The volume of Shelf Water in the Middle Atlantic Bight: seasonal and interannual variability, 1977–1987

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(Received 2 April 1990; in revised form 4 October 1990; accepted 8 October 1990)

Abstract—The volume of Shelf Water (salinity <34 psu) is determined for three regions in the Middle Atlantic Bight (MAB) and for Georges Bank from a combination of hydrographic data and shelf/slope front positions derived from satellite imagery. The hydrographic data were obtained on 49 surveys of the shelf between 1977 and 1987. In each region the shelf water volume exhibits a significant annual cycle with a range of 50–80% of the mean volume. The annual volume cycle appears to be advected southwestward from Georges Bank through the MAB with the mean circulation. Large interannual changes in volume are observed which have a range comparable to the mean volume of Shelf Water in the MAB. Both the seasonal and interannual changes in volume appear to be related to changes in the inflow to the Gulf of Maine through Northeast Channel and from the Scotian Shelf.

INTRODUCTION

The waters of the Middle Atlantic Bight (MAB) are commonly referred to as Shelf Water (ShW), a water mass characterized by a relatively low temperature and salinity in comparison to the Slope Water found farther offshore. The seaward boundary of the ShW mass is the shelf/slope front, a narrow region of sharp gradients in water properties between ShW and Slope Water. The front generally intersects the bottom near the shelf edge and extends further offshore at the surface (Wright, 1976).

The ShW in the MAB is part of a large coastal current system that begins at high latitudes in the Labrador Sea (Chapman and Beardsley, 1989), with low salinity coastal water flowing south and west along the continental margin as far as the MAB. More locally, the ShW originates from the two major inflows to the Gulf of Maine—cold, low salinity water from the Scotian Shelf which enters around Cape Sable (Smith, 1983) and warm, saline Slope Water which enters at depth through Northeast Channel (Ramp et al., 1985). These waters mix as they circulate around the Gulf and are modified by local processes (seasonal heating and cooling, and run-off and precipitation). The resulting water mass is carried from the western Gulf of Maine by the mean circulation onto and around Georges Bank (Hopkins and Garfield, 1981) and then westward past Nantucket Shoals (Beardsley et al., 1985) into the MAB. Within the MAB, the mean flow is to the southwest toward Cape Hatteras (Beardsley et al., 1976).

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The ShW mass in the MAB is circumscribed by the coast, the shelf/slope front and imaginary lines across the shelf south of Nantucket Shoals and east of Cape Hatteras (Fig. 1). How the ShW leaves this enclosure is not well known, although a number of processes have been identified. Some leaves the shelf at Cape Hatteras and is observed along the northern edge of the Gulf Stream (Ford et al., 1952). Gulf Stream Rings entrain large amounts of ShW from the shelf (Morgan and Bishop, 1977; Bisagni, 1983; Garfield and Evans, 1989). Instabilities in the shelf/slope front (Ramp et al., 1983; Garvine et al., 1988, 1989) generate shelf-break eddies which potentially can result in parcels of ShW being separated from the shelf, similar to those observed by Houghton et al. (1988). Modeling studies also indicate a steady cross-isobath transport of water past the shelf edge associated with bottom friction (Wang, 1982; Chapman et al., 1986; Chapman, 1986). These models, however, do not address the actual exchange of water across the front.

The temperature and salinity properties of the ShW in the MAB have been described (BigeLOW, 1933; Bigelow and Sears, 1935; Wright and Parker, 1976; Hayes, 1975; Manning, 1990). Wright and Parker (1976) and Hayes (1975) also present a volumetric temperature–salinity census of the waters in the MAB for different seasons. While it has been recognized from hydrographic data (Wright, 1976) and from satellite imagery (Hillard and Armstrong, 1980) that the shelf/slope front exhibits seasonal and interannual movements, the actual seasonal and interannual variability in the volume of ShW in the MAB has not been well described or analysed.

This paper presents the annual mean cycle and interannual variability of the volume of ShW in the MAB for the period 1977–1987. From the observed changes in volume a budget for ShW in the MAB is developed.

