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**Slope Water Intrusions within the Nearshore
Waters Off Long Island, New York**

by

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Technical Report

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Table of Contents

	Page
Abstract	3
1. Introduction	4
2. Background	6
2.1 The Coastal Boundary Layer Transect Project	6
2.2 Properties of Nearshore Flow and T/S Variations	7
3. Intrusion 1: September 1974	12
3.1 COBOLT Observations	12
3.2 Possible Origin and Driving Mechanisms	14
4. Intrusion 2: August 11-19, 1978	26
4.1 COBOLT Observations	26
4.2 Possible Origin and Driving Mechanisms	28
5. Intrusion 3: September 1978	49
5.1 COBOLT Observations	49
5.2 Possible Origin and Driving Mechanisms	50
6. Summary and Discussion	59
Acknowledgements	61
References	62

Abstract

From 1974 through 1978 intensive measurements were made of the salinity, temperature and current structure of the waters within 12 km of the Southern Long Island coastline. The data were derived from two sources: a mooring array from which time series of temperature, salinity and water velocity were measured at four depths at each of four offshore distances; and high resolution, daily STD and current meter surveys. During August and September intrusions of slope or outer shelf water were often observed by the STD surveys. Three intrusions have been studied in detail. Two were observed at mid-depth following periods of upwelling favorable winds. Concurrent hydrographic and current meter data suggest that these water masses were transported shoreward by a combination of wind forcing and longshore density gradients. The third intrusion, initially observed near the surface, had coinciding salinity and temperature maxima. This water mass appears to have entered the shelf as a result of a shelf/slope water exchange, possibly induced by a warm-core ring near the shelf break. Such intrusions may commonly occur during the summer and fall and may be related to the appearance of tropical fish in the Long Island vicinity during these seasons.

1. Introduction

The continental shelf off the northeast U.S. coast extends to roughly 100 km offshore, generally terminating at the 200 m depth contour. Seaward of the shelf is the continental slope, a region with a steeply sloping bottom. It has long been realized that water properties of the shelf and slope regions differ considerably.

Intense storms act to make the shelf water vertically homogeneous during winter, creating a sharp temperature, salinity, and density front near the shelf/slope break. During the late spring and summer weather systems are generally less intense than during winter, and solar radiation provides buoyancy to nearsurface waters. As a result, a pycnocline develops below a surface mixed layer. In the shelf region the pycnocline overlies a weakly stratified water mass known as the cold band, which has been described by Bigelow (1933) as a remnant of the previous winter's water mass. Constant density surfaces are roughly horizontal across the shelf/slope region during the late spring, summer and early fall; but a sharp thermohaline front still exists near the shelf break with warmer, saltier waters offshore.

During the late summer and early fall warm, saline intrusions, apparently of slope water origin, have been observed far shoreward of the shelf break by Boicourt and Hacker (1976), Gordon and Aikman (1981) and Houghton and Marra (1983). All of these investigators noted that such intrusions deliver a significant amount of heat and salt to the shelf region, and are thus important in determining the overall character of shelf water.

Boicourt and Hacker (1976) observed water properties off the Delaware Peninsula during the winter and summer of 1974. From winter measurements they found evidence of a nearbottom intrusion of slope water following upwelling favorable winds. They hypothesized that this intrusion was due to nearbottom onshore flow compensating for offshore Ekman transport. In summer they discovered a slope water intrusion which extended 60 km shoreward of the shelf break and was embedded within the pycnocline above the cold band.

From examining hydrographic data of the New York Bight area, Gordon and Aikman (1981) found that a salinity maximum (S-max) embedded within the pycnocline was a persistently recurring feature during summer and early fall. They noted that slope water intrusions, which are evidenced by a S-max, may move

shoreward within the pycnocline, which is nearly horizontal during summer and fall, without appreciable change in potential energy.

From 1974 through 1978 our group at W.H.O.I. in conjunction with investigators at Brookhaven National Laboratory conducted a number of field experiments in the coastal waters within 15 km of Long Island. This effort has been termed the COBOLT (COastal BOUNDary Layer Transect) project. Data taken in the late summer and early fall have revealed several warm, saline intrusions similar to those observed further offshore by the investigators cited above. This report will document three of the most noteworthy intrusions. For each intrusion, a description of its properties, as determined by COBOLT measurements, will be presented. This will be followed by a discussion of the intrusion's possible origins and history as inferred from concurrent satellite and hydrographic data. Discussion of the intrusions will be preceded by descriptions of the COBOLT project and relevant physical properties of the experimental area.

2. Background

2.1 The Coastal Boundary Layer Transect Project

The COBOLT project consisted of a number of separate field experiments, each of approximately one month duration. Most experiments involved measuring time series of temperature, salinity, and water velocity using an array of moored instruments. During all experiments, hydrographic surveys, which measured the above quantities at closely spaced flag stations, were performed on a near daily schedule. The experimental configuration and measurement techniques are only briefly described herein; refer to May (1979), Hopkins et al. (1979a, 1979b, and 1982) and Pettigrew (1981) for a more detailed account.

