TEMPORAL AND SPATIAL VARIATIONS OF THE CHESAPEAKE BAY PLUME*

Evon P. Ruzecki
Virginia Institute of Marine Science
College of William and Mary

SUMMARY

Historical records and data obtained during the Superflux experiments are used to describe the temporal and spatial variations of the effluent waters of Chesapeake Bay. The alongshore extent of the plume resulting from variations of freshwater discharge into the Bay and the effects of wind are illustrated. Variations of the cross-sectional configuration of the plume over portions of a tidal cycle and results of a rapid-underway water sampling system are discussed.

INTRODUCTION

Waters from Chesapeake Bay exit at the Virginia Capes and usually extend towards the south as a near-surface feature. Bay waters in the contiguous area of the continental shelf can be identified by a number of characteristics which are discussed in most of the contributions to this volume. Discussions in these companion papers refer to turbidity plumes, nutrient plumes, phytoplankton or chlorophyll plumes, freshened-water plumes, and others. Although they may be treated as separate features, each of these plumes represents Bay water as identified by the observed constituent. Inconsistencies in the shape or location of these plumes in shelf waters result from two factors, (1) the time scale over which individual sets of observations were made, and (2) the non-homogeneous character of the Bay effluent.

This paper examines the shape of the Bay plume as determined by vertical measurements of salinity under varying Bay discharges of fresh water and over time scales ranging from half a tidal cycle (6.2 hr) to several days. Results of salinity measurements made during the Superflux experiments and a rapid method of obtaining surface truth data are also presented and discussed.

CONFIGURATION OF BAY WATER ALONG THE COAST

Theoretical Basis

Movement of water through the mouth of Chesapeake Bay is dominated by tidal oscillations and strongly influenced by winds and the history of freshwater discharge into the Bay through its tributaries. In general, over a series of tidal cycles and as a result of estuarine circulation, freshened Bay water exits at the surface on the southern side of the Bay mouth (Cape Henry), is deflected to

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the right by the Earth's rotation and the general circulation of shelf waters (refs. 1 and 2), and then proceeds towards the south as part of the general shelf circulation. Estuarine-type circulation of Chesapeake Bay results in movement of shelf waters into the Bay predominantly along the bottom in deeper channels and on the northern (Cape Charles) side over the multi-tidal time frame.

During an individual tidal cycle, flooding and ebbing occur over the entire cross-section of the Bay mouth; however, phase differences and variations in the strength and duration of flood and ebb currents result in the general nontidal water movements described above. The strength and duration of nontidal currents and the depression of Bay water salinities are affected by the recent (one- to two-month) history of freshwater addition to the Bay. Hence, both the salinity and alongshore extent of the Bay plume can be expected to change seasonally with fluctuations in runoff. The general position of the Bay plume is subject to change in response to wind conditions. In particular, winds from the southern sector will tend to impart an offshore (eastward) component to the plume as a result of Ekman circulation (ref. 3).

During the summer of 1962, Harrison et al. (ref. 4) measured currents in the vicinity of Cape Henry and Virginia Beach, Virginia. They inferred from their data that nontidal surface currents in this region result in an anti-cyclonic eddy located between Cape Henry and Rudee Inlet (36°56' N to 36°50' N) centered approximately 3 km from the beach, as shown in figure 1(a). This eddy could result from flood and ebb current patterns shown in figures 1(b) and 1(c) where ebbing (easterly and southerly) currents are strongest at Cape Henry and some distance seaward of Virginia Beach and flooding (northerly) currents south of the Bay mouth are strongest close to shore (ref. 5). Hydraulic model tests (ref. 6) and field studies indicate a surface-to-bottom phase difference in currents at the Bay mouth with more saline bottom water from the continental shelf starting to flood before fresher surface water and surface water ebbing occuring prior to ebbing of bottom water.

Based on these considerations, the effluent from Chesapeake Bay should appear, in shelf waters, as a lens of freshened water (with high concentrations of Bay water constituents) extending offshore and towards the south at the end of an ebbing tide. Half a tidal cycle later this effluent plume should show a partial retraction (back into the Bay) of its northernmost portion, with dilution and southerly transport of the southernmost portion. Previous extensions of the plume might be identifiable along the coast towards the south as they move with the general shelf circulation, but they would be diluted by mixing with ambient shelf water (ref. 7). The combined effects of wind and runoff would result in offshore displacement coupled with horizontal widening and vertical thinning of the plume in response to winds with a component from the south, onshore displacement coupled with horizontal narrowing and vertical thickening in response to winds with a component from the north, and fresher water (with higher concentrations of Bay constituents) extending further south in response to increased river flow. Tidal variations and freshwater discharge effects on the Bay effluent are evident from sets of data taken near the mouth of Chesapeake Bay and in contiguous shelf waters.

Historical Evidence

Several data sets (available from the VIMS data archives) can be used to describe the influence of tides and river flow on the Bay plume. On May 9 and 10, 1973 the Virginia Institute of Marine Science (VIMS) of the College of William and Mary and the Chesapeake Bay Institute (CBI) of the Johns Hopkins University conducted a joint cruise which occupied stations in the triangular area between Cape Charles, Cape Henry, and the Chesapeake Light Tower. Stations were 1.8 km (1 n. mi.) apart (fig. 2(a)) and were each occupied twice to coincide as closely as possible with flooding and ebbing tides. Results of salinity measurements at these stations during flood and ebb are shown in figures 2(b) and 2(c), respectively. Relationships between predicted tidal currents (at $36^{o}58.8'$ N, $76^{o}00.4'$ W) and ship arrival at locations A, B, and C are shown to the left of each figure. It is evident from figure 2(b) that a flooding tide compressed the core of the Bay plume towards the Virginia Beach/Cape Henry region (location C), and lower salinity water (less than 26 $^{o}/oo$) extended as a veneer less than 5 m thick one-third of the way across the Bay mouth. During the ebbing tide (fig. 2(c)) the plume left Cape Henry and extended towards the south. It was centered approximately 10 km from the beach and remained in the upper 5 m of the water column. This response of the plume to tidal forcing agrees with the hypothetical circulation patterns shown in figures 1(b) and 1(c). Winds on May 10, 1973 averaged 3.8 m/sec (7.5 kt) from the north-northeast and appear to have had little effect on the plume.

Three other data sets provide information for comparisons of the Bay plume under differing conditions of freshwater inflow. Data from a temperature/ salinity survey of shelf waters in March of 1967 show a high concentration of Bay water moving as a plume parallel to the Virginia coast approximately 15 km offshore as indicated in figure 3. Stations a through h were occupied in alphabetical order during a six-hour period covering the last part of ebb and the first part of the flooding tide on March 18. Stations i through m were occupied a day later during similar portions of the tidal cycle. Bay water in the shelf region is indicated by envelopes representing fractions of Bay water based on salinity measurements according to:

$$f = \frac{S_s - S_m}{S_s - S_b}$$

where S_s is the salinity of shelf water, S_b is the salinity of Bay water, and S_m is the measured salinity. The quantity S_s represented the ambient bottom salinity 30 km east of the Bay mouth (32.5 $^{o}/oo$), while S_b was the lowest surface salinity at the Bay mouth (25.5 $^{o}/oo$).

