# Mediterranean lens "Irving" after its collision with seamounts

Eddies
Lenses
Canary Basin
Bottom topography
Temperature and salinity

Tourbillons
Lentilles
Bassin des Canaries
Topographie du fond
Température et salinité

**Georgiy I. SHAPIRO, Sergey L. MESCHANOV, Mikhail V. EMELIANOV**

P.P. Shirshov Institute of Oceanology, Krasikova Street 23, 117218 Moscow, Russia.

Received 12/04/94, in revised form13/12/94, accepted 24/01/95.

ABSTRACT

In January 1990 a Meddy was observed 100 km to the west of the Irving Seamount just after it had passed through a narrow passage (90 km at its narrowest) between Hyeres and Irving Seamounts located at the western edge of the Canary Basin. Vertically, Meddy "Irving" had two cores centred at 900 and 1150 m depth. In the horizontal plane the Meddy had an elliptical shape with axes of 100 and 60 km. Behind the Meddy, a wake of saline water was found which tracked the lens trajectory. Two small salty patches were observed inside the wake. They had the same temperature-salinity relationships as the lens periphery and were probably split from Meddy "Irving" during the impact with bottom topography. The patches contained approximately 20 % of the whole lens salt and 27 % of the heat excess. Despite the damage caused by the collision with the seamounts, Meddy "Irving" kept its individuality and coherent structure.

RÉSUMÉ

La lentille méditerranéenne « Irving » après son impact sur les monts sous-marins.

En janvier 1990, un tourbillon a été observé à 100 km à l'ouest du mont sous-marin Irving, juste après qu'il ait traversé le passage resserré (90 km dans sa partie la plus étroite) entre les monts sous-marins Hyères et Irving, à la limite occidentale du Bassin des Canaries.
Verticalement le tourbillon Irving est composé de deux veines, à 900 et 1150 m de profondeur. Dans le plan horizontal, il a la forme d'une ellipse dont les axes mesurent 100 et 60 km. La lentille laisse derrière elle un sillage d'eau salée dans lequel deux petites tâches salées ont été observées. Elles présentent les mêmes diagrammes TS que la périphérie de la lentille et se sont détachées du tourbillon Irving, probablement sous l'effet de la topographie du fond. Ces taches représentent environ 20 % du sel de la lentille et 27 % de son contenu thermique. Malgré la perturbation provoquée par l'impact sur les monts sous-marins, le tourbillon Irving conserve son individualité et sa structure cohérente.

*Oceanologica Acta*, 1995, **18**, 3, 309-318.

## INTRODUCTION

Mediterranean Water (MW) released through the Strait of Gibraltar has a significant influence on the hydrophysical properties of intermediate water masses in the northeast Atlantic. High-salinity MW propagates both as a large-scale continuous tongue and as submesoscale isolated lenses (Meddies) (McWilliams *et al.*, 1985; Belkin *et al.*, 1986). Meddies are generally warmer and more saline than their surroundings, and have anomalous concentrations of some chemical constituents. Due to their rapid rotation, Meddies have a very high level of specific kinetic energy, reaching 450 erg·cm$^{-3}$ (Kamenkovich *et al.*, 1987).

The advection speed of Meddies is weak (1÷4 cm·s$^{-1}$), but it may be accelerated by large-scale eddies, currents and Rossby waves (Käse and Zenk, 1987). Meddies also possess an independent ability for westward self-propagation (Nof, 1982; Shapiro, 1984) with the velocity of a few millimetres per second. Some of the Meddies have been observed thousands of kilometres away from the place of formation. One of the regions where Meddies have been observed repeatedly is the Canary Basin, see Fig. 1 (Armi and Zenk, 1984; Armi *et al.*, 1989; Belkin *et al.*, 1986; McWilliams *et al.*, 1985). Meddies are centred at approximately 1000 m depth, and according to the estimation of Armi and Zenk (1984), cover 4-8 % of the whole Canary Basin area. Possible Meddy trajectories were analysed by Kostianoy and Shapiro (1989).

Long-distance transfer of heat and salt (and any other tracer) carried out by lenses differs qualitatively from the common diffusive mechanism. The diffusion process is described by the differential equation of parabolic type and hence the excess of concentration or heat content always diminishes with distance from the source. In contrast, transportation of heat and salt by lenses could generate secondary maxima at places where lenses are destroyed and mix their content with surrounding waters. For this reason, understanding the physical mechanism of lens decay is important from the climatic point of view.

