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A Compilation and Description of Hydrographic Transects of the Mid-Atlantic Bight
Shelf-Break Front

by

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Technical Report

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Summary

Historical hydrographic transects of the Mid-Atlantic Bight shelf-break front are compiled by month and described in this report. Interannual variability of the meteorological forcing and slope water mass properties are presented as an aid in interpreting the variability of the frontal structure. Descriptions of the significant features of the front, shelf and slope water masses precede the compiled transects. The sections are limited to the upper 350 m of the water column, and a cross-shore extent of 280 m.

This report provides the observational perspective for interpreting measurements to be made during the Shelf Edge Exchange Processes (SEEP) field experiments funded by the Department of Energy.

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1. Introduction

The frontal zone at the outer edge of the continental shelf in the Mid-Atlantic Bight (MAB) has recently attracted considerable attention. Various theoretical models have been proposed to explain its shape or location, and attempts have been made to quantify the rate of property exchange across the front. Drastic and often conflicting idealizations had to be made in the models, and agreement with observation was sometimes claimed on the basis of limited evidence. It seemed to us desirable to assemble in this somewhat lengthy report much of the existing hydrographic information on the structure of the MAB shelf-edge front, together with some relevant supporting information on meteorological forcing, to provide a solid empirical perspective for the various conceptual models. The impetus was provided by the start of the Shelf Edge Exchange Processes (SEEP) observational program supported by the Department of Energy at several east coast institutions, including our own.

We have tried to portray the seasonal progression of the hydrography of shelf- and upper slope waters on either side of the front, and to give an idea of variability by showing the front in a steep as well as in a flattened mode, the upper slope water with or without a warm core ring present and by otherwise illustrating diverse physical influences to which the front is subject. The bulk of the report is a series of cross-isobath transects showing temperature, salinity and density (σ_t), arranged month by month, and chosen so as to illustrate processes on both sides of the front, in shelf-, as well as slope-water. A narrative account preceding the sections attempts to draw attention to some of their significant features.

The bathymetry of the Middle Atlantic Bight region is shown in Fig.1. The area of interest is bounded with 35°N to 42°N, 69°W - 76°W. In this area, the shelf region inshore of the 150 m isobath is a relatively simple structure. However, numerous canyons incise the (shelf-break) region (100 m to 2000 m isobath region) with the Hudson Canyon being the most prominent. The cross-shore extent of the shelf-break region varies from about 15 km near Cape Hatteras to over 50 km just west of the Nantucket Shoals area. Shelf regions inshore of the 60 m isobath are extensive at Nantucket Shoals but quickly narrow towards the mouth of Long Island Sound. Westward of this point, the extent of the region increases while getting closer to the shelf-break.

2. Data Sources

Much of the data in this collection has been selected from the extensive data library archived at the National Oceanographic Data Center (NODC) as of the end of April 1980. Only Nansen bottle data were acquired from the NODC data bank. STD transect data from collections held at the Lamont-Doherty Geological Observatory are also included for the following cruises: VEMA 32-01 (October 1974); CONRAD 19-01 (July 1975); CONRAD 19-05 (January 1976); CAPE HENLOPEN 77-01 (May-June 1977); and KNORR ACE III (August 1977).

The NODC data were supplied as station data organized chronologically for each one degree square within the area of interest from 35°-42°N; 69°-76°W. Transects containing stations that cross the boundaries of the one degree squares are therefore sorted into various positions within the data file. Unscrambling these station data has been (and is) one of the major problems in recovering transect data.

Presented in later sections is a description of a set of programs developed to facilitate this process on the WHOI VAX computer, and a discussion of contouring the transect data.

Data from the Lamont collection was supplied in the form of computer printouts. These have been hand-drafted and included in this report.

3. Acknowledgements

Much credit for organizing the NODC data, collected up to the end of 1977, into transect form must go to Ping Tung Shaw. Bert Pade subsequently hand-drafted temperature, salinity and density data from at least one hundred of these transects together with those from the Lamont collection. Jim Churchill's advice and help with the computer is much appreciated. George Heimerdinger has been instrumental in obtaining the NODC data. Charlie Flagg has provided helpful discussions and we thank May Reese for her skilled typing of the manuscript. This work was supported by Department of Energy Contract DE-AC02-79EV10005.

4. Sorting and Contouring the NODC Data

4.1 Sorting

The first step in sorting the NODC data (see flowchart in Fig.2) is to read the header information and store relevant information about each station into a file. The stored information includes: the date (time, day, month, year), NODC-supplied ship/cruise code, number of observations, deepest sampling depth, and the location of the beginning of the station information in the NODC data tape. This file of header data is stored in a keyed-index file which is processed by programs into sequential files of header data sorted out by month, year and ship/cruise (one file for each month). Station locations from each of these files may be plotted out and examined to determine which stations can be used to form transects. The file is then edited to produce groups of stations comprising transects, each transect being identified by a unique number. This data is processed by a program which fits a straight least-squares line (neglecting earth's curvature), through each group of stations, from an arbitrary near shore point. Station positions for each transect are projected perpendicularly onto the fitted line to define the relative "cross-shore" separation of stations. This additional information is stored, along with header information, in a data file. Finally, this file is fed to a program which reads, in a direct-access mode, hydrographic data for each transect from the NODC data file, interpolates the data to standard levels and produces monthly files with hydrographic data for each transect.

Flow Chart for Sorting NODC Station Data

Figure 2

4.2 Contouring

In compiling the NODC transect data and hand-drafting contoured sections it became apparent that an objective contouring scheme would be advantageous. The basic problem, of course, is that the water column is seldom sampled intensely enough to resolve details of water mass features involving maxima, minima and strong gradients in property distributions (e.g., boluses, filaments, upward protrusions and fronts). This leaves the burden of making a final decision on the data analyst or computer. The difficulty of deciding the trajectory of contour lines based on vertical and horizontal information, led to a feasibility study with a simple computer contouring program. Results of this study were sufficiently encouraging that all the NODC transects were computer generated. This program and its limitations are described next.

Contouring of the transect data is performed by program MAPA written in Fortran 77. MAPA uses Fortran-callable subroutines in the graphics display package DISSPLA[®] to produce publication quality hydrographic sections. The sections are limited, for this work, to a maximum depth of 350 meters and a total cross-shore length of 280 km. Three main aspects of the contouring program are (1) interpolation of data values onto a regular grid, (2) contouring near the bottom boundary, and (3) fitting contour lines through the interpolated data.

Firstly, the contouring package in DISSPLA[®] requires regularly spaced (in the vertical and horizontal) data. For this purpose a grid with uniform spacing of 10 meters in the vertical and cross-shore spacing of one-half the mean spacing between stations, with a maximum of 40 horizontal points, is used. At each grid point, the interpolated data value is a weighted average, based on distance from the grid point, of data within a rectangular search area. A sharply decaying weighting function ($1/x^3$) is used. In the vertical, the search distance is 25 meters on either side of the grid point and, in the horizontal, it is at least equal to the maximum separation distance between any two adjacent stations. A subroutine MDFMAT, provided in DISSPLA[®], is used for this interpolation.

The profile of the bottom boundary is defined from the bottom depth data contained in each station header information. If the bottom depth is not recorded for stations less than 350 m in sampling depth, the program asks for these depths. Topographic charts are used for this purpose. A cubic/parametric cubic spline interpolated curve, RASPLN in DISSPLA[®], is drawn through the boundary. (The "tension" parameter in RASPLN is set at 15).

The hydrographic data is linearly extrapolated beyond the maximum recorded depth. Extrapolation is to the bottom or up to 40 meters from the maximum sampling depth. Problems do arise if the maximum sampling depth is within strong vertical gradient regions, as often seen in the upper 50 meters or so in summer. When this occurs, the extrapolated contours are eliminated.

The trajectory of the contour lines is drawn by the cubic spline routine RASPLN with the "tension" parameter set at 2.5; smaller values of this parameter result in the tendency for curves to form loops (and overlap) while larger values straighten out the curves. The value of 2.5 was chosen by trial-and-error as a compromise between a pleasing smooth curve and accuracy.

5. Data Coverage

The time-span and monthly data coverage included in this report are shown in Table I. The data spans 41 years and covers the late 30's up to 1978. From 1941 to 1955, there are only two transects so that the transects of the late 30's form an isolated collection, mainly for the spring/summer months. Similarly, in the latter half of the 50's, there is a good collection of transects again with a bias towards the warmer months. By comparison, the coverage for the 60's and 70's is relatively sparse but with a more even spread throughout the year. For some months, there are two or more transects generally taken at different alongshore locations. These give some indication of alongshore variability in frontal and water mass characteristics.

