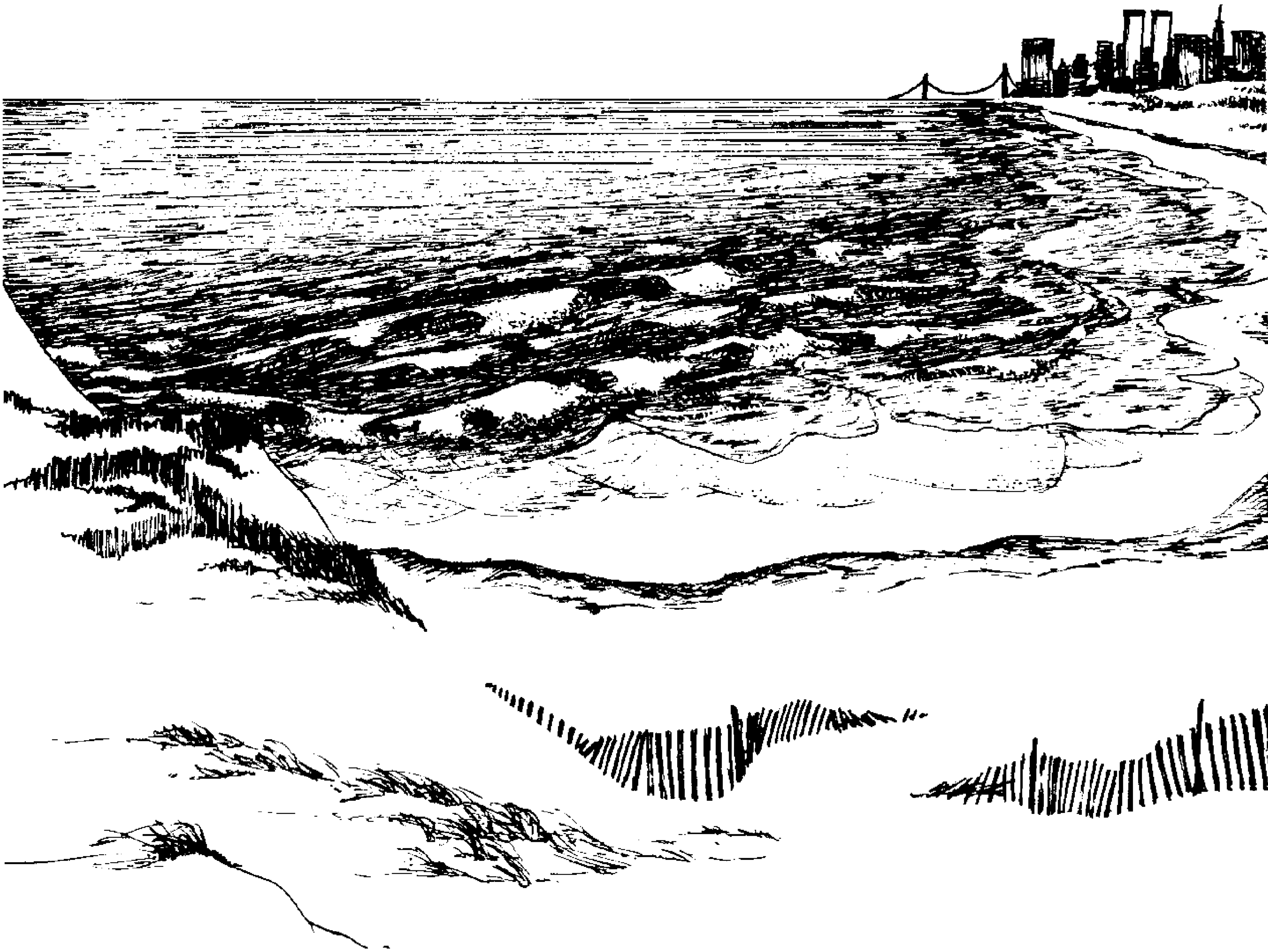
Circulation

Donald V. Hansen



MESA NEW YORK BIGHT ATLAS MONOGRAPH 3

The offshore water in the bend of the Atlantic coastline from Long Island on one side to New Jersey on the other is known as New York Bight. This 15,000 square miles of the Atlantic coastal ocean reaches seaward to the edge of the continental shelf, 80 to 120 miles offshore. It's the front doorstep of New York City, one of the world's most intensively used coastal areas—for recreation, shipping, fishing and shellfishing, and for dumping sewage sludge, construction rubble, and industrial wastes. Its potential is being closely eyed for resources like sand and gravel—and oil and gas.

This is one of a series of technical monographs on the Bight, summarizing what is known and identifying what is unknown. Those making critical management decisions affecting the Bight region are acutely aware that they need more data than are now available on the complex interplay among processes in the Bight, and about the human impact on those processes. The monographs provide a jumping-off place for further research.

The series is a cooperative effort between the National Oceanic and Atmospheric Administration (NOAA) and the New York Sea Grant Institute. NOAA's Marine EcoSystems Analysis (MESA) program is responsible for identifying and measuring the impact of man on the marine environment and its resources. The Sea Grant Institute (of State University of New York and Cornell University, and an affiliate of NOAA's Sea Grant program) conducts a variety of research and educational activities on the sea and Great Lakes. Together, Sea Grant and MESA are preparing an atlas of New York Bight that will supply urgently needed environmental information to policy-makers, industries, educational institutions, and to interested people.

ATLAS MONOGRAPH 3 describes the major features of circulation in New York Bight. All features are marked primarily by strong but variable wind-driven currents on a day-to-day basis, and may be drastically altered for periods of several weeks. The major feature of Bight circulation is a relatively slow flow to the southwest over most of the outer continental shelf with some indication of a clockwise eddy in the inner Bight. Knowledge gained from the rapid increase in oceanic observations during the last decade has revealed large temporal variability in ocean currents, says Hansen, but the number of observations remains insufficient for even a statistical description of variability in most regions.

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MESA NEW YORK BIGHT ATLAS MONOGRAPH 3

New York Sea Grant Institute
Albany, New York
October 1977

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Acknowledgments

New results that make this monograph worth doing in light of the excellent summaries of earlier work were supported primarily by the MESA New York Bight project. Special thanks are due to Dennis Mayer, to the officers and men of the NOAA Ship *Ferrel* and *Kelez*, and to the Oceanographic Division of the Oceanographic Surveys Branch, Office of Marine Surveys and Maps, National Ocean Survey, all of whom contributed in vital ways to the collection, processing, and assembly of the current meter data.

Manuscript accepted November 1976.

Abstract

Information sources on currents in New York Bight date back 65 years. Only during the last 15 years, however, has it been possible to collect sufficiently accurate data to enable quantitative statements. These more recent results indicate that the standard deviation of the currents in New York Bight, as in other oceanic areas, is several times greater than the mean flow. This temporal variation is due primarily to tides and wind. Because the wind effects are random in time, various observations are not readily combined to provide a composite description.

Data from systematic observation projects have revealed some major features of circulation in the Bight, but do not yet allow description of many details. The major feature of Bight circulation is a relatively slow flow to the southwest over most of the outer continental shelf with some indication of a clockwise eddy in the inner Bight. There is the expected exchange circulation, characterized by seaward flow of estuarine waters near the surface and landward flow of deeper waters between the Hudson/Raritan estuary and the offshore waters, and there is some indication that the landward flow may extend as far as 64 km (40 mi) offshore in the Hudson Shelf Valley. All of these features are masked primarily by stronger but variable wind-driven currents on a day-to-day basis, and may be drastically altered for periods of several weeks. This is especially so during summer in conjunction with sustained periods of little rainfall or strong southerly winds.

Introduction

Waters over the continental shelf, like the open ocean, are never still. In their movements from place to place they carry plankton or larvae, varying concentrations of salt or river water, pollutants, or they may erode and transport bottom sediments. For these and similar reasons knowledge of currents in New York Bight is frequently sought.

The reader may expect a monograph on ocean currents to present maps showing current speed and direction at various depths, perhaps with seasonal variations. This can be done only in part. Knowledge gained from the rapid increase in oceanic observations during the last decade has revealed large temporal variability in ocean currents, but the number of observations remains insufficient for even a statistical description of variability in most regions.

Ocean currents have many points of similarity to winds in the atmosphere. Often they are a direct response to wind forces on the sea surface. But the day-to-day variability of wind is such a common experience that statistical patterns, such as the prevailing westerly winds of the middle latitudes, are easily understood as the average over a large number of weather "events" (Lettau, Brower, and Quayle 1976). Because few persons have experience relating to ocean currents, this monograph attempts to provide an appreciation for the variability of currents as well as much of the general picture available for the Bight.

Fundamental to understanding any description of ocean currents is some knowledge of how such currents are measured. Such measurements are not so easy as might be imagined because there are few reference points at sea. Deep ocean currents can be measured directly and indirectly. One indirect method, the *dynamic* or *geostrophic calculation*, is based upon measurements of salinity and temperature patterns associated with the current rather than of the current itself, but it provides only current differences between vertical levels. Although it has been used extensively since the turn of the century for estimating currents in deep water, it is not applicable to the comparatively shallow depths over the continental shelf in the Bight. Inference about the currents drawn from observation of materials carried by them is another indirect method.

