2002

# Two Circulation Regimes of the Mediterranean Outflow Revealed by Lagrangian Measurements

Michael Sparrow

Olaf Boebel
*University of Rhode Island*

Vassilis Zervakis

Walter Zenk

Alán Cantos-Figuerola

*See next page for additional authors*



## Citation/Publisher Attribution

Sparrow, M., Boebel, O., Zervakis, V., Zenk, W., Cantos-Figuerola, & Gould, W. J. (2002). Two Circulation Regimes of the Mediterranean Outflow Revealed by Lagrangian Measurements. *Journal of Physical Oceanography, 32*, 1322-1330. doi: 10.1175/1520-0485(2002)032<1322:TCROTM>2.0.CO;2
Available at: https://doi.org/10.1175/1520-0485(2002)032<1322:TCROTM>2.0.CO;2

# Two Circulation Regimes of the Mediterranean Outflow Revealed by Lagrangian Measurements

MICHAEL SPARROW,*,** OLAF BOEBEL,+ VASSILIS ZERVAKIS,# WALTER ZENK,@
ALÁN CANTOS-FIGUEROLA,* AND W. JOHN GOULD&

*AINCO-Interocean, Madrid, Spain
+Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island
#National Centre for Marine Research, Athens, Greece
@Institut für Meereskunde an der Universität Kiel, Kiel, Germany
&Southampton Oceanography Centre, Southampton, United Kingdom

(Manuscript received 3 April 2001, in final form 20 August 2001)

ABSTRACT

The Eurofloat experiment was a joint initiative to examine the large-scale spreading of Mediterranean Water (MW) and Labrador Sea Water in the northeast North Atlantic. RAFOS float data from the southern (MW) portion of the Eurofloat experiment have been examined in conjunction with historical float data in order to calculate quasi-Eulerian means in an effort to separate and quantify the constituents of the spreading of the MW tongue east of the Mid-Atlantic Ridge. While recent studies focussed chiefly on the role of meddies in the shaping of the MW tongue, this analysis also examines the tongue's second constituent, that is, the ''background'' (non-meddy advective and diffusive) flow. The results suggest the existence of two regimes approximately to the north and south of the 36°N parallel (i.e., the latitude of the Gulf of Cadiz), which are distinguished by different types of dominant spreading mechanisms for MW. To the south of the Gulf of Cadiz, the background flow shows an incoherent and weak mean, whereas the mean velocity of the salt enhanced meddies is strong and to the southwest. In contrast, to the north of 36°N the mean velocity of the meddies seems to be less pronounced and the background flow is shown to be a major component in the northwestward spreading of the MW tongue. The two regimes are separated by the Azores Current, which previously has been hypothesized to act as a dynamic barrier to the southward advective spreading of the background regime, which the meddies are able to penetrate because of their high kinetic energy. Overall, the meddies are calculated to contribute to approximately half of the total salinity anomaly flux.

## 1. Introduction

The Mediterranean salt tongue (Fig. 1) dominates the salinity distribution of the main thermocline in the North Atlantic. It consists of Mediterranean Water (MW) characterized by anomalously high temperatures (≈7°–11°C) and salinities (≈35.1–36.0) centred at a depth of about 1100 m (e.g., Richardson et al. 1989).

The existence of the Mediterranean salt tongue used to be interpreted as a result of a balance between slow advection and turbulent diffusion from its source in the Gulf of Cadiz (e.g., Defant 1956; Joseph and Sendner 1958; Richardson and Mooney 1975). However, further analyses (e.g., Reid 1978; Daniault et al. 1994; Käse and Zenk 1996) have revealed that the salt tongue does not simply spread radially from its source, but rather is limited to the south and north by eastward advection of freshwater masses from the South Atlantic (Antarctic Intermediate Water) and the Labrador Sea [Subarctic Intermediate Water and Labrador Sea Water (LSW)], respectively.

Geostrophic analyses do not show a smooth current field within the salt tongue (e.g., Käse and Zenk 1996). The main reason for this is the existence of anticyclonic Mediterranean salt lenses known as meddies containing large amounts of original Gibraltar Overflow Water in their interior (e.g., McDowell and Rossby 1978; Armi and Zenk 1984; Käse et al. 1985; McWilliams 1985; Käse and Zenk 1996; Bower et al. 1997; Richardson et al. 2000).

Meddies are distinguished by their high salt and heat content, up to 1 unit of salinity and 4°C greater than their surrounding environment (e.g., Richardson et al. 2000). These meddies have been shown to release highly saline water into their surroundings, either gradually (e.g., Armi and Zenk 1984; Schultz Tokos and Rossby

** Current affiliation: Southampton Oceanography Centre, Southampton, United Kingdom.

*Corresponding author address:* Dr. Michael Sparrow, James Rennell Division (269/19), Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH, United Kingdom.
E-mail: mdsp@soc.soton.ac.uk

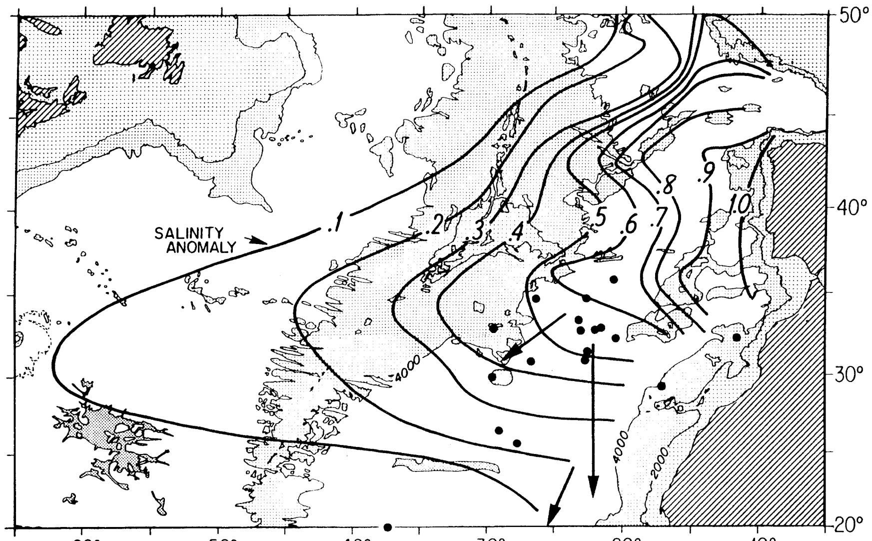


FIG. 1. Mediterranean Water tongue in the North Atlantic. The salinity anomaly is relative to 35.01 on the potential density surface 27.7 (approximately 1100 m). Displacement vectors are of three meddies observed by Richardson et al. (1989). Dots are other meddy observations. (From Richardson et al. 1989.)