Three main decay mechanisms discussed in the literature are based on analysis of observational data, results of theoretical models and laboratory experiments: (i) Lateral intrusions "eat" the lens core (Hebert, 1988); (ii) Friction with surrounding water stops rotation (Csanady, 1979; Shapiro, 1987); (iii) Rossby wave generation and nonlinear wave dispersion radiate energy away from the lens (Flierl, 1984; Shapiro, 1989).

Recently, Richardson *et al.* (1989) suggested a new and relatively fast decay mechanism: destruction of a Meddy by collision with seamounts. A float-tracked Meddy was described which was probably destroyed after a collision with a seamount at the western edge of the Canary Basin.

In this paper, we discuss an alternative for a lens to penetrate through gaps between seamounts, as observed by Pingree and Le Cann (1993) in March-April 1992, when the passage of a Meddy through a gap between seamounts west of Cape St.Vincent was tracked by an Argos drag float. We consider a similar situation at the western edge of the Canary Basin using data from a Soviet hydrographic cruise in January 1990 on board R.V. *Professor S. Dorofeev.*

Two months before our survey, in October-November 1989, an intense Meddy was observed by R.V. *Akademik Ioffe* east of the Irving Seamount (Dykhno *et al.*, 1991). Two surveys were performed. During the period between the surveys the lens travelled to the southwest at 3÷4 cm·s$^{-1}$ and the lens centre had moved from 32° 00' N, 26° 43' W on 31 October to 31° 48' N, 27° 00' W on 13 November. For that reason, we planned our investigation area to cover the region of possible Meddy location, which was expected to be up to 190 km away from the previously observed position (Fig. 1).

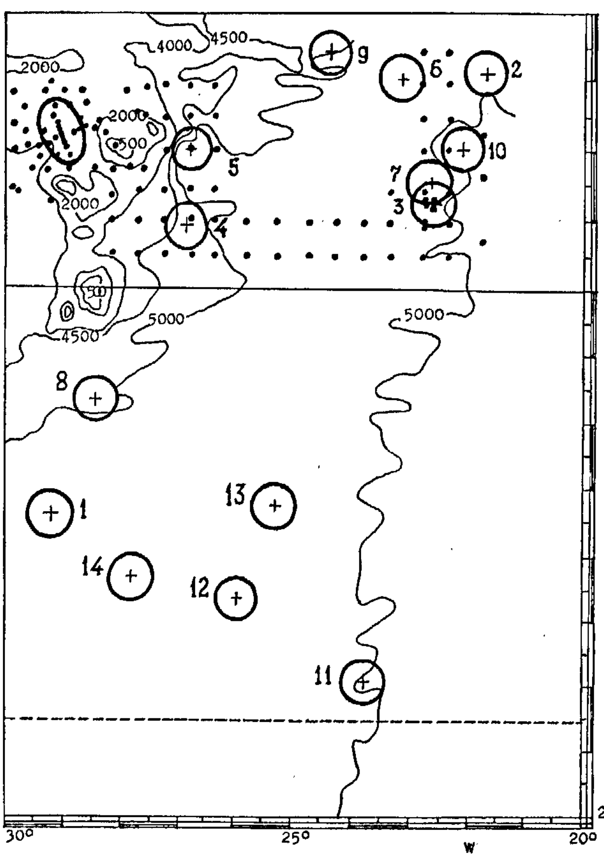


Figure 1

*Meddies in the Canary Basin: 1 - Armi and Stommel (1983); 2,3,4 - Armi and Zenk (1984); 5 - Dykhno* et al. *(1991); 6,7 - Käse and Zenk (1987); 8 - Maltsev* et al. *(1990); 9,10,11 - Richardson* et al. *(1989); 12,13 - Richardson* et al. *(1991); 14 - Williams* et al. *(1986). Isobaths 500, 2000, 4000, 4500 and 5000 m are plotted. Dots indicate locations of CTD stations carried out during the 14-th cruise of R.V.* Professor S. Dorofeev.

