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Oceanographic Variability in NAFO Subareas 5 and 6 During the 1990s[1]

by

David G. Mountain
NMFS, Woods Hole, MA, USA

ABSTRACT

The variability in temperature and salinity of the waters on the northeast U.S. continental shelf and the Gulf of Maine during the 1990's is presented and compared to the variability during a previous decade (1978-1987). A general freshening of the surface waters in the gulf and of the shelf waters in the Middle Atlantic Bight is documented. An increase in the inflow to the Gulf of Maine of cool, low salinity surface water from the Scotian shelf during the 1990's is believed responsible for the freshening. A wintertime warming of the shelf waters in the southern part of the region is noted and believed likely due to an increase in local surface heat flux (or decrease in local winter cooling). The deep waters of the western Gulf of Maine also exhibited a warming during the 1990's. This warming is believed due to reduced winter convective cooling caused, at least in part, by the freshening of the surface layer inhibiting convection.

INTRODUCTION

The continental shelf region of the northeast United States from Cape Hatteras northward through the Gulf of Maine (figure 1) comprises the coastal portions of NAFO areas 5 and 6. The region is often considered as three separate, but connected, areas. The Middle Atlantic Bight (MAB) is the broad continental shelf region between Cape Hatteras and Cape Cod. Georges Bank is a shallow bank that is, in essence, an eastward extension of the continental shelf and forms the southern boundary to the Gulf of Maine. The Gulf of Maine is a semi-enclosed sea between New England and Nova Scotia with a number of deep (> 200m) basins. Its only deep connection to the Atlantic Ocean is through the Northeast Channel between Georges Bank and Browns Bank.

The waters in this region come from two primary sources. Relatively cold and low salinity water from the Scotian Shelf enters the Gulf in the surface layers around Cape Sable. The basic properties of this Scotian Shelf Water (SSW) inflow have been described by Smith (1983). Relatively warm and saline water from the offshore slope region enters the Gulf at depth through the Northeast Channel. The properties of this Slope Water (SLW) inflow have been described by Ramp et al. (1985). These two inflows progressively mix as they move in a general counterclockwise circulation around the Gulf of Maine to form the Shelf Water (SHW) mass than enters onto the northern flank of Georges Bank. On a temperature/salinity diagram the product of this mixing falls along a line between the two water source masses (figure 2). On Georges Bank the water moves in a clockwise direction around the eastern end of the bank and westward along the bank's southern flank. The majority of the flow continues southwestward into the MAB, while a portion of the flow re-circulates around the western end of the bank. Along the southern flank of Georges Bank and through the MAB the boundary between the SHW on the shelf and the offshore SLW occurs in a frontal region, termed the shelf/slope front, that is generally located near the shelf break.

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The SHW leaves the MAB through a number of processes (e.g., near surface wind driven transport, mixing across the shelf/slope front, frontal instabilities, entrainment by Gulf Stream rings, off-shelf flow near Cape Hatteras), although the contributions by the different processes to the mass balance of the MAB are not well documented. The spatial, seasonal and interannual patterns in the temperature and salinity of the waters in this region have been discussed in numerous previous reports (e.g., Bigelow, 1927; Bigelow and Sears, 1935; Hopkins and Garfield, 1979; Hopkins and Garfield, 1981; Manning, 1990; Brown and Irish, 1993)

The purpose of this report is to describe the variability in the water properties of the northeast region during the 1990's, particularly in relation conditions during previous decades. Two recent publications have presented extensive information about the water properties in the region during the 1990's, and will be referenced frequently in this analysis. Smith et al. (2001) (subsequently referred to as S01) described conditions in the Gulf of Maine and on Georges Bank during the mid-1990's. Mountain (in press) (subsequently referred to as M02) described the variability in shelf water properties in the MAB for all of the 1990's.

DATA AND METHODS

Two hydrographic data sets are used in this analysis. Since 1991 CTD measurements have been made routinely on NMFS surveys conducted to monitor the distribution and abundance of the fishery resources on the northeast U.S. continental shelf. A stratified random survey design is used. Between 1991 and 1999 hydrographic measurements were made on over 100 surveys that covered at least some part of the shelf region. The description of conditions during the 1990's is based on these data.

The second data set is from the NMFS MARMAP program that covered the period 1977-1987 and provides for a decadal scale comparison with the measurements made during the 1990's. The MARMAP sampling covered the same shelf region from Cape Hatteras northward through the Gulf of Maine at specific, standard station locations (~150 throughout the region). The hydrographic measurements were made by water bottles and reversing thermometers, except in the last year of the program when a CTD instrument was used. During the eleven years of the program hydrographic measurements were made on 49 survey cruises.

