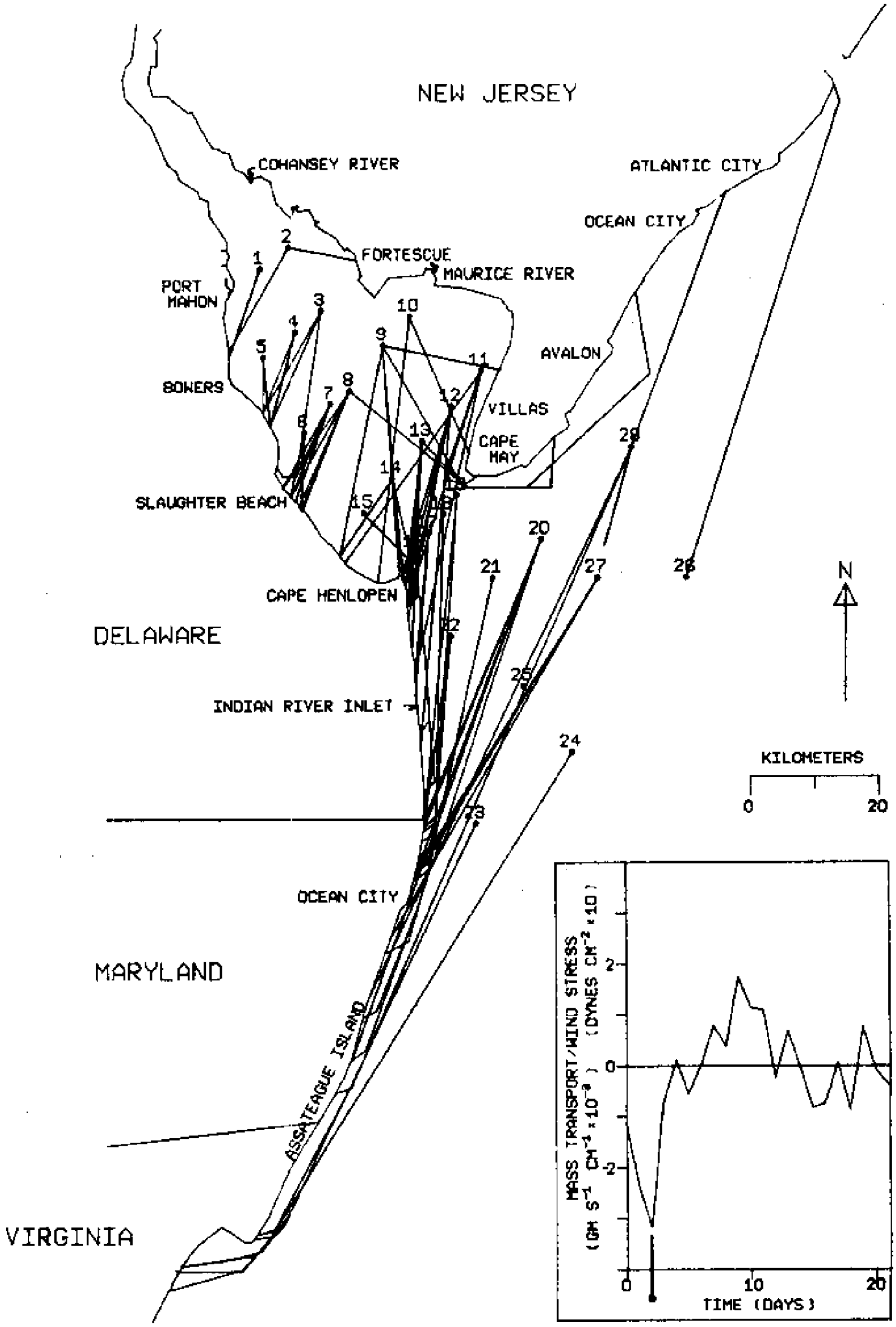

Figure 22. Apparent surface trajectories within the experimental domain for the 17 May 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ●. Time zero is the date of release.

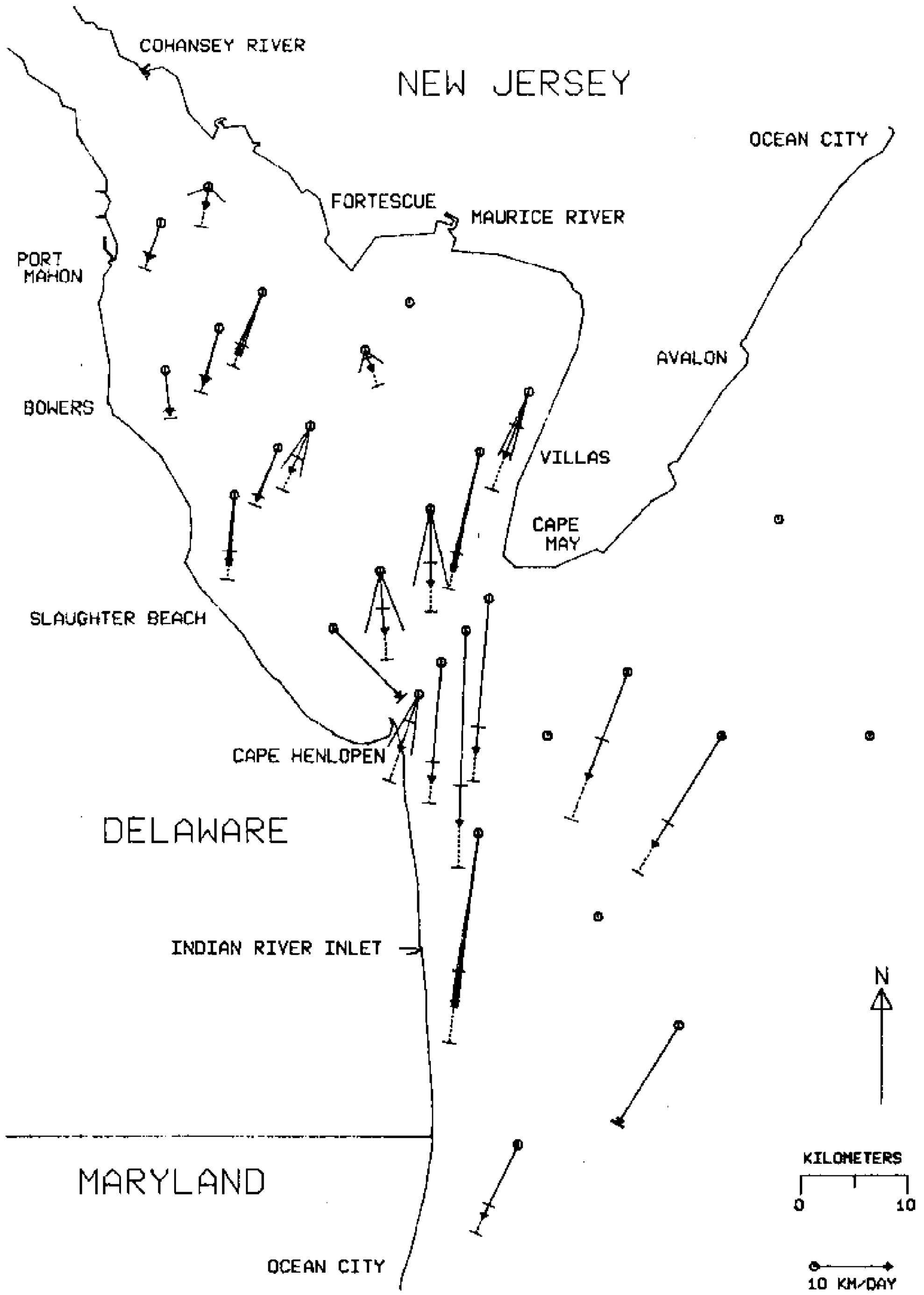

Figure 22a. Vector map of surface mean speeds and directions and associated 95% confidence intervals for the 17 May 1979 release

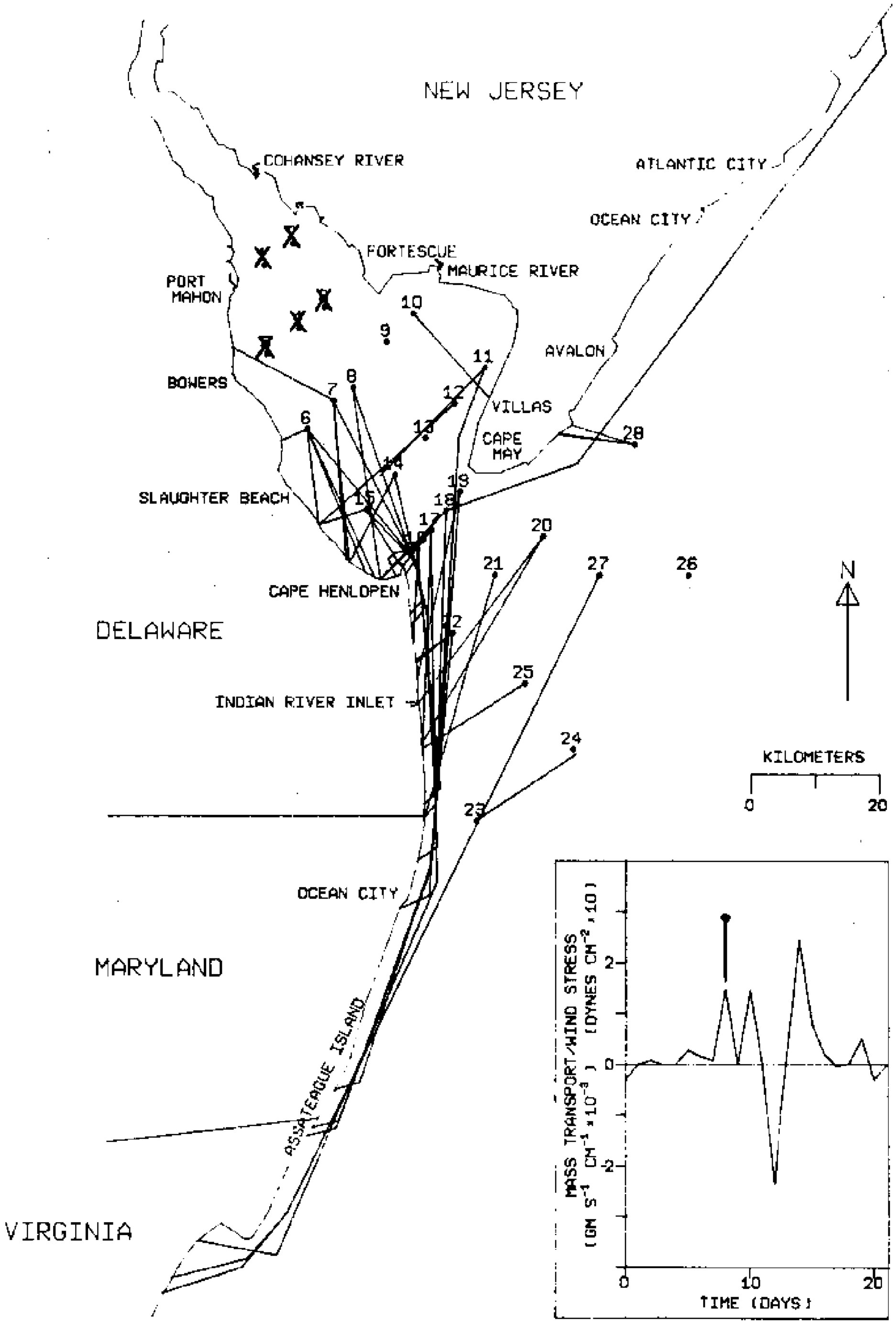

Figure 23. Apparent surface trajectories within the experimental domain for the 31 July 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

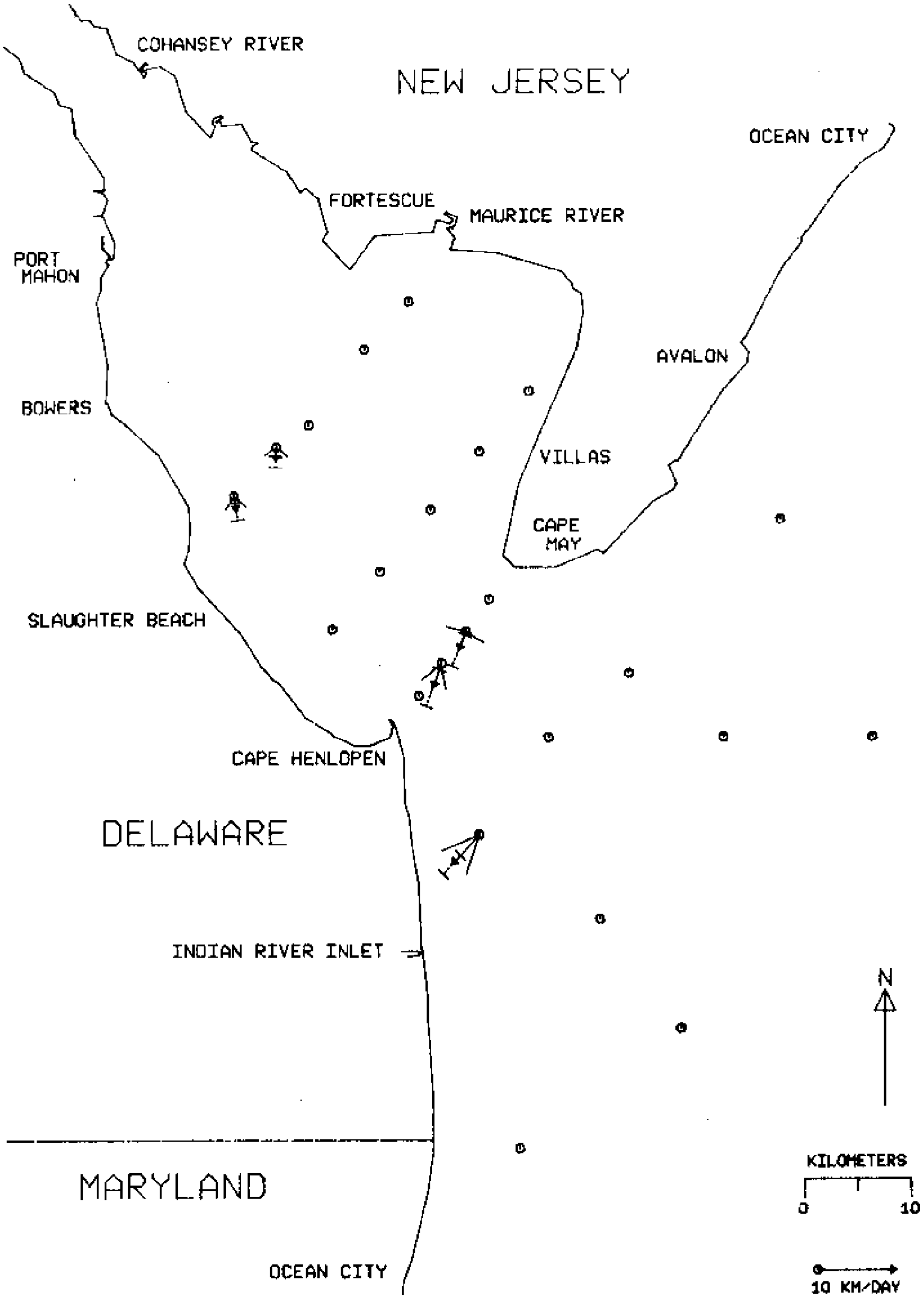

Figure 23a. Vector map of surface mean speeds and directions and associated 95% confidence intervals for the 31 July 1979 release

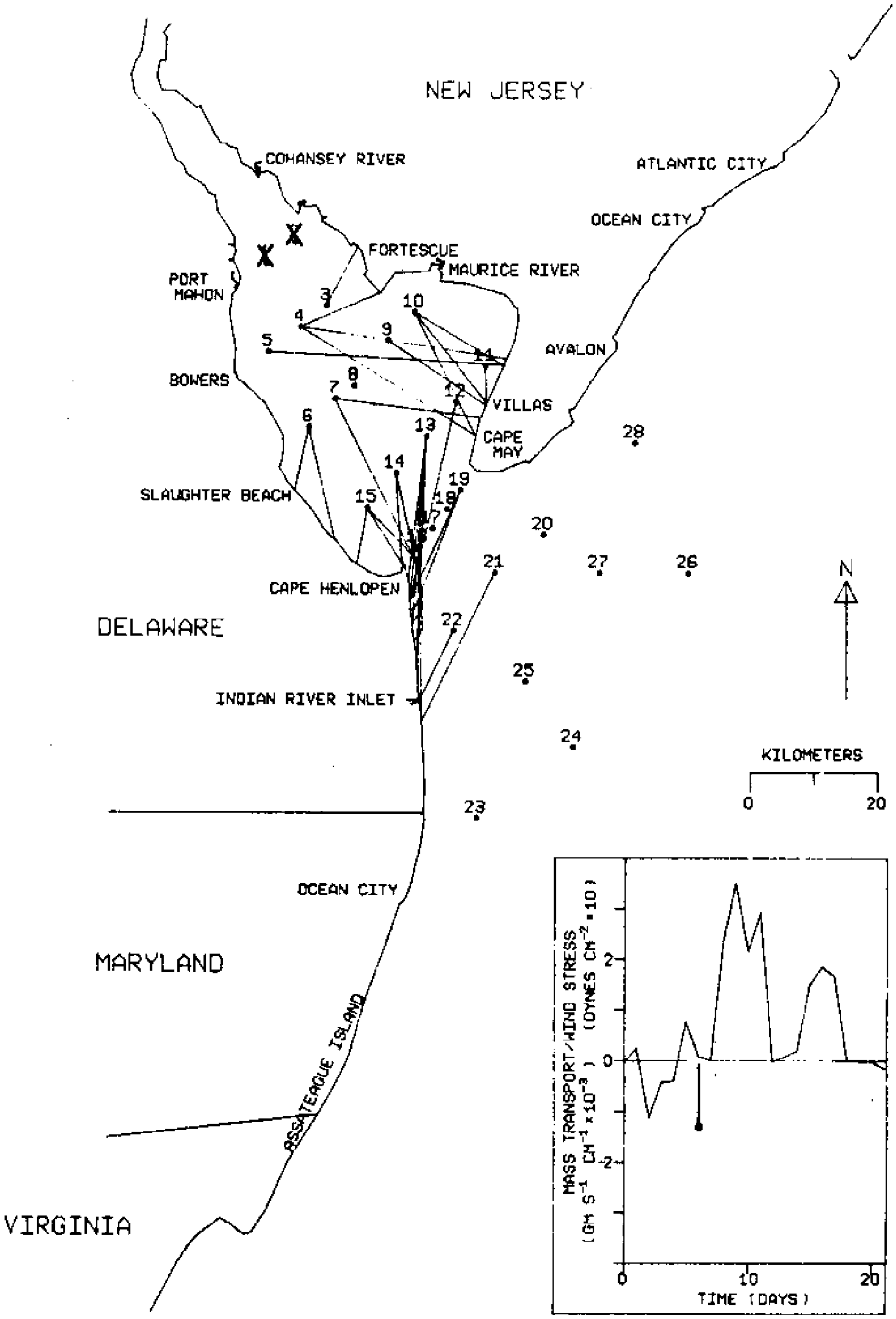

Figure 24. Apparent surface trajectories within the experimental domain for the 28 September 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

