CIRCULATION IN THE CHESAPEAKE BAY ENTRANCE REGION:

ESTUARY-SHELF INTERACTION

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SUMMARY

Current meters and temperature-salinity recorders confirm that the upper layers of the continental shelf waters off Chesapeake Bay can be banded in summer, such that the coastal boundary layer (consisting of the Bay outflow) and the outer shelf flow southward while the inner shelf flows to the north, driven by the prevailing southerly winds. These measurements show that the estuary itself may also be banded in its lower reaches such that the inflow is confined primarily to the deep channel, while the upper layer outflow is split into two flow maxima on either side of this channel.

INTRODUCTION

As oceanographers began to study the water motion in the Chesapeake Bay mouth, only a few moored instruments were employed to measure the flow field. The reasons for this sparse sampling stemmed partly from the difficulty in mooring and processing records from the instrumentation available at the time, but also stemmed partly from a sense that these few measurements, when combined with a large amount of shipboard temperature and salinity data, were sufficient to delineate the patterns of motion. Over the years, as instrument and sampling arrays became more elaborate, the flow regime in the mouth region has seemed to defy the simple expectations of the oceanographers by showing progressively smaller space scales of variability and by its complex, highly three-dimensional current patterns which are controlled by the local topography.

A knowledge of where the Bay inflow originates, where the outflow goes, and how far offshore the influence of the estuarine circulation extends would aid many studies of the Chesapeake Bay and inner continental shelf. A knowledge of the flow regime and dynamics of the Bay entrance region is crucial, however, for the construction of numerical models of the estuarine circulation. Present efforts are limited by the lack of a proper formulation of boundary conditions on the seaward end of the model (either the mouth or inner shelf). Little information is available, for instance, to answer the question of how much recirculation of water discharged on an ebb tide occurs on the subsequent flood.

The recent studies by the Chesapeake Bay Institute in the Bay mouth region under the sponsorship of the National Science Foundation, the Environmental Protection Agency, the National Ocean Survey, and the Army Corps of Engineers have provided an evolving description of the flow regime and the dynamics controlling estuary-shelf exchange. With the advent of the Superflux prospectus, an opportunity arose to enhance previously planned observational efforts by combining them with the remote sensing experiments. The following paper contains a report on the preliminary results of these measurements.

BACKGROUND

It has long been known that the classical estuarine circulation of Chesapeake Bay consists of a two-layer flow, with the upper layer discharging low-salinity water onto the continental shelf while the lower layer draws higher-salinity shelf water into the Bay (ref. 1). The inflow source and the fate of the outflow waters, however, have been revealed only recently. The drift-bottle and seabed drifter experiments of Bumpus (ref. 2) have provided some glimpses of possible water-parcel trajectories in the offing of Chesapeake Bay. These glimpses are of value, in spite of inherent biases and uncertainties in such drifter measurements, because they help formulate questions and sampling strategies for present studies. Bumpus' data suggest that, in the mean, the inflow to Chesapeake Bay occurs as a slow, broadly distributed flow from the north and east. Boicourt (ref. 3) showed that the source of the inflowing water depends on the wind direction and that the inflow is confined primarily to the deep Chesapeake Channel, near Cape Henry (fig. 1). He also showed that the Chesapeake Bay outflow turns to the south (fig. 2) and flows as a quasigeostrophic jet along the Virginia and North Carolina coast (fig. 3). The offshore boundary often occurs as a sharp salinity front and can be seen in the synthetic aperture radar images from the Seasat satellite. That this buoyant plume is affected by the Coriolis force is not surprising, although dynamical analysis has been somewhat murky. Takano's (ref. 4) well-known model of the movement of fresh water from a river into a stationary sea purports to show a cyclonic turn of the outflowing water after leaving the mouth of the river. Although the resultant predictions (illustrated in ref. 5) agree qualitatively with Boicourt's observations for the Chesapeake Bay outflow, Takano's equations contain an error in formulation such that the stream function is symmetrical on the continental shelf, and not skewed cyclonically as reported. The Coriolis acceleration should be important in the Chesapeake Bay outflow, both in the southward turn and in the narrow current formed along the coastal boundary south of Cape Henry. Even if a characteristic velocity U in the outflow were chosen as large as 50 cm/s, a Rossby number

$$R_o = \frac{U}{f\,L}$$

where a characteristic length L was taken as the width of the outflow (10^6 cm) and the Coriolis parameter f is $0.9 \times 10^{-4}\ s^{-1}$ would be less than unity (of the order ½). Beardsley and Hart (ref. 6) provide a three-dimensional dynamical model of the flow of an estuary onto a continental shelf. This treatment is dynamically correct, but more refinement is necessary to enable a careful comparison of theory and observation.

The exchange between the Chesapeake Bay and the adjacent continental shelf waters does not necessarily occur as a steady, two-layer outflow and inflow. Boicourt (ref. 3) found that the wind can dominate this exchange, such that a northwest wind in November 1971 could drive an outflow surge that, over a two-day interval, lowered the water level of the Chesapeake Bay approximately 1 m. The net water discharged during this interval amounted to 10% of the mean volume of the Bay proper. Wang and Elliott (ref. 7) and Wang (ref. 8) show that the wind-driven exchange is not as simple as first thought. Consideration must be given to the response of the Bay to local winds, but also to the response of the continental shelf to both local and non-local winds for a proper accounting of the net exchange through the Virginia Capes. Strong winds can drive outflow surges over a two-day period, but over longer periods (5-10 days), the water level in the Bay can be controlled by the set-up and set-down on the continental shelf, a process which may counteract the level change driven on the shorter time scale.

Our previous studies have shown that the inner shelf of the Middle Atlantic Bight, away from the mouths of estuaries, is dominated by wind forcing (ref. 9). The reason for this dominance is twofold: 1) the mean longshore flow (not wind-driven) from Cape Cod toward Cape Hatteras *decreases* from a maximum near the shelf break toward the coast, and 2) the inner shelf is shallow and therefore prone to wind driving. These two reasons are related in that the shoreward decrease in the mean southward flow is probably the result of increased dominance of bottom friction as the depth decreases. The southward mean flow on the continental shelf has been well documented. Recent long-term measurements (ref. 10) suggest there is a greater variability about this mean in the waters off the Chesapeake Bay than in the New York Bight or New England shelf waters (figs. 4 and 5). An example of the dominance of wind-driven motion over this mean flow for the inner shelf region is shown in figures 6 and 7. Figure 6 contains vector time series of currents measured at four moorings at the cross-shelf section off Chesapeake Bay shown in figure 6 in the summer of 1974. The strong correlation of the wind stress record from Norfolk with the 10-m current record at the inner shelf station 408A indicates clearly that the wind is the primary driving force in the region. Offshore (stations 413A, 415A, and 416B) the wind-driven motion is seen as a modulation of the mean southward flow. The means of these records are shown in figure 7, where the dots are southward flow and the crosses are northward flow. Station 408A means reveal, as could be expected from a glance at figure 6, that the prevailing southerly winds can reverse the mean southward flow in the inner shelf. The winds in July 1974 were neither sufficiently strong nor persistent to reverse the mean southward flow on the outer shelf.

