Anticyclonic Eddy Observations in the Slope Water Aboard CGC *Evergreen*

JOHN A. FORNSHELL AND W. ALAN CRIESS
U.S. Coast Guard Oceanographic Unit, Washington Navy Yard, Washington DC 20590

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ABSTRACT

An anticyclonic eddy was surveyed twice, once in late September and again two months later in early December by the CGC *Evergreen*. The two surveys involved a total of 25 CTD stations, 184 XBT's and two subsurface drogued buoys for direct current measurements during the December cruise. The eddy was tracked with infrared satellite imagery from 2 September 1977 to 24 January 1978.

In the two-month period between the first and second cruises the horizontal extent of the eddy, defined by the juncture of the 15°C isotherm with the 200 m isobath, decreased from 185 to 148 km. The baroclinic currents extended to a depth of at least 3000 m in late September and to a depth of only 1600 m two months later in December. The available potential energy referenced to 1600 m decreased from 75×10^{15} to 32×10^{15} J in the same period. The maximum baroclinic currents decreased from 103 to 73 cm s^{-1}.

Direct current measurements in early December with subsurface drogued buoys showed currents as high as 85 cm s^{-1} at 50 m. The observed shear of 10^{-3} s^{-1} was the same as the calculated value. The observed direction differed from the calculated value by 35°. By comparison to other anticyclonic eddies observed in the Slope Water this eddy was larger. Because these observations were made further to the east than most of the others reported in the literature, this eddy may have been in an earlier stage of decay.

1. Introduction

Most warm core eddies break off from the Gulf Stream southeast of Nova Scotia, east of 65°W. These anticyclonic eddies drift westward through the Slope Water where they are of considerable importance to Coast Guard search and rescue planning (Bisagni, 1976; Lai and Richardson, 1977; Morgan and Bishop, 1977). A research project to study these eddies in the Slope Water was carried out by Coast Guard Oceanographic Unit personnel during the fall of 1977. The primary goal of this investigation was to study the changes that occur in an eddy as it propagates through the Slope Water. These changes were studied by comparing the results of two cruises which surveyed the same eddy. Comparisons were made between the hydrography, currents, volume transport, available potential energy, geostrophic kinetic energy and horizontal and vertical dimensions of an eddy. The time interval between the two CTD surveys was 60 days.

Gulf Stream eddies can be tracked with infrared satellite imagery (Gotthardt and Potocsky, 1974; Vukovich, 1976; Lai and Richardson, 1977; Morgan and Bishop, 1977). This method was used in this project from 2 September 1977 to 24 January 1978 (Table 1). An anticyclonic eddy, which was observed to separate from the Gulf Stream in infrared satellite images in the first week of September, was surveyed twice by the CGC *Evergreen* (WAGO 295).[1] It was surveyed from 28 September to 1 October 1977 (Eddy I) and again two months later from 30 November to 12 December (Eddy II). During the first period Eddy I was centered at 40°31.5′N, 65°01.0′W. For the first survey 11 CTD stations and 122 XBT stations were occupied. Eighty-eight of the XBT's were to a depth of 1830 m (1000 fathoms). During Eddy II, 14 CTD stations and 62 XBT stations were occupied. Forty-four of the XBT stations were to a depth of 1830 m. At this time the eddy was centered at 39°08.7′N, 68°00.0′W. In addition to the hydrographic survey, direct current measurements were made with buoys drouged at 50 and 200 m. The ratio of window shade drogue area to buoy area was 100:1. The buoys were tracked for 12 and 21 h, respectively.

The CTD stations were all to 3000 m or the bottom depth minus 50 m in shallower water on both cruises. The instrument readings were compared with Nansen bottle data as a quality control. By taking advantage of the tight *T-S* relationship within the eddy four of the XBT stations (12, 13, 15 and 16) on the December cruise were used to generate additional hydrographic stations (Figs. 5, 10 and 12). This was done using the method given by Stommel (1947). The *T-S* diagram for Eddy II (Fig. 10) was used to determine the mean salinity value for each temperature. The XBT's used for this purpose sampled to a depth of 1830 m. Data from T-4 XBT (430 m) stations occupied as part of cooperative program with the Navy were included in the temperature diagrams of the eddy.

[1] WAGO 295 signifies a Coast Guard Oceanographic ship.

