Journal of Marine Research, 48, 75–87, 1990

$\Delta^{14}C$ balance for the Gulf of Maine, Long Island Sound and the northern Middle Atlantic Bight: Evidence for the extent of the Antarctic Intermediate Water contribution

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ABSTRACT

The radiocarbon signatures of the western Sargasso Sea and the atmosphere as a function of time over the past 200 years are known. These can be combined with seawater dissolved inorganic carbon (DIC) radiocarbon data from the Gulf of Maine and the northern Middle Atlantic Bight (MAB), including Long Island Sound (LIS), for 1983 and pre-1955 shell analyses for radiocarbon, to set the amount of Antarctic Intermediate Water (AAIW) required to balance the ^{14}C budget in the northern MAB. Approximately 40% of the water entering the Middle Atlantic Bight from the north must be AAIW, the other 60% being Sargasso Sea water. Contemporary water from LIS, a part of northern MAB, can be explained as a mixture of Sargasso Sea water and Gulf of Maine water but at times in the past more low-^{14}C water (AAIW) was added to this mixture as recorded in shells from LIS. This implies variations in upwelling rates over time in the region of the Middle Atlantic Bight.

1. Introduction

Of all the ocean water tracers, ^{14}C has, like a precocious child, provided both joy and frustration to its users. Broecker *et al.* (1960), Bien *et al.* (1965) and Craig (1969) began the taming process of this nuclide, but not until the GEOSECS results became available (Stuiver and Ostlund, 1980) was the contemporary distribution of ^{14}C in the world oceans well enough known to be used in a better understanding of the system. The contemporary oceans are influenced by bomb-produced ^{14}C which in itself provides a valuable transient tracer, especially in the upper part of the water column.

The $^{14}C/^{12}C$ ratio of surface seawater at any particular location has been changing as the result of the influence of this bomb-produced ^{14}C signal and of the degree of upwelling of ^{14}C-aged water. Surface ocean waters are the reservoirs from which most biogenic calcium carbonate is deposited. Thus, if the chronometry of a calcareous test

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is known, it can provide a record of the $^{14}C/^{12}C$ ratio of surface seawater as a function of time.

Nozaki *et al.* (1978) first showed the value of this approach by monitoring the ^{14}C variation over time in the Sargasso Sea, and coupled it to $\delta^{13}C$ and $\delta^{18}O$ measurements, by using the growth layers of a living coral from Bermuda having a 200-year-old history. This time series analysis showed marked changes in $^{14}C/^{12}C$ in the surface Sargasso Sea, first as a result of fossil fuel burning since 1870 and then the addition of ^{14}C due to atmospheric nuclear bomb testing after 1950. They also found fluctuations in the $^{14}C/^{12}C$ ratio and $\delta^{13}C$ prior to either of these anthropogenic effects which they ascribed to changes in a ^{14}C and ^{13}C depleted (relative to ^{12}C) deep water upwelling component over time. The role of deep upwelling contributions in modifying surface waters, as preserved in the ^{14}C record in corals, has been demonstrated in a series of papers by Ellen Druffel and her colleagues (1978, 1980).

In this paper we address the problem of the sources of water in the northern Middle Atlantic Bight, using seawater and calcareous test data from the continental margin region of the eastern U.S., combined with Sargasso Sea coral and seawater data obtained earlier. The GEOSECS profile of the Atlantic Ocean provides the information on the ^{14}C distribution with depth. Mollusc shells are commonly preserved in museums with good chronometric control so that such collections can be used to provide a time-series record of the ^{14}C variation in continental shelf waters.