The site of the COBOLT measurements and a typical arrangement of the moorings and flag stations are shown in Figures 2.1 and 2.2 respectively. The mooring array consisted of four moorings situated on a line nearly perpendicular to the coast and local isobaths. The moorings, located at 3, 6, 9 and 12 km from shore, were of Shelton spar buoy type described by Dimmler et al. (1976). Each carried four instrument packages which recorded averaged values of temperature, salinity, and orthogonal water velocity components at hourly intervals. The three outer moorings had sensor packages at depths of 4, 8 and 16 m below the mean sea surface plus one at 2.4 m above the bottom. The mooring at 3 km had packages at depths of 4, 8 and 12 m, together with one at 2.4 m above the bottom. The notation of Pettigrew (1981) will be used to refer to the instrument packages. Moorings are assigned numbers 1-4 progressing seaward. At each mooring, sensor package levels are given numbers 1-4, increasing with depth. A number pair consisting of mooring number followed by a package level number will refer to a particular sensor package. For example, the number pair (3, 2) denotes the sensor package at level 2 (8 m depth) of mooring 3 (9 km from shore).

Flag stations, from which the hydrographic surveys were taken, were established along a line nearly coincident with the mooring array. During most experiments stations were located at 1 km intervals from 1 to 8 km from shore, and at 2 km intervals from 8 to 12 km from the coast. At each station measurements of temperature, salinity and water velocity were made from 2 m below the surface to near the bottom at intervals of 1-2 m.

Meteorological data were taken from a shore-based 22 meter tower near the moored array and/or from a 110 m tower at Brookhaven National Laboratory, about 35 km from the project site.

Temperature and salinity measurements of the hydrographic surveys were accurate to $\pm 0.2^{\circ}\text{C}$ and $\pm 0.2 \text{ }^{\circ}/\text{‰}$ respectively. The uncertainties of temperature and salinity measured by the moored sensors were 0.02°C and $0.2 \text{ }^{\circ}/\text{‰}$ respectively. Moored velocity measurements had uncertainties of 1 cm/s for each axis and 5° in orientation.

The mooring data used in this study were initially processed in the manner described by Pettigrew (1981). Record gaps of less than 6 hours were filled using cubic spline interpolation. To achieve a common time base, values of each time series were linearly interpolated to the nearest whole hour. Velocity components were transformed into a coordinate system with axes perpendicular and parallel to the local isobath orientation as estimated from bathymetric charts. The coordinate system used throughout this report has x positive offshore and y positive alongshore towards the northeast.

Preliminary COBOLT hydrographic surveys were conducted during June, September and October of 1974. In September of 1975 data were collected from one mooring and from the hydrographic surveys. This experiment has been described by Scott and Csanady (1976). Full deployment of four moorings together with the hydrographic surveys were carried out during May 1977, March 1978 and August 1978. Due to instrument malfunction reliable data were collected from only three of the moorings during May 1977, and from only two moorings in March 1978. All moorings returned good data during August 1978.

2.2 Properties of Nearshore Flow and T/S Variations.

A companion report by Churchill (1984) considers properties of the flow measured during the COBOLT project. It was found that the longshore wind stress component is much more effective in forcing nearshore motion than the cross-shore component. The cross-shore flow response to the longshore wind was very nearly two-layered, with nearsurface flow to the right of the longshore wind and opposing or compensating flow below. In the coordinate system of this report a positive longshore wind (northeastward) is thus upwelling favorable, while a negative longshore wind is downwelling favorable.

Significant near-surface offshore flow, not driven by the wind, was measured during experiments of late summer and early fall. This flow was apparently due to longshore density gradients which are often large in the Long Island vicinity during the summer and fall. Mean longshore flow of all experiments was directed to the southwest. This is consistent with measurements further offshore in the Mid-Atlantic Bight, and is regarded as indirect evidence of a persistent longshore pressure gradient which is downward to the southwest.

Contours of temperature and salinity, created from the hydrographic survey data, are to be presented. Before considering these, it is necessary to show that they are not significantly aliased by high frequency motion. Hydrographic surveys were completed in roughly 6 hours, and, thus, significant variance at tidal or near-tidal frequencies could distort the contours. Typical spectra of temperature and salinity, computed from August 1978 data, are shown in Figure 2.3. Note that both spectra are conspicuously red and exhibit only one significant peak which is at the semi-diurnal tidal frequency. Both of these tidal peaks are relatively small so that the bulk of the variance is within the range of sub-diurnal frequencies. The percent of total variance in the 27 hour to 10.7 day band, averaged over all fifteen spectra of the August 1978 experiment, is 80 percent for temperature spectra and 83 percent for salinity spectra. The corresponding average over velocity spectra is only about 30 percent. Hydrographic surveys of temperature and salinity were, thus, not significantly aliased by tidal or other high frequency motion. Hydrographic surveys of velocity were, on the other hand, appreciably aliased.

Figure 2.1: The coastal region of eastern Long Island. COBOLIT moorings were located at circles labeled 1-4.

Figure 2.2: Cross-sectional view of the experimental configuration showing the location of moored instruments and flag stations.

Figure 2.3: Typical temperature and salinity variance spectra of the August 1978 experiment.