The Chesapeake Bay Institute planned an experiment in the Bay entrance region for January-February 1979. At the outset of this study, the expectation was that the influence of the Chesapeake Bay estuarine circulation could not be detected far offshore during this season. The reasoning was simple:

1) The magnitude of the estuarine circulation is at a minimum in winter.

2) The prevailing winds are northerly, adding a wind-driven component to the southward mean flow and restricting the

inflow and outflow of the estuary to a narrow band along the coast.

3) The water is unstratified--previous continental shelf observations show that the flow is nearly barotropic and parallel to isobaths during this season.

Earlier observations had also shown that the path of the deep inflowing water to Chesapeake Bay is strongly controlled by the topography. Whether the source of the inflowing shelf water is from the north or south of the entrance, the primary inflow is via the main channel near Cape Henry (fig. 8). If the source is from the north, the deeper water must move around the offshore extention of Middle Ground shoals before entering the Bay. Short-term current measurements indicate that there may be intermittent flow (with time scales of 4-8 days) *into* the Bay, throughout the water column on the north side of the Bay entrance, near Fisherman's Island. Temperature and salinity distributions help fuel this speculation because the stratification often appears weak or nonexistent in the North Channel area (refs. 2 and 9).

In January 1979, eleven vertical arrays of current meters and temperature-salinity recorders were moored in the Bay entrance and on the adjacent inner shelf (fig. 9). Sites were selected in an attempt to bring a balance to the conflicting requirements of spatial coverage and spatial resolution. On the inner shelf, space scales of the flow patterns were expected to be significantly greater than in the primary entrance channel, and therefore moorings MF1, MF2, MF3, and MF8 (fig. 9) have greater separations than in the entrance channel, where high resolution is desired. Mooring MF9 was located in the high-traffic area near Cape Henry. Measurements of the inflowing water at this site were deemed valuable, but a mooring would be highly vulnerable to ship collision. For this reason, the subsurface floatation was located at a depth below the keel of vessels operating in the entrance channel, and the mooring was attached to the bottom via an acoustic release.

In spite of high mooring losses due to ship collision, crab dredging, and Saudi Arabian minesweeping, the data return is sufficient to provide clues to the flow patterns. An interval of 240 common hours beginning 4 February 1979 was chosen as the most suitable for this purpose. The mean flows (fig. 10) at the four offshore moorings (MF1, MF2, MF3, MF8 in fig. 9) were remarkably consistent in both speed and direction during the 240-hour interval. The mean flows are of the order 10 cm/s to the south-southwest, parallel to local isobaths. An examination of the longer records from the offshore moorings indicates that this agreement held up for the two-month deployment of the instruments.

The measured inflow to the Bay at 10 m at mooring MF5 and 16.8 m at mooring MF9 provides more substantial indication of the flow field around Middle Ground ridge than the earlier estimates. The low mean outflow in the upper layer in the North Channel section (fig. 10; MF12 in fig. 9) is of particular interest. The question as to whether there are times when there is net density-driven inflow to the Bay throughout the water column in this area will have to await further analysis of the component of motion driven by the prevailing northwesterly winds. The progressive vector diagram of the record from 3.7 m depth at station MF12 would suggest that, in spite of the low stratification shown on the northern half of the mouth cross-section, the vertical shear of the gravitational circulation is sufficient to ensure a net outflow in the upper layer. The mean outflow at 3.7 m depth at station MF11 (5 cm/s) is consistent with the estuarine circulation, but is not as strong as that expected at station MF10 in Thimble Shoals Channel, especially in winter with prevailing northwesterly winds. The outflow to the Bay occurs as a jet along the Virginia coast, with greatest thickness near the shore, with the halocline shoaling to a high-shear lateral front 8-15 km offshore. The southward mean flow at station MF6 reflects both the outflow and the component driven by the northerly winds.

With the arrival of summer, a substantial change occurs in both estuarine and continental shelf waters. First, the stratification is increased, in the estuary by the spring runoff, and on the shelf by the spring warming. The second difference between summer and winter is that the winds switch from prevailing northwesterly in winter to prevailing southwesterly. The increased stratification on the shelf serves to allow greater independence of upper and lower layer flows. The prevailing southwesterly winds can drive a northward mean flow on the inner shelf, and may even reverse the southward mean flow on the outer shelf, if they are sufficiently strong and persistent. The expectations, then, for summertime flow are: 1) that increased stratification allows a greater chance to decouple upper and lower layer flows and therefore allows the estuarine influence to extend further offshore and, 2) the prevailing southerly winds will drive northward flow on the inner shelf.

SUMMER 1980

SUPERFLUX

The 1980 Superflux experiment was timed so that many ongoing experiments in the Chesapeake Bay mouth region could be combined conveniently to take advantage of the additional coverage and resolution provided by the other studies, especially the remote sensing experiments. The Chesapeake Bay Institute was engaged in a large-scale study of the Bay circulation for the U. S. Environmental Protection Agency and the National Ocean Survey. The goals of the experiment were to 1) obtain calibration and verification data for a three-dimensional numerical model under construction, and 2) examine the three-dimensional flow structure in the lower Chesapeake Bay and inner continental shelf, where the influence of the Earth's rotation and topographical control by channels is especially pronounced. Twenty moorings (fig. 11) were placed thoughout the Bay in late June, 1980, from the mouth to Worton Point. Instrumental resources were concentrated in the southern reaches of the Bay to provide better resolution of the flow structure there. The relatively sparse array placement in the upper reaches was deemed acceptable because moorings were located at positions where previous high-density mooring arrays had provided three-dimensional flow details. Three additional moorings (MF2, MF14, and MF7) were placed on the inner shelf to examine the flows at the Army Corps of Engineers Norfolk dredged material disposal site (MF2) and to examine the flow in the transition zone between estuary and continental shelf circulations (fig. 12).

The mean flows from the 38-day experiment show that the currents on the inner shelf were consistent with the expectations (fig. 13). The measured upper-layer currents at MF2 and MF14 were in tight agreement, with a north-northeast flow driven by the prevailing southwesterly winds. The flow at the inshore mooring MF7 shows a mean southward flow in the upper layer, *opposite to flow on the shelf immediately offshore*. Mooring MF7 is located just offshore of the expected maximum-velocity zone of the southward jet of low-salinity outflow from Chesapeake Bay. The position and strength of the velocity maximum, however, are highly variable in time, due to variations in the winds and in the Bay outflow transport. The lateral shear in the upper layer between the southward flow indicated at MF7 and the northward flow indicated at MF14 probably occurs over a much smaller lateral distance, at the lateral front (or series of fronts) along the outflowing plume.

These upper-layer flow measurements lend further credence to the earlier suggestion that the Middle Atlantic Bight shelf currents are ordered in a series of bands parallel to the coast. The outer shelf is moving south in the mean, while the inner shelf is at the mercy of the winds, such that the summer flow is typically to the north. The narrow (10-20 km) band along the coast can be affected by estuarine circulation such that, along the Virginia and North Carolina coasts, the flow is to the south. The strength and spatial extent of this influence depends primarily on the magnitude of the estuarine outflow.

Lower-layer mean currents (fig. 13) show that the estuarine inflow requirements affect the flow as far offshore as station MF2. While the speed of the lower-layer mean at MF2 is small, and therefore the direction of the mean is somewhat uncertain, the time record shows consistent flow to the southwest, broken only by a few wind-driven flow events. With only three offshore moorings and only two points in the vertical for resolving the profile, constructing a detailed flow pattern is difficult. The inflow pattern inferred from these few offshore measurements, however, is in agreement with the earlier measurements.