Average daily discharges of fresh water into Chesapeake Bay for January, February, and March 1967 were on the order of 1.3, 1.2, and 3.5 × 10^3 m^3/sec and represented between 50 and 78% of the average flows for these months for the period from 1929 to 1966 (2.3, 2.8, and 4.3 × 10^3 m^3/sec respectively) (ref. 8). Surface winds during the sampling period started at 0.8 m/sec (1.5 kt) from the north on March 18, increased and veered to blow from the south-southeast at 7.5 m/sec (15 kt) the night of March 18-19, and moderated slightly to 6 m/sec (12.5 kt) from the south-southeast the following night. Bay water configurations shown in figure 3 are therefore a first approximation of the three-dimensional shape of the plume under conditions of below-average spring discharge and an ebbing tide but widely varying wind conditions. Stations a through h show the base of the plume (a-b) with a submerged parcel of mostly shelf water off Cape Henry (at b) and a thick parcel of mostly (>50%) Bay water off Rudee Inlet (at d). The latter may represent the most southerly extension of Bay water on this particular ebbing tide. Lower concentrations of Bay water found at stations e through h are assumed to be residual from the previous tide. The seaward extension of a thin layer of Bay water sampled at stations i through m was in response to the strong southerly winds. This offshore component of surface waters would have to be replaced by an onshore intrusion of bottom water, a secondary response to surface wind stress suggested at stations i and j where an intrusion of bottom shelf water was directed towards the Bay mouth from the east-southeast. With these allowances for the wind shift, figure 3 shows the general configuration of the Bay plume at the end of ebb tide under conditions of a depressed spring discharge.

An extreme event of high freshwater discharge into Chesapeake Bay occurred as a result of the passage of Tropical Storm Agnes at the end of June 1972. Results of VIMS shelf cruises on July 6-8 and August 3-4, 1972 (ref. 7) are presented as figures 4 and 5 and show the general plume configuration in response to this high discharge. (Tropical Storm Agnes increased discharge into Chesapeake Bay from 2.1×10^3 m^3/sec on June 20 to an average of 48.1×10^3 m^3/sec on June 23-24. Previous average June flows were 1.8×10^3 m^3/sec.) Figure 4 shows the plume fifteen days after peak discharges into the Bay (Bay salinity, S_b, was taken to be 18 $^o/oo$ and shelf salinity, S_s, 32.5 $^o/oo$) with a higher concentration of Bay water extending towards the south in the same general configuration as the March 1967 plume (fig. 3) but closer to shore. Two weeks later (fig. 5) a much greater impact of the Agnes flooding was evident. Patches of Bay water were encountered as far south as Oregon Inlet, North Carolina, and the region normally subjected to 25% Bay water was covered with 100% Bay water (for fig. 5, S_b was taken to be 16 $^o/oo$ and S_s remained at 32.5 $^o/oo$). The two patches of 60% Bay water located 78 and 133 km from the Bay mouth indicate nontidal shelf currents on the order of 1.5 m/sec, assuming they are residuals from previous ebb tides. Bay water concentrations of 40% covered an area in excess of 5.5×10^3 km^2 and remained in the upper 10 m of the water column. During both sampling periods (July 6-9 and August 3-4) winds were moderate (<4 m/sec) from the northeast. Wind effect on the plume would have been to confine it to the coast and possibly force it to be deep and narrow.

Configurations of the Bay plume as represented by figures 3, 4, and 5 are based on data collected over 2- to 3-day periods and therefore suffer from lack of simultaneity. They do, however, illustrate large variations in the extent of the plume which result from extremes in the addition of freshwater to Chesapeake Bay.

SUPERFLUX EXPERIMENTS

One of the objectives of the Superflux experiments was to determine the impact of effluents from large estuaries on waters of the continental shelf. To meet this objective, the extent of the plume from Chesapeake Bay was measured using the best and most rapid techniques available. Information from aircraft-borne state-of-the-art remote sensors was augmented with shipboard surface-truth measurements and samples. The procedure allowed the measuring of surface features over a large area in a short time but provided only widely spaced vertical sampling at selected locations within the plume and the adjacent Bay and shelf areas. As expected, the remote sensing aspects of the Superflux experiments revealed the two-dimensional structure of the plume with respect to salinity, chlorophyll, suspended solids, and other constituents of surface waters in much greater detail than the traditional sampling used to estimate its three-dimensional character as shown in figures 3, 4, and 5. Additionally, the compressed sampling time (hours as opposed to days) provided better simultaneity to this synoptic coverage than had been available previously. Similar rapid coverage of only the plume area could have been accomplished in two to three hours using traditional sampling methods; however, such an experiment would have required seven fast (15-kt) ships each equipped with a fast CTD (conductivity, temperature, and depth instrument) and underway sampling equipment. It would have provided vertical as well as horizontal measurements, but ship, personnel, and equipment requirements would have been most difficult to satisfy.

In an attempt to obtain information on the cross-sectional configuration of the plume and on the horizontal distribution of temperature, salinity, and chlorophyll in the plume and adjacent waters using in situ sensors, VIMS conducted pilot studies between remote sensing flights during the Superflux experiments. Temperature/salinity measurements were made along a section of closely spaced stations extending seaward from the vicinity of Rudee Inlet, using a Brown CTD. Between stations, the CTD was incorporated into a flow-through system which pumped water from a depth of 1 m and passed it through a fluorometer to measure chlorophyll content. When the section was completed the system remained operative while the research vessel moved to the next Superflux station to obtain additional surface truth data. As the experiments progressed, two additional fluorometers were added to the flow-through system and, in final configuration, temperature, salinity, dissolved oxygen, two chlorophyll bands, and nephelometry were measured. All data were recorded on both strip charts and magnetic tape with a voice channel on the latter for time, position, and sample identification information. The flow-through system was mounted on the research vessel CAPT. JOHN SMITH as shown in figure 6.

Data Collection

Cross-plume sections of closely spaced (1 to 2 km) stations were occupied between overflights of remote sensing instrumentation during all three Superflux experiments. Whenever possible, the flow-through system was operated between stations. Cruise tracks and cross-plume section locations are shown in figures 7(a), 7(b), and 7(c) and are labeled to indicate the date each was run. Sections are shown as boxed regions and were located off Rudee Inlet on March 19 and June 24 and off Virginia Beach on October 15-16. An additional section was occupied across the Bay mouth on October 15-16 (fig. 7(c)). The section of Rudee Inlet was sampled once on March 19 and five times on June 24. The Bay mouth and Virginia Beach sections were each sampled three times on October 15 and four times on October 16 (these data were collected with the assistance of

C. S. Welch and the VIMS 1980 Introduction to Physical Oceanography class). Data on freshwater discharge into Chesapeake Bay for the period from January to October 1980 were obtained from the U.S. Geological Survey (ref. 9) and wind data for the five-day period prior to cruises were obtained from Norfolk Airport, 40 km west of the study area. Tidal current information was based on NOAA predictions in Tidal Current Tables 1980 (ref. 10).

Results and Discussion

Average streamflow data for January through October 1980 (fig. 8) along with multiannual average streamflow for the same months show that flows during February 1980 (prior to Superflux I) were less than half the normal February flows, and although April flows were higher than average, flows in June (during Superflux II) were below average as were those prior to Superflux III (August, September, and October). Thus, the seaward or alongshore extension of the Bay plume was probably not as great during the Superflux experiments as it would have been in more "normal" years. Winds measured at Norfolk for the five-day periods prior to each sampling of the plume cross-section are shown as stick plots in figure 9.

Cross-Plume Salinity Sections.- The cross-sectional configuration of the Bay plume is illustrated by positions of isohalines as functions of depth and distance offshore. During Superflux I, the section off Rudee Inlet was occupied just prior to noon on March 19 during the flooding portion of the tidal cycle and figure 10 shows that the core of Bay water, centered 2-3 km from the beach, was confined to the upper 8 m of the water column (as indicated by the 27 $^{o}/oo$ isohaline). From 5 to 12 km offshore, Bay water is confined to the upper 3 m of the water column. This seaward extension of surface plume water may have been caused by winds blowing offshore just prior to sampling.

This general configuration of the Bay plume off Rudee Inlet (nearshore core with an offshore surface extension) was again evident on June 24 (fig. 11). This short time series of sections shows the plume core initially 1 km offshore and migrating seaward as lower salinities reach the section sampled. The offshore extension of surface water is again evident but not as pronounced as in March, although winds were generally from the south prior to sampling. Sampling was conducted during the latter half of the ebbing tide and the southerly progression of Bay water is evident from the widening and deepening of the area covered by the 23 and 25 $^{o}/oo$ isohalines.