3. Intrusion 1: September 1974

3.1 COBOLT Observations

Hydrographic surveying only was done during 1974. Surveying began on September 10 and continued intermittently until October 18. The first evidence of a saline intrusion was on September 14. Figures 3.1 and 3.2 show constant property lines of the September 12 and September 14 surveys. A partial record of the longshore wind stress is given in Figure 3.3. The intrusion's appearance followed a period of upwelling favorable winds (positive in Figure 3.3) which were particularly strong between September 12 and September 14. Property lines of Figures 3.1 and 3.2 show the expected response to the wind stress; i.e., nearsurface contours had moved seaward (e.g. 20° isotherm and $30.6^{\circ}/\text{‰}$ isohaline) while deeper contours were displaced shoreward. Similar to slope water intrusions observed further offshore, the saline intrusion of September 14 is characterized by a salinity maximum embedded in the thermocline. It is contained within the 22.5 and $23.5 \sigma_t$ isopycnals and extends to roughly 5 km from shore.

Surveys were conducted daily from September 14 through September 18, during which there were two periods of significant upwelling favorable wind. The intrusion was present in each of these surveys. Its furthest onshore extent was observed by the September 15 survey, which is shown in Figure 3.4. The next full survey following September 18 was on October 4. Property contours of the October 4 survey, shown in Figure 3.5, are clearly upwelled but show no sign of an S-max. The S-max thus persisted in the study area for more than four days but less than twenty days.

Comparison of the September 12 and September 14 T/S relations at 14.5 km, Figure 3.6, shows that the S-max of September 14 was of completely different character than water of the same density measured on September 12, which indicates that the intrusion was advected from outside the study area. The September 14 T/S relation shows the S-max to be within the thermocline and below a layer which was a halocline and nearly a thermostad. These characteristics are similar to those of salinity maxima associated with slope water intrusions observed by Boicourt and Hacker (1976) and Gordon and Aikman (1981).

A saline intrusion may deliver a considerable quantity of salt to surrounding waters if conditions are favorable for mixing. The intensity of

turbulent vertical mixing is roughly proportional to the gradient Richardson number. Gradient Richardson numbers between hydrographic observations were estimated from:

$$Ri = \frac{-g\Delta\rho\Delta z}{\bar{\rho}(\Delta u^2 + \Delta v^2)} \quad (3.1)$$

where

g = gravitational acceleration.

$\Delta\rho$ = density change between levels.

Δz = vertical distance between levels.

$\bar{\rho}$ = average density.

$\Delta v, \Delta u$ = difference in longshore and cross-shore velocity between levels.

Because this calculation involves differences of quantities, it tends to magnify errors, and thus one cannot place much confidence in a particular Ri value. Nevertheless, a set of Ri numbers can be used to indicate regions where vertical mixing is likely to occur.

Due to intense stratification, Ri numbers above the S-max were high, of order 10. Below the S-max stratification was weak, but so were the currents.

As a consequence Ri numbers there were occasionally of order 1 or less.

Three of the thirteen Ri numbers at the intrusion's base, estimated from the September 14-17 data, were less than 1. Due to relatively high velocity gradients, all Ri numbers below the S-max of September 18 were less than 1. Turbulent vertical mixing of the intrusion, thus, appears to vary in time and be much more vigorous at the lower boundary.

Houghton and Marra (1983) noted that double diffusive mixing may take place below the S-max. Their analysis of measurements detailing a 1979 intrusion, however, indicated weak double diffusive mixing.

Horizontal mixing of the intrusion is influenced primarily by the horizontal velocity gradient. Due to tidal aliasing, horizontal velocity gradients cannot be determined from the survey data with much confidence. Nonetheless, it should be noted that velocity gradients at the intrusion's shoreward edge were often high. For example, on September 15 there was 8 cm/s difference between the velocity measured at 3 km and 14 m depth, which was shoreward of the intrusion, and that measured at 4 km and 14 m depth, which was within the intrusion.

Survey averaged temperature and salinity values are displayed in Figure 3.3. This Figure shows that the survey averaged temperature decreased by about 1°C with the intrusion's appearance, while the average salinity rose by about $0.3^{\circ}/\text{‰}$. The average temperature and salinity were roughly constant throughout the intrusion's presence (Sept. 14-18). Over the entire experiment there was a close to linear decrease in average temperature, likely due to surface cooling. The average salinity increased by nearly $0.5^{\circ}/\text{‰}$ during the experiment. This may be attributed to salt delivered from the intrusion. However, much of the increase could simply be due to longshore advection; because, as has been shown by Churchill (1984), longshore salinity gradients are often high near Long Island.

3.2 Possible Origin and Driving Mechanisms

During August, 1974, an extensive hydrographic survey of the New York Bight was conducted from the USCGC EVERGREEN. A summary of the data is given by Morgan et al. (1976). Figure 3.7 shows station locations and the surface salinity field as determined by the survey. Property contours of a cross-shore transect 40 km to the northeast of COBOLT, denoted as transect E in Figure 3.7, are shown in Figure 3.8. The salinity field of this figure displays a rather striking slope water intrusion, lying above the cold band, with an associated S-max extending more than 100 km shoreward of the shelf break. Water with T/S characteristics similar to the S-max of the September COBOLT surveys also formed an S-max in transect E and was located roughly 40 km from shore. Stations to the northeast of transect E (which is upstream with regard to typical longshore flow) show similar water also at about 40 km from shore. It is thus likely that the water which made up the S-max of the Sept. 14 COBOLT survey had advected onshore by roughly 30 km during the 26 days between this survey and the date of transect E.