1991) or catastrophically, when they collide with seamounts (e.g., Richardson et al. 2000). The meddies hence represent an alternative mechanism for the distribution of salt, independent of the overall advective/diffusive background transport (Käse and Zenk 1996). The relative importance and strength of these two constituents has long since been an issue of debate. Estimates of the meddies' contribution to the total salinity anomaly flux vary hugely. They include 25% (Richardson et al. 1989), more than 50% (Arhan et al. 1994), and almost 100% (Mazé et al. 1997).

A recently proposed feedback mechanism between the meddies and the background flow further complicates the estimate of their relative importance. Stephens and Marshall (1999) suggest that where meddies are dissipated by collisions with seamounts there will be a localized release of water into an isopycnal layer. They argue that this can be viewed as a convergence of the bolus transport, driving a southward flow in the subtropical gyre and generating large recirculations that extend across the Atlantic to the western boundary of the salinity tongue, in effect shifting the tongue equatorward.

There have been several attempts to quantify the overall circulation in the northeast North Atlantic at the depth of the MW tongue (e.g., Reid 1978; Saunders 1982; Sy 1988; Daniault et al. 1994; Arhan et al. 1994; Mazé et al. 1997; Paillet and Mercer 1997). However, these studies often do not give consistent results. There are two main reasons for this. First, the presence of meddies ''contaminates'' the velocity field. It has been estimated that at any one time there are at least 29 meddies in the North Atlantic (Richardson et al. 2000). Any transport estimates have to parameterize these vortices, which can often be difficult.

Second, in estimating the transport across a section using geostrophy, knowledge of a level of known motion is required. In the North Atlantic, this is a difficult requisite as water masses move in different directions at varying depths. Saunders (1982) attempted to solve this problem by choosing the absolute velocity on different sections so that the transport satisfied the Sverdrup relation. He found that between 850 and 1200 m (the depth of the MW) there was weak southward flow south of the Gulf of Cadiz (~36°N) and weak northward flow to the north. However, Paillet and Mercer (1997), on carrying out an inverse analysis, noted no such northward flow. This discrepancy clearly demonstrates the problem of not having a reliable depth of known motion.

As a first step to unravel the circulation at the depth of the MW, numerous neutrally buoyant floats (of the RAFOS and SOFAR types) have been deployed in the Mediterranean salt tongue and into meddies in particular. Floats are uniquely suited to differentiate between the meddy and ''background'' (non-meddy advective and diffusive) flow field due to the meddy's characteristic circulation pattern being reflected in the float's trajectory. The meddy and background components of the flow may thus be separated, removing a source of possible (aliasing) error in the mean flow estimates and allowing a quantitative estimate of the relative strength of the meddy and non-meddy contribution within the overall circulation.

An added advantage is that absolute velocities can be estimated from the float data, so there is no need to estimate a level of known motion, removing a major source of uncertainty. This is of particular importance for the description of the expectedly sluggish background flow, the study of which is the major issue that sets this analysis of neutrally buoyant float velocity data apart from previous analyses of meddies alone.

Recently another species of eddy has obtained increased attention: In repeated cases, cyclones have been detected in the vicinity of meddies (Käse and Zenk 1996; Richardson et al. 2000). However, due to the scarcity of such cases we have restricted ourselves here to meddies, neglecting their occasionally observed dipole structure (Oliveira et al. 2000).

## 2. Data and methods

The Eurofloat experiment was part of an international effort funded by the European Commission MAST II programme to investigate the circulation of intermediate and deep (900–1800 m) water masses (MW and LSW) in the eastern North Atlantic Ocean. The project involved Lagrangian studies using neutrally buoyant RAFOS (e.g., Rossby et al. 1986) and Marvor floats (e.g., Ollitraut et al. 1995), complemented by modeling work. In this study we shall be studying the intermediate depth RAFOS float data, while results from the deeper Marvor float data (LSW part of the experiment) and the modeling work have been published in separate articles (Speer et al. 1998; O'Dwyer et al. 2000).

Thirteen RAFOS floats were deployed in the region between the Azores and the Canary Islands from the F/S *Poseidon* between September and October 1995 (at an average depth of 930 $\pm$ 50 dbar). The quantity of data recorded by each float varied, partly because the floats were programmed for different mission lengths, but also due to the early surfacing of some floats thought to be caused by seawater leakage (the longest period any of the floats remained in mission was 21 months).

In order to broaden and increase the data coverage of the region and to obtain more accurate estimates of Eulerian velocities, the data were supplemented with historical observations at the depth of the MW: SOFAR floats from the Mediterranean Outflow Experiment (MOE; Armi et al. 1989; Richardson et al. 1989; Spall et al. 1993; Richardson et al. 2000) and RAFOS floats from the Institut für Meereskunde Programme SFB133 (Käse and Zenk 1996; Richardson et al. 2000), the Semaphore Experiment (Richardson and Tychensky 1998; Richardson et al. 2000), and AMUSE (Bower et al. 1997; Richardson et al. 2000). In all, almost 96 years of float data were available for this analysis. These data are distributed over an area covering nineteen 5° by 5° boxes. The WOCE criterion for determining the mean flow (WCRP 1988a,b) calls for 5 years of float data in each 5° by 5° box. This condition is satisfied for the area as a whole and for 9 out of 19 of the individual boxes.

In order to try to understand the different roles played by meddies and the mean background flow, the data were split into two groups. The gradation was achieved by examining the individual float tracks (as floats caught within meddies exhibit tight, anticyclonic spirals) and in situ temperature from the floats' temperature sensors, which have an estimated precision of 0.02°C in the case of the RAFOS floats (Boebel et al. 1999). Data from floats outside of meddies were considered representative of the background flow (Fig. 2a) and those within, part of the meddy group (Fig. 2b). In many cases individual float tracks were split into two or more meddy and nonmeddy (background) components.

