NOTES AND CORRESPONDENCE

Reconstructed Mediterranean Salt Lens Trajectories

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ABSTRACT

The existence of energetic anticyclonic mid-depth vortices of Mediterranean Water (meddies) questions the validity of a conventional advective–diffusive balance in the eastern Atlantic subtropical gyre. A mesoscale experiment in the Azores–Madeira region reveals a link of these meddies to large-scale subsurface meanders. For the first time it is shown that meddies may have strong surface vorticity, indicative of a generation process involving the Azores Current—a deep reaching near-surface jet.

1. Introduction

A unique feature of the subtropical gyre of the North Atlantic is the presence of an anomalously warm and salty tongue at intermediate depths (1000–1200 m), the origin of which is the outflow of Mediterranean Water through the Strait of Gibraltar. The Mediterranean outflow mixes with Atlantic thermocline waters and then follows the slope of the Gulf of Cadiz. Southeast of Cape Saint Vicente it departs from the continental slope and starts spreading primarily northward and westward along isopycnal surfaces.

To illustrate the average distribution of the salinity tongue in the northeast Atlantic, we have updated the salinity distribution according to Dietrich (1969) at 1000 m depth (Fig. 1). In addition to his dataset, mainly originating from the International Geophysical Year, we have included additional data from more recent surveys (Zenk, 1971; Siedler and Zenk, 1973; Saunders, 1981). However, stations that showed isolated, anomalously high salinities at the 1000 m level, which could possibly be attributed to meddies, were excluded. These salt-lenses represent mesoscale (100 km) anomalies (salinity excess 0.8) embedded in the saline background (Armi and Zenk, 1984).

The smoothed contour map of the background field compares favorably with both the classical picture of the Mediterranean core layer salinity (Wüst, 1936; Worthington, 1976; Reid, 1978) and a more recent mapping of climatological hydrographic data (Olbers et al., 1985). Three important properties are obvious in Fig. 1. First, in the Iberian Basin a meridional spreading of isohalines prevails; second, the westward-intruding salinity distribution off Cape San Vicente suggests an influence of the large scale topography, i.e., the Horse Shoe Seamounts; third, south of Madeira we find a prevailing zonal orientation of the mid-depth salinity contours.

2. Hydrography

In order to investigate the existence and strength of the eastern basin recirculation, several expeditions since 1981 to the Canary Basin were carried out by Kiel University. Here we will use a subset of hydrographic data and moored current meter data to reconstruct the migration and a conjectured formation of isolated Mediterranean salt lenses.

An intensive mesoscale survey area was located between the Azores and the Canary Islands; here the averaged depth exceeds 5000 m. A total of 85 CTD-stations was occupied by R/V *Poseidon* in an area measuring approximately 500 × 500 km (see Fig. 2). At 78 stations the CTD was lowered through the main thermocline to 1500 m. The investigation was performed within 14 days in late March/early April 1982 (Käse and Rathlev, 1982).

From the CTD station grid we developed quasi-synoptic horizontal maps of water properties at different depths and density surfaces. The upper thermocline maps mainly revealed a meandering Azores Current with implications for the local heat balance (Käse et al., 1985). Here we will discuss salinity distributions from intermediate depth on a constant density surface. We chose the level $\sigma_\theta = 27.6$ which, on average, is found at a depth of 995 m (Fig. 2). This level was selected to allow comparisons with the historical salinity distribution at 1000 m depth (Fig. 1).

Large meridional salinity gradients are characteristic of the *Poseidon* box. In the northeastern corner of Fig. 2, an area, A, of highly saline water ($S \geq 36.1$) is found. It lies about 0.3 above the historical mean or back-

