Structure and Origin of 18°C Water Observed during the POLYMODE Local Dynamics Experiment*

CURTIS C. EBBESMEYER**

Evans-Hamilton, Inc., Seattle, WA 98115

ERIC J. LINDSTROM***

School of Oceanography, University of Washington, Seattle, WA 98195

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ABSTRACT

Two distinct types of 18°C water (Subtropical Mode Water) were observed during the POLYMODE Local Dynamics Experiment (LDE; May–July 1978; 31.0°N, 69.5°W). These were revealed on isopyncals by salinity histograms which were bimodal. Salinity was highly correlated with oxygen, vortex stretching, and 17.5°–18.5°C thickness. The correlations are positive between salinity and both oxygen and thickness, and negative between salinity and vortex stretching. The origins of the two water types are deduced using a variety of measurements in the Sargasso Sea including apparent oxygen utilization, vortex stretching, and salinity. It is found that the modes were formed approximately 16 months prior to the LDE during the severe winter of 1976/77. Sharp horizontal salinity gradients between the two LDE water types are comparable to those observed more than a year earlier, and the spatial scale (~100 km) of the regions of saline mode water is smaller in the LDE than immediately after the 1976/77 winter (~200 km). These observations suggest that the characteristics of newly formed 18°C water may persist for several years despite strong mesoscale stirring in the Gulf Stream Recirculation Zone.

1. Introduction

In the North Atlantic Ocean convective overturning in winter forms a water mass between approximately 33°N and the Gulf Stream, and west of 45°W (Fig. 1; Worthington, 1972a). The water mass is known as 18°C water (hereafter 18° water; Worthington, 1959), or Subtropical Mode Water (Masuzawa, 1969; Warren, 1972; McCartney, 1982), and is characterized by a thermostad (Seitz, 1967) located between the seasonal and main thermoclines (Istoshin, 1961; Worthington, 1976). The vertical position of the 18° water has been examined as a function of potential density by identifying the minimum in the vortex-stretching component of potential vorticity (hereafter, vortex stretching; McCartney, 1982; Talley and Raymer, 1982). The density range embracing the 18° water varies with location and on time scales of years to decades (McCartney, 1982; Jenkins, 1982a; Talley and Raymer, 1982). This paper examines the structure and origin of 18° water observed during the POLYMODE Local Dynamics Experiment. To determine the origin it was necessary to reexamine ancillary data from cruises made at other times and locations.

The LDE was carried out during May–July 1978 slightly south of the 18° water formation area. Many results of the LDE have been summarized by Owens et al. (1982), McWilliams et al. (1983), Shen et al. (1986), and Taft et al. (1986). During the LDE, hydrographic stations were obtained within a 100-km radius of 31.0°N, 69.5°W. While computing statistics of salinity on isopycnals in the upper two kilometers of ocean, it was discovered that some histograms of salinity had two distinct modes and that this occurred only in the 18° water (Fig. 2a). The implications of these modes are the main theme of this paper.

It will be shown that the two salinity modes originated more than a year earlier during the particularly severe winter of 1976/77. During that winter, 18° water is known to have been formed (Leetmaa, 1977; Worthington, 1977). Worthington (1972a,b) suggests that cold air from the North American continent drives the heat loss from the Sargasso Sea south of New England which results in the formation of this water mass. An indication of the severity of the 1976/77 winter is given by Diaz and Quayle (1978) who computed average winter air temperatures in the New England region. By extending their calculations through 1980 they (Quayle, personal communication, 1983) found that

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* Contribution 1612 from the School of Oceanography, University of Washington, Seattle, WA 98195.

** Also affiliated with the Marine Sciences Research Center, State University of New York at Stony Brook, NY 11794.

*** Present address: CSIRO Marine Laboratories, GPO Box 1538, Hobart, Tasmania 7001, Australia.

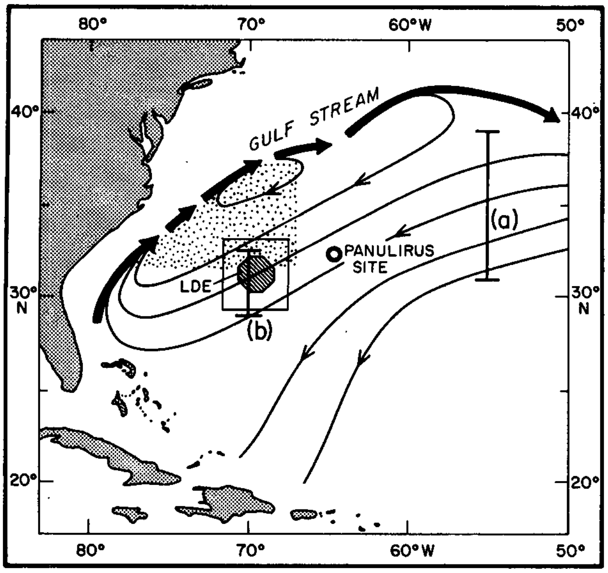

FIG. 1. Location of the POLYMODE Local Dynamics Experiment (LDE) and ancillary data superimposed on Worthington's (1976) circulation diagram for water warmer than 17°C in the Gulf Stream Recirculation Zone (arrows, lines). Notation: (hatched octagon) LDE; (stipple) northwestern Sargasso Sea survey during 30 March–14 April 1977; (box) 1954–78 historical data from the 4° square centered on the LDE; [bar (b)] section along 70°W made during 5–14 April 1977; circle, *Panulirus* site; and [bar (a)] sections along 55°W made during 10–19 October 1976 and 30 June–6 July 1977.

the value for December 1976–February 1977 was the eighth lowest during 1895–1980, and the lowest since 1934. The causes of the severe winter are discussed elsewhere by Namias (1978).

2. Methods

a. LDE Data

The LDE data consist of profiles of temperature, salinity, and dissolved oxygen at 2.5-db pressure intervals. These were obtained using a Neil Brown conductivity–temperature–pressure/depth (CTD) system fitted with a dissolved oxygen sensor. Calibration of the observations is described by Taft et al. (1986). The present analysis utilizes 382 CTD profiles which were obtained in seven surveys of the LDE region. Each survey lasted about a week and consisted of 48–57 profiles made on a nearly uniform grid with 25-km spacing.