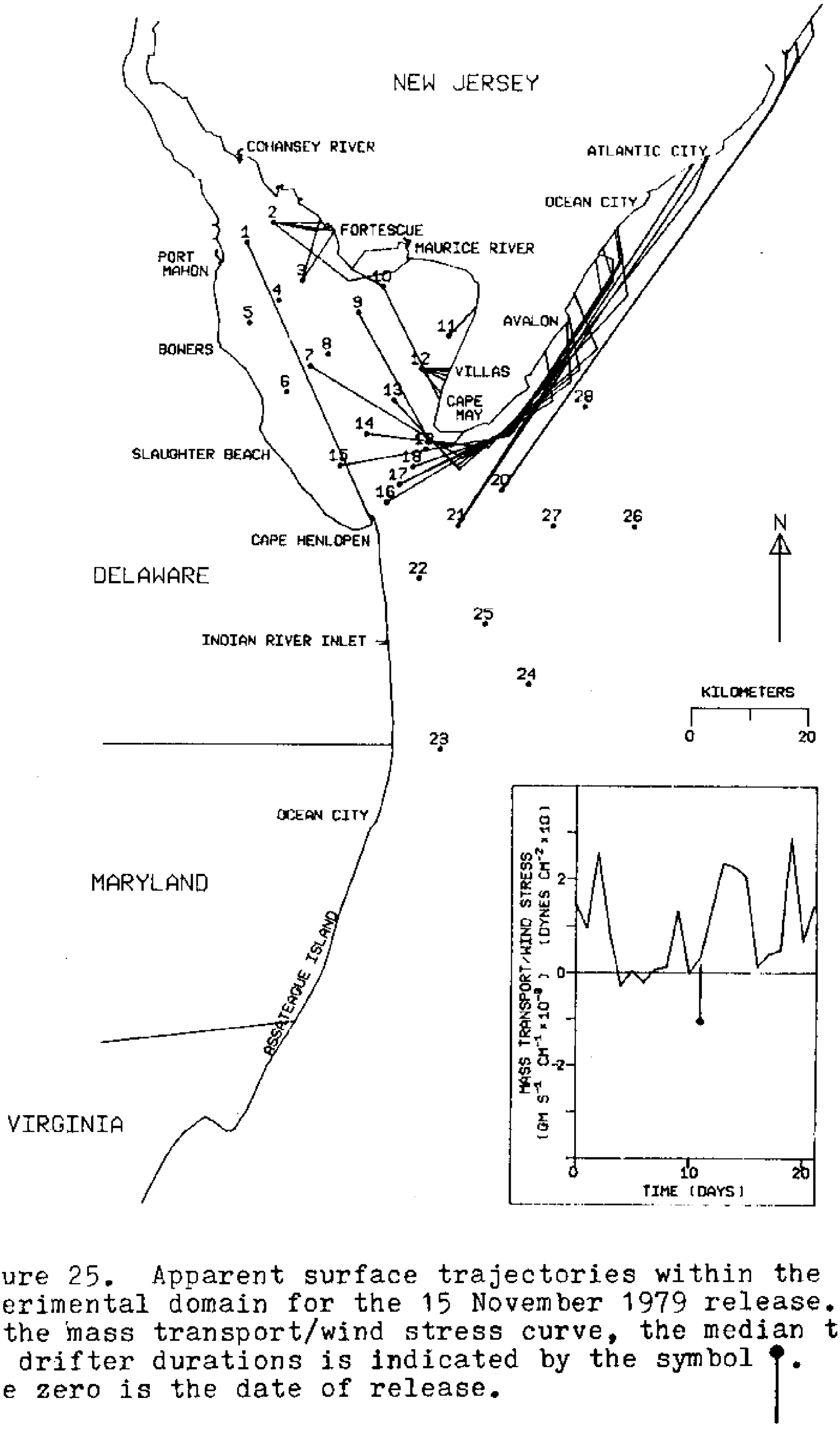

Figure 25. Apparent surface trajectories within the experimental domain for the 15 November 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

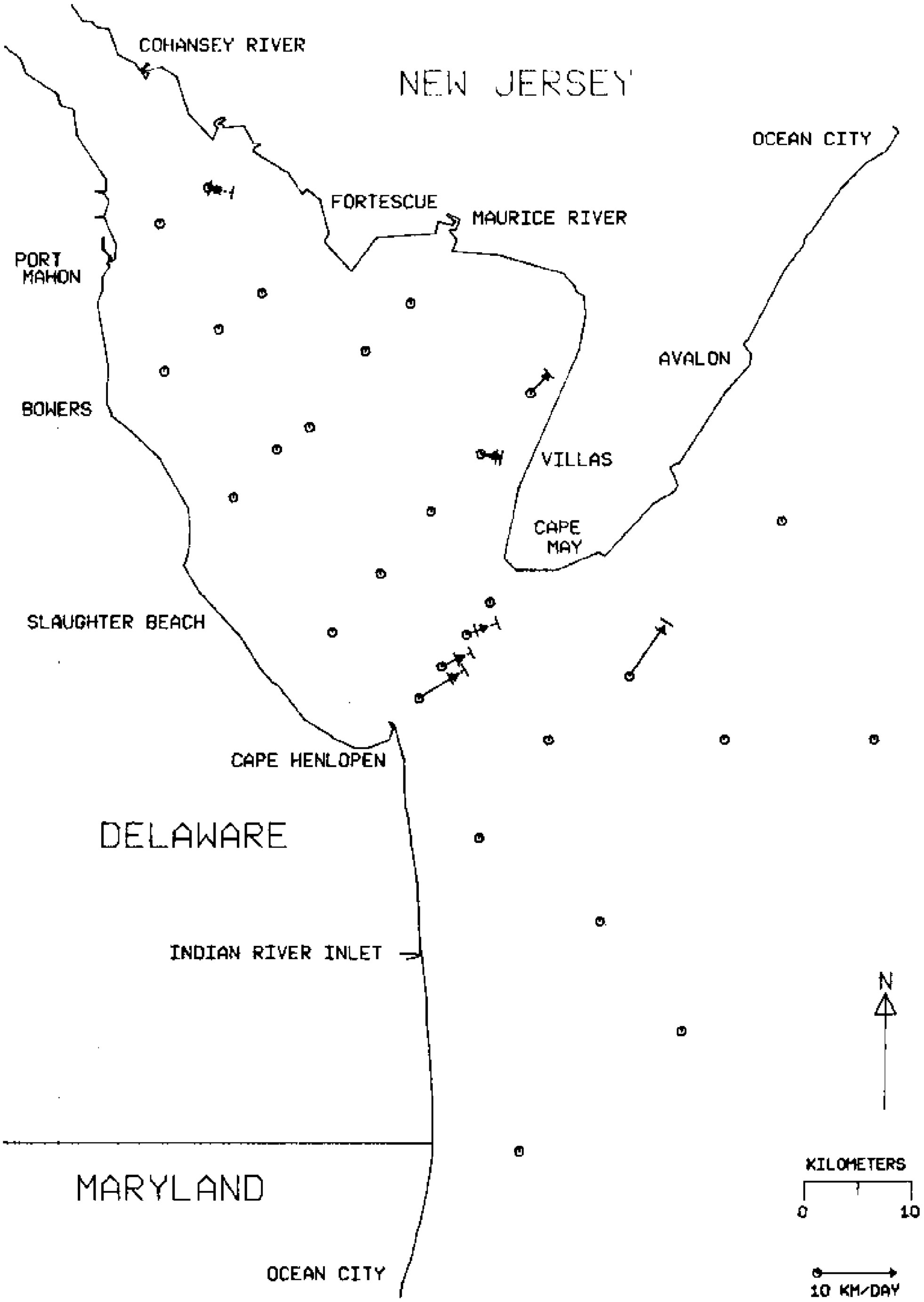

Figure 25a. Vector map of surface mean speeds and directions and associated 95% confidence intervals for the 15 November 1979 release

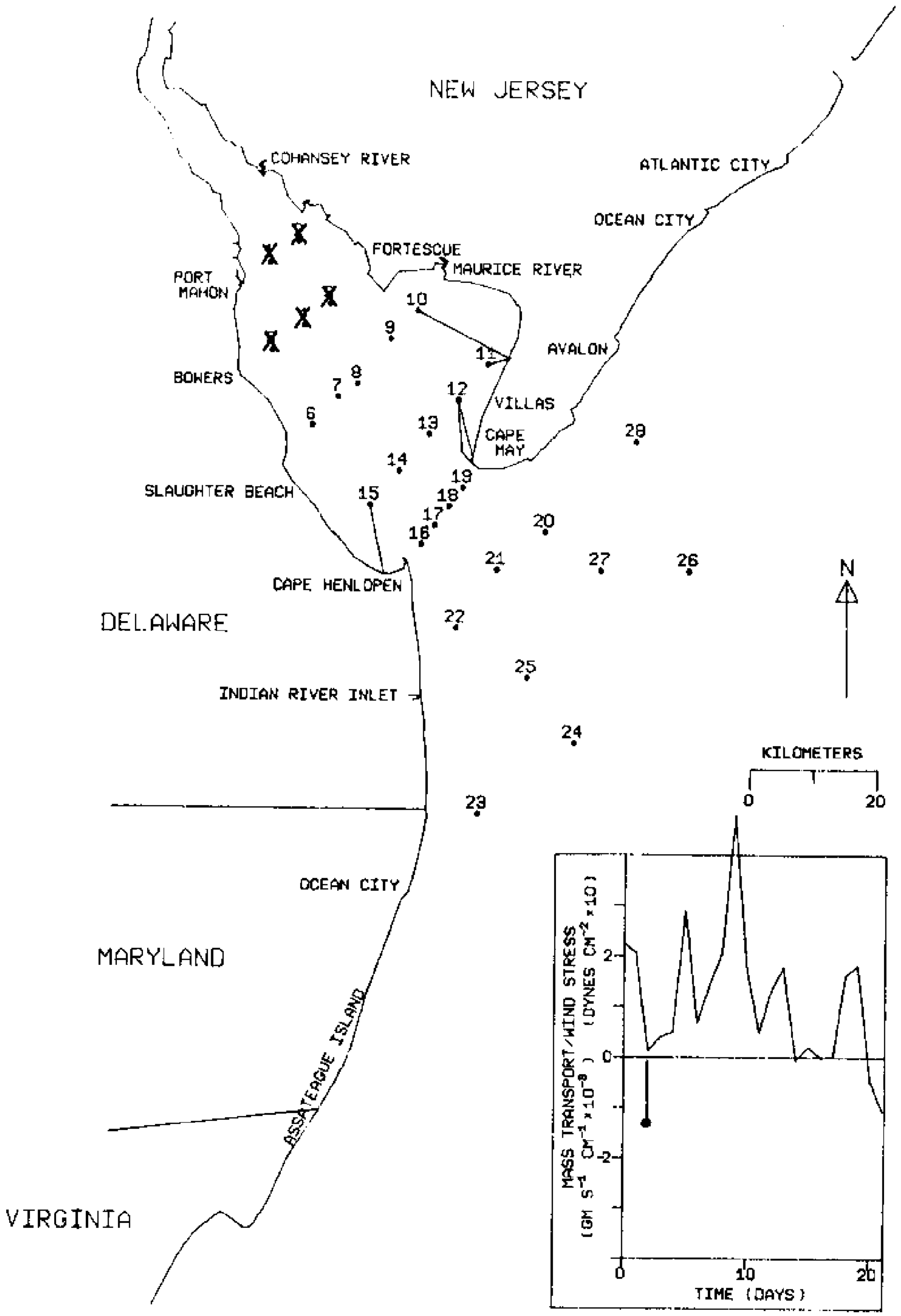

Figure 26. Apparent surface trajectories within the experimental domain for the 29 November 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

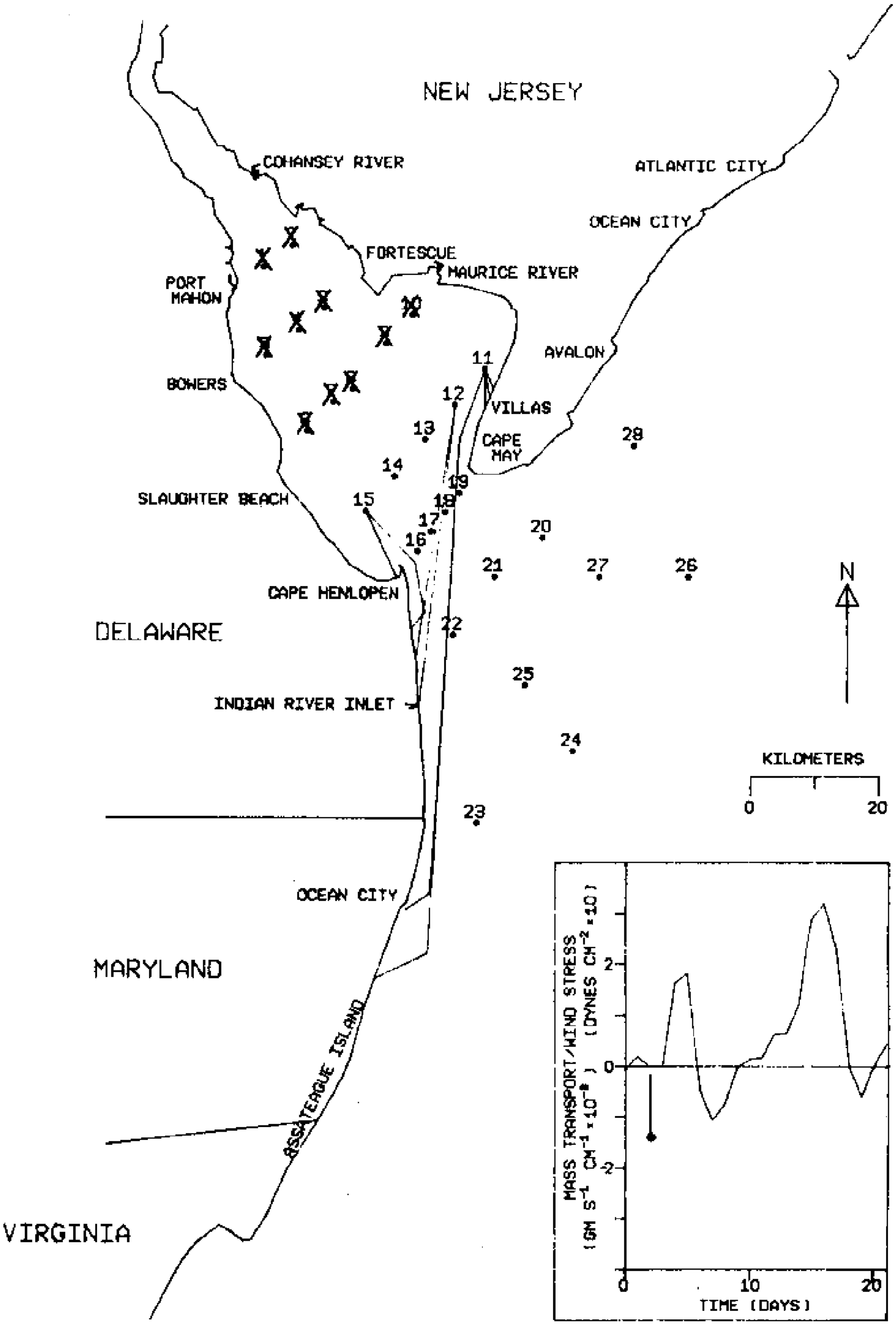

Figure 27. Apparent surface trajectories within the experimental domain for the 13 December 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

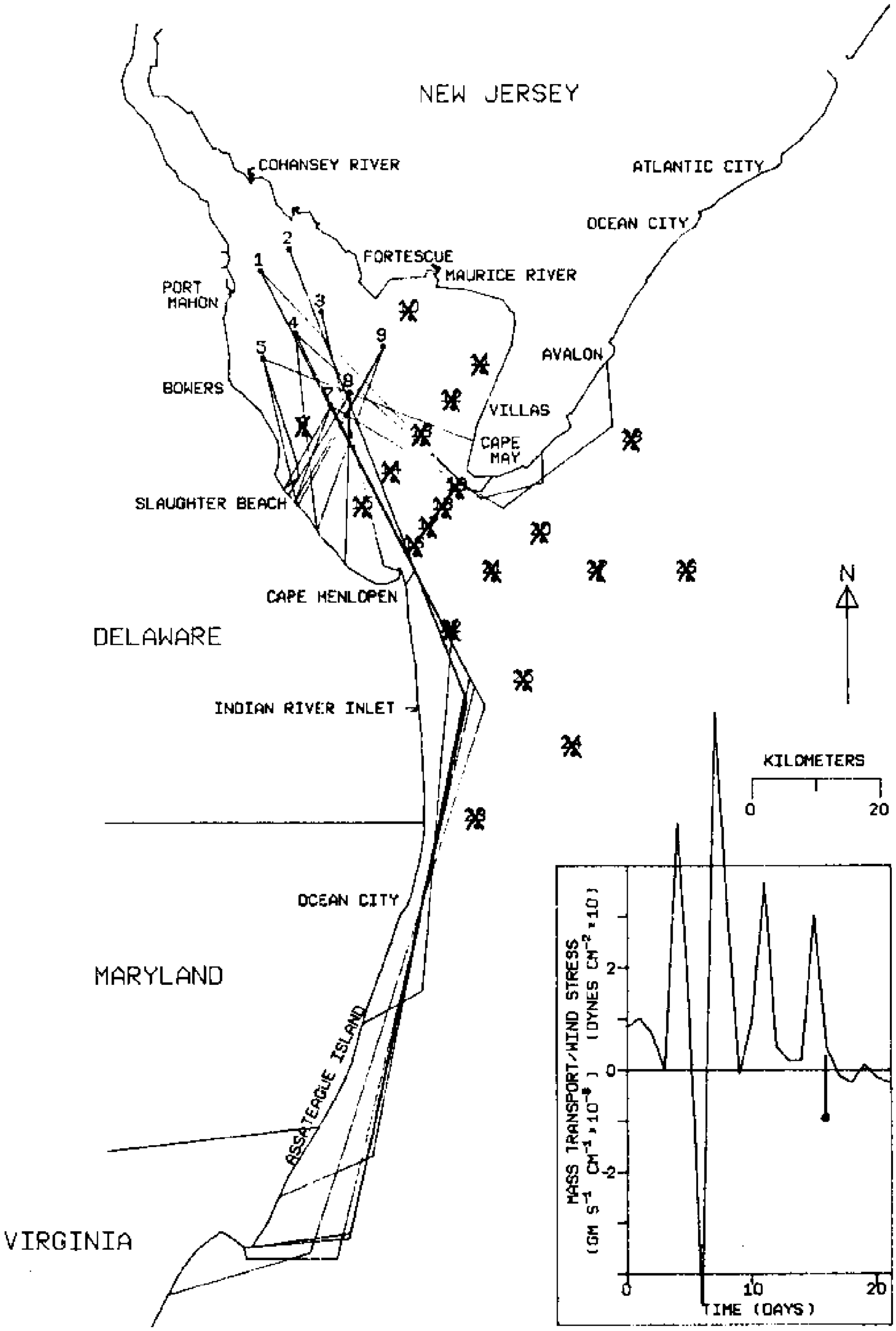

Figure 28. Apparent surface trajectories within the experimental domain for the 7 March 1980 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ●. Time zero is the date of release.