To describe the spatial and temporal variability in water properties, sub-regions of the northeast continental shelf were selected (figure 3). Three areas were chosen in the Gulf of Maine to represent the major basins – Georges Basin, Jordan Basin and Wilkinson Basin. For Georges Bank the northwest portion of the bank (NWGB) was selected to represent the water entering onto the bank from the Gulf of Maine. The MAB was divided in to five subregions, following M02.

For the areas in the Gulf of Maine the average temperature and salinity were determined for each survey in both data sets for the surface layer (0-30m depth) and for a layer near the bottom (150-200m depth). The average calendar day of the observations used in the averaging for each survey also was determined. Similar calculations were done for the surface layer in the NWGB region. In the MAB the properties of the shelf water were determined for each area on each survey, following the methods used by M02. Shelf water was identified as water with salinity < 34 PSU, representing the water inside the shelf/slope front. Generally, this is the water from the GoM/GB system that flowed southwest through the MAB. The volume of SHW in each region of the MAB also was determined on each survey.

Since the survey cruises did not occur at exactly the same time each year, direct comparison between years is confounded by the annual cycle in water properties that occurs in most areas. To allow comparison between years the annual cycle of the hydrographic properties in each area and layer was determined using the data from the MARMAP period, as done by both S01 and M02. The departure from the reference cycle for each survey value represents the anomaly for that property at the time of that survey cruise. The anomalies represent the interannual variability in the various water properties. The annual cycles derived from the MARMAP data are a consistent reference against which to compare observations from different years. When anomaly values for each subregion of the MAB were available within a 30-day period they were combined to derive an anomaly for the bight as a whole.

RESULTS

Surface layer/Shelf Water Salinity: The salinity anomalies for the upper layer of the Gulf of Maine and on Georges Bank exhibit variability that is spatially coherent around the region and temporally coherent on a multiyear time scale (figure 4). The major feature during the 1990's is a freshening by about 0.5 PSU relative to the earlier decade.

Within the MAB the SHW salinity variability was very similar to that in the Gulf of Maine/Georges Bank region (figure 5). This result is not surprising since to a very large extent the SHW in the MAB is the same water that flow around the Gulf and Georges Bank. Local freshwater input, through direct precipitation and river inflows, did contribute to the salinity variability in the MAB, but not as a major factor (M02).

Surface layer/Shelf Water Temperature: SHW in MAB experienced considerable temperature variability, with anomalies ranging from < -1 °C to about +3 °C (figure 5). The 1990's generally were warm compared to the MARMAP reference period, with an average anomaly of about + 1 °C. Averaging the anomalies during the 1990's within the different sub-regions of the MAB (see figure 3) and within three periods of the year reveals a strong a spatial and seasonal pattern to the temperature anomalies (figure 6). During the winter (first third of the year) the anomalies in the southern parts of the shelf were quite warm. The anomalies progressively decreased northward to be negative in surface layer of the basins in the Gulf of Maine (figure 7). During the middle third of the year the pattern was reverse, with negative anomalies to south and generally positive anomalies to the north. In the last third of the year, the temperature anomalies were small, being slightly negative in the Gulf of Maine and slightly positive in the other regions.

Volume of SHW in MAB: The amount of shelf water in the MAB exhibited large interannual variability (figure 5). The range in the anomalies from about –1500 km^3 to about 2000 km^3 is almost equal to the 4000 km^3 mean volume of SHW in the MAB. During the 1990's the SHW volume was on average about 1000 km^3 greater than in the earlier decade. The volume and salinity variability exhibit a strong inverse relationship through out the whole time series.

Deep properties in the Gulf of Maine: Annual cycles of temperature, derived from data during the MM period, show that the deeper layer (150-200m) of the eastern gulf (Jordan and Georges Basins) is considerable warmer than that in the western gulf (Wilkinson Basin) (figure 8). During the 1990's the deep water in Georges Basin was generally warmer than the annual cycle (figure 9). The four observations that were cooler were all from 1998. The temp/salinity anomalies of the Georges Basin deep waters during the 1990's lie along a line with a slope equal to that of the mixing line between SSW and SLW (figure 10), suggesting that much of the variability in properties results from changes in the ratio of the different source waters. In addition during the 1990's for at any salinity the Georges Basin deep water appears to have been about 0.5 °C warmer the reference period. In Wilkinson Basin the deep temperatures in the 1990's all were warmer than the annual cycle (figure 11). While the MARMAP period exhibited a significant decrease in temperature from January into April, no general winter cooling of the deep waters was evident in the 1990's.