Direct methods of providing unambiguous measurements of currents over continental shelves are either *Lagrangian,* which record displacements or trajectories of marks or particles (ideally tagged water parcels) from some initial point or points, or *Eulerian,* which record the movement of fluid past points fixed in space. Since about 1960, sophisticated but expensive methods have been developed for making these measurements, but each has had more primitive implementation as well. This monograph attempts to summarize the knowledge gained from the diverse ways of measuring currents off New York during the last 65 years, emphasizing results obtained since about 1970 and placing earlier work in perspective. Excellent presentations of early work include Haight (1942), pilot charts of the North Atlantic Ocean, Oceanographic Atlas of the North Atlantic Ocean, Bumpus and Lauzier (1965), and Bumpus (1973).

Methods of Observing and Representing Ocean Current

Indirect Methods

The dynamic method of estimating ocean currents is based upon an approximate balance between the tendency for the rotation of the earth to deflect currents to the right in the Northern Hemisphere and pressure forces. The circulation of the atmosphere about "highs" and "lows" is a good analog. The pressure forces from which the currents are estimated can in turn be calculated with sufficient accuracy from careful measurements of temperature and salinity in the ocean. This method has been used for the deep ocean for over 70 years, but has had little quantitative application in the shallower waters over the continental shelf because the simple relationship used for the deep ocean is invalid in shallow nearshore regions, and methodology for implementing more complex relationships has not been available.

Kinematic methods use distributions of distinctive properties in coastal waters, such as dilution of ocean salinity by major rivers, as indicators of water movement. Such considerations led Iselin (1939, 1955) to define the "rule of coastal circulation": the average flow is parallel to the coast, with land to the right of an observer facing downstream. This rule for the long-term average currents in the Middle Atlantic Bight has stood the test of time, but the underlying reasons for it are still not entirely understood and do not apply for shorter times.

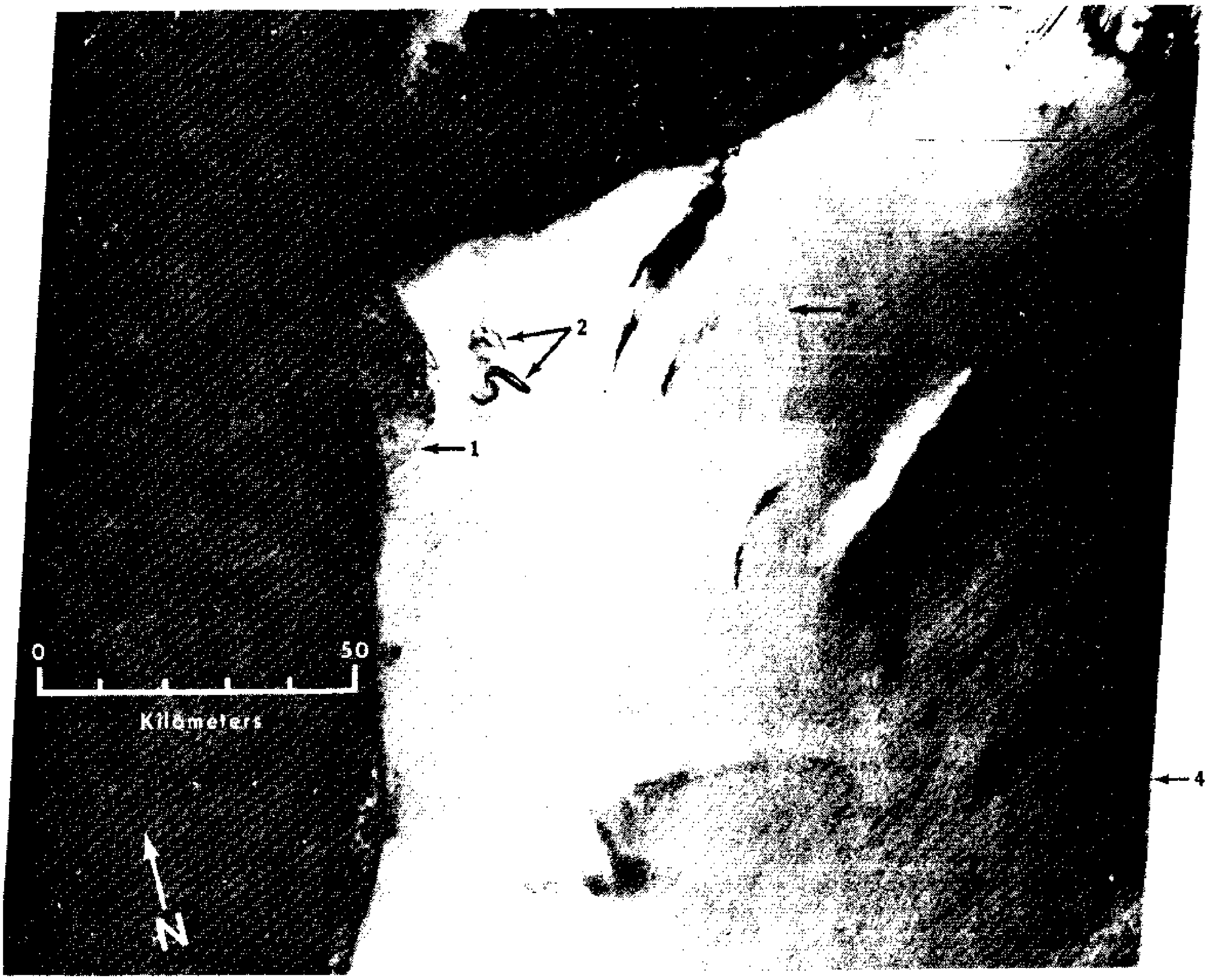
A modern application of this method is satellite imagery. In Figure 1, for example, turbid water from the Hudson/Raritan estuary can be seen southward along the New Jersey shore—a frequent but not universal pattern in such imagery. From satellite image observations, we can judge the direction of flow but can speak only generally about its speed.

Direct Methods

Lagrangian measurements best satisfy one's intuitive notion about currents: water traverses from point to point in the ocean. Nearly all present knowledge about the distribution of currents over the earth's surface has been obtained by a single Lagrangian method—from navigation data in ships' logs—in which the difference between estimated travel through the water and observed travel over the earth can be attributed to ocean currents, which set the ship off its expected courses and speed. The effects of errors in this method can be removed only by averaging over a very large number of determinations, which limits application of this method to measurements representative of large spatial scales and slowly varying temporal scales and confines it to surface currents.

Systematic derivation of this type of information began in the 1840s and was the major source of knowledge about ocean surface currents for about 120 years. Most popular atlases still derive their information from this source. Information on the pilot charts and in Publication No. 700 of the US Naval Oceanographic Office (US Navy 1965) is derived from such data and indicates flow of surface waters off New York to the southwest on the order of 25 cm/sec (0.5 knot).

Radio navigation and relocation technology made it feasible to instrument small buoys that could be released to drift freely with the ocean water and be followed or periodically relocated by ship or aircraft. These observations provide information at fine temporal and spatial resolution but their application is limited by the effects of winds on the buoys and the expense of relocating. The small number of these observations made on the Middle Atlantic Bight continental shelf tends to confirm the results of ship drift generally, but large and real differences can be found among individual observations. Howe (1962) showed surface flow off New Jersey to be generally to the southwest at speeds up to 20 cm/sec (0.4 knot), but occasional flow to the northeast was just as fast or faster.



Source: Charnell and Maul 1973

Figure 1. Satellite image of New York Bight (ERTS-1 satellite) 16 August 1972. Turbid discharge plume (1) of Hudson River can be seen near New Jersey shoreline. Distinct wavy line (2) is discolored water from waste acid disposal; less distinct lines to north may be discolored water from earlier disposal operations, perhaps of sewage sludge. Some of the relatively sharp lines (3) are naturally occurring water mass boundaries unrelated to waste disposal. Surface slicks probably due to internal waves are seen at lower right (4).

A second, long-standing Lagrangian technique for obtaining current data economically and in large numbers is drift bottles. Bottles containing information cards to be returned by the finder, usually for a small reward, and ballasted with sand to barely float are dropped at sea and allowed to drift, perhaps to shore where they may be found. Modern refinements of this technique include plastic cards or envelopes and seabed drifters (Figure 2), which are carried along by currents just above the ocean bottom. Only a small fraction of the drift devices deployed are ever recovered from most regions, but they can be economically produced and deployed in large numbers.

Drifting devices furnish quasi-Lagrangian current data because at best only beginning and end points, not entire trajectories, are obtained, and usually the length of time that a device lay on the shore before being found can only be estimated. Also, this method produces relatively little information from offshore regions because drift devices dropped farther from the beaches tend to be recovered less frequently. Nonetheless, this method has provided most of the best information about currents on the US Atlantic continental shelf prior to 1970. Current patterns and the frequent traffic on Bight beaches bring returns of around 30% for bottom drifters and monthly returns from 0 to 60% for surface drifters dropped within 32 km (20 mi) of shore (Bumpus 1973; Charnell and Hansen 1974; Hardy, Baylor, and Moskowitz 1977).