experimental domain and maps of these trajectories are given in Figures 29-37. In each series, stations not sampled are marked with an "X" and one trajectory may represent more than one drifter if release and return points are identical. Some trajectory maps are followed by a corresponding vector map of mean speeds and directions and associated confidence intervals (Figures 21a-23a, 25a, 32a-36a), if returns were numerous enough to justify presentation of a companion figure. These vector means represent the averaged estimated Lagrangian mean velocities of returned drifters which left each release point. The surface and bottom velocity vectors will be referred to as q_s and q_b, respectively. Each vector is shown as an arrow originating at the release point, the length of which is proportional to the mean speed; its direction is the mean direction of drifters returned from that station. The lines on either side of each vector mark the arc of the 95% confidence interval on the the mean direction. The short bars perpendicular to the direction of the vector represent the range of the 95% confidence interval on mean speed. Means for stations with fewer than four returns were considered unreliable and were left blank on the maps. Seven stations on various dates for which the directional

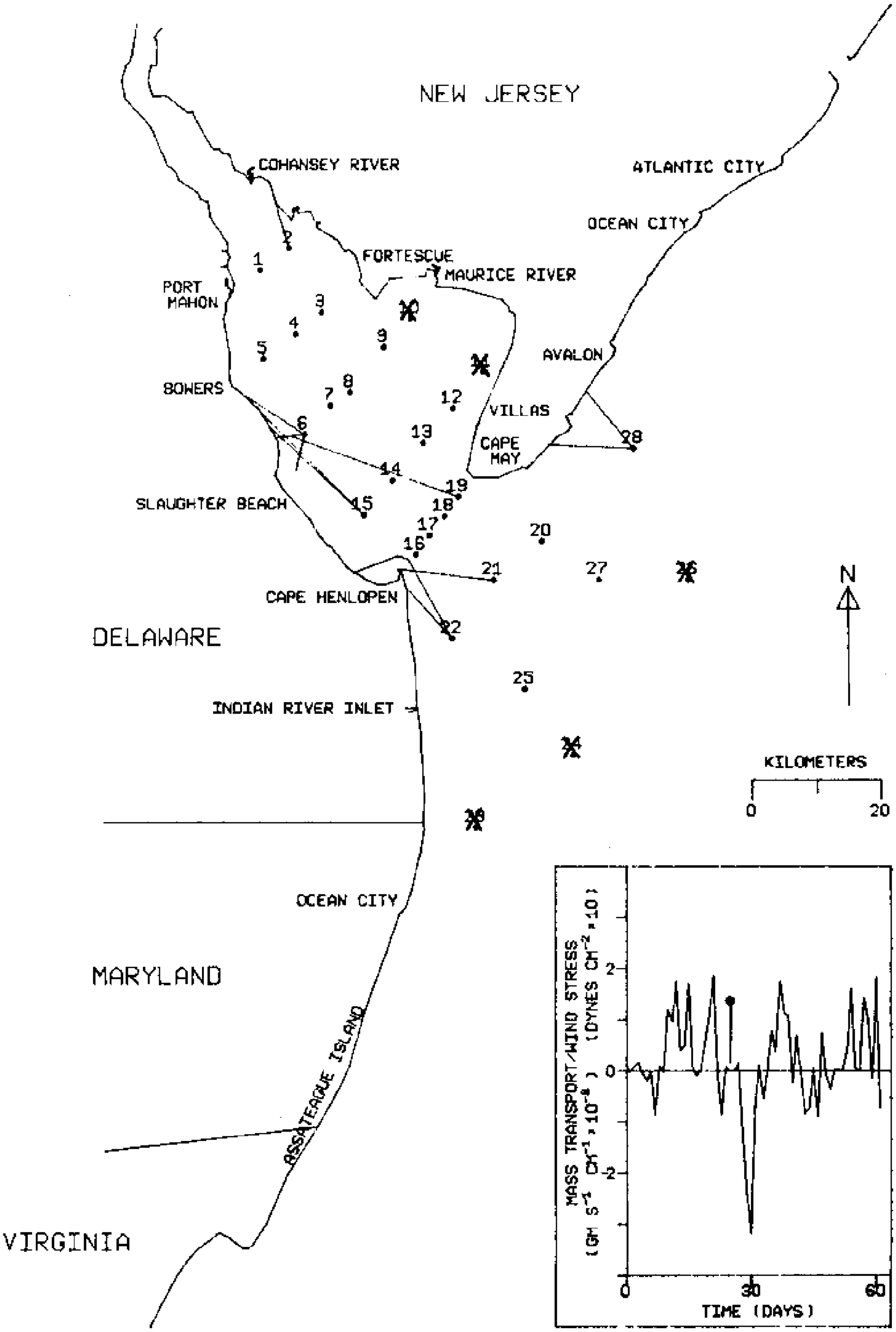

Figure 29. Apparent bottom trajectories for the 19 April 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

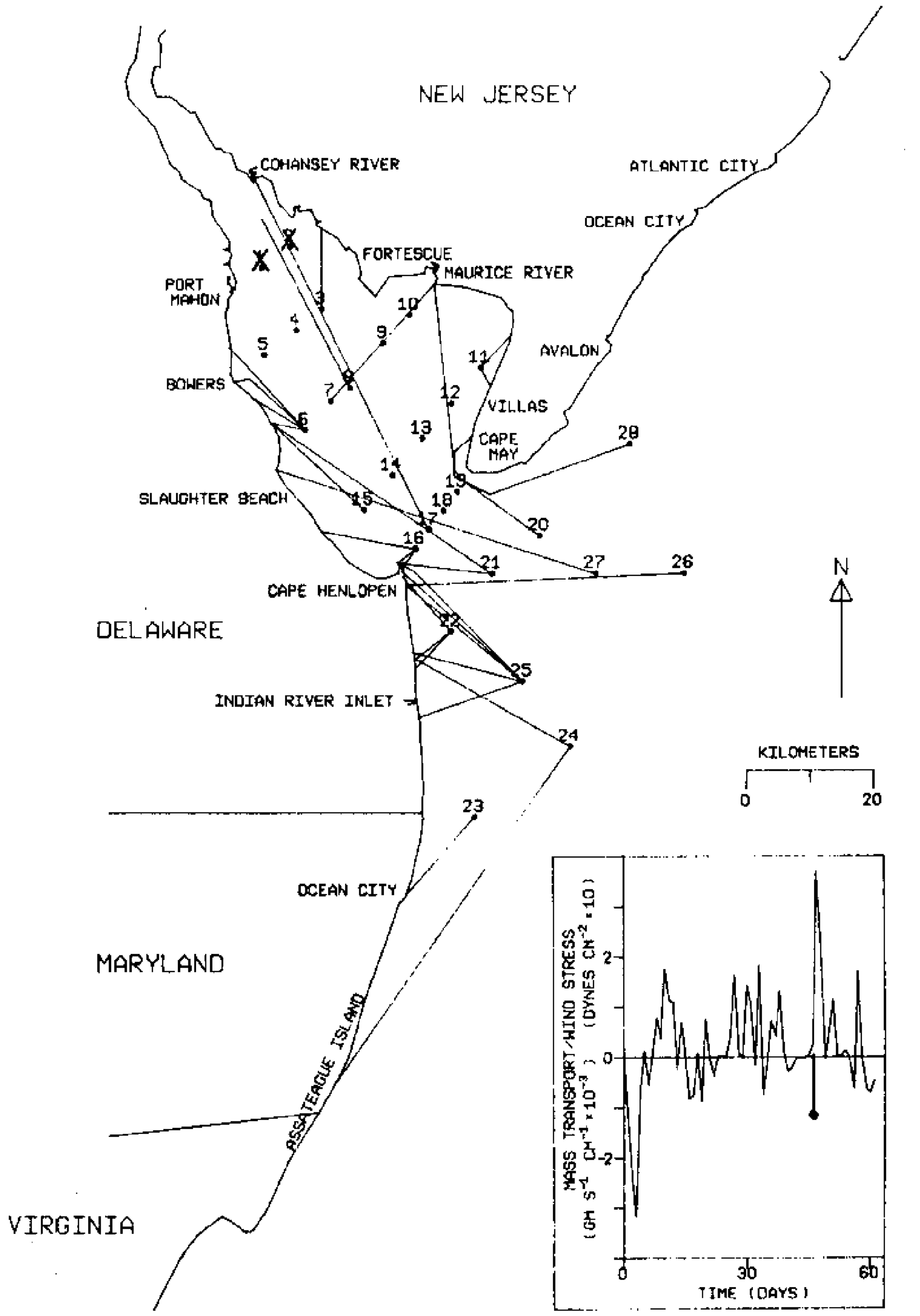

Figure 30. Apparent bottom trajectories for the 16 May 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯ . Time zero is the date of release.

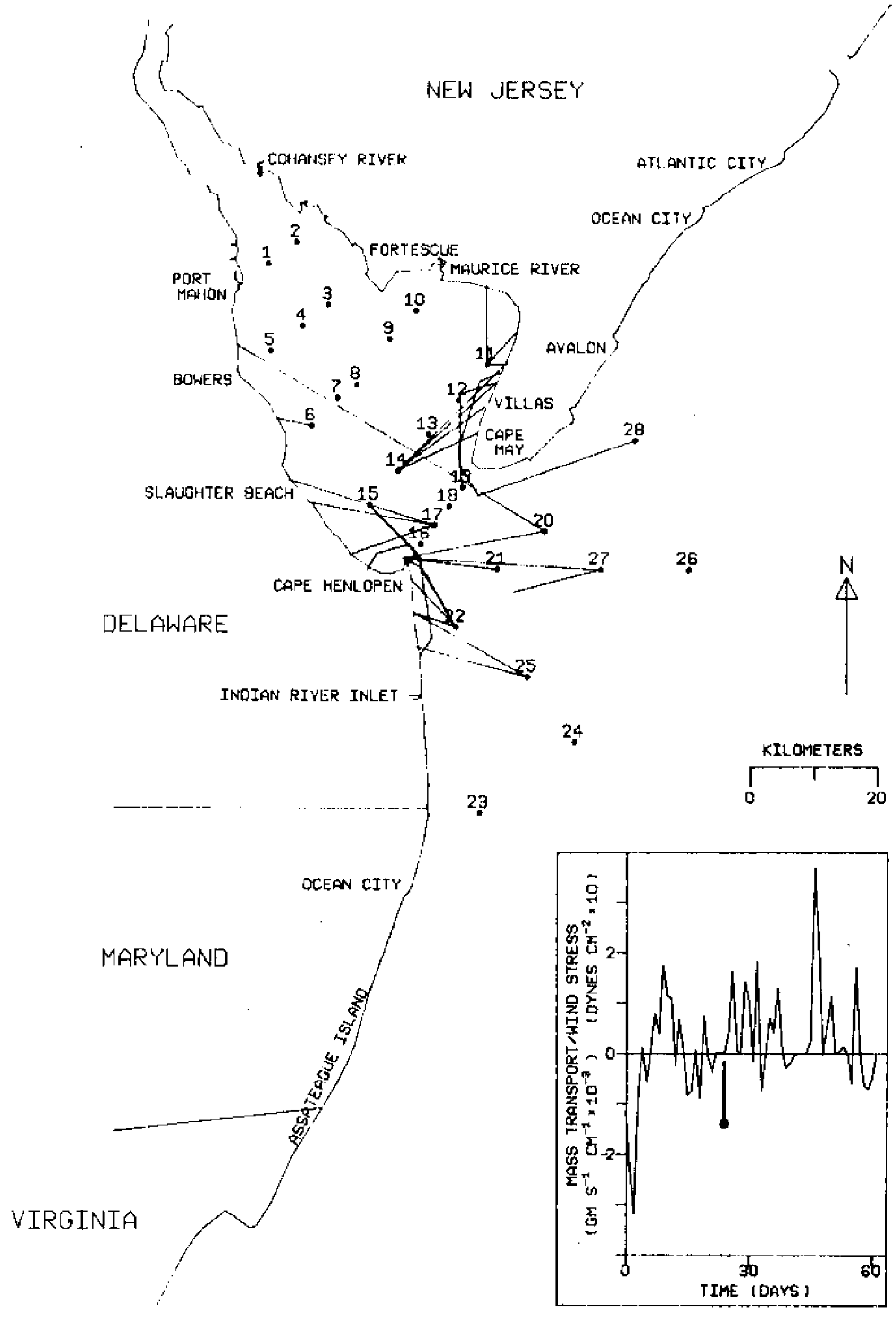

Figure 31. Apparent bottom trajectories for the 17 May 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

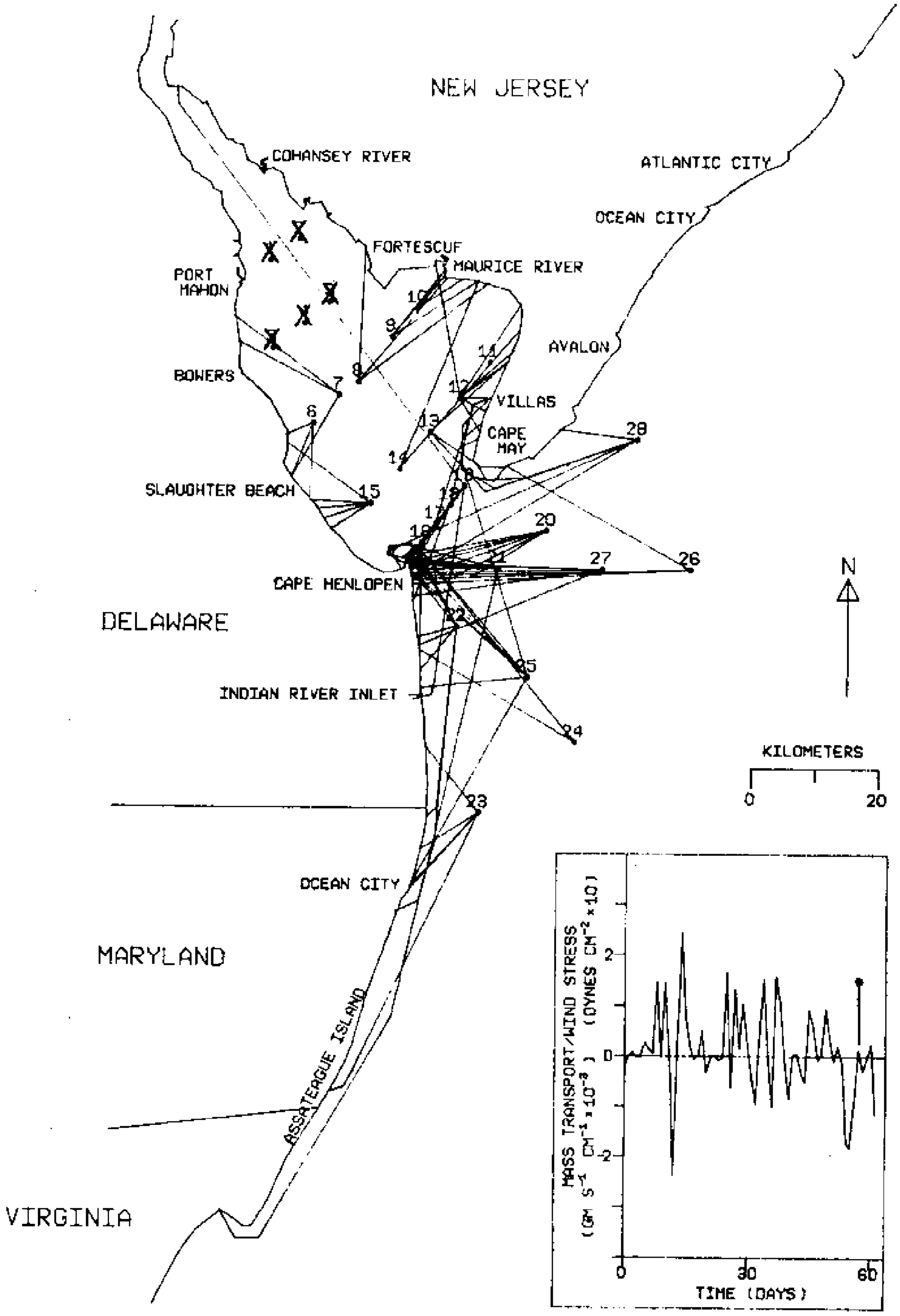

Figure 32. Apparent bottom trajectories for the 31 July 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

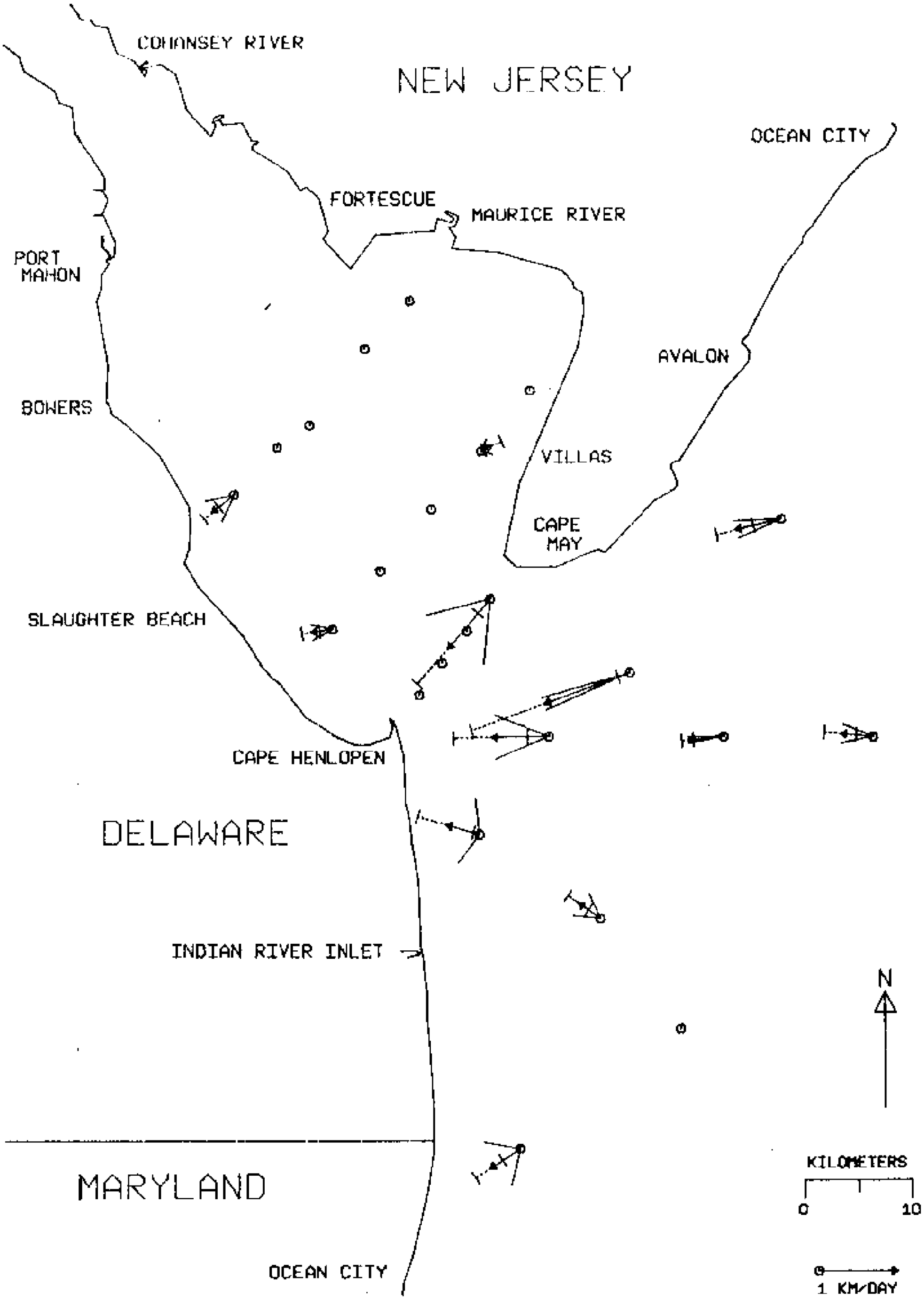

Figure 32a. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the 31 July 1979 release