A most likely cause of this supposed onshore flow is the longshore wind stress. Mean longshore wind stress of the period Aug. 20-Sept. 14, 1974, was upwelling favorable, and thus would tend to generate onshore flow below the surface mixed layer. The total onshore water parcel excursion due to the mean longshore wind stress may be estimated by:

$$\Delta X = \overline{T_y} \Delta t / (f h_c)$$

where:

$\bar{\tau}_y$ is the time averaged kinematic longshore wind stress.

f is the coriolis parameter.

h_c is the depth of the layer of compensating flow.

Δt is the time interval.

From wind velocity measurements made at the Brookhaven National Laboratory tower, I have calculated for the period Aug. 20-Sept. 14: $\bar{\tau}_y = 0.09 \text{ (cm/s)}^2$. Using $h_c = 10 \text{ m}$, gives $\Delta X = 21 \text{ km}$. This value, while somewhat smaller, compares well with the 30 km excursion supposed necessary to form Intrusion 1, especially when considering the accuracy of wind stress determined from wind velocity data (Churchill, 1984). Thus, wind forcing could have been primarily responsible for the cross-shore flow of Aug. 20-Sept. 14 which presumably brought Intrusion 1 into the COBOLT transect.

It is uncertain whether the slope water intrusion apparent in EVERGREEN transect E (Figure 3.8) persisted until the appearance of the S-max in COBOLT, or if this intrusion was in some way responsible for the COBOLT S-max. This intrusion is, nevertheless, a spectacular feature and worthy of further consideration. Similar intrusions extending far onto the shelf are apparent in the two transects adjacent to transect E. It is most likely that these transects intersected a single intrusion with a longisobath extent of roughly 200 km.

Figure 3.9, adapted from Boicourt and Hacker (1976), shows the development of a similar intrusion off the Delaware Peninsula, also during August 1974. The August 7 salinity field of this figure shows a slope water intrusion extending 20 km onto the shelf. The salinity field of August 29 has an intrusion which reaches 60 km shoreward of the shelf break. Boicourt and Hacker (1976) proposed that wind-driven cross-shore circulation (upwelling) during the few days prior to August 29 was responsible for this intrusion. While this is plausible, there are alternative explanations.

Water above the August 29 intrusion was much saltier than nearsurface water on August 7, so that the change in water column properties between these two dates could not have wholly been due to cross-shore, upwelling circulation. T/S characteristics of the August 29 S-max are similar to those of the S-max of the August 19 EVERGREEN transect E (and to the S-max of the adjacent EVERGREEN

transects). The intrusion observed by the EVERGREEN '74 survey would have arrived at the Boicourt and Hacker transect by August 29, if it persisted and advected southwestward with a mean velocity of about 30 cm/s. As can be seen in the data of Ou et al. (1981) and will be shown in section 4, a longshore velocity of such magnitude, direction and duration has, not uncommonly, been measured within shelf waters of this locality. (Coincidentally, such a mean velocity was measured by COBOLT during August 19-29, 1978.)

A noteworthy feature observed by the EVERGREEN survey was a warm-core ring in the survey's southwest corner. The ring's approximate outline and surface velocity pattern, as inferred from the dynamic topography map of Morgan and Bishop (1977), are shown in Figure 3.7. Satellite images (Morgan et al., 1976) indicate that the ring had traversed the EVERGREEN survey area, close to the shelf break, during the two months prior to the survey. Clearly evident in Figure 3.7 is a parcel of shelf water at the ring's northeast edge, apparently drawn seaward by the ring's circulation. Several investigators (Morgan and Bishop, 1977; Smith, 1978; Fornshell and Criess, 1979; and Bisagni, 1983) have reported similar entrainment of thin filaments of nearsurface shelf water by rings adjacent to the shelf break. Presently, it is uncertain whether or not warm-core rings induce deeper transport of ring and/or slope water onto the shelf. One may speculate that if such transport were to occur during the summer or fall, it would be strongest within pycnocline, which is nearly horizontal across the shelf-slope region (even in the presence of a ring), and result in a saline intrusion over the shelf, such as those commonly observed. It is of interest to note that the development of the intrusion depicted by Figure 3.9 coincided with the passage of a warm-core ring. However, lacking concrete experimental evidence of ring induced transport onto the shelf, one can only guess what influence the ring seen in the EVERGREEN survey had on the intrusion of that survey or on that observed by Boicourt and Hacker (1976).

Figure 3.1: Property contours of the September 12, 1974 hydrographic survey.

Figure 3.2: Property contours of the September 14, 1974 hydrographic survey.

Figure 3.3: Survey averaged temperature and salinity, plus longshore wind stress at the Brookhaven National Laboratory tower.

SEPTEMBER 15, 1974

Figure 3.4: Property contours of the September 15, 1974 hydrographic survey.

OCTOBER 4, 1974.

Figure 3.5: Property contours of the October 4, 1974 hydrographic survey.

Figure 3.6: T/S relations at 14.5 km.

Figure 3.7: Hydrographic station locations and the surface salinity field (‰) of the August 3-20, 1974 survey from the USCGC EVERGREEN (adapted from Morgan and Bishop, 1977). The dashed line defines a warm-core ring perimeter.

Figure 3.8: Property contours of transect E of Figure 3.7; August 19, 1974.