6. Monthly and Annual Meteorological Forcing

The variability of wind stress and air-sea heat fluxes are factors likely to influence the dynamics of the shelf/slope front. Long-term measurements of meteorological fluxes for the Middle Atlantic Bight were commenced only since 1976 with the installation of offshore NOAA data buoys. An alternative source was therefore sought from the collection of archived ship observations analyzed by the late A. Bunker as part of the computations of heat flux for the North Atlantic Ocean (Bunker, 1976). Fig. 3 shows the time-series of monthly wind stress, air-sea temperature difference, and heat flux for Marsden Square 152. Fortunately, most of the marine area of Marsden Square 152 (70°W - 80°W; 40°N - 50°N) is comprised of the western Gulf of Maine basin, the New England shelf area up to the shelf break at about the 200 m isobath, and the inner half of the New York Bight area; data from Lake Erie and Lake Ontario are not included. The location of the sampled area near the intense shipping zone of New York and the oceanographers at Woods Hole suggests that the data would be representative of shelf-wide conditions. The bias of ship observations towards periods of good weather, however, can lead to under-estimation of strong wind stress periods and air-sea fluxes. The data therefore are indicative only of gross changes in annual and monthly meteorological forcing.

The wind stress time series shows a strong bias towards winds coming from the northwest. Annual and monthly wind stresses are dominated by the strong "northwesters" during the early months of the year. Summer stresses are negligible by comparison so that the annual means may be taken to be representative of the winter stresses, averaged over the whole year (i.e., divided by a factor of about four). Maximum monthly winter stresses are approximately 0.2 Pascals with significant inter-annual variability of about the same order.

An inspection of the annual averaged stresses shows individual and groups of years with strong southeastward wind stresses. Associated with such strong stresses in the early years of the 60's is a veering of the mean wind stress from southeastward in 1961 to eastward in 1965. The period from 1962-65 was associated with severe drought and a southward dip of the westerlies off the eastern American seaboard (Namias, 1967). The southward component strengthens during 1967 to 1969. From 1970 to 1972, the wind stresses appear anomalously weak and oriented more towards the east than south. During the 50's the strength and direction of the mean stresses were more variable with the exception of the veering from southeastward to eastward stresses from 1952 to 1954. Again, this period was associated with drought conditions (Namias, 1955). Following the drought, further catastrophes, this time in the form of hurricanes, occurred during August and September 1955. The two hurricanes in August, Hurricanes Connie and Diane, are of interest because of the availability of some transect data just before and after the hurricanes' passage.

Many of the anomalous air-sea temperature differences during December to February are due to the timing of the arrival of cold winds in relation to the decline in surface water temperatures. The period from 1969 up to at least 1972 was anomalous due to the early arrival of warm winds in May and early arrival of cold winds in December. These anomalous conditions are also reflected in the patterns of wind stresses for the period.

Two noticeable features of the net heat flux data are: firstly, the smaller maximum summer heat fluxes for 1959 to 1963, and secondly, the relatively high variability of winter-time fluxes (dominated by latent heat fluxes) compared to those for summer (dominated by solar heating).

A further bulk property of the wind stress, related to the amount of work the wind does on the oceanic waters, is the time integral of the wind stresses. The time integral is defined here as the sum of the magnitude of monthly wind stress vectors. This is plotted in Fig.3 above the wind stress vectors. The most obvious feature is that much of the activity is due to the strength of the "northwesters" in winter. The lack of activity during the early years of the 70's is also noticeable.

Given this background on the meteorological forcing and its variability, the transect data are presented and analyzed in subsequent sections. The data are organized by month, and a discussion and analysis is presented at the beginning for four seasons. The seasons are defined roughly as: (A) Winter - January to March, (B) Spring - April to June, (C) Summer - July to August, and (D) Fall - September to December. The letters A,B,C,D are used as prefixes, for the figure numbers of the transects for Winter, Spring, Summer, and Fall respectively.

Temperature-salinity relationships are presented for the Winter transects (Figs.10, 11, 12). In each T/S diagram, an oblique orientation line is drawn (through the points (7°C, 33‰), (12°C, 35‰)) representing roughly the expected T/S mixing line across the shelf-break front.

A vertical orientation line is also drawn through the 35‰ salinity. In some cases, an isopycnal contour is drawn in as a dashed line.

7. Transect Descriptions

7.1 Interannual variations in slope water properties

The shelf/slope front represents a boundary between extensive water masses on the shelf and continental slope. Water mass formation episodes due to meteorological variations, and alterations in the slope and shelf water circulation, could alter the observed property gradients at the front. It is useful, therefore, to know whether significant changes in water mass properties have occurred and to try to determine what effects the changes have on the front. The data coverage limits our analysis to variations longer than the monthly time scale.

A crude analysis was performed whereby all the available transect data were bin-averaged into vertical bins for shelf areas within the 100 m isobath and slope areas beyond this isobath. Fig. 4 shows the results for slope water mass properties obtained by averaging between the depth ranges (>150 m, ≤ 200 m) and (>200 m, ≤ 300 m). Inspection of transect sections, to be presented later, shows that usually the temperature, salinity, and density at these depth ranges are between (13 - 11°C , 35.6 - 35.4 ‰, 26.8 - $27.1\sigma_{\text{T}}$) for the 100-200 m depth range, and (11 - 8°C , 35.4 - 35.1 ‰, 27.1 - $27.3\sigma_{\text{T}}$) for the 200-300 m depth range. The averaging is based on the interpolated NODC transect data. Stations where salinities greater than 35.9‰ were recorded are not included in the averages—because of possible warm core ring influence or presence of Gulf Stream water mass.

The outstanding feature of Fig. 4 is the extremely cold, fresh water masses recorded from the beginning of 1964 till almost the end of 1966. Temperature deviations of 6°C and salinities much less than 34.5‰ were recorded for the 100-200 m depth range during these years. The trends in both depth ranges parallel each other, with smaller but extreme variations being recorded for the deeper layer; the trends in the other years also parallel each other. Seasonal trends, although not well resolved, are apparent, especially during the anomalous years of the 60's, with the coldest and freshest water masses being observed during March/April and the warmest/saltiest water masses being observed during September. Whilst the 100-200 m layer may be under the direct influence of meteorological fluxes and surface mixing, the appearance of parallel trends in the deeper layer suggests the possible importance of bulk periodic advective influxes. The coincidence of the appearance of these anomalous water masses with the large scale changes in meteorological forcing, noted previously, suggests large scale water mass formation episodes in the more northern and eastern seas intruding (periodically) into the Mid-Atlantic Bight. Wright and Parker (1976) in their compilation of a volumetric temperature/salinity census for the Mid-Atlantic Bight, have noted the extreme anomaly of data recorded during March 1966. Water temperature anomalies for 1961-1965 are illustrated by Fig. 5,

from Namias (1966), where mean monthly sea surface temperatures in a 3° latitude diameter circle centered at 37.5°N , 72.5°W off the Delaware coast are plotted against a long term mean trend. Beginning in 1961, there is the appearance of colder than normal water masses for the spring and fall months, with the coldest water masses occurring during March/April. The most severe anomaly was observed in 1965 although our data (Fig. 4) indicates that even colder conditions occurred in 1966.

These local anomalies were part of extensive anomalies in the sub-polar water masses (especially 40°N - 50°N) observed in the 4-year mean for 1962-1965 (Fig. 6) and in the mean for the spring and summer months (Fig. 6). Anomalous precipitation trends observed at the New York Park Observatory are shown in Fig. 7 where the decrease in annual precipitation during 1961-1965 is evident and possibly related to a long-term trend of decreasing precipitation beginning in 1927. Namias (1966) discusses the evidence for large-scale coupled air-sea interactions in maintaining these anomalous conditions and notes the possible influx of cold Labrador water southward, beginning in 1961-1962, driven by favorable surface wind stresses. Salinities and temperatures rise gradually after the anomalous years of the 60's with isolated appearances of anomalously cold fresh water masses especially during January 1968 and April 1971. A trend, beginning in 1957 and not resolved well, of cooling and freshening followed by warmer and saltier conditions from 1959 to 1962 is suggested by the average data in Fig. 4. Density variations are not as dramatic as those of temperature and salinity suggesting that T/S changes are largely density compensating. To be noted, however, is the appearance of denser water masses during the anomalous 60's years and lighter water masses during the middle half of the 70's.

7.2 (A) Winter sections January to March

ATLANTIS January 1940 (Fig. A1) (A further station at 292 km [not shown] was used in the contouring.)