2. Hydrography

The Slope Water is cooler and less saline than the water in the warm core eddies which are observed to move through it (Fuglister, 1960). As these eddies decay, they represent a source of salt and, to some extent, heat as well. Their significance can best be seen by comparing the temperature and salinity of the eddy to the normal conditions found in the Slope Water as given by Fuglister (1960). At the time of Eddy I, the eddy had a vertical extent of at least 3000 m and a horizontal extent of 185 km. The eddy's boundaries were defined by the juncture of the 15°C isotherm with the 200 m isobath. The upper boundary of the North Atlantic Deep Water, defined by Worthington (1976) as less than 4°C and less than 35‰ in salinity, was depressed to twice its normal depth in the center of the eddy, and the 3°C isotherm was depressed to a depth of 3000 m (Figs. 1 and 2). Because this was the maximum depth to which data were collected, the actual vertical extent of the eddy could not be determined. On the north side of the eddy, there was a small eddy-like feature with a surface core temperature of more than 23°C. This appeared to be breaking off from the main body of the eddy (Figs. 1, 2 and 3). The isotherms at the 200 m level were tightly spaced, as can be seen in Figs. 1 and 3. The 15°C isotherm extended to nearly four times its normal level in the warm core eddy.

The salinity structure, as shown in Fig. 2, shows a subsurface maximum on the north side corresponding to the velocity core on the north side. There was also a larger subsurface salinity maximum near the core of the eddy. The 36 and 35‰ isohalines were both depressed to 500 and 2400 m, respectively, four times their normal levels in September (Fuglister, 1960).

Both the salinity and temperature data showed evidence of interleaving (Figs. 1 and 2). The lines

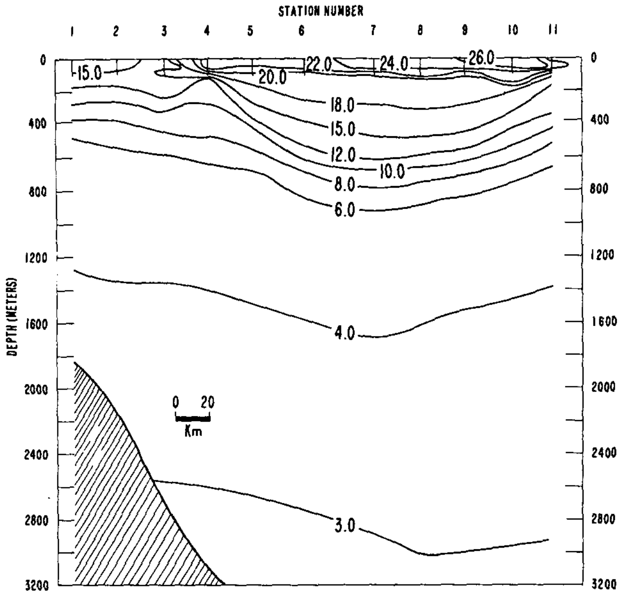

FIG. 1. North-south isotherms based on CTD data, Eddy I.

of equal sigma-t, however, show the eddy to have a vertically stable structure in the areas of interleaving.

In general, the eddy appeared to have undergone relatively little mixing with the surrounding Slope Water at the time of the first eddy cruise. The *T-S* curve for the eddy (Fig. 4) showed a very tight relationship at the time of Eddy I. Very little of the water in the eddy was North Atlantic Deep Water as de-

TABLE 1. Observations of the eddy.

Observation no.	Platform data format	Date	Latitude (°N)	Longitude (°W)
1	SMS-GOES	01/09/77	41°00′	64°00′
2	SMS-GOES	02/09/77	41°00′	63°30′
3	SMS-GOES	13/09/77	41°30′	63°30′
4	Ship/XBT	18/09/77	40°57′	64°18′
5	Ship/CTD/XBT	28/09/77 01/10/77	40°30′	65°01′
6	SMS-GOES	06/10/77	40°30′	65°15′
7	NOAA 4	10/10/77	40°30′	65°45′
8	NOAA 4	22/10/77	39°30′	66°50′
9	Ship/BTT	17/11/77	39°30′	67°50′
10	Ship/CTD/XBT Buoys	01/12/77 03/12/77	39°34′	68°00′
11	NOAA 4	24/01/78	39°00′	71°20′

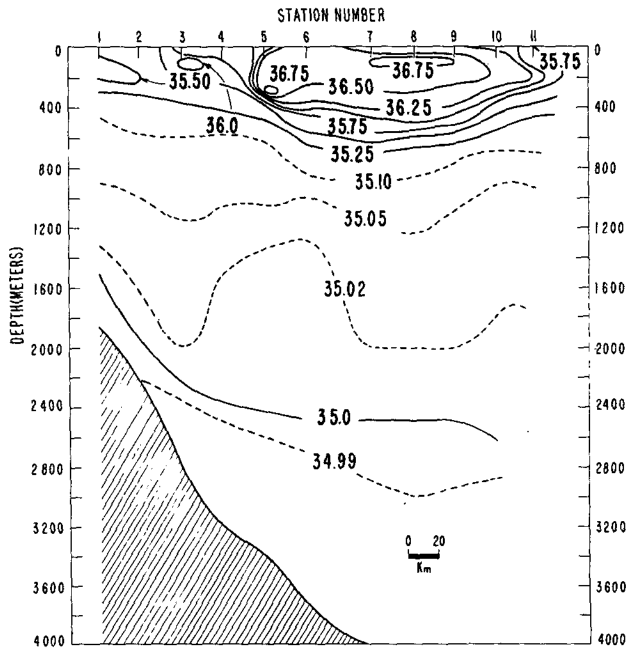

FIG. 2. North-south isohalines based on CTD data, Eddy I.