Values of pressure, salinity, and dissolved oxygen were linearly interpolated to particular potential densities (σ_θ) referenced to 0 db; hereafter units of kg m^{-3} for potential density have been deleted. On the average, the selected isopycnals are spaced at 25-db intervals. The interpolated values have been plotted on isopycnals, and for convenience placed at their mean pressures. Vortex stretching on isopycnals,

$$\frac{f}{1+\sigma_\theta}\frac{\partial \sigma_\theta}{\partial z},$$

(where f is the Coriolis parameter, and z is depth reckoned positive downwards) was computed by differencing the depth and potential density between the isopycnals immediately above and below a selected isopycnal. This quantity is conserved following the flow assuming that relative vorticity and mixing are negligible. The derivation of this quantity and its significance with respect to the North Atlantic general circulation are discussed by McDowell et al. (1982). Because vortex stretching is only one component of potential vorticity,

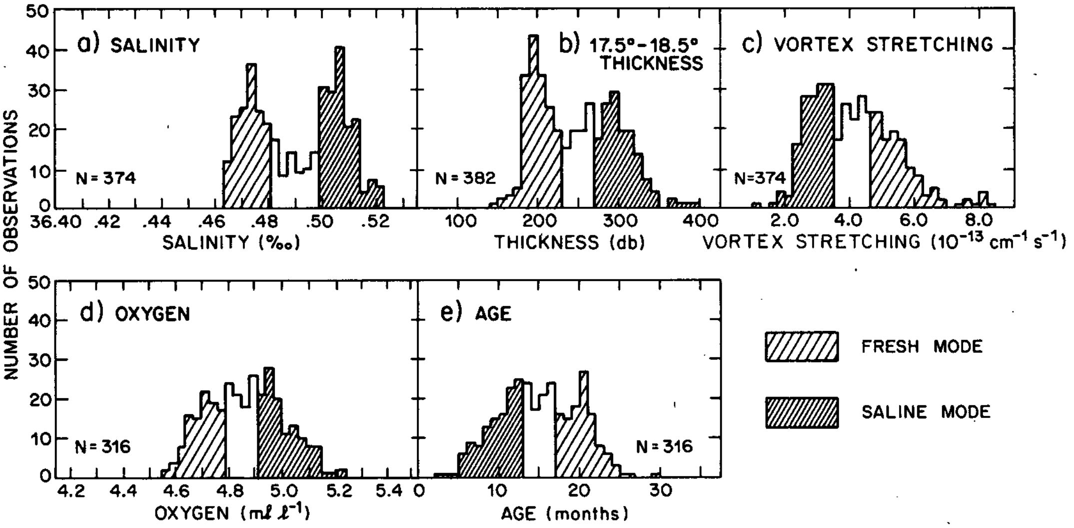

FIG. 2. Histograms of the LDE data at the core of the 18° water: (a) salinity; (b) 17.5°–18.5°C layer thickness; (c) vortex stretching; (d) dissolved oxygen; and (e) age. Hatched areas denote fresh and saline modes (see code at lower right), N is the sample size. Histograms for (a), (c)–(e) are on $\sigma_\theta = 26.43$.

it is not used in this analysis as a conservative Lagrangian tracer. Rather, it is used as an indicator of water mass structure at particular times.

In addition to salinity, oxygen, and vortex stretching on isopycnals, the pressure difference between two isotherms (17.5°C and 18.5°C) was also examined because it is a useful indicator of 18° water thickness, especially where temperature data are available only from expendable bathythermographs.

b. *Ancillary data*

To interpret the LDE observations, ancillary data were reexamined because previous analyses have not focused on the particular isopycnal of interest in this paper. The ancillary data are (see Fig. 1 for locations):

Northwestern Sargasso Sea—a hydrographic survey of the northwestern Sargasso Sea during 30 March–14 April 1977 was conducted by Leetmaa (1977) and Worthington (1977).

4° square—historical hydrographic observations were obtained within the 4° square centered on the LDE for the period 1954–78 from the National Oceanographic Data Center.

70°W section—CTD profiles along 70°W between approximately 29°–33°N during 5–14 April 1977 were obtained by Ebbesmeyer et al. (1986).

Panulirus site (32.2°N, 64.5°W)—hydrographic casts were made during 1954–78, usually once or twice per month.

55°W sections—hydrographic data along 55°W between approximately 31°–39°N during 10–19 October, 1976 and 30 June–6 July 1977 were obtained by McCartney et al. (1980).

3. Results

Analysis of the 18° water can be simplified if the variability on a single isopycnal is representative of the entire water mass. In the following sections this is demonstrated for the LDE data by first defining the vertical extent of the 18° water, and then examining salinity anomaly histograms and relationships of properties with one another. As a result the origin of the two modes is investigated on a single isopycnal ($\sigma_\theta = 26.43$).

a. *Vertical extent of the 18° water*

Vertical profiles of vortex stretching have previously been used to define the location of 18° water (Talley and Raymer, 1982; McCartney, 1982). The profiles often show a density range of low vortex stretching coincident with the 18° water. Minimum values indicate where the 18° water is most isolated from the influences of the seasonal and main pycnoclines.

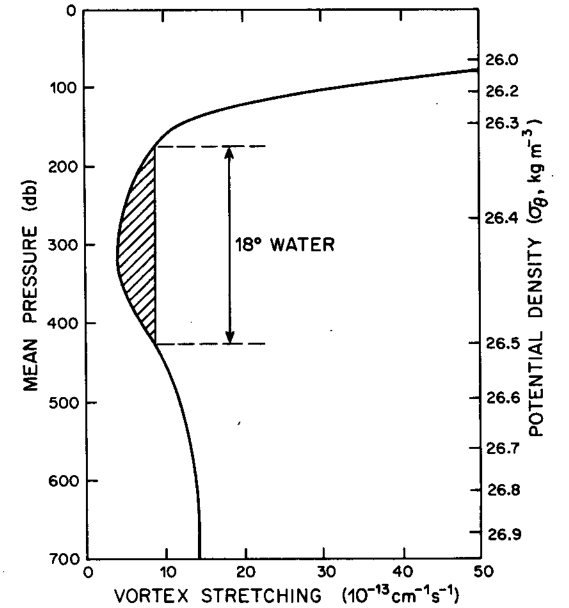

FIG. 3. Mean profile of vortex stretching versus potential density for the LDE data. Hatched area indicates pressure and density ranges of the 18° water.

