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Journal of Marine Research, 45, 319–345, 1987

Bottom waters of the Gulf of Maine, 1978–1983

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ABSTRACT

The properties of the bottom waters (>100 m) of the Gulf of Maine are described using hydrographic data from 26 surveys between May 1978 and December 1983. The average temperature and salinity of the bottom water are presented from the different surveys for four regions of the Gulf—Wilkinson, Jordan, and Georges Basins and the Northeast Channel. The spatial variability across the Gulf was larger than the temporal variability in any region. The bottom water originates from Slope Water that enters the Gulf through the Northeast Channel. It is modified within the Gulf by vertical mixing with the near-surface waters of Scotian Shelf origin. A box model for the property changes during the summer-fall period indicates that the advection and mixing processes are of approximately equal importance in determining the bottom water properties. A winter convective input to the bottom layers is shown to occur only from the coastal areas around Wilkinson Basin in years when the surface salinity there was relatively high (>33.0‰). Advection and mixing rates calculated by the box model are in agreement with direct measurements of the inflow to the Gulf (Ramp *et al.,* 1985) and mixing estimates from a budget for the intermediate layer waters in the Gulf (Hopkins and Garfield, 1979).

1. Introduction

The Gulf of Maine is a large, semi-enclosed basin lying between the New England states and Nova Scotia. While at the surface it appears open to the North Atlantic Ocean, below 100 m depth the only connection from the Gulf is through the narrow, deep Northeast Channel between Georges Bank and Browns Bank (Fig. 1a). Within the Gulf the bottom topography is characterized by deep (>200 m) basins separated by shallower, rough areas. The topographically restricted exchange with the offshore waters and the separate deep basin areas are important features contributing to the characteristics of the deep waters of the Gulf of Maine.

The general hydrography and circulation of the Gulf have been described by Bigelow (1927), Hopkins and Garfield (1979), and Brooks (1985). At the surface, cold, low salinity (<32.0‰) water from the Scotian Shelf enters the Gulf around Cape Sable. Direct measurements indicate that the Scotian Shelf input has a large seasonal dependence with a maximum transport in the winter and an annual average transport of $0.14 \times 10^6\ m^3\ s^{-1}$ (Smith, 1983). The salinity of this inflow also exhibits a seasonal

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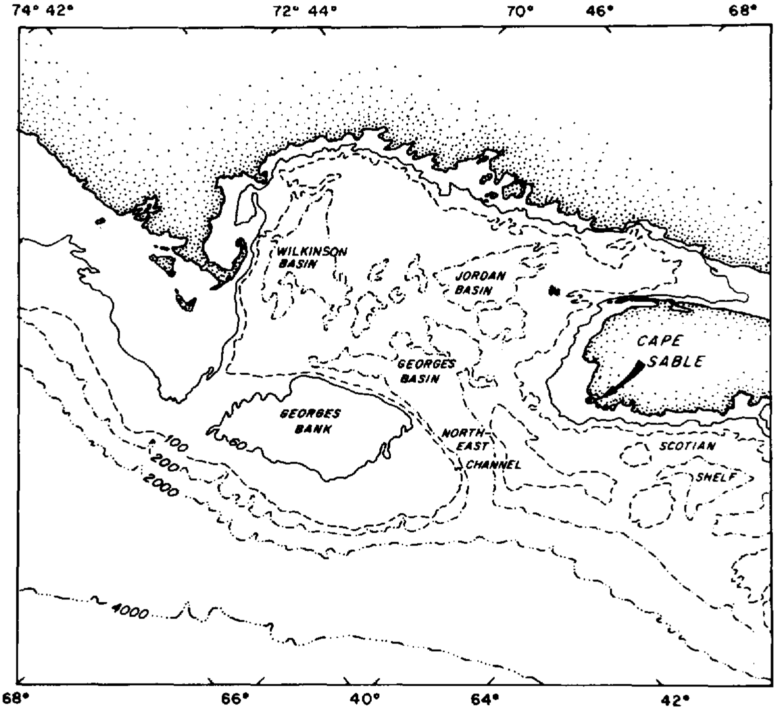

Figure 1. (a) Bathymetry of the Gulf of Maine. (b) MARMAP station locations (·) in the Gulf. Boundaries of the Basin areas (____) and the stations selected for averaging (○) are indicated.

pattern with a maximum in the late summer and a sharp decrease between October and December. At depth, warm, high salinity Slope Water enters from offshore through Northeast Channel. Measurements in the channel show that the net seasonal inflow of Slope Water has a maximum of 0.35×10^6 m^3 s^{-1} in summer and an annual average of $0.26 \pm 0.06 \times 10^6$ m^3 s^{-1} (Ramp *et al.*, 1985). Interannual variability in the penetration of Slope Water into the interior of the Gulf is indicated by Brooks (1985), who observed that 34‰ water extended into northern Jordan Basin in June of 1982, but was limited largely to Georges Basin in June of 1983. The major exit of water from the Gulf occurs in the near-surface layers around the eastern end of Georges Bank, although some may exit through the western side of Great South Channel and over Nantucket Shoals (Butman *et al.*, 1982).

Within the Gulf, Hopkins and Garfield (1979) have identified three layers in the water column. The surface layer is marked by a seasonal thermocline that develops in the spring. The intermediate layer is characterized by a temperature minimum that represents a remnant of a water mass produced by cooling-induced convection during

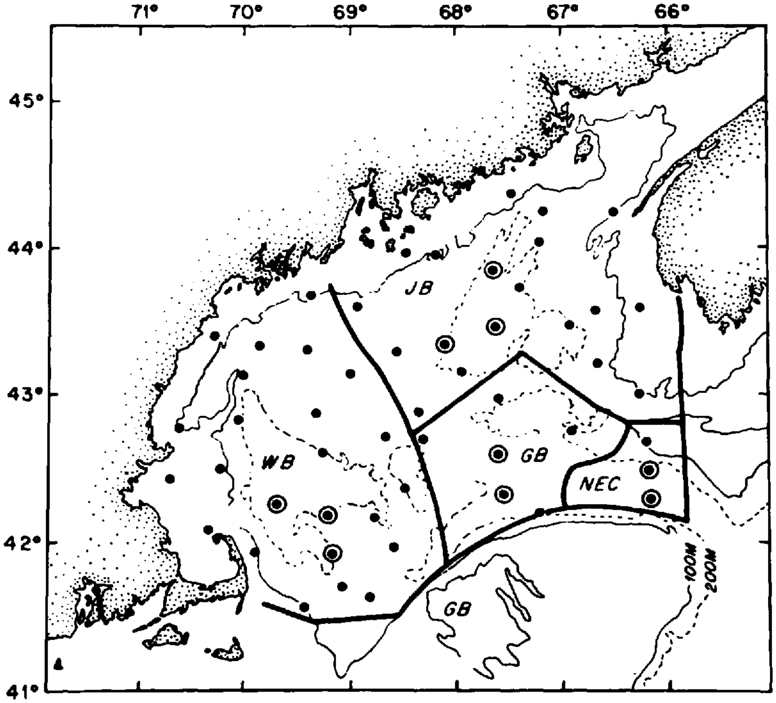

Figure 1. (Continued)

the previous winter. This convection is generally limited to the upper 100 m, although it may extend in some cases to near bottom (Brown and Beardsley, 1978). In the winter the surface and intermediate layers merge into a single, vertically uniform layer.

The bottom layer lies below the direct influence of convection and is most strongly influenced by the inflow of Slope Water through Northeast Channel. While the characteristics of the surface and intermediate layers have been well described (Bigelow, 1927; Hopkins and Garfield, 1979) the bottom waters of the Gulf of Maine have not received comparable attention.

The bottom waters are not only a large portion of the Gulf waters (38%, as defined below) but they also have an important influence on the biological productivity of the Gulf. The Slope Water entering the bottom layer through the Northeast Channel is a significant source of phytoplankton nutrients for the Gulf ecosystem. Schlitz and Cohen (1984) estimate that this input could supply 30% of the nutrients needed for the primary production in the Gulf of Maine and on Georges Bank. The purpose of this report is to describe the properties of the bottom waters of the Gulf of Maine, their variability across the Gulf and through time, and to identify the processes that determine these properties.

2. Data and methods

The primary data sets for this analysis are hydrographic measurements made as part of the Marine Resources Monitoring Assessment and Prediction (MARMAP) program. MARMAP is an interdisciplinary program to measure the distribution of plankton, nutrients and physical water properties over the continental shelf from Cape Hatteras to the Gulf of Maine (Sherman, 1980). Within the Gulf of Maine, observations have been made 3–6 times a year at 52 standard station locations, separated by about 30 km (Fig. 1b). Hydrographic measurements are accomplished using water sampling bottles with reversing thermometers at up to 15 standard depths. Salinity determinations are generally performed on a Guildline Autosal, although on some cruises determinations were done at sea with a standard bench salinometer. The accuracy of these observations is approximately ±0.02°C in temperature and ±0.01‰ in salinity. Data from 26 MARMAP surveys between May 1978 and December 1983 are considered here (see Table 1), although not all stations were occupied on each survey.