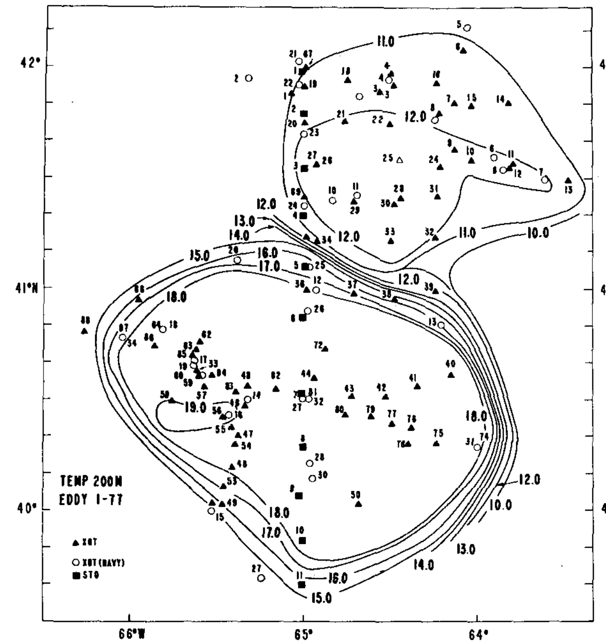

FIG. 3. Horizontal isotherms at 200 m, Eddy I.

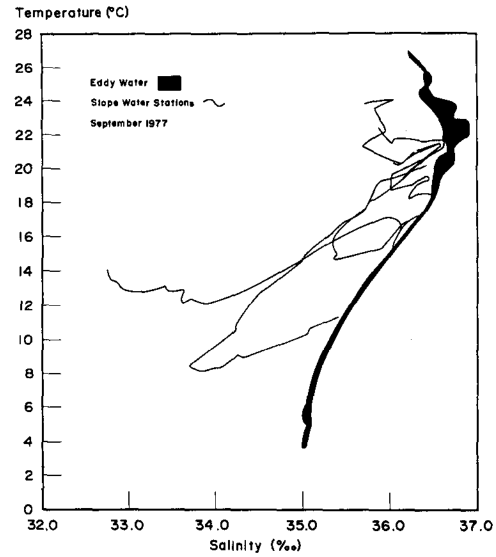

FIG. 4. *T-S* curve from Eddy I.

fined by Worthington (1976). The *T-S* range of the eddy coincides with the range for the Gulf Stream given by McLellan (1957).

At the time of Eddy II the eddy had moved to the southwest, a distance of 167 n mi in 60 days at an average speed of 2.79 n mi day^{-1}. Lai and Richardson (1977) give an average speed of 5 n mi day^{-1} for anticyclonic rings and 3 n mi day^{-1} for cyclonic rings. It had decreased in diameter to 148 km and had a surface temperature which was elongated in the NW–SE direction. At 200 m the horizontal isotherms had a more characteristic ring structure (Fig. 5). The isotherms were not so tightly packed at the time of Eddy II. The 15°C isotherm extended to 340 m, twice its normal depth (Fig. 6). The temperature and salinity values observed below 1600 m (Figs. 6 and 7) indicated little difference from the temperature and salinity values at the same depths in the North Atlantic Deep Water which underlies the Slope Water in this area (Fuglister, 1960). The baroclinic currents calculated at 1600 m and referenced to 3000 m were found to be zero within the accuracy of the measurements. For these reasons, it was concluded that the eddy had diminished vertically to a maximum depth of 1600 m.

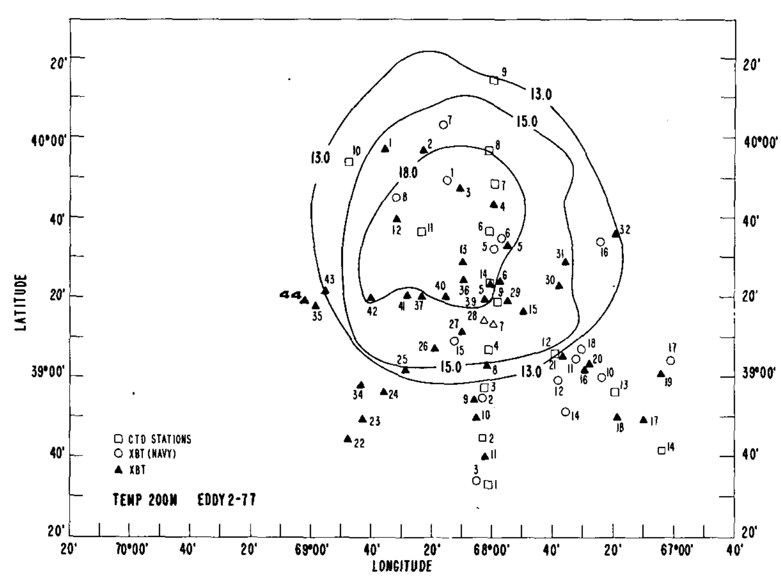

FIG. 5. Horizontal isotherms at 200 m, Eddy II.

