Abstract—Twenty-eight hydrographic surveys of the Middle Atlantic Bight (MAB) were conducted during 1977–1987 as part of the National Marine Fisheries Service's Marine Resources, Monitoring, Assessment, and Prediction program. The average temperature and salinity for Shelf Water (<34 psu) in the MAB were determined for each survey. While temperature followed a well-defined seasonal cycle, the Shelf Water salinity exhibited large interannual variations. A stepwise multiple linear regression model is used to show that variations in river discharge and in precipitation can explain 70% of the year-to-year changes in the Shelf Water salinity.

INTRODUCTION

One hundred years ago, after conducting an oceanographic survey of the Middle Atlantic Bight (MAB: 35–42°N, 69–76°W) aboard the US Fisheries schooner Grampus, Libbey (1891) wrote:

Data eventually obtained will undoubtedly lead to important generalizations bearing upon the questions of physical geography and biological physics, or the relation of marine species to their physical environment.

Since that time oceanographers have determined that waters in the MAB are subject to seasonal and interannual changes in response to variations in river run off, solar heating, convective cooling, wind mixing/advection, and oceanic intrusions. The combination of these meteorological and oceanic processes affects the character of the water on a variety of space and time scales. Although progress has been made in examining some of the individual physical mechanisms, neither a description nor an understanding of the environmental variability is yet complete.

Mainly because of interest in fish stock variations, ocean dumping, and other pollution in this region, a series of papers have been published regarding the marine environment of the MAB. In the late 1970s, the general characteristics of the physical environment were addressed (Beardsley et al., 1976; Wright and Parker, 1976; Davis, 1979). Follow-up physical oceanographic studies in the last decade have focused on more specific processes such as “cold pool” formation (Houghton et al., 1982), mixing rates (Han and Niedrauer, 1981), wind-induced circulation (Beardsley and Haidvogel, 1981; Beardsley and Boicourt, 1981), and Shelf/Slope Water exchanges (Walsh, 1988).
More recently, the origin of MAB water, as seen from $^{18}O$ ratios, has been investigated (Fairbanks, 1982; Chapman et al., 1986; Chapman and Beardley, 1989). It is understood that some MAB water travels from as far away as the Denmark Straits, a 5000 km journey along the coast through a variety of mixing/exchange mechanisms, such as the addition of Hudson Bay and St Lawrence River water (Sutcliffe et al., 1976); however, the characteristics of MAB water are considerably different from those of Arctic meltwater.

The purpose of this article is to report on oceanographic conditions in the MAB during the recent decade (1977–1987) from a set of shelf-wide surveys, and, in particular, to show that the dominant mechanism governing interannual variations of salinity is local river run off and precipitation. This hypothesis, first reported by Bigelow and Sears (1935) and supported by Ketchum and Keen (1955), proposes that fresh water accumulates, at times, in such a way that shelf-wide variations in depth-averaged salinity may result. Despite the fact that annual input of rivers and precipitation amounts to little more than 1% of the total volume of MAB water and depending on how one defines "Shelf Water", much of the salinity variability may be explained by local meteorologic processes.

DATA

A total of 49 hydrographic surveys of the Northeast Continental Shelf were conducted approximately once per season during 1977–1987 (Fig. 1) as part of the National Marine Fisheries Service’s (NMFS) Marine Resources, Assessment, and Prediction (MARMAP)
program. The entire MAB portion (Fig. 2), discussed in this report, was occupied 28 times with 93–106 stations each time.

Standard hydrographic procedures were used at each station. Except for the last three cruises of 1987, water bottles fitted with reversing thermometers were used to sample temperature and salinity at standard NODC depths (1, 5, 10, 20, 25, 30, 35, 50, 75, 100, 150, 200, 250, and 300 m). For most of the May cruise (DEL8704) and the entire September (DEL8708) and November (DEL8710) cruises in 1987, a CTD (conductivity,
temperature and depth profiling instrument) was used to sample the water column (averaged to approximately one observation per meter) to a maximum depth of 300 m. Water samples were collected on each CTD cast at near-surface and near-bottom depths in order to correct the CTD-measured salinity data. The corrections were small however, of the order of 0.01 practical salinity units (psu).