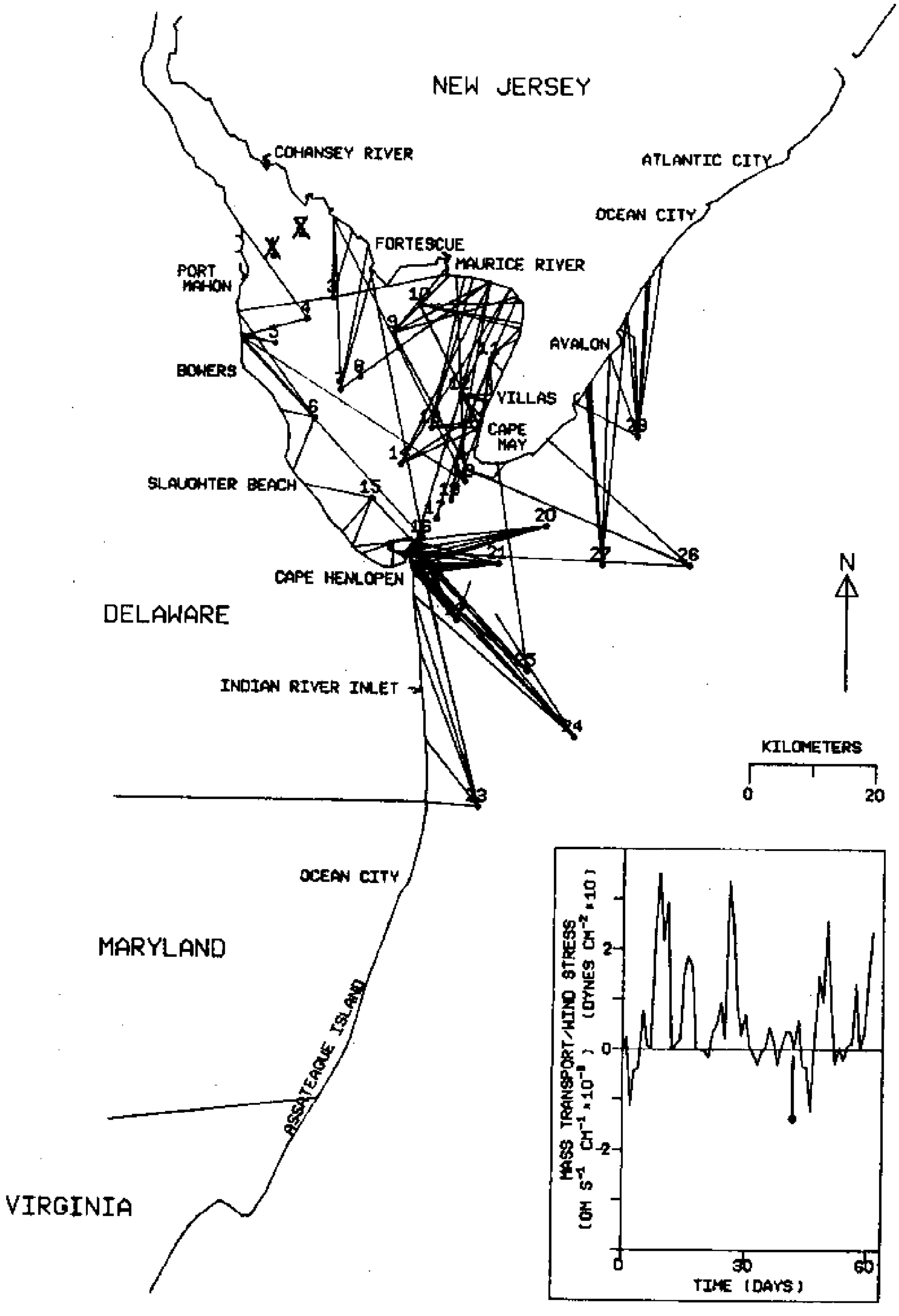

Figure 33. Apparent bottom trajectories for the 28 September 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯ . Time zero is the date of release.

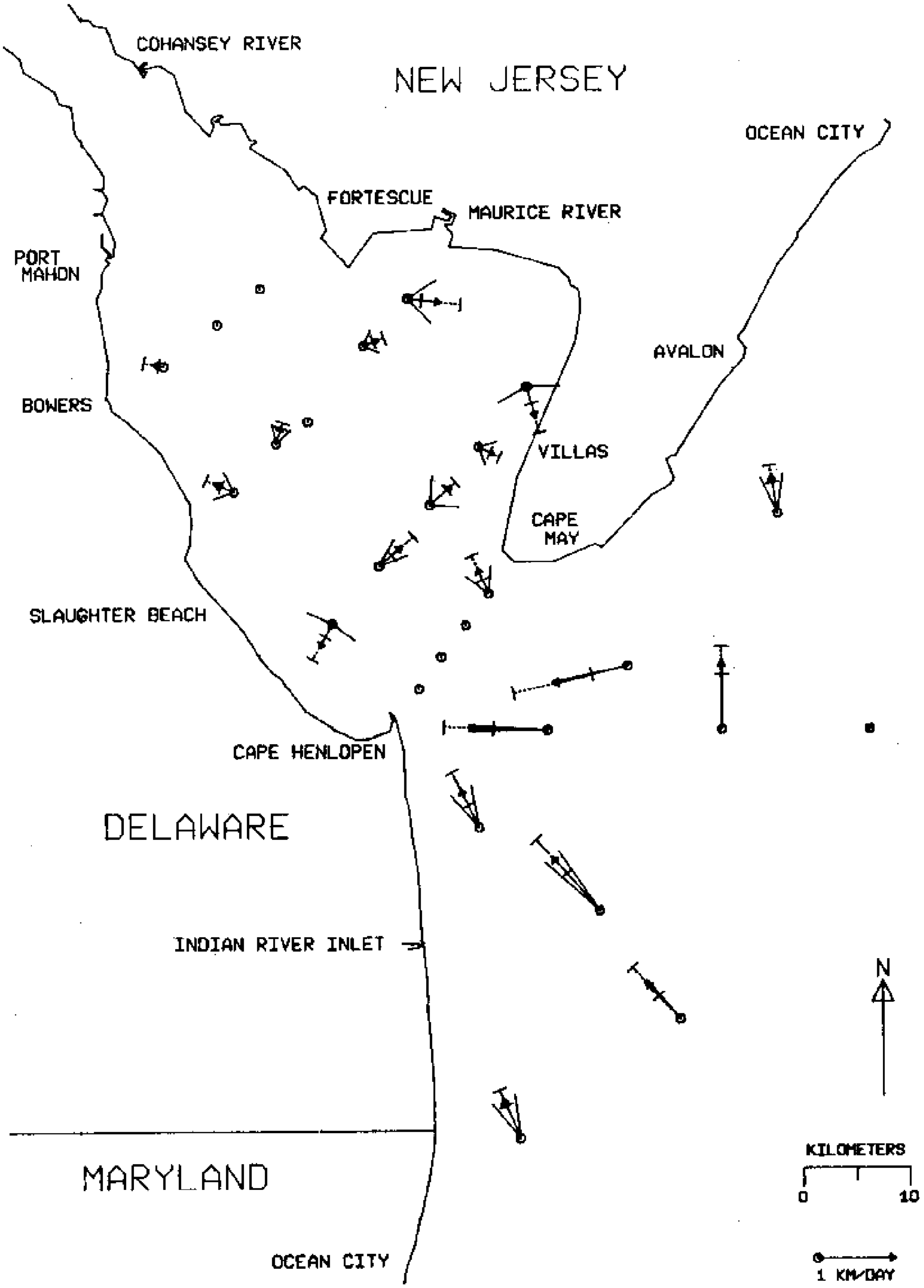

Figure 33a. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the 28 September 1979 release

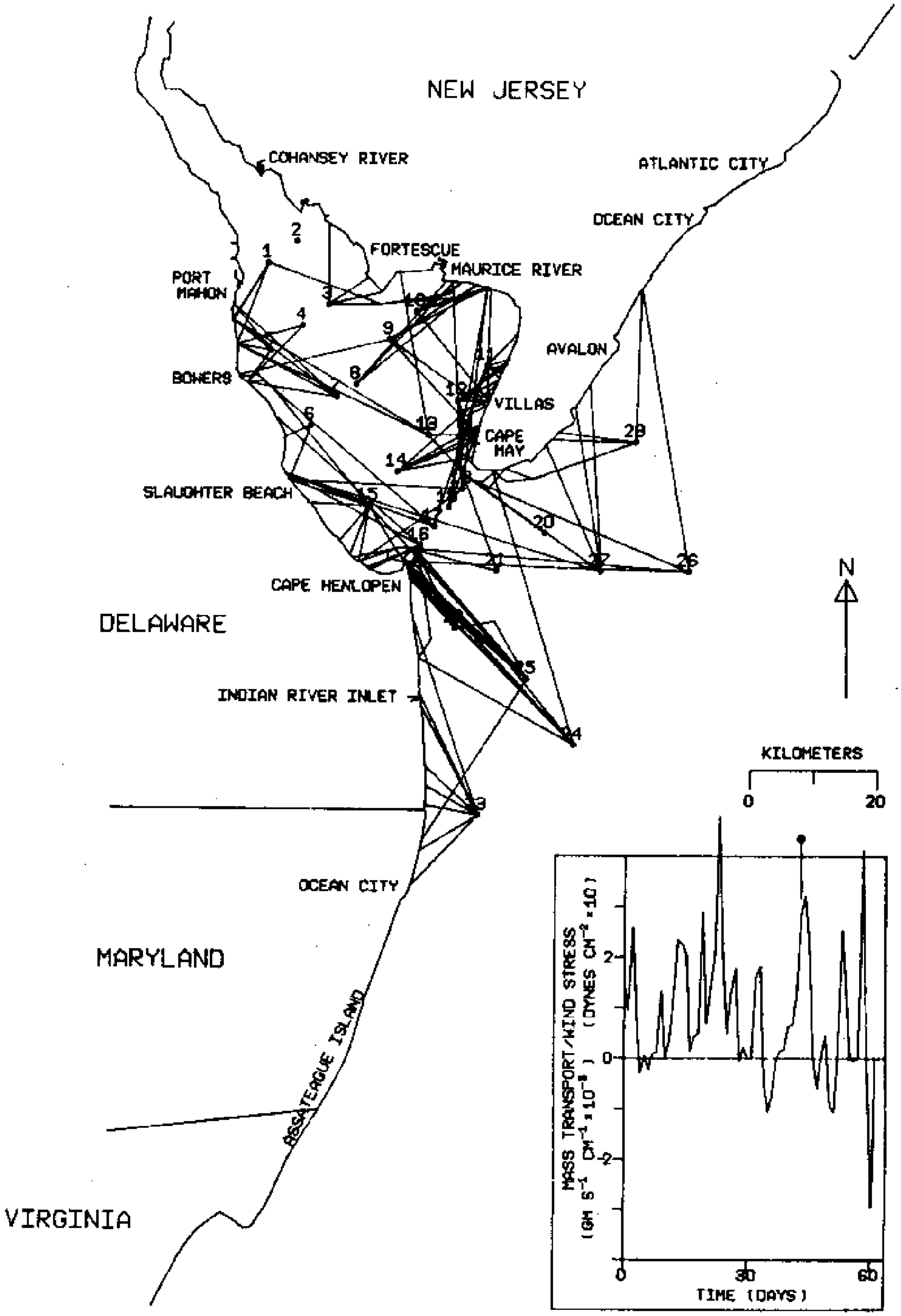

Figure 34. Apparent bottom trajectories for the 15 November 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯. Time zero is the date of release.

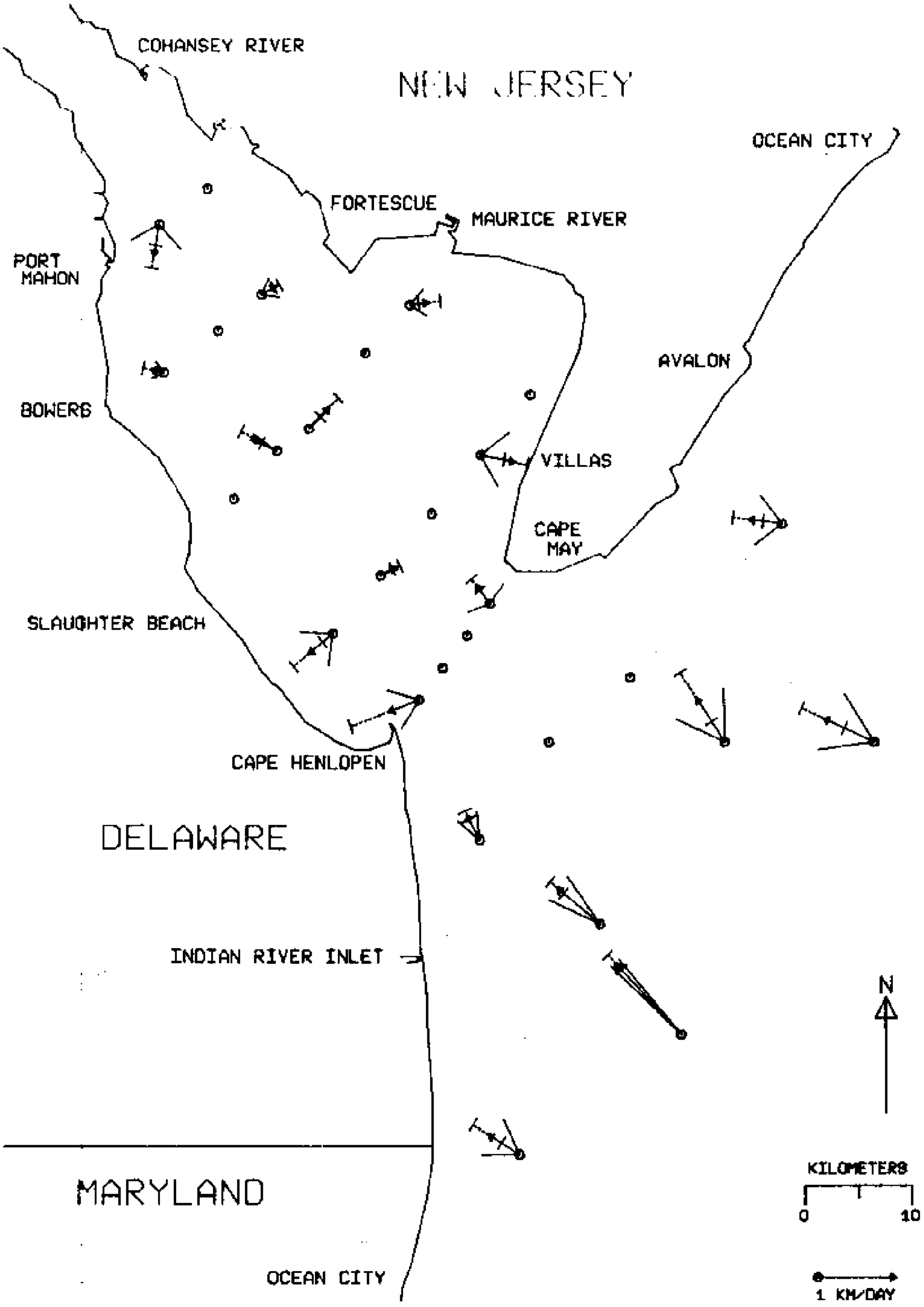

Figure 34a. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the 15 November 1979 release

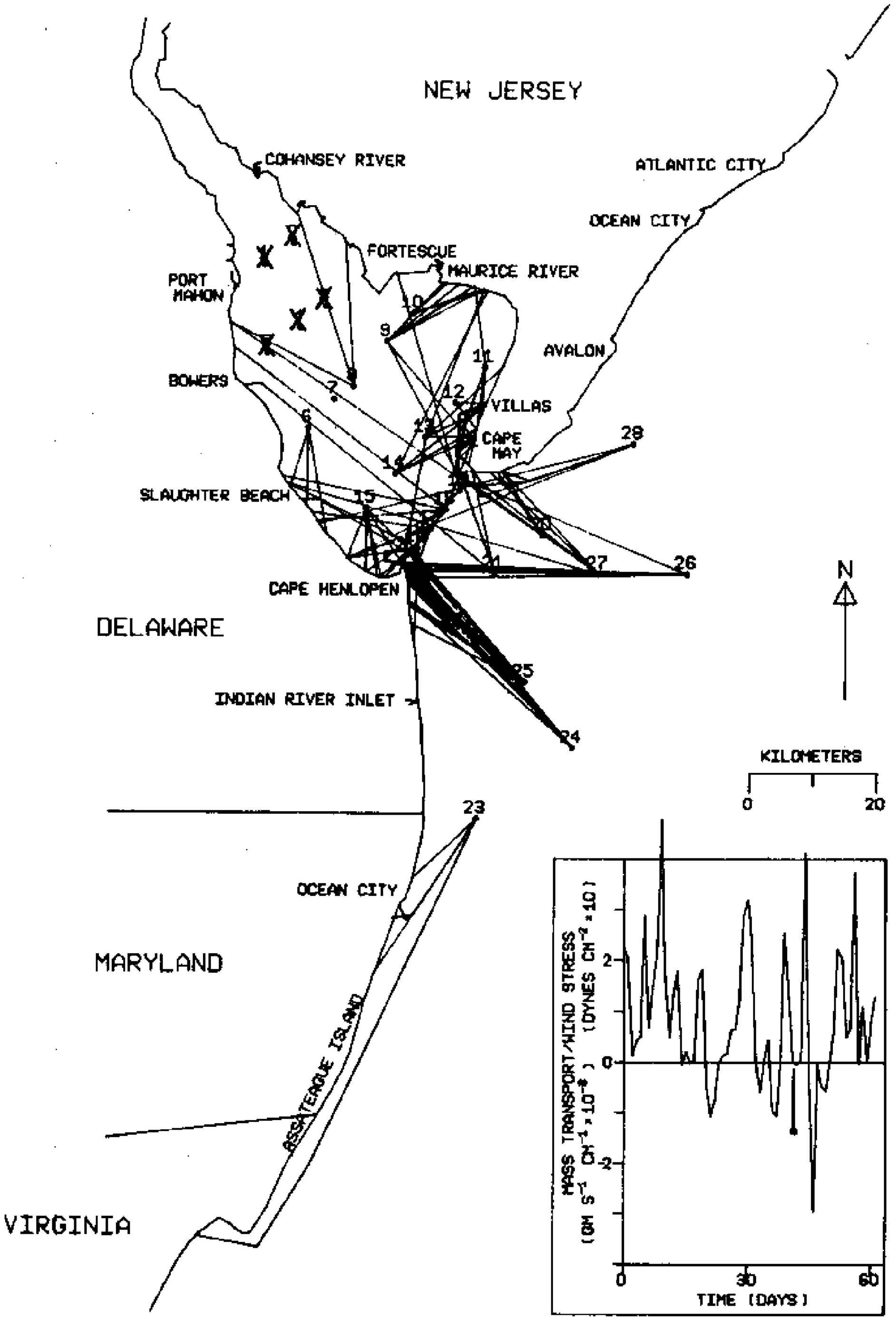

Figure 35. Apparent bottom trajectories for the 29 November 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯ . Time zero is the date of release.