The vertical profile of mean vortex stretching was computed for all LDE data (Fig. 3). In the seasonal pycnocline values in excess of 50×10^{-13} cm^{-1} s^{-1} are found at densities less than $\sigma_\theta = 26.08$. The lowest average vortex stretching (4.1×10^{-13} cm^{-1} s^{-1}) occurs at $\sigma_\theta = 26.43$. At greater densities the vortex stretching again increases, reaching a maximum value of 14.9 $\times 10^{-13}$ cm^{-1} s^{-1} at $\sigma_\theta = 27.35$ in the main pycnocline. The 18° water lies in a density range centered about the vortex stretching minimum. The lower limit of this range is chosen at the top of the main pycnocline where there is an inflection point of vortex stretching. The upper limit was taken at the same value of vortex stretching. With this definition the 18° water lies in the density range of 26.33–26.51 where the vortex stretching is less than 8.7×10^{-13} cm^{-1} s^{-1}. In other words, on the average, the 18° water lies in the pressure range of 175–425 db, with its core at 325 db ($\sigma_\theta = 26.43$).

b. *Vertical structure of 18° water*

Jenkins (1982a) found significant correlations between salinity, oxygen, and stability in the 18° water at the *Panulirus* site. For the LDE data, linear regressions were computed between salinity and oxygen, vortex stretching, and 17.5°–18.5°C thickness. Figure 4 shows vertical profiles of the correlation coefficient (r) between salinity and the three other properties. In the 18° water the correlations are high and significant at the 95% confidence level, except in the upper portion of the 18° water for salinity versus vortex stretching where the correlation coefficient changes sign. Near the 18° water core the correlations are near their highest magnitudes (0.7–0.8). The vertical profiles of the slopes

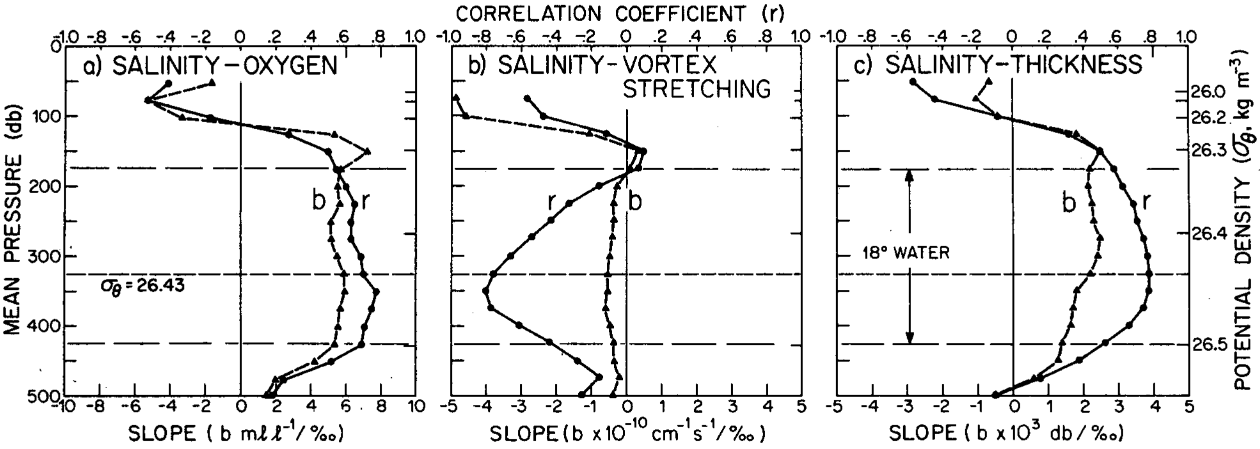

FIG. 4. Vertical profiles of the correlation coefficient (*r*, dots) and slope (*b*, triangles) from linear regressions of LDE data: (a) salinity versus oxygen; (b) salinity versus vortex stretching; (c) salinity versus 17.5°C–18.5°C thickness. Salinity, oxygen, and vortex stretching are computed on isopycnals.

of the linear regressions are also shown in Fig. 4. In the 18° water, the slopes are reasonably uniform. The high correlation and the uniformity of the slopes suggests that a single isopycnal ($\sigma_\theta = 26.43$) can be used to represent the 18° water.

The regressions and data are shown in scatter diagrams for the isopycnal at the 18° water core (Fig. 5). It is evident that the observations are clustered about two salinities; the histogram of salinity most clearly shows the bimodality (Fig. 2a). The high correlations

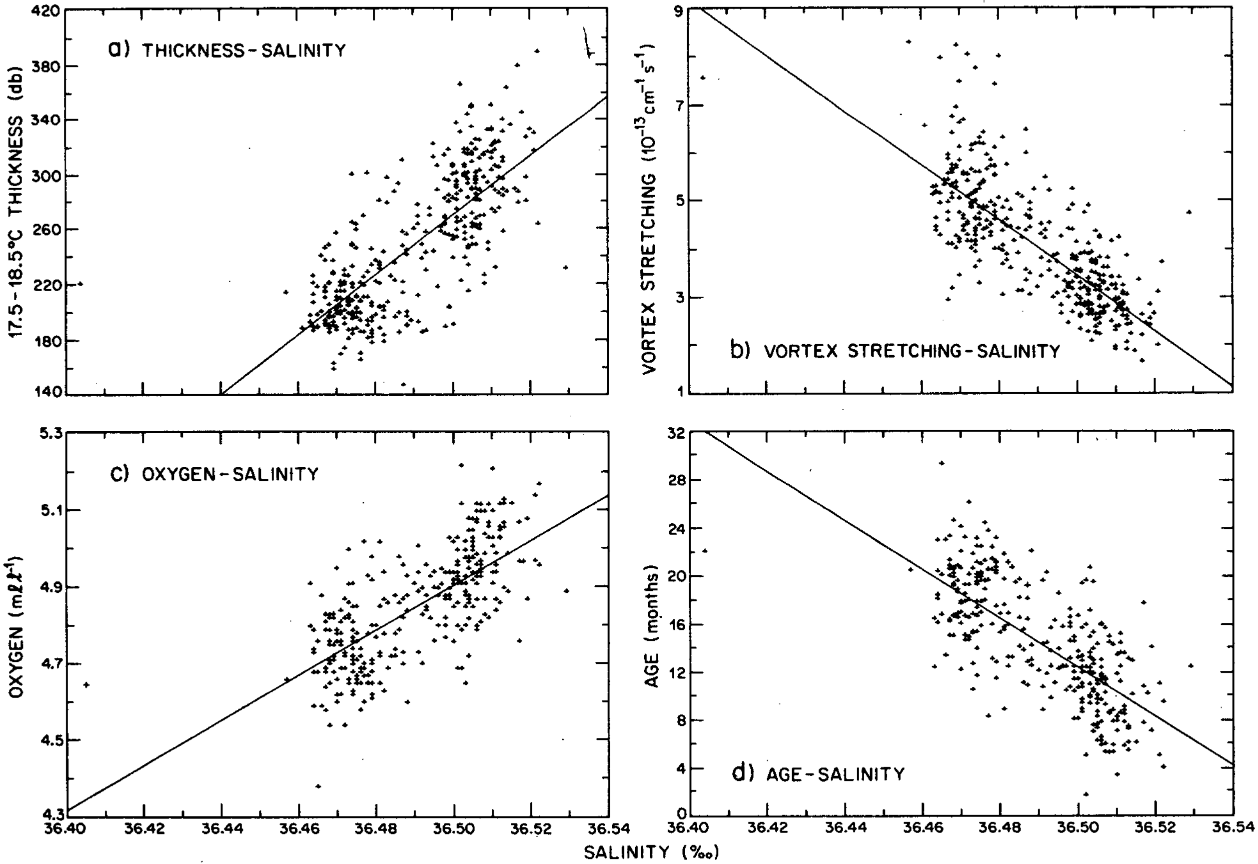

FIG. 5. Scatter diagrams from LDE data at the core of the 18° water: (a) 17.5°–18.5°C thickness versus salinity; (b) vortex stretching versus salinity; (c) oxygen versus salinity; (d) age versus salinity. Salinity, oxygen, and vortex stretching are computed on σ_θ = 26.43. Lines in each panel represent linear regressions.