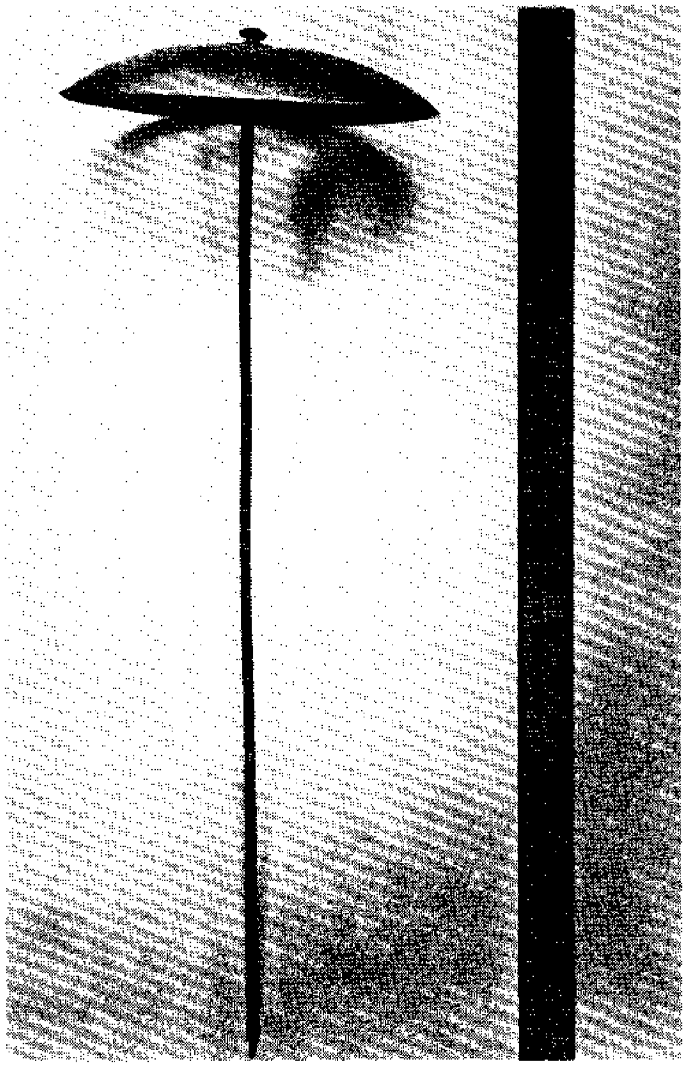


Figure 2. Seabed drifter (Courtesy of NOAA's Atlantic Oceanographic and Meteorological Laboratories)

Results from over 28,000 returned drifters along the coast from Maine to Florida between 1960 and 1970 have been published by Bumpus and Lauzier (1965) and Bumpus (1973). The number of winter recoveries of surface drifters is too small to provide much information on circulation during this season. The few winter returns may be attributed to a combination of net offshore flow of surface water and reduced beach traffic. During other seasons, however, returns are more numerous. The inferred flow over the continental shelf agrees in direction with the southwesterly flow inferred from ship drift but is somewhat weaker, typically 18 cm/sec (10 mi/day) or less. Near large estuaries, results tend to be confused or ambiguous.

Seabed drifters are returned more consistently in all seasons and suggest only weak seasonal features. Indicated flows are on the order of 0.9 to 1.3 cm/sec (0.5 to 0.7 mi/day), with relatively strong onshore components and spatially variable alongshore components. Bumpus and Lauzier (1965) inferred an offshore bottom drift over the outer shelf and an onshore drift over the inner one-half to three-fourths of the shelf. This inference is made ambiguous by the fact that the data are biased by the selective return of drifters cast up on beaches. Drifters that move offshore or otherwise escape the region are usually lost, though some are recovered at sea by fishing vessels. Major estuaries, such as the Hudson/Raritan, attract bottom drifters but seldom surface drifters. Estuarine circulation, in which brackish and riverine waters flow seaward near the surface and more saline seawaters enter the estuary near the bottom, can account for this difference.

Eulerian Methods. Serial observations of currents at fixed sites are defined as Eulerian. Prior to the advent of reliable moored current meter technology, the only extensive source of Eulerian current data was that obtained from some 40 lightships stationed along the East Coast from Maine to Florida. Currents typically were measured hourly with a drift pole, the speed and direction of drift away from the anchored ship was estimated from a line attached to the pole. Results of more than 350,000 such observations taken between 1911 and 1939 are given by Haight (1942) for use by mariners and others. Because many of the observation sites, especially those with the most extensive records, are strongly influenced by tidal inlets and other local effects, the results have only local application so far as average currents are concerned.

During the last five years it has become technologically and economically feasible to make current measurements over the shelf with current meters (Figure 3) in the ocean. These instruments collect much more detailed, simultaneous information on currents at discrete points than was previously possible, but the cost of instrumentation and logistics for data collection limits their use to a small number of selected sites where important problems or concepts need to be studied.

Also, present current meter designs are less than perfect. A principal problem is measurement contamination by high frequency effects such as surface wind waves. At best such effects make the flow record erratic or "noisy," and at worst the apparent flow tends to be exaggerated by high frequency motions. The nearer to the surface a measurement is attempted, the more severe the problem. Consequently few modern measurements are very near the surface.

Extensive use is being made of this techology in the MESA New York Bight project. Results from some measurements made during spring and summer 1974 at a site sufficiently near the Long Island shore where flow was predominantly east or west are shown in Figures 4 and 5. Flow varied considerably, alternating between east and west over a few days. The data variability shown in Figure 4 has in fact been reduced by low-pass filtering of the original measurements. Such a filter suppresses events in the flow, such as tidal currents that occur within a day, and spreads sharp transitions of flow over adjacent time intervals. The resulting data show that a random measurement of flow at this location would probably have a speed of 25 to 50 cm/sec (0.5 to 1.0 knot) and might be either to the east or to the west.

Another method of presenting current meter measurements is with a progressive vector diagram