Results of salinity measurements made across the Bay mouth and off Virginia Beach on October 15-16 are shown in figures 12 and 13 (note the reversal of the time axis in these figures when compared to fig. 11). The dashed lines in these figures indicate secchi depth, Cape Henry is on the left in figures 12(a) and 13(a), and Virginia Beach is on the left in figures 12(b) and 13(b). At the Bay mouth, two parcels of freshened water were evident (off Cape Henry and in the centered portion of the Bay) during the first maximum ebb current sampling on October 15 (fig. 12(a)). Intrusions of high salinity water at the bottom and along the Cape Charles (northern) portion of the Bay mouth are evident during the flooding portion of the tidal cycle. During the following ebb (1600 to 2100 hr in fig. 12(a)) the salinity structure bore a closer resemblance to flooding rather than ebbing conditions, a situation that is contrary to what is expected considering tide and wind conditions (see fig. 9). Off Virginia Beach during this same time (fig. 12(b)) a lens of freshened water was evident at the beginning of the flood portion of the tidal cycle and the seaward portion of the Bay plume was delineated by a strong frontal region 15 km offshore. The final Virginia Beach sections on October 15 show an offshore migration of the plume and an onshore extension and upward movement of higher salinity bottom water. Bay mouth conditions the following day (fig. 13(a)) show a somewhat well-defined plume base near Cape Henry; however, lowest surface salinities were measured during the predicted flooding portion of the tidal cycle. The core of high salinity bottom water remained within 5 km of Cape Henry but showed a northward migration during the flooding tide and a southerly migration during ebb. The parcel of low salinity surface water off Cape Charles on the first section (approximately 0900 on October 16) is most likely a remnant of the Bay plume from the previous tide. Winds on October 15-16 were from the south (fig. 9) and probably served to transport the Bay plume and other surface waters offshore and to the north. During the following flooding tide (0900 on October 16) Bay water returned from offshore and entered around Cape Charles. Support for this suggestion of recirculation of the Bay plume is available from salinity data collected off Virginia Beach on October 16 (fig. 13 (b)). Here, lowest salinities were found 15 km offshore during the start of the flood portion of the tidal cycle when a well-pronounced plume should have been evident close to shore.

Figures 10 through 13 therefore illustrate changes in the cross-sectional structure of the Bay plume that result from variations in freshwater additions to Chesapeake Bay (high springtime flows, moderate late spring flows and very low late summer flows) and local wind conditions (wind from the southerly and northerly sectors).

Flow-Through System Results.- An example of the raw output from the flow-through system (fig. 14) shows substantial fine-scale variation in the output signals from the Brown CTD (conductivity and temperature) and two Turner design fluorometers (fluorescence and nephelometry). Records of this sort have been processed for the triangular-shaped cruise track run on March 19, 1980 (see fig. 7(a)) to yield 30-second averages of temperature, salinity, and fluorescence. This cruise track is shown in greater detail in figure 15. In this figure "event" marks, where loran positions were taken, are shown as numbered x's and each dot along the cruise track is the approximate midpoint of a 30-second average. Superflux station locations, times, observed fronts, and the positions of stations along the Rudee Inlet section are also shown. Measurements of temperature, fluorescence, and computed salinity along this cruise track are shown in figure 16. As in figure 15, each 30-second average is represented by a data point. Frontal regions are clearly evident (events 14, 19, and 28-29) and show temperature, salinity, and fluorescence differences between the Bay plume and adjacent shelf waters.

When displayed on a T/S (temperature/salinity) correlation diagram (ref. 11), comparisons between salinity, temperature, and chlorophyll content (as fluorescence) can be made. To do this, each 30-second averaged value of fluorescence was identified with its associated T/S class (class width of 0.5^{o}C and 0.5 ^{o}/oo). The sum of all fluorescence values in each T/S class was then normalized against the grand total of all fluorescence values. The total number of temperature, salinity, and fluorescence samples for each T/S class was normalized in a similar way to determine sample distribution in T/S space. Plots of both results are shown as figures 17(a) and 17(b) with T/S classes which sum to 75% of all fluorescence or samples measured enclosed in a heavy line and classes which total 50% of all fluorescence or samples measured marked with a closed circle in the upper right corner. In both cases, the predominant modes representing most fluorescence and greatest number of measurements run from 6.5°, 22 °/oo to 4.5°, 28 °/oo. If fluorescence-producing material were uniformly distributed over the study area, figure 17(a) would be a duplicate of figure 17(b). The difference between figures 17(a) and 17(b) is presented as figure 17(c) and shows greater-than-uniform fluorescence in the modal classes between 22 and 24 °/oo and the classes between 25.5 and 28 °/oo with greatest elevations at 22 to 23 °/oo and 26.5 to 27.5 °/oo (classes in figure 17(c) with negative values have a large bar across the number). These two groups of classes represent 19.88 and 10.29% of total fluorescence and 15.29 and 7.48% of all samples, respectively. The fluorescence-depressed class within the 75% mode represents 19.83% of total fluorescence and 28.96% of all samples. This crude analysis suggests two populations of fluorescence-producing materials associated with lower (Bay) salinities and higher (shelf) salinities. A more thorough investigation of this condition can be accomplished by comparing results of remote sensors designed to measure fluorescence with those which measured salinity. Indeed, the next reasonable step to take in the Superflux program would be a thorough comparison of remotely sensed and in situ data.

CONCLUSIONS

Previously collected data show the response of the Chesapeake Bay plume to large fluctuations in freshwater discharge and variations over a tidal cycle. Rapid sampling of closely spaced stations during the Superflux experiments provided information on the vertical character of the Bay plume at selected locations and indicated fluctuations in width and depth of this feature over a tidal cycle. These measurements also showed that the surface wind stress can easily displace the plume in a short period of time. Data of this sort, when coupled with remotely sensed data, provide a third and fourth dimension to information on the spatial and temporal character of features such as the Chesapeake Bay plume. Comparison of remotely sensed data with in situ measurements is the next logical step in the Superflux program.