Tanaka *et al.* (1986) have shown that about 50% of the carbon in the calcareous tests of mussels, oysters and other molluscs is derived from metabolic carbon and 50% from dissolved inorganic carbon (DIC). If the primary source of food for an organism depositing a calcareous test is marine plankton, the $^{14}C/^{12}C$ of the test corrected for fractionation based on the $^{13}C/^{12}C$ will be independent of the two sources of carbon. If, however, terrestrial carbon is metabolized, the fractionation corrected $^{14}C/^{12}C$ of the test will be higher than that for DIC. In this case the test having the lowest value of fractionation corrected $^{14}C/^{12}C$ will be the closest indicator of the DIC value. The most direct method of determining the terrestrial carbon component is to assay tests and the waters in which they are growing. Because it is surrounded by land, Long Island Sound provides us with a severe test of the utility of molluscan shells as indicators of seawater $^{14}C/^{12}C$ and it is here that the experiment relating $^{14}C/^{12}C$ ratios of seawater DIC and shell was executed. Surface seawater samples collected along a Woods Hole-to-Sargasso Sea traverse, in association with the SEEP program, were analyzed for ^{14}C as were Long Island Sound and Gulf of Maine shells, of known time of capture, from the collection at Yale's Peabody Museum of Natural History.

2. Methods and results

Surface seawater samples were collected from piers and jetties along Long Island Sound. Sampling sites in LIS are shown in Figure 1. At each of seven sites 100 kg of

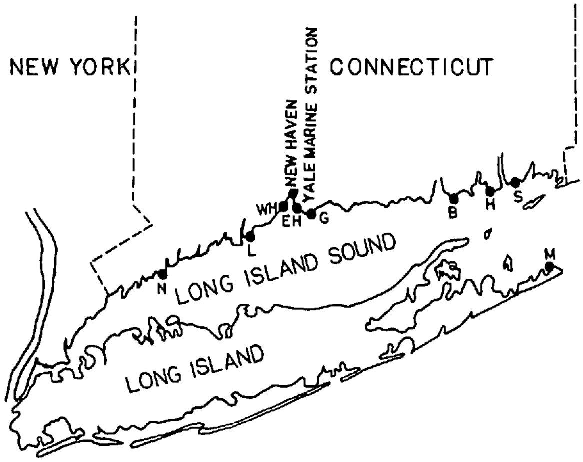

Figure 1. Location map of sampling sites in Long Island Sound: N-Noroton Pt., Stamford; L-Lordship Beach, Stratford; WH-West Haven; NH-New Haven; EH-Morris Cove, New Haven; G-Guilford; B-Black Pt., Old Saybrook; H-Harkness Memorial Park, New London; S-Stonington; M-Montauk Pt., Long Island.

seawater were collected for ^{14}C analysis. Suspended material trapping was minimized by collecting seawater during calm sea conditions. When necessary, particles were removed by decantation. Live molluscs were captured during 1975 and 1983 at the seawater sampling sites and others along the shoreline in LIS. Two- to three-year-old individuals, based on size, were chosen for this study.

Seawater samples were also taken at Montauk Point on Long Island and Provincetown on Cape Cod. An intertidal snail (*Littorina*) was collected from Montauk Point. In addition, surface seawater was collected along the SEEP-I-08 Cruise in April, 1984.

The method of extraction of DIC from the seawater samples involved the acidification of 100 kg of seawater and sparging with CO_2-free air simulating the system described by Linick (1980). 250 ml of 2N NaOH solution (CO_2-free) were used to collect the extracted CO_2. Each seawater sample was analyzed for total CO_2 using the Gram titration method (see Stumm and Morgan, 1970); salinity, by the conventional silver nitrate titration method; and temperature and pH. Most of the CO_2 samples extracted from seawater were analyzed for $\delta^{13}C$ to be used in calculating a fractionation corrected ^{14}C value as described below.

Approximately 20 g of shell calcium carbonate were roasted in air at 450°C for 30 minutes, pulverized in a mortar, weighed, and treated with 2N HCl in a vacuum system to release CO_2 gas. Separate 10 mg fractions of pulverized shell were analyzed for $\delta^{13}C$. For this analysis the sample was roasted at 380°C for three hours under vacuum and retained under vacuum for at least six hours prior to release of CO_2 with 100% phosphoric acid for the $\delta^{13}C$ measurement.