The cool temperatures in the Georges Basin deep water during 1998 resulted from a change in characteristics of the Slope Water entering the Gulf of Maine. Drinkwater et al. (2002) document the westward extension of the Labrador Slope Water (LSW) during 1997 along the Scotian Shelf and into the Gulf of Maine in early 1998. The LSW is a few degrees cooler than the warmer slope water it replaced. The LSW was evident in the Gulf through 1998, but was gone by the beginning of 1999.

DISCUSSION

The 1990's were characterized by low salinities in the surface layers of the Gulf of Maine and through the MAB. S01 identified this freshening and attributed it to changes in inflows to the Gulf of Maine system. Measurements of SSW inflow around Cape Sable and of the SLW inflow through the Northeast Channel were made in the late 1970's by Smith (1983) and by Ramp et al. (1985), respectively. The mean SSW inflow was 0.14 x 106 m3s-1 and the mean SLW inflow was 0.26 x 106m3s-1. Comparable current meter measurements in the mid 1990's indicated 0.30 x 106m3s-1 for the SSW inflow and 0.14 x 106m3s-1 for the SLW inflow. While the total inflow during the two periods was about the same, but the relative contributions by the two inflows was reversed. The greater SSW inflow during the 1990's is believed to have caused the lowering of the salinity in evident in Fig. 4.

The changes in the inflows also could have changed the type and amount of nutrients and plankton advected into the Gulf by those inflows. Such changes could have implications for the productivity at the lower trophic levels. Subsequent analyses would be needed to investigate those possibilities.

M02 showed that changes in the SHW volume in the MAB during the 1990's were very similar to changes in the volume transport into the Gulf of Maine in the measurements reported by S01. M02 concluded that the changes in the inflows to the Gulf system were the primary cause not only of the salinity variability throughout the region, but also of the changes in the volume of SHW in the MAB, at least on an interannual time scale. On a decadal scale, the cause for the approximate 1000 km3 increase in SHW volume during the 1990's relative to the MARMAP reference period could not be identified. Regardless of cause, the changes in the location of the shelf/slope front associated with changes in the SHW volume in the MAB could have important implications for local living marine resources. This would be particularly true for the bivalve populations that reside on the outer shelf in the MAB as movement of the front could change in water mass overlying the animals, with accompanying changes in the temperature and planktonic prey organisms.

The temperature changes during the 1990's suggest greater local surface heat flux (or less cooling) during the winter on the southern part of the shelf. The progressive, northward decrease in winter warming could have been due to a comparable decrease in surface heat flux. The greater inflow of SSW into the surface layers of the Gulf of Maine would be expected to have caused cooler surface layer water temperatures. The surface layer temperature changes in winter may have resulted from a combination of greater surface heat flux through out the region and an advective cooling from the north. A detailed, quantitative analysis of the surface and advective heat fluxes would be needed to assess the causes of the temperature changes shown in figures 6 and 7.

The deep waters in the western Gulf of Maine are characteristically cooler than those in the eastern Gulf because of greater winter convection there. As shown by Mountain and Jessen (1983) and Mountain and Manning (1994) higher surface layer salinities in the western Gulf during winter result in deeper convective mixing that cools the deep waters. During a number of years in the 1990's the deep waters of the western Gulf did not exhibit a significant winter cooling, but instead remained relatively warm (figure 11). The lack of cooling likely was due to lower surface layer salinities (e.g., figure 4) inhibiting deep wintertime convection. Reduced atmospheric cooling (increased surface heat flux), as suggested above in relation to the surface layer temperatures through out the region, also may have contributed to the reduced convection. Again, a more detailed analysis will be needed to quantitatively determine the cause of the deep temperature changes. The warmer bottom temperatures in the western Gulf of Maine during the 1990's could have had important implications for the benthic community and for temperature sensitive resources species in the region such as Northern shrimp.

SUMMARY

During the 1990's the salinity of surface waters in the Gulf of Maine region and the shelf water in the MAB was lower than during the previous decade. An increase inflow of low salinity water from the Scotian Shelf into the Gulf of Maine is believed the primary cause of the salinity changes throughout the region.

The volume of Shelf Water in the MAB was about 1000 km^3 larger on average during the 1990's compared with the previous decade. The cause of this decadal change is not known.

Changes in the surface layer and Shelf Water temperature relative to the previous decade exhibited a spatial and seasonal pattern, marked particularly by warmer conditions during the winter in the southern MAB. The temperature variability like was caused by a combination of changes in the local, atmospheric surface heat flux and changes in the advective heat flux associated with changes in the inflow to the Gulf of Maine system.

The deep waters of the western gulf were significantly warmer in the 1990's compared to the previous decade. This increase is believed due to a reduced wintertime convection caused by the lower surface layer salinities in the Gulf of Maine.