The ratio of float data in the meddy group to that in the background group was approximately 1:3 or 24 float years versus 72 float years (though it must be remembered that floats were often purposely launched in meddies, so the actual probability of launching a float in a meddy in the ocean is much smaller). In addition, it should be noted that Richardson (1993), by examining historical float data within eddies, showed that the northeast North Atlantic contained anticyclones of roughly the same size as meddies, though with slower swirl speeds and weaker warm core anomalies. In this analysis all are treated as part of the meddy group since similar propulsion mechanisms are likely to apply for both types of anticyclones and both are discrete sources of high salinity water.

## 3. Calculation of Eulerian means

Mean quasi-Eulerian velocities can be calculated from the float data by averaging all the Lagrangian velocity information within a certain area or "box." Using a smaller box size gives more resolution, but increases the uncertainty of the mean. Let $u$ and $v$ be the zonal and meridional components of the velocities. The mean velocities, $U$, $V$, and the standard deviation, $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$ (where $u' = u - U$), due to the eddy field are first calculated. Following a modified form of Krauss and Böning (1987), the means and their associated uncertainties are presented as

$$U \pm \frac{0.9\sqrt{\overline{u'^2}}}{\sqrt{Nm}}, \tag{1}$$

where $Nm = (N \times Dt)/2T$ and $N$ is the total number of observations, $Dt$ is the sampling interval, $T$ is the Lagrangian integral timescale, and $Nm$ is the number of statistically independent data (number of degrees of freedom). The second term of (1) gives a 63% confidence interval according to the Student's t-test (Krauss and Böning 1987; Riser and Rossby 1983; Flierl and McWilliams 1977) for $Nm > 10$ (Ollitrault 1994).

Estimates of the Lagrangian timescale of the background flow were made using Taylor theory (Taylor 1921), where $T$ was found to vary between 3.5 and 12 days (depending on the area studied), though the uncertainties associated with these estimates were large. Therefore, the decision was made to follow Ollitrault

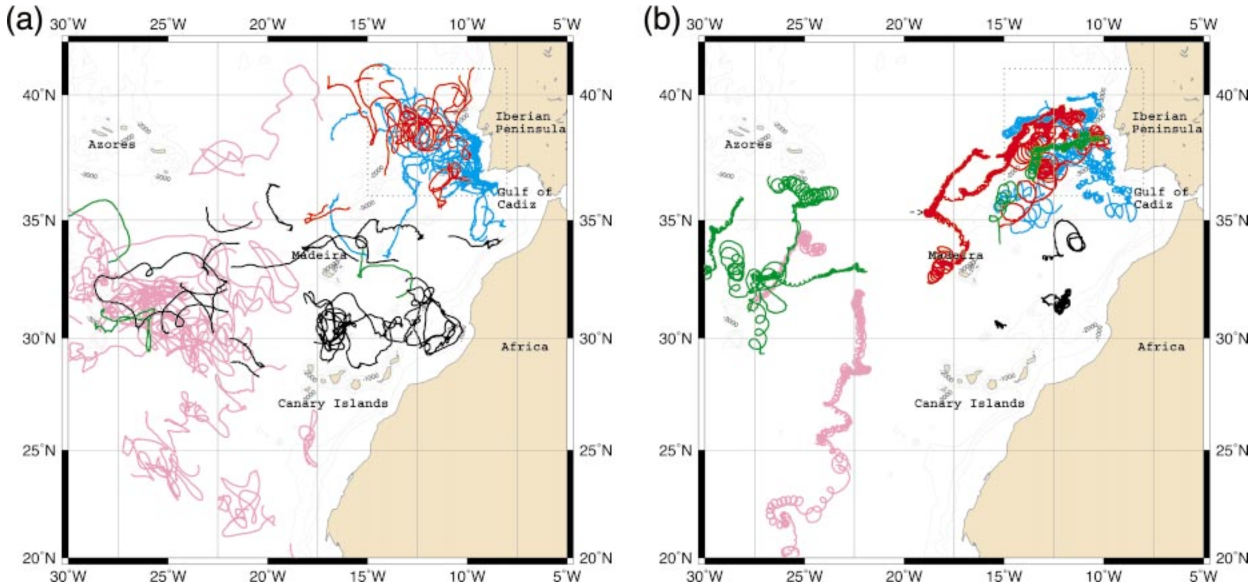


FIG. 2. (a) Background group of floats. Black float tracks are Eurofloats, pink are MOE floats, red are SFB113 floats, blue are AMUSE floats, and green are floats from the Semaphore Experiment. The 5° × 5° grid is superimposed. The dashed box shows the area shown by Fig. 3c. Bathymetry every 1000 m down to 3000 m is also shown. (b) Meddy group of floats. The color designations, grid, dashed box, bathymetry is the same as in (a). The black arrow north of 35°N shows the collision location of the meddy pathway with the Azores Current (Käse and Zenk 1996).

(1994) and use a value of $T = 5$ for the background flow.

The uncertainties in the velocities of the meddy data would be unrealistically large if based upon the rotating paths of the meddies. For this reason, these data were filtered with a third-order 32-day Butterworth filter and the error estimates based on these smoothed velocities. Thirty-two days was chosen as the filter length as it is the longest rotational period associated with the meddy data (see section 5). In this case, integral timescales were calculated to be 12 days in the zonal direction and 15 days in the meridional. Note that the difference between $T = 5$ days for the background flow and $T = 12$ to 15 days for the meddy motion implies that the meddy motion is less prone to perturbations through external factors.

The area covered by the float data is divided into grid boxes, and means and associated uncertainties are calculated. Different box sizes were tried and for the whole area of study a 5° × 5° grid was found to give a suitable balance between resolution and uncertainty of the means (Figs. 3a,b). The amount of data in each box ranged between 61 and 6840 for the background group and 109 and 2066 for the meddy group on the 5° × 5° grid. Means calculated for $N \leq 60$ are not shown. It should be noted that the condition for $Nm > 10$ is satisfied in all boxes except for that at 37.5°N, 30°W in the meddy data ($Nm = 4.5$) and at 42.5°N, 20°W in the background group ($Nm = 6.1$).