To undertake the analysis, a definition of what constitutes the bottom water of the Gulf of Maine is needed. As evident from Hopkins and Garfield (1979) the three characteristic water masses are not distinctly separate and their temperature and salinity ranges have considerable overlap. They identify the bottom water as that which lies below the Maine Intermediate Water, below the penetration depth of vertical convection during the previous winter. Because the amount and depth of convection varies from year to year, such a definition makes difficult a quantitative analysis of the bottom water properties over a multiyear period. Because of the large temporal and spatial variability in water properties, we also have found no temperature-salinity envelope or density range that provides an adequate and consistent definition of bottom water. Instead we have somewhat arbitrarily defined the Gulf of Maine bottom water simply as the water lying below 100 m depth. As such it is generally below the depth of winter convection and the core of Maine Intermediate Water as defined by Hopkins and Garfield. The majority of the descriptions and conclusions given here remain valid regardless of the specific definition chosen for bottom water.

To calculate the average water properties each station on the MARMAP grid was assigned an area and a bottom depth which, when using all stations, combined to yield a close approximation to the volume of the Gulf of Maine. Due to the spatial variability in the bottom water properties, we grouped the stations into four regions—three representing the major basins (Georges Basin, Jordan Basin, and Wilkinson Basin) and the fourth being the Northeast Channel where the major inflow of water occurs (Fig. 1b). The average temperature and salinity at a station were calculated using linear interpolation in the vertical between observed data points. The average properties for a region were calculated by weighting each station average in the region by the volume that station represents. The averaging was done for the bottom water

Table 1. Average temperature and salinity for the small station groups shown in Figure 1b.

		0–50 m							
		Wilkinson Basin		Jordan Basin		Georges Basin		Northeast Channel	
Cruise	Month	*T*(°C)	*S*(‰)	*T*(°C)	*S*(‰)	*T*(°C)	*S*(‰)	*T*(°C)	*S*(‰)
1978									
ARGUS 78-04	May	5.91	32.36	—	—	6.85	32.39	—	—
ALBATROSS IV 78-07	July	10.39	32.01	—	—	10.12	32.32	—	—
BELOGORSK 78-01	August	—	—	—	—	11.52	32.27	—	32.51
BELOGORSK 78-03	October	—	—	—	—	11.10	—	—	—
BELOGORSK 78-04	November	9.50	32.66	9.42	33.14	10.15	32.61	—	—
1979									
DELAWARE II 79-03	March	4.41	33.29	—	—	—	—	—	—
DELAWARE II 79-05	May	6.50	32.72	6.54	32.50	6.65	32.59	7.77	32.49
ALBATROSS IV 79-06	July	12.04	32.25	—	—	—	—	—	—
BELOGORSK 79-01	August	11.57	32.39	10.91	32.82	12.22	32.56	—	—
ALBATROSS IV 79-11	October	11.45	32.62	—	—	11.87	32.83	12.39	33.03
ALBATROSS IV 79-13	December	—	—	9.55	33.61	9.03	33.08	10.53	33.37
1980									
ALBATROSS IV 80-02	March	4.90	33.61	—	—	—	—	4.34	32.76
EVRIKA 80-01	May	6.17	33.40	5.76	32.91	6.54	33.26	—	—
*DELAWARE II 80-03	June	7.60	33.14	—	—	10.70	33.17	—	—
EVRIKA 80-06	August	13.11	32.60	10.52	32.90	11.48	32.79	—	—
ALBATROSS IV 80-10	October	11.95	32.88	10.12	33.29	14.79	33.44	13.31	33.34
ALBATROSS IV 80-12	December	7.38	33.26	—	—	—	—	5.85	31.97
1981									
ALBATROSS IV 81-01	March	4.59	33.25	4.29	32.85	4.66	33.06	4.13	32.56
DELAWARE II 81-03	May	8.10	32.95	6.87	32.63	7.08	32.82	6.73	32.56
ALBATROSS IV 81-14	December	7.58	32.89	—	—	8.04	32.76	8.57	32.16
1982									
ALBATROSS IV 82-02	February	4.09	32.67	—	—	3.70	32.65	3.01	32.21
DELAWARE II 82-03	June	7.22	32.56	7.40	32.62	7.94	32.78	7.07	32.83
DELAWARE II 82-09	November	9.34	32.96	8.72	33.06	9.23	32.98	10.18	32.81
1983									
DELAWARE II 83-01	January	6.45	33.24	—	—	6.52	33.28	6.29	32.66
ALBATROSS IV 83-04	June	9.62	32.00	8.08	32.24	8.30	32.19	7.55	32.06
DELAWARE II 83-09	December	—	—	7.86	32.80	7.80	32.82	8.01	32.45

*With EVRIKA 80-04.

Table 1. (Continued).

50–100 m

		Wilkinson Basin		Jordan Basin		Georges Basin		Northeast Channel	
Cruise	Month	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)
1978									
ARGUS 78-04	May	4.24	32.77	—	—	4.80	32.80	—	—
ALBATROSS IV 78-07	July	4.48	32.91	—	—	5.22	32.99	—	—
BELOGORSK 78-01	August	—	—	—	—	5.46	32.81	—	33.74
BELOGORSK 78-03	October	—	—	—	—	6.36	—	—	—
BELOGORSK 78-04	November	7.47	33.04	8.81	33.36	7.47	32.89	—	—
1979									
DELAWARE II 79-03	March	—	33.43	—	—	—	—	—	—
DELAWARE II 79-05	May	4.30	33.23	5.07	33.23	6.06	33.45	6.75	33.45
ALBATROSS IV 79-06	July	4.59	33.10	—	—	—	—	—	—
BELOGORSK 79-01	August	5.15	33.15	6.38	33.43	5.50	33.46	—	—
ALBATROSS IV 79-11	October	6.88	33.09	—	—	9.10	33.51	11.42	33.96
ALBATROSS IV 79-13	December	—	—	8.50	33.80	8.95	33.46	10.91	34.00
1980									
ALBATROSS IV 80-02	March	4.89	33.61	—	—	—	—	5.12	33.20
EVRIKA 80-01	May	5.00	33.55	5.03	33.11	5.62	33.51	—	—
*DELAWARE II 80-03	June	4.88	33.36	—	—	5.67	33.46	—	—
EVRIKA 80-06	August	5.88	33.23	6.42	33.44	5.31	33.28	—	—
ALBATROSS IV 80-10	October	6.65	33.27	7.24	33.60	9.37	33.28	9.15	33.97
ALBATROSS IV 80-12	December	7.30	33.29	—	—	—	—	8.15	33.53
1981									
ALBATROSS IV 81-01	March	4.60	33.35	4.69	33.11	4.97	33.28	5.28	33.11
DELAWARE II 81-03	May	5.17	33.17	5.43	33.00	5.33	33.12	5.74	33.12
ALBATROSS IV 81-14	December	7.58	32.93	—	—	7.33	33.04	7.59	33.09
1982									
ALBATROSS IV 82-02	February	4.46	32.83	—	—	4.84	33.00	4.69	32.91
DELAWARE II 82-03	June	4.13	32.93	5.11	33.07	5.21	33.25	6.41	33.88
DELAWARE II 82-09	November	8.25	33.18	8.64	33.48	8.33	33.36	9.81	33.51
1983									
DELAWARE II 83-01	January	6.46	33.26	—	—	6.56	33.35	7.21	33.21
ALBATROSS IV 83-04	June	5.31	32.74	5.67	33.00	5.67	32.83	5.33	32.80
DELAWARE II 83-09	December	—	—	7.87	33.04	8.03	33.15	8.16	33.33

*With EVRIKA 80-04.

Table 1. (Continued).