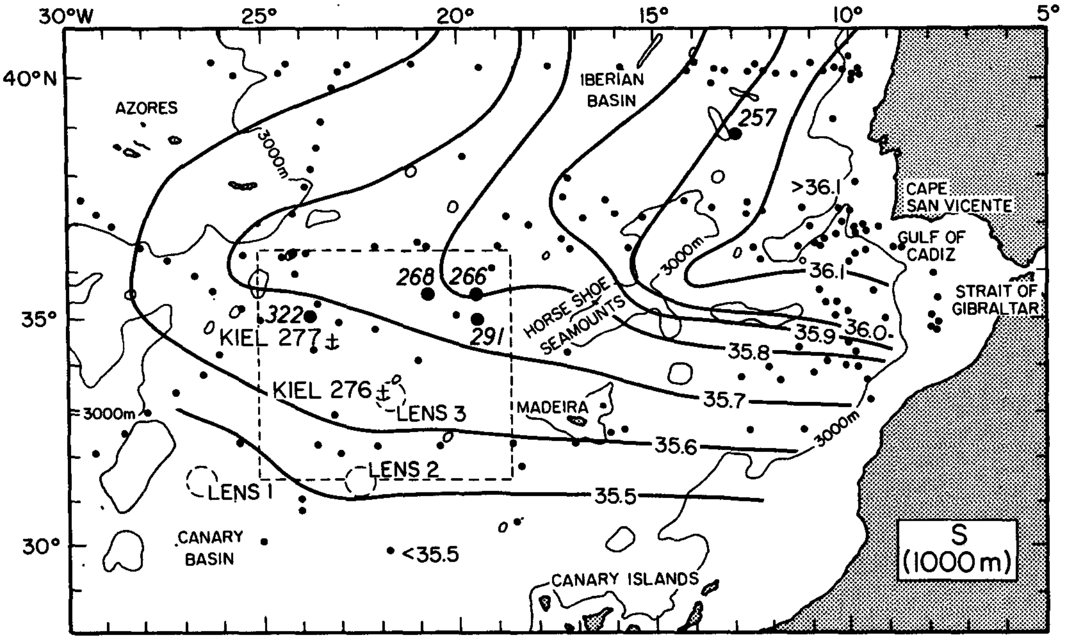

FIG. 1. Mean salinity distribution west of the Straits of Gibraltar at 1000 m depth updated from G. Dietrich's Atlas (1969) of the northern North Atlantic. Superimposed are the *Poseidon* box with selected CTD stations and the mooring sites KIEL 276, 277. Lenses 1-3 refer to those observed by Armi and Zenk (1984) in June 1982. Unlabeled dots represent the historical database.

ground field in Fig. 1. We further note a central area of nearly homogeneous water in which two highly saline features, B and C, are noticeable. Both are situated south of A and have similar maximum salinity, exceeding 35.8. It is worthwhile mentioning that the homogeneous center part coincides with the deep reaching frontal zone described elsewhere (Käse and Siedler, 1982; Käse et al., 1985, Siedler et al., 1985). It suggests intensive horizontal stirring of water properties by the Azores Current eddies. Features B and C compare favorably with the concept of a large salt lens found in 1981 in the same region. The location of "Lens 2" (Armi and Zenk, 1984) coincides with the position of feature "C" in Fig. 2. Three main factors, the similarity in horizontal scale, the maximum salinity and the dynamic topography (to be discussed later), suggested that B represents a complete meddy and C the northern edge of another meddy.

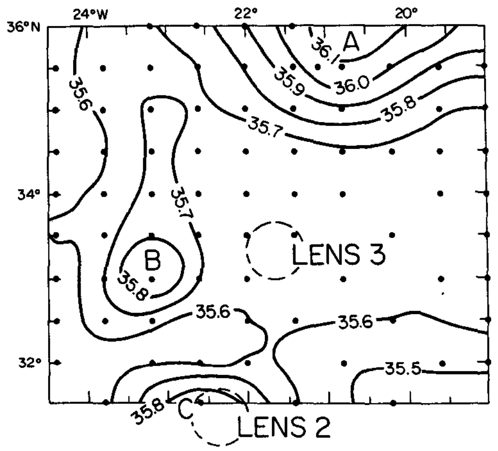

FIG. 2. Salinity distribution on the isopycnal surface $\sigma_\theta = 27.6$ in the Canary Basin in March–April 1982. Underlying grid shows the *Poseidon* stations (Käse and Siedler, 1982; Siedler et al., 1985).

To illustrate water masses present in the *Poseidon* box we show five salinity profiles, as located in Fig. 1, together with their temperature/salinity relationship in Fig. 3. The salinity structure underneath the North Atlantic Central Water demonstrates the range of variability encountered in the northern Canary Basin. Stations 268 and 257 are closely related. They both show high salinity above 36.1, which is a more typical value for stations near the source regions south of Cape S. Vincente. Station 268 in the center of feature A is about 0.4 salinity units higher than the climatological mean. In contrast, station 322 is representative of the background field. It is situated westward of pool A in the nearly homogeneous region. It is a mixing product of Subpolar Mode Water and Mediterranean Water which form a climatical frontal zone at the northwestern edge of the Mediterranean Water tongue (McCartney and