This early section illustrates a wintertime interaction of a warm core ring (WCR) with the shelf/slope front. The core of the eddy ($\sim 14^{\circ}\text{C}$, 35.0‰) is cooler and fresher than the core of "typical" WCRs (17 - 18°C , 36.4‰) representative of the Eighteen Degree Sargasso Sea Pycnostad). Whilst the sampling spacing is too coarse to resolve more than the large scale interactions, it appears that significant water movement was induced on the upper continental slope. Evidence of this interaction is the enhanced property gradients at the onshore side of the asymmetrical WCR. The last four stations were taken within about half a day during which period, assuming a translation speed of 5 cm s^{-1} , the eddy center would translate less than four kilometers. Thus, the asymmetry could not be due to eddy translation. If the pycnocline slopes are in approximate geostrophic equilibrium, then the greater slope at the inshore edge by a factor of about three, must correspond to a similar increase in the ring's tangential velocities. The onshore edge of the eddy is located between offshore stations 4 and 5, where the recorded bottom depth changes from 760 m to 2340 m.

The relatively cooler and fresher water mass in the top 50 m of the extreme offshore station has T/S characteristics resembling those of water at the offshore edge of the shelf/slope front. It is important to note that this water mass is not shelf water (6° , 33‰). Vertical migration of isoclines up the continental slope and a retreat onshore of the bottom of the shelf/slope front are noticeable features of this section.

The anomalous core T/S properties are difficult to explain without further information. Intense winter cooling and mixing with entrained water is a possibility — but the lowering of salinity from 36.4‰ to 35.8‰ by mixing with water of salinity, say, 35‰ , would require a volume exchange approximately three quarters that of the WCR.

A further wintertime WCR section is that of the CHAIN cruise during March 1972. Associated with the ring was a relatively large cool, fresh surface lens of water near the offshore edge of the ring. In the April 1972 issue of the Gulf Stream monthly summary, this surface lens of water was described as a "Shelf Water" eddy caused by meandering of the Slope Front. However, an inspection of the sections clearly shows that the surface lens is part of a deeper perturbation penetrating the slope water. The WCR is probably a decaying remnant of a larger ring which may have formed earlier. Data collected during this cruise indicates that perturbations of the isopycnals extend down to at least 1500 m; isopycnal slopes increase with depth as commonly observed with WCRs.

At the offshore edge of the WCR, the slopes of the temperature and salinity isoclines are steeper than those for density. This is presumably the result of mixing of the waters of the fresh lens and the "thirteen degree" core of the WCR. By comparison with the shelf/slope front, the property changes across the lens have a more diffused appearance. The lens appears to be mixing across the top of the WCR towards the shelf slope front. Complete mixing of the lens with the thirteen degree core would reduce the core's salinity to below 35.2‰ .

Just before this WCR observation, a transect along the same track had been made from 31 Jan. - 2 Feb. 1972. The Gulf Stream monthly analysis for February 1972 showed a weak ring, centered about 20 km to the east of this transect on the 10th of January. The ring subsequently proceeded southwestward crossing the transect line and is west of the transect line when surveyed next on the 9th of February. The CHAIN cruise of Jan/Feb appears to have caught the rear end of this weak ring. The shelf/slope front near the shelf edge is very diffuse, and the 34‰ salinity isocline has been entrained and swept around well offshore, approximately 100 km. The T/S properties of water near the shelf edge and visual structure of the frontal boundary suggest active mixing in the top 100 m of the shelf break region.

The KNORR section of January 1971 also illustrates the interaction of an anticyclonic ring structure with the shelf/slope front. No warm core rings were reported for this period. A further early February

transect from air-dropped BT's, reported in the January 1971 issue of Gulf Stream Monthly, here shown in Fig. 8, again shows an anticyclonic structure located within about 120 km of the shelf-break region. Curvature of the isoclines below 100 m are weaker than that for typical WCRs, but significant entrainment of waters near the shelf/slope front has taken place. The KNORR section shows isopycnal slopes of the order of 2.5×10^{-3} and the dynamic height relative to 1500 m indicates surface velocities of nearly 40 cm s^{-1} (Fig. 8) sweeping the cool fresh shelf/slope water about 120 km offshore over a depth of about 100 m. Inshore of this jet, a weaker return flow with a subsurface maximum current of about 10 cm/s appears at the 150 m depth level. Above this weaker jet, the waters of the shelf/slope front move in the opposite direction with surface velocities larger than 10 cm/s. The next survey of the front from the ROCKAWAY in March 1971, even though crude, shows an elongated "front" extending well into the slope water. The front looks much like a thermocline with its base at about the 50 m depth. Three frontal zones are seen in the density section: a near shore river plume front confined to within about 40 km of the coast, the shelf break front, and far offshore, the surfacing of the extended shelf break front. Compared with the KNORR cruise of January 1971, all of the density isopleths have migrated up in the slope water. Surveys of the offshore shelf/slope front reported in the Gulf Stream Monthly of March 1971 show that the extrusion of the shelf/slope front was a characteristic feature for most of the Middle Atlantic Bight area.

The structure of the front during the relatively strong wind stress years of the early 60's is illustrated by the CHAIN cruises of January 1961 and 1962. Both sections were taken along similar transects proceeding offshore from the mouth of Long Island Sound. Here, again, the fronts are elongated and the offshore surface of the fronts is unresolved. Nearshore, there is a coastal front, about 30 km in cross-shore scale, of cool fresh water flowing from Long Island Sound. In 1961, the waters of this front are warmer, saltier, and with a greater density contrast across the front. Below the coastal front of 1961, there is an anomalous warm salty pool of bottom water separated from the shelf/slope front by a relatively homogeneous mass of water $\sim 8^\circ\text{C}$, 33‰ . Mayer et al. (1979) report a similar observation in February/March 1975. The January 1962 sections show, to a lesser extent, a mid-shelf doming of the 32.8‰ isohaline. These features all indicate anomalous mid-shelf water mass distributions.

Offshore of the shelf-break the steepness of the fronts changes and they become flatter roughly following the 50 m depth level. The offshore side of both fronts is very diffuse with a vertical density gradient of at least $.4 \sigma_T/100 \text{ m}$ in the slope water. The isopycnal slopes near the shelf-break are steeper for the front of 1961, but geostrophic velocities relative to 350 m (not shown) are about 5 cm/s between the fifth and sixth stations for 1961, and for 1962 there is a strong jet near station 6 with maximum surface velocities of order 30 cm/s. This jet is to a large part due to the downward depression of the slope water isopycnals giving rise to an anticyclonic circulation (mini ring). The scale of this ring

structure is, however, much smaller than the ones discussed previously. The salinity stratified thirteen degree water mass centered at about the 100 m level and the temperature stratified 35.4 ‰ water mass at about the 150 m level are curious features of both sections.

The EVERGREEN transect of January 1968 resolves poorly a diffuse shelf-break front. The T/S distribution (Fig. 10) shows salinities in the deep layers to be fresher by about .2 ‰ than the expected salinity of about 35 ‰. Assuming geostrophy, the relatively flat isopycnals of the slope water below 150 m do not however suggest westward influxes of fresher water.

The two January 1975 sections were taken just before the arrival of a warm core ring which was centered at 39°15'N, 71°15'W on the 4th of February (Gulf Stream Monthly, January 1975). Most of the EVERGREEN/KNORR stations were taken on the 20-21 January except for the 5th to the 7th stations which were taken on 27-28 January.

Both stations show similar weak and steep coastal fronts, but the EVERGREEN transect taken further south shows a more homogeneous, fresher, and cooler water mass over the shelf. The front in this section is barely detectable with a horizontal gradient near the shelf break of order .05 σ_T /10 km compared to .13 σ_T /10 km for the northern section. In both sections, the thirteen degree water mass extends to the surface. In the northern section, the thirteen degree water mass is more extensive and reaches down to 150 m, whereas in the southern section it reaches to about the 110 m depth.

Although the domed structure of the slope water isoclines in the northern transect is suggestive of upwelling, an inspection of winter transects reveals that typically the 7° isotherm is below 350 m. On this basis, the observation of the 7° isotherm near the 300 m mark in the southern section suggests upward migration of isotherms there. The observed downward slope of isopleths for the last two stations suggests perturbations of the slope water by vertical motions of at least 50 m scale. The frontal structure of the southern transect may be affected by the close presence of the Hudson Canyon.

Salinities greater than 33.6 ‰ observed at the mid-shelf region for January 1975 are larger than the values observed in the other January transects — typically around 33 ‰ or less. The northern January 1975 section shows mid-shelf salinities around 34 ‰. This is 1 ‰ higher than "typical" values and when one considers that the salinity difference between shelf and slope waters is of the order of 2 ‰, the higher salinities in 1975 represent a substantial accumulation of salt on the shelf. This observation, together with the high slope water surface salinity of 35.6 ‰ suggests previous mixing, possibly by warm core ring(s). Two rings were observed in the slope water for 1974 (the Gulf Stream issues for 1974).