To examine the flow structure in more detail, a 1° × 1° analysis was performed in the area off the Iberian Peninsula where the data density was high (see Figs. 2a,b and 3c). In order to be able to interpret the diagram more easily, in this case the errors have not been included. However, only those grid points where N was greater than 37 are shown (corresponding to 5 and 2 degrees of freedom for background and meddy flow, respectively). In the 1° × 1° grid, the amount of data in each grid point varied between 38 and 390 for the background group and 41 to 173 for the meddy group.

## 4. Results

Figure 3a shows the Eulerian means calculated for the background group of floats on the 5° × 5° grid. The background flow can be split into two regions separated by the 36°N parallel (the approximate latitude of the Gulf of Cadiz). South of 36°N, the mean velocities are generally small and show no consistent flow direction. The overall mean background flow for this region is equal to 0.12 ± 0.05 cm s$^{-1}$ (or 0.12 ± 0.12 cm s$^{-1}$ at 95% confidence intervals) at an angle of 246°.

An apparent flow divergence exists along the 22°W meridian, between 25° and 36°N. This near zero flow regime is confirmed by results from a seven year current meter record at 33°N, 22°W (KIEL276, star in Fig. 3a) at 1000-m depth, which showed mean velocities of only 0.30 ± 0.79 cm s$^{-1}$ to the west and 0.15 ± 0.61 cm s$^{-1}$ to the north (Zenk and Müller 1988).

In contrast, north of 36°N the mean flow usually has a significant northern component (the exception being at the grid point centerd at 37.5°N, 15°W where the flow is almost entirely westward). Near the coast of Portugal this is to be expected as MW is carried northwards by

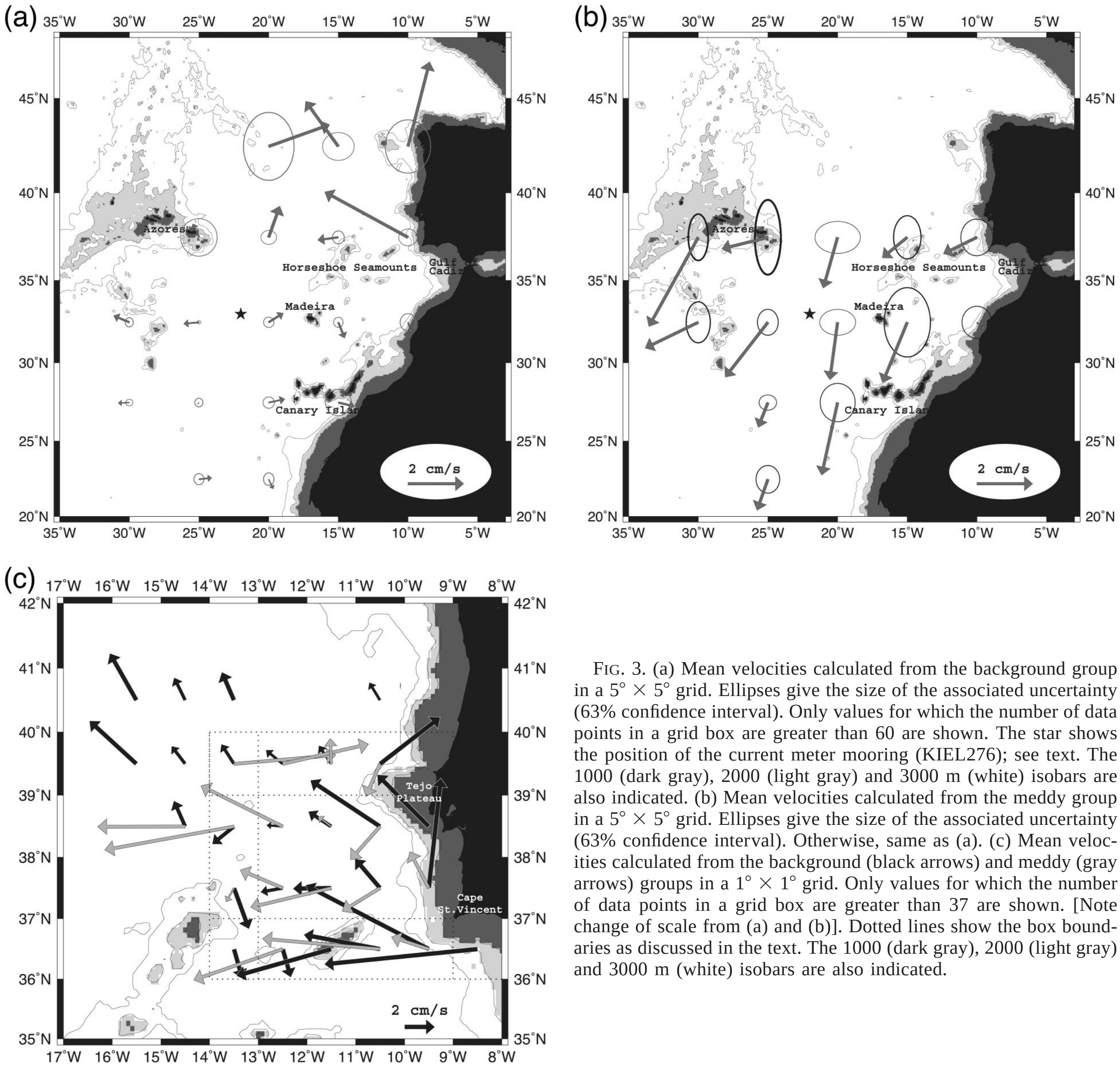


FIG. 3. (a) Mean velocities calculated from the background group in a 5° × 5° grid. Ellipses give the size of the associated uncertainty (63% confidence interval). Only values for which the number of data points in a grid box are greater than 60 are shown. The star shows the position of the current meter mooring (KIEL276); see text. The 1000 (dark gray), 2000 (light gray) and 3000 m (white) isobars are also indicated. (b) Mean velocities calculated from the meddy group in a 5° × 5° grid. Ellipses give the size of the associated uncertainty (63% confidence interval). Otherwise, same as (a). (c) Mean velocities calculated from the background (black arrows) and meddy (gray arrows) groups in a 1° × 1° grid. Only values for which the number of data points in a grid box are greater than 37 are shown. [Note change of scale from (a) and (b)]. Dotted lines show the box boundaries as discussed in the text. The 1000 (dark gray), 2000 (light gray) and 3000 m (white) isobars are also indicated.

the Mediterranean Undercurrent (MU; e.g., Bower et al. 1997; Price and O'Neil-Barringer 1994). The overall mean background flow north of 36°N is equal to 1.8 ± 0.3 cm $s^{-1}$ (or 1.8 ± 0.6 cm $s^{-1}$ at 95% confidence intervals) at an angle of 303°.