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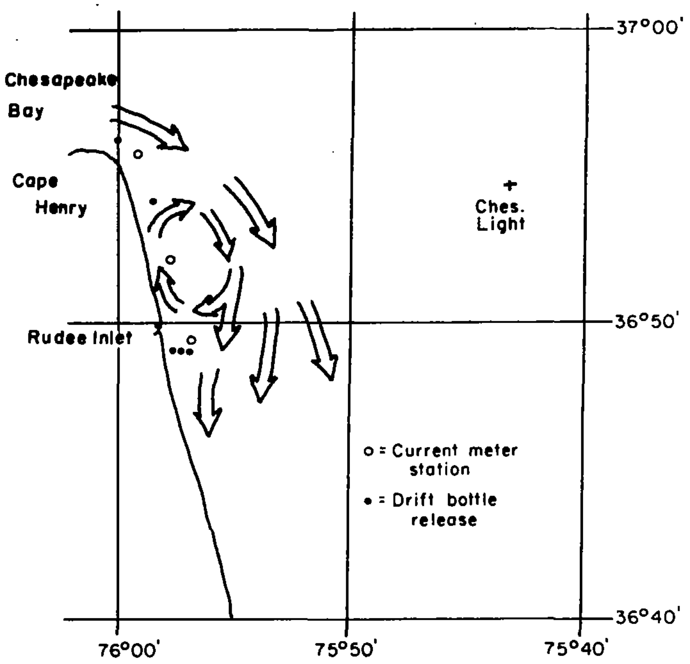
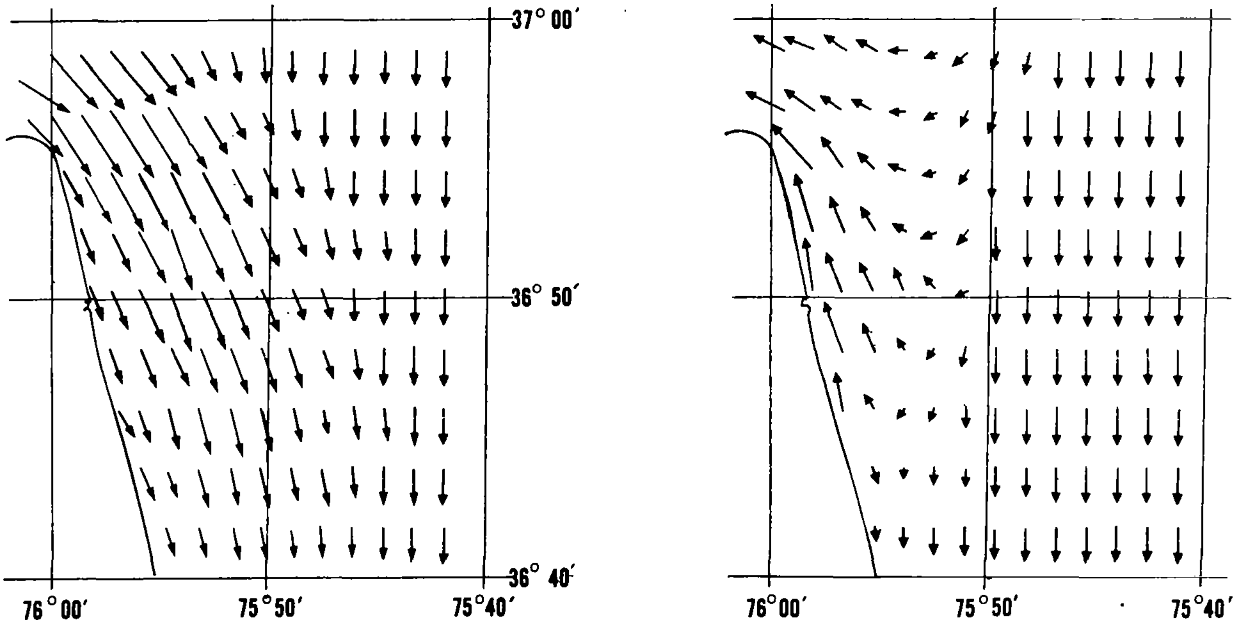


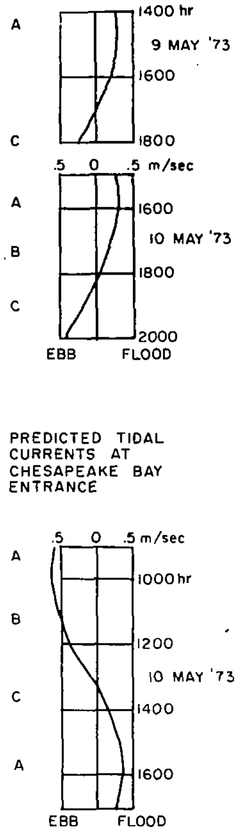
(a) Nontidal residual configuration.

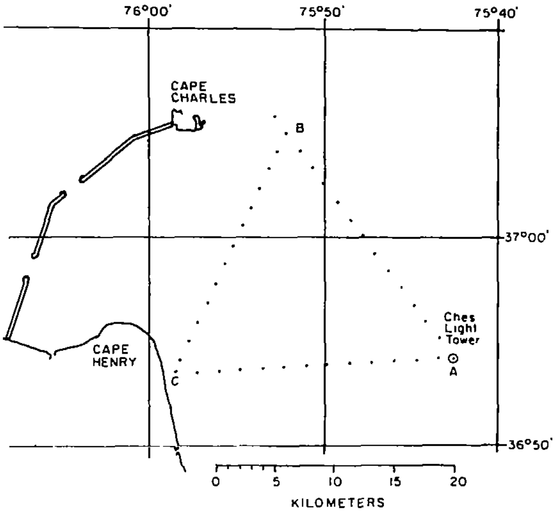


(b) Hypothesized ebb configuration.

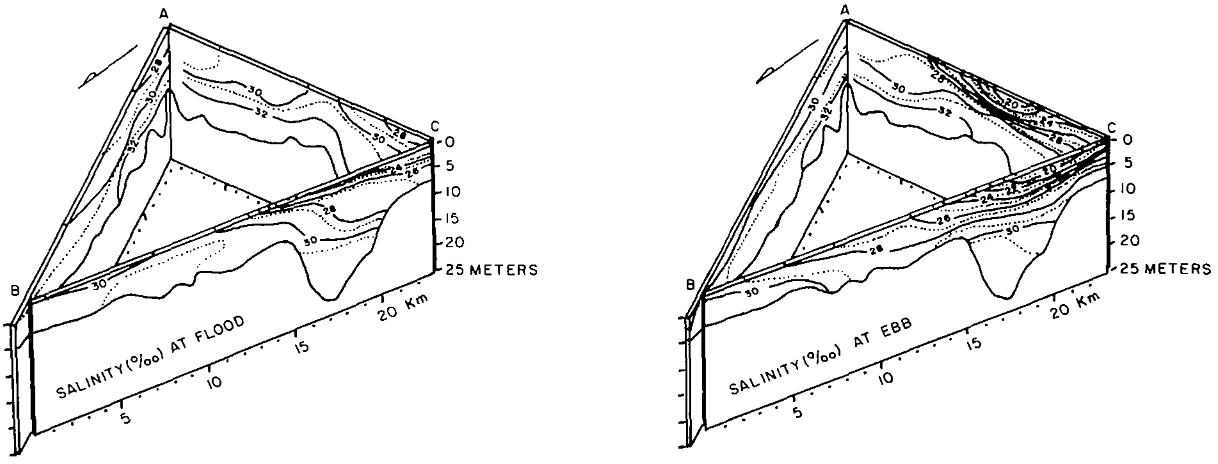
(c) Hypothesized flood configuration.

Figure 1.- Schematic representation of surface currents off Cape Henry and Virginia Beach, Va., showing nontidal residual and hypothesized ebb and flood configurations.





(a) Station locations.



(b) Flood conditions.

(c) Ebb conditions.

Figure 2.- Flood and ebb salinities at the mouth of Chesapeake Bay on May 9 and 10, 1973.

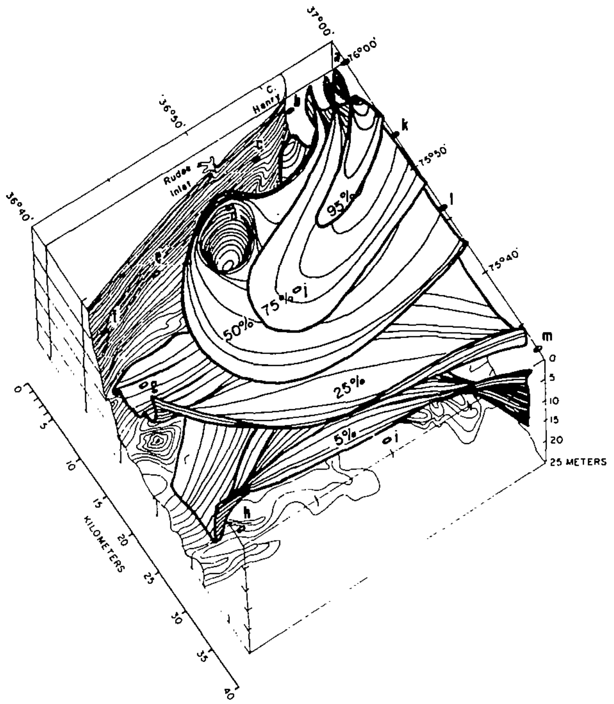


Figure 3.- Envelopes representing various fractions of Bay water on the continental shelf during March 18 and 19, 1967.

