An Alternative Hypothesis for the Origin of the ''Mediterranean'' Salt Lens Observed off the Bahamas in the Fall of 1976

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19 August 1998 and 12 January 1999

ABSTRACT

A hypothesis is presented that the original salt lens, or ''meddy,'' observed off the Bahamas in the fall of 1976 may have been formed, not near the Mediterranean outflow, but instead in the vicinity of the northwest corner (51°N, 43°W) of the North Atlantic Current. An eddy was observed near the northwest corner by an isopycnal RAFOS float deployed during the 1993–95 North Atlantic Current Experiment, and had nearly identical temperature/salinity properties as those of the Bahamas lens. Hydrographic evidence of thick homogeneous layers with similar properties near the northwest corner suggest a possible formation mechanism by which surface eddies containing warm and saline waters are cooled and subducted. A plausible scenario is made whereby a northwest corner eddy might be advected southward in the Newfoundland Basin by the flow around the high pressure ridge east of the North Atlantic Current and then enter the recirculation gyre immediately south of the Gulf Stream. Such an eddy could be advected to the site of the Bahamas lens in just three years, perhaps much more quickly than an eddy of Mediterranean origin and without encountering the topographic barrier of the Mid-Atlantic Ridge. This conclusion is ironic because the Bahamas lens is considered the first observation of an eddy of Mediterranean origin, and led to the coining of the term ''meddy.''

1. Introduction

McDowell and Rossby (1978) reported the discovery of a lens of water with a warm salty core 20 km in diameter and 200 m thick floating at 1000-m depth roughly 200 km east of the Bahamas. The high temperature and salinity anomaly (about 2°C and 0.4 psu greater than the surrounding waters of the same density) suggested that the waters must have originated in the outflow from the Mediterranean Sea. The well-known spreading of increasingly dilute salty water across the North Atlantic from the Mediterranean provided the obvious pointer to such a distant source. The subsequent discovery of warm salty lenses in the eastern Atlantic (Armi and Zenk 1984) provided further support for the Mediterranean Water origin. However, later studies have cast some doubt on this hypothesis. At any plausible drift rate across the Atlantic and assuming it was formed off the Iberian Peninsula, 5500 km to the east (Käse et al. 1989; Bower et al. 1995), the original meddy must have been at least 5 years old (Richardson and Tychensky 1998). Furthermore, analysis of historical hydrographic data has revealed no meddies west of the Mid-Atlantic Ridge (Richardson et al. 1991). In this note compelling evidence is given that the Bahamas ''meddy,'' or lens, instead had its genesis at the northwest corner of the North Atlantic Current.

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2. Observations

In late January 1994, an eddy was observed in RAFOS float trajectory data southeast of the northwest corner (NWC) of the North Atlantic Current (NAC) at 49°30′N, 41°30′W. Soon afterward, an isopycnal RAFOS float (number 316) was entrained into this anticyclonic rotating lens as seen from the float's orbital motions (Fig. 1), which begin around 10 February 1994. The float makes eight anticyclonic revolutions in the lens before the lens was advected rapidly southward to approximately 46°N and then to the west. Due to this large translational speed of the lens (over 0.5 m s^{-1}), the orbital motions of the float are obscured. After the eddy's forward progress was slowed, the float was observed making five more anticyclonic revolutions before being expelled from the lens. Despite the rapid and irregular motion of the lens in the energetic eddy field just east of the NAC, the float remained in the central core of the lens for over two months (10 March to 26 May). This can be seen most clearly from the float's elevated temperature of 10.7 to 10.8°C while in the core (Fig. 2a), compared to about 10°C while in the far-field