The measured upper-layer flows in the Bay entrance cross-section (fig. 13) *are not* consistent with expectations. The strong outflow on the southern side of the cross-section is expected, but both the rapid decrease to the north and the strong outflow in the North Channel (M5) are surprises. An examination of synthetic aperture radar imagery from Seasat shows that a pronounced lateral front, aligned with the Middle Ground shoals, occurs near station M3. The time records of currents at stations M3 and M4 show strong tidal flows, but the means are consistently less than 1 cm/s. The strong upper-layer currents at M5 are a surprise because the expectation was that the flow would be weak out of the estuary, or perhaps even directed into the estuary. This expectation was sufficiently well-embedded that a legitimate worry has arisen as to our ability to interpret Eulerian means in the presence of highly channelized flows. Large Stokes velocities are possible when a strong reversing tide interacts with a complex bottom topography.

The cross-sectional structure of the Bay entrance mean currents is shown in figure 14. The classical estuarine circulation is clearly in evidence in the deep channel near Cape Henry, with a surface outflow and a subsurface inflow jet. The mean currents at station M3 show that the low mean flows are consistent throughout the water column here. The two-layer entrance flow is again in evidence in the North Channel (station M5). Clues to the dynamics of the flows over the shoals and in the North Channel region are provided by the temperature-salinity recorders on the moored current meters. Low-frequency currents can be correlated with both the salinities and the stratification in the mouth cross-section to help unravel their interdependence. Perhaps the question as to the Eulerian measurements' suitability can be decided by a careful look at the correlations at tidal frequencies and below. The salinity variability signal, at both tidal and subtidal frequencies, is sufficiently large to suggest that this technique is a promising avenue toward deciphering the Bay-shelf exchange processes . Figures 15 and 16 contain two realizations of the salinity structure in the Bay mouth cross-section. One section (fig. 15) was measured during a Superflux overflight on 23 June 1980. The nearly horizontal pycnocline and the occurrence of the salinity minimum on the north side of the entrance are the result of southerly winds. A more typical situation occurs on 15 July (fig. 16), where the salinity structure in the southern half of the mouth section corresponds more closely to the mean current structure (fig. 13).

The salinity sections indicate that the current measurements probably miss a significant part of the upper layer outflow. Practical considerations prevent routine mooring of current meters much shallower than the 2.7-m depth of the uppermost instruments in the summer 1980 measurements. The salinity sections also suggest that the subsurface inflow may at times reach the surface near station M3 and not in the North Channel as previously had been expected. Current measurements from the Wolf Trap cross-section (WT1-WT5 in fig. 11) show that the lower layer can reach the surface in mid-estuary.

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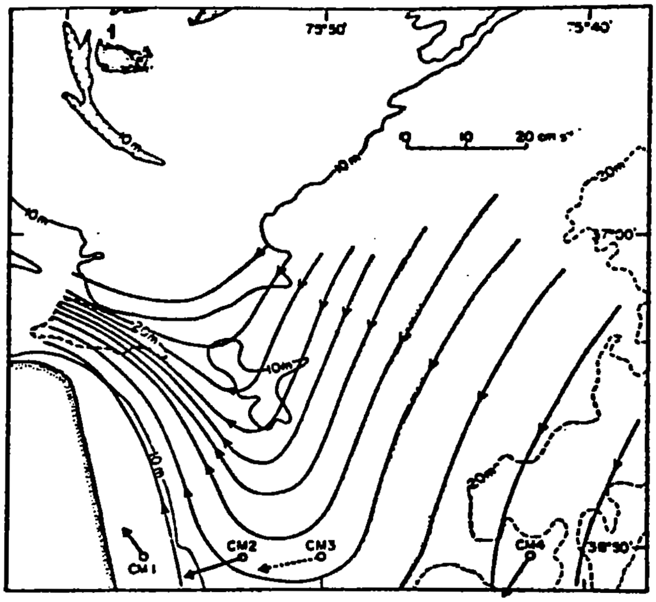
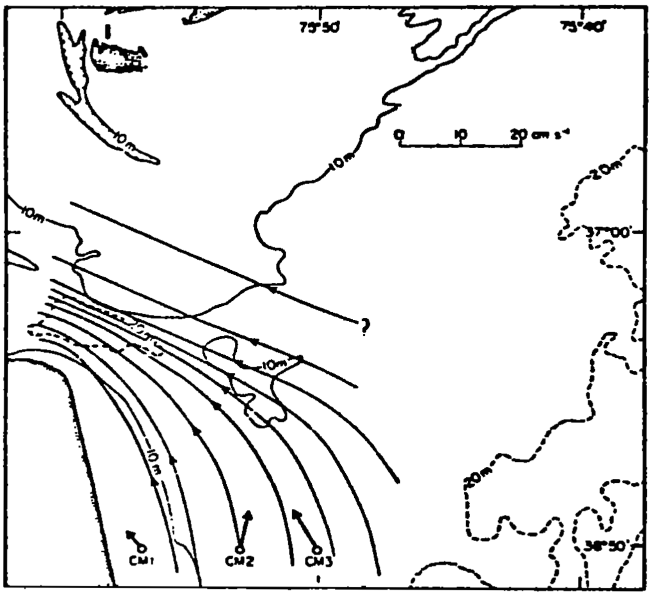


(a) Calm or northerly winds.



(b) Southerly winds.

Figure 1.- Inflow (lower layer) streamline pattern for periods of calm or northerly winds, and for periods of southerly winds.