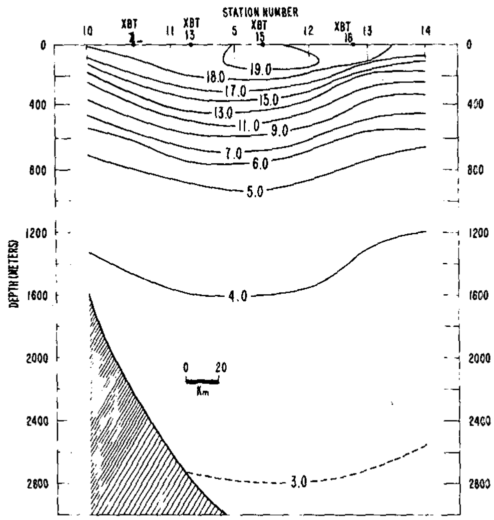

FIG. 6. NW–SE isotherms based on CTD data, Eddy II.

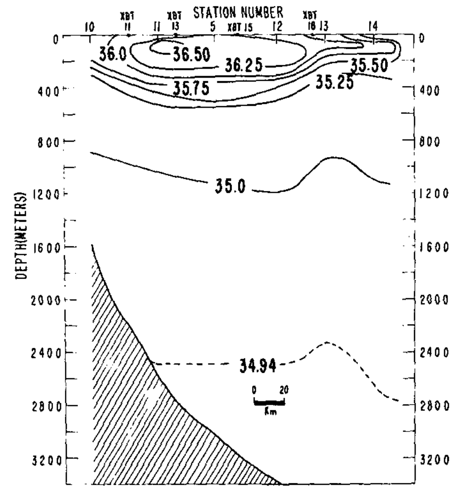

FIG. 7. NW–SE isohalines based on CTD data, Eddy II.

The salinity of the upper portions of the eddy had decreased from a maximum of 36.75 to 36.50‰ (Figs. 2 and 7). The maximum temperature decreased by 7°C in the upper layers during the same time period (Figs. 1 and 6). The mixed-layer depth at the time of Eddy I was 50 m, and by the time of Eddy II it had increased to 100 m (Fig. 8). These changes imply a significant amount of surface cooling with thermally driven convection and wave mixing. The eddy exhibited a stable stratification on a length scale greater than hundreds of meters.

The temperature in the upper 200 m decreased by approximately 2°C in the 60 days between Eddys I and II (Figs. 1 and 6). During a one-week period when two northwest gales blew through the area the upper 200 m cooled by 1°C. Those changes which occurred during the second eddy cruise are shown in Figs. 6 and 9. This would give a 60-day cooling rate of 0.7 kcal cm^{-2} day^{-1} and a rate of 2.8 kcal cm^{-2} day^{-1} for the one week of observation during Eddy II. This also suggests a significant amount of surface cooling with thermally driven convection playing an important role.

The *T-S* curve for the eddy at the time of Eddy II (Fig. 10) shows a tight relationship between salinity and temperature in the eddy. The *T-S* relationship shown here agrees with the definition of Gulf Stream Water given by McLellan (1957). It also coincides with the curve from Eddy I if only the upper 1600 m are considered. The stations along the boundary of the eddy (horizontal hatching in Fig. 10) are