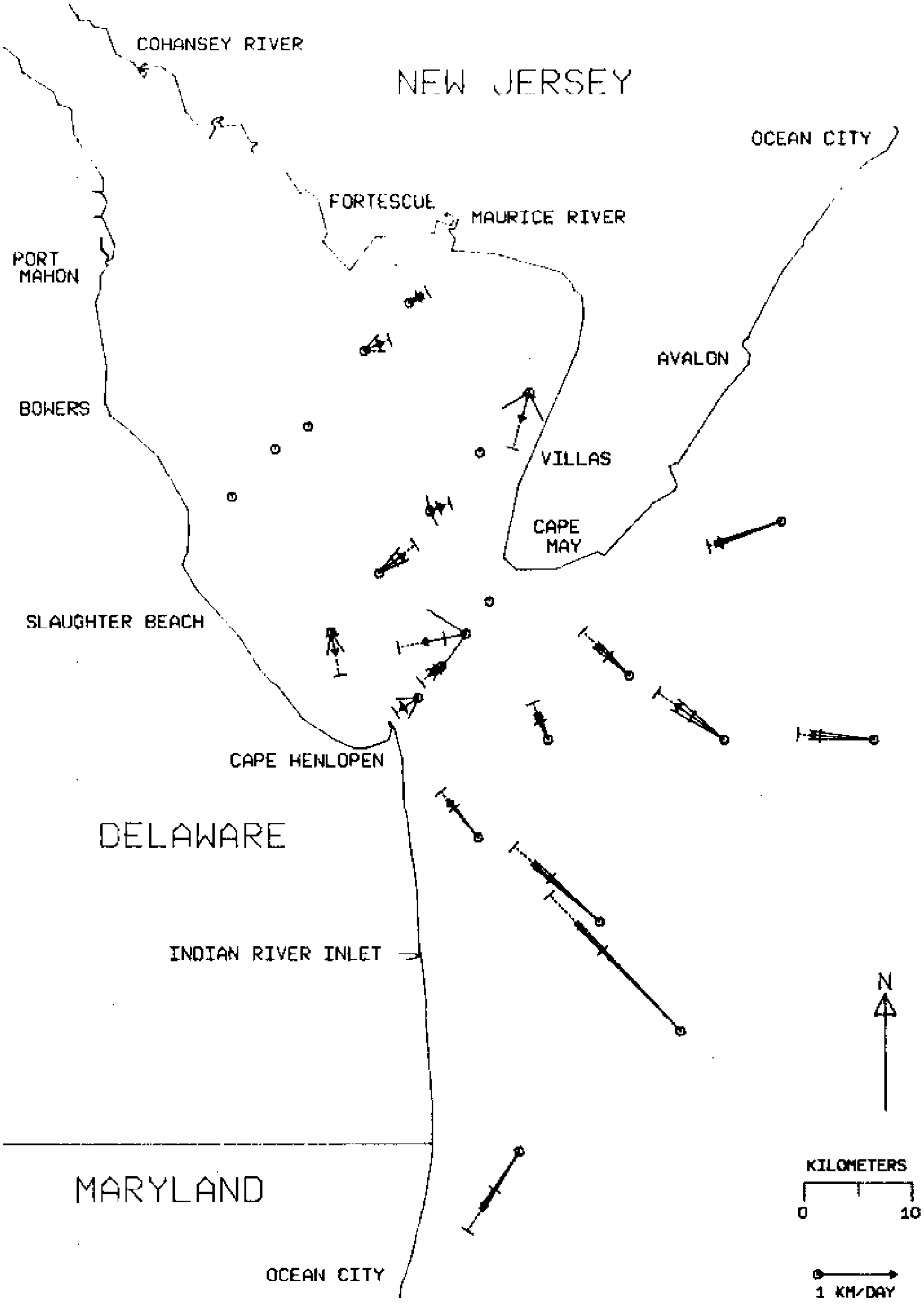

Figure 35a. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the 29 November 1979 release

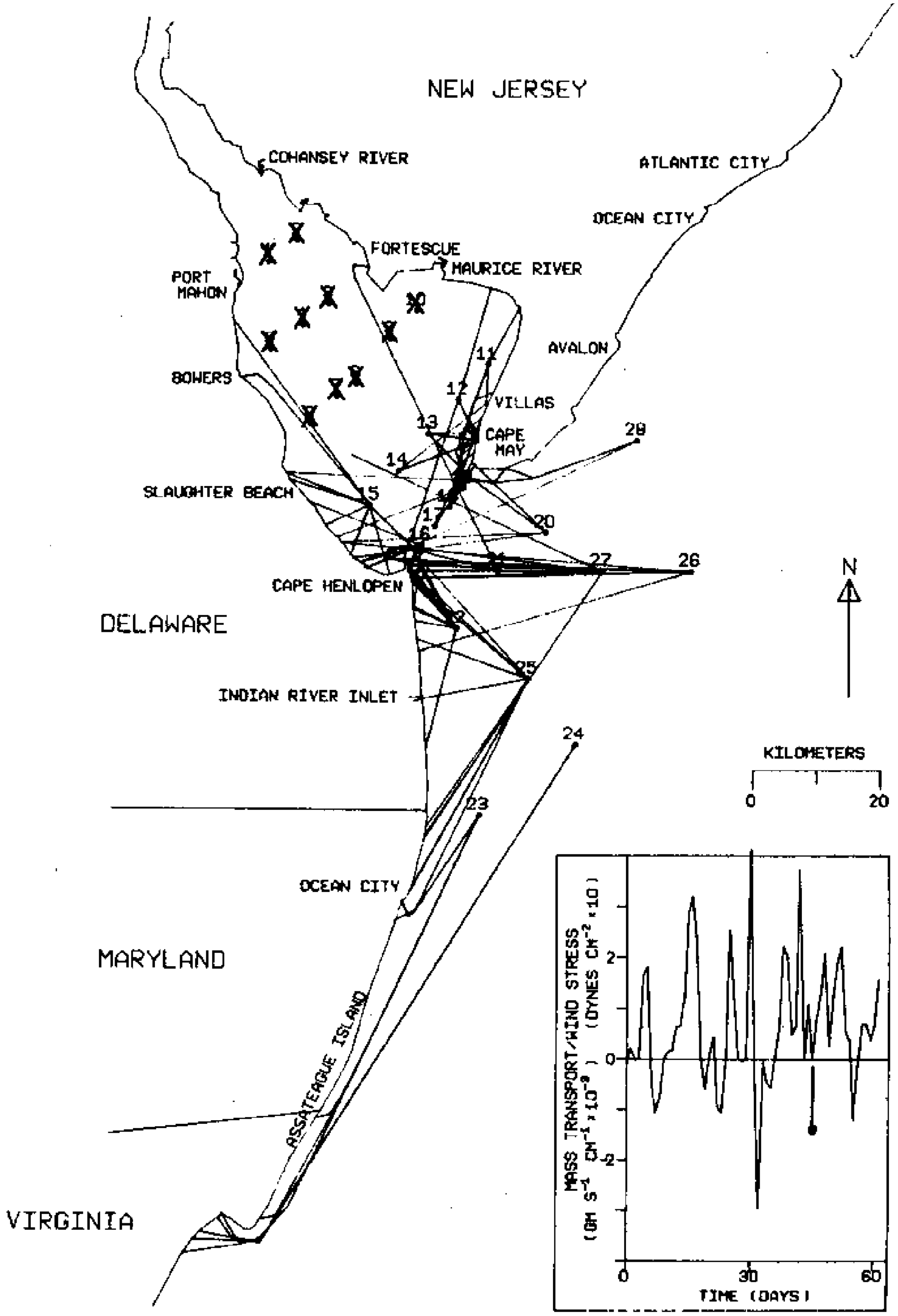

Figure 36. Apparent bottom trajectories for the 13 December 1979 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯ . Time zero is the date of release.

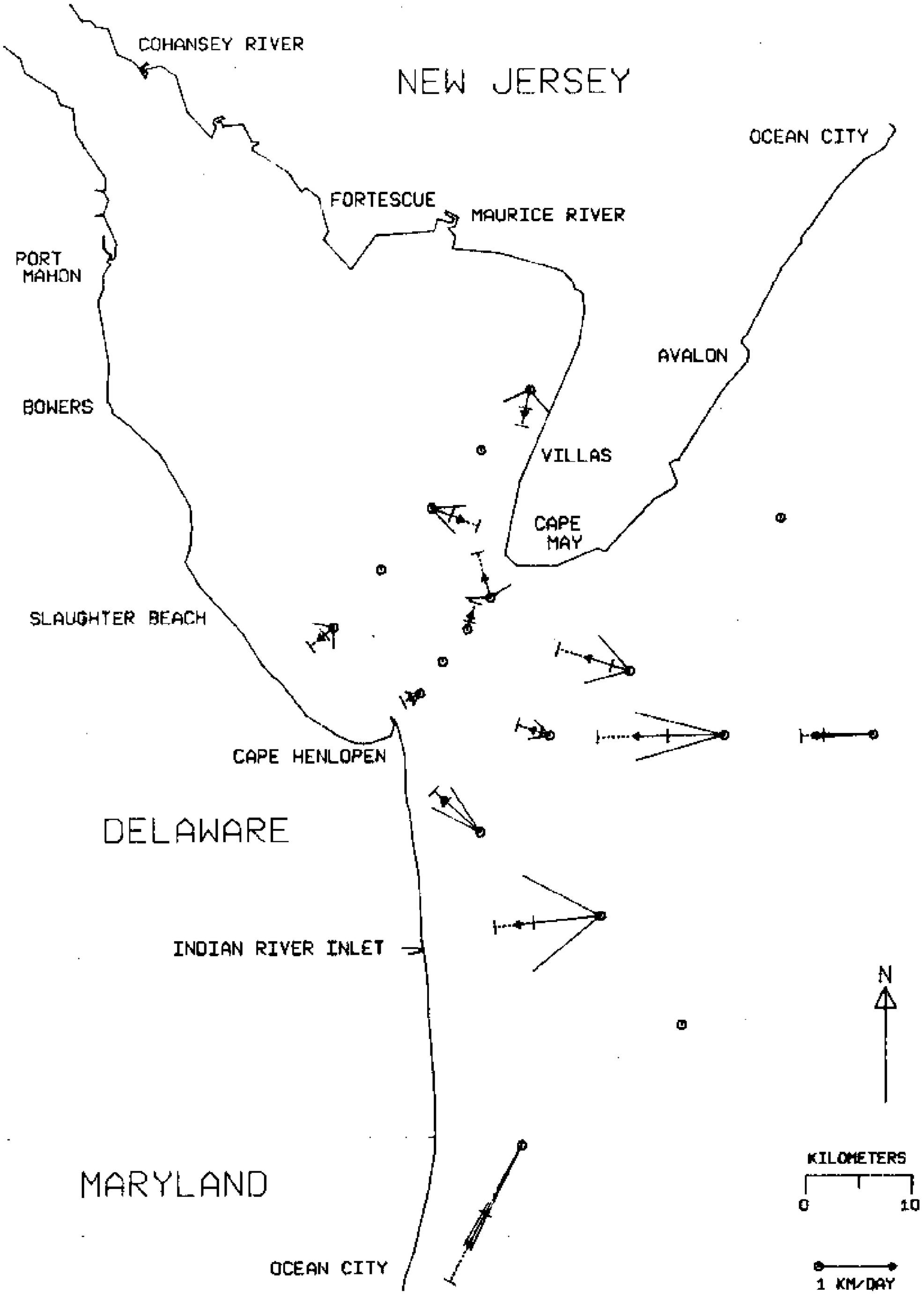

Figure 36a. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the 13 December 1979 release

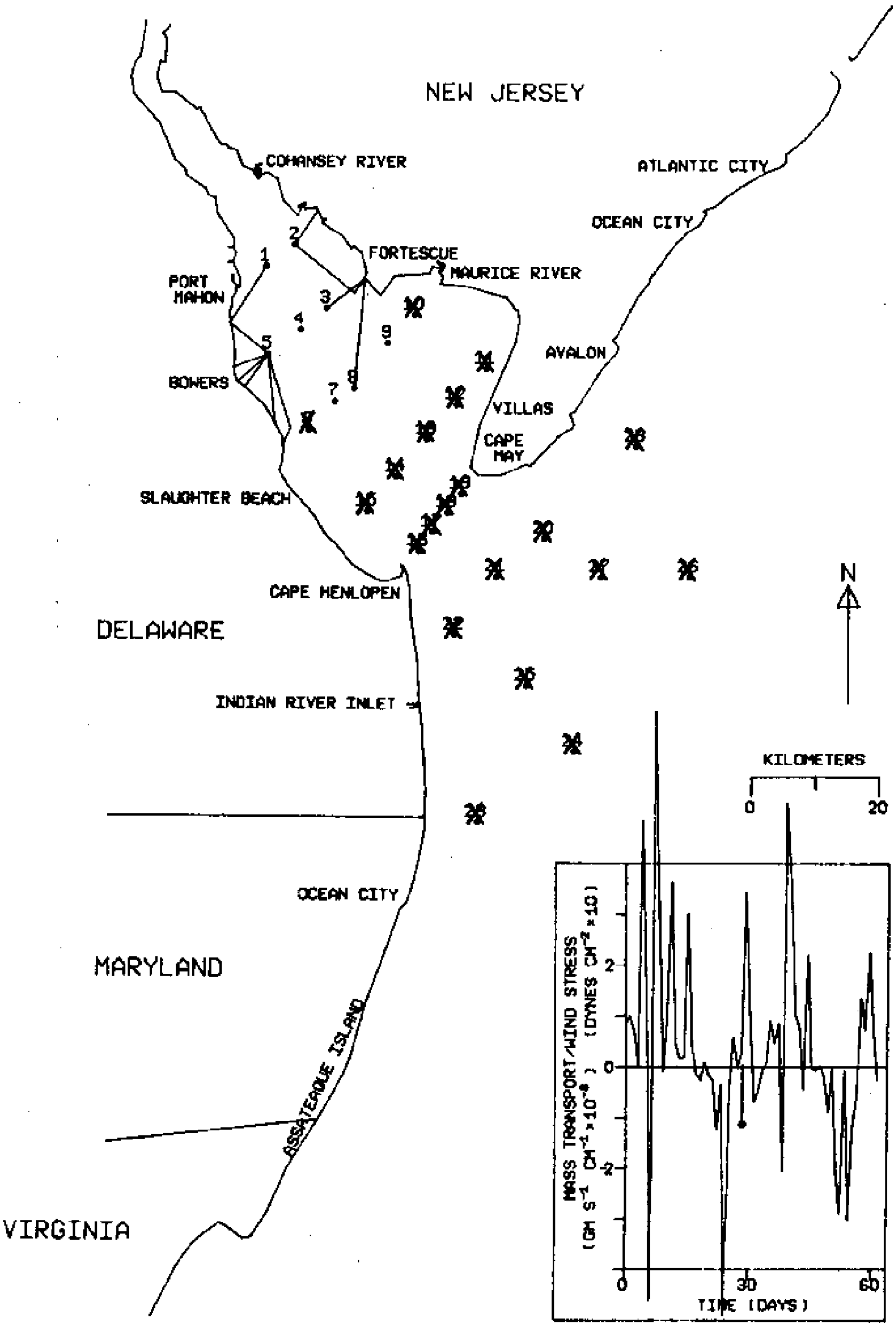

Figure 37. Apparent bottom trajectories for the 7 March 1980 release. On the mass transport/wind stress curve, the median time for drifter durations is indicated by the symbol ⫯ . Time zero is the date of release.

confidence interval was greater than 180° were similarly omitted. Stations not sampled on a particular date are not shown. While the apparent trajectory and vector maps were both constructed from common data, they each provide a distinct view of the motion, the trajectory maps showing (apparent) fluid particle paths and the vector maps the associated vector field. This difference in presentation is, of course, inherent in the conceptual frames used in the classical Lagrangian and Eulerian representations of fluid motion. The trajectory maps provide a measure of the variability in motion from each release point, since apparent trajectories are drawn for each drifter returned; this measure can sometimes be ambiguous, since the maps do not individually identify multiple drifters with identical trajectories. In contrast, the vector maps provide a quantitative measure of variability through the confidence intervals.

Tables 4 and 5 show the number of drifters returned for each station on each date, surface and bottom. These numbers can be used when interpreting the vector means and confidence intervals. A large confidence interval for either speed or direction can result from a wide range of speeds or directions in the

Table 4. Number of surface drifters returned from each station for each release date

Station number	Release date								
	19 Apr	16 May	17 May	31 Jul	28 Sept	15 Nov	29 Nov	13 Dec	7 Mar
1	3	X	14	X	X	1	X	X	5
2	3	X	4	X	X	5	X	X	2
3	5	6	9	X	1	2	X	X	1
4	2	14	17	X	3	0	X	X	3
5	2	19	13	X	2	0	X	X	5
6	2	18	20	5	2	0	0	X	X
7	4	13	15	5	2	1	0	X	4
8	0	10	13	2	0	0	0	X	2
9	6	7	5	0	1	1	0	X	3
10	X	5	2	1	3	2	2	X	X
11	X	16	5	3	1	7	11	8	X
12	3	0	13	1	1	15	2	2	X
13	2	8	8	0	5	3	0	0	X
14	2	12	6	2	4	2	0	0	X
15	0	12	16	3	3	3	1	7	X
16	0	5	8	3	1	4	0	0	X
17	1	7	11	4	0	6	0	0	X
18	3	9	8	5	0	4	0	0	X
19	2	12	10	3	3	0	0	0	X
20	0	10	6	2	0	4	0	0	X
21	2	5	1	1	1	2	0	0	X
22	0	7	9	5	1	0	0	0	X
23	X	0	9	2	0	0	0	0	X
24	X	0	6	0	0	0	0	0	X
25	0	0	0	1	0	0	0	0	X
26	X	0	1	0	0	0	0	0	X
27	2	7	5	2	0	0	0	0	X
28	2	7	4	3	0	0	0	0	X

* "X" indicates the station was not sampled on that date

Table 5. Number of bottom drifters returned from each station for each release date

Station number	Release date								
	19 Apr	16 May	17 May	31 Jul	28 Sept	15 Nov	29 Nov	13 Dec	7 Mar
1	0	X	0	X	X	4	X	X	1
2	1	X	0	X	X	0	X	X	2
3	0	1	0	X	4	5	X	X	4
4	0	0	0	X	2	2	X	X	0
5	0	0	0	X	4	5	X	X	6
6	3	4	1	7	6	2	3	X	X
7	0	1	0	3	4	6	0	X	0
8	0	1	0	3	0	4	3	X	2
9	0	0	0	3	5	5	11	X	0
10	X	0	0	2	5	4	5	X	X
11	X	2	3	0	8	9	7	6	X
12	0	0	0	8	10	8	2	4	X
13	0	0	0	3	4	6	5	5	X
14	0	0	5	2	5	5	5	3	X
15	2	1	2	8	4	12	7	13	X
16	0	3	0	3	4	7	8	7	X
17	0	1	3	1	1	3	7	2	X
18	0	0	0	2	2	3	8	6	X
19	1	0	1	7	4	5	2	4	X
20	0	1	2	6	9	2	10	4	X
21	1	2	1	9	11	2	7	5	X
22	2	3	4	9	8	14	22	17	X
23	X	1	0	5	10	9	9	7	X
24	X	2	0	3	8	14	10	3	X
25	0	5	2	9	8	14	15	12	X
26	X	1	0	4	3	5	6	9	X
27	0	1	2	5	11	5	5	10	X
28	2	1	1	7	9	5	5	3	X

* "X" indicates the station was not sampled on that date

sample, and/or from a limited number of returns.