		100 m—Bottom							
		Wilkinson Basin		Jordan Basin		Georges Basin		Northeast Channel	
Cruise	Month	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)	T(°C)	S(‰)
					1978				
ARGUS 78-04	May	5.37	33.45	—	—	5.55	33.85	—	—
ALBATROSS IV 78-07	July	5.69	33.74	—	—	6.45	34.26	—	—
BELOGORSK 78-01	August	—	—	—	—	6.37	34.01	—	34.94
BELOGORSK 78-03	October	—	—	—	—	6.96	—	—	—
BELOGORSK 78-04	November	6.06	—	7.19	34.00	7.65	34.05	—	—
					1979				
DELAWARE II 79-03	March	—	33.56	—	—	—	—	—	—
DELAWARE II 79-05	May	4.73	33.48	6.42	33.96	7.67	34.52	8.42	34.86
ALBATROSS IV 79-06	July	5.08	33.58	—	—	—	—	—	—
BELOGORSK 79-01	August	5.08	33.57	6.55	33.99	7.61	34.52	—	—
ALBATROSS IV 79-11	October	5.52	33.65	—	—	8.47	34.65	8.87	35.03
ALBATROSS IV 79-13	December	—	—	7.61	34.23	8.63	34.36	8.90	35.03
					1980				
ALBATROSS IV 80-02	March	5.00	33.68	—	—	—	—	7.61	34.49
EVRIKA 80-01	May	4.58	33.60	5.41	33.53	6.21	34.01	—	—
*DELAWARE II 80-03	June	4.97	33.65	—	—	6.18	34.13	—	—
EVRIKA 80-06	August	5.14	33.48	5.72	33.76	6.14	34.02	—	—
ALBATROSS IV 80-10	October	5.30	33.54	6.57	34.05	7.05	34.24	8.13	34.91
ALBATROSS IV 80-12	December	5.75	33.60	—	—	—	—	8.48	34.68
					1981				
ALBATROSS IV 81-01	March	4.32	33.43	7.02	33.83	6.86	34.18	8.11	34.62
DELAWARE II 81-03	May	4.44	33.34	6.22	33.77	6.46	34.26	6.61	34.27
ALBATROSS IV 81-14	December	6.05	33.39	—	—	6.85	34.15	6.96	34.49
					1982				
ALBATROSS IV 82-02	February	6.03	33.66	—	—	6.89	34.38	6.51	34.41
DELAWARE II 82-03	June	5.51	33.59	6.39	33.89	6.33	34.30	6.86	34.67
DELAWARE II 82-09	November	6.44	33.76	7.39	34.14	7.47	34.30	8.17	34.67
					1983				
DELAWARE II 83-01	January	6.75	33.70	—	—	7.40	34.16	7.56	34.40
ALBATROSS IV 83-04	June	5.45	33.24	6.24	33.60	7.13	33.91	7.88	34.42
DELAWARE II 83-09	December	—	—	7.68	33.95	8.32	34.44	8.19	35.07

*With EVRIKA 80-04.

(depth >100 m) as well as the surface (0–50 m) and middle (50–100 m) layers. A volumetric temperature-salinity distribution was also calculated using a cell size of 0.5°C temperature by 0.2‰ salinity.

To separate temporal changes in properties for a region from spatial variability, it is important to use observations made at the same locations. Since few of the surveys sampled at all of the standard station locations, we have chosen 2 or 3 of the most commonly occupied stations in the deepest parts of the four regions to be an indicator of the average properties of each region (Fig. 1b). This allows estimation of the local temporal change between surveys with little bias from spatial variability. The initial description of the water properties (Section 3) uses only the data from these selected stations. The subsequent analysis uses the data from all of the stations occupied in each region.

3. Properties of Gulf of Maine bottom water

Using the selected stations indicated in Figure 1b, the area weighted average properties of the three layers have been calculated when each of the selected stations in a basin were occupied. The results are listed in Table 1. Wilkinson Basin (WB) and Georges Basin (GB) were the most frequently sampled regions with each having 22 sets of observations. Northeast Channel (NEC) had 16 and Jordan Basin (JB) had 13. On seven surveys the selected stations in all four regions were sampled.

Since the observations used to calculate the average values in Table 1 are from essentially the same locations and same depths in each case, the uncertainty in the average values is determined primarily by the accuracy of the original individual observations—0.02°C and 0.01‰. Additional uncertainty due to variability in station location and to the use of linear interpolation in the vertical might double or triple these for a total estimated uncertainty of about 0.06°C and 0.03‰. The spatial variability of the water properties in each basin is indicated by the standard deviation of the property values about the listed means. The average standard deviation for all of the basins on all of the cruises is 1.36°C, 0.25‰ in the surface layer, 0.68°C, 0.28‰ in the middle layer, and 0.64°C, 0.35‰ in the bottom layer. These values are more than an order of magnitude greater than the sampling accuracy and represent real variability of the water properties. In the surface layer the large standard deviation for temperature is due to the large vertical temperature gradient associated with the thermocline in the summer and fall. In the bottom layer the deviations result largely from the horizontal variability of properties that exists across the Gulf.

To illustrate the range of properties for the bottom water in each region and the relationships between the different regions, the average bottom water values from Table 1 are plotted in a temperature-salinity diagram in Figure 2. There is a progression from warm, salty to cool, fresh properties in going from NEC to GB, JB, and finally to WB. The distribution of points from each region overlap the adjacent

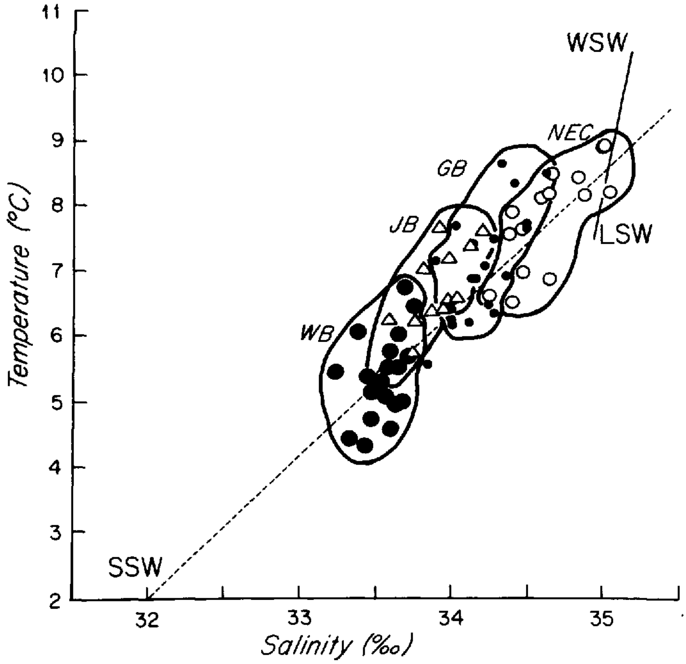

Figure 2. Temperature-salinity diagram of the average bottom water values in Table 1. Each point represents the average properties for a basin during the cruise using the selected stations in Figure 1b. Envelopes are drawn for the values in Wilkinson Basin (●) (WB), Jordan Basin (△) (JB), Georges Basin (●) (GB), and the Northeast Channel (○) (NEC). The Warm (WSW) and Labrador (LSW) Slope Waters of Gatien (1975) and the Scotian Shelf Water (SSW) of Hopkins and Garfield (1979) are indicated with an approximate mixing line (---) between the shelf and slope waters.

regional distributions in this progression. Included in Figure 2 are the characteristic temperature-salinity values of Labrador Slope Water and Warm Slope Water at 200 m offshore of the Gulf of Maine as given by Gatian (1975), and the near-surface Scotian Shelf Water as given by Hopkins and Garfield (1979). The progression of bottom water properties in the different regions falls closely along a mixing line between Slope Water and Scotian Shelf Water properties.

Each of the average points in Figure 2 is itself derived from a distribution of temperature-salinity values. The nature of this distribution differs from region to region. The standard deviations of the water properties in the bottom layer of WB are about half of those for either JB or GB. This is illustrated by the volumetric temperature-salinity distributions for the three basins from two surveys in May and October, 1980 (Fig. 3). Generally the majority of the water in a region is concentrated in a few cells. WB is characterized by a tight distribution of properties which usually

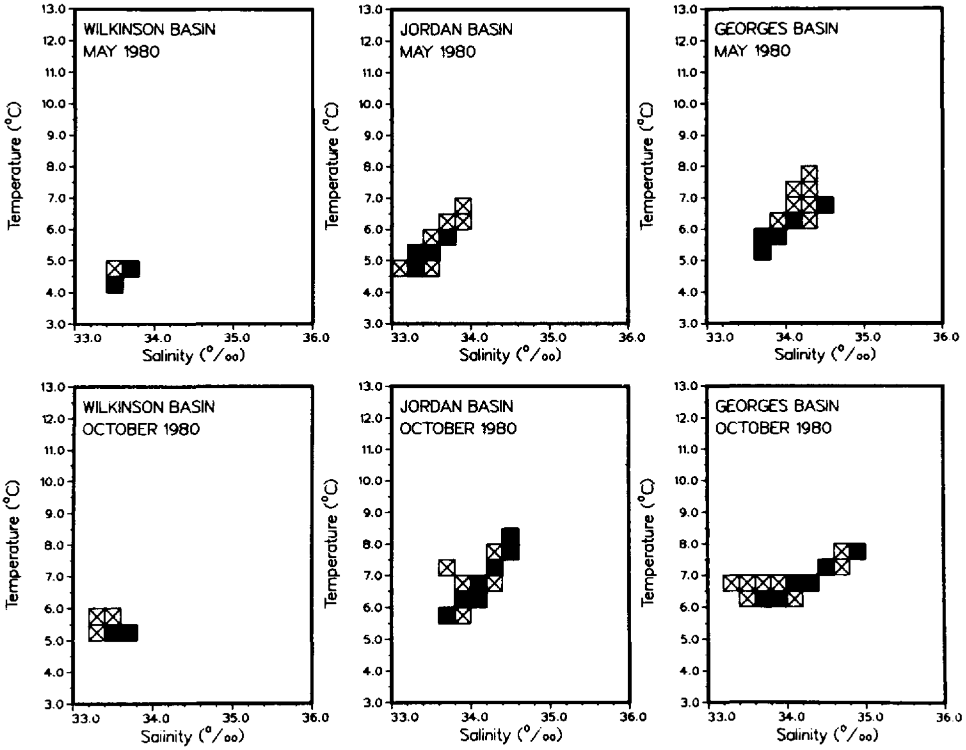

Figure 3. Volumetric temperature-salinity diagrams for the bottom waters (>100 m) of Wilkinson, Jordan, and Georges Basins in May and October 1980. In each diagram the solid cells have the largest volumes and together represent 75% of total volume. The cross hatched cells make up the remaining 25%.

contains less than half the number of cells as either JB or GB, meaning that the bottom waters in WB are more homogeneous in temperature, salinity, and density than those in the other areas of the Gulf.