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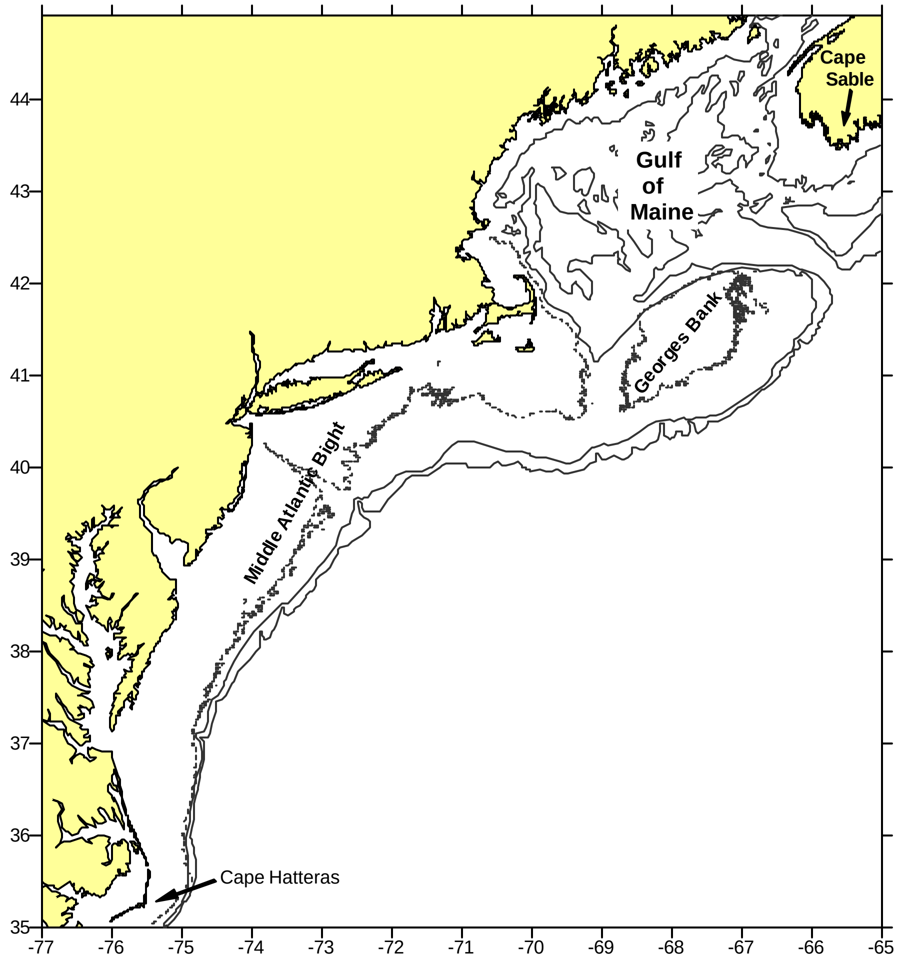

Fig. 1. The northeast U.S. continental shelf region.

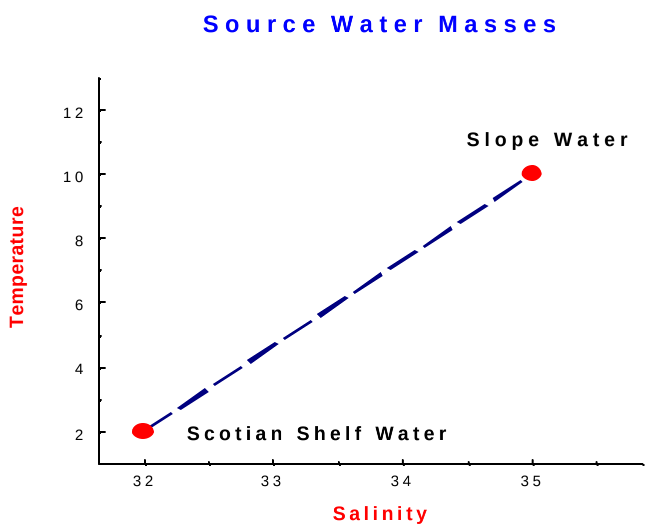

Fig. 2. Temperature/salinity diagram for mixing of the two primary water masses entering the Gulf of Maine: Scotian Shelf Water (SSW) and Slope Water (SLW).