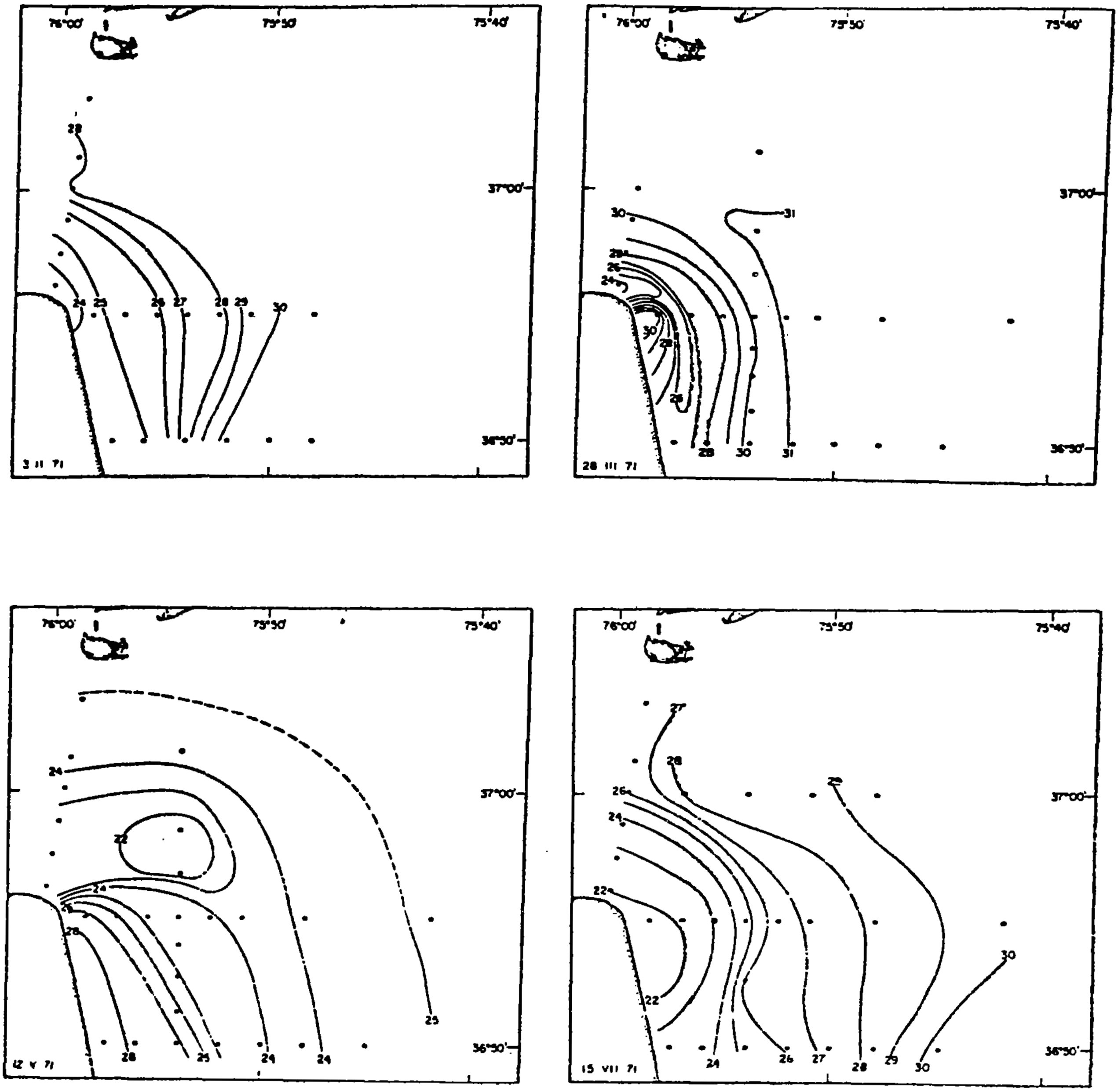


Figure 2.- Surface salinity distributions, Chesapeake Bay mouth region (from ref. 3).

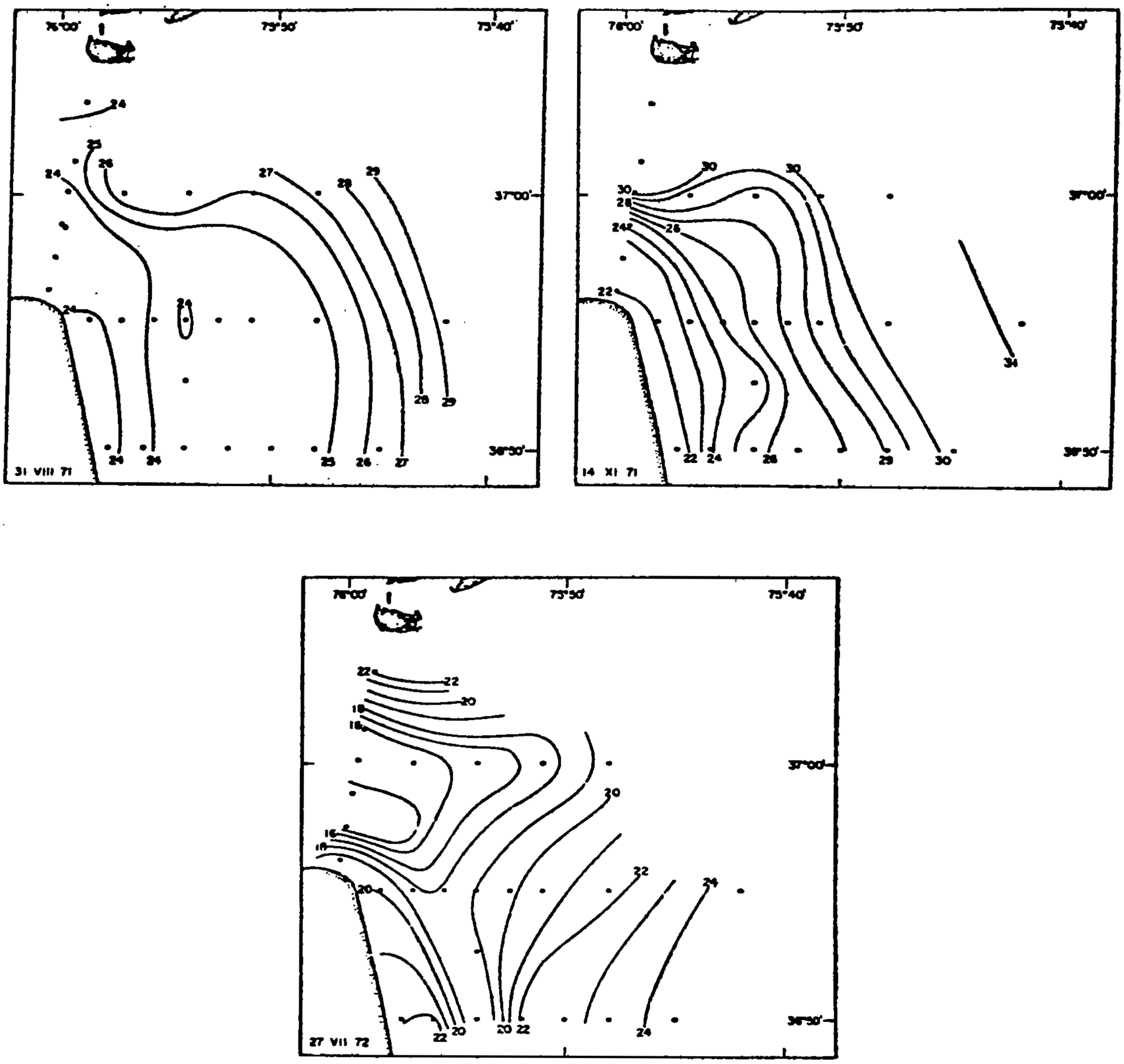


Figure 2.- Concluded.

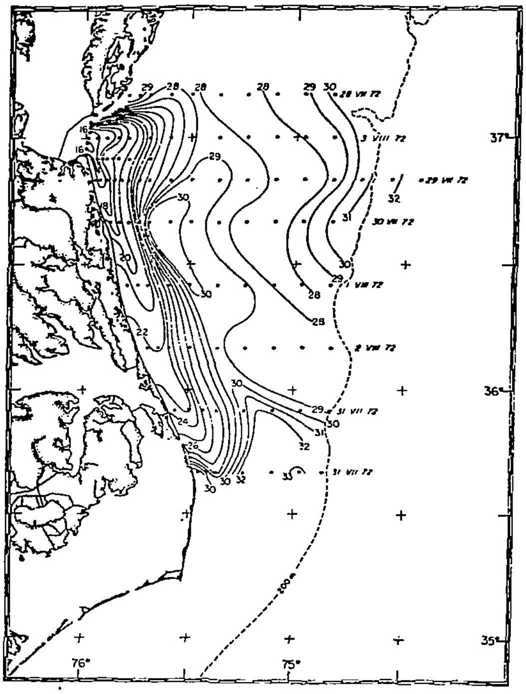


Figure 3.- Surface salinity distribution, July-August 1972 (from ref. 3).