More detail of the flow structure of the MU is provided by the high resolution 1° × 1° grid analysis (Fig. 3c). The MU can be observed following the coast of Portugal with associated velocities as high as 10.1 ± 3.7 cm $s^{-1}$. Results from long-term Eulerian observations at 1000-m depth (Daniault et al. 1994) at 40.08°N, 9.85°W give an average speed of 6.6 cm $s^{-1}$, which is less than the maximum velocities observed from the 1° × 1° grid, but close to the 5.0 ± 2.5 cm $s^{-1}$ from the nearest grid point at 39.5°N, 10.5°W.

Away from the coast, the background flow still has a significant northward component at the depth of the MW (see Fig. 3a). In the 1° × 1° grid, away from the MU, the background flow shows a general trend to the northwest, the exceptions being the vectors south of 38°N. Strong northward flow was observed by Mazé et al (1997) at 43°N, 12°–13°W, which they considered to be due to meandering of the MU. Saunders (1982) observed a weak northward transport across 41.5°N drawn from the western North Atlantic. He suggested that, by entrainment, this could assist the northward spreading of MW. Such a flow drawn from the western North Atlantic is also observed in the results of Reid (1978), but is not seen in the studies of Paillet and Mercer (1997) or Stephens and Marshall (1999). There is some evidence for such a flow from the Eulerian mean centered at 42.5°N, 20°W (Fig. 3a), but without more data to the west of this grid point it is impossible to draw any firm conclusions.

The meddy Eulerian means (Fig. 3b) tend to show faster velocities both north and south of the Gulf of Cadiz. They demonstrate a more consistent flow direction than the corresponding background flow. The mean flow is always to the southwest (with the exception of the mean at 32.5°N, 10.0°W, but here the velocity is very small compared to the uncertainty). The overall average for all the meddy data is 1.4 ± 0.2 cm s$^{-1}$ (1.4 ± 0.5 cm s$^{-1}$ at 95% confidence intervals) at an angle of 220°. This compares to typical meddy mean velocities of 2 cm s$^{-1}$ to the southwest observed by Richardson et al. (2000).

From the 1° × 1° data set (Fig. 3c), several observations may be made. The two meddy mean vectors along 9.5°W (at 36.5° and 37°N) roughly follow the path of the MU. However, west of 10.5°W, most of the vectors (representing meddies that have split from the MU) do not follow the background flow, revealing their independent nature in a significantly different flow field to that shown in Fig. 3b. The velocity vectors along 36.5°N show the path of the meddies formed at Cape St. Vincent as they travel in a curved path, eventually moving to the southwest (Fig. 2b).

## 5. Interpretation

These results suggest that two different types of spreading mechanisms are responsible for the shape of the MW tongue (east of the Mid-Atlantic Ridge, due to our data distribution). To the south of the 36°N parallel the background flow shows weak mean flow with little directional consistency, whereas the flow due to the presence of meddies is strong and to the southwest. Hence, within this area, it is dominated by meddy pathways (including their wakes and destruction), though it should be noted that a slow steady diffusion cannot be excluded.

To the north of 36°N, however, the background flow would seem to be the significant factor in the shaping of the MW tongue. A detailed study of meddy trajectories and characteristics has recently been carried out by Richardson et al. (2000). Their data also suggests that meddies move, on average, to the southwest, though near the Iberian coast (east of about 12°W) the meddies initially tend to be carried northwards by the MU, consistent with the results from the 1° × 1° grid (Fig. 3c). Therefore, at least near the Iberian coast, the meddies may still have a significant effect on the salinity anomaly north of 36°N.

These results lead to the following conceptual model in accordance with dedicated observations (Bower et al. 1997): Meddies are preferably formed from the MU near Cape St. Vincent (and also, to a lesser extent, at the Tejo Plateau to the north). Upon detachment, the meddies move westward into the Iberian Basin, with a significant number destroyed at the Horseshoe Seamounts

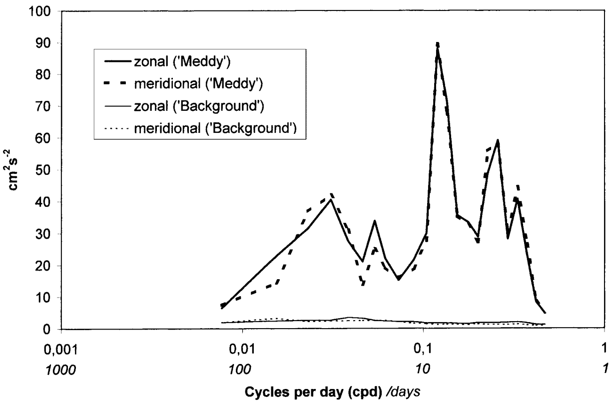


FIG. 4. Variance conserving spectral distributions of zonal (solid line) and meridional (dashed line) kinetic energy for the background (thin lines) and meddy (thick lines) groups of floats using all available data divided into 128 day segments.

(e.g., Richardson et al. 2000). The salt released here contributes directly to the northern background salt-transport to the northwest. Meddies that circumvent the Horseshoe Seamounts tend to follow a curved path before moving to the southwest. They eventually provide a source of salt for the southern part of the Mediterranean salt anomaly, which, conceivably has a second source at its easternmost limit by means of meddies that escaped the Gulf of Cadiz directly to the south.

Examination of the Lagrangian Kinetic Energy spectra calculated for all of the float data (Fig. 4) demonstrates the peak energies associated with the meddy group are much higher (89 cm$^2$ s$^{-2}$) than the background data (3 cm$^2$ s$^{-2}$) because of the higher rotational velocities associated with the former. The two energy peaks of 89 cm$^2$ s$^{-2}$ at approximately 9 days and 41 cm$^2$ s$^{-2}$ at 32 days correspond to meddies, as well as the anticyclones observed by Richardson (1993) and Oliveira et al. (2000), which are roughly the same size as meddies but with a slower rotation period and weaker warm core anomaly.