The CO_2 gas obtained from seawater or shell carbonate was converted to benzene in a vacuum system and assayed for ^{14}C with a liquid scintillation counter following our normal procedures at Yale (Nozaki and Turekian, 1977).

The results of radiocarbon analysis are reported using the $\delta^{14}C$ and Δ nomenclatures ("age corrected") of Stuiver and Polach (1977) based on Broecker and Olson (1959):

$$\delta\,^{14}C = \left(\frac{A_s}{0.95\,A_{ox}} - 1\right) \times 1000 \quad (1)$$

and

$$\Delta = \delta^{14}C - (2 \times \delta^{13}C + 50) \times \left(1 + \frac{\delta^{14}C}{1000}\right) \quad (2)$$

where A_{ox} is the $^{14}C/^{12}C$ ratio in NBS oxalic acid standard in 1950 and A_s is the corresponding ratio in the sample corrected to the time of isolation from the reservoir. The reported 1 sigma errors for Δ values are those associated with counting statistics and standard reproducibility. The decay correction was made using the ^{14}C half-life of 5730 years.

Salinity, TCO_2 and DIC carbon isotopic values for LIS, Montauk Point and Provincetown seawaters are given in Table 1. SEEP-1-08 cruise results are given in Table 2. Carbon isotopic values of modern and pre-bomb shell carbonates from LIS and elsewhere are given in Tables 3 and 4, respectively.

3. Discussion

a. The contemporary and pre-1955 Δ values for shells and DIC in LIS. The results for modern (1983) molluscs (Table 3) and associated water (Table 1) are plotted in Figure 2. Modern shell carbonates have Δ values which range from +88 to +135 with a mean of +110 ± 4 (S.E.). The seawater DIC ranges from +67 to +101 with a mean of 92 ± 5. If Δ (DIC) = +92, shells = +110 and half the carbon in the shell is metabolic carbon (Tanaka *et al.*, 1986), we can calculate the average fraction of terrestrial carbon making up the metabolic carbon found in the shell by assuming that Δ for marine metabolic carbon is the same as Δ (DIC) and Δ for 1983 terrestrial metabolic carbon is +234 (Levin *et al.*, 1985). Such a calculation shows that approximately 13% of the carbon in shells from nonsewer impacted areas of Long Island Sound is of terrestrial origin.

The Yale Peabody Museum of Natural History shell collection includes material collected in Long Island Sound and the Gulf of Maine during 100 years prior to the introduction of bomb ^{14}C. Analysis of this material allows us to estimate the pre-bomb Δ value of seawater DIC in LIS after correcting for the metabolic effect discussed above (Table 4).

Table 1. Salinity, TCO_2, pH, and $\delta^{13}C$ and radiocarbon as Δ of coastal seawaters from Long Island Sound and other northeastern U.S. sites.

Site	Date of collection	Salinity (‰)	TCO_2 (mmole/l)	pH	$\delta^{13}C$ (‰) (of extract)	Δ (‰)
Long Island Sound, CT						
Stamford	7/22/83	27.07	1.90	7.77	(−1.5)	+ 67 ± 9
Stratford	7/22/83	26.08	2.13	6.70	−1.5	+ 92 ± 11
West Haven	8/21/83	20.93	1.56	7.74	−4.2	+ 82 ± 14
New Haven	6/27/83	25.03	1.93	7.89	+0.3	+ 73 ± 10
Guilford*	7/08/83	27.0	2.00	7.90	−0.1	+101 ± 6
Old Saybrook	7/08/83	28.72	1.90	8.10	−1.1	+ 89 ± 10
Long Island, NY						
Montauk Pt.	11/12/83	29.92	—	—	0.0	+ 89 ± 12
Cape Cod, MA						
Provincetown	11/10/83	31.25	—	—	(0.0)	+130 ± 12

*Mean value for 7 samples.
$\delta^{13}C$ values in parentheses are assumed for determining Δ.