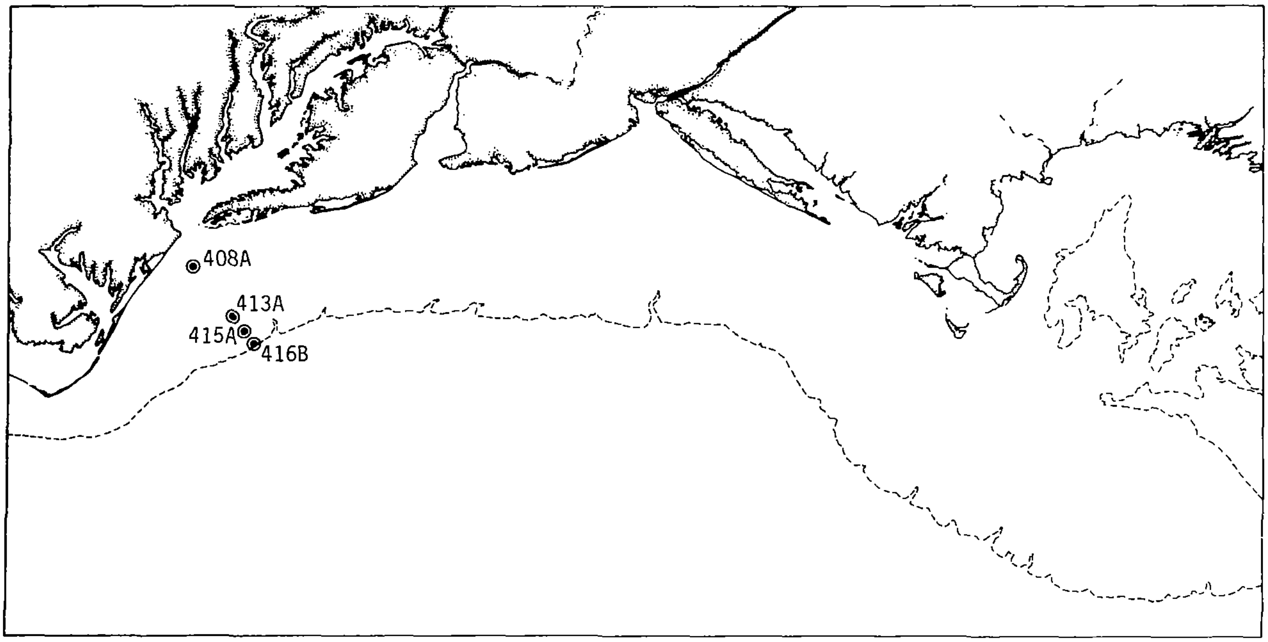


Figure 4.- Map of Middle Atlantic Bight showing current meter mooring positions for records in figure 3 (adapted from ref. 10).

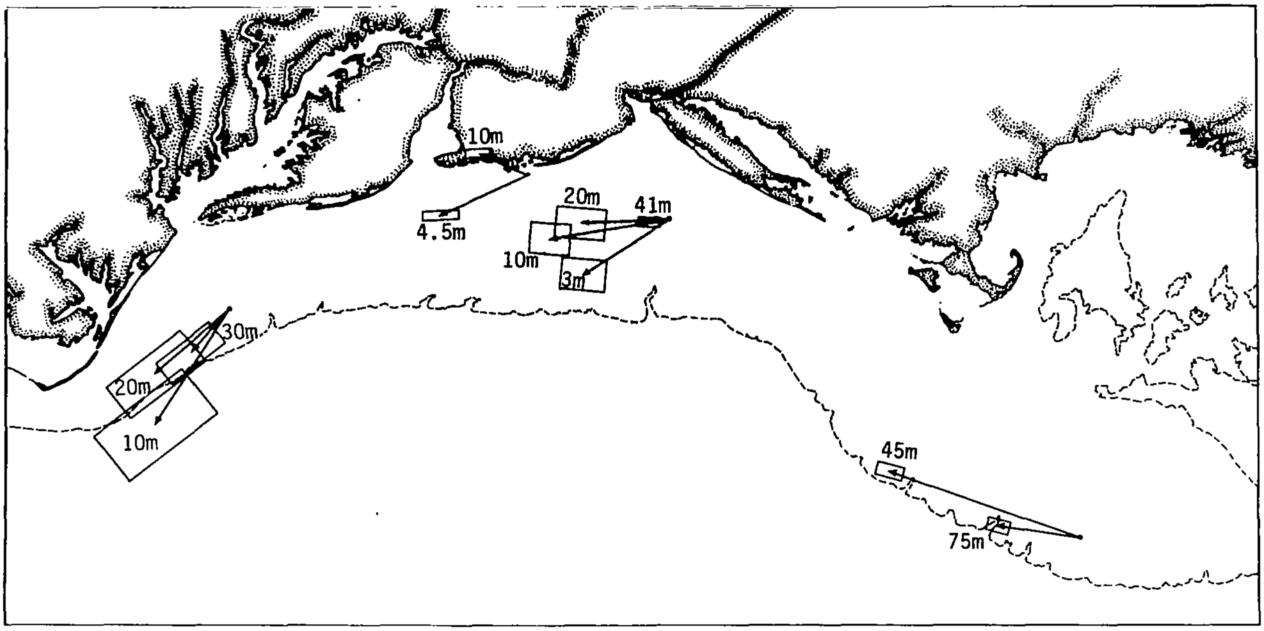


Figure 5.- Map of long-term currents computed from one year or longer current time series with moored current meters in the Middle Atlantic Bight and Georges Bank region (adapted from ref. 10). Standard error for each mean current computation is indicated by rectangle around head of current vector.

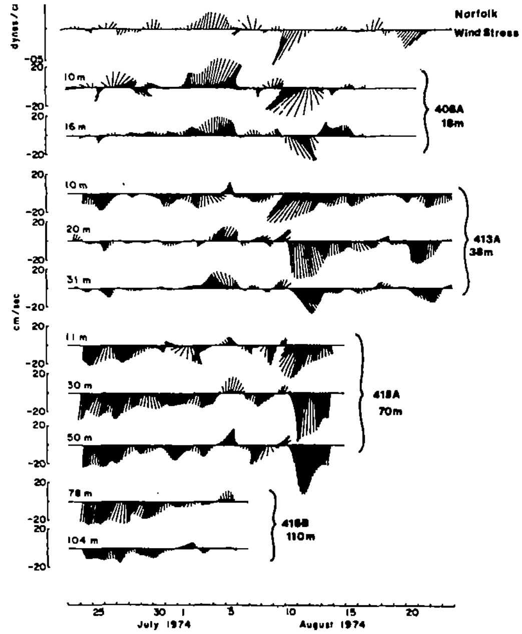


Figure 6.- Summer vector time series of Norfolk wind stress and subtidal currents measured at cross-shelf section off Chesapeake Bay shown in figure 1. Current measurement depths are shown to the left and mooring designations and local water depths shown to the right. North is upward, approximately parallel with the alongshelf direction.