The depths of the standard stations range from 11 to 1207 m. Only seven stations, however, are seaward of the 200 m isobath. Since the focus of the MARMAP survey series is on waters on the shelf, the analysis is limited to the upper 100 m of the water column and, as discussed below, to water fresher than 34 psu.

Thirty-four closely spaced (20–30 km) standard stations make up a series of cross-shelf transects labeled A–E in Fig. 2. Each transect contains six or seven stations, designed to be occupied consecutively. Traversed in less than a day, the transects provide a fairly synoptic measure of the vertical water mass structure.

Details of the procedures at sea may be found in KIRSCHNER (1980) and PATANJO et al. (1982). Temperature and salinity records are presented elsewhere in the form of contour plots (MANNING and LIERHEIMER, 1988; HOLZWARTH and MANNING, 1989; MANNING and HOLZWARTH, 1990).

Three other data sets, in addition to the hydrographic data, were used in this study.

(1) Monthly mean time series of river discharge were obtained for the Chesapeake Bay, Long Island Sound, Gulf of Maine, and St Lawrence systems. Each of these systems represents the combination of several major rivers. The Gulf of Maine system, for example, is the combination of the Saco, Kennebec, Androscoggin, and the Penobscot Rivers. All the US river data were collected by United States Geological Survey (USGS). The length of time series used to calculate long-term monthly means was 13 years for the Gulf of Maine system and 48 years for the LI Sound and Chesapeake Bay systems. The “St Lawrence River” data, obtained through the Great Lakes Environmental Research Laboratory (QUINN, personal communication), is an 87-year record of discharge from the Great Lakes system.

(2) Precipitation was recorded by NOAA’s National Weather Service Station at New York City. Values for each month are published by the National Climatic Data Center as “Local Climatological Data” releases.

(3) Shelf slope front positions, obtained from NMFS analysis of satellite data (STROUT, 1988), were recorded along a line across the southeast of Sandy Hook, NJ. For each month of the MARMAP time period, a record of the on (negative)/off (positive)-shore displacement relative to the 200 m isobath was available. Long-term means for each month were also available so that residuals (interannual variation) could be computed.

**ANALYSIS METHODS**

Four methods, described below, were used to analyse the data. Since it is necessary to briefly discuss the seasonal cycle in the hydrographic data before any discussion of interannual variability, the first three methods address aspects of seasonal variability. They are presented only as background to the more important focus of this report, interannual variability.

(1) For each MARMAP cruise the area of the MAB was divided among the stations occupied on the cruise and then a weighting was assigned to each station to represent its contribution to the total area. Using these weights, a volumetric temperature–salinity
(T–S) analysis was conducted of the waters in the MAB from the surface to 100 m depth, using a cell size of 0.5°C and 0.2 psu. The method, developed by Montgomery (1958), is used here to identify the water masses in the MAB.

For cruises on which any area of the MAB was more than approximately 100 km from the nearest occupied station the sampling was felt to be inadequate and no volumetric analysis was conducted for that cruise. For example, the cruises in 1981 and 1982 were excluded from the analysis because they did not adequately sample the region just north of Cape Hatteras.

The distribution of volume by salinity is particularly important since in the MAB salinity is a better water mass tracer than is temperature. The analysis is presented for each 3 month period (winter, December–February; spring, March–May; summer, June–August and autumn, September–November). As discussed in the next section, this analysis is used to define “Shelf Water” as the water with salinity less than or equal to 34 psu.