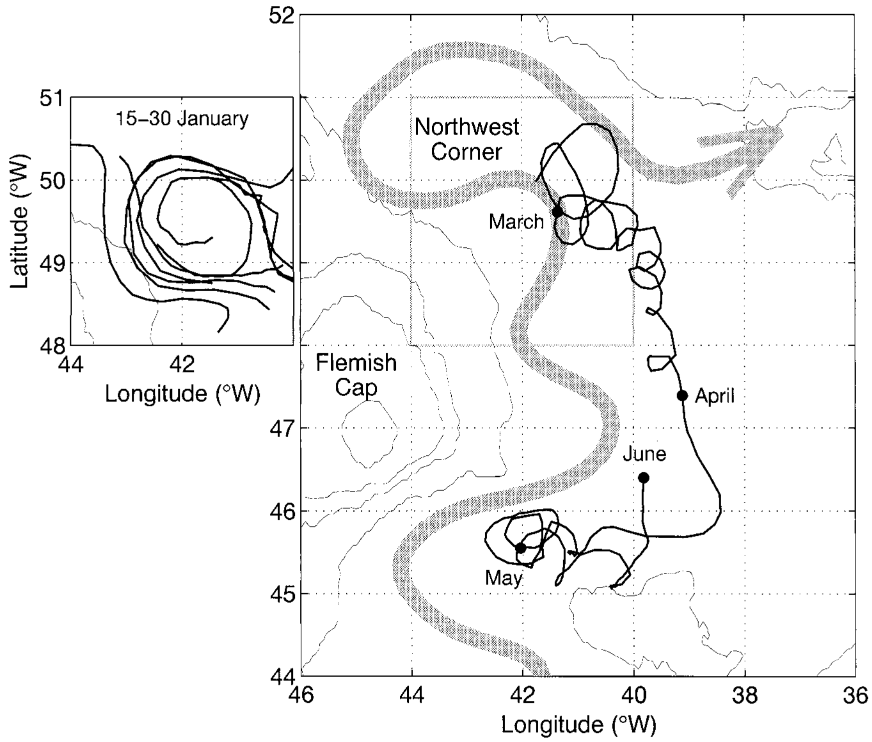

FIG. 1. (Small panel) Trajectories of seven RAFOS floats that orbited the northwest corner eddy several weeks before the entrainment of float 316. (Large panel) Trajectory of RAFOS float 316 while in the NWC eddy, with the schematized path of the North Atlantic Current (Rossby 1996) shown in gray. The light gray rectangle denotes the region shown in the small panel.

of the lens before entrainment into and after expulsion out of the core.

The float was designed to be isopycnal and remain on the 27.2 σ_θ surface (although data from a CTD cast made concurrent with the float deployment suggests the float's density was actually 27.1 σ_θ) as well as to measure static stability by cycling to density surfaces 0.1 σ_θ above and below this nominal surface (Rossby et al. 1994). While the float was trapped in the eddy, the depth of the 27.1 σ_θ surface varied between 500 and 650 dbars (Fig. 2b). Using the float's density and temperature and inverting the equation of state for seawater (Boebel et al. 1995), the salinity of the lens was calculated as ~35.4 psu, giving the lens temperature and salinity properties similar to that of the original meddy (11°C, ~35.6 psu). For about a month (mid-March to early April), the float's density surface appears to be at the interface between the low stratification core and the pycnocline below the lens (Fig. 2c). The stratification inside the lens was at most half that of outside, with a buoyancy frequency of 2.2×10^{-3} s^{-1}. We emphasize "at most" because the thickness of the upper (27.0 to 27.1 σ_θ) pycnostad may have prevented the float from reaching the upper density surface prior to its scheduled return to the nominal surface. The nearly uniform temperature of the upper pycnostad (Fig. 2d) indicates that the lens had been convectively mixed quite recently. The increased stratification in the upper layer and the decreased observed pressure after mid-April might indicate that the float had moved outward away from the center of the lens.