DATA AND METHODS

Two data sources are used to determine the volume of ShW in the MAB. The first is hydrographic data collected as part of the National Marine Fisheries Service Marine Resources Monitoring, Assessment and Prediction (MARMAP) program. MARMAP was an interdisciplinary program to measure the distribution of plankton and physical water properties over the continental shelf from Cape Hatteras to the Gulf of Maine (Sherman, 1980). Sampling was done on a standard grid of stations which included about 90 stations in the MAB (Fig. 1). The typical station spacing was about 30 km. Between 1977 and 1987 hydrographic measurements were made on 49 MARMAP surveys, although not all stations were occupied on each survey. The measurements were made by using water bottles with reversing thermometers, except in the last year of the program when an electronic conductivity–temperature–depth profiling instrument (CTD) was used. The accuracy of the data is at least 0.02°C and 0.02 psu (practical salinity units).

The monthly mean positions of the shelf/slope front along eight transect lines across the shelf are used to estimate the volume of ShW that extended off the shelf beyond the MARMAP sampling area (see Fig. 1). These positions were determined from satellite imagery and have been published annually in a series of reports (e.g. Hillard and Armstrong, 1980). The time series of front positions were obtained for this study from R. Armstrong (personal communication).

For this report ShW is defined as water with a salinity less than 34.0 psu. Manning (1990, Fig. 3) shows the volume of water in the MAB as a function of salinity for the four seasons, derived from the same MARMAP hydrographic data set. In each season there is a distinct
Fig. 1. Location of the standard MARMAP hydrographic stations (•) Boundaries are indicated for four regions of the shelf: Georges Bank (GB), southern New England (SNE), the Middle Atlantic Bight apex (APX) and the southern part of the shelf (SS). The eight transect lines along which the shelf/slope front positions were available from satellite data are indicated by the dashed lines. The two stations used to calculated the pressure gradient through Northeast Channel (Figs 8 and 9) are circled (○).
peak in volume between 32.5 and 33.5 psu that represents the core of the ShW mass. The volumes decrease to lower values between 34 and 35 psu and then have a tendency for larger volumes at salinities above 35 psu, representing the Slope Water mass found on the outer edge of the shelf. Using an oxygen isotope to salinity relationship, FAIRBANKS (1982, Figs 8 and 10) shows that the mixing lines defining the waters in the Gulf of Maine and the New York Bight intersect the characteristic Slope Water line at a salinity of about 34 psu. The results of both MANNING (1990) and FAIRBANKS (1982) support 34.0 psu as a cut-off value for identifying ShW.

To determine the volume of ShW, the MAB was divided into three regions—southern New England (SNE), the New York Bight apex (APX) and the southern part of the shelf (SS) (see Fig. 1). A fourth region covering Georges Bank was also considered since most ShW enters the MAB from Georges Bank. The volume of ShW in one of the regions during a MARMAP survey was calculated in two parts. First the volume of ShW in the MARMAP survey area was determined from the hydrographic data. Then the amount of ShW that extended beyond the MARMAP sampling was estimated from the position of the shelf/slope front. The sum of the two results was the total volume for the survey.

For the volume calculation based on the hydrographic data the area of a region (see Fig. 1) was apportioned among the stations occupied on the survey. For each station the thickness of the water column with salinity less than 34.0 psu was multiplied by the area assigned to the station to obtain a volume and the volumes for all of the stations were summed to yield a total. To avoid bias due to differences in station coverage, the total volume of each region was also determined. These total volume values varied by 5–10% between different surveys. To account for this artifact, the calculated ShW volume for each survey was multiplied by the ratio of the mean volume for the region to the region volume calculated for that survey. The average Julian day of sampling in the region was determined for each survey and used to represent the date of the volume estimate. Due to limited station coverage on some surveys, a volume estimate could not be made for some areas on some surveys.

To estimate the volume of ShW that extended beyond the hydrographic sampling area, the water shoreward of the shelf/slope front, as observed in satellite imagery, was assumed to be ShW. The along-shelf length of each region was apportioned among the satellite transect lines which crossed the region (see Fig. 1). The volume associated with each transect was determined by multiplying the assigned length first by the distance that the front extended beyond the hydrographic sampling area in the month of the survey and then by an assumed average thickness of 40 m. These products were summed for the different transects and added to the volume calculated from the hydrographic data to obtain the estimated volume of ShW that existed in the region during the MARMAP survey. The 40-m thickness value was chosen after review of the hydrographic data from near the shelf edge and from other historic data that included sampling beyond the shelf edge to the front.