The change in the average properties of the bottom waters through time is plotted in Figure 4. No consistent, dominant annual cycle is evident throughout the Gulf. A pattern of decreasing temperature and salinity from winter through the spring and increasing property values from summer through fall does appear characteristic of WB. Some tendency for a similar seasonal pattern may also occur in the other areas but the temporal resolution between surveys is not sufficient to confirm this tendency. Both the between-cruise and the between-basin differences indicated in Figure 4 are large compared to the estimated accuracy of the average values in the figure.

In WB a progression of lower annual minimum temperature and salinity values occurred from 1978 to 1981. In 1982 both parameters increased with only a small spring decrease being observed that year. In both JB and GB the outstanding event was

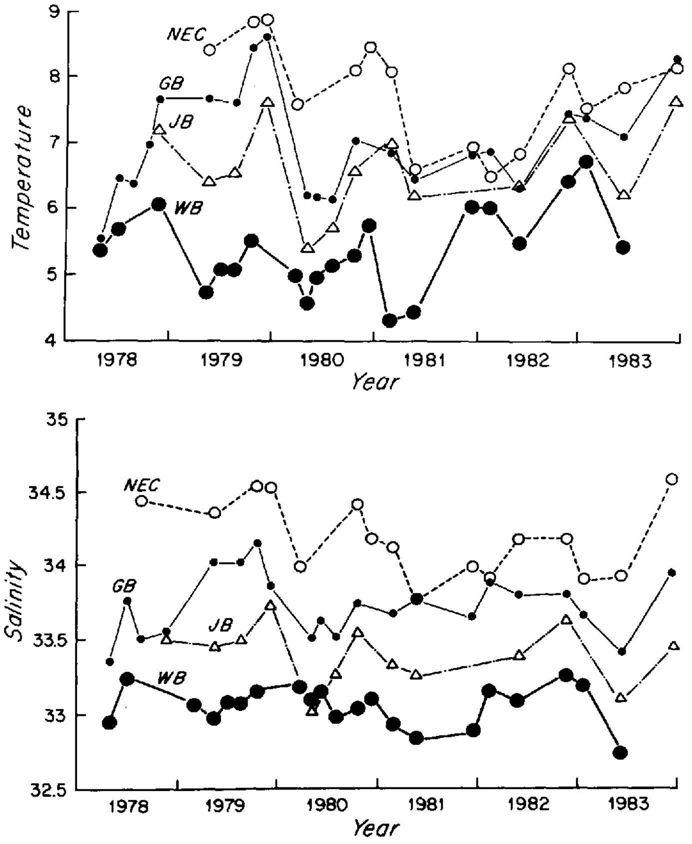

Figure 4. (a) Temperature (°C) and (b) salinity (‰) of the bottom waters in the four groups of selected stations in Figure 1b.

a sharp decrease in both temperature and salinity from late 1979 to mid-1980. NEC exhibited warm, high salinity properties (>8.4°C, >34.8‰) throughout 1979. While a decrease in temperature and salinity similar to that observed in JB and GB may have occurred in NEC in early 1980, as suggested by the March observations, the data are insufficient to show the magnitude and duration of the change. In the spring of 1981 the temperature in NEC abruptly decreased and remained low (<7°C) until the fall of 1982. The salinity in NEC showed a similar though less abrupt pattern. Taken together the curves indicate that from 1978 through early 1981 a wide range of bottom water properties existed across the Gulf with differences of about 3–4°C and 1.2–1.5‰ salinity between the average basin values. From mid-1981 to mid-1982 the range became much narrower (1–2°C, 0.8–1.1‰) when the NEC values decreased and the WB values increased.

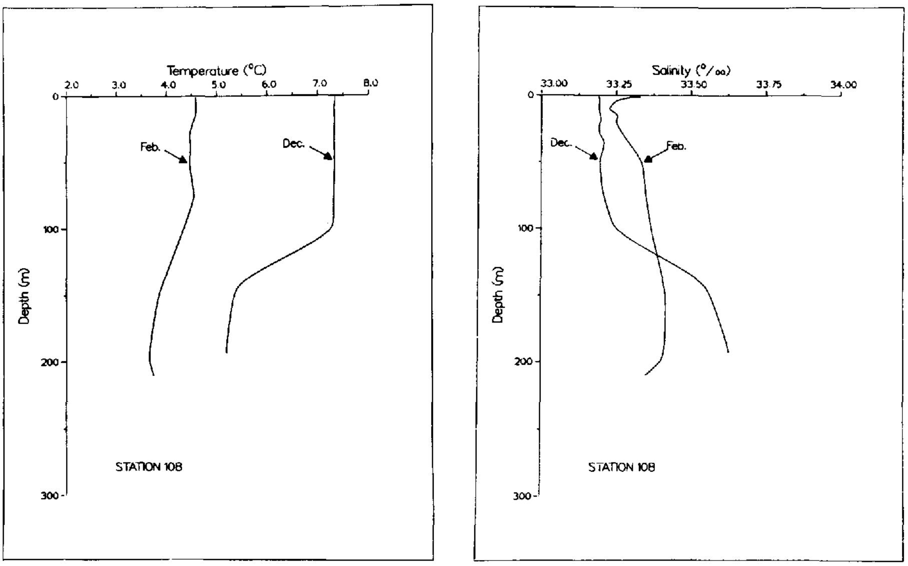

Figure 5. Temperature and salinity at the southern most selected station in Wilkinson Basin (see Fig. 1b) in December 1980 and February 1981.

4. Processes controlling the bottom water properties

The properties of the bottom waters are determined by three primary physical processes. The first is the advection of Slope Water into the deep layer of the Gulf through NEC, which warms and adds salt to the bottom water. The second is density-driven vertical convection caused by surface cooling in the winter which inputs colder, fresher water of comparable density into the intermediate layer and occasionally the bottom layer. The third process is turbulent mixing, enhanced by the strong tidal currents and irregular bottom topography of the Gulf, that continuously causes vertical exchange of properties across isopycnal surfaces.

a. Convection and mixing. The cooling and freshening of the deep waters observed in WB from winter through spring is consistent with the input of cold, lower salinity water from the surface layers. Earlier studies (Hopkins and Garfield, 1979; Bigelow, 1927) found that direct vertical convection in winter was generally limited to about 100 m depth and did not extend into the interior of the bottom layer as defined here. A review of the data from the late winter (January—March) surveys also shows this to be true. Therefore, the overwinter changes in bottom water properties are not controlled simply through direct local vertical convection penetrating into the lower layer. Two of the years in the data set (1981 and 1982), which had sampling coverage at the beginning, middle and end of the cooling period, show that the cooling process is more complicated and varies considerably between years.

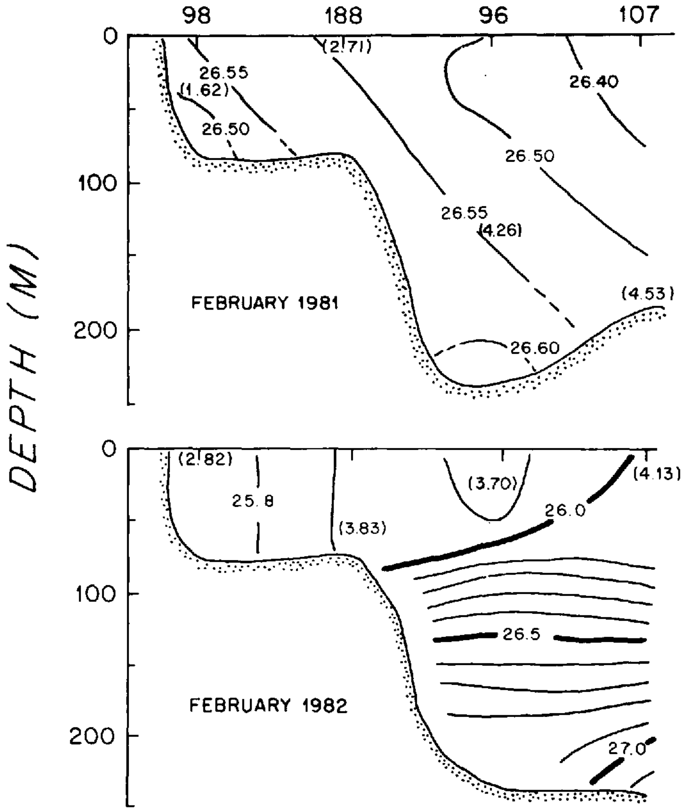

Figure 6. Density (sigma-*t*) distribution across Massachusetts Bay and Wilkinson Basin in (a) February 1981 and (b) February 1982. The minimum temperature (°C) in each water column is indicated in parentheses.