2) In order to investigate the seasonal variation in cross-shelf structure, mean profiles of salinity were constructed for each of the four seasons mentioned above. Mean values were calculated at the standard NODC depths listed above. Some of the near-bottom values, however, were deleted from the mean when the number of observations at those depths was less than half what it was near the surface. The results are reported for transects C and E only. Transect A had very few observations per season (2–3) and therefore, is not included. Transects B and D were similar to transect C.

3) To calculate mean properties of Shelf Water over the entire MAB, the results from (1) above were used to calculate a volume-weighted mean temperature and salinity ≤34 psu. The seasonal cycle for temperature and for salinity was calculated by fitting up three harmonics (1, 2, and 3 cycles per year) to the data, as discussed by Mountain and Holzwarth (1989). The resulting seasonal cycle is described by the equation:

\[
S = \sum_{j=1,3} \left( M_j + A_j \cos (2\pi JD/P_j) + B_j \sin (2\pi JD/P_j) \right),
\]

where \( S \) is salinity; \( M_j \) is the mean salinity for the \( j \)th component; \( JD \) is the Julian day; \( A_j \) is the cosine amplitude of the \( j \)th component; \( B_j \) is the sine component of the \( j \)th component; and \( P_j \) is the harmonic period for the \( j \)th component. To determine interannual variability for the subsequent analysis, this seasonal cycle was removed from the salinity data.

4) Finally, a multiple linear regression model, discussed in more detail later, was used to explain the interannual variability of salinity. The river discharge; precipitation, and shelf/slope front data sets, discussed earlier, are inputs to this model.

RESULTS

Seasonal variability

The T–S volumetric analysis indicates that there is a single dominant water mass in the MAB Shelf Water. The single peak in seasonal mean volumetric salinity distributions (Fig. 3), however, may shift from season to season or year to year. Although there may be a small band of fresher water very near the mouths of local rivers during certain months of the year, it is not large enough or distinct enough to constitute a separate water mass. It mixes with external sources that are advected into the region from the north.
There are a few seasonal differences that may be inferred from Fig. 3. (1) The peak in per cent volume shifts from a maximum of 33.25 psu in the spring to a minimum of 32.5 in the autumn. (2) The tightest distribution occurs in the spring when more than 50% of the volume falls between 32.25 and 33.75 psu. (3) The multiple peaks of the winter distribution are most likely an artifact of the small number of cruises contributing to the mean and demonstrates the need for several years of data to define accurately the seasonal “mean” structure.

The results in Fig. 3 indicate a second water mass in the MAB at salinities above about 35 psu, which is referred to as Slope Water (Bigelow and Sears, 1935). A minimum in volume generally occurs between 34 and 35 psu. To analyse the variability in the salinity of
Shelf Water, a boundary between Shelf Water and Slope Water must be chosen. For this report 34 psu is used as the upper limit of Shelf Water in order to focus on the core of the Shelf Water mass and to minimize the influence of variations in the amount of Slope Water on the shelf. Other choices could be made [e.g. WRIGHT and PARKER (1976) use 35 psu] and the sensitivity of the results to this choice are presented below.

Mean profiles of salinity for both the New York Bight transect (C) and the Great South Channel transect (E) are presented for each season in Fig. 4. Unlike the temperature profiles (not shown), which are drastically different from one season to the next due to seasonal warming and the influence of the cold pool, the salinity structure remains

![Seasonal mean cross-shelf salinity profiles for transect “C” running southeast from the Hudson–Raritan Estuary. Contour intervals are 0.5 psu.](image)

Fig. 4. (a) Seasonal mean cross-shelf salinity profiles for transect “C” running southeast from the Hudson–Raritan Estuary. Contour intervals are 0.5 psu.
relatively constant all year. Except for a slight increase in vertical stratification during the summer period, migration of isohalines from one season to the next appears minimal.