The CONRAD section of January 1976 shows a contorted front with

active exchanges taking place on either side of the front. From the coast to the inshore edge of the front the waters are vertically well-mixed, and cross-shore temperature and salinity gradients increase offshore. The cross-shore density gradient is relatively constant up to 80 km inshore of the front. The gradient is about .1 σ_T /10 km. The slope water is relatively warm (more than 14°C) with a tongue of 35.6 ‰ salinity water intruding inshore and upwards from the 150 m depth level and a pycnostad extending from the surface to a depth of 100 m. A surface lens of water (12°C, 34.4 ‰) is centered approximately 25 km offshore of the front and has a maximum depth of order 25 m of the 24.4 σ_T contour. The lens is not shelf water (<10°, <34 ‰), but has T/S properties similar to those at the offshore edge of the front. The T/S properties of this transect (shown in Gordon and Aikman 1981) have a tight figure 7 relation, characteristic of intense winter mixing (Flagg 1977). The contorted shape of the front suggests that the front is not in equilibrium. The distance between top and bottom intersections of the front (approx. 30 km) is larger than the baroclinic radius of deformation. Taking a cross front density gradient $\Delta\rho = .2 \sigma_T$, depth of front = 100 m, and $f = 10^{-4} s^{-1}$, the baroclinic radius of deformation $(g'H)^{1/2}/f$ is of order 4.5 km.

The fresh surface lens is possibly related to impulsive wind forcing and a similar lens formation is reported by Posmentier and Houghton (1981) during the SWIG I cruise of March 1979.

The BEAR cruise of February 1956 was one of the most detailed upper layer Nansen bottle transects ever conducted. Shelf water properties are vertically well-mixed. By comparison with the January transects, shelf conditions are relatively cold and fresh with a homogeneous density distribution up to the beginning of the front at about the 80 m isobath level. Two fresh lenses of shelf/slope water are located offshore: one still partly attached to the front and centered about 20 km offshore, and another about 50 km offshore of the front. Upward protrusions of isopycnals are evident just offshore of the front and 40 km further offshore. Although upwelling due to divergence of the offshore directed surface Ekman flux might be a cause, the explanation for the second protrusion is not clear. The T/S characteristics of the slope water (Fig. 11) below 150 m are not tight. Errors in salinity titrations could be a cause but the cold shelf conditions and active mixing at the front suggest severe weather conditions. The correct explanation is not obvious.

Hydrographic conditions observed on the BEAR cruise of February 1957 are in sharp contrast to those of 1956. This transect, first discussed by Ketchum and Corwin (1964), shows vertically well-mixed conditions extending across the shelf into the slope water region. A slope water pycnostad (14°C, 35.6 ‰) extends from the surface down to 150 m. Unfortunately, the widest sampling distance occurs right across the shelf/slope front. The front is marked by strong temperature and salinity gradients: roughly 5°C and 1.8 ‰ over 20 km. Isopycnals at the front are almost vertical with a cross-frontal gradient of about

.26 σ_T /10 km. Mid-shelf conditions have become saltier in comparison to 1956. This is evident in the T/S property curves shown in Fig. 11. The tight T/S line across the front now originates from a salinity of about 33.2‰, representing the salinity just offshore of the homogeneous mid-shelf region. Inshore of the mid-shelf region, a T/S curve characteristic of the coastal front is observed.

Even more saline mid-shelf conditions are evident in the CRAWFORD transect of February 1959 off Long Island Sound. Apart from the coastal front, relatively homogeneous conditions prevail across the shelf up to the inshore side of the shelf/slope front. Near the bottom of the mid-shelf region there is a slightly dense, warm, salty water mass, approximately 20 m thick and of a horizontal scale less than the distance between sampling stations. The shelf/slope front has an extended diffuse appearance and lies above a halostad (constant salinity layer) about 150 m deep. This halostad is temperature stratified. By comparison, the thermostad centered at the 110 m level is about 60 m thick. Strong upward intrusions of deep, cold, relatively fresh slope water up the continental slope are evident. The 6° isotherm, which is normally located at about the 480 m depth level in the slope water, has crept up to the 270 m — suggesting that the slope water is possibly being forced by an anticyclonic ring. The T/S curve for the shelf/slope front is not tight and the mixing line has been rotated clockwise relative to the mixing lines for 1956 and 1957. The clockwise rotation reflects the reduced density difference across the front due to the more saline shelf water.

The EVERGREEN cruise of February 1968 shows an anomalously flat front. However, the front is poorly resolved and the transect is located close to the Hudson Canyon. The anomalous fresh slope water mass observed for the EVERGREEN transect of January 1968 is not seen in this February transect (Fig. 10).

The slope water transect of CHAIN February 1969 shows the shelf/slope front separated from a warm salty (13°C, 35.6‰) deep lens of water. The density of the salty lens is similar to that at the offshore edge of the shelf/slope front. This is shown in the T/S curve where the $\sigma_T = 27$ contour is shown as a dashed line. The mixing line at the front, dominated by salinity changes, gives way to a region of isopycnal mixing in the top 150 m of the slope water, while the deeper waters are temperature stratified. The transition implies the possibility of cabbelling and/or double diffusion processes enhancing the large-scale mixing processes evident in the upper 150 m pycnostad.

An ALBATROSS IV transect taken 10 days later and 55 km west of the CHAIN transect shows a rather surprising alteration of the slope water and frontal characteristics. The 35‰ isohaline is 60 m deeper; the density contrast at the front has considerably weakened and the slope water T/S characteristics between 35‰ and 35.4‰ follow isopycnal contours.

The period from 27 February to 5 March 1974 represents one of the

most intensive observational periods of the MAB shelf/slope front. Hydrographic data collected during this period included the detailed DALLAS cruise series described by Flagg and Beardsley (1975) and the EVERGREEN cruise series. Maps of the surface temperature, salinity and density are illustrated in Figs. 13a,b,c respectively. A warm core ring which was observed on 27 February (Gulf Stream, March 1974) is also sketched on the maps.

The surface property maps show an intensified front near the northwestern end of the warm core ring. Westward of the ring, the surface expression of the front curves in toward shore with a weakening of horizontal property gradients. The weakest property gradients occur near the Hudson Canyon area. A coastal front, some tens of kilometers in width, begins from the north of Long Island Sound; isopleths veer inshore, proceeding southward before becoming parallel to shore. The coastal front appears to leave the shore half way down Long Island. Thereafter the front appears to mix cross-shore and occupies about half the shelf width by the time it reaches Delaware Bay.

Current meters moored near the 71°W longitude, from the 27th of February to the end of March, and extending to the 120 m isobath, showed a mean westward drift (Flagg and Beardsley, 1975). The topography of isopycnals within the front and ahead of the WCR indicated frontal undulations with a longshore wavelength of order 80 km and a cross-shore lengthscale of 25-60 km (Flagg and Beardsley, 1978). Flagg and Beardsley, (1978) show that the growth rate of baroclinically unstable frontal waves is too slow to cause the frontal undulations. The possibility that the undulations are an upstream wake effect of the WCR has not, however, been examined. Entrainment of the near surface waters of the front at the northern portion of the WCR is clearly shown in the surface maps. Possible onshore movement of the bottom of the front during the WCR interaction is indicated by the EVERGREEN transect of March 1974 taken along the 70.5°W longitude. Shelf conditions are relatively homogeneous and a front with a cross-shore lengthscale of order 60 km separates shelf waters from the WCR. In contrast, the EVERGREEN transect within the New York Bight, to the southwest of the Hudson Canyon, shows a weak diffuse thermaline front separating shelf waters from a warm salty (>14°, >35.6‰) slope water pycnostad of order 150 m deep. Proceeding further downshelf (towards the southwest), the EVERGREEN transect of February 1974 (the last transect shown on the surface maps) shows stratified shelf conditions with no evidence in the density distribution of a shelf/slope front. Temperature and salinity data do show a property front with increased cross-shore gradients; however, the T/S characteristics of the waters at this front are such that they are density compensating. The sampling spacing is also too large to resolve the front. As remarked previously, the coastal front appears to have mixed with mid-shelf waters. The result is a vertically well-mixed density distribution with the cross-shore density gradient increasing offshore. The mean cross-shore density gradient is of order .20 σ_T /10 km compared to the almost homogeneous shelf conditions near Nantucket Shoals. The T/S plot, Fig. 11 shows that the top 100 meters of the shelf-break and slope water region lie close to a line of constant

density. Under such conditions, cabbelling near the shelf-break region is a possibility, but the data coverage is too sparse to take this suggestion further. Isopycnal mixing and/or cabbelling are also possible near the shelf-break region for the transects further upshelf — as shown by the T/S plots for the EVERGREEN March 1974 transects (Fig. 12).

Summing up, extreme longshore variability of the shelf/slope front and shelf water mass properties was observed during the intensive observational period from 27 Feb. to 5 March 1974.