In February 1981 the deepest waters in WB were about 1.5°C cooler and 0.2‰ fresher than in the previous December (Fig. 5) and were nearly a full degree colder than the surface layer. Other stations in WB also had minimum temperatures at or near the bottom, which is not indicative of either simple vertical mixing or of vertical convection penetrating from surface cooling. At the same time the cooling and freshening of the bottom water in WB could not have been due to advection of colder water at depth into the basin, since no colder or fresher bottom water existed in the Gulf. The source of the changes was a convective input of cold, dense water from the shallow surrounding coastal regions. The distribution of density across Massachusetts Bay and WB in March 1981 (Fig. 6a) shows that a band of water with sigma-*t* values greater than 26.55 extended from the shallow stations in the bay down into the depths of WB. The minimum temperature in each water column closely followed this band of dense water. The density differences involved are well resolved by the accuracy of

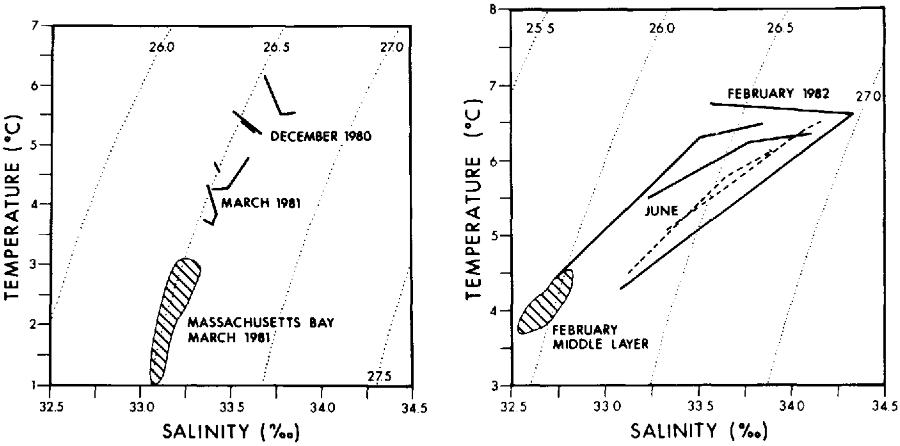

Figure 7. Temperature-salinity diagrams for waters below 100 m depth at stations (a) in December 1980 and March 1981, with an envelope for Massachusetts Bay coastal waters in March 1981 and (b) in February (____) and June (---) 1982, with an envelope for the February 1982 middle layer properties. The dotted lines are isopycnal (sigma-*t*) contours.

observations -≈ ±0.01 sigma-*t* units. On a temperature-salinity diagram (Fig. 7a) the water properties below 100 m in WB in March 1981 appear the result of a mixing between the WB water observed in December 1980 and the water observed in the shallow coastal stations in March in about a two to one ratio. The volume of coastal water needed to cause the observed change is about equal to the volume of the coastal area in and around Massachusetts Bay. The shallow coastal waters (1.1–2.7°C, 33.1 – 33.3‰) underwent a more intense cooling than the surface layers of the open Gulf (4.6–4.8°C) and attained a sufficiently high density to convect or form a density current and mix with the nearby deep waters of WB. This process accounts for the observed temperature minimum values being associated with the high density water at depth and not with the shallower uniform layer at the surface formed by local vertical convection.

The subsurface temperature minimum feature evident in Figure 5 existed across both WB and JB in March, 1981, but not in GB or NEC. The density of the water at the minimum increased progressively across the Gulf (Fig. 8) from less than 26.2 in JB to above 26.5 over most of WB. The density of the water at the coastal stations indicated in the figure follows the same pattern and was of about equal density to the nearby temperature minimum water farther offshore. In JB the temperature minimum was observed in the depth range of 50–100 m. Thus the potential input by convection from the coastal areas was to the waters above the bottom layer of the basin. The cooling and freshening that did occur in the bottom waters of JB and GB in 1981 must have occurred through vertical mixing between the intermediate layer and the bottom layers. The average density of the bottom layer in WB increased over the winter while

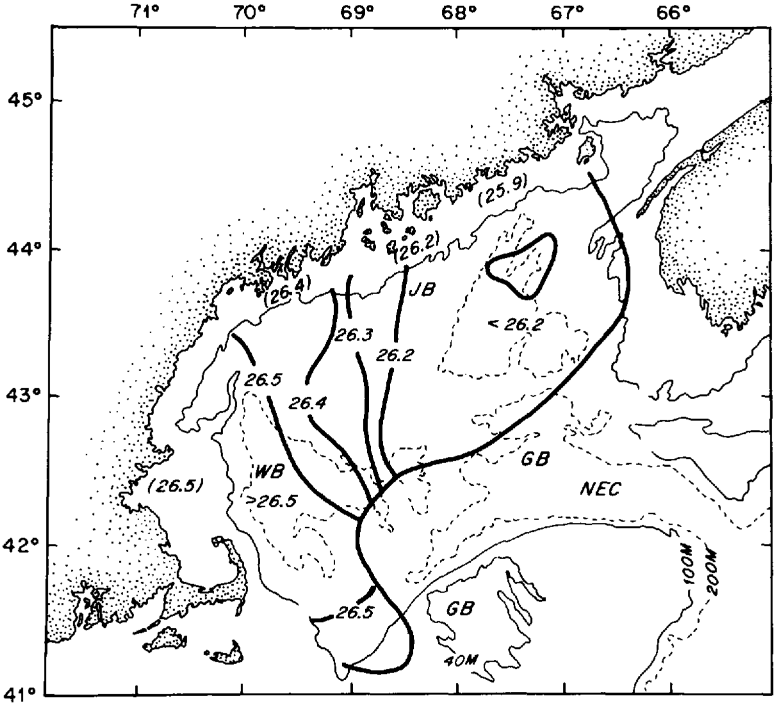

Figure 8. Density (sigma-*t*) of the minimum temperature water in March 1981. Coastal water density values are also indicated around the coast in brackets. Station locations are shown in Figure 1b. Outside of the contoured area no subsurface temperature minimum was observed.

it decreased in both JB and GB, consistent with the dominant processes being convection and vertical mixing, respectively.

The vertical density gradient below 100 m in WB during February 1982 was ten times that observed in March 1981 (Fig. 6). The water in Massachusetts Bay in February 1982 had a relatively low salinity (32.2–32.6‰) and density (25.7–25.9). No input of cold, fresh properties through convection into the deeper layers would be expected from these conditions. A temperature-salinity diagram for the waters below 100 m at the three selected stations in WB shows that no vertical input of colder, low salinity from the coastal areas did occur in 1982 (Fig. 7b). For February the curves each show an increase in temperature and salinity with depth below the middle layer, but they are separated on the diagram, indicating the horizontal variability in the water properties across the basin. The curves for the June observations also have an increase in temperature and salinity with depth, but are nearly coincident with each other and lie between the February curves. The change in water properties from February to June, as indicated by Figure 7b, appears the result of horizontal mixing in the basin with little indication of a change in vertical structure through the input of

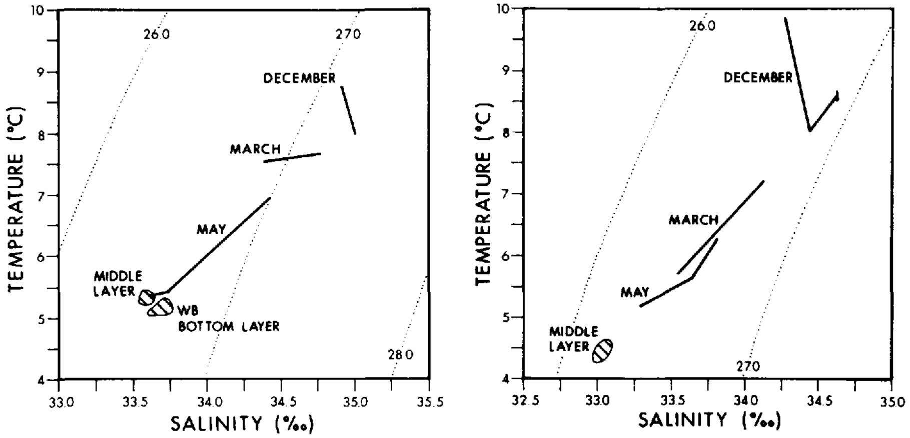

Figure 9. Temperature-salinity diagrams for the bottom waters in (a) Georges Basin and (b) in Jordan Basin in December 1979 and March and May 1980. The March middle layer properties in each basin and the bottom water properties in Wilkinson Basin in March are included. The dotted lines are isopycnal (sigma-*t*) contours.

cold, low salinity water from the coastal regions or through mixing with the middle layer above.