The annual cycle of ShW volume was determined for each region. A multiple linear regression model was used to fit an annual harmonic (365-day period) to the volume estimates for a region. The significance of the harmonic coefficients was tested using the method of FOFOFF and BRYDEN (1975) and BROWNLEE (1965). If significant at the 95% level, the annual curve was accepted. The standard deviation of the residuals (i.e. the differences between the original data and the calculated annual curve) was determined. Any points more than two standard deviations from the curve were assumed not to be
characteristic of the true annual cycle. The harmonic regression was repeated with these points excluded. A semi-annual harmonic (period 365/2 days) was fitted to the residuals from the annual cycle, but was not significant in any of the regions.

The methods outlined above represent a number of choices and compromises that introduce errors, which may affect the validity of the results presented. First is the choice of 34.0 psu as a cut-off value for ShW. WRIGHT and PARKER (1976) used 34.5 as the upper limit of ShW. To test the sensitivity of the results to the cut-off value, all calculations also were done with this higher value and in the Discussion the results are shown to be very similar to those obtained for 34.0 psu.

A second concern is the use of any constant cut-off value for ShW which, in essence, treats ShW as conservative. Precipitation, run-off and cross-frontal mixing with Slope Water all can modify the salinity of water on the shelf. While the fresh-water sources influence the characteristic salinity of ShW (MANNING, 1990), as will be argued in the following section, they do not make a significant contribution to the volume of the ShW. The effects of cross-frontal mixing are more difficult to assess quantitatively. The 34.0 psu cut-off is assumed to represent the water inside the shelf/slope front. In the volume and budget calculations presented here, no explicit differentiation is made between water crossing the frontal boundary by an advective process or by having its salinity altered through a mixing process. In either case, the water is considered lost from the ShW mass. The importance of frontal mixing to the results will be addressed in the Discussion.

A third concern is limitations of the MARMAP sampling scheme for estimating the volume of ShW. The sampling does not provide a detailed picture of the structure of the shelf/slope front. The 30 km station spacing allows the location of the shelf/slope front to be estimated with an error of order ±15 km. For any area of the shelf the ShW volume in the frontal region is determined by the sum of estimates from four or five stations along the length of the front. There is no reason to expect the errors from these estimates to be biased. Instead the errors most likely would be distributed normally. In that case the average error would be of order ±7 km. With a water depth at the front of about 80 m and an along-shelf length for the different areas of about 200 km, the expected error in the estimated volume of ShW would be of the order of ±100 km³. This error is small compared to the changes in ShW volume that are considered in the analysis.

RESULTS

Annual cycle of Shelf Water volume

The mean annual cycle in ShW volume was determined for each of the four regions of the shelf shown in Fig. 1. The original volume data and the calculated annual cycles are plotted in Fig. 2. The range of the annual cycle (minimum to maximum) is a substantial proportion of the mean volume in each region of the MAB—48% in SNE, 72% in APX and 80% in SS. For the MAB as a whole (i.e. the sum of the curves for the three regions), the range is 55% of the mean. The seasonal range in volume on Georges Bank (860 km³) is comparable to the other regions, but due to the large area of the bank the ratio of range to mean volume is only 25%.

There is a steady progression in the phase of the annual cycle from Georges Bank southwestward through the MAB. For example, the maximum volumes in the calculated annual curves occur on Julian days 12, 130, 191 and 219 on Georges Bank, SNE, APX and
SS, respectively. This progression corresponds to an average speed of 3–4 cm s\(^{-1}\), which is comparable to the mean velocity through the MAB (Beardsley et al., 1976) and suggests that the annual cycle of ShW volume advects from the Gulf of Maine/Georges Bank region through the MAB as part of the mean circulation.

Fig. 2. The volume of shelf water (10\(^3\) km\(^3\)) in the four regions of the northeast continental shelf: (a) Georges Bank, (b) Southern New England, (c) the Middle Atlantic Bight Apex, and (d) the southern part of the shelf. For each region the observed volumes are indicated by symbols coded by year. The solid line represents the calculated annual cycle of volume. The dashed lines are ±1 SD from the annual curve.
The residuals of the original volume data from the calculated annual curves indicate the interannual variation in ShW volume and represent anomalies relative to the annual mean cycle. These anomalies are plotted for each region on an 11-year time axis in Fig. 3. For surveys on which the entire MAB was sampled, the anomalies from the three regions were summed to yield an anomaly for the MAB as a whole. These anomalies are plotted in Fig. 4 and are concentrated in the first and last thirds of the sampling period. Early 1978 was characterized by a large positive anomaly of about 2000 km$^3$. The anomaly then decreased to around −300 km$^3$ through most of 1980. From the middle of 1984 to the middle of 1986 the volume anomaly decreased steadily from +800 to −1600 km$^3$. It then increased to +1600 km$^3$ by the end of 1987. These fairly steady changes in volume anomaly over 1- to 2-year periods represent 60–90% of the mean volume of the MAB (3600 km$^3$).