The BEAR transect of March 1957 shows remarkably homogeneous shelf conditions separated from a warmer and saltier than usual slope water pycnostad (15°C , 36 ‰). The 36 ‰ salinity slope water suggests a recent or impending warm core ring interaction; isotherms and isohalines of the slope water appear to have deepened by about 50 m and the isopycnal slopes suggest a southwestward jet, extending deeper than 350 m into the slope water, between the last two offshore stations. An additional BEAR transect, not shown here, taken off Long Island Sound does show a warm core ring in the slope water.

The March 1958 BEAR transect off Long Island shows a coastal front separated from a slightly warmer, more saline and denser mid-shelf bolus. The bolus is about 25 km wide, 30 m high and located on the relatively flat section of the shelf. The shelf/slope front is poorly resolved; note also that the transect is taken over four days, the first five stations being completed on the 6th and 7th of March and the last two on the 9th and 10th of March. The upper 300 m of the slope water is weakly stratified and upward protrusions of isopleths, up the continental slope, are evident — note, however, that the 11°C isotherm, usually near the 200 m mark, is depressed. The T/S distribution (Fig. 12) shows that much of the slope water and the offshore waters of the shelf/slope front fall along the $\sigma_T = 27$ contour. The convergence of the T/S curve for the shelf/slope front to that for the slope water, along a constant σ_T contour, suggests mixing along isopycnal contours along the under side of the shelf/slope front. The rapid offshore deepening of isopleths for the last two stations suggest a large scale slope water perturbation — an anticyclonic ring? — further offshore.

The effects of the anomalous 1960 years are seen in the two ALBATROSS IV transects of March 1965 and 1966. The corresponding T/S diagrams (Fig. 12) include not only the transect data shown here but also other ALBATROSS IV meridional transects (not shown here) along 69.5°W , 71.5°W and 72.5°W . The hydrographic structure of the shelf-break region is not resolved but extensive regions of cold fresh water masses ($<4^{\circ}\text{C}$, <33 ‰) are seen in the top 100 m. Inshore protrusion of warmer, saltier slope water, centered at about the 150 m level, are common features of the transects. Isotherms and isohalines associated with these protrusions are steeply inclined but the isopycnals rise smoothly offshore — suggesting westward flow along the slope. The temperature of the slope water below 100 m during March 1966 is cooler by about 3°C and the water is fresher.

7.2 (B) Spring sections April to June

The BEAR transect of April 1957, taken after the passage of what was probably a warm core ring, shows a surprising contrast to the remarkably homogeneous shelf conditions observed at the end of March 1957. Shelf waters are highly salinity stratified, and springtime warming and development of a thermocline are evident shoreward of the shelfbreak region. The BEAR cruise of May 1957, taken at about the same time as the April cruise, shows a more homogeneous salinity distribution, with the shelf/slope front located along a deeper isobath (~ 100 m); this shelf condition is consistent, with the exception of the warming trend, with that observed along the same Hudson Canyon transect in March 1957.

The April and May transects clearly suggest that isohalines, located at the edge of the cold pool in the Long Island transect, move offshore to the shelfbreak region as one proceeds towards the Hudson Canyon. There is also a corresponding convergence of shelf/slope front isohalines (say between 33.4 ‰ and 35 ‰) towards the Hudson Canyon transect. The shelf/slope front therefore undulates onshore a distance of order 40 km on a longshore scale of order 100 km. Undulations of isopleths within the front, of the same order as the onshore undulation, are also evident. Whether this is due to bulk advective movement and/or mixing is not resolvable. Substantial contrasts in the slope water dynamics are also evident in the two transects. The Hudson Canyon transects show a deep slope water pycnostad ($>14^{\circ}\text{C}$; >35.6 ‰) extending down to 200 m with the isotherms and isohalines being at least 50 m deeper than that observed in the Long Island transect. The Long Island transect shows a narrow boundary layer (~ 10 km in width) on the continental slope where isopleths are depressed about 80 meters or more. In geostrophic balance, a strong southwestward jet would be produced over the continental slope and shelf-break region.

Light lenses of fresh water are seen at the coastal boundary and inshore side of the shelf/slope front in the Hudson Canyon transect. The lenses are riding on top of the thermocline and the offshore lens is fresher than that observable in the March 1957 transect. In fact, the mid-shelf salinities are at least .2 ‰ fresher than in March — suggesting bulk import of fresher waters.

A detailed large-scale slope water transect is provided by the CHAIN cruise of April 1959. The Gulf Stream normally would cross this transect near the 3000 m isobath; however, the sections clearly show the Gulf Stream to be much further east of its normal position. The appearance of a subsurface cool, fresh water mass centered at the 80 m depth at the furthest offshore station suggests entrainment of water near the shelf break by the Gulf Stream. The relatively ordered appearance of the density structure contrasts sharply with the contorted temperature and salinity distributions in the upper 200 meters. Salinity and temperature isopleths are sharply inclined and almost vertical whereas the density distribution shows smooth cross-stream undulations — implying that mixing is predominantly

along isopycnals. The warm salty lens at the furthest offshore stations is connected to a large slope water mass, >35.4 ‰ salinity, centered at the 150 m level. The connection to the interior water mass occurs at the onshore edge of the lens representing the meeting place between the cooler fresher onshore waters with the light lens. Also noticeable at this meeting point is the surfacing of the onshore $\sigma_T = 26.6$ isopycnal; cabbelling is a possibility.

Stations from the ATLANTIS cruise of May 1938 were completed from 29-31 May with the exception of the second station which was occupied on the 17th of May. The extruded appearance of the cold pool is partly due to the coarse sampling grid — resulting in a poorly defined bottom topography (slicing off the shelf-break region) and coarse detail. The large scale picture shows, however, an interaction of the cold pool with warmer saltier water offshore. The appearance of 18° , 36 ‰ salinity water at the furthest offshore station indicates a recent or imminent warm core ring interaction. The slope waters and the top 50 m of the shelf waters are predominantly temperature-stratified; it is then not surprising to find almost horizontal isopycnal zones which are common to both shelf and slope waters. The surface waters of the shelf and shelf-break region are horizontally stratified by salinity. This stratification is greatest near the coast and at the surfacing of the shelf/slope salinity front (between 34 ‰ and 35 ‰).

The BEAR cruise of May 1958, near the Hudson Canyon, displays a somewhat similar large scale shelf/slope interaction. A noticeable difference is the strong horizontal salinity stratification over the shelf with what appears to be mid-depth intrusions, 20 km in cross-shore scale, right to the coast. Consequently shelf water isopycnals are inclined in contrast to the expected pycnocline structure of ATLANTIS May 1938. Thermal wind velocities for the shelf relative to the bottom suggest surface velocities of order 5 cm s^{-1} southwestward, with maximum velocities near the shelf-break region. The density structure of the front at the onshore edge of the warm salty lens is not resolved. Upward protrusion or doming of isopycnals in this region are indicative of upwelling and/or cabbelling.

A further BEAR transect, off the east end of Long Island, taken during the same period, shows an intense coastal front and a temperature-stratified mid-shelf region. The warm core ring, evident in the southern Hudson Canyon transect, has presumably passed by a few weeks earlier, leaving a 200 m deep pycnostad extending from the 50 m depth level. The salinity structure at the shelf-break region is very diffuse and extends out into the upper 50 m of the slope water. An inclined shelf/slope front is evident with density contrasts larger than those of wintertime. Again, doming of the isopycnals is evident about 50 km offshore of the shelf-break.

The GOSNOLD transect of May 1972, taken during a UNESCO-NODC training program, shows a detailed picture of numerous water masses and fronts in the upper 50 m. Again, as with the April 1959 CHAIN transect, the density

structure is surprisingly well behaved. The salinity bolus furthest offshore has apparently been around long enough for the top 30 m of its surface to become temperature stratified. The weak horizontal density gradient through this bolus suggests that the bolus has little relative vorticity and is embedded within the bulk flow of the surface slope water. Centered about forty kilometers inshore from the center of this bolus is a fresher bolus of roughly the same size. The vertical salinity stratification in this bolus is sufficiently strong to produce density perturbations, 20 m deep and 30 km wide, in an otherwise smoothly varying density distribution.

Geostrophic velocities of this bolus relative to 350 m are of order 5 cm s^{-1} at the surface in an anticyclonic sense. Centered a further 40 km inshore is an even fresher salinity bolus. This bolus is about 20 km offshore of a cold pool ($<7^\circ\text{C}$, 32.6 ‰) located onshore of the 100 m isobath. Above this pool are to be found the lightest surface waters with steeply inclined isopycnals between the third and fourth stations, suggesting westward flow. The opposite curvature of isopycnals inshore of this front would produce anticyclonic horizontal shear. The steepest frontal density gradients occur offshore of the cold pool producing westward velocities of at least 15 cm s^{-1} relative to the bottom. Isopleths in the slope water are depressed about 50 m below their usual levels except for an upward protruding region about 20 km wide.