Following a suggestion originally made by Sy (1988), it may be that the Azores Current (AC), which is the Mid-Atlantic Ridge at about 34°–36°N, acts as a dynamic barrier to the advective southward spreading of the MW. In contrast, the meddies are able to penetrate this barrier because of their high kinetic energy. Such meddy interaction with the AC can be seen by the unusual southeastern displacement of one float in Fig. 2b.

The inherent average velocity of the meddies relative to the background flow can be determined by subtracting the northern/southern background average vectors from the respective meddy estimate. This results in average velocities of 2.3 ± 0.6 cm s$^{-1}$ at 160° north of 36°N and 1.3 ± 0.5 cm s$^{-1}$ at 218° south of 36°N. This clearly shows that the meddies are not simply advected by the background flow at the depth of the MW in either of the two regions.

The cause of this resultant southwestward meddy motion is still under investigation. McDowell and Rossby (1978) suggest the $\beta$ effect is responsible for the westward movement of mesoscale eddies. Nof (1982), using a three-layer model (one layer representing the meddy) concluded that the $\beta$-induced westward drift is slow, citing a figure of $7.4 \times 10^{-2}$ cm s$^{-1}$ for meddies observed off the Bahamas. He concluded that the presence of advection is required to reproduce the observed velocities of meddies.

Richardson et al. (1989) and Hogg and Stommel (1990) suggest a possible connection with the flow field above 800 db, as in the upper layers the mean flow field is generally southwestward, increasing in speed toward the surface (Saunders 1982).

Another hypothesis (Käse et al. 1989; Käse and Zenk 1996) is that the westward translation of the meddies is mainly due to accompanying cyclonic partner eddies (vortex pairs), dislocated from the meddy core. Recent observations by Richardson et al. (2000) suggest that such features may be commonplace and might even be observed in satellite data if adequate in situ calibrations were available (Oliveira et al. 2000).

The cyclonic partner eddy scenario also provides a plausible explanation for the stalling (lack of migration) of meddies observed repeatedly in the meddy trajectories at points where they change direction. However, simple vortex pair dynamics would suggest the cyclone–meddy pair would translate in a straight line, so it would seem necessary for other forces to be acting upon the vortex pair. Such an effect could quite easily be generated by a connection to the surface flow or the $\beta$ effect.

## 6. Transport estimates

Regardless of the actual mechanism responsible for the meddies differential propagation, an estimate of the meddies' contribution to the total salinity anomaly flux is necessary when determining the relative importance of the meddies. Superimposed on the $1° \times 1°$ mean velocities of Fig. 3c is a box enclosing the area of this study with the highest data density. Continuity implies that the volume of fluid entering this box at its southeastern border must equal the volume of fluid leaving the northern, western, and southern boundaries.

It is well documented that the MU follows the northern rim of the Gulf of Cadiz (e.g., Bower et al. 1997). It can be assumed that the mean vector centered at 36.5°N, 8.5°W represents the majority of the transport associated with the MU. As the flow has not yet reached any of the promontories where meddies are formed, it represents the total inflow into the box.

In order to calculate the transport into and out of the box, an assumption must be made about the depth of the MW layer. For this calculation a core MW thickness of 350 m is assumed. This choice is justified by noting that the study of Saunders (1982) shows the mean flow to be significantly different from that of the MW above 850 m and below 1200 m. (In fact, the choice of the MW thickness will not affect the final meddy to background ratio.)

Using the velocity estimate centered at 36.5°N, 8.5°W, the inflow to the box is calculated to be $3.9 \pm 2.2$ Sv (1 Sv $= 10^6$ m$^3$ s$^{-1}$). This is within the range of previous estimates of the transport of the MU, which vary from 2.9 Sv (Zenk 1975) to 6.5 Sv (Howe 1984).

The transport associated with the meddies can be estimated from

$$\begin{aligned}&\text{meddy transport}\\&\quad = (\text{western boundary area}\\&\qquad \times \text{westward meddy velocity} \times dX)\\&\qquad + (\text{southern boundary area}\\&\qquad\quad \times \text{southern meddy velocity} \times dY),\end{aligned} \tag{2}$$

where $dX$ and $dY$ describe the ratio of the respective boundary that is, on average, occupied by meddies. Each boundary area is equal to the length of the boundary multiplied by the MW depth of 350 m. To a first approximation, only the average westward meddy velocities within the box ($1.8 \pm 0.7$ cm s$^{-1}$) are significant (average southward meddy velocity $= 0.1 \pm 0.8$ cm s$^{-1}$).

A meddy centered on the western boundary would occupy 18% of the length of the boundary (assuming an average meddy diameter of 100 km). A single meddy can be calculated to occupy the boundary for 64 days a year (a ratio of 0.18). Hence, if only one meddy crossed the boundary a year, $dX$ would equal 18% of 0.18, or 0.032.

However, in the Iberian Basin, Richardson et al. (2000) calculated that 17 meddies a year are formed with an average lifetime of 256 days. Moving westward at 1.81 cm s$^{-1}$, a single meddy will remain within the box for 272 days. Thus, an average of 16 meddies will make it across the western boundary, and $dX$ is therefore equal to $16 \times 0.032 = 0.51$.

Therefore [neglecting the southward component in (2)], the meddy transport can be calculated to be $1.8 \pm 0.7$ Sv.

Averaging all the data within one degree of the box's boundary, the background outflow is $3.2 \pm 2.1$ Sv (taking into account the percentage of the western boundary that is, on average, occupied by meddies).

The total outflow (background plus meddy) is therefore equal to $5.0 \pm 2.2$ Sv, which, compared to the inflow of $3.9 \pm 2.2$ Sv demonstrates that, within the limits of the uncertainties, volume (and hence, to a first approximation, mass) is conserved within the box.

Knowing the transport associated with the meddy and background flow, the meddies can be calculated to be responsible for approximately a third of the total volume transport out of the box. However, it is the ratio of meddy to background contribution to the salinity anomaly that is of interest in this study. Relative to 35.01, the background salinity ranges from 35.1 to 36.0 (Fig.