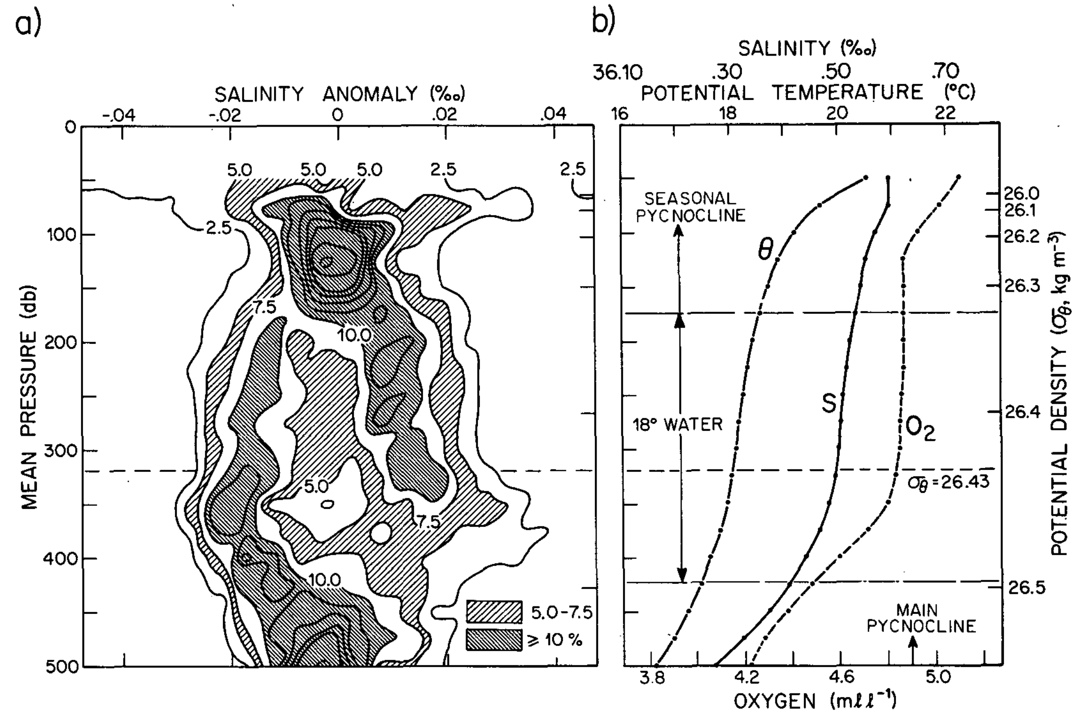

FIG. 6. (a) Relative frequency of salinity anomalies on isopycnals from LDE data contoured at 2.5% intervals. Codes for hatched areas are shown at lower right. (b) Mean profiles of potential temperature (θ), salinity (S), and dissolved oxygen (O_2) versus potential density.

between properties suggests that the bimodality might be seen in histograms of 17.5°-18.5°C thickness, vortex stretching, and oxygen (Fig. 2b-d). However, only for 18° water thickness is the bimodality also evident.

It can be further established, by a comparison of salinity histograms on different isopycnals, that the salinity bimodality is present throughout the 18° water. For this comparison, it was desirable to eliminate the effects of the mean salinity profile by examining anomalies. A departure from the mean, or anomaly, is defined as $\delta S = S - \bar{S}$, where S is the individual observation, $\bar{S}$ is the mean of all the LDE observations, and all values are on a selected isopycnal.

The relative frequency of salinity anomalies was examined in the density range between the seasonal and main pycnoclines (Fig. 6). Throughout the 18° water where the mean vertical gradients of temperature, salinity, and oxygen are weak (Fig. 6b), there are two maxima (or modes) of relative frequency. At the core of the 18° water, the salinity difference between the two modes is larger than on any other isopycnal.

An interesting feature of Fig. 6a is the connection of the modes with the seasonal and main pycnoclines. The mean salinity profile (Fig. 6b) indicates that diapycnal mixing would tend to produce positive salinity anomalies at the transition between 18° water and the seasonal pycnocline, and negative anomalies between 18° water and the main pycnocline. It appears that diapycnal mixing may explain the connection between the saline mode and the prominent maximum in the seasonal pycnocline, and the connection between the fresh mode and the frequency maximum at the top of the main pycnocline.

Even though there is some evidence for diapycnal mixing of salinity in the upper and lower portions of the 18° water, there is other evidence, presented later, that these effects are small at the 18° water core. In this analysis, salinity will be traced along the isopycnal at the 18° water core neglecting the effects of diapycnal mixing.

The characteristics of the modes may be summarized using the regressions of salinity with the various properties. This is illustrated by the shading of the histograms in Fig. 2. The inner boundaries were computed from those in the salinity histogram and the linear regressions. The properties associated with the peaks of the salinity modes are listed in Table 1. The saline mode is accompanied by lower vortex stretching, higher

TABLE 1. Characteristics of the two LDE salinity modes on the isopycnal $\sigma_\theta = 26.43$.

	Mode	
Variable	Fresh	Saline
Salinity (‰)	36.473	36.506
Oxygen (ml l^{-1})	4.74	4.93
Vortex stretching (10^{-13} cm^{-1} s^{-1})	5.11	3.22
17.5°-18.5° thickness (db)	211	282
Age (months)	19.1	12.3

oxygen, and larger 17.5°–18.5°C thickness, whereas the fresh mode is accompanied by higher vortex stretching, lower oxygen, and smaller 17.5°–18.5°C thickness.

c. Horizontal structure of the 18° water

To gain an understanding of the spatial distribution of the water in the two modes, maps of salinity were prepared on $\sigma_\theta = 26.43$ from the LDE data (Fig. 7). The maps were hand-contoured and the modes were distinguished by shading salinities less than 36.48‰ (fresh mode) and greater than 36.50‰ (saline mode). The mesoscale variability of the two modes is characterized by homogeneous regions separated by sharp gradients. This was expected from the bimodal distributions because the gradient regions correspond to the gap between the two modes in the histogram (Fig. 2a). The gradients persist as continuous features for distances of 200 km and have a typical strength of 0.02‰ in a distance of 20 km. The regions of relatively homogeneous fresh, or saline mode waters persist for distances of 100 km but the salinity variations are less than 0.02‰. This structure will be compared with that observed after the winter of 1976/77 in subsequent discussion.