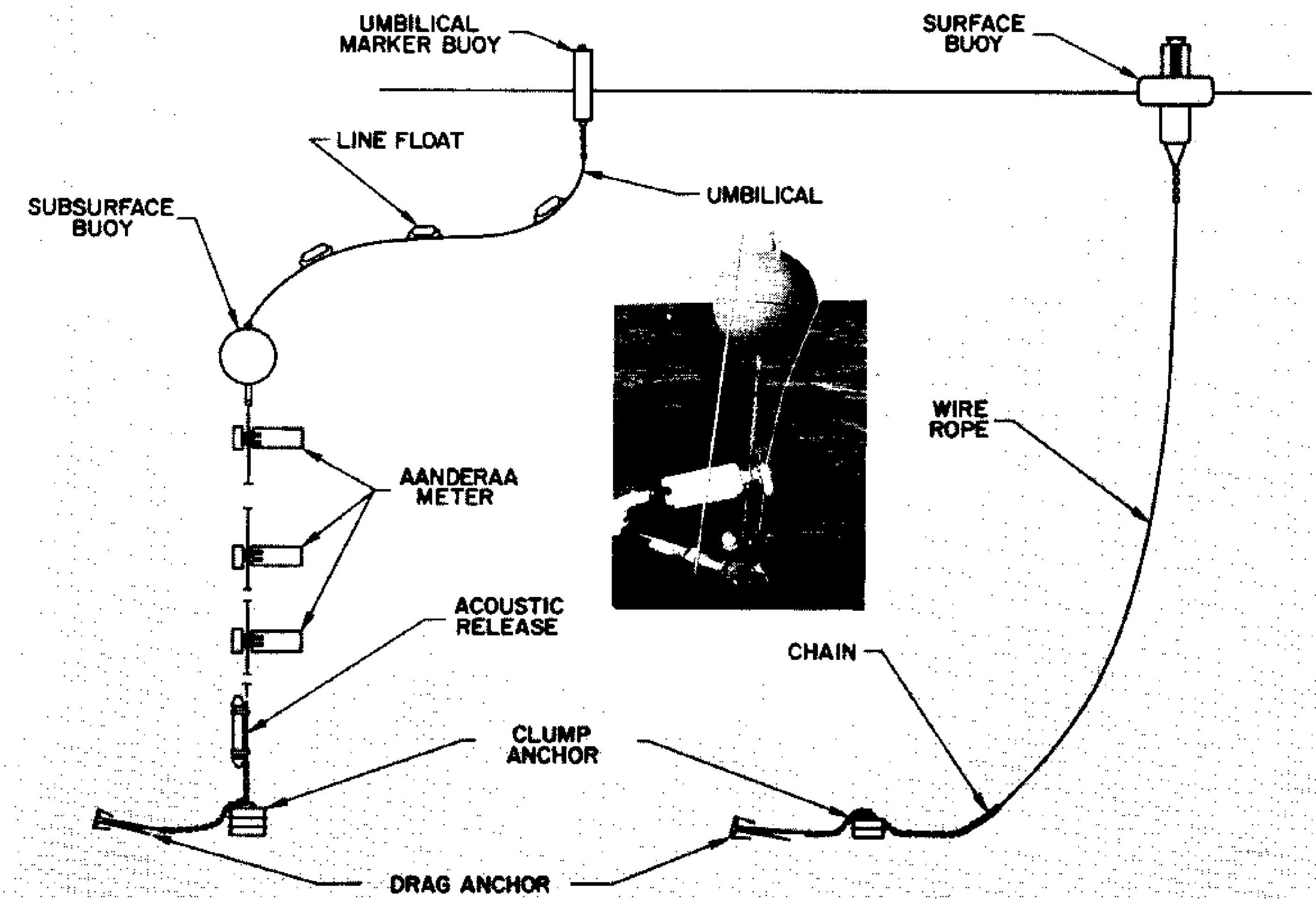
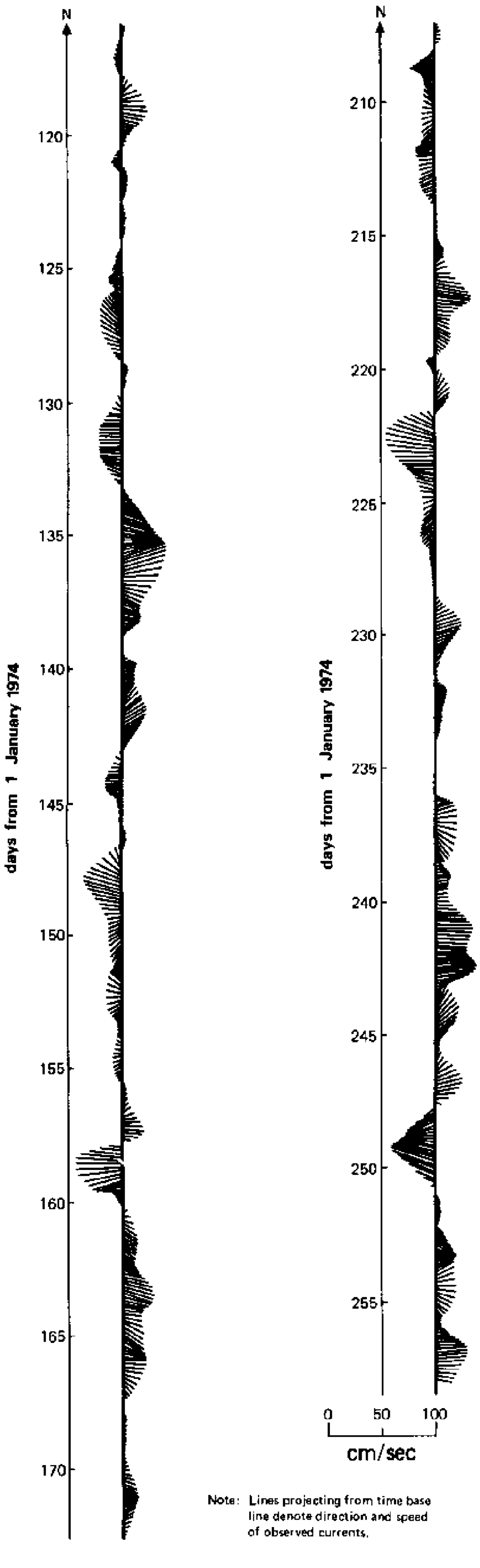


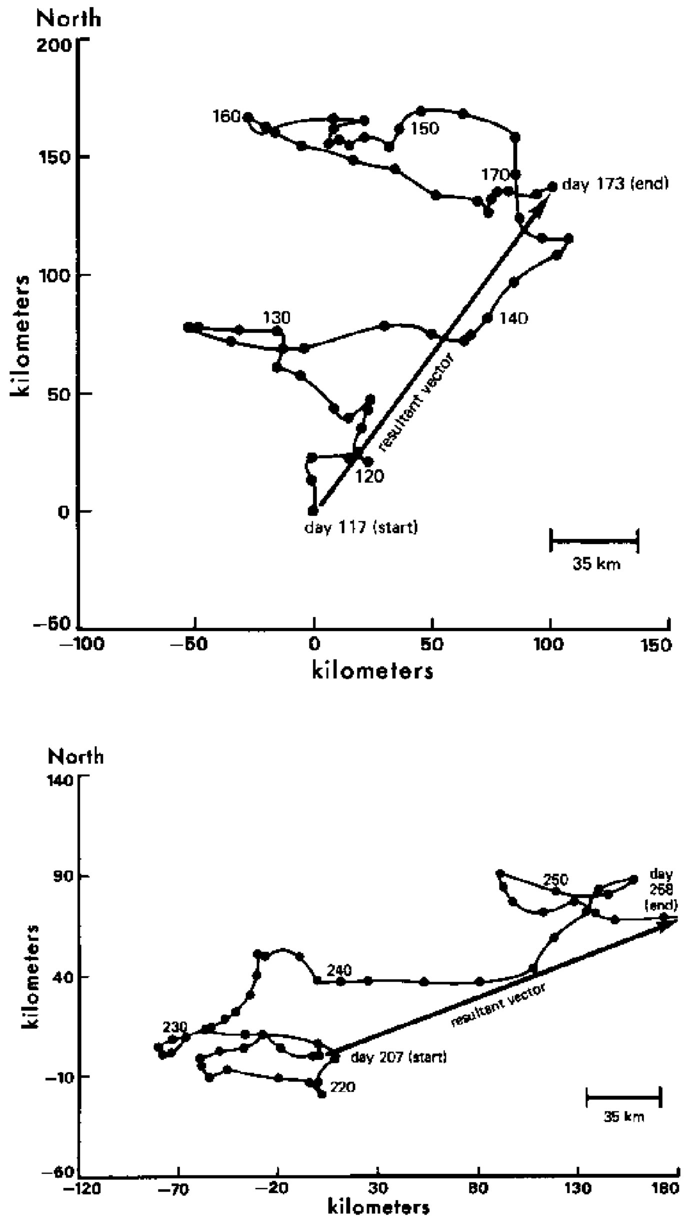
Figure 3. Modern current meters (Courtesy of NOAA's Atlantic Oceanographic and Meterological Laboratories)

(Figure 5)—a graphical addition of a series of current measurements from a particular location. If water movements were horizontally uniform, the resulting pattern would be the same as that of the trajectory of every parcel of water in the region. Of course the currents are not uniform, but the method nonetheless is useful for providing a graphic description of the flow. Principally, it visually enhances the most slowly



Source: NOAA's Atlantic Oceanographic and Meteorological Labs

Figure 4. Observed currents south of Long Island, spring and summer 1974 (see Map 1, site 4)



Note: dots = one day time interval

Source: NOAA's Atlantic Oceanographic and Meterological Labs

Figure 5. Progressive vector diagram of current observations in Figure 4

varying aspects of the current. A straight line connecting points for any two times on the resulting curve represents the direction and speed of the average flow past the measurement point during the corresponding time interval. The direction of the average velocity is the same as that of the displacement, and the average speed of the flow is the displacement divided by the corresponding time interval.

The average flow past the site off Long Island, shown in Figure 5, was to the northeast at 3.3 cm/sec (0.06 knot), or perhaps no net flow at all. The time period over which measurements are obtained is important to the particular problem. For example, construction activities are often concerned with the maximum currents over periods, however brief, while the residual flow over several weeks is usually of importance in addressing chemical pollution problems.

Because only a partial data base is presently available for New York Bight, or for the Middle Atlantic Bight generally, conclusions regarding average conditions must be considered tentative, subject to improvement as additional observations become available. Today's urgent social and environmental concerns are spurring an unprecedented rate in current observations over the continental shelf, especially in the Middle Atlantic Bight. By 1980, a much more complete description should be possible. The remainder of this monograph is devoted to making such statements about circulation in New York Bight as presently seem reasonable.