Two transects taken during intense warm core ring activity close to the continental slope are provided by the CAPE HENLOPEN 77-01 cruises of April-May 1977. The positions of the transect in relation to warm core rings observed on the 4th May 1977 are shown in Fig. 14. In the northern section (notice vertical scale change) waters of the cold pool ($<5^\circ\text{C}$) reach temperatures lower than 3°C reflecting the severity of the cold winter of 1976-77. Highly salinity-stratified coastal water masses occur within 60 km of the shore and in the top 20 m of the water column. Proceeding offshore, in the mid- and outer shelf regions, the salinity stratification weakens considerably in relation to temperature stratification. The appearance of water masses with temperatures $>15^\circ\text{C}$ and salinities >36 ‰ in the slope water region are indicative of warm core ring activity. The transect location map (Fig. 14) shows that these water masses may be mixed remnants of eddy P. Between this water mass and the outer shelf water mass occurs a narrow ($\sim 15 \text{ km}$ scale) intense front right up against the continental slope. Across this front, salinities change by 2 ‰ and temperatures by more than 5°C . Contouring of isopycnals across this front is made difficult by the wide sampling spacing at this critical location. However, note that the T/S properties of the water masses on either side of this front are such that, in the top 40 m, the densities are roughly the same.

The southern transect shows warmer, saltier shelf conditions and a strong but weaker front against the continental slope. The cooler, fresher bolus 30 km offshore of the shelf-break appears to be a filament entrained by the warm core ring (Fig. 14).

The ATLANTIS transect of June 1937 shows complex water mass features associated with a relatively smoothly varying density distribution. The section shows again a highly stratified coastal water mass region separated from a more homogeneous but temperature-stratified mid- and outer shelf region. The distinctive feature of the top 100 m of the slope water region is the presence of boluses of water masses of complex T/S properties. The temperature section seems to indicate a cold bolus centered at 40 m at the fifth offshore station. However, the salinity section clearly shows that the coldest water mass associated with this bolus is salinity-stratified (weakly), and the freshest water mass occurs at the surface. The surface water mass properties are similar, though saltier, than the shelf water mass near the shelf-break region. It therefore appears that this bolus cannot be explained solely as a "calving" process of the cold pool; exchanges of surface water masses are also involved. A saltier and presumably older bolus appears at the last station. The top 20 m appears to have mixed and a relatively cold, fresh water mass is located just beneath the thermocline. An extensive halostad more than 160 m deep, and relatively fresh (35.2 ‰ or less in salinity) occurs in the slope water beneath the 100 m depth level. This halostad is temperature stratified though the temperatures are about two degrees cooler than normal. If the data is accurate, then it suggests extensive water mass formation or influx of fresher, cooler slope water.

A less complex picture is presented by the ATLANTIS cruise of June 1939. Again boluses are evident across the top 100 m of the slope water. Three fronts are evident: the near-shore coastal front, the shelf-break front at the edge of the cold pool, and about 80 km further offshore, a temperature-salinity front at the inshore side of a warm band of water extending into the top 30 m of the slope water. Centered less than 20 km inshore of this front is a doming of isopycnals associated with a fresher surface mass of water ~50 m deep, 20 km wide; the upward doming suggests cyclonic circulation in contrast to the characteristic depressed isopycnals associated with surface lenses. The salinity distribution suggests that offshore of the shelf-break front, water masses which have mixed across the front have been contained within 70 km of the front. The furthest bolus centered at 40 m depth (associated with a slightly fresher surface lens) suggests further that these water masses are being transferred intermittently towards the Gulf Stream.

The ATLANTIS transect of June 1955 shows a section of the Gulf Stream water mass flowing near Cape Hatteras. Subsurface entrainment of what appears to be cold pool waters is taking place about 50 km offshore. The appearance of the 7°C isotherm near the 300 m depth level on the continental slope suggests that isoclines against the slope are elevated relative to those further northward.

The BEAR cruise of June 1958 shows a detailed section across the Nantucket Shoals region. A tidal front appears to have formed near the 40 m isobath with what appears to be small-scale boluses ~15 m deep, 15 km in scale offshore of this front and embedded within the thermocline. The mid- and outer shelf regions are highly density-stratified both vertically and horizontally with the weakest gradients being associated with

the cold pool near the 90 m isobath. A subsurface shelf-break front rises from the 110 m isobath, about 50 m in 10 km, and isopycnals level off 10 km offshore of the bottom position of the front. Offshore of the front, a 30 m deep, 20 km scale surface lens lies above a larger bolus of what appears to be cold pool water, centered at the 60 m depth level. Containment of water masses exchanged across the front are also apparent in the salinity section.

Two transects during the anomalous years of the 1960's are the ALBATROSS IV transects of June 1965 and 1966. In the top 150 m, the salinity structure is diffuse and relatively fresh compared to the other June transects. An inshore protrusion of relatively warm salty slope water centered at 150 m is seen in the 1965 transect: similar to the ones observed in the ALBATROSS IV transects of March. In 1966, there is an isolated relatively warm salty water mass associated with upward doming isopycnals in the top 150 m. The inshore protrusion of 1965 is associated with anticyclonic curvature of isopycnals.

An interesting feature of the ALBATROSS IV 1978 sections is the apparent upward protrusion of warm saline slope water 30 to 40 km off the shelf-break. These features are in contrast to the wedge-like inshore protrusions of slope water observed in the other June transects. The salinity sections show that waters less than 32 ‰, normally associated with coastal waters, occur as a thin wedge extending right to the shelf-break region.

7.2 (C) Summer sections July to September

All of the stations of the ATLANTIS cruise of July 1939 were taken between the 8th - 10th July 1939 except for the 9th offshore station, where the surface bolus was observed, which was taken on July 15th. Extensive salinity stratification is evident in the top 100 m or so of both the shelf and slope water. This is also true, though less well resolved, for the ATLANTIS cruise of July 1940. Upward protrusions of salty slope water offshore of the shelf-break region are evident. In the July 1939 section, this protrusion is associated with a rupturing of isopycnals at the surface.

The BEAR cruises of July 1958 represent a fine detailed collection of transects near the Nantucket Shoals region. A section further down-shelf is provided by the CRAWFORD transect; note that the first three inshore stations were taken on the 19th of July whereas the stations further offshore were taken on the 8th and 9th. Extensive longshore variability of property distributions is revealed by these transects. Firstly, the most eastern transect shows that inshore of the 40 m isobath tidal mixing is at least as strong as thermal stratification processes. Proceeding westward to the CRAWFORD section, salinity and thermal stratification lead to the development of an intense coastal front reaching out to the mid-shelf region. The coldest cold pool water, located near the bottom in the most eastward transect, is inlaid by intrusions along the bottom of warmer, saltier slope water further west.

Undulations of isopycnals at the shelf-break region are evident with a shock-like appearance of isopleths for the short transect taken during 20-21 July. For this transect, upward intrusions of slope water $<8^{\circ}\text{C}$ up the continental slope are evident. This is also seen in the most eastward transect.

The CRAWFORD section shows, however, a deep upward protrusion at least 40 km offshore, and on the continental slope isoclines are depressed. These sections provide some evidence of undulations (~ 50 m in vertical scale) of slope water isoclines causing changes in property distributions near the shelf break.

The July CHAIN cruise during the cold year of 1961 shows extensive seaward intrusion of the cold pool waters into the slope water. Isohalines between 34 ‰ and 35 ‰ extend from the shelf-break region to over 100 km offshore centered at about the 90 m depth. The continuity of the 12°C , 35.4 ‰ slope water mass between 100-150 m depth range is severed by upward excursion of deep slope water ~ 40 km off the continental slope. Extensive eastward flow of the slope water is suggested by the downward offshore inclination of isopycnals.

The CONRAD 19-01 July 1975 transect was taken just after or behind a warm core ring centered at 38.5°N , 72°W on August 4th (Gulf Stream, August 1975). The salinity section shows a core of slope water >35.4 ‰ over 100 m deep with depressed isopycnals suggesting anticyclonic circulation. The 6°C isotherm, visible at the furthest offshore stations, suggests massive upheaval of offshore isoclines. A cool, relatively fresh mass of water located well offshore represents probably cold pool waters entrained offshore. Inshore of this water mass, a tongue of the salty slope water protrudes upward, then inshore at least 40 km just under the main pycnocline.

The appearance of a very salty (>36 ‰) water mass in the slope in the August 1938 cruise of ATLANTIS suggests a recent WCR interaction. Further evidence is the extensive region of relatively fresh water well offshore in the top 40 m.

Compared to the ATLANTIS section of July 1939, substantial changes have occurred with the appearance of a warm core ring in August 1939. The August transect is not synoptic in time: for reference, the date during which each station was taken is noted at the top of the station positions for the temperature transect. On the shelf, an onshore intrusion centered at the 25 m depth level and a return offshore intrusion at the 40 m level appear to have taken place. The 34 ‰ isohaline is located further offshore on the shelf-break. Bolus-like features of the cold pool appear to be an artifact of the disparity in sampling times.