Figure 3.9: Salinity field off the Delaware Peninsula on August 7 and August 29, 1974. Adapted from Boicourt and Hacker (1976).

4. Intrusion 2: August 11-19, 1978.

4.1 COBOLT Observations

Hydrographic surveying in conjunction with measurements from moored sensors was carried out during August and early September of 1978. Velocity and wind stress data from this experiment are presented in Figures 4.1-4.3.

Figures 4.1 and 4.2 show longshore and cross-shore velocity time series from all current meters except (3,3) (i.e. at 9 km offshore, 16 m depth) which malfunctioned. These time series have been low passed filtered using a Stallings P3 filter (McCullough, 1968) with a 26 hour cutoff. Shown in Figure 4.3 are longshore and cross-shore wind stress time series (unfiltered) together with the water velocities at mooring 4.

Hydrographic surveying began on August 2. The first sign of a saline intrusion was seen in the survey of August 11, Figure 4.4, which followed 8 days of weak to moderate upwelling favorable winds. Longshore winds were downwelling favorable from August 11 through August 13. Downwelling circulation during this period is clearly discernible in the cross-shore velocity record of Figure 4.2. Property contours of the August 13 survey, in Figure 4.5, are obviously downwelled. Water with salinity greater than 32.4‰ , which formed the S-max of August 11, had apparently advected offshore, nearly out of the transect.

The longshore wind component shifted to an upwelling favorable direction on August 14. Moored current meter records of August 14 show significant offshore flow near the surface, consistent with Ekman forcing. The saline intrusion, which is evidenced by contours of the August 14 survey in Figure 4.6, presumably was advected back into the transect by the upwelling circulation. This intrusion, roughly outlined by the 32.4‰ isohaline and contained within the 22.5 and 24.5 σ_t isopycnals, appeared in all surveys from August 14 through August 19. The intrusion's onshore extent ranged 6 to 10 km from shore. The configuration varied significantly as exemplified by contours of the August 14, 17 and 19 surveys shown in Figures 4.6-4.8. The intrusion detailed by the August 17 survey, Figure 4.7, has a convoluted form which suggests interleaving with less saline water. Low Richardson numbers (< 1 .) indicate a tendency for vigorous vertical mixing in the interleaved region. The intrusion seen in the August 19 survey, Figure 4.8, encompasses the largest portion of the transect and shows no interleaving. It is reassuring to note

that records of the moored salinity sensors are, at all times, consistent with the hydrographic observations of the intrusion.

Winds of August 14-19 were light and upwelling favorable. During this time the location of the $24.5 \sigma_t$ isopycnal remained roughly constant while lower valued isopycnals, close to the shore, moved upward. The result was a spreading of the nearshore isopycnal fan. This observation is consistent with the notion that water of the intrusion moved shoreward over the $24.5 \sigma_t$ density surface either by onshore advection associated with upwelling or by mixing, causing nearshore isopycnals to move apart.

Circulation during August 19 and 20 was of downwelling character, despite very light upwelling favorable longshore wind. The intrusion was absent from the August 20 survey, Figure 4.9, and from all ensuing surveys, despite frequent upwelling circulation episodes. It must be concluded that the intrusion advected alongshore past the COBOLT transect sometime after August 19. Water of the intrusion had moved alongshore at a mean speed of 22 cm/s during the 8 days when it was observed within the transect. This implies the intrusion's longshore extent was at least 150 km.

As for Intrusion 1, Richardson numbers indicate a greater tendency for vertical mixing below Intrusion 2's S-max than above. Twenty percent of the Richardson numbers at the intrusion's upper boundary were less than 1; whereas at the lower boundary fifty percent of the Richardson numbers were less than 1. Favorable conditions for lateral mixing of the intrusion are indicated by frequently high horizontal velocity gradients at the intrusion's landward edge, commonly 5-10 cm/(s · km).

Figure 4.10 shows the T/S correlation at 12 km before, during and after the intrusion's presence. The August 16 T/S relation shows the S-max to be embedded within the pycnocline/thermocline, and just below a layer with a large salinity and small temperature gradient. At temperatures greater than 12°C, water of the same temperature is considerably more saline after the intrusion than before. One may suppose that this increase was due to mixing of the intrusion with surrounding water. However, because there was little longshore velocity shear in the upper 16 m (Figure 4.1), water above the intrusion would have advected past the transect along with the intrusion. The slower moving nearbottom water, measured shortly after the intrusion's disappearance, was

likely once in contact with the intrusion. Although Richardson numbers indicate a tendency for vertical mixing below the S-max, the salinity of nearbottom water changed very little during the intrusion's presence. This is probably because nearbottom water of the COBOLT transect forms part of the weakly stratified cold band, which can assimilate a significant amount of salt without appreciable change in salinity.

4.2 Possible Origin and Driving Mechanisms.

Figure 4.11 shows hydrographic stations occupied by the Russian research vessel BELOGORSK during August 18-22, 1978. Property contours of the transect offshore of the Hudson River mouth, in Figure 4.12, clearly show a slope water intrusion within the pycnocline, extending to 50 km from shore. Based on the longshore velocity records of Figure 4.1, Intrusion 2, observed by COBOLT, would have advected into the Hudson vicinity by the time of the BELOGORSK survey. It is fairly certain, therefore, that this same intrusion is that shown in the BELOGORSK transect. This supports the notion that Intrusion 2 was water from the slope region.