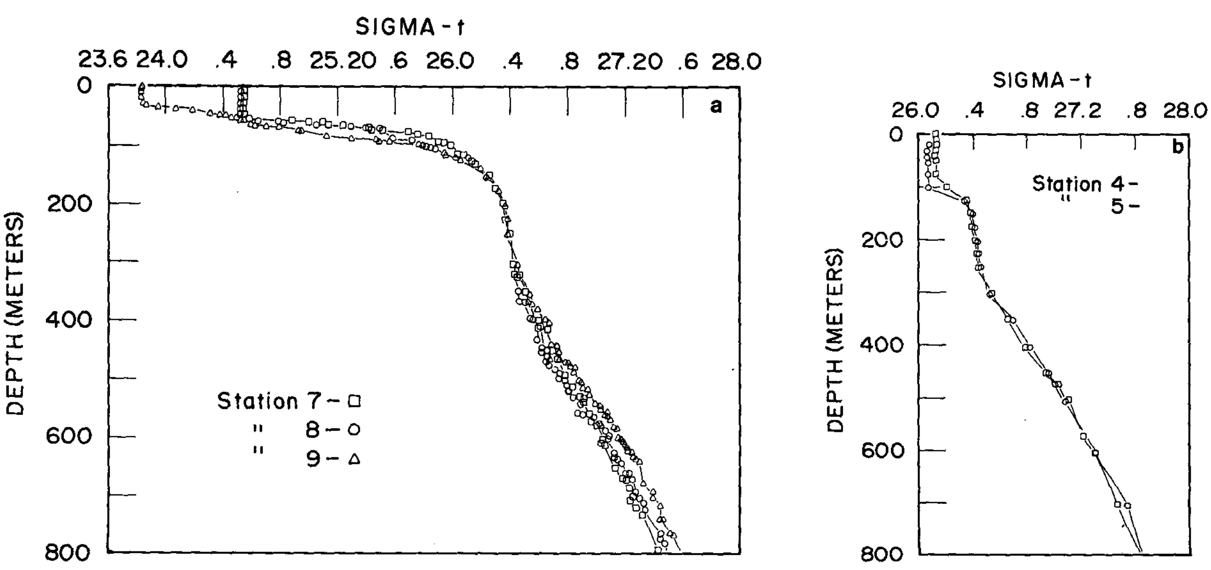

FIG. 8. Sigma-*t* versus depth for Eddy I (a) and Eddy II (b).

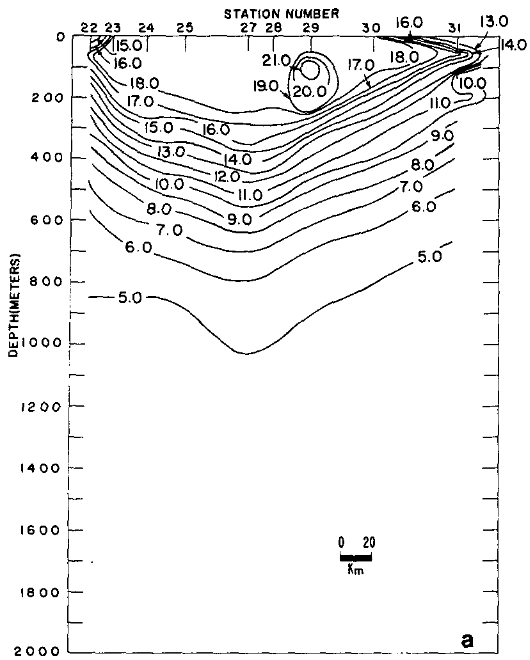

FIG. 9a. SW–NE XBT transect of the eddy 4 December 1977.

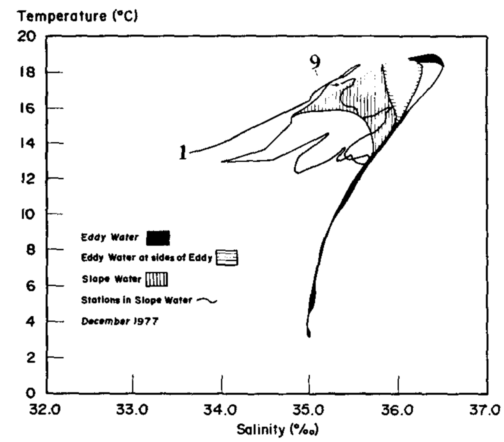

FIG. 10. *T-S* curve for Eddy II. 1. A Slope Water station showing Shelf Water near the surface. 9. A Slope Water station north of the eddy showing only Slope Water.

intermediate between Gulf Stream Water and Slope Water as defined by McLellan (1957).

3. Currents

The baroclinic currents observed on Eddy I were stronger on the south side of the eddy (Fig. 11). The level of no motion was chosen as 3000 m based on hydrography. The maximum currents were 103 cm s^{-1} on the south side of the eddy with the 10 cm s^{-1} isotach extending to 2200 m. The currents were weaker and not as deep on the north side. The surface currents in the eddy-like feature north of the eddy were 30–40 cm s^{-1} toward the east.

The baroclinic currents observed on Eddy II are shown in Fig. 12. By using 3000 m as a level of no motion, it was found that the currents were zero at 1600 m. Therefore, it was reasonable to treat 1600 m as the level of no motion. The maximum current based on CTD/XBT data was 73 cm s^{-1} in the southeast side of the eddy. As had been seen on Eddy I, the currents were asymmetric with the strongest currents on the side farthest from the continental shelf break.

Direct current observations were made as part of the Eddy II cruise. A buoy drouged at 50 m was tracked for 12 h. These observations were started between XBT station 15 and CTD station 12 where the 15°C isotherm was at 300 m within 24 h of the time the stations were occupied (Figs. 6, 12 and 13a). In calculating the currents, it was assumed that they followed a curved path which was perpendicular

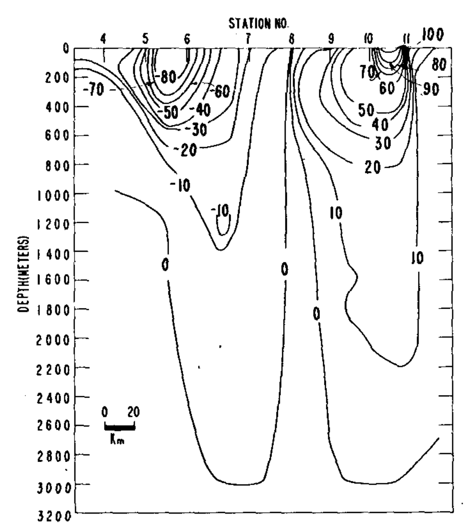

FIG. 11. Baroclinic currents versus depth, Eddy I. Negative values indicate flow into the page and positive values indicate flow out of the page.