By plotting the float trajectory relative to the moving center of the lens (Fig. 3), the orbital motion shows up clearly with a 4-day period corresponding to a relative vorticity of -0.33 of the local Coriolis parameter. The average orbital velocity at a radius of 20 km was 0.36 m s^{-1}. The erratic motion of the lens makes it difficult to examine its radial structure in any greater detail. Nonetheless, previous studies of lenses (i.e., Prater and Sanford 1994) show that the extent of solid-body rotation and the radius of the homogeneous property core are similar. Thus we can assume that the lens's core was at least as large as the extent of the trajectories (given that the temperatures measured by the float in the range of 10.7° to 10.8°C were representative of the core temperature) and thus had a diameter of at least 40 km. At one point, the influence of the eddy extended over 100 km as seen in earlier float trajectories (Fig. 1). The float was finally expelled from the lens near 45°30′N, 42°W. The subsequent fate of the lens is not known. Table 1 summarizes the scales of the Bahamas lens and this lens.

A review of archived hydrographic data has identified late winter hydrocasts from the Newfoundland Basin with pycnostads with *T*/*S* properties to match the Bahamas lens. The one found closest to the NWC is shown

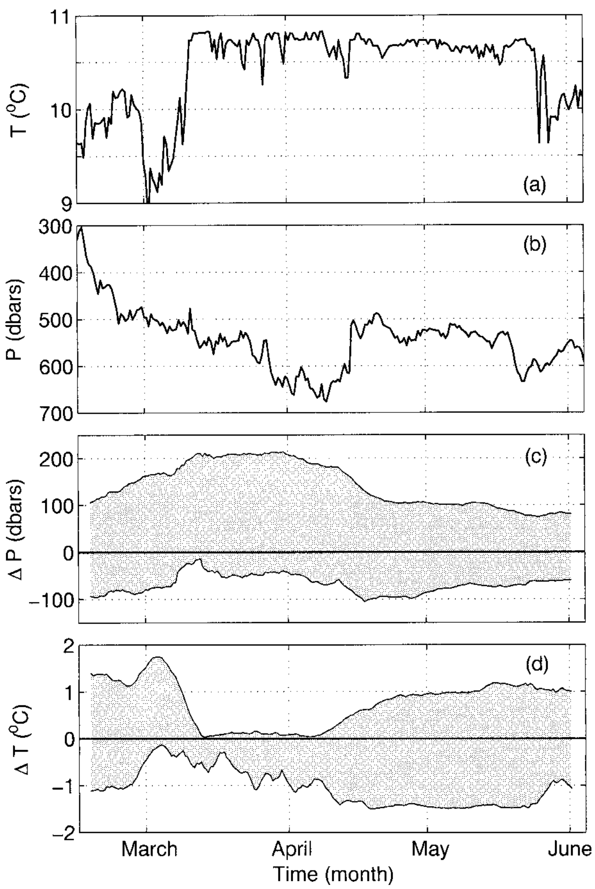

FIG. 2. (a) Temperature recorded by the float on the 27.1 σ_θ density surface. (b) Pressure recorded by the float on the 27.1 σ_θ density surface. (c) Pressure differential between the 27.1 σ_θ density surface and the 27.0 (upper line) and 27.2 (lower line) σ_θ surfaces. The density stratification in the upper layer was reduced during March and the first half of April. (d) Temperature differential between the 27.1 σ_θ density surface and the 27.0 (upper line) and 27.2 (lower line) σ_θ surfaces. The thermal stratification disappears in the upper layer from mid-March to early-April. It appears that the float was positioned at the lower edge of the homogeneous core of the eddy given the very small temperature difference and low stratification above the nominal surface and high stratification below.