Average Currents

Open Shelf

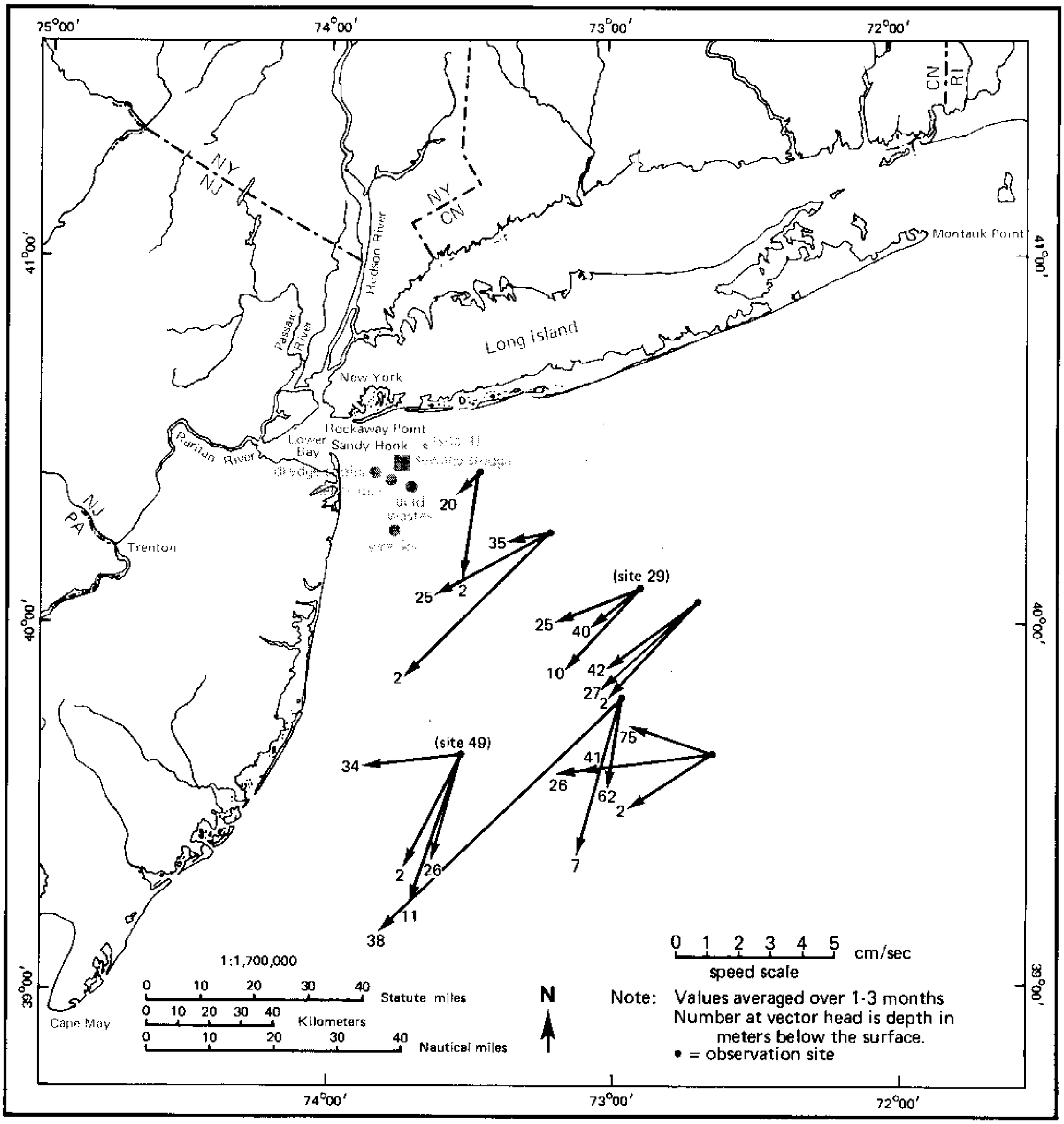
The most complete summary of circulation in New York Bight, and on the US continental shelf, is that of Bumpus (1973). His review of results from the pre current meter era is most appropriate for drawing conclusions about the relatively large-scale, slowly varying aspects of circulation. Although these have certain points of ambiguity–arising from the fact that only start and end points of the drifter trajectories, often separated by considerable distance, are known, and that the interpretation is biased very strongly by those drifters that happen to move shoreward and thereby are recovered–the inferences drawn by Bumpus tend to be corroborated in newer data.

Beardsley, Boicourt, and Hansen (1976) summarized some recent observations of circulation over the Middle Atlantic Bight. Map 1 shows the part of their data most appropriate to the Bight, but typical of much of the Middle Atlantic Bight. The flow is toward the southwest, generally following the shoreline; this agrees with earlier inferences. The speed of the flow, however, is significantly below estimates of the (surface) flow. The average speed of flow along this section of the continental shelf is approximately 3.7 cm/sec (0.07 knot), which is sufficient to move the water volume of the entire Middle Atlantic Bight between Cape Cod and Cape Hatteras past New York in about nine months. These rates are not well established, however. There is a lot of year-to-year variation. During the fish kill episode in summer 1976 much weaker average currents and reversal of the average currents were observed off New Jersey.

Current measurements reported by Webster (1969) and Luyten (1977) show that southwestward flow parallel to depth contours and having speeds on the order of 5 cm/sec (0.1 knot) 200 m (656 ft) above the bottom occurs on the average in depths between 1,000 and 4,000 m (3,280 and 12,120 ft) on the continental slope along 70°W. These observations, taken with those reported by Beardsley and his associates (1976), suggest that southwestward mean flow is characteristic of much of the shelf and slope region out to the deep ocean off the Middle Atlantic Bight.

When current meters are attached at several depths in a single mooring on the open shelf, they typically show a gradient of speed, with slower average flow near the bottom and faster average speeds higher in the water column. Speeds recorded nearest the surface are in fact in good agreement with those inferred by Bumpus (1973), but in the newer data these surface speeds have been observed considerably farther seaward. Another point of agreement with Bumpus' inferences is the recurrent finding that flow veers shoreward near the bottom. This shore-

Map 1. Distribution of averaged currents, winter and spring 1975



Source: NOAA's Atlantic Oceanographic and Meteorological Labs

Lambert Conformal Conic Projection

ward bottom flow is likely to be important to the movement of eggs and larvae of marine organisms and with regard to waste disposal practices. The relatively high and constant rate of return of seabed drifters noted by Charnell and Hansen (1974) can probably be attributed to this shoreward bottom flow. Bumpus' inference of offshore bottom flow over the outer shelf is not corroborated, however.

Hudson Shelf Valley

Hudson Shelf Valley is a particularly fine example of shelf valley morphology. Water depth in the shelf valley is nearly double that of the nearby open shelf over a considerable section across the Bight. The valley sides constrain flow to more or less follow the valley axis. Conflicting conclusions have been drawn concerning the direction of the average flow in the valley (Charnell and Hansen 1974; Lavelle, Keller, and Clarke 1975), but those conclusions are based on a short series of observations. Recent long records collected by the MESA New York Bight project indicate that the average flow within the valley is in fact shoreward. Average shoreward speeds as fast as 5 cm/sec (0.1 knot) have been observed over periods as long as a month. Apparently the general shoreward flow near bottom has its greatest manifestation in the shelf valley. The mechanism for this shoreward flow is not yet clear, and like the flow elsewhere, it is heavily masked by temporally varying currents. Some possible causes of this shoreward flow are pressure force related to the distribution of temperature and salinity, such as occurs in estuaries, or as an indirect effect of surface wind.

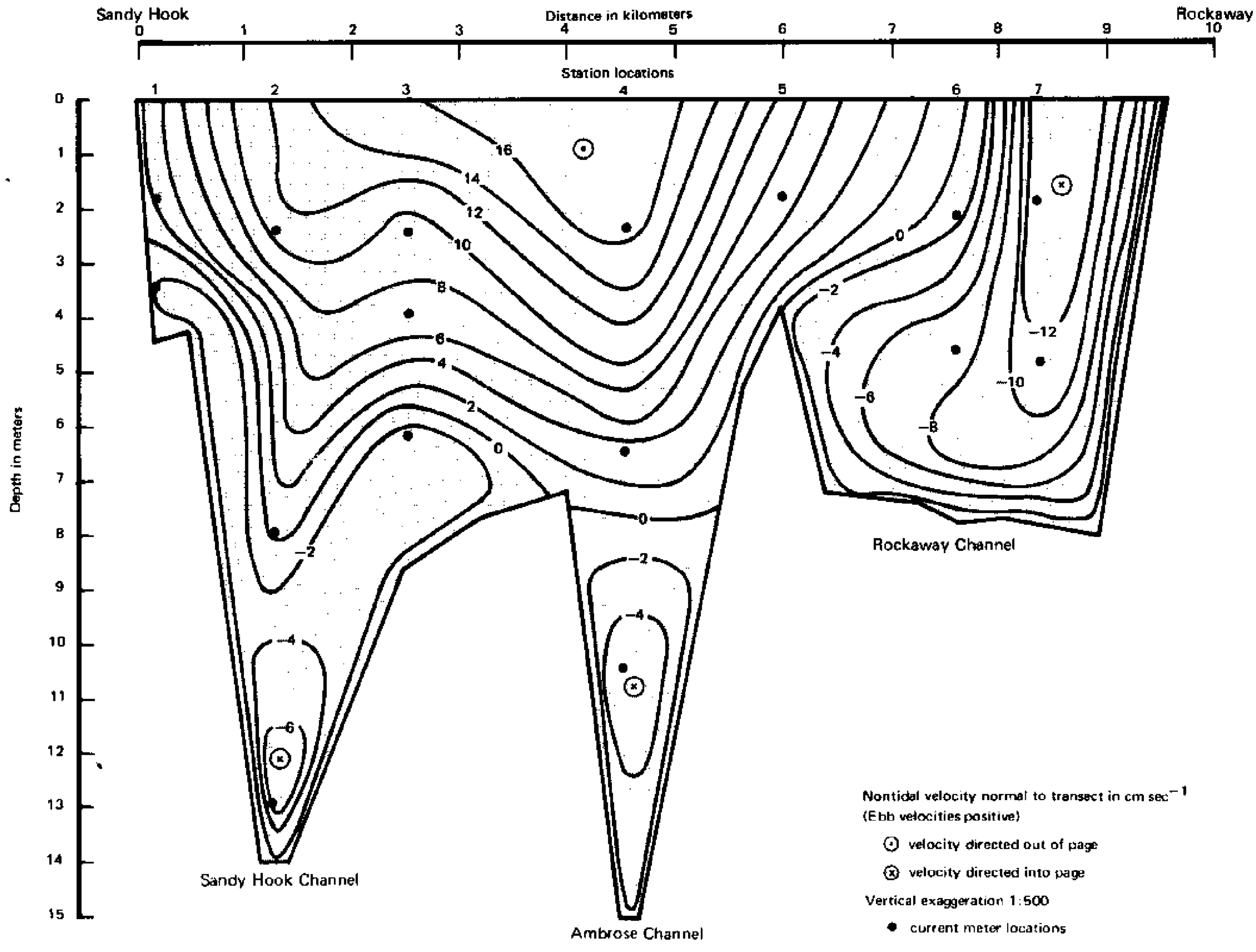
Hudson/Raritan Estuary

Directly inshore from Hudson Shelf Valley is the entrance to the Hudson/Raritan estuary. Estuarine circulation has been described for the Hudson estuary by Stewart (1958), Charnell and Hansen (1974), and Kao (1975).