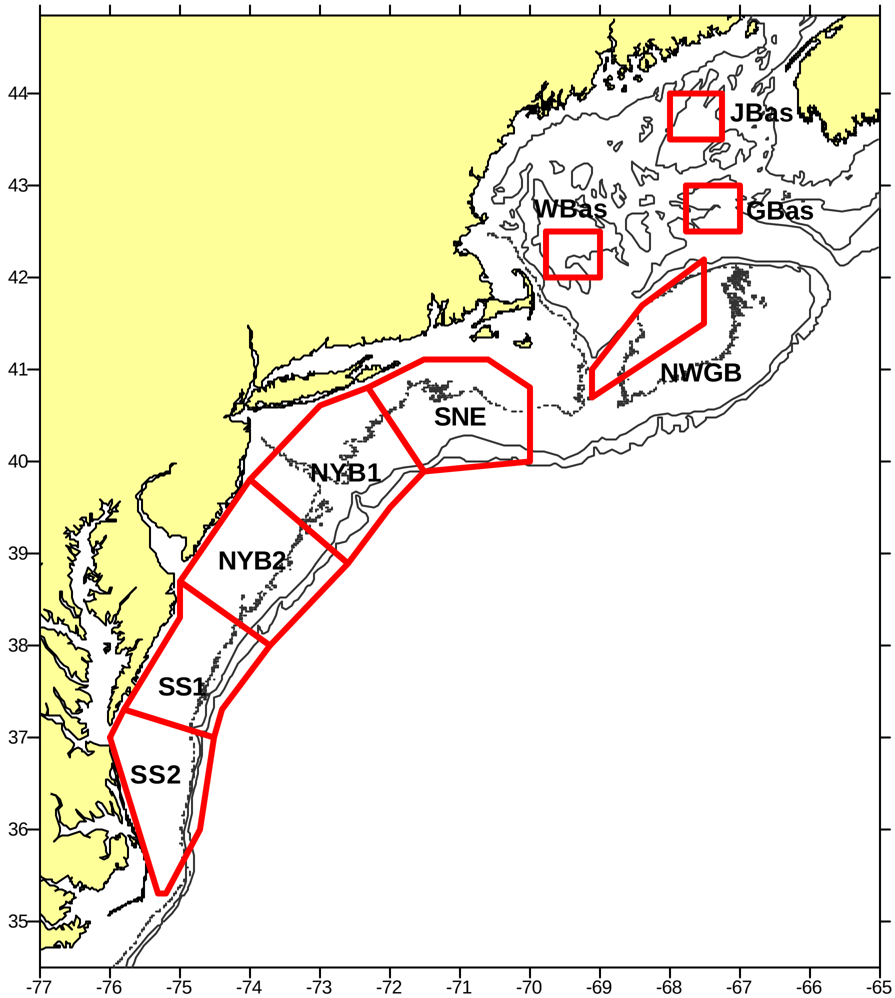

Fig. 3. Sub-regions of the northeast U.S. continental shelf region.

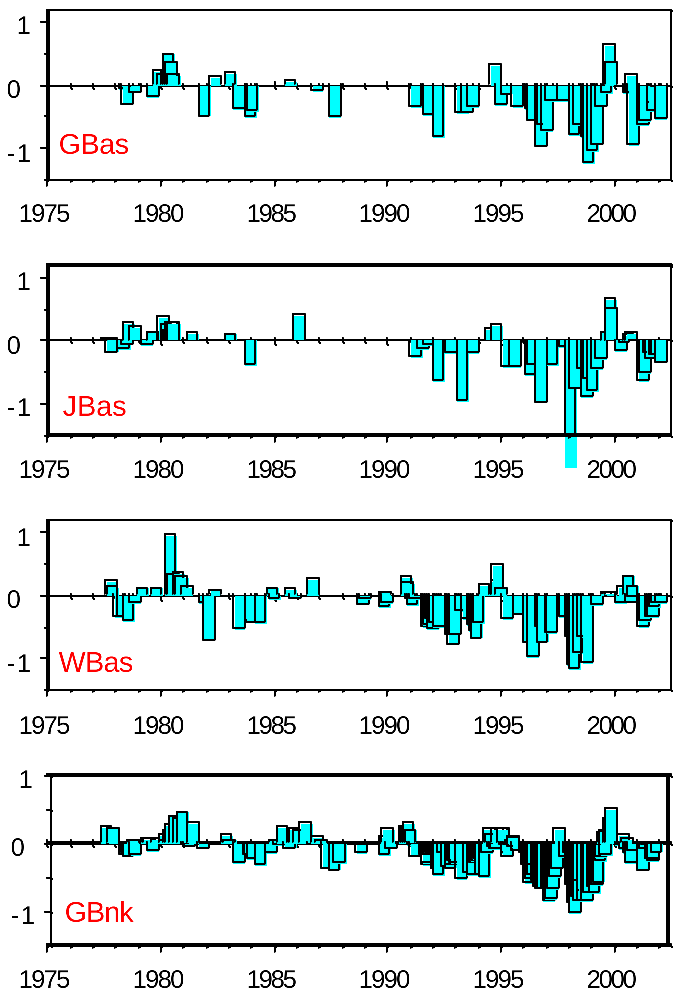

Fig. 4. Salinity anomalies for the surface layer (0-30m) of Georges Basin (Gbas), Jordan Basin (Jbas), Wilkinson Basin (Wbas) and northwestern Georges Bank (NWGB).