Δ values of six mollusc shell carbonate collected from Long Island Sound and the Gulf of Maine from 1866 to 1937 range from −96 to −37 with a mean of −72 ± 5 (Table 4). No particular pattern in time and space is apparent. Broecker and Olson (1959) reported a Δ value of −52 ± 9 for a carbonate molluscan shell (species not indicated) collected live at Port Jefferson, Long Island during the fall of 1954 with a Δ value (recalculated) for surface seawater near the site of the shell collection in 1954 of −86 ± 9. We believe that this wide range in Δ values is due either to variable amounts of terrestrial carbon in the diet of the various organisms or variable composition of the water entering Long Island Sound from the shelf (see Table 1).

Table 2. ^{14}C analysis of surface seawater DIC from SEEP I-08 cruise (Apr. 17–May 1, 1984).

Site	Water depth at site (m)	Δ (‰)
40°14′N, 70°55′W	130	+106 ± 12
40°06′N, 70°55′W	180	+109 ± 12
39°55′N, 70°35′W	460	+106 ± 15
39°49′N, 70°55′W	910	+112 ± 14
39°36′N, 70°55′W	2300	+99 ± 18
39°24′N, 70°55′W	2560	+109 ± 17
39°00′N, 70°55′W	2850	+136 ± 15
38°49′N, 70°56′W	2971	+145 ± 14
38°34′N, 70°55′W	3380	+164 ± 12

$\delta^{13}C = 0$ was assumed for Δ calculation.

Table 3. Carbon isotopic analyses of shells collected alive in Long Island Sound in the summers of 1975 and 1983.

Location & sample description	$\delta^{13}C$ (‰)	Δ (‰)
Morris Cove, New Haven, CT		
Mercenaria mercenaria		
date: 8/75	−1.4	+128 ± 13
Bradley Pt., West Haven, CT		
Modiolus demissus (Dillwyn)		
date: 8/21/83	+0.1	+115 ± 14
Crassostrea virginica		
date: 8/21/83	−1.8	+129 ± 13
Peabody Museum Marine Station, Guilford, CT		
Versella demissa		
date: 7/08/83	+0.2	+110 ± 10
Littorea		
date: 7/08/83	−0.5	+104 ± 12
Crassostrea virginica		
date: 7/08/83	−1.8	+135 ± 13
Black Pt., Old Saybrook, CT		
Mytilus edulis		
date: 7/08/83	+1.0	+99 ± 10
Harkness Memorial Park, New London, CT		
Littorina littorea		
date: 7/02/83	+1.3	+106 ± 13
Lordship Beach, Stratford, CT		
Mytilus edulis		
date: 7/22/83	−1.3	+105 ± 14
Noroton Pt., Stamford, CT		
Mytilus edulis		
date: 7/22/83	−2.2	+88 ± 14
Montauk Pt., NY		
Littorina littorea		
date: 11/12/83	+1.5	+112 ± 8

b. Contemporary DIC Δ for the northern Middle Atlantic Bight and the Sargasso Sea. The Δ (DIC) values of surface seawater collected on the "*Oceanus*" SEEP-01-08 expedition in late April, 1984 are plotted against latitude together with surface water temperatures in Figure 3. The shelf waters of this transect have a Δ of about +106, higher than LIS waters by about 10 per mil.

In the water sampled near the continental slope the Δ values increase seaward to +164 which compares well with surface water DIC in the Sargasso Sea for that time, based on extrapolation from the Bermuda coral data (Nozaki *et al.*, 1978). According

Table 4. Carbon isotopic analyses of historic seashells from the Peabody Museum of Natural History collection.