4. Time of origin

In the previous section it was shown that the LDE property variability on $\sigma_\theta = 26.43$ has a number of unique characteristics with respect to other isopycnals in the 18° water: 1) mean vortex stretching was minimal; 2) correlations between salinity, oxygen, vortex stretching, and 17.5°–18.5°C thickness were all large and near their maxima; and 3) the salinity histogram was most strongly bimodal. Because of this combination of features, the origin of the salinity modes was sought by investigating the variability of 18° water on this isopycnal at other times and locations.

The winter in which the two modes were formed can be deduced using apparent oxygen utilization (AOU; Redfield, 1942) computed from the LDE data and an apparent oxygen utilization rate (AOUR). AOU is the difference in oxygen concentration within a water parcel from its value at 100% saturation. An estimate of the time (age) since saturation, i.e., when the parcel obtained its characteristics during exposure to the atmosphere, may be computed if the AOUR is known (age = AOU/AOUR). Jenkins (1980) has estimated AOUR at various depths in the Sargasso Sea, thus providing the necessary information to estimate the age of the modes.

The age calculation was made using AOUR = 0.36 ml l^{-1} yr^{-1} as obtained by interpolating Jenkins's (1980) data[1] to the mean depth (325 m) of $\sigma_\theta = 26.43$ in the LDE data. Since the LDE spanned a two month period the ages were corrected to a common time, taken as 1 June 1978. Figure 2e shows the histogram of age and Fig. 5d shows the scatter diagram of salinity versus age. Utilizing the linear regression of salinity versus age (Fig. 5d), it was found that the two modes have approximate ages of 12 months (saline mode) and 19 months (fresh mode).

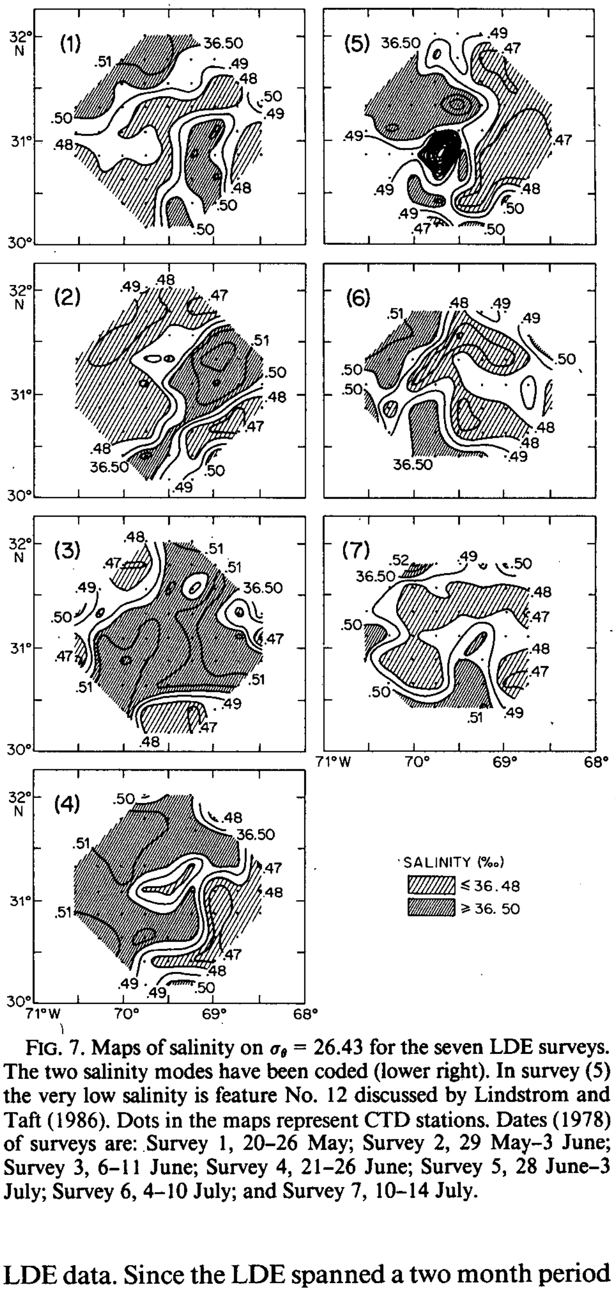

FIG. 7. Maps of salinity on $\sigma_\theta = 26.43$ for the seven LDE surveys. The two salinity modes have been coded (lower right). In survey (5) the very low salinity is feature No. 12 discussed by Lindstrom and Taft (1986). Dots in the maps represent CTD stations. Dates (1978) of surveys are: Survey 1, 20–26 May; Survey 2, 29 May–3 June; Survey 3, 6–11 June; Survey 4, 21–26 June; Survey 5, 28 June–3 July; Survey 6, 4–10 July; and Survey 7, 10–14 July.

There is substantial uncertainty in the age calculation because of questions regarding the AOUR values (Jenkins, 1980). Since the pathway is unknown between the modes, place of origin and the LDE site, the AOUR values may have changed over time. The value of AOUR used herein was determined from estimates in the 18° water alone and is considerably larger than the AOUR value (0.17 ml l^{-1} yr^{-1}) obtained from a regres-

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[1] Some of the AOUR values given by Jenkins (1980) were misprinted. The correct values are: AOUR = 0.10 ml l^{-1}/yr at $\sigma_\theta = 26.5$; and AOUR = 0.094 ml l^{-1}/yr at $\sigma_\theta = 26.6$.

sion of AOUR estimates versus depth (Jenkins, 1982a,b). The smaller value is heavily weighted by AOUR estimates in the main pycnocline and is inappropriate for the present age calculation (Jenkins, personal communication, 1983). However, it is sufficient that the age calculation distinguish a particular winter because that is the only time in which 18° water can be formed. The ages since the three winters prior to the LDE are: 4 months since the 1977/78 winter; 16 months since the 1976/77 winter; and 28 months since the 1975/76 winter; where the ages equal the time since the midpoint of each winter taken as 1 February. The LDE age calculations lie within 3–4 months of the central date for the 1976/77 winter and thus indicate this as the most probable time of formation.

To confirm the age calculation, time series of salinity, AOU, and vortex stretching were examined on $\sigma_\theta = 26.43$ at the *Panulirus* site during 1975–78 (Fig. 8). Because this site is immediately upstream from the LDE and downstream from portions of the 18° water formation area (Fig. 1), changes in 18° water seen there should be representative of those seen at the LDE. To check this contention annual averages of salinity on $\sigma_\theta = 26.43$ were computed for the *Panulirus* site and from the historical hydrographic data in the 4° square centered on the LDE (Fig. 9). Since both time series show comparable fluctuations, the *Panulirus* data are considered to be representative of the LDE for the present purposes.