The layer-averaged salinities for MAB Shelf Water are plotted in Fig. 5. Salinities are highest near the beginning of the year when stratification is at a minimum, precipitation and run-off are low, and evaporation in coastal waters is high, and fall to a minimum in early summer at the arrival of high spring river run-off. The seasonal cycle, indicated by the solid line in this figure, is removed from the data and the residuals are used as input to a regression model discussed below.
Interannual variability

To investigate the causes of interannual variability, a multiple linear regression analysis was conducted on Shelf Water salinity vs potential meteorological and oceanographic forcing functions with the seasonal cycles removed from both dependent and independent variables.* The particular forcing functions, discussed earlier and listed in Table 1, were chosen for three reasons: (1) the data sets were readily available in monthly mean form, (2) the data sets were long enough to provide a seasonal cycle which could then be removed to investigate interannual variability, and (3) they were relatively independent processes.

Initially, before the forcing functions were input collectively to a multiple regression analysis, simple regressions of salinity vs the individual forcing functions were determined by a least squares method. The results are listed in Table 1. The purpose of these initial linear regressions was to determine two important parameters. The first parameter was the best lag time (LAG). The correlation (R) varied according to the number of months lagged between the forcing function observation and hydrographic observation. The second parameter to be determined was the best number of months (NMTHS) to sum the forcing function anomaly. Both LAG and NMTHS were incremented through dynamically reasonable values until the absolute value of the correlation was maximized. If a strong correlation (>99% confidence level) was not found between a particular forcing function and salinity then the forcing function was discarded from further analysis.

The best LAG and NMTHS value for each forcing function is listed on the third and fourth lines of Table 1. Except for the St Lawrence term where it was necessary to apply a 17 month LAG, a LAG of 0 is listed. However, since the observations were summed over 4 months, in the case of US river discharge for example (see NMTHS, Table 1 line 4), not only the month immediately preceding the cruise, but 2, 3, and 4 months preceding the cruise were included in the calculations, each with equal weight.

Table 1. Simple linear regression results

<table>
<thead>
<tr>
<th>Force</th>
<th>SSF</th>
<th>USDC</th>
<th>STLW</th>
<th>PRECIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>-0.40</td>
<td>-0.78</td>
<td>-0.45</td>
<td>-0.67</td>
</tr>
<tr>
<td>C. L.</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>LAG</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>NMTHS</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

SSF = Shelf/slope front position along Sandy Hook, New Jersey transect.
USDC = sum of Chesapeake, LI Sound, and Gulf of Maine discharge.
STLW = St Lawrence River discharge.
PRECIP = precipitation at JFK Airport.
R = correlation coefficient.
C. L. = confidence level of correlation.
LAG = no. of months lagged between meteorologic and ship observation.
NMTHS = no. of months meteorologic data was summed.

*A seasonal cycle was not available for precipitation.
Since the correlation changed very little with changes in NMTHS, the value of NMTHS chosen for each forcing function was not critical. If precipitation, for example, was summed over 6 months rather than 10, it still produced a significant correlation ($R = 0.58$). A value of 10 was used, though, since it produced the maximum correlation ($R = 0.67$). The value of LAG chosen for each forcing function was equally robust. In the case of US rivers, if a few months of LAG were applied, correlations were not as high, but they were still significant. In the case of the St Lawrence, LAGs ranging from 15 to 19 months were significant. According to SUTCLIFFE et al. (1976), a LAG of 11 months was found for St Lawrence influence in the Gulf of Maine and, therefore, allowing another 6 months passage into the MAB, a LAG of 17 months was physically reasonable and in agreement with the objective results.

In the first paragraph of this section, three conditions for choosing input data sets were listed. The last of the three conditions was the most difficult to meet and needs to be qualified here. All the forcing functions chosen for testing were not entirely independent; they were somewhat correlated themselves. All rivers on the east coast of the United States, for example, were fairly coherent and therefore the model results did not improve if more than a few rivers were included as inputs. To reduce the number of independent variables, therefore, the US rivers were lumped together by taking the sum of their anomalies. (The “anomalies” are derived by subtracting out seasonal cycles.) Similarly, the US river discharge records are significantly correlated ($R = 0.61$) to JFK airport precipitation records; but, as shown later in a stepwise multiple regression model, these two parameters are sufficiently independent to be retained as separate terms.