The transect between Sandy Hook and Rockaway Point is sufficiently wide and bathymetrically complicated that a simple description is hardly adequate. Figure 6 shows the distribution of inward and outward flow with depth and lateral position observed and averaged over several tidal cycles. Seaward flow occurs near the surface and along the south side of the transect (left side of Figure 6), and the inflow occurs mainly in the navigation channels and along the northern side of the transect (right side of Figure 6). Details of this pattern vary almost daily in response to local winds and river level, but the basic pattern can be expected to persist in this and similar estuaries such as Delaware Bay.

Inner Bight

Since about 1965, concern for the effects and ultimate fate of waste materials dumped in the Bight has engendered increasing interest in details of circulation in the inner Bight. Some evidence of a semi-permanent anti-cyclone (clockwise) eddy motion in the inner Bight exists (Charnell and Hansen 1974). Figure 5 shows currents in the northern limb of this eddy; the flow at a comparable depth and distance offshore from New Jersey was to the



Source: From Kao 1975

Figure 6. Current velocities averaged over several tidal cycles along Sandy Hook-Rockaway Point transect

northwest during this time; farther offshore the flow was almost certainly to the southwest. As has already been seen, however, the flow in the Bight has a large temporal variability. In addition, it is not unusual in this area to find the direction of the average flow to change by 90° to 180° with depth. Such great variability is associated with competing influences of tidal currents, estuarine and shelf valley circulation, and local wind effects. Further work is required before the complicated motion in the inner Bight can be adequately described. Possibly, water movements in the inner Bight are most usefully regarded as a dispersion process rather than an advective process. That is, the currents may be so random that only their statistical effects, not their organized patterns, can be used for management of activities.

Temporal Variation Mechanisms

Recurrent in the foregoing sections has been the difficulty of separating organized features of the flow from a large temporal variability. Temporal variability is in fact a principal attribute of circulation. The principal contributions to the temporal variability are surface winds and tides.

Wind-Driven Currents

Surface winds are probably the most important source of current activity over most of the open continental shelf, and the one most difficult to adequately describe and explain. Haight (1942) stated that the average of all the lightship data shows the speed of the surface current as 1.4% of the wind speed, directed 14° to the right of the wind direction. This veering to the right is due to the Coriolis effect: in the northern hemisphere the earth's rotation subjects moving parcels to an apparent force, turning them to the right. Wind currents around most of the lightships individually are sufficiently obscured by residual flows, tidal inlet, and other coastal effects as to cause large local differences from their overall average pattern.

Only with moored current meters has it become possible to gain real insight into the nature of wind-driven currents. Figure 7 shows an example of the visual similarity between winds and currents in the Bight during the winter of 1974. These current data were collected at a location not far from that of Figures 4 and 5, and exhibit the same kind of temporal variability. The relationship between current and local winds is particularly clear in Figure 7, but winds at considerable distance can also produce strong currents. The familiar "northeaster," such as that on 1-3 December 1974, is particularly effective in exciting currents on the shelf. A relatively simple conceptual model for this response to winds has been suggested by Beardsley and Butman (1974) and has been supported by other observations (Beardsley et al 1976).

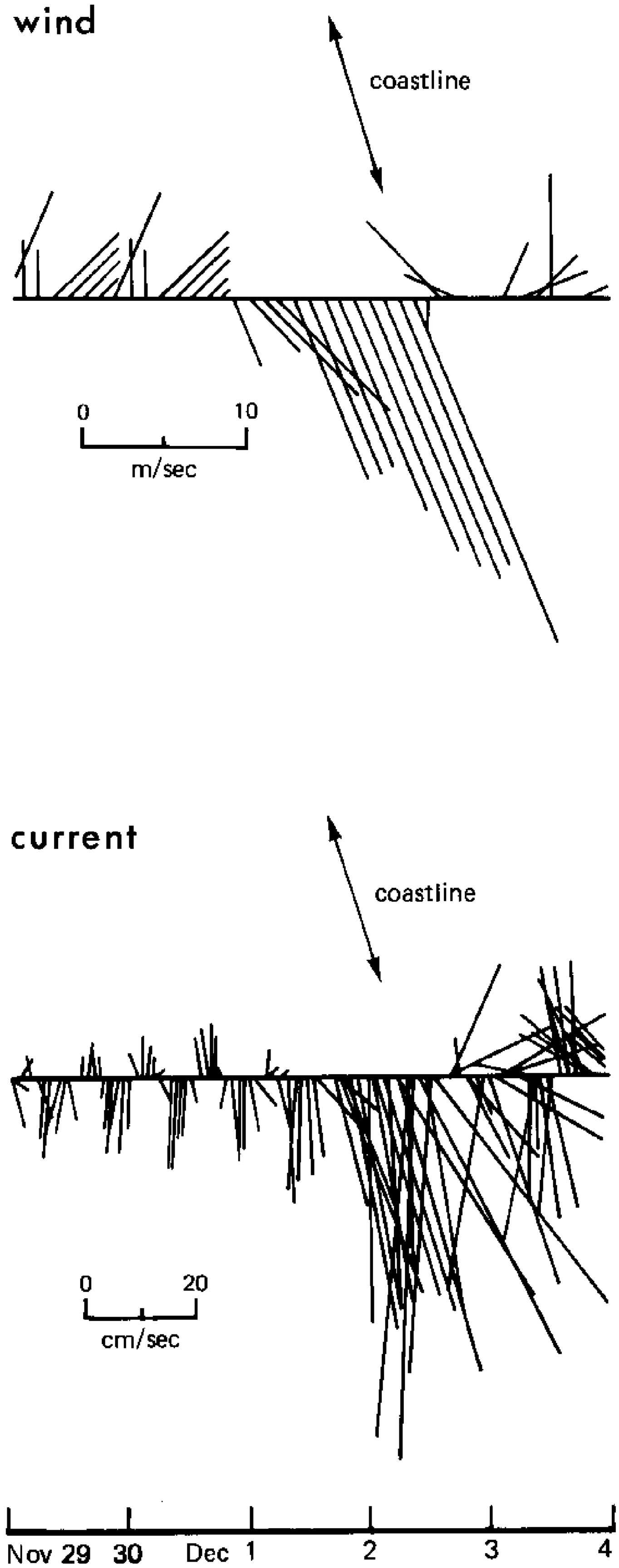
The intense winter low-pressure systems that spawn northeasters off the coast have a pattern that reasonably matches the shape of the coast, thus producing strong surface wind stresses uniformly along the shelf to the west, southwest, and south, generally following the shore from Cape Cod to Cape Hatteras. Deflection of the surface current to the right causes sea level to rise along the coast (Swanson 1976). The level of the open sea does not change significantly, however, so an onshore slope of the sea surface is induced, giving rise to pressure forces that drive a strong alongshore flow to the southwest at all depths. Exploration of the nuances and variations of this conceptual model are just beginning. The influence of winds on the average motion, for instance, is unknown; the average flow over the shelf is to the southwest, while the average wind is from the west. Nonetheless, the basic logic seems an adequate and consistent explanation of salient features of the current observations.

Local wind is not always a good indicator for currents, however. A strong meteorological event may be experienced along the coast many miles away. The currents generated in that distant region can propagate along the coast like a pulse disturbance or wave to appear at other points along the coast at a later time (shelf waves). Unlike the more familiar surface gravity waves, however, the associated movement is overwhelmingly horizontal. The vertical part of the motion is so subtle as not to be noticed by lay observers.

Because this portion of the continental shelf is relatively broad and shallow, and the winds unfavorable, the Middle Atlantic Bight is not known for coastal upwelling. Nonetheless, the physical processes that produce major upwelling areas elsewhere are also active here, but are somewhat less effective. The veering of surface current to the right of the wind (due to the Coriolis effect), gives rise to pressure gradients that drive strongest currents along the shelf and affect weaker cross-shelf flows. Winds from the northeast move surface waters onshore, forcing offshore flow, or downwelling, below. Conversely, winds from the southwest move surface waters offshore and cause onshore flow or upwelling of the deeper waters. Thus, winds from the south, southwest, or west can be expected to lead to onshore flow of colder or more saline waters. Such events do not usually occur with sufficient intensity or persistence that the upwelling waters make their way to the surface or the shoreline. Downwelling of onshore waters under the influence of winds from the northeasterly quadrant can be detected only in subsurface observations offshore.