Intrusion 2 entered the COBOLT transect either by cross-shore advection of offshore water, or by longshore advection of an already existing nearshore intrusion. Longshore velocities at sensors (3,4) and (4,4), which bracketed the S-max as first observed on August 11, were near zero throughout the 8 days prior to August 11. Longshore advection is thus not likely to have brought the intrusion into the transect.

A hydrographic survey of the continental shelf off western Long Island was done in early August 1978 as part of the MESA (Marine EcoSystem Analysis) project. MESA stations which form cross-shore transects in the COBOLT vicinity are shown in Figure 4.13. Figure 4.14 shows property contours of the transect slightly to the northeast of COBOLT. Note that the salinity field of this transect indicates a mid-depth saline intrusion at about 85 km from shore. Water with T/S characteristics similar to the S-max of Intrusion 2 was about 70 km from shore. A mean onshore velocity of 8 cm/s would have advected this water to a location longshore of the COBOLT transect by August 11. Without significant longshore salinity variation, this is the approximate velocity necessary to transport the waters of Intrusion 2 into the COBOLT transect.

COBOLT velocity measurements may be used to test the likelihood of such a flow. Wind stress components and cross-shore velocities averaged over the period August 3-10, from the time of the MESA transect to the intrusion's first appearance in the COBOLT transect, are shown in Figure 4.15. Unfortunately, there is no velocity information in the region where the intrusion was first observed, between levels 3 and 4 of mooring 4. However, averaged velocities at mooring 4 show significant offshore transport above level 3; while, the significant onshore velocities at moorings 1 and 2 suggest possible compensating onshore flow between levels 3 and 4 of mooring 4.

Churchill (1984) reported that during many "events" of constant wind heading, cross-shore flow of a particular direction was confined within a single density band. This makes it possible to detect cross-shore flow unresolved by the current meter array. Figure 4.16 is a plot of daily averaged σ_t against daily averaged cross-shore velocity at each sensor package during the period August 3-8 (except August 5 during which the longshore wind shifted briefly to the southwest from an otherwise steady northwestward direction). There is a clear separation between onshore and offshore flow near $22 \sigma_t$, with offshore flow at lower density and predominately onshore flow at greater density. All values with $\sigma_t > 24$ are from nearbottom current meters. The relatively small magnitude and occasional positive sign of these velocities can be attributed to frictional effects (i.e. Ekman veering).

The density range associated with onshore velocities, $22-24.5 \sigma_t$, roughly corresponds to the pycnocline S-max of Intrusion 2. During the period considered in Figure 4.16, the pycnocline lay between levels 3 and 4 of mooring 4. Thus, as Figure 4.16 indicates, the onshore flow within the pycnocline was seldom measured at mooring 4. Velocities between 22 and $24 \sigma_t$ indicate that the mean value of this unmeasured flow may have been as high as 8 cm/s. It is, therefore, plausible that Intrusion 2 was advected from offshore primarily during the 8 days prior to August 11.

It is of interest to investigate possible mechanisms instrumental in driving the cross-shore flow of August 3-10, which apparently brought Intrusion 2 into the nearshore region.

One likely possibility is wind stress acting to force nearsurface waters offshore and compensating onshore transport below. As Figure 4.3 indicates,

the longshore wind stress was predominately upwelling favorable during August 3-10. Average wind drift velocity can be estimated by:

$$\overline{u_{WD}} = \tau_y / (f \overline{h_{WD}}) \quad (4.1)$$

where

$\overline{u_{WD}}$ is the vertically and temporally averaged cross-shore velocity of the wind drift layer.

$\overline{h_{WD}}$ is the average depth of the wind drift layer.

Using $\overline{h_{WD}} = 16$ m, which should be the approximate value at mooring 4, gives: $\overline{u_{WD}}$ (August 3-10) = 2 cm/s. This is roughly 4 cm/s less than the vertical average over the August 3-10 mean velocities of the upper 3 current meters of mooring 4. This large difference cannot wholly be attributed to error in estimating the wind stress, and is fairly certain indication that a significant portion of the cross-shore flow during August 3-10 was not directly wind driven.

Churchill (1984) found that significant longshore density gradients often occur in shelf waters off Long Island during the summer and fall. Relative geostrophic velocities resulting from a longshore density gradient profile can be estimated by the thermal wind equation:

$$u(z_2) - u(z_1) = \frac{-g}{\rho f} \int_{z_1}^{z_2} \frac{\partial \rho}{\partial y} dz \quad (4.2)$$

where:

y, z are the longshore, vertical coordinates

g is gravity

ρ is density

Figure 4.17 shows cross-shore geostrophic velocity profiles calculated from the density profiles of three pair of MESA stations (Figure 4.13). Each station pair was oriented approximately along isobaths. Although there are differences between these profiles, all show 2-4 cm/s offshore velocity at the

surface relative to 16 m. If these profiles are typical of the time period, density induced flow could have accounted for roughly half of the nearsurface offshore flow during August 3-10, and also for a sizable portion of the deeper onshore flow.

To summarize, Intrusion 2 appears to have been of slope or outer shelf origin. It seems to have been advected shoreward primarily during the period, August 3-10, by a combination of wind forcing and density related flow.