1). A meddy typically has an associated salinity 0.2–1.0 higher than its surrounding environment (e.g., Armi et al. 1989).

Taking an ''average'' background salinity of 35.6 and an ''average'' salinity of 36.2 (0.6 higher than the background) for the meddies, the meddies can be calculated to be responsible for 53% ± 28% of the salinity anomaly relative to 35.01. This compares with 25% (based on 8–12 meddies formed a year with lifetimes of 2–3 years; Richardson et al. 1989), more than 50% (calculated from a hydrographic section along 15°W that crossed three meddies; Arhan et al. 1994) and almost 100% (based on hydrographic data off the Iberian Peninsula; Mazé et al. 1997).

## 7. Summary

This study has examined the propagation of floats caught within meddies compared to those advected by the mean background (nonmeddy advective and diffusive) flow. It is suggested that the background flow is the significant factor in the spreading of the Mediterranean Water tongue north of the approximate latitude (≈36°N) of the Gulf of Cadiz (at least away from the Mediterranean Undercurrent). However, to the south of this latitude the distribution of salt would seem to be mainly achieved by meddy migration (and destruction), the ''background'' flow being unable to cross the dynamic barrier of the Azores Current.

Meddies are preferably formed from the Mediterranean Undercurrent near Cape St. Vincent (and also, to a lesser extent, at the Tejo Plateau to the north). Upon detachment, the Meddies move westward into the Iberian Basin, with a significant number destroyed at the Horseshoe Seamounts (e.g., Richardson et al. 2000). The salt released here contributes directly to the northern background salt-transport to the northwest. Meddies that circumvent the Horseshoe Seamounts tend to follow a curved path before moving to the southwest. They eventually provide a source of salt for the southern part of the Mediterranean Salt Anomaly, which, conceivably has a second source at its easternmost limit by means of Meddies that escaped the Gulf of Cadiz directly to the south.

To the south of the Gulf of Cadiz, the overall mean background flow has a velocity of 0.12 ± 0.05 cm $s^{-1}$ at an angle of 246°; north of 36°N, the mean velocity is 1.8 ± 0.3 cm $s^{-1}$ at 303°. The overall average for all the meddy data is 1.4 ± 0.2 cm $s^{-1}$ at 220°. The inherent average velocity of the meddies relative to the background flow is 2.3 ± 0.6 cm $s^{-1}$ at 160° north of 36°N and 1.3 ± 0.5 cm $s^{-1}$ at 218° south of 36°N, clearly demonstrating that the meddies are not passively advected at the depth of the MW in either of the two regions.

By comparing the meddy and background components of the flow within a closed box, the meddies can be calculated to be responsible for 53% ± 28% of the salinity anomaly relative to 35.01. This compares to previous estimates of between 25% (Richardson et al. 1989) to almost 100% (Mazé et al. 1997).

Although the results from this article should help to explain why such different estimates are likely to occur (depending on whether the estimates are made north or south of the Gulf of Cadiz), it is clear that more long-term studies are required to further resolve these differences. In particular, a combination of an Eulerian current meter array that monitors the strength and structure of the MU south and west of southern Portugal, combined with a concurrent mesoscale resolving field of floats covering the western North Atlantic between 30° and 45°N (corresponding to roughly 1000 floats) would provide significant constraints on the relative importance of meddy versus background flow. The high number of floats renders such a study as currently too expensive, but hopefully a balanced combination of synoptic float surveys, hydrography, and satellite altimeter data might provide a reliable mesoscale resolving dynamic field for the intermediate layer in the near future.

*Acknowledgments.* We would like to thank Claudia Schmid for her guidance with the RAFOS data; Kathy Schultz Tokos who tracked most of the SFB floats; and Tom Rossby, Kevin Speer, and the anonymous reviewers of this manuscript for their helpful comments on the paper. We are also grateful to Phil Richardson for supplying Fig. 1. Officers and crew of the F/S *Alkor* and F/S *Poseidon* contributed significantly to the success of these programes during various cruises between 1992 and 1996. The Eurofloat project was funded by the European Commission MAST II Programme (MAS2-CT94-0102) and the Kiel (SFB 133) data were partly supported by the Deutsche Forschungsgemeinschaft, Bonn.

REFERENCES

Arhan, M., A. Colin de Verdière, and L. Mémery, 1994: The eastern boundary of the subtropical North Atlantic. *J. Phys. Oceanogr.,* **24,** 1295–1316.

Armi, L., and W. Zenk, 1984: Large lenses of highly saline Mediterranean Water. *J. Phys. Oceanogr.,* **14,** 1560–1576.

——, D. Herbert, N. Oakey, J. F. Price, P. L. Richardson, H. T. Rossby, and B. Ruddick, 1989: Two years in the life of a Mediterranean salt lens. *J. Phys. Oceanogr.,* **19,** 354–370.

Boebel, O., C. Schmid, G. Podestá, and W. Zenk, 1999: Intermediate water at the Brazil–Malvinas Confluence Zone: A Lagrangian view. *J. Geophys. Res.,* **104** (C9), 21 063–21 082.

Bower, A. S., L. Armi, and I. Ambar, 1997: Lagrangian observations of meddy formation during A Mediterranean Undercurrent Seeding Experiment. *J. Phys. Oceanogr.,* **27,** 2545–2575.

Daniault, N. J., P. Mazé, and M. Arhan, 1994: Circulation and mixing of the Mediterranean Water west of the Iberian Peninsula. *Deep-Sea Res. I,* **41,** 1685–1714.

Defant, A., 1956: Die Ausbreitung des Mittelmeerwassers im Nordatlantischen Ozean. *Deep-Sea Res.,* **3** (Suppl.), 465–470.

Flierl, G. R., and J. C. McWilliams, 1977: On the sampling requirements for measuring moments of eddy variability. *J. Mar. Res.,* **35,** 797–820.