The direction and strength of currents very close inshore, *littoral currents,* are also very dependent upon the direction and strength of the wind and upon the local wind waves and surf. The general flow is parallel to the shore and downwind, but with nearly onshore winds or surf, the direction of the current locally can critically depend upon the orientation of the coastline, and even upon the offshore bathymetry. Where littoral currents meet in opposition, seaward flowing rip currents can occur. These can be very dangerous to bathers who may become exhausted attempting to swim toward the beach against the strong seaward flow.

The large wind-induced variability of the currents is the major impediment to making more definitive statements on circulation in the Bight. Because the wind effects are so important, and the winds occur randomly in time, usually it is not feasible to combine data collected for different sites at different times. Thus, although a considerable amount of data have been collected since about 1970, these data do not necessarily provide a comprehensive overall description of currents in the Bight.



Source: From Swift et al 1976

Figure 7. Surface winds and currents observed off Long Island before and during a storm, winter 1974

Tidal Currents

The easiest part of the temporal variation of currents to describe is that associated with tides. Tides and tidal currents are determined primarily by the relative motions of the earth/moon/sun system, which are precisely regular and predictable. Observations of tidal phenomena from various times and places may therefore be combined for a logically consistent description. The long-established standard procedure is to observe the appropriate variable (tidal height or current) at sufficiently frequent intervals over an adequate time span, then determine the amplitude and phase of variations of the same period as the astronomic process from which they arise (Swanson 1976).

Typically, hourly measurement series 15 or 29 days long are used to quantify the principal diurnal and semidiurnal frequencies. The procedure is less satisfactory for tidal currents than for tidal heights because currents are more subject to nontidal influences, such as surface wind, which contribute error to an analysis. An effective, but tedious and expensive, means of coping with this problem requires use of longer data series to reduce errors. Once determined for any location, tidal currents, like tides, are in principle predictable forever after, or until engineering works such as channel deepening or diking and filling of coastal marshes sufficiently modify the hydraulic regime to affect tidal processes. Unfortunately tidal currents are not a large enough part of the total variance on the open shelf to make their prediction alone particularly useful to commerce. Their understanding and description are, however, important for isolating other, less regular effects.

Because tides are repetitive, and tidal currents vary less with depth than wind-driven currents, for example, the lightship data reported by Haight (1942) are more suitable for tidal analysis than for determining either average flow or surface wind effects. Only six lightship sites were occupied in the Bight. More detailed description of tidal currents in the Bight is possible from the moored current meter data being collected for the MESA New York Bight project. The analysis is being done by the National Ocean Survey of NOAA. The dominant behavior of the tidal current regime in the Bight can be inferred from the M_2 constituent, the semidiurnal tide associated with the moon (Swanson 1976).

Map 2 shows results of analysis for the M_2 constituent at several sites in the Bight apex. The points of the ellipse indicate the head of a vector from the center, denoting speed variation and direction of flow associated with this tidal constituent over a tidal cycle. These analyses, characterized by maximum speeds of 8 to 20 cm/sec (0.16 to 0.4 knot), indicate that the semidiurnal tidal currents usually rotate clockwise about very narrow ellipses. This agrees with lightship results on surface currents in the apex. Two instances in which the rotation is counterclockwise are probably from interference in the analysis by nontidal perturbation of the current. Closer to the bottom the current rotation is counterclockwise due to the influences of bottom friction and rotation of the earth.

Some additional features are revealed in the results of data from measurements nearer to the bottom (Map 2). First, the greater number of stations provides a more general description of the M_2 tidal constituent. Perhaps most obvious is the relatively strong tidal current in the entrance to the estuary. Tidal current predictions for this region show tidal currents over 100 cm/sec (1.9 knot). Such speeds are typical of inshore and estuarine regions.

Map 2 also shows the tendency for the flow to be rectilinear and parallel to boundaries such as the shore and subsurface features such as the sides of Hudson Shelf Valley. Flow becomes weaker with distance offshore, to less than 10 cm/sec (0.2 knot) for the most important constituent in the apex. Comparison of Map 2 with Figures 4 and 7, from which tidal currents have been removed, makes it clear that tidal currents are usually not dominant in offshore areas of New York Bight.

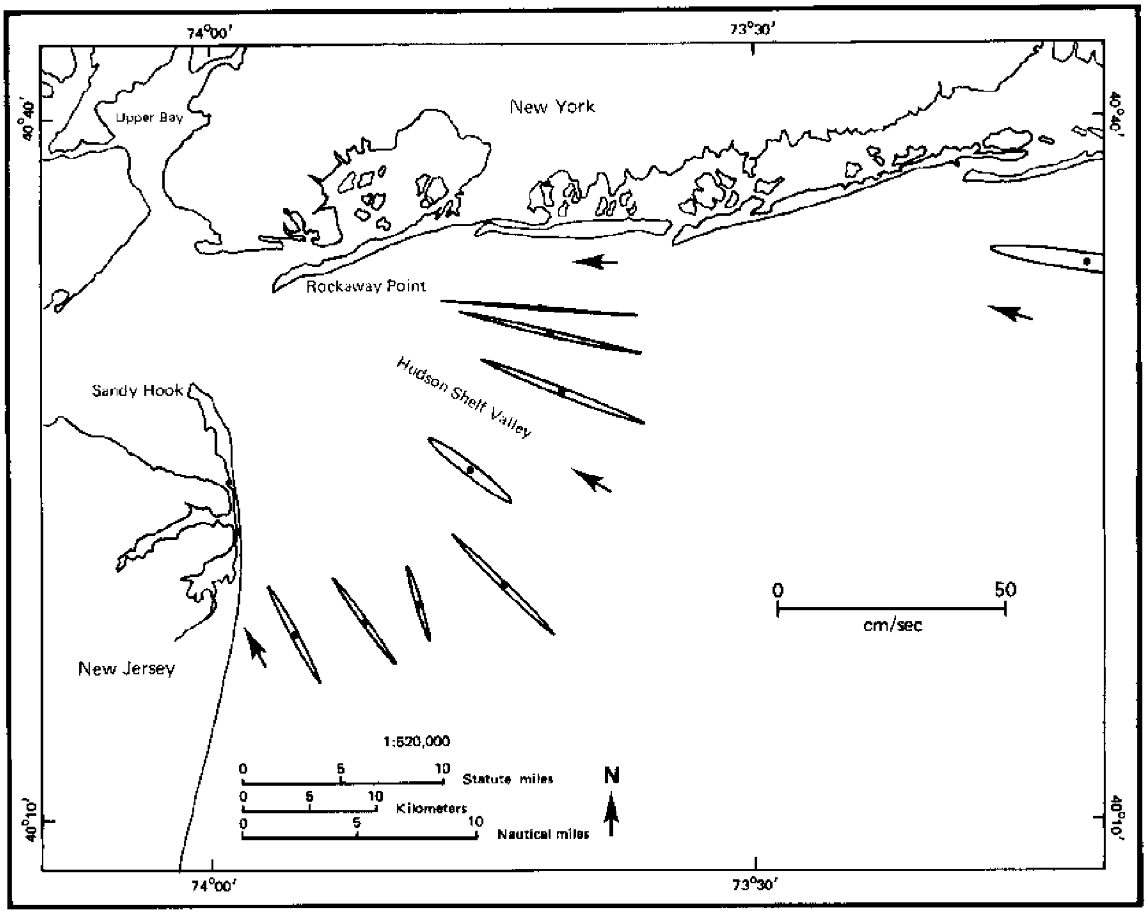
Seasonal Patterns

Pronounced seasonal variations are observed in oceanographic (Bowman and Wunderlich 1977) and meteorological (Lettau et al 1976) variables associated with circulation. It is reasonable, therefore, to expect a pronounced seasonal cycle in the strength or pattern of the circulation. Much of the published literature relating to the "cold pool" or "winter water" found on the outer shelf during summer (Bigelow 1933; Ketchum and Corwin 1964; Bumpus 1973; Bowman and Wunderlich 1977) implies that a more or less stationary pool of relict winter water slowly changes character in place through mixing with adjacent waters.