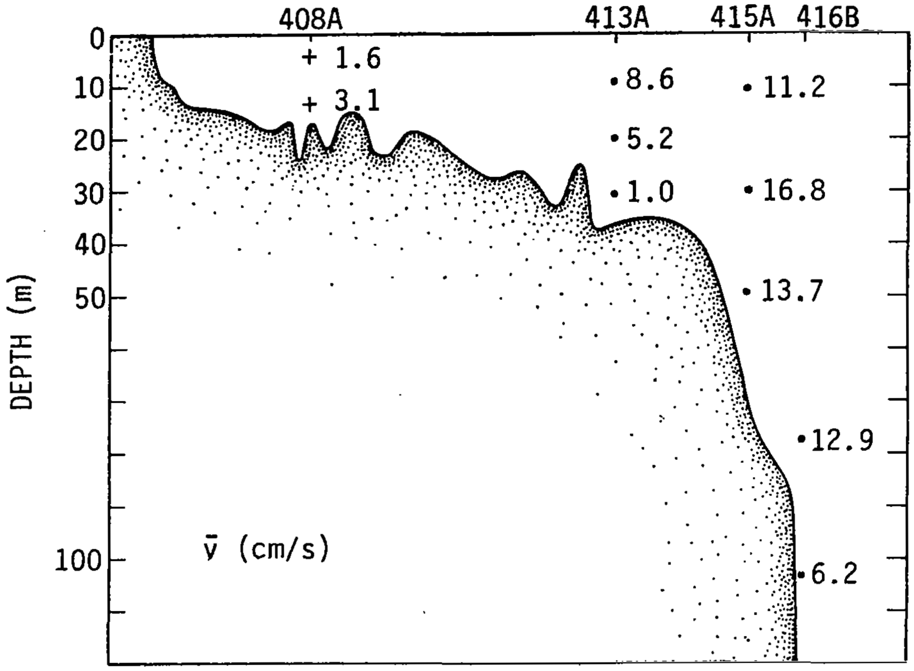


Figure 7.- Long-term mean longshore flow v̄ for July and August 1974 (adapted from ref. 9).

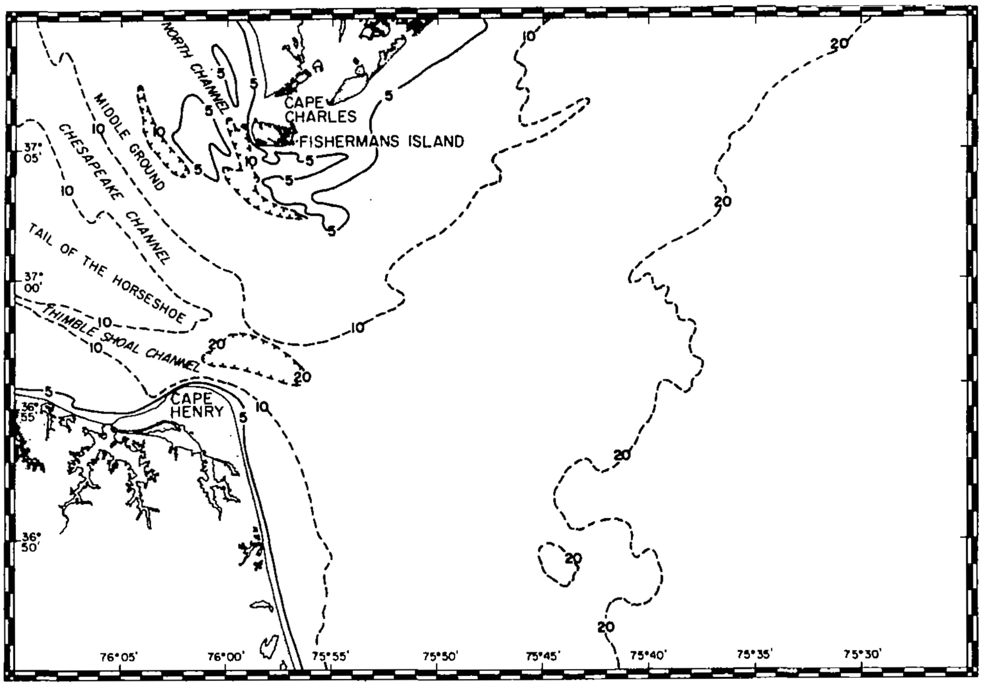


Figure 8.- Bathymetry of the Chesapeake Bay mouth region.

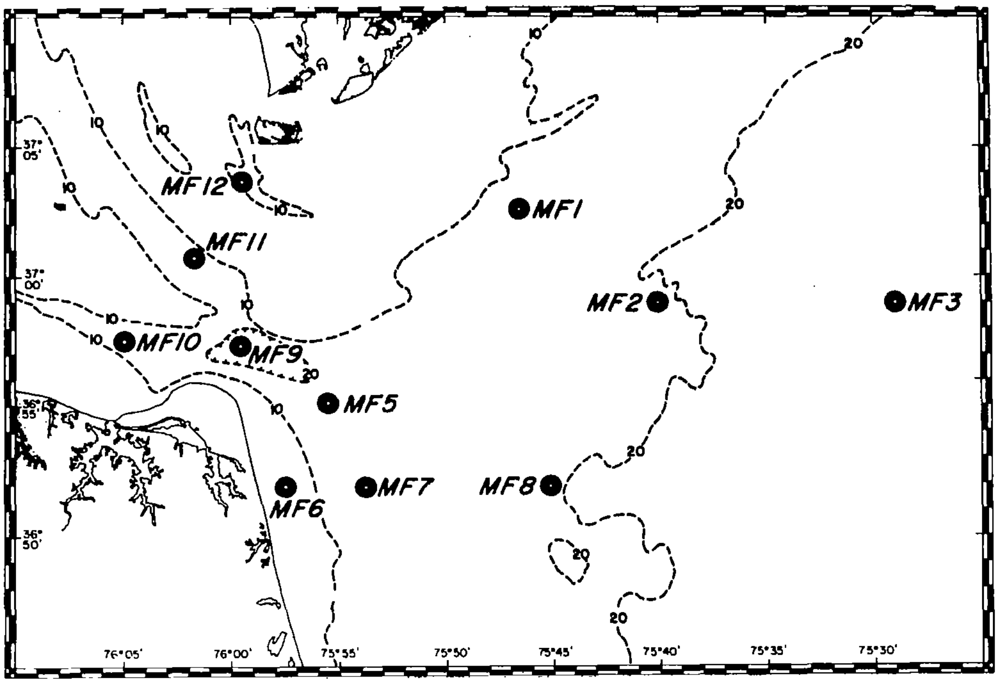


Figure 9.- Mooring positions for January-March 1979 experiment. Norfolk dredged material disposal site is located at station MF2.