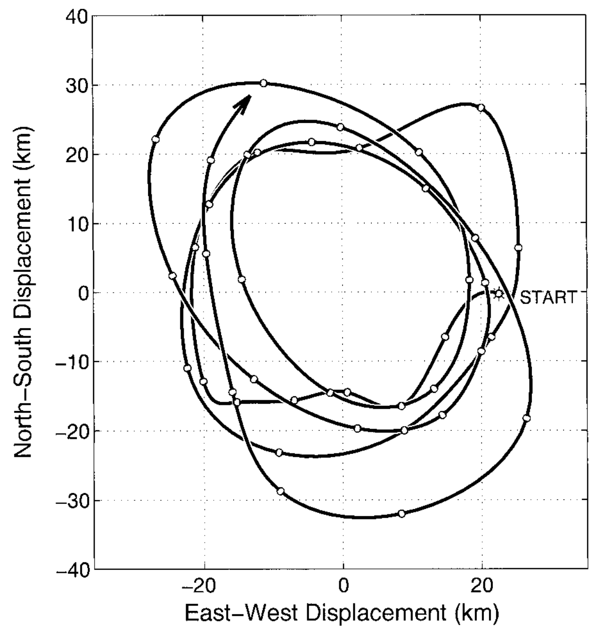

FIG. 3. Trajectory of float 316 during the month of March relative to a reference frame moving with the center of the eddy. The data positions are given every half-day (open circles) and the trajectory is a cubic spline fit through those positions. The orbital period is about four days, which corresponds to a vorticity Rossby number of −0.33. The mean orbital velocity of the float was 0.36 m s^{-1}. From the temperature of the float given in Fig. 2a, a lower limit of the eddy's core diameter is 40 km.

in Fig. 4 together with the center profile from the Bahamas lens. The upper panels show the profiles while the *T*/*S* curves appear below. The profile from the NWC shows a well-mixed patch 300 m thick centered at 450-m depth. The properties of this patch (temperature, thickness, depth, and location) are very similar to that of the NWC eddy, and although we have no evidence that this hydrocast was in an eddy, the location of the cast was directly in line with the path of the NWC lens.

The most likely mechanism by which convectively mixed surface waters are transformed into a subsurface eddy is by subduction. Typical winter mixed layer depths in this region are about 300 m (Robinson et al. 1979; McCartney and Talley 1982) and thus are consistent with the layer thicknesses observed. It is unlikely that a 500 or 600 m deep mixed layer can form south or east of the NAC and then have the top 250 m recapped locally since little restratification, if any, would occur by late March (i.e., Figs. 2 and 4). The actual subduction may occur as follows: The NAC, after passing Flemish Cap, can take two routes, either continuing directly toward the NWC or it can turn northeast towards the Charlie Gibbs Fracture Zone, bypassing the NWC in which case the NWC becomes a semi-detached anticyclonic eddy from the NAC (Lazier 1994). Without constant replenishment, its loss of heat to the atmosphere in winter will cool it off, increasing its density accordingly. When the NAC switches back toward the NWC, but with its warmer, lighter water, it now overruns

TABLE 1. Comparison of the two lenses.

Parameter	Original "meddy"	Northwest corner lens
Overall radius (km)	>50	>20
Core radius (km)	10	>20
Pycnostad thickness (m)	200	>200
Core temperature (°C)	11.0	10.8
Core salinity (psu)	35.6	~35.4*
Potential density (kg m^{-3})	27.15	27.1
Vorticity Rossby number	−0.20	−0.33

* The salinity is obtained from the density of float 316 (27.11 σ_θ estimated with a CTD cast concurrent with the float deployment) and the len's core temperature as measured by the float.