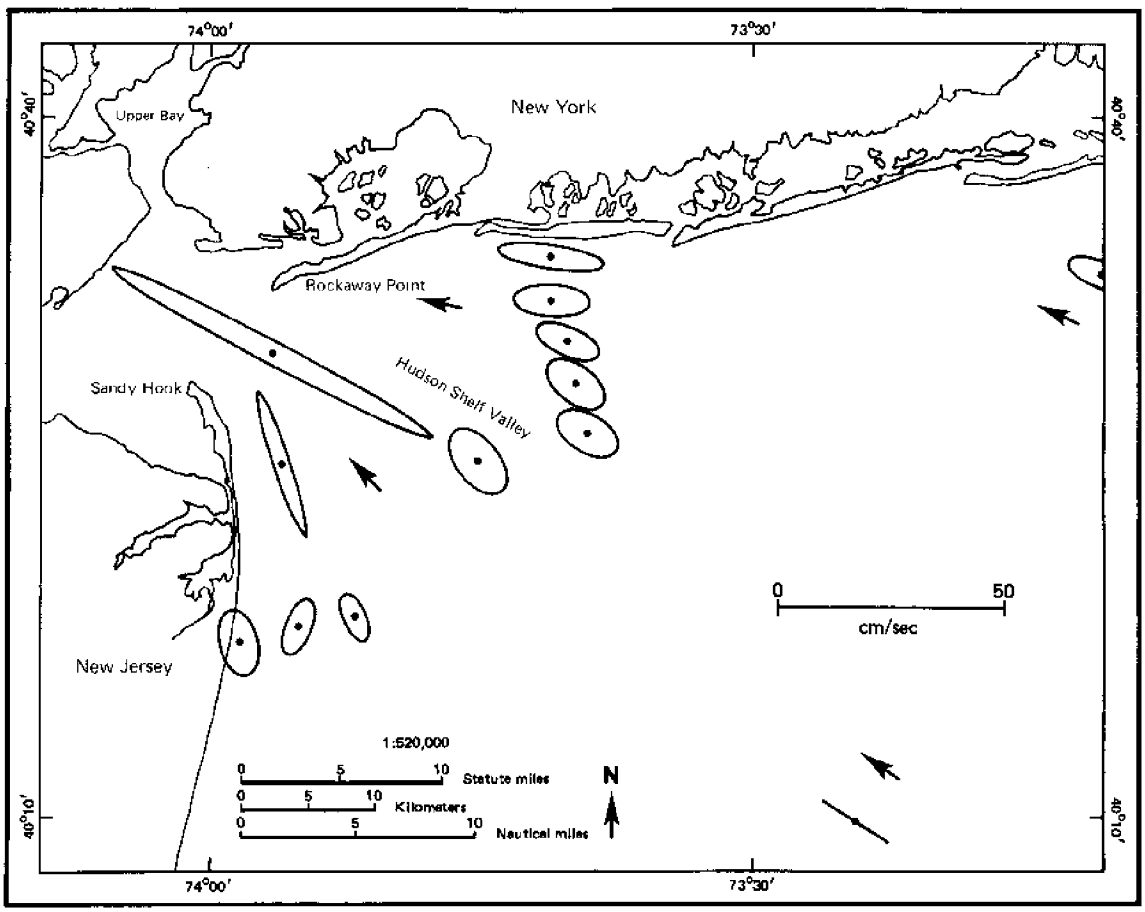
Bumpus (1969) reports evidence of reversals of the southward surface current off New Jersey and the Delmarva Peninsula during summer when the prevailing wind is from the south. Such persistent reversals were indicated especially during the mid-1960s drought when the salinity and density gradients, which evidently play a role in maintaining circulation, were diminished. Data collected in the MESA New

Map 2. Tidal current ellipses for M2 tidal constituent

8 meters above bottom



3 meters or less above bottom



Rotation is predominantly clockwise at 8 m (26 ft) above the bottom, counterclockwise at 3 m (10 ft) or less above the bottom.
The centers of ellipses are the station locations.

Arrows indicate direction of progress of the maximum M_2 flood current velocity.
Current velocity vectors rotate 360° in 12 to 42 hours.

Source: From Patchen et al 1976

Mercator Projection

York Bight project indicate that weakening and reversal of the average currents off New Jersey may have contributed to the development of anoxia and fish kill in this region during summer 1976.

The difference in return rates of surface drifters during summer and winter reported by Bumpus (1973), Charnell and Hansen (1974), and Hardy and his associates (1977), suggests persistent movement of surface waters offshore in winter, onshore in summer. Return rates of bottom drifters, however, suggest little seasonality in direction of the near-bottom flow in the Bight, but the strongest near-bottom currents probably occur in winter.

Such data as are now available suggest that the "average" currents out on the open shelf may vary little between summer and winter. Observations (unpublished) made by the MESA New York Bight project during the last few months indicate that the currents may change as much from one summer to another as from summer to winter. Table 1 summarizes some results of current measurements made on the open shelf approximately 56 km (35 mi) south of Long Island for about a month during summer 1974 and two months during winter 1974-75. This particular site happens to be where the "cold pool" is observed during summer. The current measurements indicate that direction and speed of flow at this site are the same in both seasons, to the southwest at a few kilometers per day, but decreasing with depth below the surface. Also apparent, especially in the winter data, is the shoreward veering of the current near the bottom.

The standard deviation of the observed currents is included in Table 1 as a final demonstration of circulation variability. The data were subjected to high- and low-pass filters to separate contributions to the current variation occurring more rapidly than 40 hours (σ_H) from those occurring more slowly than 40 hours (σ_L). The more rapid fluctuations are associated primarily with tides and rapid wind shifts such as occur during the passage of fronts, and the slower fluctuations are usually due to more general weather patterns. The standard deviation typically exceeds the mean value of the flow over several weeks by a factor of 3 to 10 or more. The standard deviation at comparable depths 26/30 and 46/44 m (85/98 and 151/144 ft) is observably greater in winter than in summer, especially in the high-pass filtered data, evidently reflecting increased storm activity.

The major contributions to the variability of currents are associated with particular time scales of variation. Most of the variability within a few kilometers of the shore is associated with tidal currents of diurnal and semidiurnal periodicity, and meteorological events occurring from 1 to 10 days. Farther offshore, the waters are more influenced by oceanic current variations which have time scales of 40 days or longer. Details of this transition are not yet available. The most energetic current variations are spatially very coherent or well organized. It is clear from Map 1 that average currents measured over several months are similar all across the continental shelf; in Map 2 the tidal currents are arranged in systematic ways. Similarly, currents generated by meteorological events of a few days duration are similar over great distances, but more so in the alongshore direction than in the offshore direction.

Table 1. Currents observed at an open continental shelf site

Station	Depth m	Average Speed cm/sec	Current Direction °T	σ_L cm/sec	σ_H cm/sec
40°07.0′ 72°51.0′ Summer 1974 35 days	2	7.9	208	12.3	20.9
	26	4.9	236	13.2	15.2
	46	2.5	223	7.4	7.8
40°07.0′ 72°54.5′ Winter 1975 65 days	16	5.0	201	12.6	15.2
	30	4.6	227	12.6	18.1
	44	1.3	243	8.2	10.3

Source: NOAA's Atlantic Oceanographic and Meteorological Labs

Summary

This monograph's aim is to extract from newer data sources some recent information on spatial variation of the general southwesterly drift over the Middle Atlantic Bight continental shelf, and to instill in the reader a healthy suspicion of results of observations over short intervals. Temporally variable flow, which can exceed the average flow by a factor of 10 or more, is a fundamental characteristic of circulation. The "average" can be expected to occur infrequently if at all. Information for any particular application must be evaluated in terms of this characteristic.

Because of the high degree of variability encountered, it is usually not possible to combine various short series of observations into a unified description. Systematic sets of data such as are reported by Haight (1942), Bumpus (1973), and as are presently being collected in the MESA New York Bight project are necessary.

The general picture that is emerging is as follows. The outer Bight is characterized by average currents to the southwest at speeds of about 4 to 5 cm/sec (2 mi/day) at the surface, decreasing to one-half or less of that speed closer to the bottom (Map 1). There is evidence that this general pattern may be altered or even reversed for periods as long as two to three months, especially during summer, and especially over the relatively shallow shelf area off New Jersey. These reversals are associated with sustained periods of low rainfall or strong southerly winds.

Since the inner Bight is more variable, it is still not possible to map the currents in detail. Such variability is due to the collective influences of the angular shape of the coastline, the presence of the Hudson/Raritan estuary and its associated tidal and river flows, the major topographic influence of Hudson Shelf Valley, and subtle but important differences in water depth off New Jersey as compared to off Long Island. There is evidence, in the form of measurements such as those shown in Figures 4 and 5, indicating periods of sustained flow to the east off Long Island and to the north off New Jersey, to suggest the existence of a clockwise eddy in the Bight apex. However, it is not always present, and observations are inadequate to map either its seaward or alongshore extent.

The estuarine circulation shown in Figure 7 has also been observed only to a very limited extent, but knowledge of estuaries is generally sufficient to assure that a seaward flow of surface water—preferably on the Sandy Hook side of the channel—and landward flow of deeper more saline water—preferably on the Rockaway Point side of the channel—is to be expected in the mean over any period of several days.

Hudson Shelf Valley, and farther offshore, Hudson Canyon, are outstanding physical features of New York Bight that are expected to have significant influences on the currents. Only in the last three years has it become possible to investigate this influence directly. Results indicate a net shoreward flow in at least some parts of the shelf valley over periods of several weeks or more, but the full spatial extent of this flow, and the frequency of its occurrence, are largely unknown.

Thus, quite a lot is known after all about the general features of circulation in the Bight. Although because of the great temporal variability and the considerable spatial variability, especially in the inner Bight and nearshore regions, it is at present impossible to map the average current patterns with any degree of confidence. One of the principal objectives of the present MESA New York Bight project is to obtain the additional necessary information.

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