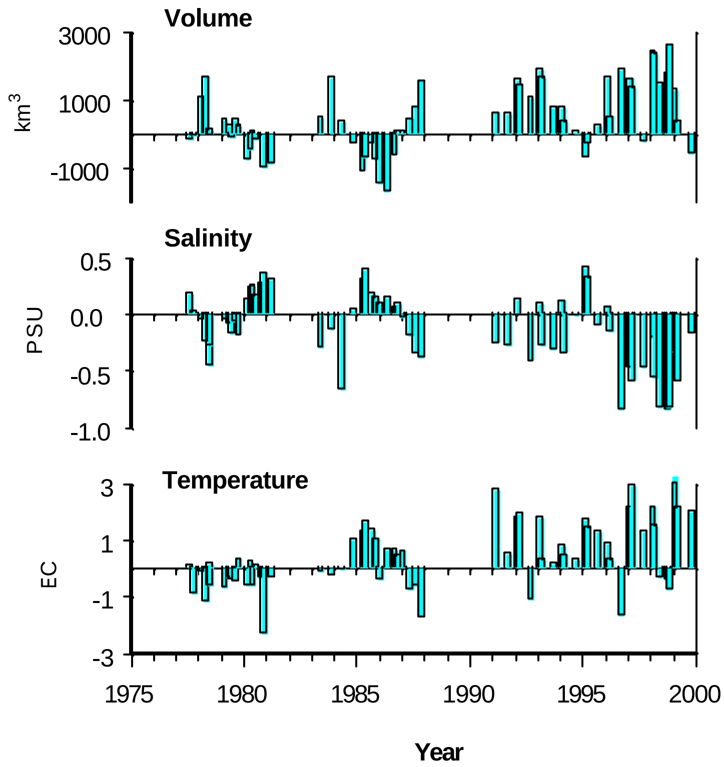

Fig. 5. Anomalies for Shelf Water volume, salinity and temperature in the MAB.

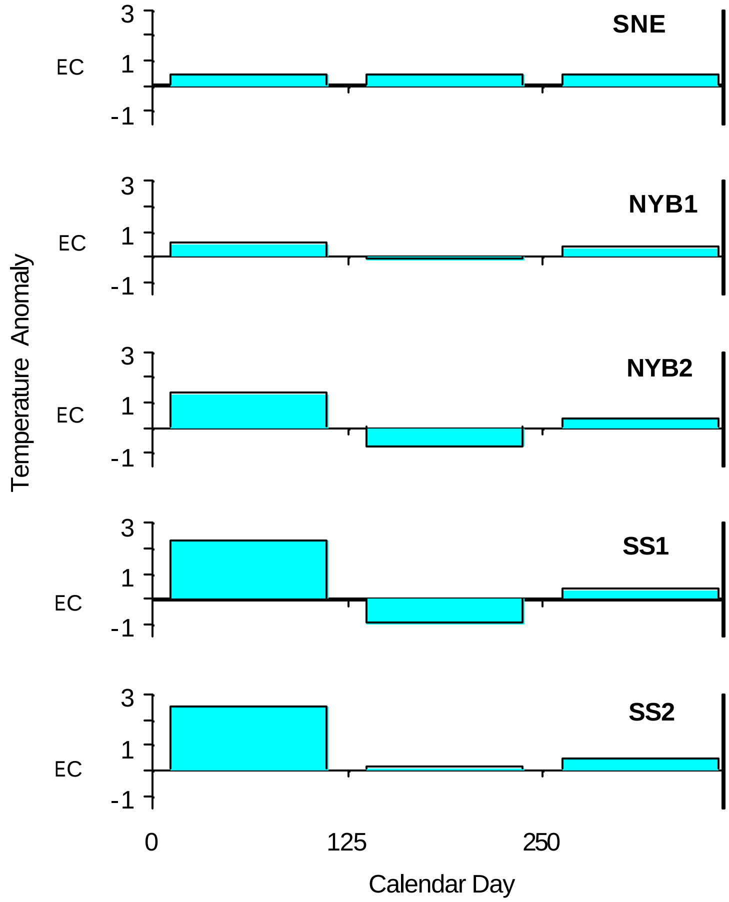

Fig. 6. Average temperature anomalies for Shelf Water in sub-regions of the Middle Atlantic Bight (see Fig. 3) during the 1990s's during three periods of the year.