Sample description	^{13}C (‰)	Δ (‰)
A. Long Island Sound		
(1) *Geukensia elemissa* (Dillwyn)		
Site: Double Beach, Branford, CT		
Year: 1937	−0.2	−51 ± 18
(2) *Mercenaria mercenaria* (Linne)		
Site: Stonington, CT		
Year: 1935	+1.1	−77 ± 10
(3) *Ensisdirectus conrad*		
Site: West Haven, CT		
Year: 1922	−1.3	−96 ± 11
(4) *Crassostrea virginica*		
Site: New Haven, CT		
Year: 1881	+0.7	−75 ± 9
(5) *Mercenaria mercenaria* (Linne)		
Site: Long Island Sound		
Year: 1866	+0.1	−37 ± 15
(6) *Argopecten irradians* (Hamark)		
Site: Long Island Sound		
Year: 1866	−2.2	−94 ± 12
B. Gulf of Maine		
(7) *Arctica islandica*		
Site: Gulf of Maine (77 m depth)		
Year: 1878	*	−53 ± 7
(8) *Mercenaria mercenaria*		
Site: Quahog Bay, ME		
Year: 1873	*	−54 ± 7

*$\delta^{13}C$ = 0 ‰ is assumed for calculation of Δ values.

to surface water temperature and the satellite imaging of that area during the time of the expedition, there was then present a warm core ring of the Gulf Stream. We therefore use Gulf Stream as synonymous with Sargasso Sea based on the ^{14}C record. The sample taken at Provincetown (MA) has a high Δ which probably is due to the ephemoral effect of Gulf Stream water intrusion at the time of sampling.

c. Controls on the time variation of DIC Δ in the northern Middle Atlantic Bight. The sources of water to the Middle Atlantic Bight are the north (Gulf of Maine) and the Gulf Stream. The northern water itself represents upwelling deep water, ultimately probably dominated by Antarctic Intermediate Water (AAIW), and Sargasso Sea (or Gulf Stream) water. An integrated summary of transport and mixing of the major

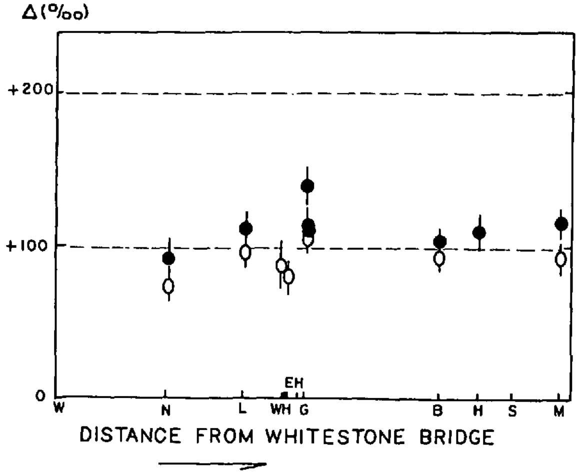

Figure 2. Geographical distribution of Δ values for clam shells captured in 1983 (●) and dissolved inorganic carbon in seawater (O) in 1983.

sources of water is given by Chapman *et al.* (1986) and a focus on slope water by Csanady and Hamilton (1988).

Along the way carbon dioxide exchange with the atmosphere also occurs. It can be shown that this effect as well as the effect of riverine input of carbon on the $\Delta^{14}C$ of the MAB is small. Based on the study by Chapman *et al.* (1986), an annual exchange of the shelf water is estimated to be 17.6×10^{12} cubic meters per year. Assuming 2 moles of total dissolved inorganic carbon (DIC) per cubic meter, 3.56×10^{13} moles of DIC per year is exchanged. An annual mean wind speed of 6 to 8 meters per second, characteristic of this region, translates to a sea-air exchange of carbon dioxide between 14 and 19 moles of carbon per square meter per year (Broecker *et al.*, 1985).