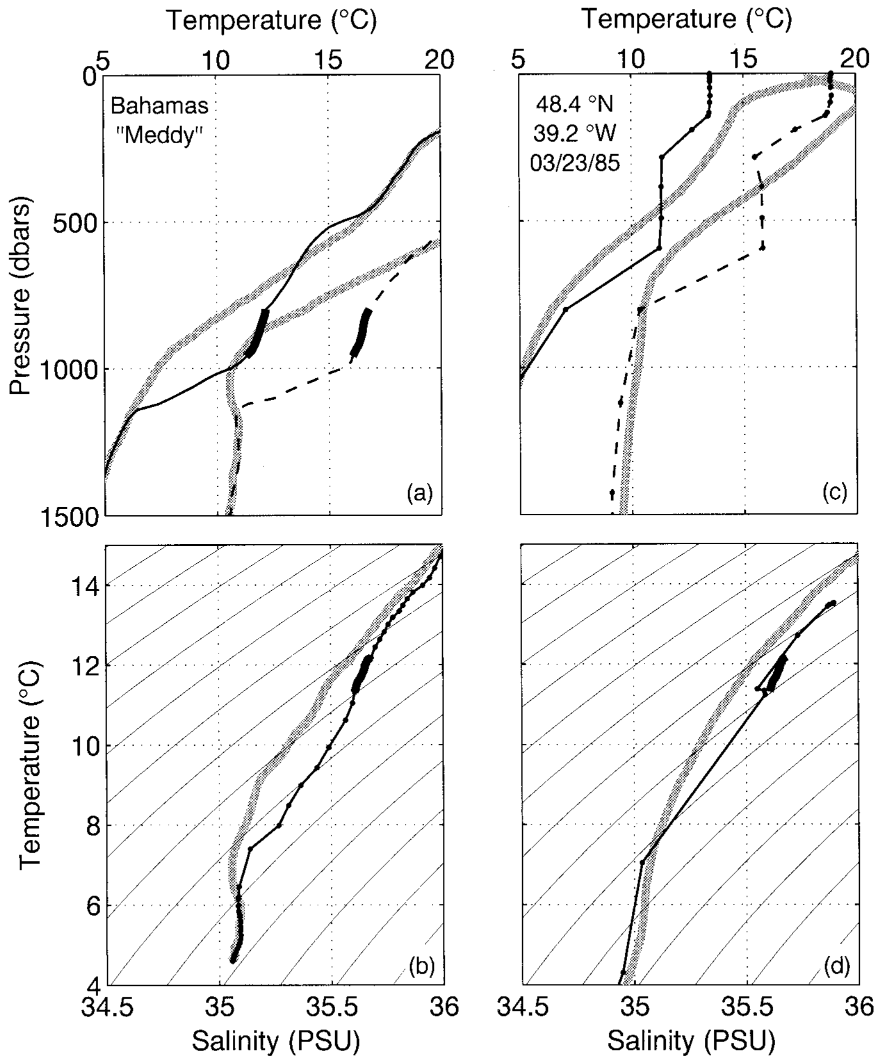

FIG. 4. Hydrographic property profiles (a, c) and *T–S* relationships (b, d). In (a) and (c) *T* is denoted by black solid lines and *S* by black dashed lines. The thick gray lines in all panels are representative background conditions for *T* and *S.* The thick black line segment denotes *T* and *S* properties in the core of the Bahamas lens. (a) Profile in the center of the McDowell and Rossby (1978) eddy. (b) *T*/*S* plot of data shown in (a). (c) Profile 200 km southeast of the NWC. A homogeneous layer of waters 300 m thick is found having properties identical to the Bahamas lens. The layer has already been subducted under warmer and saltier waters. (d) *T*/*S* plot of data shown in (c).

and pushes the cooled-off waters downstream, that is, to the southeast where they subduct and become detached from the NAC at the first meander trough of the subpolar front (Fig. 1). The strong anticyclonic vorticity of the eddy keeps it from being sheared apart during this transition. Eddies can almost always be found at or near the NWC in RAFOS float trajectories from the NAC Experiment (Anderson-Fontana et al. 1996), and those formed in the winter months would be more likely to subduct. Regardless, the question remains—is it possible for lenses formed at or near the NWC to reach the Bahamas?