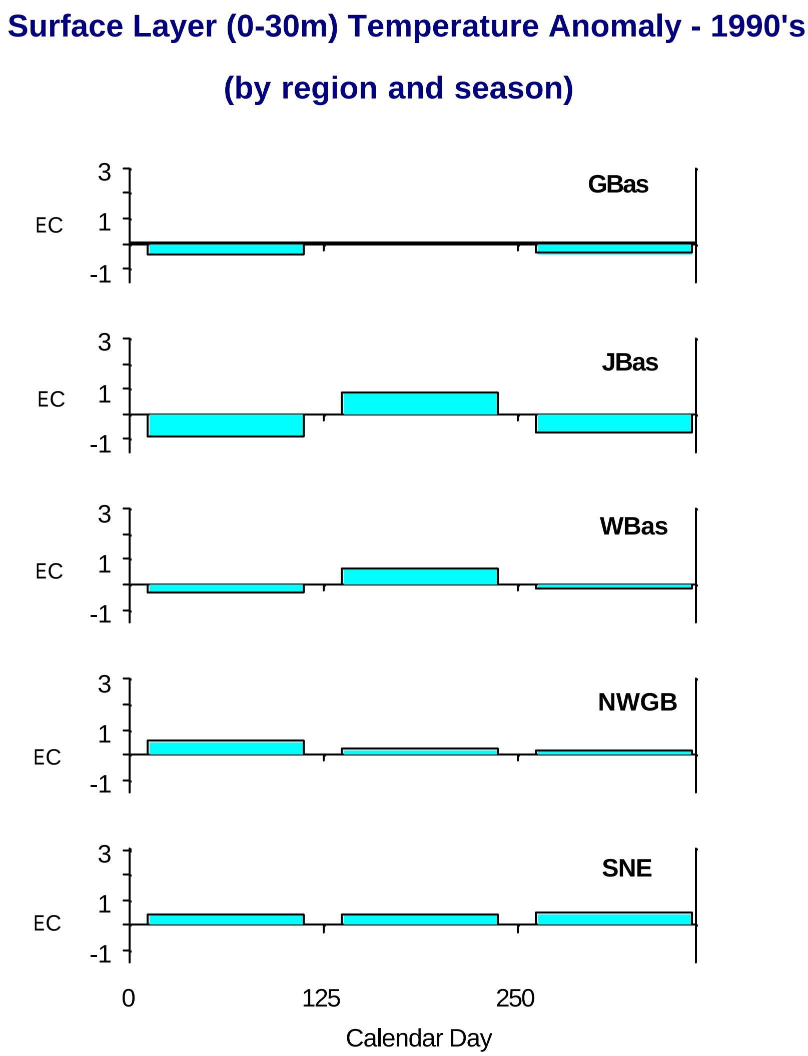

Fig. 7. Average temperature anomalies for the surface layer (0-30m) in regions of the Gulf of Maine and Georges Bank (see Fig. 3) during the 1990s's during three periods of the year.

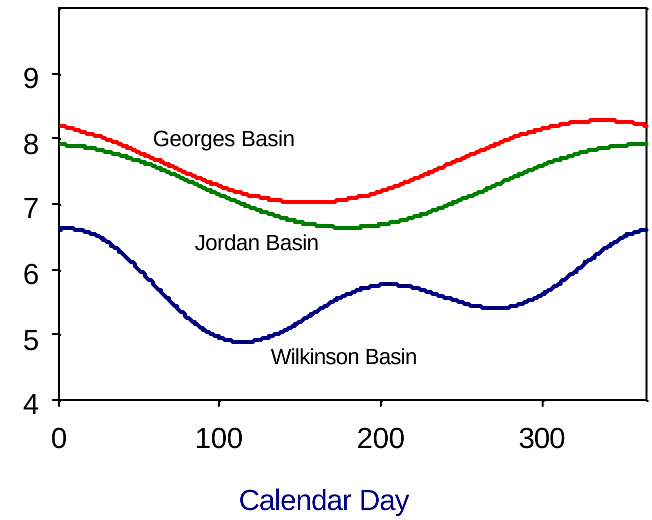

Fig. 8. The annual cycle of temperature in the deep layer (150-200m) of Georges Basin, Jordan Basin and Wilkinson Basin in the Gulf of Maine.