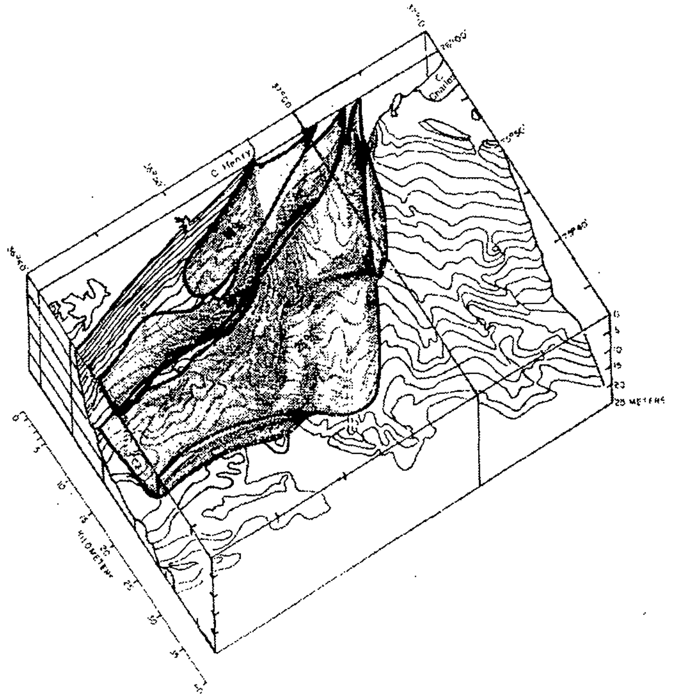


Figure 4.- Fractions of Bay water on the continental shelf on July 6-8, 1972, 15 days after peak flooding from Tropical Storm Agnes.

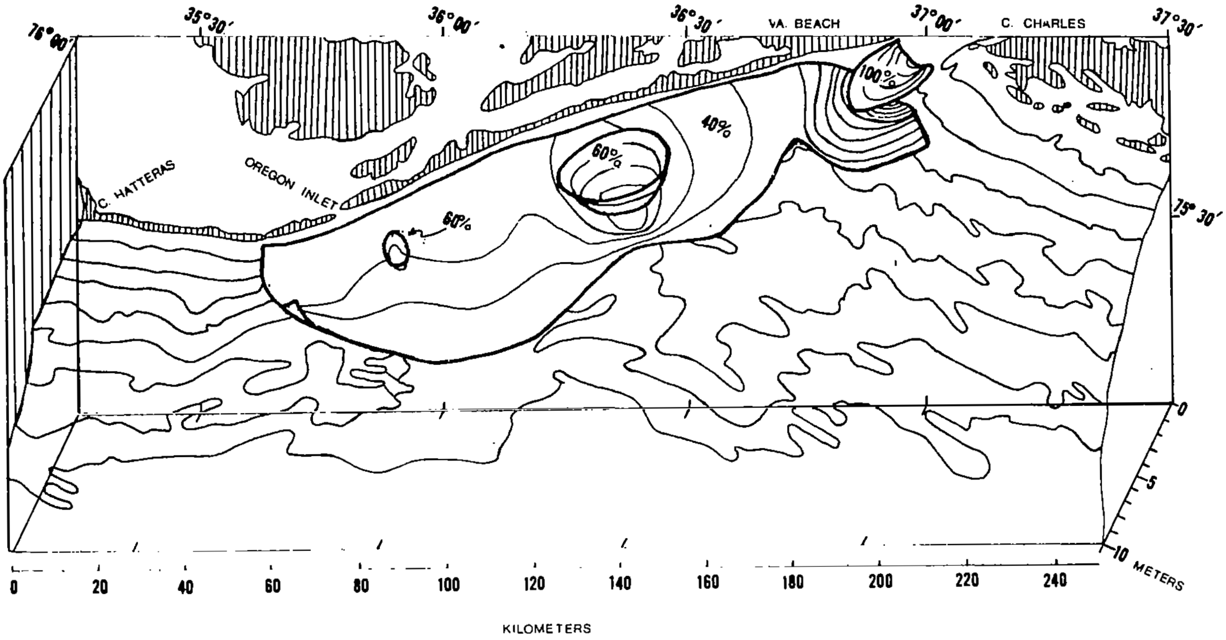


Figure 5.- Fractions of Bay water on the continental shelf on August 3 and 4, 1972, 41 days after peak flooding from Tropical Storm Agnes.

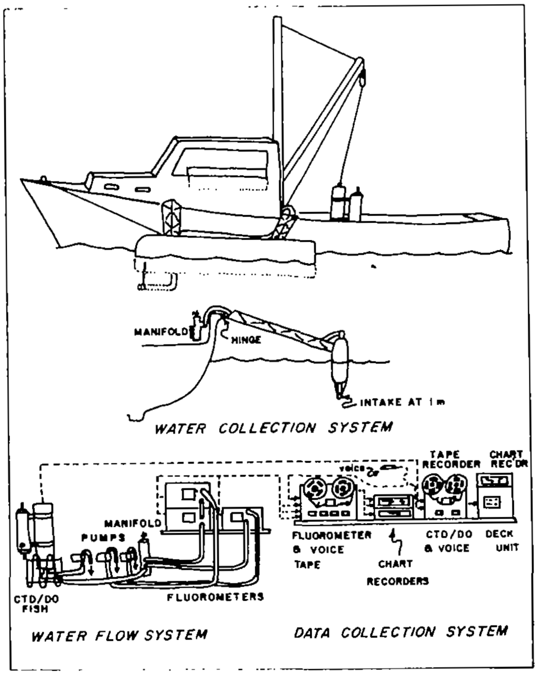


Figure 6.- Flow-through system used to collect temperature, salinity, D.O., chlorophyll, and nephelometry data from a depth of 1 m while cruising at 5 m/sec (10 kt).

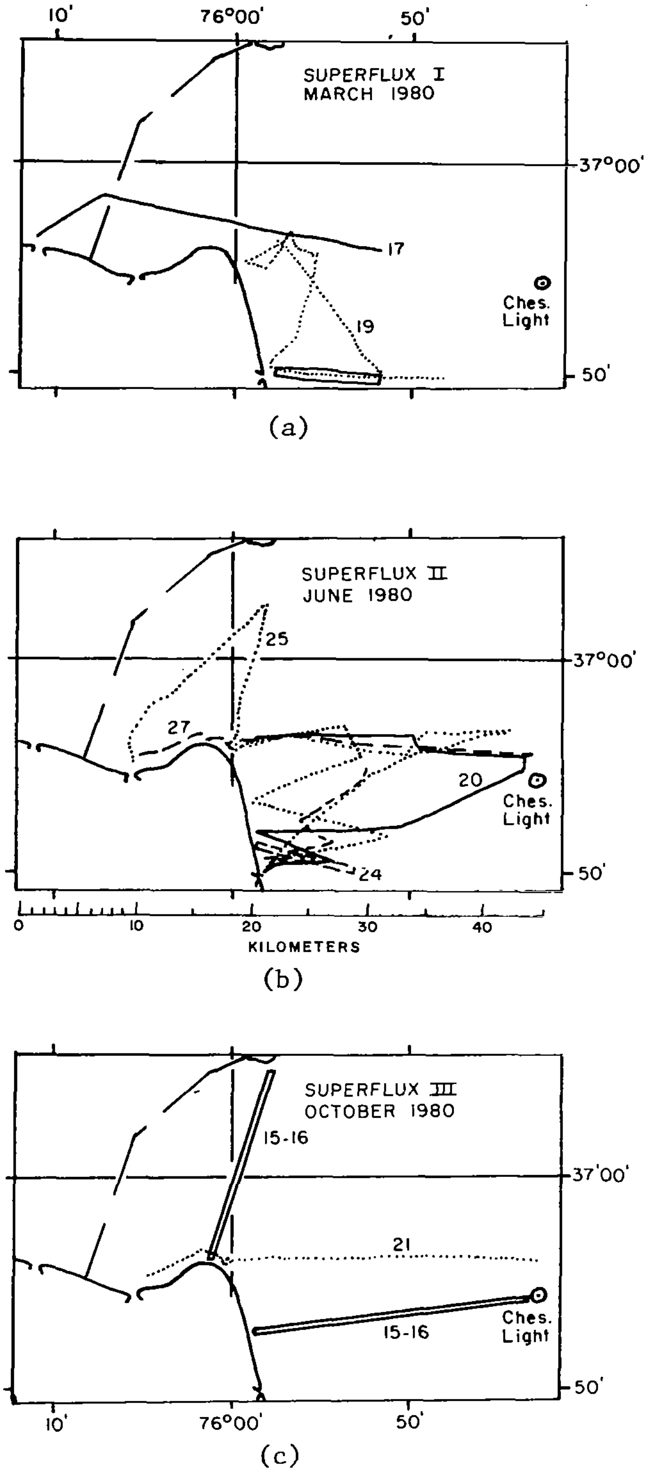


Figure 7.- Cruise tracks of R/V CAPT. JOHN SMITH during Superflux experiments. Sectional data were obtained from boxed regions on March 19, June 24, and October 15 and 16, 1980.