Compared to the ATLANTIS cruise of July 1940, significant changes have occurred in the property distributions for ATLANTIS August 1940. An extensive tongue of salty slope water emanates from a core region centered well offshore at the 50 m depth level. The tongue protrudes

downward and inshore almost to the continental slope, getting fresher as it protrudes in. A relatively homogeneous wedge of fresher water lies above this tongue. Isopycnal slopes suggest a weak broad south-westward flow over most of the slope water. A reversal takes place about 20 km inshore of the core of the saltiest slope water (a further offshore station, not shown, has been used to continue the contours). Compared to the July 1940 transect, the slope water surface layers have warmed by 2°C or more, especially on the shelf. Onshore advection of saltier slope water is evident in the top 20 m with what appears to be a compensating outflow at the 50 m depth level below the pycnocline.

The four transects of BEAR August 1955 give a detailed picture of longshore variability. The most eastward transect was taken a day or two after the passage of Hurricane Diane on the 19th. Earlier, Hurricane Connie had crossed inland along Chesapeake Bay on the 13th of August (see Neumann et al. 1978). During this period, winds were predominantly onshore within the New York Bight region. The BEAR transect taken on the 19th of August occurred during the passage of a weakened Hurricane Diane; weather data was not recorded at any stations except the last one where a Beaufort-scale wind force of 6-7 was noted. Consider the transects of the 15th of August, just after Hurricane Connie, and that of the 19th of August, during Hurricane Diane. Both transects show that the intense salinity front between 33 ‰ - 34 ‰ is displaced about 40 km onshore in the top 20 to 30 meters relative to its deeper position. This, however, is not the case for the almost vertical front observed during 16-17 August. Also, the front observed on the cruise of 10-22 August (note that only the second station was taken on the 10th, the others were on the 21st-22nd), after Hurricane Diane, is diffuse and inclined well offshore. The vertical thermal structure in the top 30 m is also more diffuse and the surface waters are cooler.

An interesting difference between the two BEAR cruises of August 1958 is the salinity structure in the upper 150 m and the associated isocline excursions in the deeper slope waters. In the more westward section, a region of warm ($>12^{\circ}\text{C}$) salty (>35 ‰) water is located within 40 km of the continental slope and between the 60 m and 160 m depths. Associated with this slope water core is anticyclonic curvature of isopycnals and fresher water located offshore of this core. In the eastern section, waters of similar properties to the western core, are located in a much smaller region between the 100 and 130 m depth; the deep isoclines are further up the slope and the salinity structure in the top 100 m has a more "compressed" appearance.

A large-scale picture of longshore variations in shelf and slope water properties is provided by the Coast Guard EVERGREEN cruise of August 1974. The southernmost transect shows a warm core ring located close to the continental slope. The transect, taken a few days later off Long Island Sound on the 19th, gives a strong hint of a weak warm core ring-like feature associated with a salty (>36 ‰) core centered

at 90 m. Further evidence of this ring-like feature can be seen in the New York-Bermuda XBT transect series reported by the Naval Oceanographic Office (Gulf Stream, December 1974); the weak ring is observed in the transect conducted on the 12-14 September 1974 — suggesting that the ring is drifting at about 6 cm/s southwestward. This ring was not detected, however, on the frontal analysis charts reported in the Gulf Stream. The salinity distribution in all transects is indicative of onshore intrusions of water centered at about 20-25 m and return out-flows at about the 40 m level. Strong salinity fronts exist near the shelf-break region (presumably the advective flows offshore of their fronts are strong enough to sweep away any intrusive shelf water flows into the slope water).

A further warm core ring interaction picture is provided by the KNORR ACE III transect of 7-9 August 1977. The Experimental Ocean Frontal Analysis chart for 10 August 1977 shows that the KNORR transect just crosses into Eddy N. A further eddy (L) is located southwestward. These eddies were both observed earlier as shown in Fig.14.

Again onshore salinity intrusions centered at about the 20 m level are evident. The saline waters of the warm core ring are seen at the last station.

During September, the onset of surface cooling and deepening of the surface mixed-layer commences. The BEAR transect of September 1952 shows an anomalous upward protrusion of relatively fresh deep slope water (<35 ‰) associated with an anticyclonic density perturbation structure. A double salinity front is visible: one near the shelf-break and another one at the onshore side of the upward protruding deep salinity layer. A warm pool of surface water, 20 m deep, 60 km length, is located between these fronts. A cool "bolus", centered at 50 m depth and associated with a slightly fresher lens, is located just inside of the offshore front. The deep upward salinity protrusion therefore appears to be associated with the distinctive fronts and water masses in the surface layers.

Two transects along Hudson Canyon are the ATLANTIS cruise of September 1956 and the BEAR cruise of September 1957. An S-shaped shelf-break salinity front is clearly visible in the 1956 transect whereas the 1957 transect shows an offshore protrusion centered at 50 m and a more well-mixed surface layer. Slope water salinities during 1957 are saltier than those of 1956. This is possibly an indication of an interaction with a WCR for the 1957 transect; additional data collected during the BEAR cruise of September 1957, about 100 km further upshelf, shows 18 degree slope water salinities >36.4 ‰ — indicative of a WCR. Upward excursions of isoclines for the last two stations of the BEAR 1957 transect are clearly visible. The WCR interaction shown in the detailed transect of EVERGREEN September 1964 also shows anomalously deep cold water migrating up the continental slope. The shelf-break salinity front, during this interaction, does not protrude into the slope water but appears to be "sliced-off" or "calved" at the shelf-break region.

7.2 (D) Fall sections October to December

The ATLANTIS cruise of October 1937 is a further (but poorly resolved) picture of a WCR interaction. The shelf-break topography is not well defined. Onshore excursions of the well-mixed salinity in the top 30 to 40 m is evident on the shelf. The calving of the salinity front at the shelf-break and upward excursion of isoclines on the continental slope are evident.

The ATLANTIS transect of November 1938 shows the intermediate stage in the progress to vertically well-mixed winter conditions. The pycnocline in the top 150 m of the slope water is diffuse due to the thermocline being on top of the halocline. The saltiest slope water centered at about 120 m depth lies just below the pycnocline. The shelf water is relatively salty and the coarse sampling suggests a shelf-wide anticyclonic curvature of isopycnals.

The remnant effects of a WCR interaction observed in August 1939 is shown by the ATLANTIS transect of October 1939. The shelf-break region is again poorly resolved. The most noticeable effect is the remnant mass of warm salty water with a core >35.8 ‰ centered at 110 m. Isopycnal curvature associated with this mass suggests anticyclonic circulation. In the top 50 m a salinity front is located at the onshore edge of this circulation. At the offshore edge is a surface bolus or section of a filament of cooler fresher water mass.

Relatively well-mixed, vertical and horizontal conditions are shown for the surface layers for the two VEMA October transects of 1974. The top 30 to 40 m are principally salinity stratified. More complex salinity/temperature stratified waters exist below within the pycnocline. The Hudson Canyon transect shows a shelf-break salinity front with an offshore mid-slope water front. This latter front is associated with anticyclonic curvature of the deep slope water isopycnals. Just inshore of this front, in the top 20 m, is a slightly cooler fresher water mass. Below 150 m, property gradients for the Hudson Canyon transect are noticeably greater than those for the southern transect. The salty slope water at about 90 m for the southern transect is possibly the remnants of the earlier WCR observed in the August transects.

The appearance of warm (>18°C) salty (>36 ‰) slope water in the CRAWFORD cruise of November 1956 is suggestive of a WCR interaction. There is no clearly defined shelf-break front. The CRAWFORD section of December 1956, taken within a few days later, along the Hudson Canyon shows two salinity fronts: a narrow (<10 km) front 30 to 40 km inshore from the shelf break and a more diffuse front surfacing 30 to 40 km offshore. Between these fronts, the water is relatively homogeneous. The coarse sampling of the earlier November transect may have missed the shelf-break front.

A further illustration of substantial longshore variability is evident in the two BEAR cruises of November 1957. Surface waters of the

southern section are cooler, saltier and denser; the slope water pycnocline is more diffused. Deep perturbations of the slope water pycnostads centered at 150 m are seen in the southern transect. Along the continental slope relative vertical excursions 80 m or more in scale, of isoclines can be seen.