In the *Panulirus* time series, the properties characteristic of the two modes were not apparent prior to the 1976/77 winter. However, shortly afterward the low AOU values indicated that the isopycnal had been recently ventilated, and the modal values of salinity and vortex stretching were first observed. The isopycnal apparently was not ventilated during the 1977/78 winter since the AOU values did not show an appreciable decrease after that winter. Therefore, taken together, the age calculations and the *Panulirus* time series both indicate that the modes seen in the LDE originated during the winter of 1976/77.

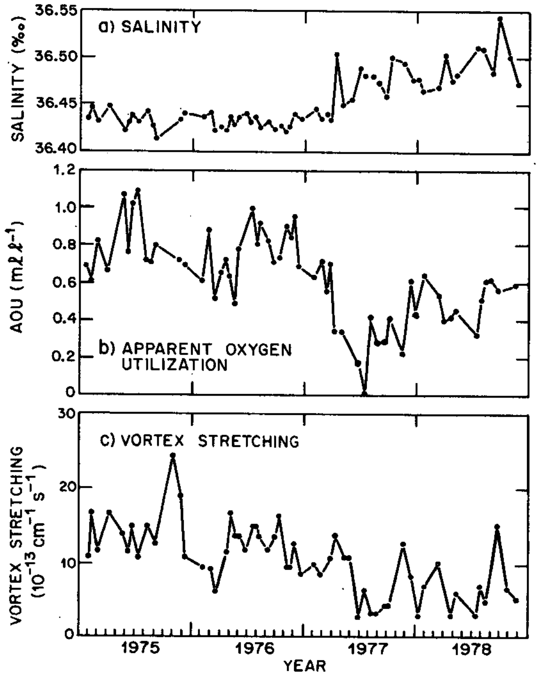

FIG. 8. Time series on $\sigma_\theta = 26.43$ at the *Panulirus* site: (a) salinity; (b) apparent oxygen utilization; (c) vortex stretching. Each dot represents values obtained from a hydrographic station.

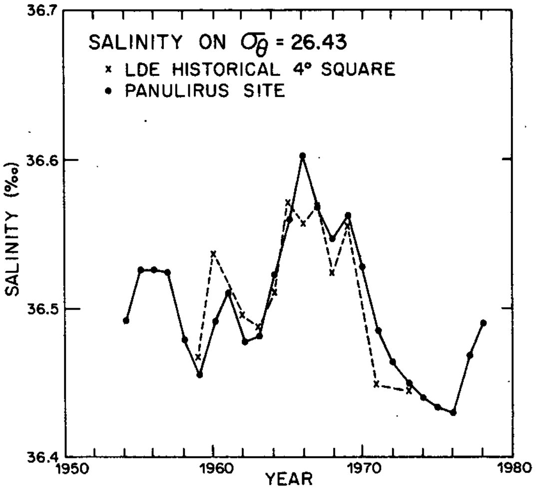

FIG. 9. Annual average salinity on $\sigma_\theta = 26.43$ at the *Panulirus* site (solid) and 4° square centered on the LDE (dashed).

5. Spatial distribution of modal salinities

It has been established that the scalar characteristics of the two 18° water modes of the LDE originated during the winter of 1976/77. However, the observed spatial homogeneity within each mode may have occurred at a later date by horizontal mixing or may be a relic of the formation process. To examine the evolution of the horizontal structure, observations made after the 1976/77 winter were searched for evidence of relatively homogeneous salinity modes on $\sigma_\theta = 26.43$.

Salinity modes in the ancillary data were defined by criteria established by the LDE mapping. That is, a salinity mode had a range of salinity less than 0.02‰ over a horizontal distance in excess of 100 km. The choice of a maximum salinity range within a mode is based qualitatively on the histogram of salinity from the LDE (Fig. 2a); the range is approximately 0.02‰ for both fresh and saline modes. That the salinity modes of the LDE are relatively homogeneous over horizontal scales of ~100 km is apparent qualitatively by inspection of Fig. 7.

To assess the horizontal scale quantitatively, Shen et al. (1986) computed the covariance of salinity versus horizontal lag on an isopycnal ($\sigma_\theta = 26.42$) nearly identical to the one on which salinity has been mapped in this paper ($\sigma_\theta = 26.43$). The covariances were averaged over the seven LDE surveys and over all direc-

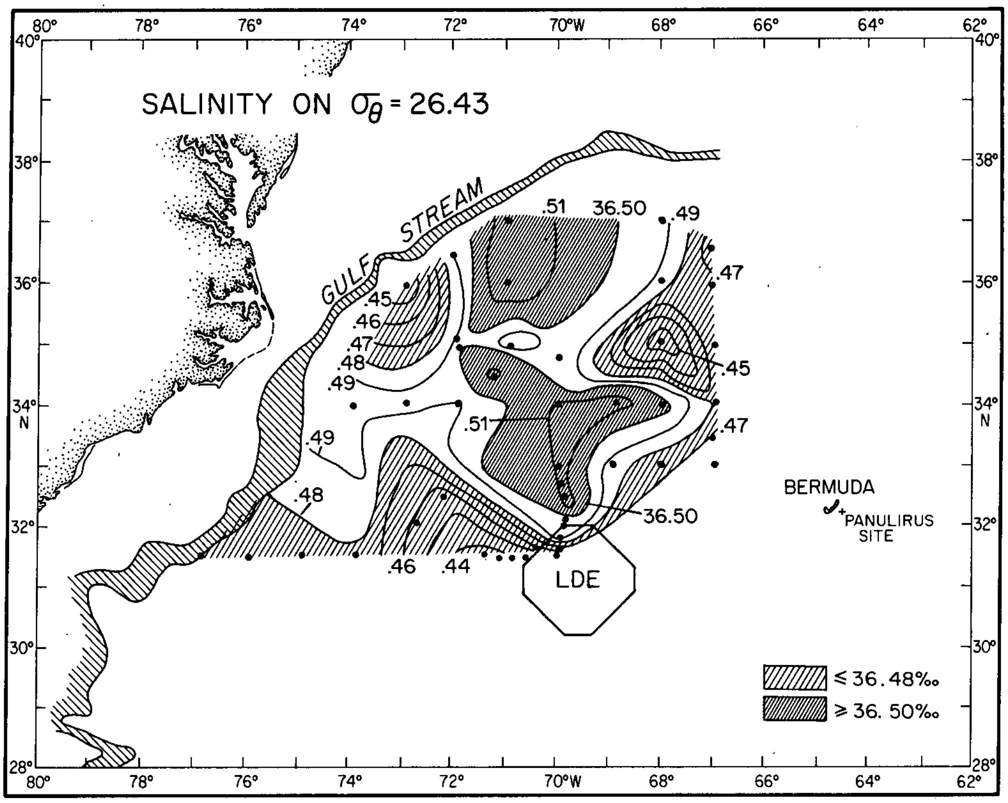

FIG. 10. Salinity (‰) in the northwestern Sargasso Sea on $\sigma_\theta = 26.43$ during 30 March–14 April 1977. Dots indicate locations of hydrographic data from Leetmaa (1977), Worthington (1977), and Ebbesmeyer et al. (1986). Also shown are the locations of the LDE and the *Panulirus* site. The hatched areas correspond to salinities in the fresh and saline LDE modes (see code at lower right). Gulf Stream position (also hatched) from the U.S. Dept. of Commerce/NOAA (1977).

tions. The result showed that the covariance decreased by approximately half at a lag of 50 km, and was near zero at 100 km. Thus for the present purposes a region will be considered homogeneous on an isopycnal and a salinity mode if it has a salinity range of less than 0.02‰ over a distance of at least 100 km. With this criterion salinity modes were sought in three ancillary datasets: over the northwestern Sargasso Sea; along 55°W; and at the *Panulirus* site.