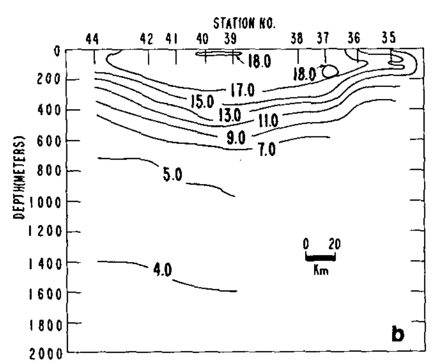

FIG. 9b. East-west XBT transect of the eddy 11 December 1977.

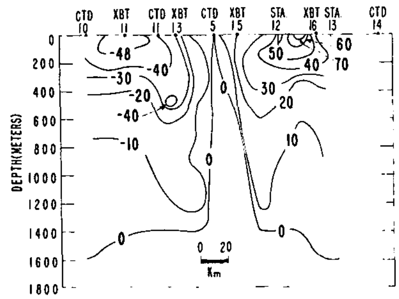

FIG. 12. As in Fig. 11 except for Eddy II.

to the line of stations. The track of the buoy intersected the hydrographic station line at an angle 35° off the perpendicular. The calculated current was 63 cm s^{-1} and the observed current was 85 cm s^{-1}. If, in fact, the current was not perpendicular to the line of stations, then most of the difference can be accounted for. The buoy drouged at 200 m showed a current of 70 cm s^{-1} as compared to a calculated value of 47 cm s^{-1}. This buoy was also deployed at a point where the 15°C isotherm was at 300 m (Fig. 13b). This second drift study was made three days after the CTD/XBT stations were occupied. The observed shear from 50 to 200 m was 10^{-3} s^{-1}, the same as the calculated value. The difference between the observed and calculated currents at 200 m may also be accounted for by the currents not being perpendicular to the CTD/XBT transect. It may also be due to time-dependent variations in the currents. Another possibility is that there is a barotropic component in the eddy current field, like that reported for the Gulf Stream by Fuglister (1963). The differences, however, are not large enough to clearly establish the presence of a barotropic current.

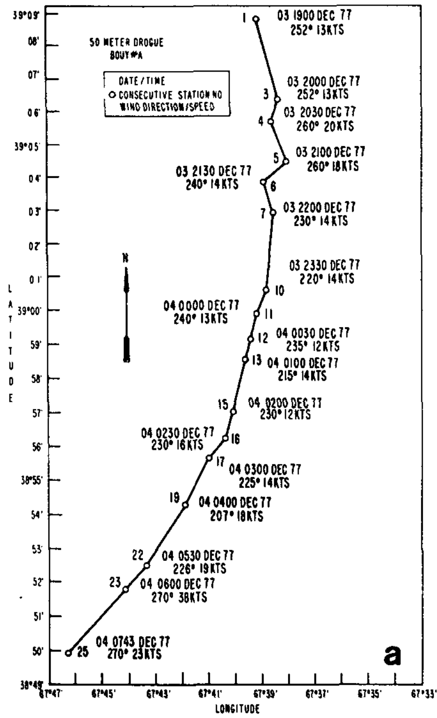

FIG. 13a. Track of the buoy drouged at 50 m.

4. Volume transport

On Eddy I the average volume transport observed was 47 Sv. On Eddy II the average volume transport had decreased to 17 Sv. This represents a 64% reduction in the volume transport due to baroclinic currents. The eddy's volume had decreased by some 66% in this same time period. More than half of the decrease was in the reduction of the