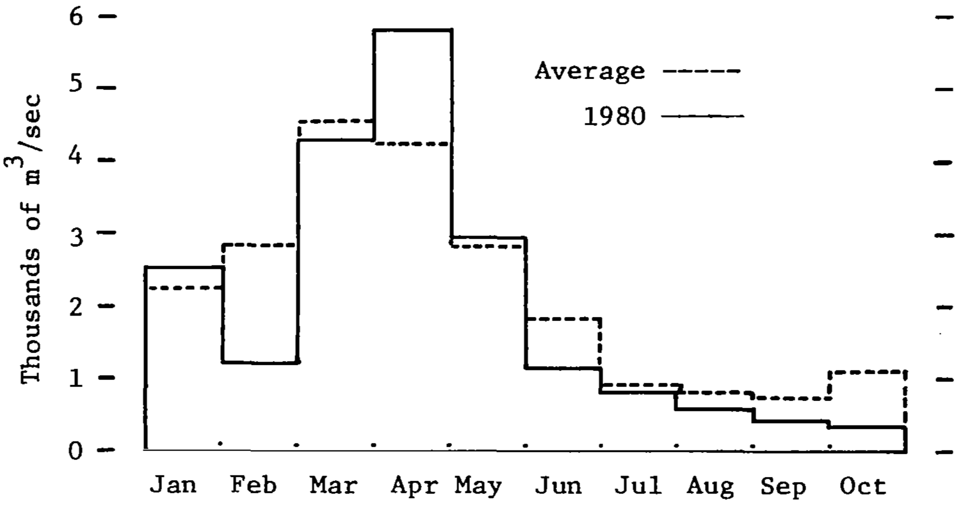


Figure 8.- Average monthly streamflow into Chesapeake Bay for the months January through October. Multiannual averages are dashed lines, 1980 averages are solid lines.

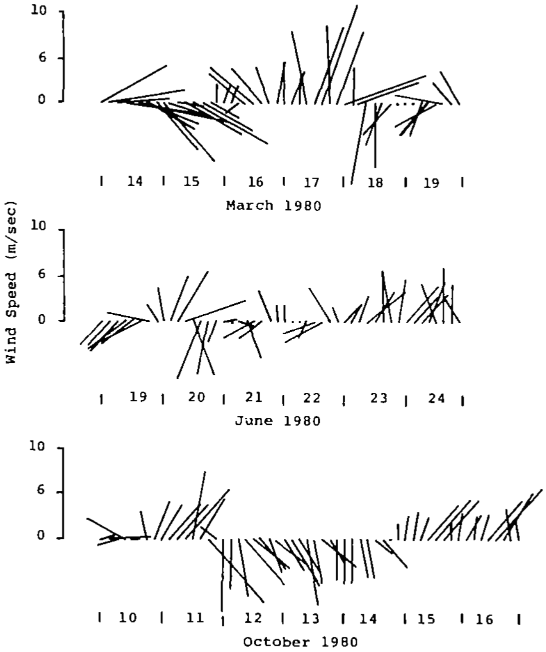


Figure 9.- Stick plots of winds at Norfolk, Va. for five-day periods prior to plume section sampling on March 19, June 24, and October 15 and 16, 1980. North is to the top of the page and sticks point in the direction the wind was blowing.

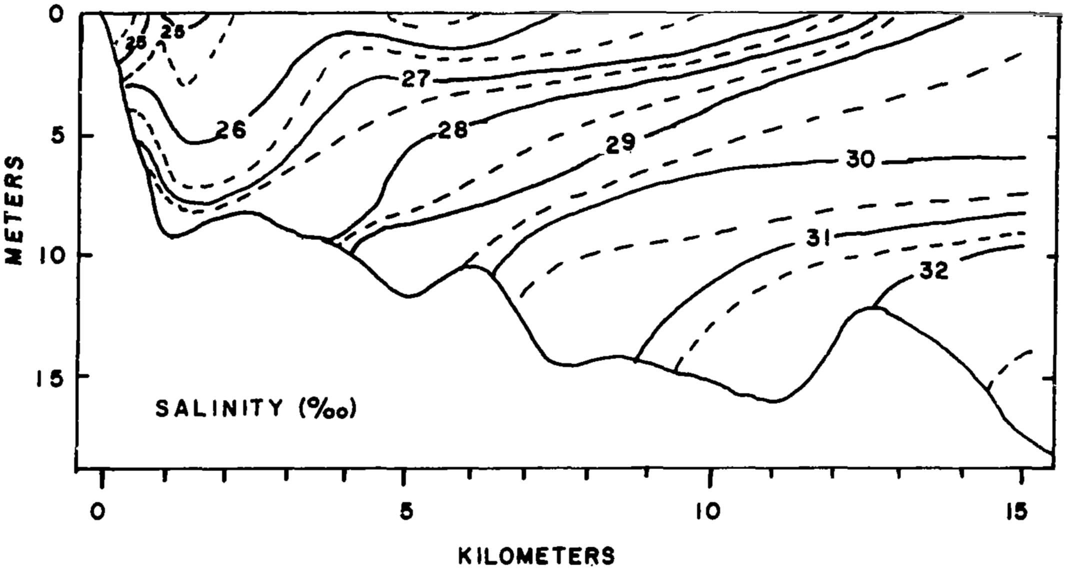


Figure 10.- Salinity distribution off Rudee Inlet on March 19, 1980.