A map of salinity on $\sigma_\theta = 26.43$ was constructed for the northwestern Sargasso Sea from observations made during a fortnight shortly after the 1976/77 winter (30 March–14 April 1977; Fig. 10). Because the horizontal sampling interval exceeded the distance criterion (100 km) over most of the map, only larger-scale homogeneous regions could be detected. Nevertheless there is one region which meets the criterion and has a scale of approximately 200 km. It is the more southerly region of 18° water with salinity identical to the saline mode of the LDE. 18° water is known to have been formed on this isopycnal during the 1976/77 winter (Leetmaa, 1977; Worthington, 1977). Moreover, vortex stretching in the southern region is nearly identical to that of the LDE saline mode (2.5×10^{-13} cm^{-1} s^{-1}; Fig. 11). The meridional section of vortex stretching shown in Fig. 11 was constructed from CTD casts and shows the southern portion (32°–33°N) of the southern homogeneous region. Therefore, neglecting circulation, the saline mode could have originated north of the LDE.

Another location to examine for salinity modes is suggested by the age of the LDE modes and Worthington's (1976) circulation diagram (Fig. 1). The origin for the LDE mode waters was estimated by scaling the distance that a water parcel would have traveled along the diagram to reach the LDE. The distance equals the age (16 months) multiplied by a representative speed, taken as 4 cm s^{-1}. This is the speed estimated by Talley and Raymer (1982) for the advection of 18° water in the 1000 km upstream of the *Panulirus* site. It is also approximately equal to the mean speed at 300 m depth near the 18° water core obtained from a year of direct current measurements in the LDE (1978–79; 4.6 cm s^{-1} toward the southwest; Owens et al., 1982; McWilliams, 1983). The result places a possible origin in the vicinity of the observations made along 55°W.

The observations at 55°W were made three months after the 1976/77 winter and were interpolated to $\sigma_\theta = 26.43$ (30 June–6 July 1977; Fig. 12). Between 36.8° and 38.3°N the salinities lie in the range of 36.48–

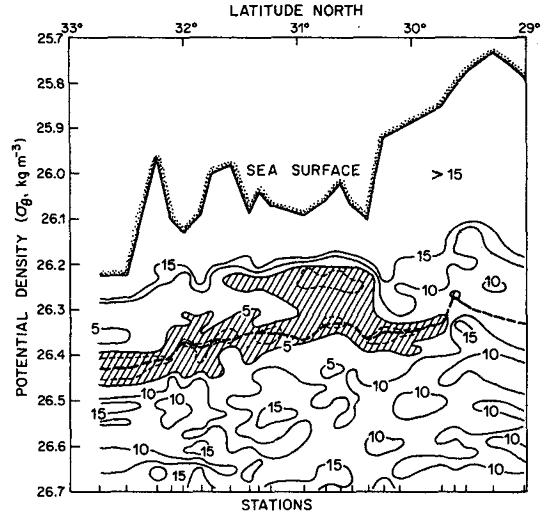

FIG. 11. Meridional section of vortex stretching along 70°W during 5–14 April 1977. Three contours are shown: 5, 10 and 15 ($\times 10^{-13}$ cm^{-1} s^{-1}). The hatched area denotes values less than 5×10^{-13} cm^{-1} s^{-1} and the lighter dashed lines surround regions where the vortex stretching is less than 2.5×10^{-13} cm^{-1} s^{-1}. The heavier dashed line intersects the lowest vortex stretching at a given latitude.

36.50‰ and meet the criteria for modes. Comparable homogeneity is also found between 35.1° and 35.8°N, but the horizontal scale (80 km) is somewhat shorter than our criterion. Previous analysis of these data indicates that the homogeneous regions were formed during the 1976/77 winter (Talley and Raymer, 1982). Between these saline regions and farther south there are lower salinities (~36.43‰) which, as shown later, are indications of water characteristics formed prior to the 1976/77 winter.

To detect homogeneous regions at the *Panulirus* site the distance criterion was divided by the advective speed noted earlier (4 cm s^{-1}). This yields a time interval of approximately a month in which salinity must fluctuate by less than 0.02‰ in order for a homogeneous region to have been evident. In Figure 8a there are three intervals lasting one to three months between the 1976/77 winter and the time of the LDE in which the salinity fluctuated by less than 0.02‰ (Table 2). The salinity in one of these intervals (13 December 1977–14 March 1978) equaled that in the fresh LDE mode (36.46–36.48‰). Assuming a representative speed of 4 cm s^{-1} the fresh LDE mode could have arrived from the *Panulirus* site.

The search of the ancillary data indicates that homogeneous regions similar in size or larger than those found in the LDE occurred in much of the 18° water formation area shortly after the 1976/77 winter (Table 2). Of the five regions shown by the observations, the most saline one occurred in the northwestern Sargasso Sea with a salinity range equal to that in the LDE saline mode. It appears that this mode persisted with little dilution during approximately 16 months after the 1976/77 winter.

Two fresher modes were observed several months after the 1976/77 winter (30 June–30 August 1977, Table 2). The region at 55°W had a salinity range (36.48–36.50‰) lying between the two LDE modes, whereas the mode at the *Panulirus* site was slightly fresher (36.47–36.49‰). These observations suggest that fresher modes were also formed during the 1976/77 winter. The age of the LDE fresh mode and the closeness of its salinity to those observed a few months after the 1976/77 winter, indicate that the LDE fresh mode may have also persisted with little dilution for 16 months.

6. Evolution of the modes

The LDE and ancillary data suggest a scenario for the evolution of the salinity modes from birth through migration and decay.

a. Birth

Modes of various salinities and dimensions originate during colder than normal winters in which there is formation of new 18° water. A result of convective overturning can be sizeable regions (order of several hundred kilometers) in which the salinity is relatively homogeneous on isopycnals near the core of new 18° water (Figs. 10 and 12). Each region apparently has a distinct salinity and is separated from other regions by horizontal gradients which are comparable to those seen in the LDE (cf. gradients in Figs. 7, 10 and 12).