For the other years in the time series, 1980 seems similar to 1981 with the waters in the coastal areas around WB being of equal density to the bottom water in the basin. The coastal water was sufficiently saline (33.5‰) in March 1980 that when dense enough to convect (at 3.8°C), it did not change the bottom water temperature or salinity as much as in 1981. In 1979 the coastal salinities were not measured over the winter and the potential for convective input is not known. In 1983 severe winter cooling did not begin until after the January observations and thus the cooling period was not sampled that year.

With the exception of 1980 JB and GB exhibited only relatively small decreases in temperature and salinity during the winter. As described above for 1981, these changes resulted from vertical mixing of colder, fresher water from above into the bottom waters with little direct input through vertical convection or convection from the surrounding coastal areas. In 1980 the bottom water in both GB and JB showed a large drop in temperature and salinity during the winter and spring. Using one station from each basin for illustration, the deep values show a progressive cooling and freshening from December 1979 through March and into May 1980 (Fig. 9a, b). The change occurs along a line consistent with a vertical mixing between the deeper waters and the middle layer values in each basin. The colder, fresher bottom waters of WB observed in March 1980 are also a possible mixing end member for the changes in GB, although not for those in JB. No significant advection of deep waters from WB to GB is believed

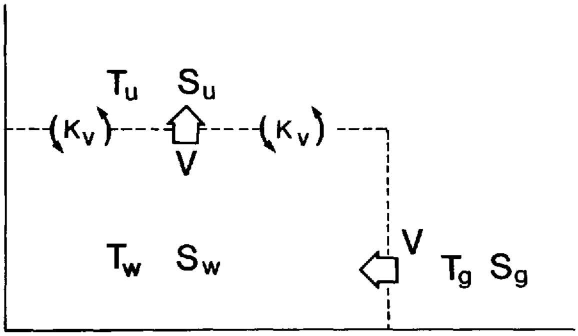

Figure 10. Schematic diagram of the box model for the water property changes in the bottom layer in Wilkinson or Jordan Basin (Eqs. 1a and 1b). T_w and S_w are the temperature and salinity into bottom layers of the basin. T_u, S_u, and T_g, S_g are the property values in the middle layer of the basin and the bottom layer of Georges Basin, respectively. V is the horizontal transport of water into the bottom layer of the basin. K_v is the vertical mixing coefficient.

to have occurred, however, since there is no evident source of replacement water for WB.

b. Advection and mixing. The bottom water properties in all three basins reach their annual minimum values in spring or early summer (the May–June cruise in this data set, see Table 1). After that the temperature and salinity increase through December. During this latter part of the year, surface cooling has ceased and advection of Slope Water through NEC and local vertical mixing become the dominant processes affecting the bottom water properties.

The advection of water properties could be indicated by geostrophic current estimates of the water circulation in the Gulf. However, due to the uncertainty of reference level and the small number of stations that extended below 200 m, geostrophic current calculations do not provide a reliable or unambiguous estimate of the flow rates within the bottom layer of the Gulf. Instead, a box model which balances heat and salt transport offers a better means to estimate flow rates between the basins within the Gulf.

The box model used here is shown schematically in Figure 10. The increase in temperature and salinity from summer into late fall in WB and JB is assumed due to the advective input of water horizontally from the bottom layer of GB and to vertical mixing with the middle layer above. Horizontal mixing within the deep layer of the basin is assumed to keep the properties there always spatially uniform, allowing a box model approach to be used. A compensating outflow of water must occur, likely through a general upwelling across the entire basin, as indicated by the vertical arrow in Figure 10. The observed net inflow of water at depth through NEC (Ramp *et al.*,

1985) does require such an upwelling for the Gulf as a whole. For this model the rates of change of heat and salt in the bottom layer of WB or JB are expressed as:

$$\rho c_p \frac{dT_w}{dt} = \rho c_p [V(T_g - T_w) + \left(\frac{K_v \cdot A}{H} - V\right)(T_u - T_w)]/VOL \tag{1a}$$

$$\frac{dS_w}{dt} = [V(S_g - S_w) + \left(\frac{K_v \cdot A}{H} - V\right)(S_u - S_w)]/VOL \tag{1b}$$

where V is the horizontal transport from GB and K_v is the vertical mixing coefficient. The subscripted T and S terms are the temperature and salinity values in the different layers as shown in Figure 10. C_p is the heat capacity, ρ is the water density (assumed to be 1 g cm^{-3}) and VOL is the volume of the bottom layer of the basin, A is the area of interface between the layers and H is the vertical distance between the observations.

For convenience the vertical mixing may be expressed as an equivalent transport:

$$W = \frac{K_v \cdot A}{H}. \tag{2}$$

The net vertical exchange of properties resulting from the combination of turbulent mixing and upwelling may be expressed as a net vertical transport:

$$U = W - V. \tag{3}$$

For comparing the contribution of vertical and horizontal processes to the property balance of the bottom waters of the gulf, it is the net vertical transport that is of most interest. The model equations then become:

$$\rho c_p \frac{dT_w}{dt} = \rho c_p [V(T_g - T_w) + U(T_u - T_w)]/VOL \tag{4a}$$

$$\frac{dS_w}{dt} = [V(S_g - S_w) + U(S_u - S_w)]/VOL. \tag{4b}$$

In using observations to apply the model the temperature and salinity properties input from the middle layer and from Georges Basin are assumed to change linearly with time:

$$T = T_i + \frac{(T_f - T_i)}{\Delta t} * t \text{ and } S = S_i + \frac{(S_f - S_i)}{\Delta t} * t \tag{5}$$

where the subscripts i and f refer to the initial and final observations, Δt is the time difference between them and t is time since the initial observation. The flow field also is assumed to be steady, so that U and V are constant. Eqs. 4a and 4b are intergrated over the time between observations to yield the property changes that would occur in the bottom layer of the basin for any choice of U and V. From Eq. 4a the set of U and V values that yield the observed temperature change is found and from Eq. 4b, the set

Table 2. Horizontal (V) and vertical (U) transports ($\times 10^6$ m^3 s^{-1}) into Wilkinson Basin and Jordan Basin derived from the box model in Figure 10 (see text for explanation). The values in parentheses are the range of solutions obtained from the limits of uncertainty of the data used in the model.

	Wilkinson Basin	
	V	U
1978	0.10 (0.07–0.13)	0.08 (0.05–0.11)
1979	0.04 (0.03–0.05)	0.07 (0.04–0.10)
1980	0.04 (0.02–0.06)	0.07 (0.04–0.10)
1981	0.10 (0.08–0.13)	0.13 (0.10–0.16)
1982	—insufficient data—	
1983	—insufficient data—	
Average	0.07	0.09

	Jordan Basin	
	V	U
1978	0.50 (0.36–0.82)	0.18 (0.14–0.25)
1979	0.35 (0.25–0.59)	0.16 (0.10–0.23)
1980	0.35 (0.27–0.47)	0.10 (0.07–0.14)
1981	—no solution—	
1982	0.39 (0.27–0.74)	0.22 (0.15–0.35)
1983	0.53 (0.38–0.91)	0.32 (0.17–0.63)
Average	0.42	0.20

that yield the observed salinity change. The intersection of these two sets is the desired solution for U and V.

For input to the model, water properties representing an entire basin are desired instead of just the select stations used for Table 1. A set of average water properties were derived using all available stations in a basin for cruises on which at least half of the stations in the region were occupied. Comparisons indicate that if the stations are well distributed the uncertainty in average properties from having only half of the stations, as opposed to all of the stations, is about ±0.1°C and ±0.05‰. The model results using observations with the greatest time separation between the summer temperature minimum and the latest cruise in each year are given in Table 2. Since the form of (4a) and (4b) is identical, the model solution can be ill defined if temperature and salinity are closely correlated. As an indication of the stability and uncertainty of the solutions, the range of U and V values that result from varying the water properties by ±0.1°C and ±0.05‰ are included in Table 2.

For WB the model results show that the average input by advection from GB is about equal to the input from the middle layer above (≈ 0.07–0.09×10^6m^3 s^{-1}). For JB the horizontal advective input is about twice the vertical input and about six times the advective transport into WB. Table 2 indicates that the model results are quite consistent between years. The results for each year are also reasonably stable to uncertainties in the water property values, with the extreme answers being within a factor of two of the listed solution.