A regression analysis indicates that the location of the shelf/slope front at the surface, as determined by satellite imagery, can account for approximately 50% of the variance in the ShW volume in the three regions of the MAB shown in Fig. 2b–d. The ShW volume variability, however, results from movement of the shelf/slope front throughout the water.
column and there is considerable movement of the front along the bottom. For example, in the autumn of 1979 the MARMAP data indicate that the bottom of the front was within 40 km of the mouth of Narragansett Bay, approximately 100 km shoreward of its position the previous spring.

**Shelf Water budget**

Change in the volume of ShW indicates that there is a difference between the rate at which water enters the MAB and the rate at which it leaves. A ShW budget can be expressed as

\[
\dot{V} = T_i - T_o, \tag{1}
\]

where \(\dot{V}\) is the rate at which the ShW volume changes, \(T_i\) is the rate at which ShW enters and \(T_o\) is the rate at which ShW leaves. Using this budget relationship, the rate of outflow from the system can be estimated from knowledge of the rate of inflow and of the volume changes. Two budgets are constructed—one for the Gulf of Maine/Georges Bank region (Fig. 5), whose estimated outflow becomes the inflow to a budget for the MAB (Fig. 6).

The inflow to the Gulf of Maine/Georges Bank region is the sum of the two major sources of water for the whole shelf system—the inflow from the Scotian Shelf around Cape Sable and the deep inflow through Northeast Channel. RAMP et al. (1985) present the annual cycle of the Northeast Channel inflow, which has significant annual and semiannual components. The annual cycle of the Cape Sable inflow has been determined by fitting an annual harmonic to the monthly mean transport measure by SMITH (1983). Other sources of water to the shelf system [e.g. river run-off (BU. E. 1970) and precipitation (BUNKER, 1976)] are not significant, being almost two orders of magnitude smaller than the two major contributions, and are ignored. These fresh-water sources are important in determining the variability in salinity of ShW (MANNING, 1990), and would be critical for a salt budget. For a mass budget, however, the actual rates of inflow are small (e.g. 0.005 x 10^6 m^3 s^{-1} for mean total river input vs 0.400 x 10^6 m^3 s^{-1} for the combined mean Northeast Channel and Scotian Shelf inflows). The resulting inflow term, \(T_i\), has maximum value in the winter and a minimum in the late spring (see Fig. 5). The volume rate of change, \(\dot{V}\), is determined from the time derivative of the annual volume curve in

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**Fig. 4.** Anomalies in the shelf water volume (10^3 km^3) for the entire Middle Atlantic Bight.
Fig. 2a. The rate of outflow from the Gulf of Maine/Georges Bank region, estimated from equation (1), is high in the winter and relatively low from the spring through the autumn.

The outflow from the Gulf of Maine/Georges Bank region is used as the inflow term for the MAB ShW budget. The rate of change of ShW volume, \( \dot{V} \), in the MAB is the time derivative of the sum of the annual volume curves for the three regions of bight (Fig. 2b–d). The estimated rate of outflow from the MAB (dotted line in Fig. 6) has a minimum in the spring and is relatively constant from the late summer through the early winter. This budget assumes all of the outflow from Georges Bank enters the MAB. If, instead, 20% of the outflow from Georges Bank were assumed to occur off the southern side of the bank and the inflow to the MAB were reduced accordingly, the rate of outflow from the MAB would be similar to that in Fig. 6. The mean outflow would be reduced, matching the

Fig. 5. The annual cycle of the three terms in the shelf water budget (equation 1) for Georges Bank: inflow, \( T_i \) (---); volume rate of change, \( \dot{V} \) (---); and outflow, \( T_o \) (---). The units are \( 10^6 \text{ m}^3 \text{ s}^{-1} \).

Fig. 6. The annual cycle of the three terms in the shelf water budget (equation 1) for the Middle Atlantic Bight: inflow, \( T_i \) (---); volume rate of change, \( \dot{V} \) (---); and outflow, \( T_o \) (---). The units are \( 10^6 \text{ m}^3 \text{ s}^{-1} \).
reduction in inflow, but the annual cycle still would be characterized by a distinct minimum in the spring and near-constant values in the late summer and early winter.