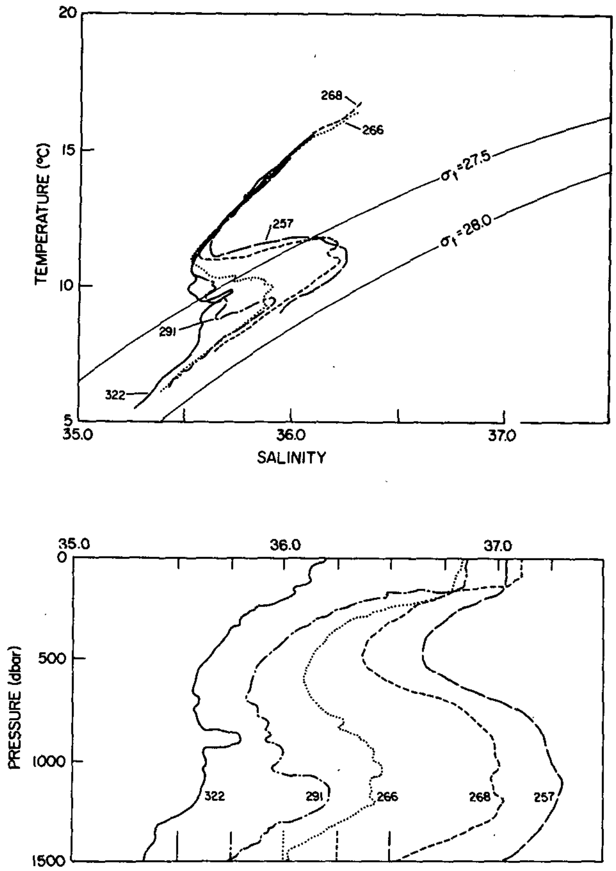

FIG. 3. *T-S* relationships (top) and salinity profiles (bottom) of selected CTD stations. Locations are given in Fig. 1. Salinity scale refers to station 322. Consecutive profiles are shifted by 0.2 salinity units.

Talley, 1982). The remaining two stations 266 and 291 show a large amount of interleaving and indicate strong frontal mixing between water found at stations 268 and 322.

3. Long-term time series

Observations of two long-term current meter mooring sites (KIEL 277, 276) located at (35°N 23°W, 33°N 22°W) give an impression of the strong variability in the *Poseidon* box (Müller, 1984; Siedler et al., 1985). In addition to other levels, each mooring contained one Aanderaa current meter with a temperature sensor in the Mediterranean Water level at 1140 m (277) and 1032 m (276) depths. In Fig. 4 we present low-pass filtered temperature, speed and direction time series from both instruments, where periods smaller than 1 day have been suppressed.

The most prominent features in the temperature records are episodic events, indicating possible advection of the various structures similar to those found during the hydrographic surveys in June 1981 and March/April 1982. Mean and extreme values are compared with box-averaged temperatures from the mesoscale CTD survey (Table 1). Close to features A and B temporal and spatial averages agree to within 0.1 K. At mooring 276 we find a mean difference of 0.6 K. The general agreement suggests the frequent occurrence of different states with either high or low temperatures depending on advection and percentage composition of (a) warm, saline Mediterranean Water and (b) cold, less saline water of subpolar origin. These findings can be further clarified by consideration of the mesoscale circulation during the course of the experiment.

TABLE 1. Statistics of low-pass filtered data from mooring sites KIEL 277 and 276 (Müller, 1984) and box-averaged CTD-data.

	Mooring number		*Poseidon*	
	KIEL 277305	KIEL 276305	CTD Survey	
Nominal depth (m)	1140	1032	1150	1031
Time	11 Mar 82–20 Apr 83	8 Mar 82–13 Apr 83	Mar–Apr 82	Mar–Apr 82
Temperature (°C)				
Mean	8.54	8.60	8.64	9.21
Std. dev.	±0.31	±0.25	±0.70	±0.67
Max.	9.64	9.26	11.16	11.57
Min.	7.83	7.95	7.72	8.43
East component (cm s^{-1})				
Mean	−1.28	1.42	—	—
Std. dev.	±1.25	±1.27	—	—
North component (cm s^{-1})				
Mean	−0.29	−0.59	—	—
Std. dev.	±1.55	±2.78	—	—
Mean direction (deg)	257	113	—	—