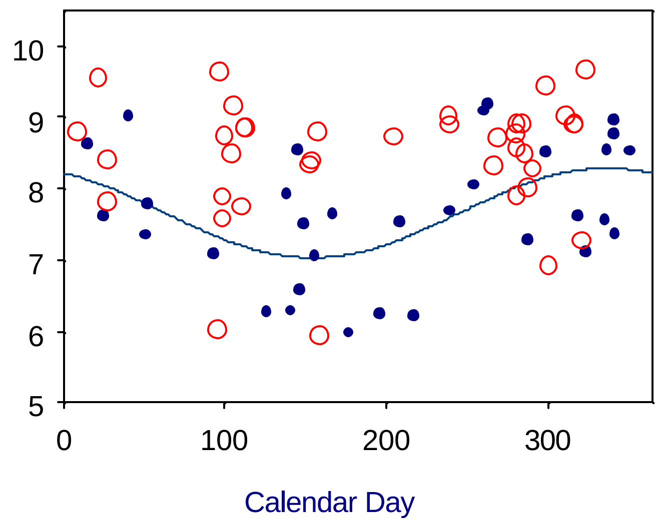

Fig. 9. Deep layer (150-200m) temperature in Georges Basin from surveys during the 1990's (open circles) and during the MARMAP period (filled circles). The annual cycle for the temperature is indicated by the solid line.

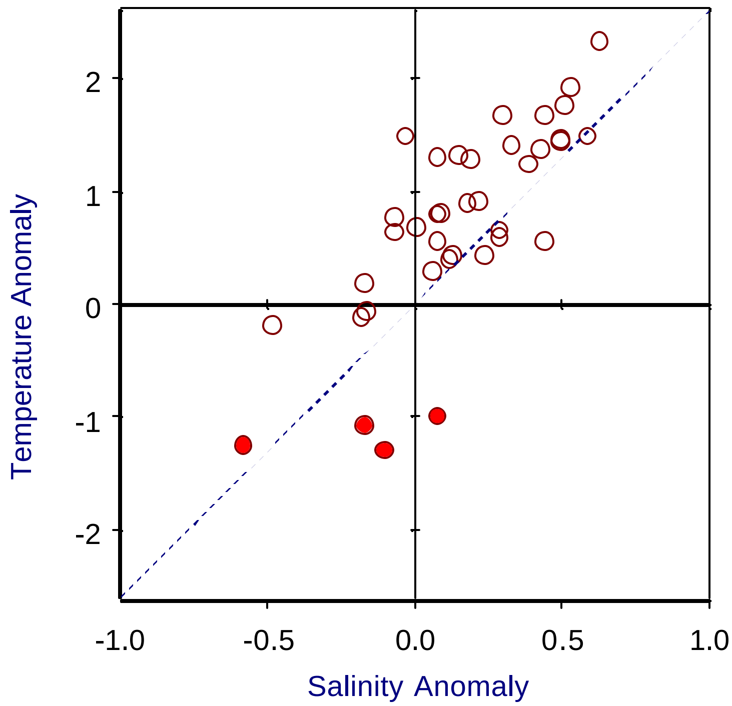

Fig. 10. Anomalies of deep layer (150-200m) temperature and salinity in Georges Basin from surveys during the 1990's. The filled circles are observations from 1998. The mixing curve between Scotian Shelf Water and Slope Water (see Fig. 2) is indicated by the dashed line.

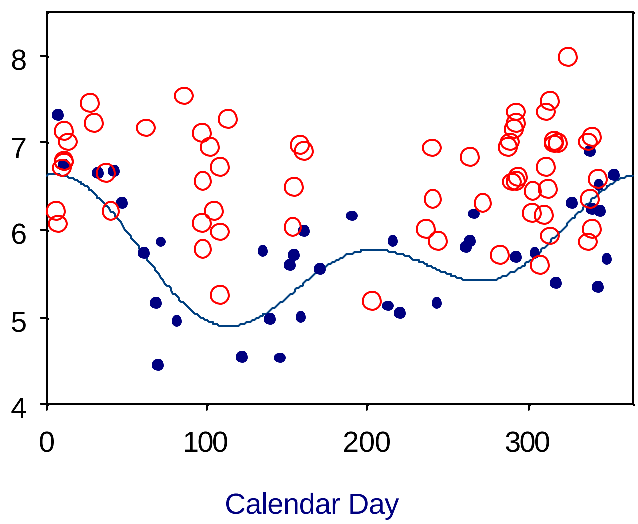

Fig. 11. Deep layer (150-200m) temperature in Wilkinson Basin from surveys during the 1990's (open circles) and during the MARMAP period (filled circles). The annual cycle for the temperature is indicated by the solid line.