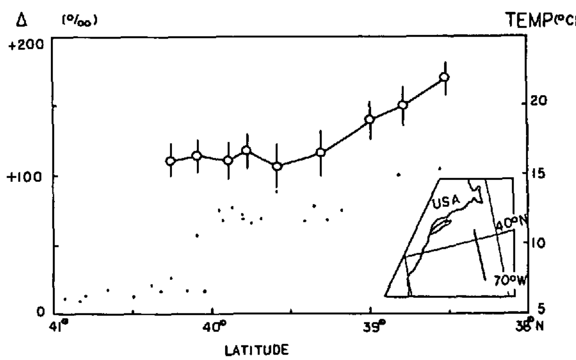

Figure 3. Distribution of Δ values of surface seawater DIC collected offshore in the Middle Atlantic Bight area as a function of latitude along the traverse shown in the inset (from Table 2). The points are surface seawater temperatures. A jump of the temperature around 40N shows a boundary between the inner and outer shelf water. The relatively larger Δ values observed between 39N and 38N are due to passage into warm core ring water.

Multiplying the area of the Mid-Atlantic Bight (1.1×10^{11} square meters) by the unit exchange rate, the annual carbon dioxide exchange rate obtained is $1.5\text{-}2.1 \times 10^{12}$ moles carbon per year, corresponding to only 5% of the exchange of carbon by water mixing alone. Indeed atmospheric exchange will tend to make the sample higher in $\Delta^{14}C$ than if exchange had not occurred. Therefore, omitting sea-air exchange of carbon dioxide in the following discussion does not diminish the strength of our conclusions. The riverine input of dissolved inorganic carbon in this region is negligible, less than 0.5% of the total exchange.

The variation over time of Δ of the western Sargasso Sea is recorded in the Bermuda coral analyzed by Nozaki *et al.* (1978). If we assume a simple mixing of Sargasso Sea water and upwelling water to make the northern source water entering the Middle Atlantic Bight, we can use the historic data to arrive at mixing proportions of the two endmembers as recorded in the Gulf of Maine in the pre-bomb, pre-industrial time.

The Δ for the primary upwelling water, Antarctic Intermediate Water, is presumed invariant over time. The highest value of this Δ must be less than or equal to the pre-1900 values observed in carbonate shells growing in the Middle Atlantic Bight area (including Long Island Sound). This means that Δ must be less than -90 (Table 4). The lower limit is set by the GEOSECS data (Stuiver and Ostlund, 1980) which do not permit values less than -120 at the latitude of the Middle Atlantic Bight.

We can calculate the mixing proportions of AAIW and Sargasso Sea water to form the water found in the Gulf of Maine. We first do this for a time prior to the major atmospheric perturbations of $^{14}C/^{12}C$ and we rely on historical calcareous test data. Δ for the two clams (*Arctica* from 77 meters depth and *Mercenaria* from considerably shallower depths) from the Gulf of Maine collected between 1873 and 1878 (Table 4), after corrections for a 13% terrestrial organic carbon contribution to the Δ of the shell as discussed, yields a Gulf of Maine water DIC Δ of -61 between about 1870 and 1878. (We use the 13% terrestrial organic contribution as a reasonable estimate although it may be lower in the Gulf of Maine relative to Long Island Sound for which the only reliable estimate has been made.) At the same time the Bermuda coral data (Nozaki *et al.*, 1978) indicate a Δ of -40. The ^{14}C composition of the Gulf of Maine water, as the result of mixing of the two water types is (converting the Δ value to the $^{14}C/^{12}C$ ratios relative to a standard):

$$\left(\frac{^{14}C}{^{12}C}\right)_S x + \left(\frac{^{14}C}{^{12}C}\right)_A (1 - x) = \left(\frac{^{14}C}{^{12}C}\right)_G \tag{3}$$

where the subscripts S, A and G refer to Sargasso Sea, AAIW, and Gulf of Maine respectively; and x is the fraction of Sargasso Sea water with $(1-x)$ being the fraction of AAIW.

If we use a Δ for AAIW of -90, the value of x is 0.6. If we use the extreme lower value for AAIW of -120, x becomes 0.75. Therefore the water in the Gulf of Maine has 25% to 40% Antarctic Intermediate Water.