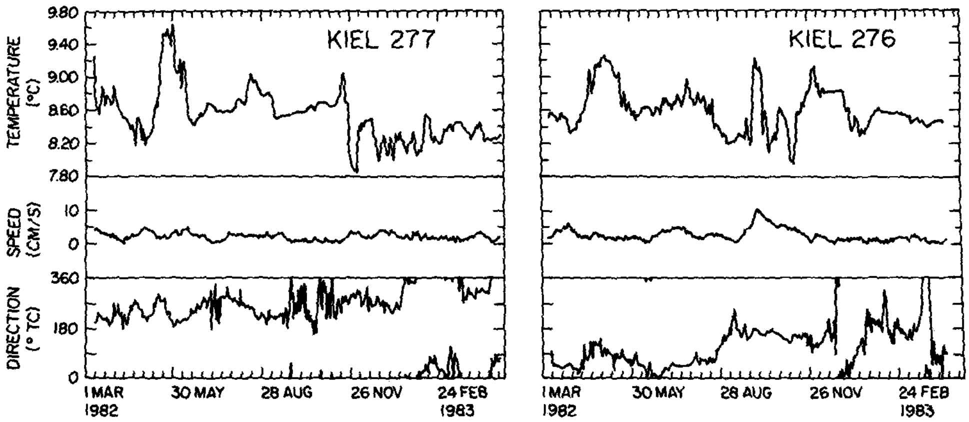

FIG. 4. Time series of current and temperature from moorings KIEL 277 and KIEL 276.

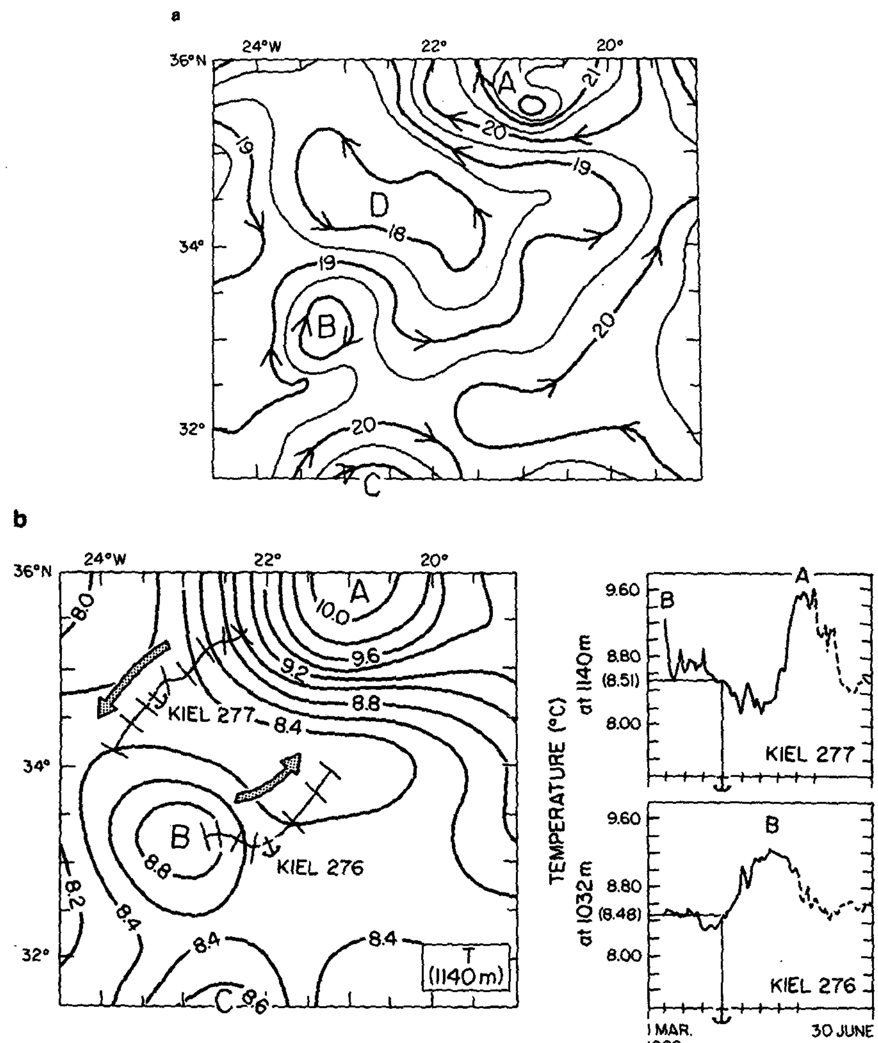

FIG. 5. Maps of (a) dynamic topography (dyn cm),—1100/1450 db—and (b) temperature distribution (°C) at 1160 m depth calculated from the CTD grid in the *Poseidon* box. Superimposed on (b) are progressive and regressive vector diagrams obtained from current meters at 1160 m (KIEL 277) and 1032 m (KIEL 276). Temperature time series from these moorings are reproduced on an expanded scale from Fig. 4. Tickmarks are identical with those in the vector diagrams and represent 10 day intervals. The anchor symbols denote position and, respectively, the time of observation of the hydrographic survey.