Both the trajectory and vector mean maps for the surface and bottom provide evidence that strongly supports the classical theory of estuarine circulation: seaward surface flow and landward bottom flow within the estuary. This circulation also clearly continues onto the adjacent shelf, in agreement with Bumpus (1965, 1973). The results are also in accord with those of drifter studies in other estuaries (Paskausky and Murphy, 1976; Prytherch, 1929; Hollman and Sandberg, 1972; Larkin and Riley, 1967; Gross and Bumpus, 1972). Of most relevance, however, is the study by Norcross and Stanley (1967) using drifters on the continental shelf near Chesapeake Bay. Their results are quite similar to the present ones. This suggests that Chesapeake Bay and Delaware Bay have similar residual Lagrangian circulations with the q_s field at the mouth generally seaward, while the q_b field showed strong convergence on the mouth from offshore.

The first two columns of Tables 6 and 7 provide a statistical summary of surface and bottom returns, respectively, within the experimental domain from all stations on each date. Surface return percentages ranged

	Total Study Area		Bay (Stations 1-15)		Offshore (Stations 20-28)	
	Percent returned	Mean speed (km/day)	Percent returned	Mean speed (km/day)	Percent returned	Mean speed (km/day)
19 April 1979	10.0	3.57	13.1	2.82	5.0	8.97
16 May 1979	40.2	12.58	53.8	10.13	20.0	16.19
17 May 1979	39.7	10.81	53.3	8.32	22.8	14.99
31 July 1979	15.4	4.27	14.7	3.06	11.9	5.59
28 Sept 1979	8.7	3.73	14.4	3.64	1.5	2.14
15 Nov 1979	14.8	3.47	18.7	2.83	4.4	7.00
29 Nov 1979	4.6	2.80	10.7	2.80	0.0	----
13 Dec 1979	6.3	4.57	22.7	4.57	0.0	----
7 March 1980	20.8	2.95	20.8	2.95	----	----

Table 6. Statistics on surface drifter returns

	Total Study Area		Bay (Stations 1-15)		Offshore (Stations 20-28)	
	Percent returned	Mean speed (km/day)	Percent returned	Mean speed (km/day)	Percent returned	Mean speed (km/day)
19 April 1979	5.2	0.48	4.6	0.48	8.3	0.62
16 May 1979	11.9	0.58	7.7	0.47	18.9	0.69
17 May 1979	9.0	0.73	7.3	0.51	13.3	0.85
31 July 1979	19.0	0.49	15.6	0.32	25.3	0.58
28 Sept 1979	22.9	0.55	18.8	0.30	34.2	0.77
15 Nov 1979	23.6	0.48	20.5	0.33	31.1	0.68
29 Nov 1979	28.2	0.66	19.2	0.34	39.6	0.89
13 Dec 1979	26.7	0.64	24.8	0.31	31.1	0.90
7 March 1980	7.5	0.43	7.5	0.43	----	----

Table 7. Statistics on bottom drifter returns

from 4.6% to 40.2%, while the bottom return range was 5.2% to 28.2%. With the exception of April 19, the inverse correlation between the percentages on each date for surface and bottom suggests the strong influence of mass continuity, as explained in the previous section; low surface percentages, interpreted as strong surface offshore or seaward flow, correspond with high bottom returns, implying strong onshore or landward flow along the bottom.

Over the study period, there was a relatively large range of surface speeds, from 2.8 km/day to 12.6 km/day, although only on May 16 and 17 did surface speeds depart from the 3 to 5 km/day range. Bottom drifters, in water isolated from the direct effect of the wind and its variability, had rather consistent speeds, 0.4 to 0.7 km/day. Notice that there is roughly an order of magnitude difference in surface and bottom speeds. Both the percentage returned and speeds for both surface and bottom are low in comparison to other estuarine studies (Tables 2 and 3). The speeds are also low compared to those found in other studies in the Middle Atlantic Bight. Bumpus (1973) found the southerly surface flow over the shelf in the Middle Atlantic Bight to have speeds of about 20 km/day with speeds of about 10 km/day for the northerly reversals. Bottom speeds ranged from about 1 to 2 km/day.

After examining Tables 6 and 7, and the apparent trajectory maps (Figures 21, 22, 30, 31), it is clear that the results of the May 16 and 17 releases were very similar. Because the residual circulation is defined as the movement of water averaged over many tidal periods, a difference of one day in sampling times is small. Therefore, the May 16 and 17 releases may be considered near replicates. The similarity of results shows that the drifters did actually respond to forcing with periods much longer than a day.

The summary statistics in Tables 6 and 7 reveal some similarities and differences between the inferred residual circulation on the shelf and that in the Bay. Tables 6 and 7 show mean speeds and directions for two groups, in Bay releases (Stations 1-15) and shelf releases (Stations 20-28), as well as for the study area as a whole. The inverse variation over the nine release dates between surface and bottom return percentages for all twenty-eight stations as a group is evident. The same is true for both the Bay and the offshore subsets.

The behavior of the speed data for the two subsets is also similar to that for the whole group; surface speeds were rather variable while bottom speeds were not. However, both surface and bottom speeds were slower for returns from Bay stations than for returns from the offshore stations. The percentage of surface returns from Bay stations was greater than from offshore stations, but conversely, the percentage of bottom returns from Bay stations was lower than from offshore stations. This lower percentage of bottom drifters returned from Bay stations may in part be due to the relatively steep vertical excursions imposed on bottom drifters by the bathymetry of the Bay, especially since the bottom drifters are designed to resist vertical motion.

For the study area as a whole, there was a marked difference in the circulation from one release to another, as can be seen in the apparent drifter trajectories of each release along with the accompanying statistics given in Tables 6 and 7. During the study period there was a general decrease with time in the percentage of surface drifters returned and an increase in the percentage of bottom drifters returned. Although

March 7 had only limited sampling, the higher surface percentage and lower bottom percentage obtained then suggests a return to the same proportions between surface and bottom returns obtained during the first three releases in April and May of the previous year. This suggests an intensification of offshore surface and onshore bottom flow in the second half of the calendar year.

There was considerable variation over the study period in the patterns of apparent surface trajectories, as well as in the surface return percentages. The first four releases (Figures 20-23) resulted in a q_s field from the Bay stations (numbered 1-15) and the Bay mouth stations (numbered 16-19) which was seaward, as it was for every release. This movement, however, was inclined towards the Delaware shore. This inclination increased through May 17 and then decreased on July 31. Once outside the Bay, q_s was generally southward along the coast. Movement from the offshore stations (numbered 20-28) was generally southerly except on April 19, when the few returns from these stations were from the New Jersey coast to the north.

The mass transport/wind stress data for wind in the $75^{o}/225^{o}$ direction (see inset, Figures 20-23 and Figure 10) help explain the surface return percentages for the first four releases. Positive values represent wind stress in the 75^{o} direction, implying offshore surface flow; negative values represent wind stress in the 255^{o} direction, implying onshore surface flow. The relationship between these wind data and the return data for the first four releases was used as a standard for judging the degree to which the wind data explained the return data for the remaining releases. During the median time surface drifters were out for the April 19 release, positive values dominated and the 10% return rate was reasonable for persistent offshore flow. The values for the May 16 and 17 surface median time were strongly negative, and onshore flow is consistent with the 40% return rate for both dates. Positive mass transport/wind stress values were weakly dominant during the July 31 surface median time. An intermediate return (between 10% and 40%) was expected and 15% was observed.

For the fifth release on September 28 (Figure 24), the q_s field at the upper Bay stations (numbered 1-10) showed motion toward the New Jersey shore rather than the Delaware shore. From the remaining Bay stations and the Bay mouth stations, q_s was then directed out of the Bay and south towards the Delaware coast. However, the extent of southward movement along the coast was quite limited compared to that for the first four releases and there were nearly no returns from the offshore stations. The low return from offshore and the low total return, 9%, were below that predicted from the mass transport/wind stress data (see inset, Figure 24), since the lack of strong positive or negative values would predict an intermediate return rate. However, note that after the median time, strongly positive mass transport/wind stress values dominated, which indicates that further return of surface drifters was highly unlikely. The November 15 pattern for q_s (Figure 25) was radically different from that of all other releases. Except for one drifter, returns from all stations were either on the New Jersey shore of the Bay or north along the New Jersey coast. The offshore stations were, again, poorly represented. This was expected from the strong, positive peaks in the November 15 mass transport/wind stress data (see inset, Figure 25). The positive dominance was not quite as strong as on April 19 (Figure 20), making the 15% total return understandable. The 75°

wind for this period had a peak stronger than all but one other date which helps explain the reversal of flow toward the north. The alongshore wind (30°) record during this time had the strongest northward values of any of the dates.

The Bay stations on November 29 (Figure 26) had only 16 returns, 15 of which were from New Jersey. Generally, q_s was seaward, but none of the drifters were recovered from beyond the Bay. The Bay mouth and offshore stations had no returns, which was expected from the dominance of high positive mass transport/wind stress values. This dominance of high positive values continued well beyond the median time, which helps explain the 5% total return. The Bay mouth and offshore stations again had no returns for the December 13 release (Figure 27). This and the 6% return rate were unpredicted considering the very small positive values of mass transport/wind stress for this date (see inset, Figure 27). However, after the median time, high positive values dominated, as after the September 28 and November 29 median times when the total returns were comparable. Bay sampling was quite limited on December 13. A few drifters from the Bay stations entered shelf waters and q_s for those was southward along the coast. The March 7 release (Figure 28) included only a few stations, all within the upper Bay, but the resulting pattern was reminiscent of that for the first four releases. The mass transport/wind stress graph for this date was much more strongly positive than for any other date, making the 21% return higher than expected and the lack of strong reversal of flow to the north surprising.

The pattern of apparent bottom trajectories remained persistent throughout the study period (Figures 29-37), although there was a large change in the percentages returned. Drifters released within the Bay moved laterally, often with an up-Bay component, resulting in a line of divergence roughly following the major axis of the Bay. From the offshore stations there was usually a strong convergence toward the mouth of the Bay. Penetration of the Bay was routine, but less frequent than might have been expected. Many bottom drifters from the shelf beached on the Delaware coast from Cape Henlopen to the Maryland state line.

The mass transport/wind stress values for the 75° wind direction help explain the observed change in percentages of bottom drifters returned over the study period. The mass transport/wind stress curve for the first four releases (see insets, Figures 29-32) was weakly positive or negative, indicating weak or no offshore surface flow which implies weak onshore bottom flow and low bottom returns. Low bottom returns were observed (Table 7), although 19% for July 31 was high compared to the previous three dates. The next four dates, September 28 through December 13, had extremely high mass transport/wind stress values (see insets, Figures 33-36). Strong offshore surface flow was expected to be compensated by strong onshore bottom flow, resulting in high bottom returns, as observed. March 7, however, had relatively high positive mass transport/wind stress values (see inset, Figure 37), and the 8% bottom return was much lower than anticipated.

The Lagrangian vector representations of mean speed and direction for the entire study period, for surface and bottom, are shown in Figures 38 and 39, respectively. These two figures should be considered in combination with Figures 40 and 41. Figure 40 shows the

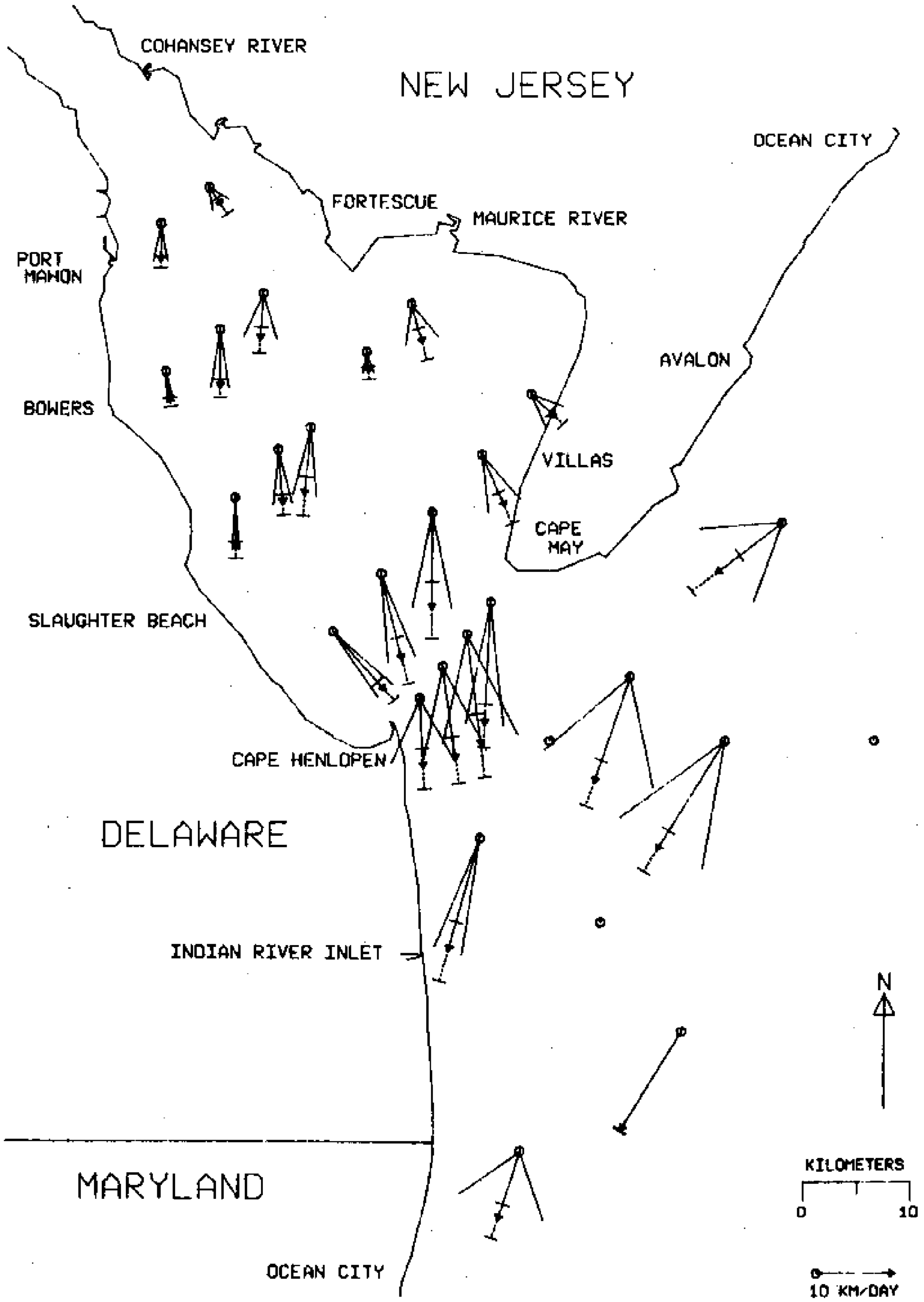

Figure 38. Vector map of surface mean speeds and directions and associated 95% confidence intervals for the study period

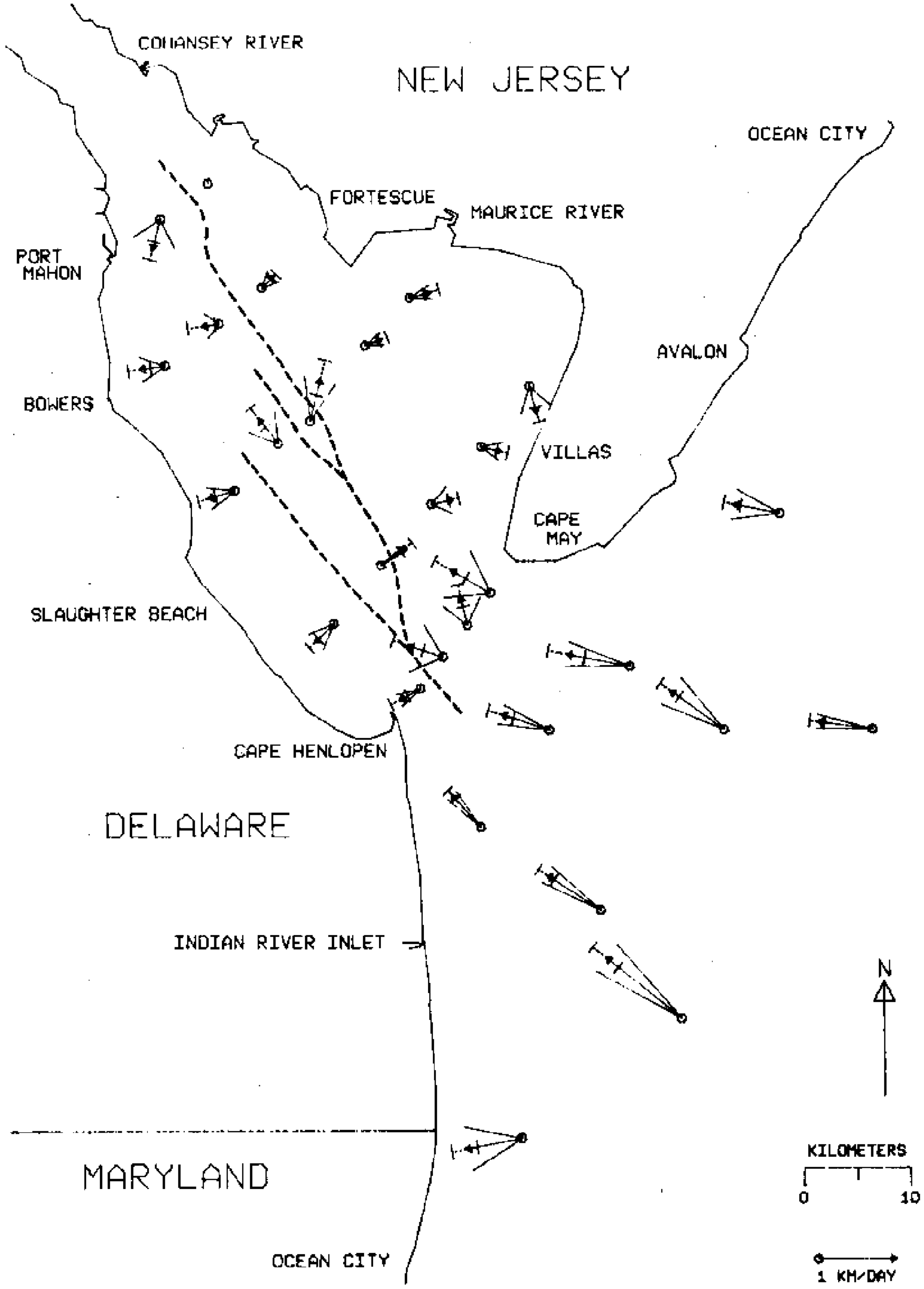

Figure 39. Vector map of bottom mean speeds and directions and associated 95% confidence intervals for the study period