While the budget in equation (1) provides an estimate of the outflow from the shelf, it does not provide information on where along the shelf the outflow occurs. The relationship between the inflow, outflow and ShW volume does have implications for where the water leaves the shelf. A simple model of the MAB is a box with water entering at the northern end near Nantucket Shoals and flowing southwestward at a constant rate. Outflow occurs at a uniform rate across the entire length of the shelf/slope front and what water remains exits at Cape Hatteras. Two relationships exist between the rates of flow and the volume of water on the shelf:

\[ T_i = T_{fr} + T_{CH} \]  \hspace{1cm} (2a)

\[ V = 0.5 \cdot T_{fr} \cdot TT + T_{CH} \cdot TT, \]  \hspace{1cm} (2b)

where \( T_i \) is the inflow rate, \( T_{fr} \) is the net outflow rate across the front (through the side of the box), \( T_{CH} \) is the outflow rate at Cape Hatteras, \( V \) is the mean volume of ShW and \( TT \) is the travel time through the box (Nantucket Shoals to Cape Hatteras). The volume calculation in equation (2b) is the product of the transport rate and the travel time between where the transport enters and exits the shelf. For the component of the flow exiting at Cape Hatteras (\( T_{CH} \)) the time is the travel time along the entire shelf, \( TT \). For the component exiting across the front (\( T_{fr} \)), the mean location for exiting is halfway along the shelf and the mean travel time is one half of \( TT \). From these equations the outflow across the front can be expressed as

\[ T_{fr} = 2 \cdot (T_i - V/TT). \]  \hspace{1cm} (3)

For annual mean values in the MAB (\( T_i = 0.4 \times 10^6 \text{ m}^3 \text{ s}^{-1} \), \( TT = 210 \text{ days} \) and \( V = 3600 \text{ km}^3 \)), \( T_{fr} = 0.4 \times 10^6 \text{ m}^3 \text{ s}^{-1} \) and \( T_{CH} = 0 \).

The assumed rate of inflow to the MAB would be reduced by the amount of water that exits the system off the southern side of Georges Bank. A reduced value of \( T_i \) in equation (3) would result in a lower value of \( T_{fr} \), but an increase in \( T_{CH} \). For example, with the inflow reduced by 20%, \( T_i = 0.32 \times 10^6 \text{ m}^3 \text{ s}^{-1} \), \( T_{fr} = 0.24 \times 10^6 \text{ m}^3 \text{ s}^{-1} \) and \( T_{CH} = 0.08 \times 10^6 \text{ m}^3 \text{ s}^{-1} \). Whichever values are used, the implications from equation (3) are that the majority of outflow from the MAB occurs across the frontal boundary, and relatively little ShW transits the entire bight to exit at Cape Hatteras.

**Shelf Water residence time**

The residence time of water on the shelf can be determined by dividing the volume of ShW by the rate at which the water leaves the shelf. For the annual mean values used above (\( V = 3600 \text{ km}^3 \), \( T_i = 0.4 \times 10^6 \text{ m}^3 \text{ s}^{-1} \)) the mean residence time is about 100 days. This is considerably shorter than the 4.6 years of Wright and Parker (1976) and the 1.4 years of Fairbanks (1982). Both of these earlier estimates were based on a salinity budget that balanced local river inflow with the Slope Water input needed to produce ShW of the observed characteristic salinity. Neither estimate included the freshening contribution entering from the Scotian Shelf and the Gulf of Maine. For this reason Fairbanks identified his number as a maximum estimate for the residence time.
Fig. 7. The annual cycle of the instantaneous residence time of shelf water in the Middle Atlantic Bight.

Using the sum of the annual volume curves for the three regions in the MAB (Fig. 2b–d) and the outflow rate estimated above (dotted line in Fig. 6), an instantaneous estimate of the residence time also can be calculated (Fig. 7). The residence time has a distinct peak in the spring and is fairly constant during the rest of the year. Assuming a well-mixed shelf region, the instantaneous residence time indicates the likelihood that a parcel of water would be retained on the shelf; or more rigorously, the inverse of the instantaneous residence time is the probability that a parcel would leave the shelf on a particular day.