If these propositions are valid for the present, we can predict the composition of contemporary northern shelf and slope water as reflected in the Gulf of Maine. In 1983 the Sargasso Sea had a Δ of +164. If Δ for AAIW is −90 then the Gulf of Maine Δ value for 60% Sargasso Sea and 40% AAIW would be +62 at the present time. If 75% Sargasso Sea and 25% AAIW with a Δ of −120 were the mixing endmembers, the Gulf of Maine in 1983 would have Δ = +93. As the sites closest to the Labrador Sea water presumably feeding the Gulf of Maine sampled by the TTO program have Δ values close to +50 (Broecker *et al.*, 1985), and two water samples from the Gulf of Maine sampled over an eight-month period yield an average value of +55 (personal communication, M. Kashgarian), we believe that the higher Δ (−90) for AAIW is most compatible with the results.

If we assume that the Middle Atlantic Bight and its arm, the Long Island Sound, itself is a mixture of water coming from the north (Gulf of Maine) and Gulf Stream water (characterized by the Sargasso Sea at Bermuda), we can calculate the proportions of each component in the Middle Atlantic Bight as a function of time.

Gulf of Maine water with Δ = +62 (corresponding to Δ = −90 for AAIW) mixes with Gulf Stream water (Δ = +164) to yield the mean value for Long Island Sound (Δ = +92) in 1983 in the proportions: 29% Gulf Stream water and 71% Gulf of Maine water.

Our calculation for the present day budget for the Middle Atlantic Bight implies that all supply of AAIW to the surface waters of eastern North America is effected north of the Middle Atlantic Bight. We now ask if there has been any indication of significant upwelling of AAIW into the Middle Atlantic Bight in the past.

We start by setting the Δ value of the Gulf of Maine waters as a function of time using the model of the mixing of 40% AAIW and 60% Sargasso Sea water. Prior to the sharp increase in atmospheric ^{14}C from nuclear bomb testing, the variations over time in Sargasso Sea surface water were more subdued, yet the Bermuda coral indicates that significant variations did occur in the past. Between about 1880 and 1950 the Suess effect is clearly imprinted on the Sargasso Sea. Prior to that time Nozaki *et al.* (1978) report variations in Δ that they ascribe to upwelling effects at Bermuda. These variations, whatever their causes, can be included in our modeling.

Table 5 shows the Δ values of Sargasso Sea water from the Bermuda coral data, calculated Gulf of Maine water, assuming 60% AAIW with Δ = −90, 40% Sargasso Sea, and Long Island Sound water inferred from shell data for specific time units between 1866 and 1983. Where Δ for Long Island Sound water is less than the Δ for both Sargasso Sea and Gulf of Maine water outside of analytical uncertainties, an additional source of low Δ water (AAIE) is required. These times are designated in Table 5.

These results indicate that AAIW was more aggressively supplied to the Middle Atlantic Bight prior to 1935 than since then. This could have occurred farther north by changing the mix of Sargasso Sea and AAIW in the Gulf of Maine. Of course it is

Table 5. Components of Long Island Sound (LIS) water over time based on $\Delta^{14}C$.

Collection Year in LIS w = water, s = shell	Long Island Sound Δ	Gulf Stream (a) Δ	Gulf of Maine (b) Δ	Type (See below)
1973 (7w)	−92 (±5)	+164	+62	I
1954 (ls, lw)	(−60 to −86)(c)	−58	−71	I
1935–1937 (2s)	−70 (±10)	−38	−59	I
1922 (1s)	−106 (±10)	−30	−54	II
1880 (1s)	−80 (±10)	−40	−60	II
1866 (2s)	−70 (±10)	−45	−63	I

Type I Can be explained by a mixture of Gulf of Maine and Gulf Stream waters.
Type II Cannot be explained by a mixture of Gulf of Maine and Gulf Stream waters. Requires low Δ water in addition—probably AAIW.