Stations for the ATLANTIS/HERWIG cruise of November 1971 were taken by the ATLANTIS from the 6th till the 7th of November except for the first station which was taken by the HERWIG on the 12th. The surface slope water $>22^{\circ}\text{C}$ is very warm by comparison to the other November transects. A definite anticyclonic ring structure is associated with a halostad core $>35\text{‰}$ centered at 100 m and 100 km in cross-shore scale. The relatively fresh salinity structure located offshore of the center of the core suggests entrainment and offshore anticyclonic advection of fresher shelf/slope waters. This surface water mass is relatively uniform in temperature and the pycnocline structure is predominantly a function of temperature stratification. An inspection of the Gulf Stream issues for the latter half of 1971 shows that there were no warm core rings near this section though a WCR had passed by a month earlier.

The detail in the December transect of ATLANTIS 1947 is poor, but the progression to vertically well-mixed winter condition is evident. An extruded salinity is shown in the CHAIN cruise of December 1958. A halostad of salinity $>35.6\text{‰}$ and associated with offshore deepening isopycnals suggests northeastward flow of slope water. The last station is of course too far off to resolve the slope water mass structure. Another WCR picture is provided by the CHAIN cruise of December 1972. Stations were taken during 5-6 December except for the seventh offshore station conducted on the 12th.

The two ALBATROSS IV transects of December 1965 and 1966 show the hydrographic structure during the anomalous years of the 60's. The 1965 section shows anomalously fresh slope water down to the limit of sampling: the coldest water mass ($<5^{\circ}\text{C}$) observed, within the sampling limits, is located below the main pycnocline. The appearance of relatively warm salty slope water centered at 150 m, evident in other transects of 1965-66, is seen in the 1964 transect.

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Figure 1

Bathymetry of the Middle Atlantic Bight shelf/slope region. Transect data in this report are located within the range 36°- 42°N; 69°- 76°W. The offshore extent of the data included is up to about the 4000 m isobath.

METEOROLOGICAL FORCING FOR MARSDEN SQUARE 152

Figure 3

Bunker's (unpublished) meteorological data for Marsden Square 152. Wind directions refer to the direction toward which the wind is blowing. The wind stress magnitude is the annual average of the monthly wind stress amplitudes.

Figure 4 Time-series of monthly averaged transect data for Mid-Atlantic Bight slope water deeper than 100 meters. Solid lines represent data averaged between 100 meters to 200 meters and dashed lines for data averaged between 200 meters to 300 meters.

Figure 5 Comparison of monthly mean sea-surface temperature (dashed line) and long-term average (solid line) for a 3° latitude diameter circle centered at 37.5°N, 72.5°W. (after Namias, 1966)

Figure 7 Annual precipitation recorded at the New York Central Park Observatory (solid line) and five year non-overlapping means (dashed line). (after Namias, 1967)

Figure 6 Sea-surface temperature anomalies for the four year period from 1962-1965 (right diagram). Below normal temperatures indicated by stippling. Anomalies in Fahrenheit degrees. (after Namias, 1966)

Figure 8 Slope water temperature profile from 16 airdropped BT's. Surface outcropping of the slope front and the north wall of the Gulf Stream are indicated.

Figure 9 Geostrophic velocities relative to 1500 m for the KNORR cruise of January 1971.

Figure 10 Temperature-salinity diagrams for the January transects. The oblique orientation line is drawn through the points (7°C, 33‰), (12°C, 35‰). Dashed lines represent isopycnal contours. Where discernible, square symbols are for data from 0-50 m, open circles for 50-100 m, filled triangles for 100-150 m and squares rotated 45° for 150 m and beyond.

Figure 11 As for Fig. 10; February transects.

Figure 12 As for Fig. 10; March transects.

Figure 13(a)

Figure 13(b)

Figure 13 Surface hydrographic maps, for temperature (a), salinity (b), and density (c), from data taken on the DALLAS cruise and EVERGREEN cruise. A Warm Core Ring detected on the 27 Feb 1974 is also shown.

Figure 14 Location of CAPE HENLOPEN transect lines in relation to frontal features noted on the frontal analysis chart for the 4th May 1977.

Figure A1 (a)

Figure A1 (b)

Figure A1 (c)

Figure A2 (a)

Figure A2 (b)

Figure A2 (c)

Figure A3 (a)

Figure A3 (b)

Figure A3 (c)

Figure A4 (a)

Figure A4 (b)

Figure A4 (c)

Figure A5 (a)

Figure A5 (b)

Figure A5 (c)

Figure A6 (a)

Figure A6 (b)

Figure A6 (c)

Figure A7 (a)

Figure A7 (b)

Figure A7 (c)

Figure A8 (a)

Figure A8 (b)

Figure A8 (c)

Figure A9 (a)

Figure A9 (b)

Figure A9 (c)

Figure A10(a)

Figure A10(b)

Figure A10(c)

Figure A11(a)

Figure A11(b)

Figure A11(c)

Figure A12(a)

Figure A12(b)

Figure A12(c)

Figure A13(a)

Figure A13(b)

Figure A13(c)

Figure A14(a)

Figure A14(b)

Figure A14(c)

Figure A15(a)

Figure A15(b)

Figure A15(c)

Figure A16(a)

Figure A16(b)

Figure A16(c)

Figure A17(a)

Figure A17(b)

Figure A17(c)

Figure A18(a)

Figure A18(b)

Figure A18(c)

Figure A19(a)

Figure A19(b)

Figure A19(c)

Figure A20(a)

Figure A20(b)

Figure A20(c)

Figure A21(a)

Figure A21(b)

Figure A21(c)

Figure A22(a)

Figure A22(b)

Figure A22(c)

Figure A23(a)

Figure A23(b)

Figure A23(c)

Figure A24(a)

Figure A24(b)

Figure A24(c)

Figure B1 (a)

Figure B1 (b)

Figure B1' (c)

Figure B2 (a)

Figure B2 (b)

Figure B2 (c)

Figure B3 (a)

Figure B3 (b)

Figure B3 (c)

Figure B4 (a)

Figure B4 (b)

Figure B4 (c)

Figure B5 (a)

Figure B5 (b)

Figure B5 (c)

Figure B6 (a)

Figure B6 (b)

Figure B6 (c)

Figure B7 (a)

Figure B7 (b)

Figure B7 (c)

Figure B8 (a)

Figure B8 (b)

Figure B8 (c)

Figure B9 (a)

Figure B9 (b)

Figure B9 (c)

Figure B10(a)

Figure B10(b)

Figure B10(c)

Figure B11(a)

CH 77-01 05 77 102

Figure B11(b)

Figure B11(c)

Figure B12(a)

Figure B12(b)

Figure B12(c)

Figure B12(c)

Figure B13(a)

Figure B13(b)

Figure B13(c)

Figure B14(a)

Figure B14(b)

Figure B14(c)

Figure B15(a)

Figure B15(b)

Figure B15(c)

Figure B16(a)

Figure B16(b)

Figure B16(c)

Figure B17(a)

Figure B17(b)

Figure B17(c)

Figure B18(a)

Figure B18(b)

Figure B18(c)

Figure B19(a)

Figure B19(b)

Figure B19(c)

Figure C1 (a)

Figure C1 (b)

Figure C1 (c)

Figure C2 (a)

Figure C2 (b)

Figure C2 (c)

Figure C3 (a)

Figure C3 (b)

Figure C3 (c)

Figure C4 (b)

Figure C4 (c)

Figure C5 (a)

Figure C5 (b)

Figure C5 (c)

Figure C6 (a)

Figure C6 (b)

Figure C6 (c)

Figure C7 (a)

Figure C7 (b)

Figure C7 (c)

Figure C8 (a)

Figure C8 (b)

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Figure C9 (a)

Figure C9 (b)

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Figure C10(a)

Figure C10(b)

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Figure C11(a)

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Figure C25(a)

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Figure C26(a)

Figure C26(b)

Figure C26(c)

Figure C27(a)

Figure C27(b)

Figure C27(c)

Figure C28(a)

Figure C28(b)

Figure C28(c)

Figure C29(a)

Figure C29(b)

Figure C29(c)

Figure D1 (a)

Figure D1 (b)

Figure D1 (c)

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Figure D3 (a)

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Figure D4 (a)

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Figure D5 (a)

Figure D5 (b)

Figure D5 (c)

Figure D6 (a)

Figure D6 (b)

Figure D6 (c)

Figure D7 (a)

Figure D7 (b)

Figure D7 (c)

Figure D8 (a)

Figure D8 (b)

Figure D8 (c)

Figure D9 (a)

Figure D9 (b)

Figure D9 (c)

ATLANTIS II/WALTER HERWIG

November 1971

Figure D10(a)

Figure D10(b)

Figure D10(c)

Figure D11(a)

Figure D11(b)

Figure D11(c)

Figure D12(a)

Figure D12(b)

Figure D12(c)

Figure D13(a)

Figure D13(b)

Figure D13(c)

ALBATROSS IV

December 1964

Figure D14(a)

Figure D14(b)

Figure D14(c)

Figure D15(a)

Figure D15(b)

Figure D15(c)

Figure D16(a)

Figure D16(b)

Figure D16(c)

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