Interannual variations in Shelf Water volume

The large changes in ShW volume indicated in Fig. 4 imply long-term (1–2 years) changes in the balance between the inflow and outflow terms of the ShW budget. Since the volume of water is the integral of the flow rate, changes in flow rates should have preceded the observed volume changes. Unfortunately, few direct measurements of the inflow or outflow terms exist to investigate the causes of the long-term variability in ShW volume. SMITH (1989) reports on the Scotian Shelf inflow to the Gulf of Maine for the period November 1978 to May 1985. The Northeast Channel measurements of RAMP et al. (1985) ended in 1978.

MOUNTAIN and JESSEN (1987) use a box model with the MARMAP hydrographic data to estimate the inflow through Northeast Channel during the autumn of each year from 1978 to 1983 (except for 1981). These estimates range from 0.35 to $0.53 \times 10^6$ m$^3$ s$^{-1}$ and in the mean are comparable to the direct measurements of RAMP et al. (1985). Using subsequent MARMAP sampling, a similar box model estimate of the inflow has been made for the autumn of 1985 (the only other year for which sufficient hydrographic data exist). With the inherent uncertainty in the average water properties input to the model, the range of estimated flow is from negative inflow (not a meaningful result for the box model) to a maximum of $0.07 \times 10^6$ m$^3$ s$^{-1}$. The implication is that the inflow through Northeast Channel was unusually low in the autumn of 1985.

Additional indirect indications of the inflow through Northeast Channel are provided by the pressure gradient between the channel and the interior of the gulf. The pressure gradient field has been related to the variability in the channel inflow on synoptic (RAMP et al., 1985) and seasonal (MOUNTAIN and JESSEN, 1987) time scales, as well as to the vertical
structure of the inflow (Hopkins and Garfield, 1979). The baroclinic pressure gradient at 100 m depth between Jordan Basin and Northeast Channel has been calculated for all occupations of two stations in the MARMAP data set (see Fig. 1) such that higher values would indicate a tendency for inflow to the Gulf of Maine. The relationship between the pressure gradient and the inflow in Northeast Channel is shown in Fig. 8, where the inflow estimates from the Mountain and Jessen (1987) box model are plotted against the average pressure gradient during the cruises used in the box model calculations. While there are only five points, the two variables are significantly correlated at above the 99% confidence level. The pressure gradient values are plotted on an 11-year time axis in Fig. 9. A value in the spring of 1987 has been added from data reported by Garrison et al. (1989), using observations close to the chosen MARMAP station locations. Through 1984 the pressure gradient exhibits relatively small variability, within one standard deviation of the mean. In late 1985 and early 1986 the pressure gradient is strongly negative, implying a low rate of inflow; and for 1987 it has large positive values, implying an unusually high inflow.

The possible causes of the three largest anomalies of ShW volume in Fig. 4 are considered. These events are the extreme high volumes in the first half of 1978 and in late 1987 and the extreme low volume which occurred in early 1986.

The large ShW volume in the spring and summer of 1978 was previously noted by Chamberlin (1978) and by Hilland and Armstrong (1980). Chamberlin (1978) suggested that the large volume was due to the low number of warm-core rings interacting with the shelf and a reduction in the loss of water from the shelf by ring entrainment. From October 1977 to May 1978 only two Gulf Stream rings interacted with the shelf west of Georges Bank (Mizenko and Chamberlin, 1979; Celone and Chamberlin, 1980) and in four of these months there were no rings present west of 71°W. While the existing observations provide no better explanation, relating the presence of rings to loss of water from the shelf can be quite uncertain. The rate of entrainment by rings can vary greatly.

Fig. 8. The relationship between the baroclinic pressure gradient (10⁴ cm s⁻²) through Northeast Channel and the transport through the channel (10⁶ m³ s⁻¹) calculated by the box model of Mountain and Jessen (1987).
Fig. 9. The calculated baroclinic pressure gradient \(10^4 \text{ cm s}^{-2}\) through Northeast Channel. The dashed lines represent \(\pm 1\) SD about the mean. Higher values indicate a tendency for increased inflow to the Gulf of Maine and lower values, a tendency for reduced inflow.

(\text{GARFIELD and EVANS, 1989}) and counter examples can be found in the data set, for example from December 1983 to August 1984 no rings interacted with the shelf west of 71°W, but the ShW volume anomaly in the autumn of 1984 was negative.