Only after several preliminary tests, not reported in Table 1, were model inputs finalized. Tests were conducted on various layers of the water column (0-30 and 30-100 m) and various sub-areas of the MAB (north and south), but the differences were insignificant. In subsequent runs of the model, therefore, only one layer (0-100 m) and one area (MAB) were considered.

Preliminary tests were conducted on temperature as well as salinity, but as expected, even when additional data such as wind and air temperature (also from New York City) were input to the model, no more than 28% of the interannual variability could be explained. As seen in the bottom panel of Fig. 5, the interannual variability of temperature is small (approx. 1°C) when compared to the seasonal variability (approx. 8°C) and therefore, it is very difficult to explain statistically in a multiple linear regression model.

<table>
<thead>
<tr>
<th>Force</th>
<th>SSF (1 psu km⁻¹)</th>
<th>USDC ($10^{-5}$ psu m⁻³ s⁻¹)</th>
<th>STLW ($10^{-5}$ psu m⁻³ s⁻¹)</th>
<th>PRECIP ($10^{-6}$ psu cm⁻¹)</th>
<th>MULTI (psu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_R^2$</td>
<td>0.00</td>
<td>0.62</td>
<td>0.07</td>
<td>0.05</td>
<td>0.70</td>
</tr>
<tr>
<td>C.L.</td>
<td>0.45</td>
<td>0.99</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>PE</td>
<td>-2.9</td>
<td>-0.5</td>
<td>-3.2</td>
<td>0.1951</td>
<td></td>
</tr>
<tr>
<td>PEE</td>
<td>0.8</td>
<td>0.2</td>
<td>1.2</td>
<td>0.0801</td>
<td></td>
</tr>
<tr>
<td>DF</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$P_R^2 = \text{partial } R^2$ or % of the variability explained by the term.
C.L. = confidence that respective term is a significant addition to the model using a Student t-statistic.
PE = parameter estimate, regression coefficient (units listed in line 2).
PEE = error associated with PE.
DF = degrees of freedom associated with the model.
Finally, after determining “R”, “LAG”, and “NMTHS”, a stepwise multiple linear regression was conducted for MAB salinity (0–100 m). The partial $R^2$ contribution of each forcing function is listed in the first line of Table 2. The discharge of US rivers (USDC) was the dominant term (62%) while the St Lawrence River (STLW) and JFK airport precipitation (PRECIP) contributed another 7 and 5%, respectively. The shelf/slope frontal position, although marginally correlated ($R = -0.40$) to salinity when regressed alone, becomes insignificant ($PR^2 = 0.00$) when added to the multiple regression model. The regression coefficients (or parameter estimates, PE) and their associated errors (PEE) are listed on lines 3 and 4. The units associated with these parameter estimates (slopes) are listed near the top of the table. The last column, labeled “MULTI”, contains four numbers; (1) the total $R^2 = 70\%$ (adjusted for degrees of freedom), (2) the estimate of the regression intercept = 0.1951 psu, (3) the error associated with that estimate = 0.0801, and the degrees of freedom = 23. The final result leads to the equation:

$$S_a = -2.9 \times \text{USDC} - 0.5 \times \text{STLW} - 3.2 \times \text{PRECIP} + 0.1951,$$

where the dependent variable, $S_a$, is MAB salinity (0–100 m) with its seasonal cycle removed (i.e. anomaly). Each of the independent variables and their corresponding units are listed in Table 2. The observed vs model values are plotted in Fig. 6.

**DISCUSSION**

Unlike temperature which follows a well-defined seasonal cycle, salinity in the MAB can change dramatically from one year to the next. Approximately 70% of this interannual
variation in salinity can be explained by changes in river discharge and precipitation. A multiple linear regression model can hindcast layer-averaged salinity to within a few tenths of 1 psu.