The bottom water of JB could be the source of the inflow to WB, in part or in total. Observations do not exist in both basins on enough surveys to use the model for estimating the transport required by this circulation pattern to account for the observed changes in WB.

The total transport through GB is estimated by the model to be $0.42 - 0.49 \times 10^6$ $m^3\ s^{-1}$, depending upon how much of the inflow to WB is supplied by JB. Given the uncertainty of the predicted transport into JB indicated in Table 2, this range is consistent with the $0.35 \times 10^6 m^3\ s^{-1}$ average summer inflow through NEC reported by Ramp *et al.* (1985). The inflow into each basin requires a compensating upwelling velocity of 3×10^{-4} cm s^{-1} in WB and $14–18 \times 10^{-4}$ cm s in JB. The average model results in Table 2 indicate that the volume of water below 100 m in WB would be replaced in 127 days and JB in 27 days. The water in GB would be replaced in 26 days with no vertical processes being considered.

The average net vertical exchanges predicted by the model correspond to downward vertical velocities of $3–8 \times 10^{-4}$ cm s^{-1}. These are of the same order as the 2×10^{-4} cm s^{-1} derived by Hopkins and Garfield (1979) from a property balance of the intermediate layer. Using Eqs. 2 and 3 the vertical mixing portion of the net vertical exchange can be calculated to yield estimates of $K_v \approx 5\ cm^2\ s^{-1}$ for WB and $K_v \approx 20\ cm^2\ s^{-1}$ for JB. Given the large tidal currents and uneven topography of the Gulf of Maine, the implication is that the vertical fluxes derived from the box model could be accomplished by a realistic level of vertical mixing.

The box model is not suitable for the winter-spring period (December to June). The change in properties, particularly for the middle layer, cannot be assumed linear in time as in Eq. 5. When winter convection does enter the middle layer, the changes there occur quickly compared to the 3-6 month time between cruises. In order to obtain an indication of the seasonal variation of the inflow of Slope Water into the Gulf, the baroclinic pressure gradient relative to 200 m was calculated between a station in NEC and one in WB, as done by Hopkins and Garfield (1979). This approach ignores the barotropic pressure forcing which may also be important. The results are grouped into winter-spring (December to May) and summer-fall (June to November) periods (Fig. 11) with each cruise being represented by a different curve. Similar to the findings of Hopkins and Garfield (1979) an out-of-Gulf tendency exists in the middle layer which is strongest in the winter-spring period. An inflow tendency exists in the bottom layer which is weakest in the winter-spring period. This seasonal pattern in the bottom layer is similar to that measured in NEC by Ramp *et al.* (1985), who found low transport into the Gulf from February to May in 1977 and from April to May in 1978.

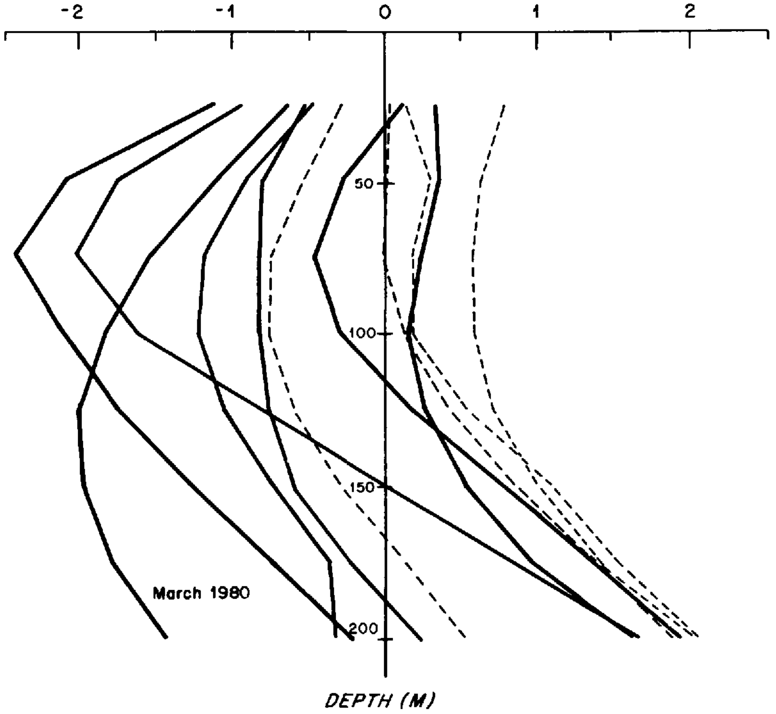

Figure 11. Baroclinic pressure gradient ($\times 10^4$ cm s^{-2}) between Wilkinson Basin and Northeast Channel relative to 200 m depth for different cruises in December to May (——) and June to November (---). Positive values indicate an in-Gulf tendency (higher pressure at Northeast Channel) and negative values indicate an out-of-Gulf tendency.

5. Gulf of Maine salinity

Large changes in water properties occurred not only in the bottom layer of the Gulf of Maine, but throughout the water column. Table 3 lists the average salinity for the whole Gulf of Maine calculated from basin averages when at least half of the stations in each basin were occupied. In the fall of 1979, 1980 and 1982 the average salinity of the Gulf was >33.5‰, but in the fall of 1981 it was <33.0‰. Between October 1980 and December 1981 the average salinity in the whole Gulf decreased steadily by 0.6‰. This decrease resulted from the cooler, fresher slope water entering at depth through NEC (Fig. 4), and from fresher surface layer waters that entered the Gulf around Cape Sable. By November 1982 the average salinity had increased again by 0.5‰. These large changes indicate that the variation in the inflowing properties observed at NEC must have continued for a number of months to affect the entire Gulf and that the observations in Table 1 and in Figure 4 are not highly aliased. The large changes in salinity occurring within and between years makes establishing a salt budget for the

Table 3. Volume-weighted average salinity in the Gulf of Maine (surface to bottom) from surveys in which over half of the stations in each of the four regions (see Fig. 1) were occupied.

Year	Month	Salinity (‰)
1979	May	33.19
	December	33.63
1980	October	33.59
1981	March	33.33
	May	33.17
	December	32.99
1982	November	33.52
1983	January	33.40
	June	32.81

Gulf of Maine a difficult and time-dependent problem. The box models of Brown and Beardsley (1978) and of Hopkins and Garfield (1979), which assumed uniform input properties to the Gulf and yielded estimates of the NEC transport that were less than half of the value directly measured by Ramp *et al.* (1985), likely suffered because of the salinity variability.

6. Discussion

Convection caused by surface cooling during winter is important to the bottom water properties in two ways. Over the whole Gulf convection penetrates through the middle layer to form the Maine Intermediate Water of Hopkins and Garfield (1979), providing a cold, relatively fresh source to mix downward into the bottom layer. Secondly, with high salinity water (>33.0‰) in the coastal areas around western WB, winter cooling can create water dense enough to convect to the bottom of the basin. The surface salinity more than the severity of the winter cooling appears to determine if this convective mechanism occurs. For example, Figure 12 shows the winter of 1982 to have been as cold and windy as the other years (1977-1983). In addition the coldest surface layer water temperatures developed then (Table 2), but no deep convection occurred, because the coastal salinities were too low (<32.6‰). Even if the waters had cooled to their freezing point (−1.7°C) they would not have convected into the bottom layer. On the other hand, in 1980 the surface salinities were high (33.5‰) and the waters needed to cool only to 3.8°C to become dense enough to convect to the bottom. This convection causes the WB bottom water to be more uniform in its properties than the deep water in the other basins, as illustrated in Figure 3.

Continual vertical mixing with the fresher waters above results in the progression of decreasing salinity in the bottom water from NEC to GB, JB and finally to WB, as shown in Figure 2. While the wintertime convective process, when it does occur, always cools and freshens the bottom layer and advection from NEC always warms and increases the salinity, the thermal effect of the vertical mixing process changes through

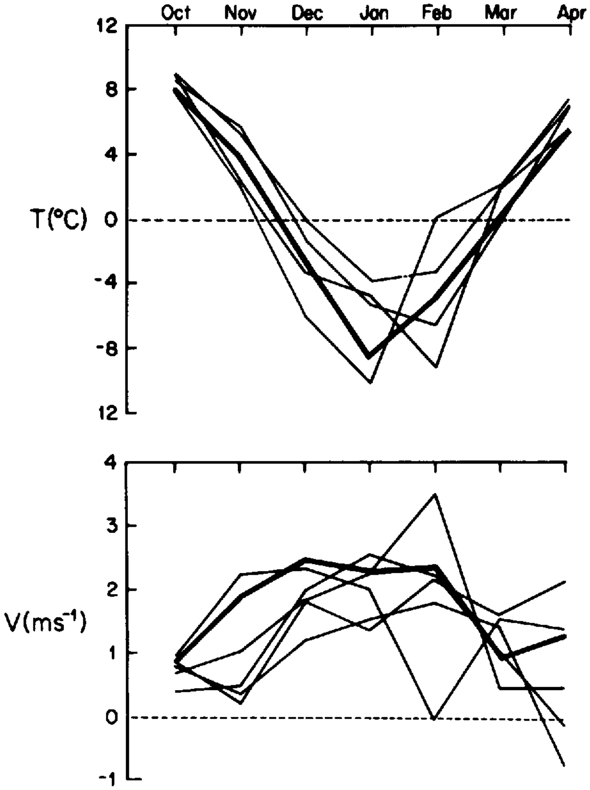

Figure 12. Monthly average air temperature (°C) (top) and resultant northwest wind component (MS^{-1}) (bottom) measured at the Portland, ME International Jetport for the periods October to April during 1977–1983. The heavier curves represent 1982.

the year. During the winter and through the beginning of the summer the intermediate layer is cooler than the bottom layer and mixing cools the bottom waters. In the fall the middle layer is warmer and the mixing warms the bottom waters. The cooling process of convection to form the cold intermediate water and subsequent mixing of this cold water into the bottom layer causes the minimum temperature on the bottom water to occur in the late spring or early summer, well after the onset of seasonal surface warming.