The larger negative volume anomaly that reached a minimum in the spring of 1986 suggests a reduced inflow and/or increased outflow from the MAB in the second half of 1985 and early 1986. The box model estimate of the Northeast Channel inflow during the autumn of 1985, presented above, was unusually low—at most, only 15% of the inflow calculated for other years. The pressure gradient index of the inflow also indicates low values during the autumn of 1985 and early 1986. A low rate of inflow would be consistent with the low volume of ShW observed in the spring of 1986. By early 1987 the pressure gradient index of the Northeast Channel inflow had turned strongly positive. A change from a negative to a positive index in the autumn of 1986 would be consistent with the increase in the volume anomaly from large negative values in the spring of 1986 to the positive ShW volume anomalies which developed through 1987.

**DISCUSSION AND CONCLUSION**

The annual cycle and the interannual variations in the ShW volume described above have important implications for the physical oceanography of the MAB. The volume changes appear not to originate locally, but instead, appear to result from changes in the major inflows to the Gulf of Maine. This is true for both the annual cycle and the interannual variations in ShW volume and supports the view of \text{CHAPMAN and BEARDSLEY (1989)} that the flow through the MAB is part of a large coastal current system that has its origins far to the northeast.

All of the results presented are based upon using 34.0 psu as the upper limit of ShW. To test the sensitivity of the result to this value all of the calculations also were done using a value of 34.5 psu. The annual mean volume of ShW in the MAB increased about 20% to 4400 km\(^3\). In the four regions of the shelf the phase of the annual cycle in volume shifted an average of 8 days earlier. The amplitude of the annual cycle decreased in each region, being about 85% of the 34.0 psu amplitude for Georges Bank and SNE, 72% for APX and
55% for SS. The annual budget for 34.5 psu ShW had the same features as in Fig. 6, with a distinct spring minimum in outflow. The residence time for 34.5 psu had the same features as in Fig. 7, although the spring peak was reduced to about 270 days and the values during the rest of the year generally were 80–120 days. The box model calculations (equations 2 and 3) result in 80% of outflow occurring across the front \( T_{fr} = 0.32 \times 10^6 \text{ m}^3\text{s}^{-1} \) and 20% exiting the shelf at Cape Hatteras \( TA_{CH} = 0.08 \times 10^6 \text{ m}^3\text{s}^{-1} \). The similarity of the results for 34.0 and 34.5 psu indicates that these results are not critically dependent upon the specific definition of ShW.

A second concern identified in the Data and Methods section is the effect on the results of cross-frontal mixing. Any Slope Water (>35 psu) mixed across the front to form a mixing product of less than 34 psu would be incorrectly counted as ShW which entered the MAB past Nantucket Shoals. For the final salinity to be less than 34.0 psu, however, the mixing product would have to consist primarily of ShW and relatively little Slope Water would be involved. A more critical problem would occur when the salinity of the mixing product were just above the 34.0 psu cut-off. In this case a significant volume of ShW might not be counted in the analysis even though it remained inside the front. The calculations for ShW defined by 34.5 psu would include this mixing product as ShW. The amplitudes of the annual cycles for 34.5 psu ShW are smaller than that for 34.0 psu ShW. This suggests that some of the annual variability in Fig. 2 is due to a shifting of water around the 34.0 psu cut-off value and likely is associated with mixing in the frontal region. As would be expected, the influence of this mixing increases progressively along the line of flow from GB to SS. The overall similarity in the results for 34.0 and 34.5 psu ShW, however, indicates that the conclusions presented here are not significantly affected by frontal mixing modifying the salinity of ShW.

As described above, the large changes in ShW volume during 1986 and 1987 appear due to changes in the inflow of water to the shelf system through Northeast Channel. This is, however, only a partial explanation for the large interannual variability in ShW volume. The inflow of water from the Scotian Shelf also likely plays an important role in these changes. The high pressure gradient values in 1987 (Fig. 9), used to indicate an increased Northeast Channel inflow, are due primarily to lower than average salinity in the upper 100 m of the Gulf of Maine (see MANNING and LIERHEIMER, 1988, Fig. 28). A primary source for this low salinity water would be an increase in the inflow of water from the Scotian Shelf and/or a reduction in the salinity of the inflowing Scotian Shelf water. A major source of fresh water for the Scotian Shelf system is the outflow of the St. Lawrence River (SUTCLIFFE et al., 1976). From September 1986 to January 1987 the average flow for each month in the upper St. Lawrence River was the highest monthly value since 1900 (QUINN and KELLY, 1983; QUINN, personal communication). The greater amount of fresh water could have contributed to an increased flow and decreased salinity on the Scotian Shelf and, subsequently, to low salinities in the upper layers of the Gulf of Maine and an increased pressure gradient through Northeast Channel. Simultaneous direct measurements of the inflows from the Scotian Shelf and through Northeast Channel and of the volume of ShW in the MAB will be required to substantiate the relationship between these inflows and the volume of ShW.