3. Hypothesized pathway from the NWC to the Bahamas

It must be remembered that in over twenty years, only one eddy of presumably Mediterranean origin has been found in the western North Atlantic. Thus, the proposed eddy pathway to the Bahamas will not be the one most likely traveled by any given eddy originating from the NWC, just as any pathway to the Bahamas from the Mediterranean will not be the most likely route of a meddy. What follows is speculation, but with the rather strong constraint that the hypothesized pathway is completely consistent with observations.

While the NWC is almost as remote as Cape St. Vincent, there are several major differences between the two that make the former a more plausible source. One is that there are no imposing topographic barriers between the NWC and the Bahamas comparable to the Mid-Atlantic Ridge. In fact, three of the seven meddies that were seeded with SOFAR (Richardson et al. 1989) or RAFOS (Richardson and Tychensky 1998) floats in the eastern Atlantic well away from Cape St. Vincent were fatally disrupted by interactions with seamounts well before the Mid-Atlantic Ridge was even encountered. Secondly, the mean flow west of Portugal at the depth of eastern Atlantic meddies is less than 0.01 m s^{-1} to the south (Stramma 1984), whereas in the western Atlantic there are several recirculation cells associated with the NAC and the Gulf Stream that are able to advect an eddy at speeds up to 0.10 m s^{-1}.

Rationale for a pathway from the NWC to the Bahamas will now be presented and are highlighted graphically in Fig. 5. First, to move the eddy away from its formation site, there are local recirculation cells between meander troughs of the NAC (Rossby 1996) as well as a region of offshore high pressure found in mean climatology (Carr et al. 1997), which can provide a significant advective component. Analysis from the NAC Experiment float data in this region shows a 2-yr mean southward flow in excess of 0.30 m s^{-1}. Float 316 traveled from 50° to 46°N within two months, for a mean speed of 0.08 m s^{-1}. This float was then apparently caught in a recirculation cell and advected westward at 46°N, but another eddy might have continued southward.

There is historical evidence of SOFAR (Owens 1991) and RAFOS (Anderson-Fontana et al. 1996) floats crossing southeast of the Tail of the Grand Banks from the southern Newfoundland Basin to the Gulf Stream recirculation gyre. Three floats from the NAC Experiment were deployed near 43°N, just south of the southernmost excursion of float 316, and within 10 months were as far south as 35°N, 53°W. Assuming a pathway as sketched in Fig. 5, this movement corresponds to a mean speed of over 0.05 m s^{-1} (although the floats actually traveled much faster given their convoluted trajectories).

Once south of the Grand Banks the lens could be advected rapidly by the 0.10 m s^{-1} westward velocities found in the two-year current meter means at 600 m in the recirculation gyre south of the Gulf Stream near 36°N, 55°W (Schmitz 1980). If this speed could be maintained until 62°W, then that distance could be traversed in 2.5 months. A conservative average of 0.05 m s^{-1} results in a 5-month travel time.

Assuming the lens drifts to the southern flank of the recirculation gyre by either self-advection or by the time-varying large-scale flow, the waters may not get reentrained into the Gulf Stream but turn south (and perhaps even east) in the the ‘‘C-shaped’’ recirculation discussed by Reid (1978) and shown in Schmitz and McCartney (1993), or the more elliptical circulation on the 27.0 σ_θ surface as shown by Lozier et al. (1995). Such circulation would advect the lens farther south and closer to where the Bahamas lens was found. Of special significance is the observation of an anticyclonic lens at 31°N, 70°W (only 7° north of the Bahamas lens) thought to originate in the Labrador Sea (Elliott and Sanford 1986). Near this same location Owens et al. (1982) has presented results from a 15-month current meter mooring showing speeds at 825 m of 0.024 m s^{-1} to the southwest. If this speed is used, then the lens could be advected from 35°N, 62°W to the Bahamas site at 24°N, 70°W in 27 months. If the speed was increased by 0.01 m s^{-1} for self-advection of the eddy, the time decreases to 19 months. Thus, at reasonable, even conservative, estimates of the mean speeds and directions in the North Atlantic at the depths of the NWC and Bahama lenses, a lens might be able to tra-