4. Mesoscale circulation pattern in spring 1982

The surface circulation in the area is influenced by a thin wind-driven Ekman flow converging in the vicinity of the Azores front (Stramma and Isemer, 1986). The geostrophic circulation shows a jetlike eastward flow with large amplitude meanders (Käse and Siedler, 1982). During the time of the *Poseidon* experiment a cold cyclonic meander trough, D, advects relatively fresh water southward (Käse et al., 1985) at the Mediterranean Water depth range. The geostrophic shear between 1100 and 1450 db is dominated by this cyclonic pattern. Each lens of warm and salty Mediterranean Water, however, is associated with a closed anticyclonic circulation (A, B, C, Fig. 5a). To compare the Eulerian velocity from the current meter instruments with possible particle tracks, we calculated progressive and regressive[1] vector diagrams. Hypothetical paths are shown in Fig. 5b superimposed on the horizontal temperature map. The vector diagrams exhibit a southwestward flow superimposed on feature B. Temperature at 1032 m of mooring 276 begins to rise drastically around 10 April, only a few days after the stations close to 276 were occupied. These portions of the time series are reproduced in more detail from Fig. 4. At the northern mooring, temperature increased one month later. The observed temperature events and the particle paths can be explained by the detachment of the cold trough and its development into a closed cyclonic vortex. The vector diagrams further suggest that feature B had been close to mooring 277 slightly before the CTD-survey. The high temperature after the launching of mooring 277 favors this hypothesis.

A similar reconstruction of particle paths was performed with the preceding year-long record of both moorings. Although no mesoscale hydrographic survey is available for 1981 near KIEL 277, it is possible to trace another meddy, which was situated at KIEL 277 in November, back to the region of feature A in August 1981. This suggests a similar background state as seen during spring 1982.

Taking into account the presence and possible formation of at least six anticyclonic meddies in the North Canary Basin during nine months, we would expect a major impact of this phenomenon on the subtropical recirculation at middepth. It is therefore suggested that the southward flow in the eastern Atlantic happens not only as a smooth Sverdrup-like flow, but also involves bursts of cold subpolar water which interact strongly with westward pulses of salty Mediterranean Water. The larger scale cyclonic vortices are subject to strong mesoscale stirring; the anticyclonic meddies survive and enter the westward recirculation of the Canary Current/North Equatorial Current System.

An interaction of the large-scale salt tongue and

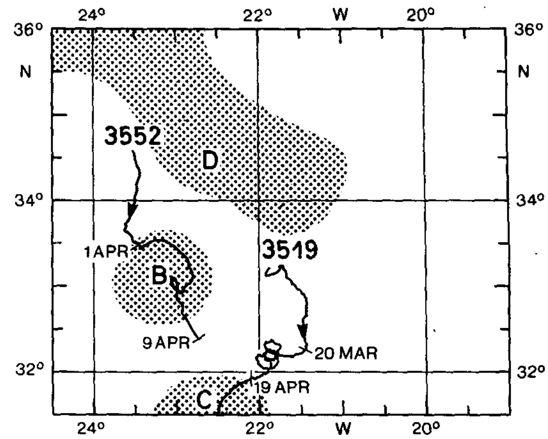

FIG. 6. Trajectories of satellite tracked drifters (drogued at 100 m) in the *Poseidon* box, March–April 1982.

meanders of the Azores Current would necessarily require that, at the generation site, meddies should have surface vorticity signals decaying after they break off from a meander. This is confirmed by the trajectories of satellite tracked drifters (Fig. 6). Drifter 3552, initially advected southward at the western edge of the cyclonic feature D, drastically changes its trajectory to a sickle-shaped path when it is trapped for 5 days by meddy B. In addition, it is indicated by drifter 3519 that meddy C has resided in the vicinity of mooring KIEL 276 about a month earlier and was advected southwestward later on.

This scenario appears to be consistent with recent theoretical studies, i.e., the local generation by instabilities (McWilliams, 1985), and bears resemblance to the heton generation problem (Hogg and Stommel, 1985).

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[1] That is, where a particle in a steady flow might have come from, rather than where it might be going.

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