The results of the box model (equation 3) suggest that most of the ShW exits the MAB across the front and relatively little survives to exit near Cape Hatteras. This is consistent with the lack of observation, by current meters, hydrographic data or satellite imagery, of a steady outflow at the southern end of the bight which is any significant fraction of the
inflow past Nantucket Shoals. The modeling studies of Wang (1982), Chapman et al. (1986) and Chapman (1986) also show the major portion of the inflow at Nantucket Shoals leaving the shelf before Cape Hatteras. The box model results indicate that a balance exists between the observed inflow rate, the observed mean volume and the assumption that the outflow occurs uniformly along the length of the front. If the outflow occurred preferentially in one area of the bight or another, the balance would not hold. The major conclusion from the box model, therefore, is that the assumption is valid—that in the mean the majority of the outflow from the MAB occurs uniformly along the entire length of the front.

The ShW budget for Georges Bank (Fig. 5) indicates that the westward flow of ShW to the MAB is maximum in the winter and has its lowest values in the autumn. From year-long current measurements Beardsley et al. (1985) and Ramp et al. (1989) conclude that the along-shelf transport inside the 100 m isobath south of Nantucket is relatively constant with no significant annual cycle. This conclusion, however, does not imply that the westward transport of ShW is constant. The hydrographic data collected from the same study (Wright, 1983) show that in the autumn of 1979 the ShW boundary (as indicated by the 34 psu isohaline) moved shoreward during the autumn and in November was shoreward of mooring N2. If the transport through the whole section remained relatively constant, then the westward transport of ShW in the autumn was very low, consistent with the autumn minimum in Fig. 5.

The annual cycle of the ShW budget (Fig. 6) indicates that the outflow of water from the MAB should have a distinct minimum in the spring. The cause of such a minimum is unclear. Gulf Stream rings can entrain considerable amounts of ShW, but the occurrence of rings does not appear to be seasonal (Garfield and Evans, 1989). Instabilities along the shelf/slope front generate frontal eddies which potentially can result in parcels of ShW being separated from the shelf (Ramp et al., 1983; Garvine et al., 1988, 1989; Houghton et al., 1988). This instability mechanism is likely a maximum in the summer and autumn when the front extends off the edge of the shelf at the surface and when the mean velocity shear across the front is strongest (Beardsley et al., 1985; Houghton et al., 1988). Wind-driven transport of near-surface waters across the front could be important in winter when the mean wind stress is directed to the southeast, across the front (Beardsley et al., 1985), although measurements do not exist to quantify this transport. Present knowledge of the processes which remove water from the MAB is not sufficient to determine the seasonal or annual contributions the processes make to a ShW budget or even to confidently identify which are the dominant processes.

The changes in the volume of ShW in the MAB described above could have important implications for the local biological productivity. The phytoplankton, zooplankton, and fish species assemblages which inhabit the shelf waters generally are distinct from those which inhabit the offshore, Slope Water regions. The shelf/slope front, to a large extent, represents a boundary between the pelagic shelf ecosystem and the pelagic offshore ecosystem, and change in ShW volume represents a change in the size of the shelf ecosystem. In particular, the large volume changes which persist over many months (Fig. 4) could effect successive generations of organisms and have an accumulative effect on the total shelf productivity.

In summary:

(1) The volume of ShW in MAB exhibits a significant annual cycle. Increased inflow to the Gulf of Maine in the winter results in a spring maximum in volume which advects
to the southwest through the MAB with the mean circulation. The seasonal range in volume of ShW in the bight is about 55% of the mean volume.

(2) A simple mass budget suggests that the outflow of water from the MAB has a distinct minimum and the residence time of water in the MAB has a distinct maximum in the spring.

(3) Large ($2-3 \times 10^3$ km$^3$) interannual changes occur in the volume of ShW in the MAB and appear, at least in some cases, to be associated with changes in the inflow of water to the Gulf of Maine.

Acknowledgements—The hydrographic data used in this report were collected and processed by a large number of people who spend many months at sea and many more months correcting reversing thermometers and analysing water samples on a salinometer. A debt of gratitude is owed to each of them and in particular to D. Patanjo. Without the continued effort of K. Sherman the MARMAP program would not have collected these data. R. Armstrong kindly provided the shelf/slope front position data used in this report.

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