Hogg, N. G., and H. M. Stommel, 1990: How currents in the upper

thermocline could advect meddies deeper down. *Deep-Sea Res.,* **37,** 613–623.
Howe, M. R., 1984: Current and hydrographic measurements in the Mediterranean Undercurrent near Cape St. Vincent. *Oceanol. Acta,* **7,** 163–168.
Joseph, J., and H. Sendner, 1958: Über die horizontale Diffusion im Meer. *Dtsch. Hydrogr. Z.,* **11,** 49–77.
Käse, R. H., and W. Zenk, 1996: Structure of the Mediterranean Water and meddy characteristics. *The Warmwater sphere of the North Atlantic Ocean,* W. Krauss, Ed., Gebrüder Borntraeger, 365–395.
——, ——, T. B. Sanford, and W. Hiller, 1985: Currents, fronts and eddy fluxes in the Canary Basin. *Progress in Oceanography,* Vol. 14, Pergamon, 231–257.
——, A. Beckmann, and H. H. Hinrichsen, 1989: Observational evidence of salt lens formation in the Iberian Basin. *J. Geophys. Res.,* **94,** 4905–4912.
Krauss, W., and C. W. Böning, 1987: Lagrangian properties of eddy fields in the northern North Atlantic as deduced from satellite-tracked buoys. *J. Mar. Res.,* **45,** 259–291.
Mazé, J. P., M. Arhan, and H. Mercier, 1997: Volume budget of the eastern boundary layer off the Iberian Peninsula. *Deep-Sea Res. I,* **44,** 1543–1574.
McDowell, S. E., and H. T. Rossby, 1978: Mediterranean Water: An intensive mesoscale eddy off the Bahamas. *Science,* **202,** 1085–1087.
McWilliams, J. C., 1985: Submesoscale coherent vortices in the ocean. *Rev. Geophys.,* **23,** 165–182.
Nof, D., 1982: On the movements of deep mesoscale eddies in the North Atlantic. *J. Mar. Res.,* **40,** 57–74.
O'Dwyer, J., R. G. Williams, J. H. Lacasce, and K. G. Speer, 2000: Does the potential vorticity distribution constrain the spreading of floats in the North Atlantic? *J. Phys. Oceanogr.,* **30,** 721–732.
Oliveira, P. B., N. Serra, A. F. G. Fùza, and I. Ambar, 2000: A study of meddies using simultaneous in-situ and satellite observations. *Satellites, Oceanography and Society,* D. Halpern, Ed., Elsevier Oceanographic Series, Vol. 63, Elsevier Science, 125–148.
Ollitrault, M., 1994: The TOPOGOLF experiment: Lagrangian data. IFREMER-Centre de Brest, 622 pp.
——, Y. Auffret, N. Cortès, C. Hémon, P. Jégou, S. Le Reste, G. Loaëc, and J. P. Rannou, 1995: The SAMBA experiment. Repères Océan, Vol. 1, SAMBA 1 Lagrangian and CTD Data, IFREMER Tech. Rep. No. 12, 488 pp.
Paillet, J., and H. Mercer, 1997: An inverse model of the eastern North Atlantic general circulation and thermohaline ventilation. *Deep-Sea Res.,* **44,** 1293–1328.
Price, J. F., and M. O'Neil-Barringer, 1994: Outflow and deep water production by marginal seas. *Progress in Oceanography,* Vol. 33, Pergamon, 161–200.
Reid, J. L., 1978: On the middepth circulation and salinity field in the North Atlantic Ocean. *J. Geophys. Res.,* **83,** 5063–5067.
Richardson, P. L., 1993: A census of eddies observed in North Atlantic SOFAR float data. *Progress in Oceanography,* Vol. 31, Pergamon, 1–50.
——, and K. Mooney, 1975: The Mediterranean outflow—A simple advection-diffusion model. *J. Phys. Oceanogr.,* **5,** 476–482.
——, and A. Tychensky, 1998: Meddy trajectories in the Canary Basin measured during the Semaphore Experiment, 1993–1995. *J. Geophys. Res.,* **103,** 25 029–25 045.
——, D. Walsh, L. Armi, M. Schröder, and J. F. Price, 1989: Tracking three meddies with SOFAR floats. *J. Phys. Oceanogr.,* **19,** 371–383.
——, A. Bower, and W. Zenk, 2000: A census of meddies tracked by floats. *Progress in Oceanography,* Vol. 45, Pergamon, 209–250.
Riser, S. C., and H. T. Rossby, 1983: Quasi-Lagrangian structure and variability of the subtropical western North Atlantic circulation. *J. Mar. Res.,* **41,** 127–162.
Rossby, T., D. Dorson, and J. Fontaine, 1986: The RAFOS system. *J. Atmos. Oceanic Technol.,* **3,** 672–679.
Saunders, P. M., 1982: Circulation in the eastern North Atlantic. *J. Mar. Res.,* **40,** 641–657.
Schultz Tokos, K., and T. Rossby, 1991: Kinematics and dynamics of a Mediterranean salt lens. *J. Phys. Oceanogr.,* **21,** 879–892.
Spall, M. A., P. L. Richardson, and J. Price, 1993: Advection and eddy mixing in the Mediterranean salt tongue. *J. Mar. Res.,* **51,** 797–818.
Speer, K. S., W. J. Gould, and J. H. LaCasce, 1998: Year-long trajectories of floats in Labrador Sea Water in the eastern North Atlantic Ocean. *Deep-Sea Res. II,* **46,** 165–179.
Stephens, J. C., and D. P. Marshall, 1999: Dynamics of the Mediterranean salinity tongue. *J. Phys. Oceanogr.,* **29,** 1425–1441.
Sy, A., 1988: Investigation of large-scale circulation patterns in the central North Atlantic: The North Atlantic Current, the Azores Current, and the Mediterranean Water plume in the area of the Mid-Atlantic Ridge. *Deep-Sea Res.,* **35,** 385–413.
Taylor, G. I., 1921: Diffusion by continuous movement. *Proc. London Math. Soc.,* **20A,** 196–221.
WCRP, 1988a: *Detailed Requirements.* Vol. I, *World Ocean Circulation Experiment Implementation Plan,* World Climate Research Programme Tech. Rep. WMO/TD-242.
——, 1988b: *Scientific Background.* Vol. II, *World Ocean Circulation Experiment Implementation Plan.* World Climate Research Programme Tech. Rep. WMO/TD-243.
Zenk, W, 1975: On the Mediterranean outflow west of Gibraltar. *''Meteor'' Forschungsergeb.,* **A16,** 23–34.
——, and T. J. Müller, 1988: Seven-year current meter record in the eastern North Atlantic. *Deep-Sea Res. I,* **35,** 1543–1574.