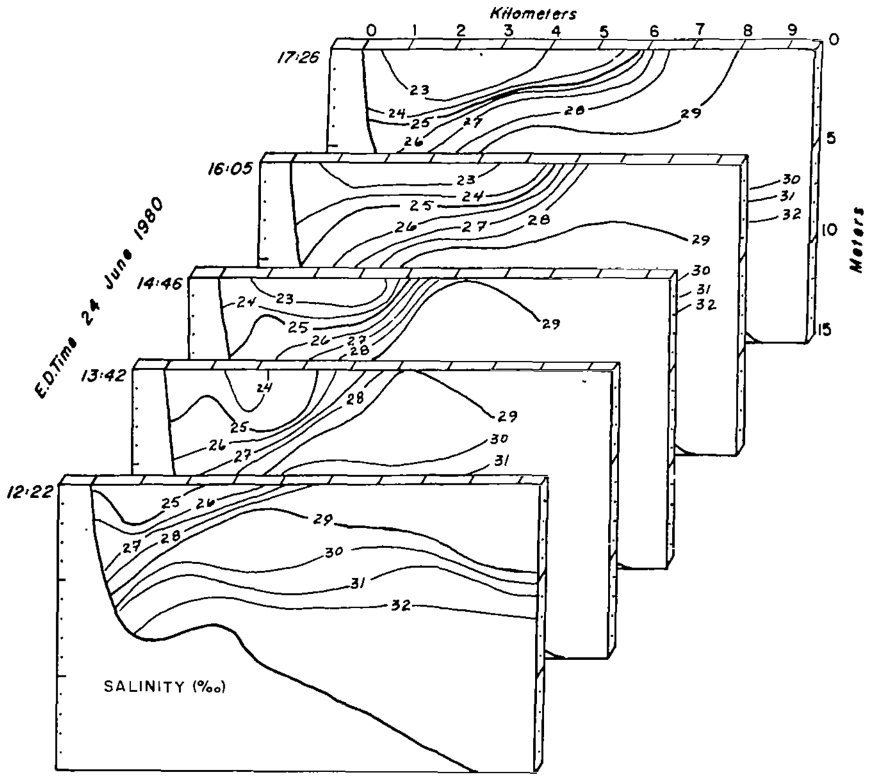
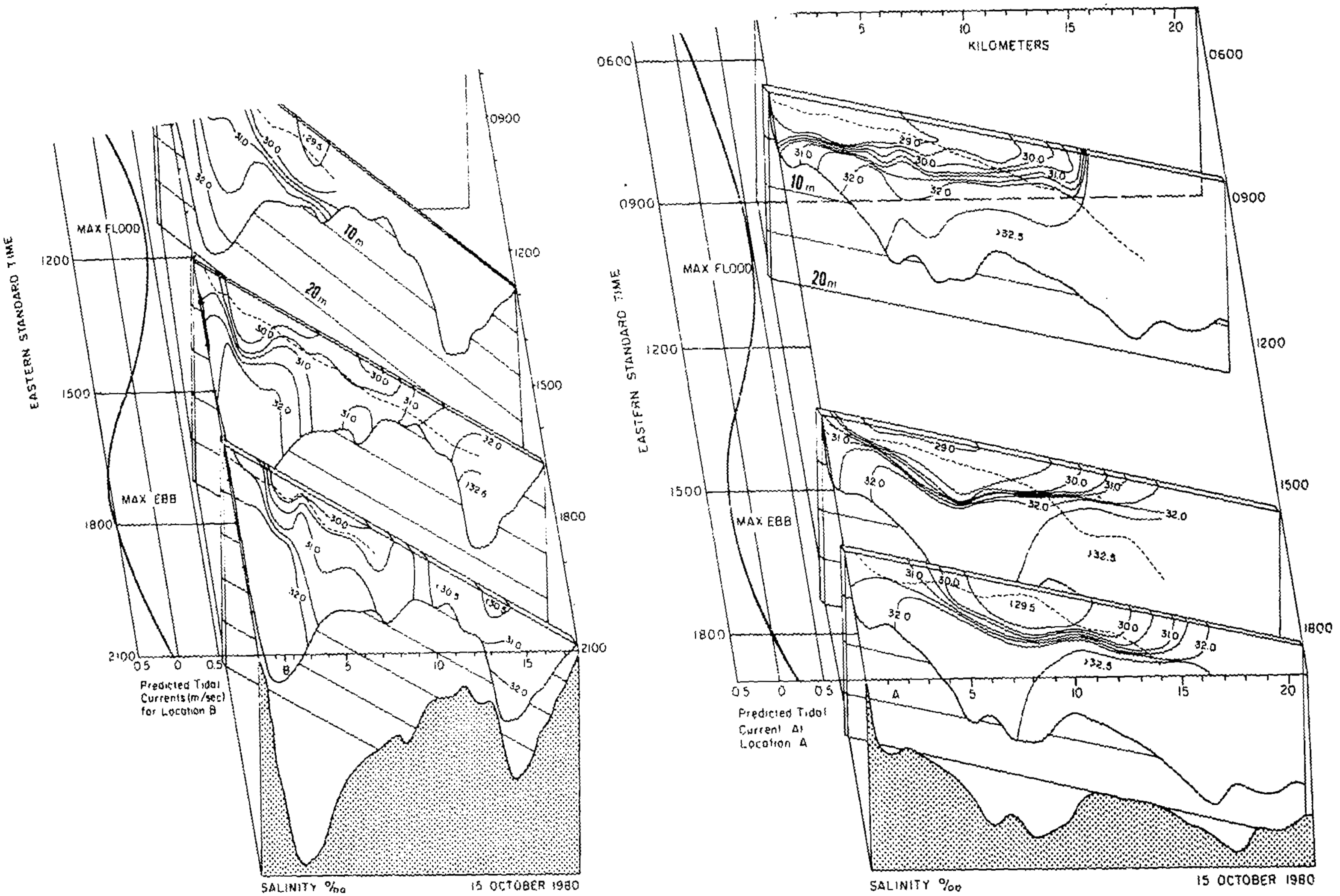


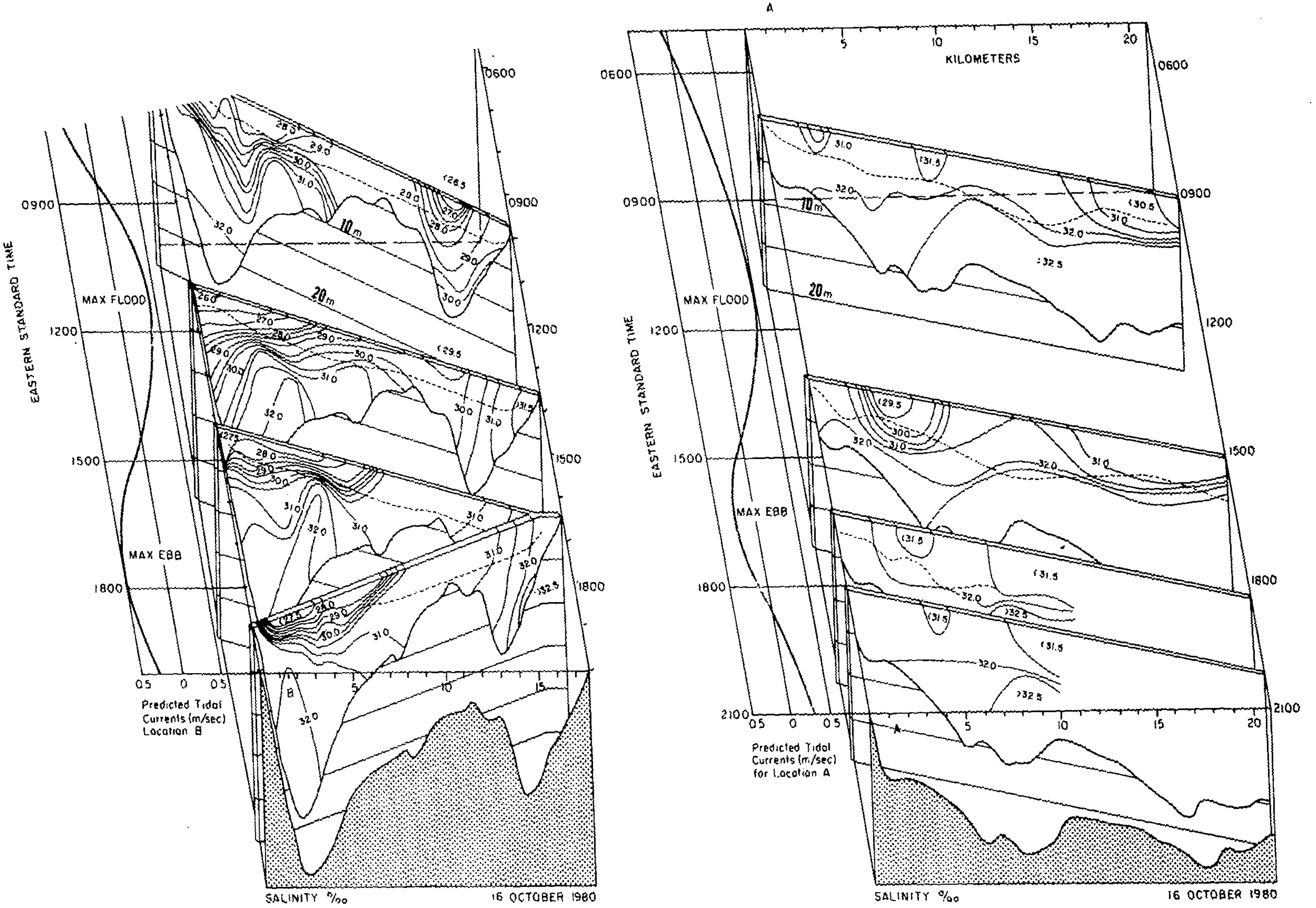
Figure 11.- Salinity distribution off Rudee Inlet on June 24, 1980.