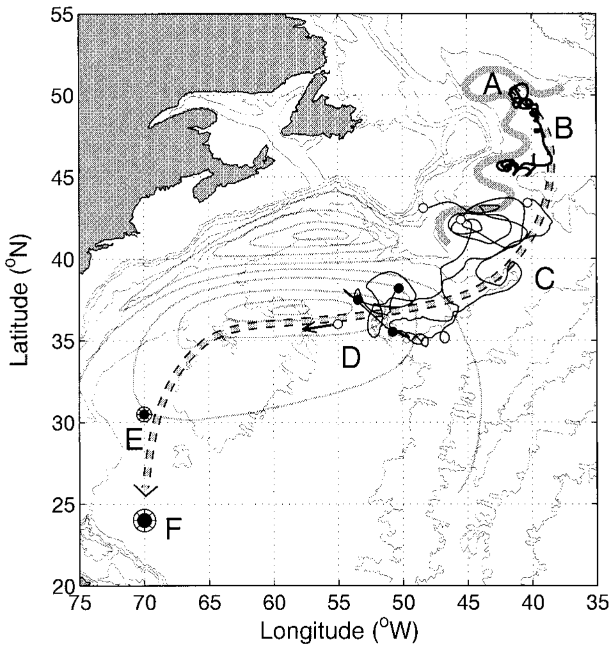

FIG. 5. Summary of a proposed pathway of a NWC lens to the site of the McDowell and Rossby (1978) eddy. (A) The northwest corner. (B) The trajectory of the NWC eddy from near its formation site to 45°N. (C) The trajectories of three North Atlantic Current RAFOS floats all on the 27.2 σ_θ density surface (Anderson-Fontana et al. 1996) and deployed around 43°N (open circles). These floats migrated to the south as far as 35°N and as far west as 53°W (solid circles) within 10 months. (D) Schematic of the Gulf Stream recirculation gyres (adapted from Hogg (1992), along with velocity vector at 600 m from Schmitz (1980). (E) Position of the Elliott and Sanford (1986) eddy, which they suggest originated in the Labrador Sea, and (F) position of the Bahamas eddy of McDowell and Rossby (1978). The thick gray dashed line is a hypothesized route of an eddy from the northwest corner to the Bahamas. The route follows the southerly flows east of a high pressure ridge offshore of the NAC, the trajectories of the RAFOS floats that crossed from the Newfoundland Basin into the recirculation gyre south of the Gulf Stream, the streamlines of the recirculation gyre parallel to the velocity vector of Schmitz (1980), and past the location of the Labrador Sea eddy of Elliott and Sanford (1986).