Figure 4.1: Low passed longshore velocities measured by moored current meters during August 1978.

Figure 4.2: Low passed offshore velocities measured by moored current meters during August 1978.

Figure 4.3: August 1978 wind stress components at Tianna Beach, Long Island, and low passed velocity components at mooring 4.

Figure 4.4: Property contours of the August 11, 1978 hydrographic survey.

AUGUST 13, 1978

Figure 4.5: Property contours of the August 13, 1978 hydrographic survey.

AUGUST 14, 1978

Figure 4.6: Property contours of the August 14, 1978 hydrographic survey.

AUGUST 17, 1978

Figure 4.7: Property contours of the August 17, 1978 hydrographic survey.

AUGUST 19, 1978

Figure 4.8: Property contours of the August 19, 1978 hydrographic survey.

Figure 4.9: Property contours of the August 20, 1978 hydrographic survey.

Figure 4.10: T/S correlations at 12 km from shore.

Figure 4.11: Hydrographic stations of the BELOGORSK, August 18-22, 1978.

Figure 4.12: Property contours of an August 18-19, 1978 BELOGORSK transect; station locations in Figure 4.11.

Figure 4.13: Hydrographic stations taken from the R/V KELEZ as part of the MESA project, August 2-3, 1978.

Figure 4.14: Property contours of an August 3, 1978 KELEZ transect; station locations in Figure 4.13.

Figure 4.15: Averaged cross-shore velocities and wind stress components ($\overline{T}_x$, $\overline{T}_y$) for the period August 3-10, 1978.

Figure 4.16: Daily average of density against daily average of offshore velocity for August 3, 4, 6, 7, and 8, 1978. For clarity values from sensor package (1,4) are not shown.

Figure 4.17: Computed geostrophic velocity profiles (solid lines), relative to the bottom, between pairs of hydrographic stations shown in Figure 4.13.

5. Intrusion 3: September 1978.

5.1 COBOLT Observations

The saline intrusion observed in September 1978 appeared while heavy water returned to the study region following the cessation of downwelling favorable winds. Water of this intrusion was much warmer than that of the August 1974 and August 1978 intrusions, and was initially observed near the surface.

The wind stress time series of Figure 4.3 shows moderately strong downwelling favorable winds during August 31 and September 1. From September 2 through September 5 winds were upwelling favorable and were generally light except on September 4 when the offshore wind stress component briefly exceeded 1 dy/cm^2 . Isopycnals of the September 2, 3 and 5 surveys, Figures 5.1-5.3, show the expected response to the wind stress record. Isopycnals were clearly downwelled on September 2 and became progressively closer to horizontal on September 3 and September 5.

A saline intrusion, contained within the 22 and 24 σ_t isopycnals, is apparent in the contours of the September 3 and September 5 surveys. On September 3 the intrusion extended from beyond the transect to 8 km from shore. Its upper edge was close to the surface at 12 km and sloped downward in the shoreward direction, closely aligned with the isopycnals. On September 5 the intrusion was located at mid-depth and was confined between 4 and 11 km from shore.

T/S relations prior to and during the intrusion are shown in Figure 5.4. Although the intrusion's maximum salinity is no higher than that of previous surveys, its T/S characteristics clearly identify it as an anomalous water mass. The S-max of the intrusion lay below a layer with a small temperature and large salinity gradient, and above a layer with a large temperature and almost no salinity gradient. In contrast to Intrusions 1 and 2 the S-max coincided with a temperature maximum.

Similar to Intrusions 1 and 2, Richardson numbers were generally 1 or less at the intrusion's lower edge but much greater than 1 at the upper edge, indicating a greater tendency for vertical mixing below the S-max than above. Richardson numbers also became progressively smaller in the seaward direction, giving rise to the speculation that the apparent decrease in the intrusion's

size from September 3 to September 5 may have, in part, been due to vertical mixing of the seaward portion.

The September 5 survey was the last during 1978. Records of the moored salinity sensors indicate that, after September 5, the intrusion continued to migrate shoreward and persisted in the transect past the records' termination on September 7. The longshore extent of the intrusion is estimated from the corresponding longshore velocity record to be at least 70 km.

5.2 Possible Origin and Driving Mechanisms.

Because the S-max of Intrusion 3 was of low density and coincided with a temperature maximum, the intrusion may have been part of a surface or nearsurface water mass. Property contours of the August 21-22 BELOGORSK transect off Rhode Island, in Figure 5.5, show a nearsurface, anomalously warm and salty water mass about 70 km from shore. T/S characteristics of this water mass were similar to those of Intrusion 3. Unlike sections of Figures 3.8, 4.12 and 4.14, nearsurface isopycnals of Figure 5.5 are nearly horizontal across the slope and shelf. Thus, during the time of and in the vicinity of this transect, nearsurface flow onto the shelf was not prohibited by the density structure. It is, therefore, possible that the warm salty bolus over shelf originated from the slope. Within the slope region of the BELOGORSK transect is a relatively cool, fresh water mass of cold band character. It may reasonably be supposed that this water mass and the warm, salty bolus over the shelf resulted from a cross-shore exchange of surface slope water with deeper shelf water.

Possible causes for such an exchange are far from clear. The warm-core ring in the vicinity during that time, which is denoted as eddy U in the August 23 NOAA frontal analysis chart of Figure 5.6, may have been involved. Note that the chart shows a surface filament of this ring protruding onto the shelf.