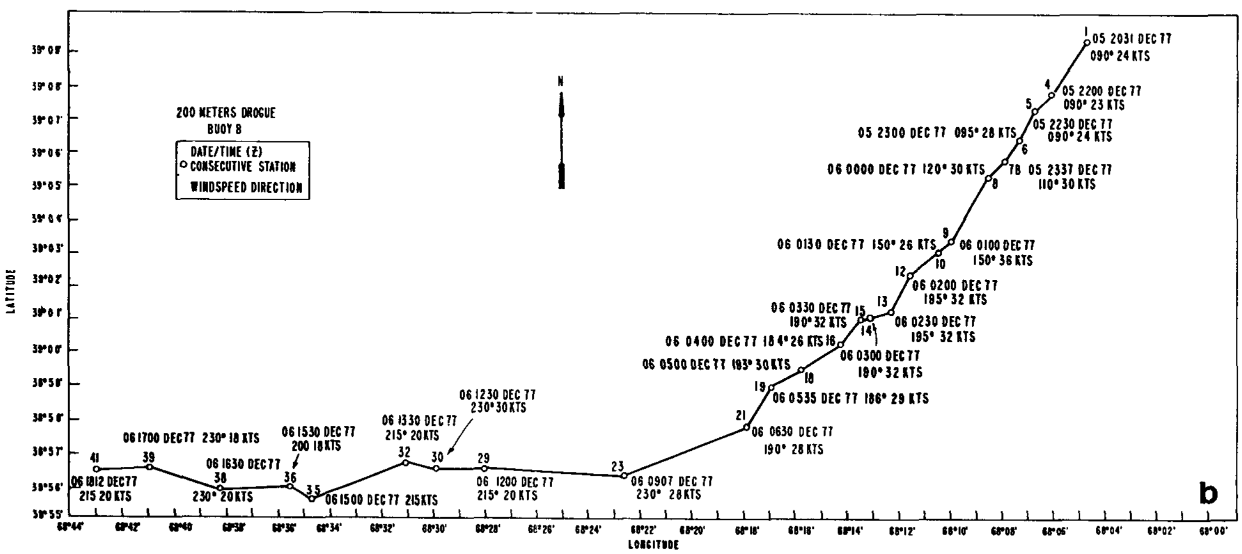

FIG. 13b. Track of the buoy drouged at 200 m.

vertical extent of the eddy. The currents in the lower portion of the eddy were relatively weak and most of the reduction in volume transport came from the decrease in the currents in the upper 1600 m.

5. Available potential energy (APE)

The available potential energy (APE) was calculated from the dynamic height anomaly (Fofonoff, 1962). All calculations were made relative to a reference station outside the eddy, in the Slope Water (Station 3 in Fig. 3). The APE was calculated for concentric rings of water in the eddy and these were summed together to determine the total APE in the eddy. The eddy had a total of 9×10^{15} J when surveyed on Eddy I. This was relative to the 3000 m reference level. To make comparisons with the eddy as it appeared on Eddy II, the APE was also calculated relative to 1600 m. This yields an APE of 7×10^{15} J. The APE relative to 1600 m on Eddy II was 3×10^{15} J, a decrease of 57% at a rate of 7×10^{13} J day^{-1}. The volume of the upper 1600 m of the eddy decreased by only 36% in the same time period. On Eddy I the unit volume APE was 175 J m^{-3} and 118 J m^{-3} on Eddy II, a reduction of 33%. The decrease in APE was due to a loss of thermal energy and a reduction in the total volume of the eddy with portions of the eddy breaking off.

The total geostrophic kinetic energy (KE) was 6×10^{14} J on Eddy I and 2×10^{14} J on Eddy II. In both cases the KE/APE ratio was 7%.

6. Decay rate

In calculating the decay rate, the eddy was assumed to be 28 days old at the time of the first CTD survey on Eddy I. The volume of the upper 1600 m decreased from 4.31×10^{13} m^3 on Eddy I to 2.76×10^{13} m^3 on Eddy II, a decay rate of 2.59×10^{11} m^3 day^{-1}. This would have given the eddy a life span of 194 days. If the total volume, to 3000 m on Eddy I and 1600 m on Eddy II is considered, the decrease is from 8.09×10^{13} to 2.76×10^{13} m^3 at a rate of 8.9×10^{11} m^3 day^{-1}. The unit volume APE decreased at a rate of 0.95 J m^{-3} day^{-1}. This would have resulted in the total dissipation of the APE in 212 days. The rate of loss of APE from all causes was 7×10^{13} J day^{-1}. This would have resulted in a life span of 133 days. These decay rates indicate a life span of from four to seven months.

7. Shelf Water interacton with the eddy

There were two observations indicating that the eddy induced some offshore flow of Shelf Water. On Eddy II, CTD station 1, on the south side of the eddy, showed a small shallow region of surface water with the *T-S* characteristics of Shelf Water. This was confirmed by a bucket sample and the ships thermosalinograph. The *T-S* curve for this station is included with the *T-S* curve for Eddy II (Fig. 10). The ship's thermosalinograph showed a similar patch of Shelf Water on the southeast side of the eddy. The *T-S* curve for CTD station 9 on the north side of the eddy showed no evidence of Shelf Water (Figs. 5 and 10).