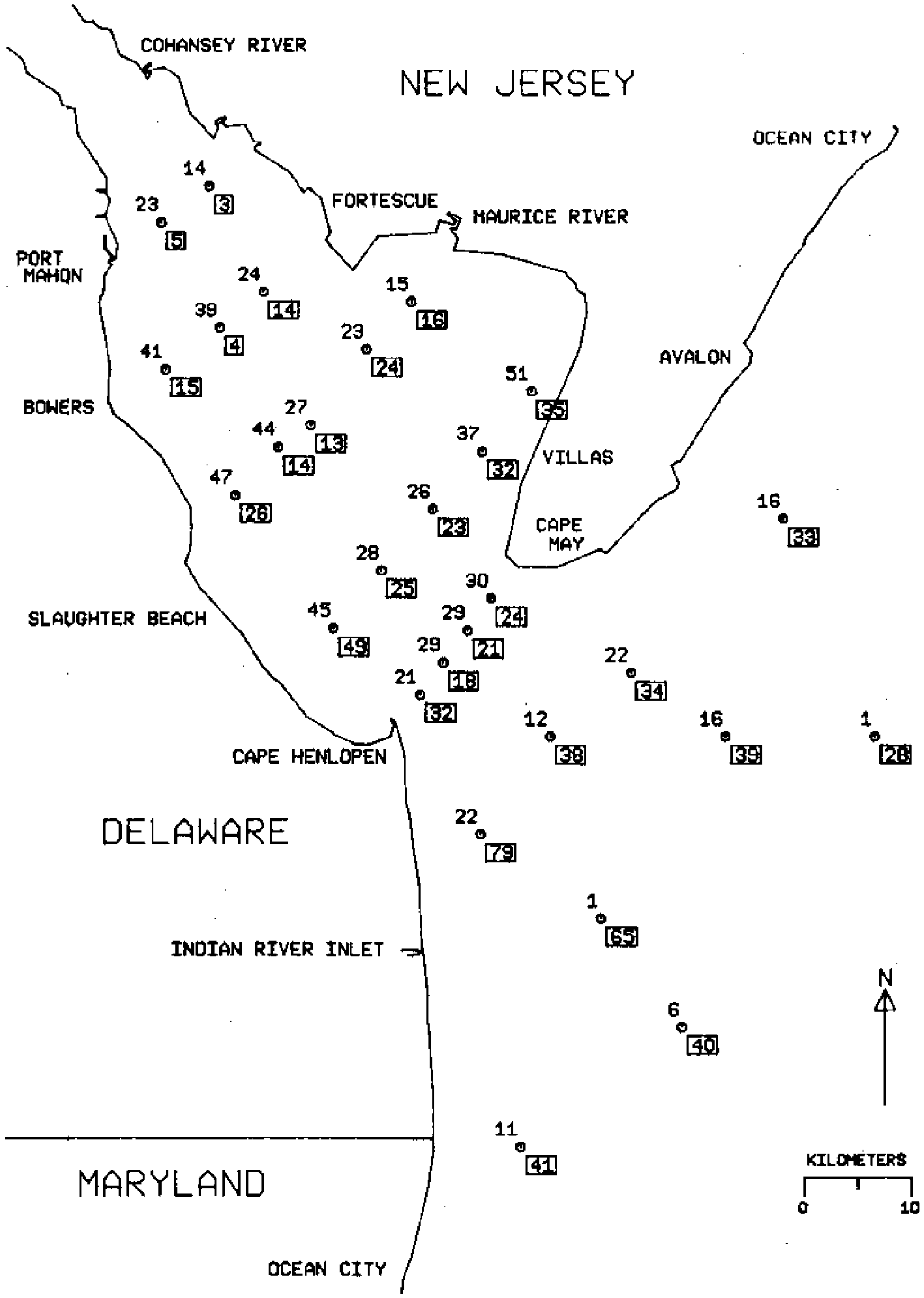

Figure 40. Total number of surface and $\boxed{\text{bottom}}$ drifters returned from each station for the study period

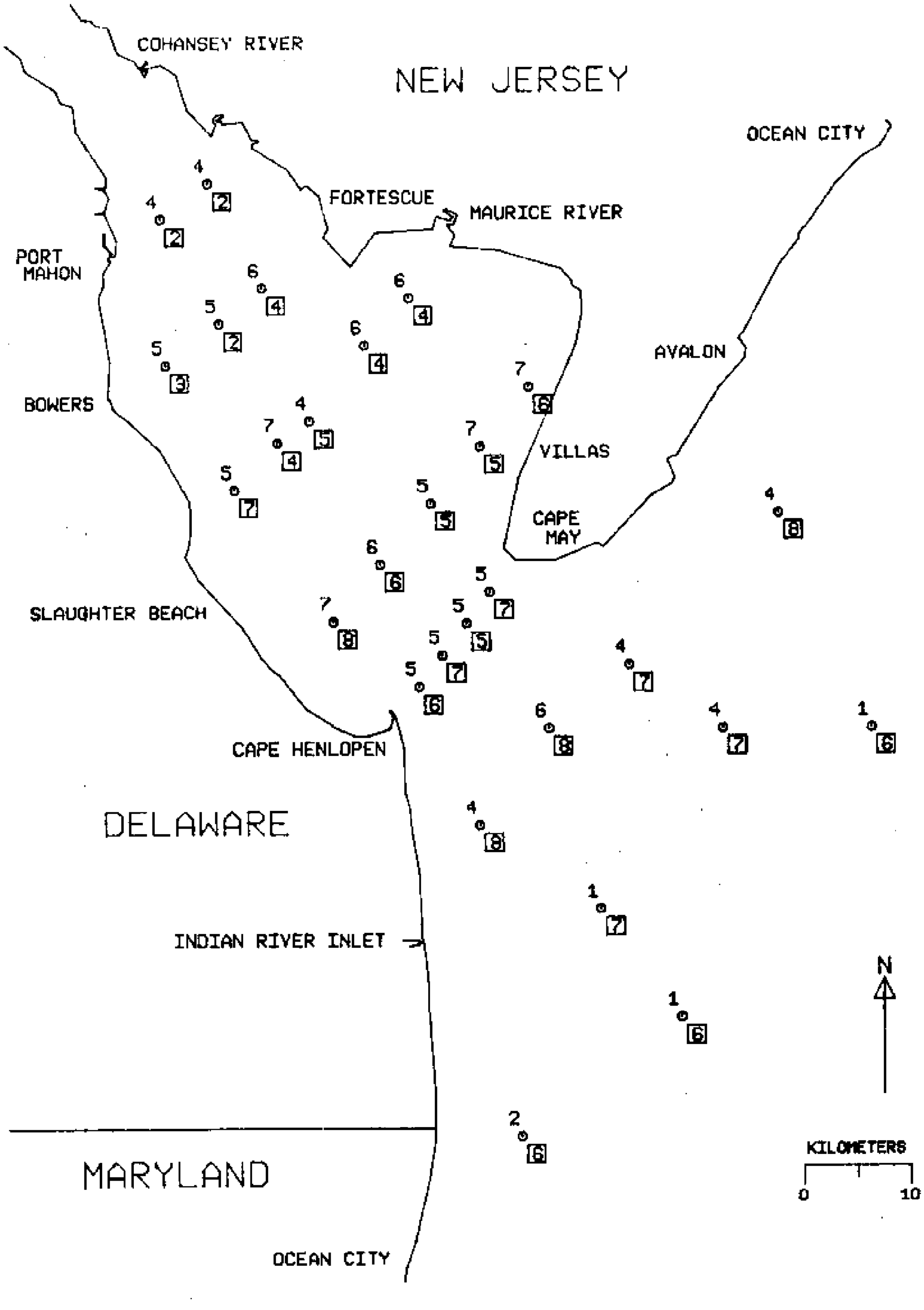

Figure 41. Number of release dates on which each station had at least one surface or bottom drifter returned

total number of drifters returned for each station for the study period and Figure 41 shows the number of dates on which each station had at least one return. The two figures together indicate that surface returns were higher and more consistent over the year within the Bay as opposed to offshore, while the opposite was true for bottom returns. Figure 41 reveals that the means shown in Figures 38 and 39 are not representative of every sampling date during the study period. Despite this, there is a high degree of coherence in the residual circulation pattern evident in these maps.

The map of surface means, q_s, for the study period (Figure 38) clearly illustrates the evidence for seaward surface flow from Bay stations and demonstrates a tendency for q_s to be directed towards the Delaware side of the Bay, as noted previously. The southerly surface drift over the shelf is also clear. The case for landward bottom flow is strongly supported by the map for q_b (Figure 39) for both the Bay mouth and offshore stations. However, within the Bay q_b diverges along a line roughly along the major axis of the Bay. Northeast of this line q_b is directed toward the New Jersey shore and southwest of this line q_b is directed toward the

Delaware shore. This line of divergence closely corresponds with the deepest parts of the Bay which are shown as dashed lines in Figure 39. Apparently, the bottom water moves upstream following the deepest channels and then spreads laterally onto the adjacent shallower areas on both sides. Over the shelf, Bumpus (1973) found the bottom drift just north of 38°30'N (about 6 km north of the Maryland/Delaware state line) to move northward, while just south of that latitude it moved southward. Some evidence in support of this divergence can be seen in Figure 39. Station 23 is the only station south of this line of divergence and is the only station for which the mean velocity has a southerly component. The maps for individual release dates (Figures 29-37) show that q_b at Station 23 varied from northerly to southerly.

Both surface and bottom residual currents are faster over the shelf than in the Bay (see Figures 38 and 39, Tables 6 and 7), but surface currents are an order of magnitude faster than bottom currents in both areas (see Tables 6 and 7). This confirms results of other studies. The average speed of surface and bottom residual currents observed in the estuarine studies cited in Tables 2 and 3 are 9 km/day and 1 km/day, respectively, while Bumpus (1973) observed surface and bottom speeds of 20 km/day and 1-2 km/day, respectively.

The mean direction confidence intervals shown in Figures 38 and 39 are all relatively narrow, indicating a consistent pattern of circulation over the study period. At the surface, the Bay mouth and offshore stations have the widest mean direction confidence intervals. This is probably due to the frequent reversals in alongshore movement from these stations as compared to the more narrowly directed seaward flow within the Bay. For the bottom, in contrast, the stations within the Bay and at the mouth have wider mean direction confidence intervals than those on the shelf. The offshore stations had narrowly directed flow converging on the Bay mouth, while movement from stations at the mouth and in the Bay was toward either shoreline. There was a consistent trend by bottom drifters to move perpendicular to the shore, both for those released at the shelf stations and for those released in the Bay.

Interpretation of Drifter Movement

Some interpretation of the apparent trajectory and mean maps is appropriate at this point. There are several sources of bias in the distribution of return points. Contributing factors include no offshore coast and spatial and temporal differences in human use of beach areas.

There is no coast offshore to the east upon which the drifters could beach. This certainly would have diminished surface returns from Stations 20-28, located offshore. Apparent surface and bottom trajectories, thus, could have an artificial onshore component resulting from bias. However, useful information is obtainable from the maps. There is a significant difference in the overall patterns of surface and bottom trajectories. Surface trajectories from the offshore stations were never directed towards the Bay mouth. If offshore returns had been possible, the impact would have been to strengthen further the inference of offshore flow at the surface. Most bottom trajectories from offshore converged on the Bay mouth and the Bay was routinely penetrated, whereas surface drifters from offshore never approached the Bay.

Now consider Stations 1-15, inside the Bay. Within the Bay there is an opportunity for returns from nearly any direction. Nevertheless, surface drifters showed only downstream movement and many entered shelf waters, beaching on the coast. Bottom trajectories often had upstream components and nearly all remained within the Bay. The fact that the surface and bottom flow within the Bay, where returns are possible from nearly any direction, is consistent with that over the shelf, where offshore returns are not possible, speaks for the validity of the flow pattern inferred from the offshore stations.

The return of drifters is, of course, dependent upon the degree of human use of the shoreline. Areas rarely visited thus might have lower returns than those areas heavily used. Evidence will be given, however, to demonstrate that this effect is minimal for the present results. There is an obvious lack of surface returns on the New Jersey side of the Bay which might be attributed to the isolated nature of this section of shoreline. Yet substantial numbers of bottom drifters were found on both sides of the Bay. This suggests that people were on the beaches on both sides of the Bay and that the surface tendency toward Delaware is real. Along the coast most returns were from south of the Bay mouth rather than north, yet the New Jersey coast is more highly developed than the Delaware, Maryland, and Virginia coasts. Gross et al. (1969), in a drifter study off the Washington-Oregon coast, concluded that most beaches there were visited sufficiently often, even where the location was rather remote.

Another possible source of bias is variation of human use of the beach with season. More people use the beach in the summer than at other times of the year. This might explain the decrease in surface percentage returns in the fall (Table 6); but as the surface percentage dropped, the bottom percentages increased (Table 7). It could also be argued that the return percentages in winter were lower than they would have been had the releases taken place in summer. A beach seeding experiment on Long Island's southern shore (Hardy et al., 1975) found total winter return percentages to be lower than those in summer, 47% compared to 59%. However, this difference is not large enough to seriously affect results. Bumpus (1973) argued that the consistency with which bottom drifters were returned throughout the year suggested that the shore was visited sufficiently all year, except for a few relatively inaccessible areas.

These sources of bias in the drifter method are real, but the results of previous experiments, as well as of the present one, suggest that their effect is minimal.

A deliberate attempt to minimize some of these problems can be made by using large numbers of drifters, as in this study. A total of 3470 surface drifters and 3940 bottom drifters was released. Use of large numbers also permits elimination of drifter returns with suspiciously long durations and thus permits calculation of more reliable mean speeds and directions with reduced confidence intervals.

Correlation of Wind and River Data with Drifter Data

Several directions were chosen and the component of the wind along each was examined. As the drifters are assumed to travel with the water, it was expected that a clear relationship would be evident between the mass transport/wind stress values for one of the wind directions and the percentage, and perhaps speed, of returns for both the surface and bottom drifters. The anticipated responses of the water to wind forcing were discussed earlier. However, the primitive state of the physical understanding of the responses led to the use of correlation coefficients to suggest the component of the wind having the most influence on the Lagrangian mean circulation of the Bay and adjacent shelf.

The response of the Bay to the wind should be quite different than the shelf, owing to its nearly enclosed nature, its relatively small fetch, and its shallow depth of water. Furthermore, the residual circulation within the Bay might largely be a response to shelf water movement from wind forcing, i.e., a response to non-local forcing. To investigate such possible differences in response to wind forcing, the returns from the Bay stations, numbered 1 to 15, were considered separately from the returns from the offshore stations, numbered 20 to 28, when correlations were computed. All twenty-eight stations were also considered as a group.

Three series of correlations were computed. The first included data from all nine release dates, the second included data from the first eight release dates, and the third included data from the first seven release dates. The first series included data for the study area as a whole and for the Bay stations. However, data from the offshore stations were not included, as these stations were not sampled on the March 7 release. Offshore station data were included for the second series when March 7 data were eliminated. However, with limited surface returns from offshore on some dates, no mean speeds could be calculated, and so, for the surface, a separate series of correlations of offshore mean speeds with wind was computed using data for the appropriate dates. The third series of correlations deleted both March 7 and December 13 data. On December 13, only five of the fifteen Bay stations were sampled; thus, by excluding data from this date any effect that this inconsistency may have had was eliminated. The summary statistics on returns for each date which were used for the correlations are listed in Tables 6 and 7 and the integrated values of mass transport/wind stress for the different directions are given in Tables 8 and 9.

Direction of wind	Release date								
	19 Apr	16 May	17 May	31 Jul	28 Sept	15 Nov	29 Nov	13 Dec	7 Mar
30°	14069	-6739	-5530	1318	422	11121	1093	-1101	11561
55°	11239	-6694	-5747	1149	-429	8578	2390	-184	14232
75°	8325	-5042	-4542	1134	-939	6337	3257	160	22011
105°	3552	-1564	-1783	792	-1161	3342	3383	1512	34650
115°	1157	-691	-1045	436	-1140	1899	3067	2075	35463
145°	-8190	983	337	-943	-1290	-4568	1440	3269	21234
170°	-14370	3202	2191	-1642	-1314	-9361	281	3087	1031

Table 8. Integrated values of mass transport/wind stress calculated using surface drifter median durations

Direction of wind	Release date								
	19 Apr	16 May	17 May	31 Jul	28 Sept	15 Nov	29 Nov	13 Dec	7 Mar
30°	15612	22666	15471	20724	20106	26766	7205	-11874	4330
55°	12044	10596	3680	12923	24130	34184	23400	6209	6414
75°	8402	3404	-3733	7593	25457	38295	35600	24773	15345
105°	2953	-1821	-7638	3758	21680	39685	46961	48214	31869
115°	365	-5110	-9395	2401	18024	37186	47348	51896	34035
145°	-9337	-20617	-19077	-8312	3290	19924	38453	48989	22351
170°	-15913	-29762	-24336	-18301	-8844	-212	21368	34312	4303

Table 9. Integrated values of mass transport/wind stress calculated using bottom drifter median durations

The resulting correlation coefficients for the surface are presented in Table 10. The clearest result is that the wind does not account for all of the variance in surface drifter returns. Figure 42 shows a sample scatter plot of total mean speed for the surface against the mass transport/wind stress values for the 55° axis orientation. The associated correlation coefficient was -0.751. The square of the correlation coefficient multiplied by 100 gives the percent of the variation in drifter data attributable to variation in the wind data (Miller and Freund, 1965). A correlation coefficient of -0.751, then, would mean that about 55% of the variation in drifter data was accounted for by differences in wind data.