The ancillary observations made shortly after the 1976/77 winter provide evidence for the birth of several modes (Figs. 10 and 12). These modes are striking, in part because a relatively long period of five years (when little new 18° water was formed; Talley and Raymer, 1982) was followed by one of the coldest winters (1976/77) recorded in the previous century. This unusual sequence led to large salinity changes on $\sigma_\theta = 26.43$.

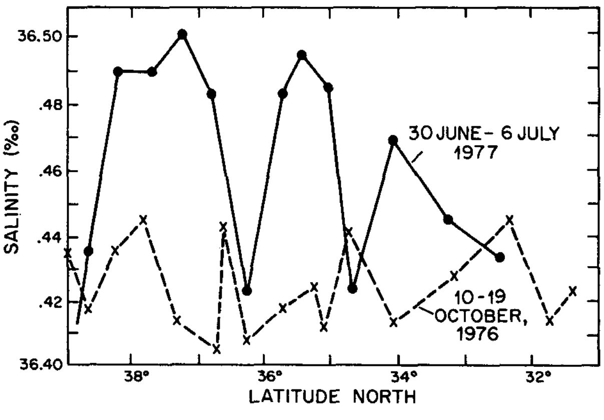

FIG. 12. Salinity along 55°W on $\sigma_\theta = 26.43$ before and after the severe winter of 1976/77 (dashed, 10–19 October 1976; solid, 30 June–6 July 1977).

TABLE 2. Summary of characteristics for salinity modes found during the interval between the 1976–77 winter and end of the LDE.

Location	Salinity range (‰)	Date	Horizontal scale (km)	Number of observations in mode	See Fig.
LDE	36.50–.52	20 May–14 July 1978	100	157	2
	36.46–.48		100	141	2
Northwestern Sargasso Sea	36.50–.52	30 March–14 April 1977	200	8	10
55°W	36.48–.50	30 June–6 July 1977	170	4	12
Panulirus Site	36.47–.49	30 June–30 August 1977	200	4	8
	36.49–.50	6 October–18 November 1977	150	2	8
	36.46–.48	13 December 1977–14 March 1978	300	4	8

Prior to the 1976/77 winter and within much of the 18° water formation area salinities averaged 36.42–36.43‰ (*Panulirus* site, 1975/76, Fig. 8; 55°W, Fig. 12). The salinity in the mode formed in the northwestern Sargasso Sea (36.50–36.52‰; Fig. 10) was 0.07–0.10‰ more saline than immediately prior to the 1976/77 winter. Therefore, during that winter the salinity increased by approximately half of the range of annual average values seen in a quarter century at the *Panulirus* site (0.18‰ range between 1966 and 1976; Fig. 9).

b. Migration

After its "birth" in the 18° water formation area, some of the homogeneous water will be carried southwestward with the mean flow of the Gulf Stream Recirculation (Fig. 1). The time required for a water parcel to traverse the Recirculation is on the order of several years based on trajectories of Gulf Stream rings (Richardson, 1980), SOFAR floats (Riser and Rossby, 1983), and eddies in eddy-resolving general circulation models (Riser, personal communication, 1983). The persistence of the modes, as suggested by the LDE data, indicates that some homogeneous regions may have lifetimes in excess of 16 months. Therefore, after their birth some of the modes will migrate across the Recirculation Zone.

In this scenario, the Recirculation Zone will remain populated with modes if new 18° water is formed every few years. The population represents approximately a balance between supply by 18° water formation and removal by the southwestward flow of the recirculation. However, there was a period of approximately five years (1972–1976) in which little new 18° water was formed (Talley and Raymer, 1982). It may be that the absence of pronounced modes during 1975 and 1976 (Fig. 8a) occurred because nearly all of the modes had been swept out of the Recirculation Zone in the first few years after the formation of 18° water had ceased.

The persistence of the LDE saline mode occurred in an area of the North Atlantic Ocean where the eddy potential and kinetic energies are large (Dantzler, 1977; Ebbesmeyer and Taft, 1979; Owens et al., 1982; Richardson, 1983). Some effect of this eddy activity may have been evident in the horizontal scales of the modes. The mesoscale size of the homogeneous regions observed in the LDE is apparently smaller than that found in the large-scale maps of isopycnal salinity seen immediately after the 1976/77 winter (cf. Figs. 7 and 10). However, the sampling in the large-scale maps was much coarser than in the LDE. If the scale difference is resolved, the characteristics of the newly formed mode waters and the gradients surrounding them were maintained despite a transition to smaller scales. This transition may be the result of active mesoscale stirring.

If the lifetime of the modes is proportionate with eddy energy, the mode waters formed elsewhere in the North Atlantic Ocean by winter overturning may survive longer than in the Recirculation Zone. An example is suggested by the observations of water characteristics in an eddy found in the western North Atlantic. Analysis of the water characteristics within the eddy suggested that they had originated several years earlier in the Gulf of Cadiz during winter overturning (Zantopp and Leaman, 1982). If the winter convection in that area also forms homogeneous saline regions, these may have considerably longer lifetimes which allow for their transit of the western North Atlantic Ocean, because the eddy energy is considerably smaller in the eastern North Atlantic Ocean (Dantzler, 1977).

c. Decay

There are a number of ways in which the homogeneous regions may lose their characteristics. In a succession of years the modes formed in one winter may be obliterated by the convective overturning in the following winter. Of course this would not apply to the modes which escape from the formation area. If a mode survives long enough, then eventually it will coalesce with the Gulf Stream. The effects of mixing will eventually modify the characteristics of the homogeneous water which escapes these fates, but the LDE data suggest that this effect is relatively small over periods on the order of one year.

7. Conclusions

Large increases of salinity (~0.10‰) occurred within the 18° water as a result of the severe 1976/77 winter.

Shortly afterward regions were observed in which the salinity was elevated and comparatively homogeneous on isopycnals over distances of 100 km (fluctuations < 0.02‰). In each region the homogeneous salinity had a different characteristic value. More than a year later some of the regions were still evident in the LDE (May–July 1978). Although the horizontal scale had been reduced, the characteristic salinity within, and the sharp horizontal gradients around, the regions had persisted without apparent change.

The observations indicate that saline waters, once formed during winter overturning, may survive for several years. The characteristic salinity and surrounding gradients persist despite strong mesoscale stirring in the Gulf Stream Recirculation Zone. This persistence indicates that some saline waters may survive sufficiently long after formation to eventually coalesce with the Gulf Stream, a pathway reminiscent of that for Gulf Stream rings. If such homogeneous waters are formed in other areas where overturning occurs, they may survive journeys spanning much of the North Atlantic Ocean.

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