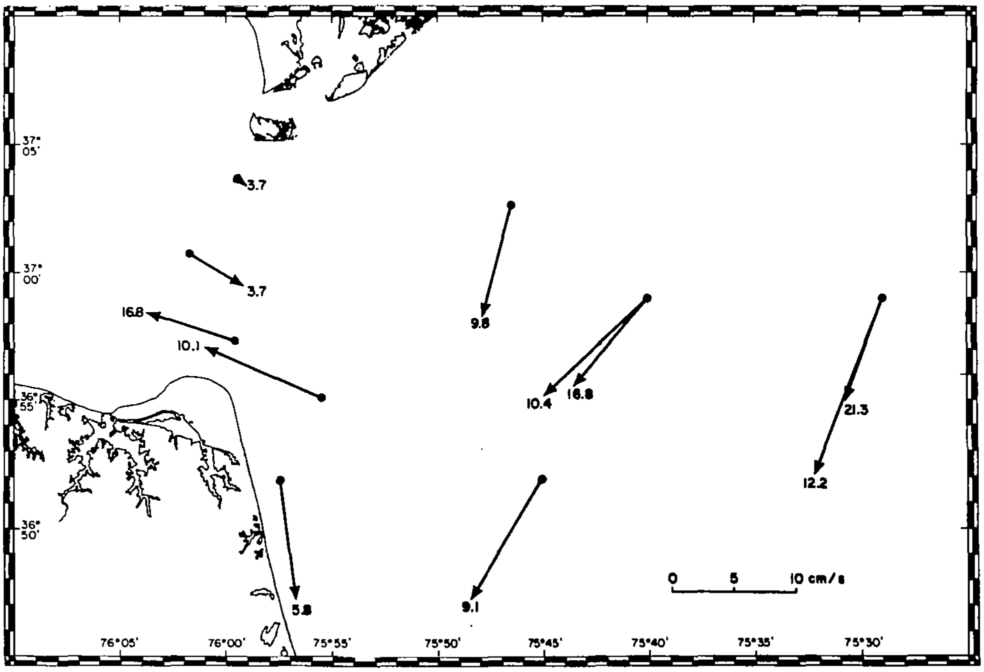


Figure 10.- Mean velocities for 240-hour interval beginning 0000 on 4 February 1979. Depths of measurements (m) are indicated at the head of the velocity arrows. Mooring position designations are shown in figure 9.

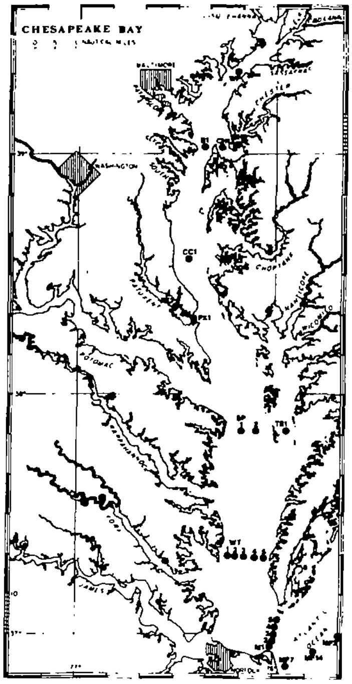


Figure 11.- Mooring locations for CRIMP80 measurement program. Chesapeake Bay and inner shelf were instrumented with 61 current meters on 23 moorings for 38 days beginning 23 June 1980.

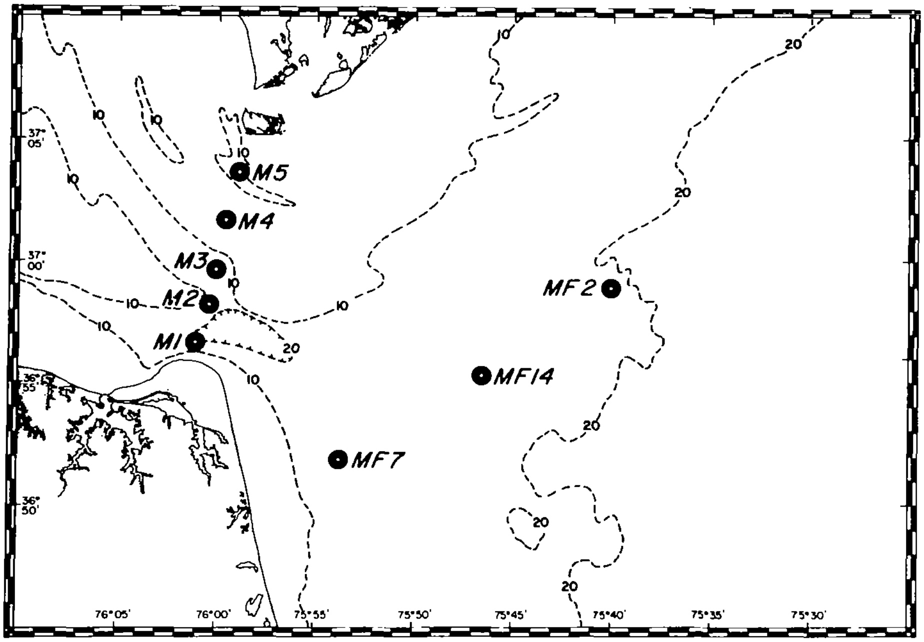


Figure 12.- Summer 1980 mooring positions.

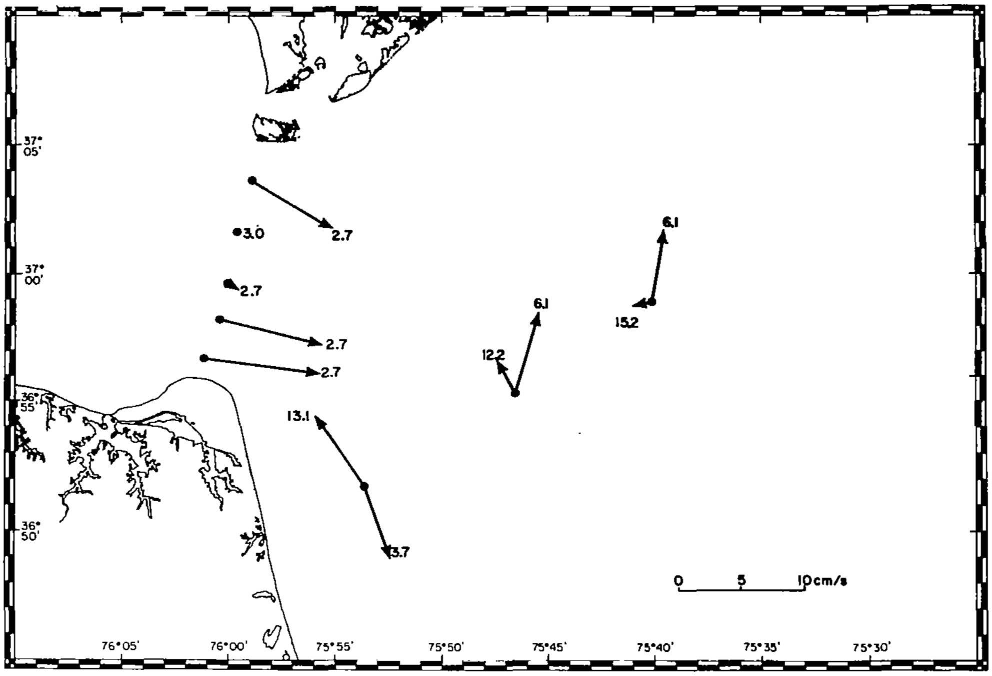


Figure 13.- Mean velocities for 38-day interval beginning 23 June 1980. Depths of measurements (m) are indicated near head of velocity arrows.