Notes: (a) From the $\Delta^{14}C$ record in a Bermuda coral (Nozaki *et al.*, 1978).
(b) Estimated values from box model described in text.
(c) Values for mollusc shell (terrestrial carbon corrected) and water, respectively, from Broecker and Olson (1959).

conceivable that general upwelling was higher along the entire eastern seaboard north of Cape Hatteras. For the past fifty years the water in the northern Middle Atlantic Bight, at least, can be interpreted as the result of different degrees of mixing of Gulf of Maine water (with a 60% Sargasso Sea/40% AAIW) and Sargasso Sea water only. A water mass, however, with AAIW-like characteristics along the 27.0 isopycnal plane was identified in upper slope water in early spring and summer in 1984–1985 during the Mid-Atlantic Slope and Ridge (MASAR) experiment by Csanady and Hamilton, (1988), indicating the supply of AAIW directly into the MAB.

4. Summary and conclusions

1. Long Island Sound (LIS) water in the early 1980's had a Δ of +92 intermediate between estimated value of +62 in its northern source water (Gulf of Maine) and +164 for Gulf Stream (or Sargasso Sea) water.

2. Shells of molluscs younger than two years of age collected from LIS simultaneously with the water collection yielded a mean Δ = +110, significantly more positive than LIS water. We ascribe the difference to the shell containing 13% of its carbon from metabolized terrestrial organic matter. Using this information dated shells in collections can be used to determine the Δ of coastal water at a given time from the Δ of the shell.

3. Gulf of Maine (GM) water Δ in 1870–1878 was about −61 from shell data and Sargasso Sea (SS) water from Bermuda coral data was −40. If we assume that the light carbon-imprinted water needed to dilute the Sargasso Sea water is Antarctic Intermediate Water (AAIW) with Δ = −90, then the proportion of SS and AAIW

needed to make GM water is 60% and 40% respectively. This proportion is effected north of Cape Cod at a variety of sites proceeding southward from the Labrador Sea.

4. The mechanism of the occasional introduction of ^{14}C-poor water is uncertain but upwelling of AAIE into slope water with subsequent incursion to the sites of sampling may have occurred either in the Gulf of Maine or in the Middle Atlantic Bight.

5. If the proportion of AAIW and SS waters composing GM is maintained over time, the proportion of northern water (GM) to SS water composing the water of the northern part of the Middle Atlantic Bight (MAB) including LIS, can be inferred from shells collected and preserved with known dates of collection.

6. Some dated shells show Δ values lower than either of the putative endmembers of the mixing waters. The explanation for this is that enhanced upwelling has occurred either in MAB or in the Gulf of Maine at these times. The periods, from our few data, when enhanced upwelling is required either in the Gulf of Maine or the Middle Atlantic Bight, are 1880 and 1922. Only a detailed study of dated shells from both the Gulf of Maine and the Middle Atlantic Bight (including Long Island Sound) can certify and extend this observation. The data are still too few to seek for correlations with the observed upwelling pattern recorded by the 200-year coral from Bermuda.

Acknowledgments. We thank D. M. Rye and P. Dixon for guidance and assistance in the $\delta^{13}C$ measurements. B. Shaw and M. Kashgarian assisted in collections and radiocarbon measurements. P. Biscaye and M. Bacon helped one of us (N.T.) in the collection of samples on the SEEP expedition. W. D. Hartman of Peabody Museum allowed us access to the shell collections. Ellen R. N. Druffel and R. G. Fairbanks read an earlier draft of this paper and their comments, as well as those of others, significantly changed this paper. The geochemistry coffee group was, as usual, patient and helpful during the many iterations of this paper. Four anonymous reviewers significantly contributed to the improvement of the paper. The study was part of the SEEP program and was supported to a large degree by the U.S. Department of Energy through grant DE-ACO2-76EV13573 to K. K. Turekian, Principal Investigator.

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Received: *23 June, 1986;* revised: *2 October, 1989.*