A correlation coefficient indicates the degree of linearity between the two variables. However, computed coefficients must also be compared with their associated significance values. Using a standard significance test involving the "Z" statistic (Miller and Freund, 1965), it was determined that for data pairs from the nine release dates, the absolute value of the correlation coefficient must be greater than 0.585 for the 95% significance level. In other words, for a correlation coefficient

Table 10. Correlation coefficients for comparisons of wind and surface drifter data

		Area under mass transport/wind stress curve						
		30°	55°	75°	105°	115°	145°	170°
(n=9)	Total percent returned	-.477	-.480	-.303	-.051	-.002	.144	.368
	Total mean speed	-.720	-.751	-.628	-.387	-.331	-.096	.443
	Percent returned (Bay stations)	-.648	-.653	-.489	-.221	-.161	.067	.485
	Mean speed (Bay stations)	-.754	-.768	-.623	-.358	-.295	-.029	.521
Mar values deleted (n=8)	Total percent returned	-.569	-.661	-.694	-.703	-.666	.166	.360
	Total mean speed	-.699	-.772	-.794	-.753	-.638	.336	.514
	Percent returned (Bay stations)	-.678	-.751	-.776	-.723	-.591	.350	.511
	Mean speed (Bay stations)	-.748	-.811	-.830	-.765	-.609	.421	.585
	Percent returned (offshore stations)	-.531	-.616	-.645	-.675	-.672	.115	.315
	Mean speed (offshore stations)	-----	-----	-----	-----	-----	----	----
Mar and Dec values deleted (n=7)	Total percent returned	-.662	-.731	-.759	-.714	-.626	.382	.522
	Total mean speed	-.734	-.793	-.813	-.751	-.639	.456	.595
	Percent returned (Bay stations)	-.698	-.761	-.784	-.722	-.610	.432	.564
	Mean speed (Bay stations)	-.763	-.818	-.835	-.766	-.639	.497	.632
	Percent returned (offshore stations)	-.643	-.703	-.726	-.693	-.624	.359	.502
	Mean speed (offshore stations)*	-.723	-.754	-.771	-.779	-.818	.556	.631

*28 Sept and 29 Nov data also deleted (n=5)

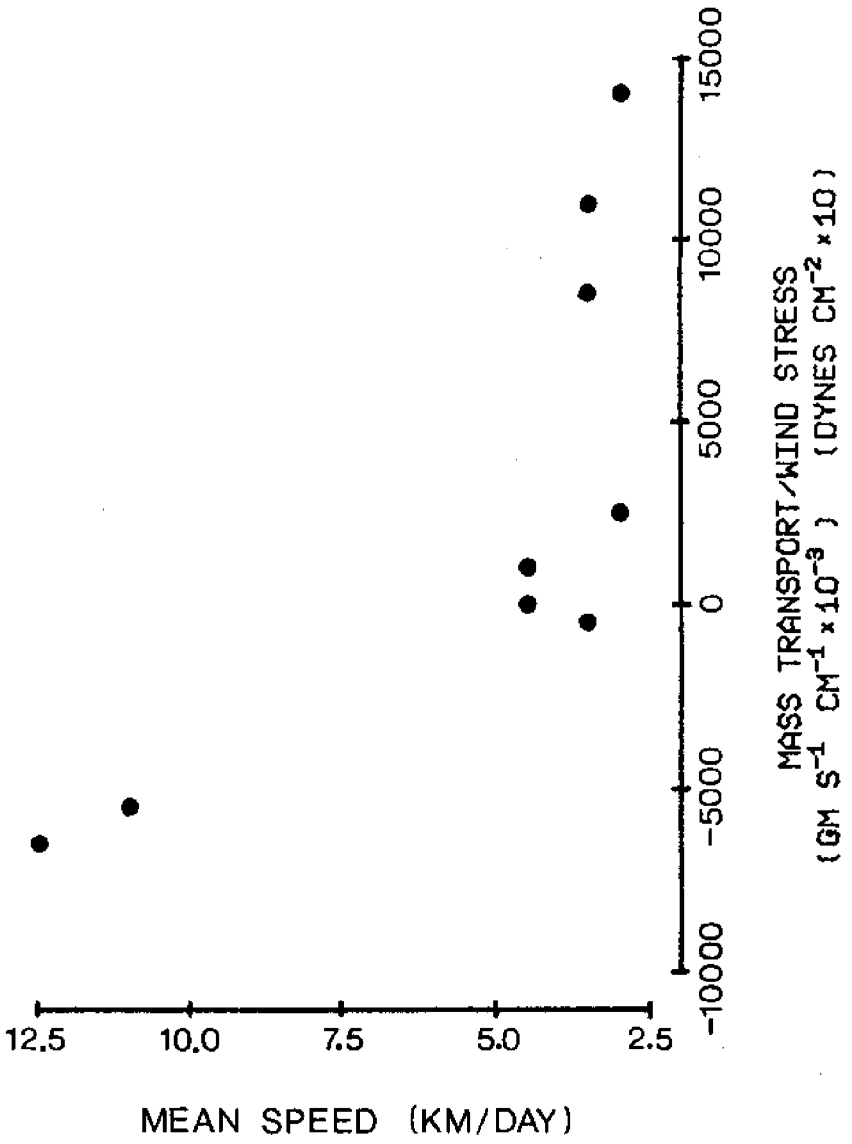

Figure 42. Scatter plot for two variables with a -0.751 correlation coefficient

greater in magnitude than 0.585 there is a probability of less than 0.05 that a linear relationship has been falsely concluded. For eight data pairs, at the 95% significance level, the absolute value of the correlation coefficient must exceed 0.626, for seven pairs it must exceed 0.676, and for five pairs it must be greater than 0.822. This is not to say that a linear relationship cannot exist for correlation coefficients less than the significance level, nor that a linear relationship is assured for correlation coefficients greater than the significance level. However, because the predicted response of the water to wind forcing is not entirely clear, it was hoped that the correlations would give some indication of which component of the wind has the greatest impact on the Lagrangian mean circulation.

The 55° and 75° directions have significant correlations and are higher in magnitude than the others. The sign of the correlation coefficients for these two directions is always negative. This indicates that a larger wind component in these directions corresponds with lower percentages returned and slower speeds, while a larger component in the opposite direction corresponds with higher percentages and faster speeds. This result is roughly consistent with the basic concept that the near surface water moves only somewhat to the right of the wind. Given that most surface flow, once offshore, is southerly along the Delaware or Maryland coast, oriented roughly north/south, winds toward 55° or 75° would be expected to force near surface water almost directly offshore, and onshore for corresponding negative mass transport/wind stress values.

Correlation coefficients for bottom returns are given in Table 11. The wind sometimes explains as much as 75% of the bottom drifter returns. The values of the correlation coefficients necessary to attain the 95% significance level for the surface correlations are applicable to the bottom correlations as well. Higher significant bottom correlations occurred for wind directions of 75° through 115° and were positive, except for the Bay speed correlations, implying that stronger winds in these directions drove more bottom drifters landward and vice versa. Winds in these directions, roughly eastward, would have generated a surface Ekman transport with average motion toward south resulting in a compensating bottom transport toward north. This would result in reinforcement of the landward drift of bottom

Table 11. Correlation coefficients for comparison of wind and bottom drifter data

		Area under mass transport/wind stress curve						
		30°	55°	75°	105°	115°	145°	170°
(n=9)	Total percent returned	-.210	.576	.783	.714	.688	.667	.651
	Total mean speed	-.265	-.302	-.245	-.193	-.179	-.081	.036
	Percent returned (Bay stations)	-.300	.505	.773	.750	.732	.720	.707
	Mean speed (Bay stations)	.156	-.566	-.751	-.676	-.652	-.620	-.586
Mar values deleted (n=8)	Total percent returned	-.375	.518	.838	.885	.880	.842	.789
	Total mean speed	-.538	-.606	-.329	-.105	-.063	.044	.147
	Percent returned (Bay stations)	-.438	.448	.804	.880	.881	.885	.811
	Mean speed (Bay stations)	.224	-.544	-.756	-.739	-.728	-.686	-.633
	Percent returned (offshore stations)	-.237	.604	.836	.823	.806	.749	.685
	Mean speed (offshore stations)	-.695	-.158	.290	.512	.539	.591	.636
Mar and Dec values deleted (n=7)	Total percent returned	-.065	.784	.846	.865	.866	.839	.786
	Total mean speed	-.743	-.579	-.386	-.257	-.229	-.130	-.011
	Percent returned (Bay stations)	.107	.846	.853	.835	.829	.785	.716
	Mean speed (Bay stations)	-.154	-.767	-.748	-.701	-.692	-.655	-.596
	Percent returned (offshore stations)	-.096	.760	.829	.848	.846	.817	.770
	Mean speed (offshore stations)	-.619	.038	.230	.345	.361	.406	.462

drifters toward the Bay mouth (oriented along 120°) from offshore and toward the head of the Bay from within the Bay. Somewhat puzzling, however, are the negative speed correlation coefficients for the Bay. One would expect to find high returns to correlate with higher speeds, as is the case for the offshore stations.

The response of an estuary to atmospheric forcing is not well understood. Wang and Elliott (1978) and Wang (1979a,b) have studied the response of Chesapeake Bay and found it to be complicated. For time scales less than four days, local forcing was dominant. Local longitudinal winds were found to force a seiche oscillation in the Bay. A northward (southward) wind corresponded to a barotropic, i.e., vertically coherent, flow of water into (out of) Chesapeake Bay. At longer time scales, the effect of fluctuations of coastal sea level, or non-local forcing, became important. The east-west wind was coherent with sea level both in the Chesapeake Bay and at the coast. It was suggested that a northward (southward) wind would result in Ekman transport offshore (onshore). However, the same northward (southward) wind would also tend to drive water upstream (downstream) in Chesapeake Bay, in opposition to the non-local forcing. In the case of an eastward (westward) wind, water would be driven offshore (onshore) but no opposing motion would occur within Chesapeake Bay. Thus, the east-west wind should be a more effective forcing agent in such a coupled coastal ocean-Bay response.

These papers also showed that the response to non-local forcing was barotropic throughout Chesapeake Bay. However, while the response to local wind forcing was barotropic in the lower Chesapeake Bay, it was not barotropic in the upper Bay. It was argued that, although the effect of local wind stress was dominant in the upper Chesapeake Bay, its effect decreased in the lower Bay. This may have been due to the decreased vertical density stratification of the lower Bay, allowing the effect of wind to extend deeper. In the lower Bay, then, the effect of sea level fluctuations and concurrent slopes would be dominant and the resultant pressure gradients would produce a barotropic flow. A drop (rise) in sea level at the mouth would then result in flow towards (away from) the mouth.

In comparing the present results with those of Wang and Elliott (1978) and Wang (1979a,b) for Chesapeake Bay, there are several differences in analysis of the wind data that should be noted. The values of mass transport/wind stress used in correlations for the present study were integrations over a discrete time period determined for each individual deployment date. In the Chesapeake Bay studies, power spectra were used to compare the continuous wind and sea level records during the two month and one year study periods. Plots of the magnitude coherence-squared between wind stress and other variables were examined and low-pass filtered time series of wind and other variables were compared. The wind, mean speed, and percentage returned data in this study were integral values rather than time series and this prevented comparable analysis. Nevertheless, the results of these Chesapeake Bay studies were used to interpret the data from the present study.

The portion of Delaware Bay considered in the present study is most similar to the lower Chesapeake Bay. Consequently, it can be argued that the response of Delaware Bay to both local and non-local atmospheric forcing should be barotropic. The period of the fundamental seiche mode in Delaware Bay is roughly 0.4 day compared to 2-3 days in Chesapeake Bay. Therefore, since the methods used could not resolve a time scale of less than one day, any purely local response in the form of a seiche mode was irrelevant. Therefore, only a coupled coastal ocean-Bay response was considered. The major axis of Delaware Bay is not parallel to the adjacent coast, in contrast to Chesapeake Bay. As a result, in the coupled response for Delaware Bay, there is no opposition between local and non-local forcing for any wind orientation. Thus, where alongshore wind produces opposing local and non-local responses in Chesapeake Bay, in Delaware Bay one expects that both offshore and alongshore winds would be important for both local and non-local atmospheric forcing. Winds toward 30° to 120° would result in flow out of the Bay, while winds toward 210° to 300° would result in flow into the Bay, if results for Chesapeake Bay were applicable.

The correlation coefficients between the different wind directions and surface returns (Table 10) agree to some extent with these deductions. An alongshore wind would be at 30° (aligned with the East coast in general) and an offshore wind would be 120°.

The components of wind computed at directions from 30° to 115° are moderately well correlated with surface drifter returns. Larger components of the wind in these directions would move more water offshore and out of the Bay faster, resulting in lower surface returns and slower speeds for those surface drifters that did reach shore. A large negative component of the wind, corresponding to computed winds in the opposite range of directions from 210° to 295°, should have produced opposite results, more returns and faster speeds. Consequently, the correlation coefficients should have been negative as well as large for these orientations, and this was the result.

Correlations between bottom returns and wind directions ranging from 75° to 170° (Table 11) were large and positive. Wind along these directions apparently drove bottom drifters landward. Considering only the Bay station correlations, the directions close to 170° (southward winds) agree with the Chesapeake Bay results cited. Ekman transport on the shelf should then raise sea level at the mouth of the Bay and force a barotropic flow up-Bay. For directions close to 75°, the Chesapeake Bay results are not applicable; these winds should have caused a drop in sea level at the Bay mouth, either by moving water offshore via Ekman transport or otherwise, resulting in a barotropic flow downstream and so, negative correlations within the Bay.

For the offshore stations, positive correlations with wind directions ranging from 75° to 170° can be explained by simple two layer shelf circulation. Surface water moved offshore, either by Ekman transport or otherwise, would require an onshore flow along the bottom resulting in positive correlation.

Apart from the speed correlations, no significant difference was found in the correlations for the Bay and shelf stations. Winds in roughly the first quadrant correlated negatively with surface returns while winds in roughly the second quadrant correlated positively with bottom returns. There was an overlap in wind directions with high correlations, from 75° to 115°, and they were of opposite sign for surface and bottom returns. This suggests a simple two layer flow satisfying continuity, both in the Bay and offshore, as originally postulated. Seaward surface currents caused by roughly offshore winds are compensated by landward bottom currents and vice versa, both in the Bay and in the coastal waters. This is substantiated by the percentages returned (Tables 6 and 7) for each deployment date. High (low) surface returns correspond to low (high) bottom returns.

Nevertheless, it is disconcerting that in the Bay the bottom speed and percentage correlations are consistently of opposite sign, while offshore they are not. The negative speed correlations between the Bay bottom returns and offshore winds are consistent, however, with the results cited for Chesapeake Bay. Offshore (onshore) winds would cause a drop (rise) in sea level at the Bay mouth causing a downstream (upstream) barotropic flow in the Bay and a reduction (increase) in the upstream flow along the bottom. This would result in negative bottom speed correlations. The positive speed correlations between the offshore winds and shelf station bottom returns suggests a two layer flow over the shelf. Offshore winds would drive surface water offshore, requiring a compensating return flow along the bottom. Thus, positive bottom speed correlations would result.

The integrated values of river flow are shown in Table 12. There was no significant correlation between river flow and the drifter returns (Table 13). For the river flow correlations, the same coefficient values as for surface and bottom wind correlations are necessary

Table 12. Integrated values of volume of river flow for surface and bottom median times on each release date

Release date	Integrated volume flow ($m^3\ s^{-1}$)	
	Surface	Bottom
19 April 1979	11479	14044
16 May 1979	1447	23743
17 May 1979	956	11881
31 July 1979	1427	9736
28 September 1979	981	16842
15 November 1979	4307	16700
29 November 1979	516	14621
13 December 1979	1179	13517
7 March 1980	1898	6901

Table 13. Correlation coefficients for comparisons of river and drifter data

		Surface	Bottom
(n=9)	Total percent returned	-.205	.185
	Total mean speed	-.240	.395
	Percent returned (Bay stations)	-.280	.075
	Mean speed (Bay stations)	-.306	.180
(n=8) Mar values deleted	Total percent returned	-.200	-.067
	Total mean speed	-.271	.003
	Percent returned (Bay stations)	-.289	-.151
	Mean speed (Bay stations)	-.334	.280
	Percent returned (offshore stations)	-.159	.032
	Mean speed (offshore stations)	----	-.067
(n=7) Mar and Dec values deleted	Total percent returned	-.273	-.006
	Total mean speed	-.299	.003
	Percent returned (Bay stations)	-.304	-.079
	Mean speed (Bay stations)	-.343	.248
	Percent returned (offshore stations)	-.244	.068
	Mean speed (offshore stations)	-.330*	-.001

*28 Sept and 29 Nov data also deleted (n=5) for the 95% significance level. However, there was only weak variation in river flow, unlike most years, and this would tend to result in low correlation coefficients.

CONCLUSIONS

The Lagrangian mean residual circulation of Delaware Bay and the adjacent shelf has been documented in detail. Results show classical estuarine residual circulation with both seaward surface and landward bottom currents present. The seaward surface residual flow in the Bay is directed toward the Delaware shore, consistent with Coriolis effects, while the bottom residual flow diverges along the major axis of the Bay towards both shores. The deepest channels of the Bay roughly correspond with the major axis; apparently, bottom water travels upstream in the deep channels and then spreads laterally onto the adjacent shallower areas on both sides.

The estuarine circulation extends at least 40 km onto the adjacent shelf, the extent of the study area. This extension onto the shelf supports work by Beardsley and Hart (1978) who modeled the influence of an estuary on shelf circulation, treating the estuary as a volume source in the upper layer and as a volume sink of similar magnitude in the lower layer. Surface residual motion on the shelf is generally toward the south, although it can reverse and flow northward, while the bottom currents converge on the Bay mouth.

The speed of the residual currents on the shelf is consistently faster than that in the Bay. However, over the entire study area, the surface circulation is an order of magnitude faster than the bottom circulation. Both surface and bottom current speeds in the Bay are slower than those observed in other estuaries. The currents on the shelf are also slower than previously reported for the Middle Atlantic Bight.

Wind and river conditions during the study period were not characteristic of their long-term means. Consequently, it was not practical to present mean residual circulation patterns corresponding with seasonal periods in wind and river runoff following the method of Paskausky and Murphy (1976). Temporal variation in the circulation pattern does occur, although the surface circulation is more variable with time than is the bottom, both in speed and direction. In general, the return percentages suggest that offshore surface flow and onshore bottom flow intensified in the second half of the calendar year.

River flow showed little correlation with residual circulation, but other years, in which runoff changes were more dramatic, might have shown a greater correlation. The wind record explained much of the variance in drifter movement and correlations between wind and drifter data were unexpectedly similar for the Bay and the shelf. In general, offshore winds drove surface water downstream/offshore and bottom water upstream/onshore in a simple two layer flow. This pattern reversed for onshore wind. Enough of the variance in drifter movements is left unexplained, however, that other forcing should be considered. In particular, the estimated tidally rectified current is of the same order of magnitude as the observed surface residual velocities and, no doubt, has a large impact on the residual circulation. In addition, it varies strongly at periods of several weeks to months, depending on which tidal components are dominant (Ianniello, 1977).

The residual circulation found should have a strong effect on the movement of blue crab larvae. Because the surface currents are an order of magnitude faster than the bottom currents, larvae would have to spend time in bottom versus surface water in a ratio of 10 to 1 in order to return or remain in Delaware Bay. This could be accomplished with daily vertical migrations or perhaps by a single descent. This, however, would have to occur before the distance offshore was so great that larvae could not be returned via bottom residual currents within the 40 day larval period (Costlow and Bookhout,1959).

An exchange of larvae with other estuaries, particularly Chesapeake Bay, is likely. The July 31 release demonstrates that surface transport from Delaware Bay to Chesapeake Bay is possible in approximately 26 days. In addition, results from this study and those of Bumpus (1973) show that south of the Maryland-Delaware state line the bottom transport is towards the south. Bumpus (1973) and Norcross and Stanley (1967) also showed that bottom transport south of 38°30'N moves toward the mouth of Chesapeake Bay; Bumpus estimated speeds of about 1-2 km/day. As a result, larvae could also travel in a surface layer to bottom layer sequence and arrive at the mouth of Chesapeake Bay.

Estuarine circulation in Delaware Bay clearly extends onto the adjacent shelf. This extension has been shown to also exist for Chesapeake Bay (Norcross and Stanley, 1967), suggesting that the extension of estuarine circulation onto the shelf could be expected for all estuaries similar in physical description to Delaware Bay and Chesapeake Bay. A valuable objective for other studies, thus, would be to document this extension in other estuarine-shelf systems. Beardsley and Hart (1978) modeled the influence of an estuary on shelf circulation. Wang and Elliott (1978) and Wang (1979a,b) demonstrated the influence of the shelf on estuarine circulation. Another future goal, then, would be to use more refined methods, such as current meters and tracked drogues, to quantify the exchange of water between the estuary and the shelf.

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