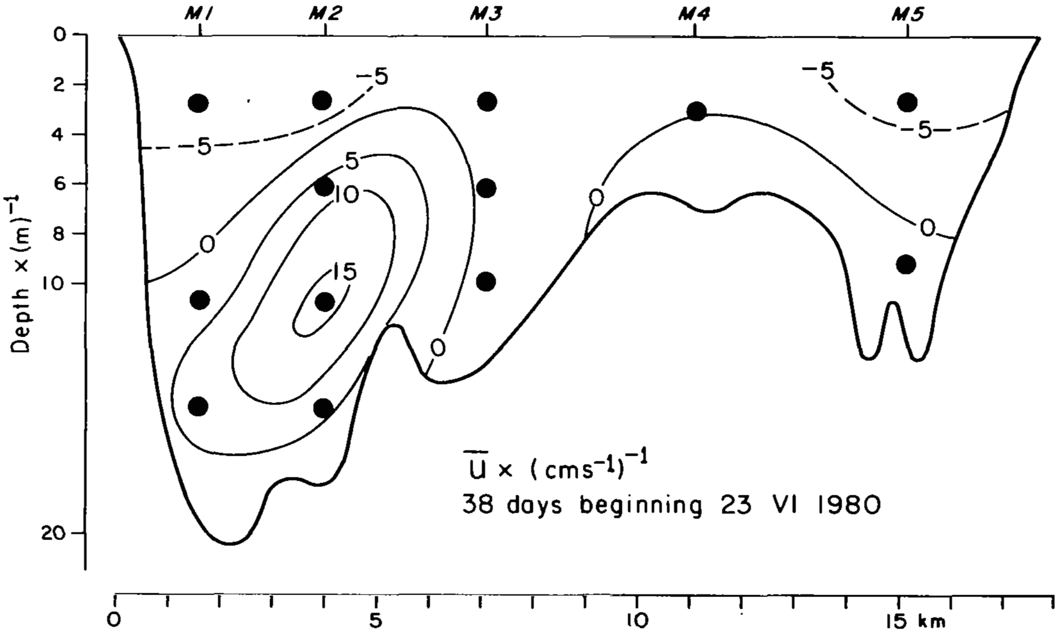


Figure 14.- Mean velocity through the Chesapeake Bay mouth for an interval of 38 days beginning 23 June 1980. Positive velocities are into the Bay. Current meter positions are indicated by the solid circles. Vertical exaggeration is 500:1.

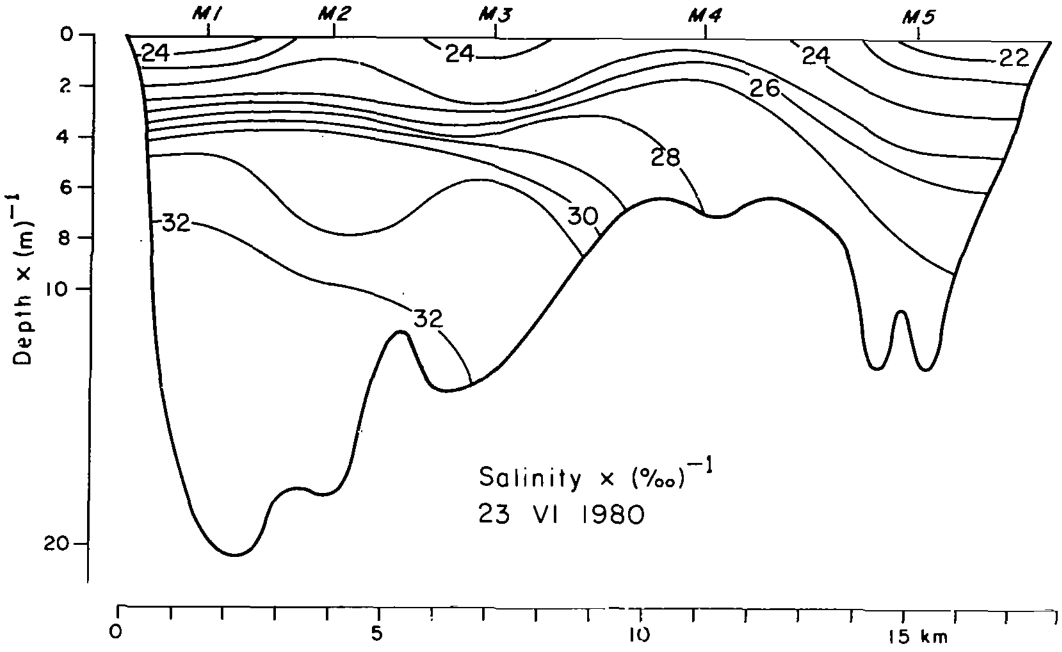


Figure 15.- Salinity distribution in the Chesapeake Bay mouth section for 23 June 1980. Vertical exaggeration is 500:1.

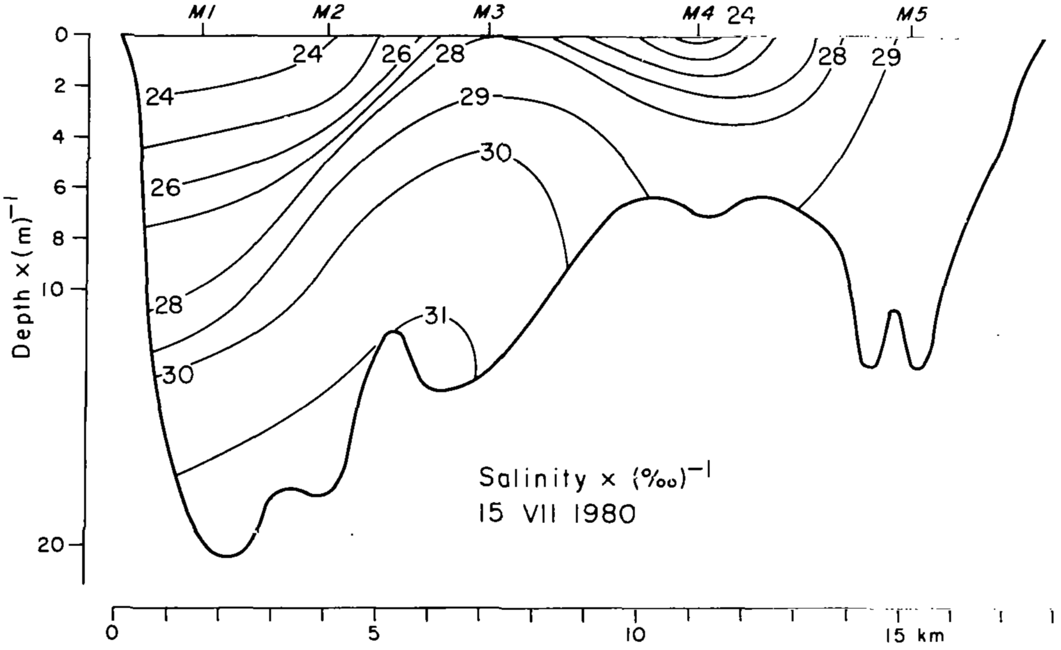


Figure 16.- Salinity distribution in the Chesapeake Bay mouth section for 15 July 1980. Vertical exaggeration is 500:1.