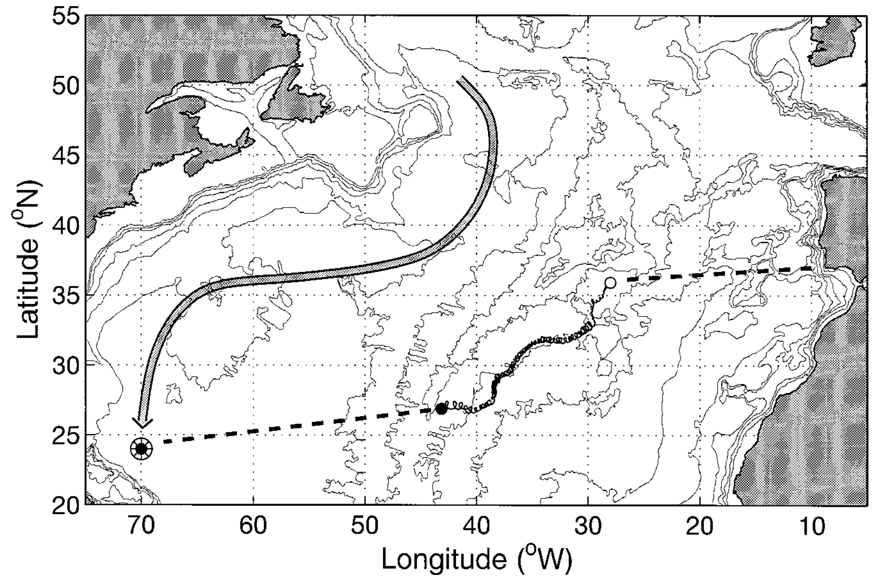

FIG. 6. Comparison of the proposed pathway of a NWC lens (thick gray line) to that of Richardson and Tychensky (1998). The Richardson and Tychensky eddy's trajectory begins with a open circle and ends with a closed circle. The dashed lines on either side are hypothesized trajectories by which the eddy originates near the Mediterranean outflow and ends near the Bahamas.

verse the distance from the NWC to the site of the Bahamas lens in less than three years.

Recently, Richardson and Tychensky (1998) reported on a meddy in the eastern Atlantic tracked by a RAFOS float. This meddy was found approximately 1700 km from Cape St. Vincent and translated an additional 1700 km to the southwest over the next 1.5 years, at an average speed of 0.036 m s^{-1}. The trajectory of this meddy is shown in Fig. 6, along with the hypothesized pathway of a NWC lens presented above. Richardson and Tychensky (1998) calculated the meddy to be about 2.8 years of age when tracking ceased and estimate that an additional 1.4 to 2.1 years would be needed to reach the Bahamas site, giving a final travel time of 4.2 to 4.9 years, significantly longer than the NWC lens estimate. In addition, the C-shaped recirculation currents in the western North Atlantic between the latitudes 25°N and 30°N are actually eastward (Reid 1978), thus would oppose the westward movement of meddies.

Even without interaction with topography, thermocline eddies will decay over time and lose the property anomalies of their core waters. The meddy best studied for its structure and rate of decay is Meddy Sharon in the eastern Atlantic (Armi et al. 1989; Hebert et al. 1990; Schultz Tokos and Rossby 1991). This lens was found near 32°N, 22°W, about 1200 km from Cape St. Vincent, and was about two years old (Richardson and Tychensky 1998). At that time its pycnostad was 600 m thick with a core radius of 25 km. Two years later, a survey found Sharon to have no discernible core but with central water properties of 10.0°C and 35.7 psu. The meddy shown in Fig. 6 (Richardson and Tychensky 1998) had core properties of 11.0°C and 36.1 psu after three years. The dimensions of the lens near the NWC and lenses near Cape St. Vincent appear to be comparable in radius, although the NWC lens does not have the elevated temperature and salinity of a newly formed meddy. From Bower et al. (1995), the largest coherent orbital float tracks in the vicinity of newly formed meddies off Portugal had a diameter of almost 100 km. Similarly, other floats near float 316 in Fig. 1 had orbits of about 100 km, but these floats left the area after only one to two weeks.

4. Summary

In this note, an eddy formed near the northwest corner of the North Atlantic Current is described based on observations from a RAFOS float. The eddy had water properties (10.8°C, 35.4 psu) similar to that of a meddy found near the Bahamas (11.0°C, 35.6 psu) (McDowell and Rossby 1978). A hypothesis is presented such that eddies formed in the NWC could be subducted and advected to the Bahamas site more quickly and with much less chance of catastrophic topographic interaction than an eddy formed near the Iberian Peninsula, thus making the NWC a possible source of the original meddy.

Acknowledgments. This project was supported by a National Science Foundation Grant 9531878 and a joint National Science Foundation and Office of Naval Research Grant N0001492J1651. The RAFOS float data were obtained through the considerable engineering efforts of Jim Fontaine and the computer processing skills of Sandra Anderson-Fontana. The many dissusions among the RAFOS and NAC research group led to this paper, which was greatly improved following the comments of two anonymous reviewers.

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