Let us now consider the likelihood that the saline bolus of the August 21-22 BELOGORSK transect advected into the COBOLT transect by September 3 (roughly 50 km onshore and 100 km southwestward longshore). The bolus would have covered the longshore distance between the transects, if it had moved with a longshore velocity nearly equal to that measured at the COBOLT moorings.

Although nearsurface velocities measured by COBOLT current meters were predominately offshore during August 21-September 3, surface drifter data of Bumpus (1973) indicates a tendency for onshore flow in the vicinity of the BELOGORSK transect (to the west of Nantucket shoals) during August and September. It is, therefore, possible that a portion of the saline bolus depicted by the BELOGORSK transect advected into the COBOLT site during September 2-5, sinking beneath the fresher, lighter coastal water.

The NOAA frontal analysis chart of September 6, Figure 5.7, shows a well defined area identified as mixed slope and shelf water (mixed SL+SH) just seaward of the COBOLT transect. This lends further credence to the hypothesis that intrusion was part of a surface water mass.

In summary, the saline intrusion of September 1978 moved into the COBOLT transect during the return of heavy water following a coastal downwelling. The associated S-max coincided with a temperature maximum. An examination of BELOGORSK hydrographic data and NOAA frontal analysis charts suggests that the intrusion may have been part of a warm and salty nearsurface bolus formed by an exchange of shelf and slope water (possibly induced by a warm core ring).

SEPTEMBER 2, 1978

Figure 5.1: Property contours of the September 2, 1978 hydrographic survey.

SEPTEMBER 3, 1978

Figure 5.2: Property contours of the September 3, 1978 hydrographic survey.

SEPTEMBER 5, 1978

Figure 5.3: Property contours of the September 5, 1978 hydrographic survey.

Figure 5.4: T/S correlations.

Figure 5.5: Property contours of an August 21-22, 1978 BELOGORSK transect; station locations in Figure 4.11.

Figure 5.6: NOAA frontal analysis chart, August 23, 1978.

Figure 5.7: NOAA frontal analysis chart, September 6, 1978.

6. Summary and Discussion.

Intrusions 1 and 2 were similar in that their S-max was embedded within the thermocline/pycnocline, and both were observed between 22.5 and 24.5 σ_t following periods of upwelling favorable winds. Intrusion 3 differed from these in that it was much lighter, and its S-max coincided with a temperature maximum. Richardson numbers indicated that turbulent vertical mixing of all intrusions was more vigorous below the S-max than above.

It is not possible to construct with certainty the history of these intrusions from available hydrographic and satellite data. It has been the intention here to investigate the feasibility of possible origins and transport mechanisms.

All intrusions appear to have been of slope or outer shelf water origin. The onshore transport of anomalously salty water which formed Intrusions 1 and 2 seems to have been within the nearly horizontal pycnocline and driven by a combination of wind forcing and longshore density gradients. Intrusion 3 may have been a nearsurface salty bolus observed 70 km from shore two weeks prior to the intrusion's appearance in the COBOLT transect. If such were the case, then density or pressure induced flow, and not wind forcing, was most likely to have brought the intrusion shoreward.

This study has found a strictly circumstantial link between slope water intrusions and warm-core rings adjacent to the shelf. As pointed out in section 3.2, development of the intrusion reported by Boicourt and Hacker (1976) coincided with the passage of a warm-core ring, as did the appearance of Intrusion 2 (although not discussed here). The exchange of shelf and slope water suggested by Figure 5.5 also occurred in the presence of a ring. However, until there is firm experimental evidence documenting warm-core ring induced transport onto the shelf, no conclusion can be drawn from these coincidences.

To this author's knowledge, this report is the first published account of slope water intrusions within very nearshore waters. Such intrusions can be of significant environmental and social consequence. As a case in point, wastes are routinely dumped into the slope water off New York State at Deep-water Dumpsite 106. The possibility that such wastes may occasionally be transported into coastal waters should affect the judgement of environmental consequences of such dumping.

A knowledge of the time of year and typical frequency of these intrusions would be valuable in evaluating their impact. As noted previously, lengthy water parcel excursions across the shelf are unlikely during the vertically homogeneous conditions of winter and early spring. To this author's knowledge, slope water excursions over the middle Atlantic Bight have been observed exclusively during the summer and fall. Aside from the 1974 and 1978 experiments discussed in sections 3, 4 and 5, summer or fall COBOLT surveys were conducted in 1975 and 1976. Surveys in 1975 (July 21-29, August 18-September 2, September 15-22) revealed a possible mid-depth intrusion on September 15 and 16. Only six surveys were done in 1976 (August 21-26), from which no S-max was apparent. Based on the limited set of COBOLT observations, an appearance of one or two nearshore slope water intrusions per year is not unrealistic.

Tropical fish are often netted in waters of or close to Long Island during the summer and early fall (Alperin and Schaefer, 1965; and Hickey and Lester, 1980). Many of the tropical species discovered are small and not strong swimmers, and are thus likely to have been passively carried from southern regions by water mass movement. Although there is presently no firm evidence which links slope water intrusions with the appearance of tropical fish, it is conceivable that very nearshore intrusions, such as those studied here, may play some role in the transport of these fish.

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