(a) Bay mouth.

(b) Virginia Beach.

Figure 12.- Salinity structure across the Bay mouth and off Virginia Beach on October 15, 1980. Rotation of each section with respect to the time axis indicates time elapsed during sampling. Dashed lines indicate secchi depth.



(a) Bay mouth.

(b) Virginia Beach.

Figure 13.- Salinity structure across Bay mouth and off Virginia Beach for October 16, 1980.

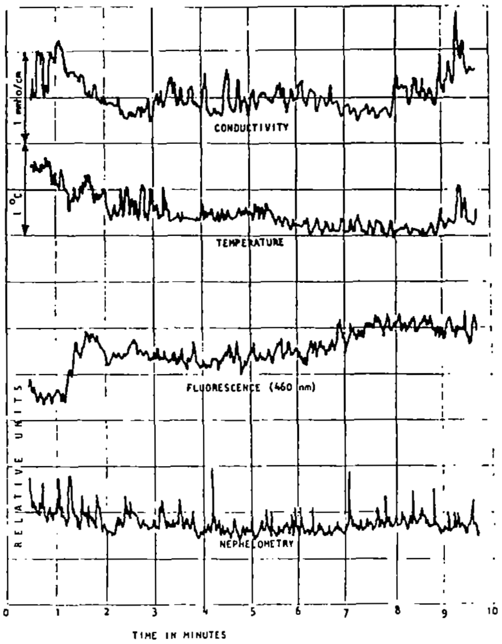


Figure 14.- Example of analog records of conductivity, temperature, fluorescence, and nephelometry obtained from the flow-through system (fig. 6) June 27, 1980.

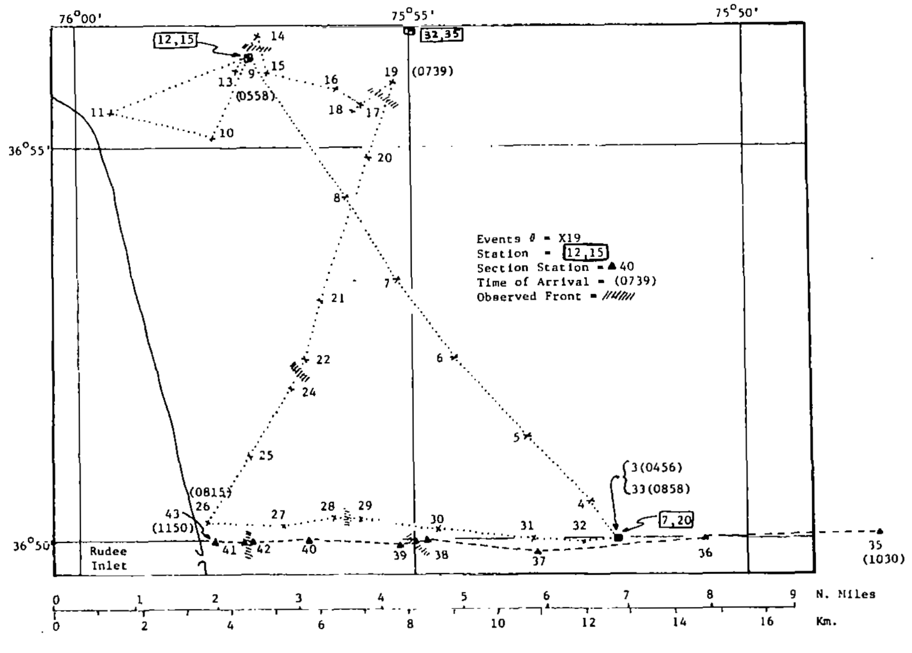


Figure 15.- Detailed cruise track of R/V CAPT. JOHN SMITH on March 19, 1980.

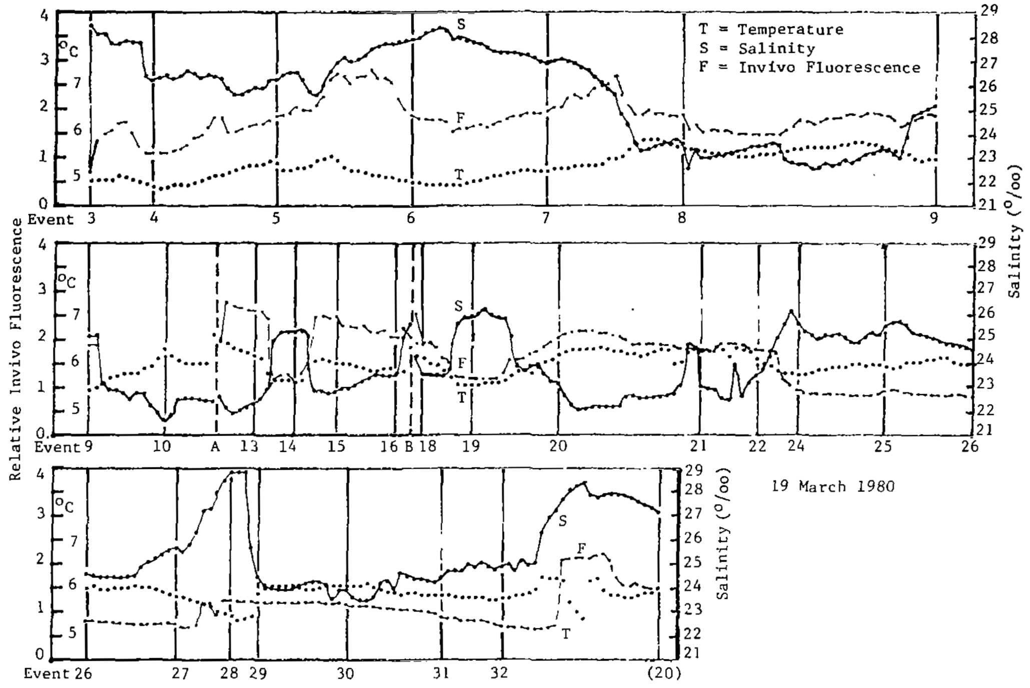
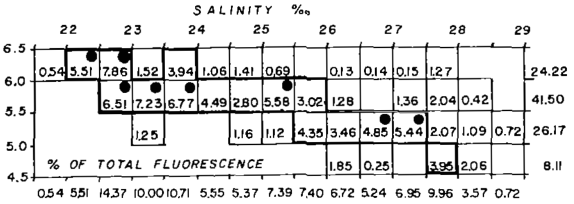
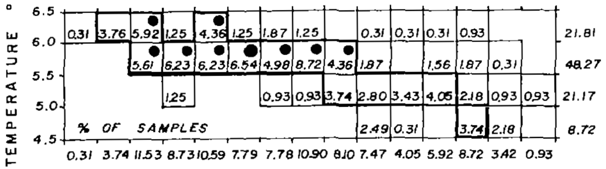


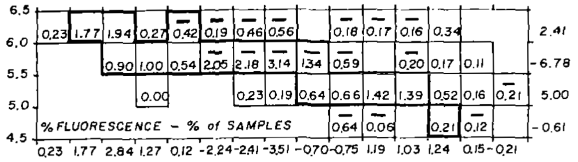
Figure 16.- Temperature, salinity, and fluorescence data obtained along cruise track shown in figure 15.



(a) Total samples.



(b) Samples measured.



(c) Difference between (a) and (b).

Figure 17.- Temperature/salinity correlation diagrams showing percent of total fluorescence, percent of samples measured, and their difference for temperature, salinity, and fluorescence data displayed in figure 16.