8. Eddy observations

The eddy was observed eleven times between 1 September 1977 and 24 January 1978. These observations are summarized in Table 1. The first surface

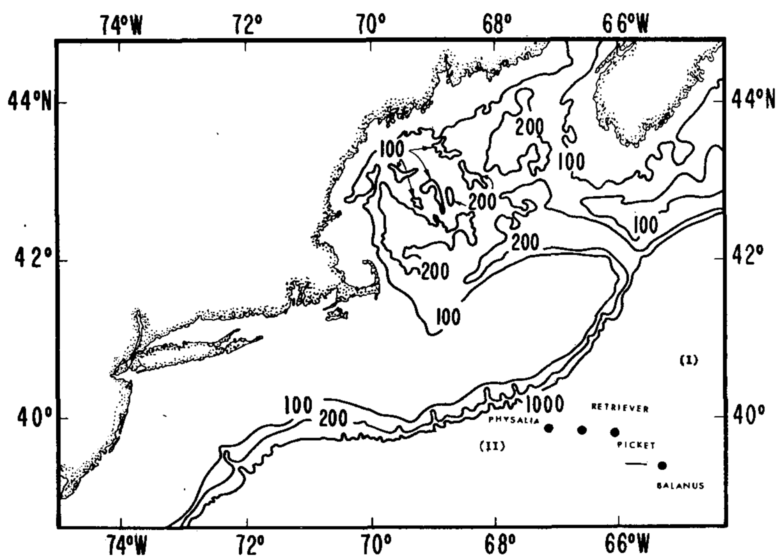

FIG. 14. Relative locations of the Eddy I survey, New England Seamounts and the Eddy II survey.

observation was by a ship XBT survey on 18 September 1977 (J. P. Dean, personal communication). The BTT observation by Richardson *et al.* (1979) showed velocities comparable to those observed in early December aboard the CGC *Evergreen*. The position given for this observation is estimated from the central point in the smallest circle of the satellite-tracked buoy (BTT). After the 24 January 1978 satellite observation there were no further distinct observations of the eddy known to the authors. It would appear to have lost its surface thermal signature in late January. However, the eddy may have persisted for much longer as indicated by the decay rate observed in the period between the two *Evergreen* surveys. The center positions based on shipboard observations are accurate to ±10 n mi. The satellite observations are accurate to ±30 n mi.

9. Discussion and summary

Most of the previous work on warm core eddies in the Slope Water has been done further to the west than the two surveys conducted in the project reported here. Bisagni (1976) summarized work describing several warm core eddies in the Slope Water with emphasis on the area bounded by 38°40′–39°00′N and 71°00′–72°30′W. These eddies had an average diameter of 100 km as compared to 185 km in September and 146 km in December for the eddy surveyed here. The vertical extent was typically 1 km as compared to 3 km in September and 1.6 km in December for the eddy reported on in this study. The eddy observed by Morgan and Bishop (1977) off the New Jersey Coast east of Cape May was also about 100 km in diameter and 1 km in vertical extent. Because the eddies reported to the west of our survey area may have been older, their smaller size may simply represent a later stage of decay.

Warm core eddies drifting southwestward in the Slope Water frequently are recaptured by the Gulf Stream, either as the result of a northward meander of the Gulf Stream or near Cape Hatteras where the eddies drift into contact with the Gulf Stream (Bisagni, 1976; Richardson and Lai, 1977). As a result they frequently have a shorter life span than is indicated by their observed decay rates.

One of the most noticeable changes in the eddy between the two cruises was its reduction in vertical extent from more than 3000 m to only 1600 m. As was pointed out by one of the reviewers the eddy passed over the New England Seamounts between Eddy I and Eddy II. Some of these sea mountains rise to within 2000 m of the surface (Picket 1968 m, Balanus 1471 m, Bear 1162 m). Their positions are shown in Fig. 14. It is difficult to assess the influence of these seamounts on the eddy because their horizontal extent is two orders of magnitude smaller than the eddy. Nonetheless, they may have influenced the decay of the lower portion of the eddy.

TABLE 2. Summary of dynamic parameters of Eddys I and II.

	Eddy I	Eddy II
Diameter (km)	185	148
Vertical extent (km)	3	1.6
Maximum baroclinic currents (cm s^{-1})	103	73
Observed currents at 50 m (cm s^{-1})	—	85
Observed currents at 200 m (cm s^{-1})	—	70
APE relative to 3000 m (J)	9×10^{15}	—
APE relative to 1600 m (J)	7×10^{15}	3×10^{15}
Total geostrophic KE (J)	6×10^{14}	2×10^{14}
APE m^{-3} (J)	175	118

The results of the two cruises are summarized in Table 2. There was some evidence of eddy-induced offshore flow at the time of Eddy II. It was considerably less at this time than that observed by Morgan and Bishop (1977). Relative to other eddies which have been studied (Cheney and Richardson, 1976; Barrett, 1971; Saunders, 1971) the APE of the eddy surveyed in this project was lower. Also, its aging appeared to be faster. The projected life span was shorter by a factor of 2. The geostrophic kinetic energy (KE) decreased during the period of the survey but the ratio of the total KE to APE remained constant. The primary mechanisms of aging appeared to be surface cooling and the reduction in size of the eddy by the shedding of masses of water.

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