Though the origin of MAB water is far to the north, the mechanisms that influence the water mass properties are apparently local meteorologic processes. The only non-local process considered in this study, St Lawrence discharge with a 17 month lag, is shown to have significant but minor influence on the MAB. The actual discharge for the St Lawrence is large compared to the US rivers, but, when seasonal cycles were removed, the local US river signal became 2–3 times larger than that of the St Lawrence (Fig. 7). The combination of the Great Lakes and controlled locks within the St Lawrence Seaway evidently dampen the variability of the latter.

After several preliminary tests, it was concluded that variations in river discharge, precipitation, and salinity occurring over monthly time scales are coherent along the entire northeast coast and adjacent shelf. Attempts to differentiate individual meteorologic influences on sub-areas of the shelf and sub-layers of the water column were unsuccessful.

The relative difference between precipitation and local river discharge in terms of their influence on Shelf Water salinity is also difficult to establish. When local rivers are removed from the model, the remaining terms explain 52% of the variance. When precipitation is removed from the model, the remaining terms explain 64%. Local rivers is shown again to be a slightly more important term. This is in agreement with findings by Ketchum and Corwin (1964), who were able to “predict” salinity off the south coast of Long Island using only the Connecticut River outflow records. The dominance of the river term may be due both to the influence of snow melt and a tendency for evaporation to balance precipitation. Nevertheless, precipitation, if taken from more than a single weather station, may explain a larger percentage of the variability. Hence, river discharge
Middle Atlantic Bight salinity

and precipitation are certainly related parameters, but they each contribute independently a significant degree to the final representation of interannual change in salinity.

Finally, how are the results affected by the definition of "Shelf Water"? As shown in the first three lines in Table 3, if water less than 31 psu is removed from the analysis, the correlation of salinity with river discharge falls a small degree, from -0.73 to -0.69. However, when the upper limit on salinity is increased from 34 psu to 35.5 psu, the correlation of salinity with river discharge falls off from -0.73 to -0.51. Hence, the

Table 3. Effect of "Shelf Water" definition on US river discharge vs layer-averaged salinity correlation

<table>
<thead>
<tr>
<th>Shelf Water definition</th>
<th>Correlation coefficient ((r))</th>
<th>Significance level ((C.L.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower bound change</td>
<td>(S &lt; 34)</td>
<td>-0.73</td>
</tr>
<tr>
<td>Upper bound change</td>
<td>(30 &lt; S &lt; 32.5)</td>
<td>-0.54</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 33.0)</td>
<td>-0.70</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 33.5)</td>
<td>-0.74</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 34.0)</td>
<td>-0.71</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 34.5)</td>
<td>-0.67</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 35.0)</td>
<td>-0.58</td>
</tr>
<tr>
<td></td>
<td>(30 &lt; S &lt; 35.5)</td>
<td>-0.51</td>
</tr>
</tbody>
</table>
selected forcing functions best explain the variability in the core of the Shelf Water volume shown in Fig. 3 (32.5–34 psu) and the choice of 34 psu as an upper boundary for Shelf Water was appropriate.

The 30% of interannual variability not explained in this study evidently is due to those processes which were not considered, such as evaporation, mixing/exchange across the shelf/slope interface, and production/subsequent advection of other source waters from the north (Arctic meltwater, Cold Pool Water). Their influence on the salinity, however, even if the data were currently available, would be hard to distinguish from the inherent noise.

Acknowledgements—The author would like to thank all those who took part in the decade of MARMAP surveys aboard the Delaware II, the Albatross IV, and other vessels. Thanks also to Dan Patanjo and Lisa Lierheimer for processing the data and to Drs Mountain and Ingham for helpful reviews of the manuscript.

REFERENCES


BIGELOW H. B. and M. SEARS (1935) Studies of the waters of the continental shelf, Cape Cod to Chesapeake Bay. II. Salinity. Papers in Physical Oceanography and Meteorology, 4, 1–94.