The changes in the properties of the bottom waters of the different basins of the Gulf result not only from changes in the deep waters inflowing through NEC, but also from changes in the surface waters entering the Gulf. For example when the temperature and salinity of the bottom layer at NEC decreased from the spring of 1981 to the summer of 1982, there was no comparable change in the bottom waters of any of the interior basins. In WB the bottom waters became warmer and saltier, exhibiting little cooling or freshening over the winter and into the summer of 1982. As discussed above, due to low surface layer salinities no convective input occurred around WB in the winter of 1982. Also the vertical mixing of the middle layer properties into the bottom layer probably was reduced by the strong density stratification evident in Figure 6b. The input of fresher surface water to the Gulf, by inhibiting the vertical exchange processes, had a larger effect on the bottom waters in WB than did changes in the slope water properties entering in the bottom layer through NEC. Conversely, years with high surface salinity input (e.g. 1979, 1980) resulted in stronger, more effective vertical processes in the following winter and yielded colder, fresher bottom water in WB. The consequence is that the wide range of properties across the Gulf that existed from late 1979 to 1981 became a narrow range during 1982 when the inflow properties at NEC changed, as shown in Figure 4.

A suppression of the vertical exchange processes during winter, as in 1982, would reduce, at least temporarily, the upward flux of nutrients from the bottom waters into the photic layer. Such a reduction could have important implications for the primary production not only in the Gulf, but also on Georges Bank whose waters originate from the surface layers of Wilkinson Basin (Hopkins and Garfield, 1981).

The suppression of vertical exchange over the winter of 1982 may have extended over Jordan Basin, as well. Brooks (1985) reports that the 34‰ isohaline penetrated further into Jordan Basin in June 1982 than in June 1983. The JB bottom layer salinity listed in Table 1 is also higher in June of 1982 than in June of 1983. These differences could have resulted from a reduced inflow of Slope Water to the basin in 1983, as suggested by Brooks, or from reduced mixing between the bottom layer and the lower salinity middle layer in 1982 as proposed above for Wilkinson Basin. Unfortunately, with the absence of winter observations around Jordan Basin in 1982 we are unable to address this question.

The source of the low salinity winter coastal water observed around Jordan Basin—as compared to the higher coastal values found around Wilkinson Basin—is suggested by the measurements of Smith (1983). These measurements show that the inflow of water to the Gulf of Maine from the Scotian Shelf around Cape Sable had a significant seasonal cycle in both the volume transport and the salinity during 1979 and 1980. The transport, which was near zero (or even out of the Gulf) from June to October of 1979, increased sharply in November and remained high through February, 1980. The near surface salinity exhibited a sharp decrease in November to less than 32‰, at the same time that the major inflow to the Gulf began. With an average speed of about 5 cm s^{-1} this input of low salinity water beginning in November would spread about 300 km around the coastal regions of the Gulf during the winter—from Cape Sable to about Penobscot Bay. This seasonal input of low salinity surface water beginning in the late fall would account for the low salinity of the winter coastal waters around Jordan Basin which inhibit a wintertime, coastal convective input to the bottom waters of Jordan Basin.

The changes in water properties observed in NEC are consistent with a shift in the proportion of the Warm Slope Water and Labrador Slope Water characteristics of Gatien (1975). Colton (1968) and Ramp *et al.* (1985) both present examples of similar changes in water properties in NEC. Gatien (1975) shows that the boundary between the Warm and Labrador Slope Waters occurs near the NEC. The changes in the input properties to the Gulf of Maine could be due to movement of this boundary, though no direct observations exist to support this hypothesis. The surface layer waters entering the Gulf come primarily from the Scotian Shelf. The salinity of those waters is related to the fresh input from the St. Lawrence River (Sutcliff *et al.*, 1976). Measurements of the St. Lawrence River outflow (Drinkwater, personal communication) do not indicate an increase in 1979 or 1980 that might have caused the large decrease in the surface layer salinity observed at NEC in late 1980 and through 1981. The sources of variation in the properties of the water entering the Gulf of Maine remain unknown.

A seasonal variation in the inflow of Slope Water to the Gulf through NEC, as observed by Ramp *et al.* (1985) and suggested in Figure 11, would reduce the advective input of heat and salt to the interior basins over the spring. The convective and vertical mixing processes thus could act more effectively in the spring to alter the bottom waters of the Gulf than in the fall of the year. This could contribute to vertical mixing apparently dominating advection in the spring to generally lower the bottom water salinity while advection outweighs mixing in the fall to increase the salinity. The large property changes observed in the spring of 1980 in both JB and GB also may have been related to a reduction in the inflow. The pressure gradient calculated between WB and NEC in March, 1980 (Fig. 11) had a large out-of-Gulf tendency extending to 200 m depth. If the pressure gradient is indicative of the inflow at NEC, then the spring of 1980 would have had the least input of heat and salt into the Gulf of the years sampled. Vertical mixing could then have resulted in the large changes in the temperature and salinity observed in JB and GB in early 1980, as suggested in Figure 9.

A reduced inflow to the Gulf in the spring of 1980 also could have resulted from wind forcing through a mechanism suggested by Ramp *et al.* (1985). They show that variability in the Northeast Channel flow is coherent at periods of 2-11 days with both subsurface pressure and longshore wind stress at Portland, Maine. They propose a conceptual model in which northeast wind stress piles water up along the Maine coast, increasing the coastal sea-surface pressure which drives an out-of-Gulf flow through Northeast Channel. The reverse occurs from southwest winds. A review of subsurface pressure records from Portland, however, does not show a greater frequency of high pressure events in early 1980 as compared to the other years. The seasonally averaged wind at Portland does have a northeast component in the spring of 1980, in contrast to the other years except 1983. To refer to seasonally averaged forcing, however, would require extending the conceptual model of Ramp *et al.* (1985) from the wind forced band (2-11 days), which their data support, to the seasonal band, for which no supporting data exist and which would likely involve different dynamics.

7. Conclusions

The bottom waters of the Gulf of Maine originate from Slope Water entering through the Northeast Channel. Spreading into the Gulf it is modified by mixing from above with water of Scotian Shelf origin. The deep waters become progressively fresher and colder from the Northeast Channel to Georges Basin to Jordan Basin and finally to Wilkinson Basin. Box model calculations for the fall period indicate that the advective and vertical mixing processes are of approximately equal importance in determining the bottom water properties in Wilkinson and Jordan Basins. In addition wintertime convection into the bottom layer can occur from the shallow coastal areas around Wilkinson Basin in years when the coastal salinity there is high ($> \approx 33.0‰$). The resulting spatial (between basin) variability in bottom layer properties is larger than the temporal variability (seasonal and interannual) at any one location.

Interannual changes in the bottom water properties result from changes in the character of the Slope Water entering at depth through the Northeast Channel. Changes in the inflowing surface layer properties are also important by affecting the coastal salinities and thereby determining the potential for direct convective input of the surface layer properties to the bottom waters. A change in the temperature and salinity of the inflowing waters at Northeast Channel occurred in 1981 and appeared to have persisted for over a year into the fall of 1982. The result was a large decrease in the average salinity of the whole Gulf, but an increase in the salinity in Wilkinson Basin due to the lower surface salinities suppressing the freshening convective input there.

Acknowledgments. The authors wish to express their thanks to the many persons who took part in the collection of the data used here. A particular debt of gratitude is owed to Daniel Patanjo, who processed most of the data and made it ready for analysis. The subsurface pressure data was provided by Wendell Brown of the University of New Hampshire. The comments of an anonymous reviewer are acknowledged for improving the formulation and presentation of the box model. Reference to a product or trade name does not constitute an endorsement by the National Marine Fisheries Service. This is MARMAP contribution MED/NEFC 85-08.

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Received: *26 March, 1986;* revised: *20 February, 1987.*