## MATERIALS AND METHODS

Our data were gathered from 30 December 1989 to 21 January 1990 during the first phase of the 14-th cruise of R.V. *Professor S. Dorofeev* (USSR) to the west of the Canary and Madeira Islands (Fig. 1). The complete data set includes 109 hydrographic stations arranged in three adjacent surveys. The first one consists of three meridional sections along 21° 50', 22° 20', 22° 50' W, and several additional stations which were occupied at the south-eastern part of the study area where the tongue of MW had been found. The second survey included two zonal sections along 30° 25' N and 30° 55' N. The third comprehensive survey (78 stations, 9-19 January) was performed in the vicinity of the Seamounts Meteor, Hyeres, Irving, Cruiser and Plato (Fig. 2). East of the seamounts, the stations were spaced nominally by 46 km zonally and by 48 km meridionally. After we had encountered the Meddy at the western part of the study area, a spiral zigzag section (st. 38-54, 10-12 January) was carried out to locate the lens border. Along this section, the stations were occupied mainly at the nodes of a triangular grid spaced by 25 km (Fig. 2). Immediately after the zigzag section, two straight-line sections (st. 60-69 and 70-75) with spatial resolution of 5÷15 km were made along the lens main axes on 13–14 January. Some of the stations of the zigzag and straight-line sections were taken at the same locations, showing negligibly small variations between vertical profiles separated by several days. So we can consider the 5-day survey of the lens as a "snap-shot" picture.

Measurements were made by a sounding system consisting of mechanically connected "Hydrozond" (USSR) and SBE-19 "Seacat" (USA) CTD profilers. Vertical profiles of temperature and salinity used in this investigation were obtained by the "Seacat" profiler with accuracy better than 0.01 °C and 0.01 psu. The "Seacat" operated in autonomous mode from the ocean surface down to 2000 m. Water samples for chemical analysis were drawn from 8–14 depth levels by "Hydrozond" equipped with 1-litre bottles.

The concentration of dissolved oxygen was measured by Winkler titration (thought to be accurate to within 0.1 $ml \cdot l^{-1}$, phosphate, silicate, nitrate were determined by colorimetry (accurate to 3 %, 5 %, and 5 %, respectively), and the value of pH was measured by ion-meter I-115 (USSR) with an accuracy of 4 %. Special investigation of water samples for heavy metal distribution was carried out

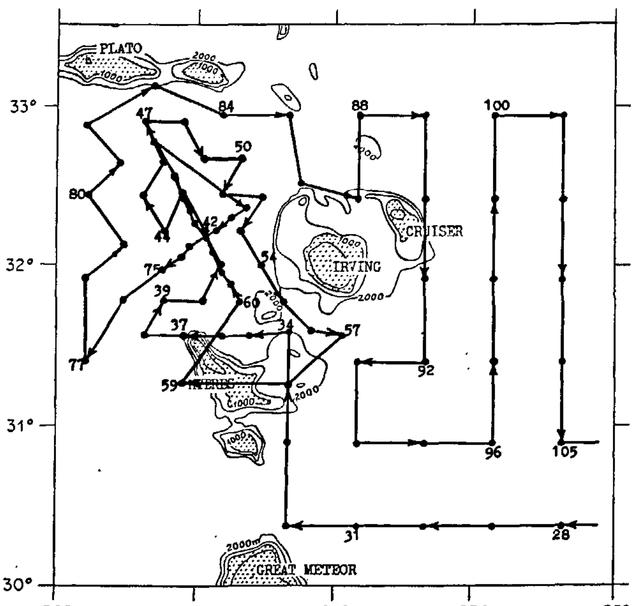


Figure 2

*Map of the third CTD-survey (with station numbers) carried out during the 14-th cruise of R.V.* Professor S. Dorofeev.

in a shorelab after the end of the expedition. The methodology and instrumentation is described by Osipov *et al.* (1991).

RESULTS AND DISCUSSION

In the eastern part of the Canary Basin, the Mediterranean salt tongue was observed at depths of 700-1300 m. The southern border of the MW tongue coincided with the position of the southern branch of the Azores front which was observed in the upper layer down to 300 m depth (Zatsepin *et al.*, 1991). An intensive staircase structure lying under the tongue of Mediterranean origin was also revealed. Homogeneous layers had thicknesses from 8 to 55 m. In the southern zonal sections along 30° 25' N and 30° 55' N, a patch of low salinity with S = 35.30-35.40 psu was found at depths of 800-1200 m. The observed salinity minimum is probably related to the penetration of Antarctic Intermediate Water (AAIW) into the Canary Basin from the south.

**CTD observations of Meddy "Irving"**

On January 10-14, 1990 a Meddy was surveyed with maximum salinity of 36.21 psu (hereafter Meddy "Irving") approximately 100 km to the west of the top of the Irving Seamount (Fig. 3). At the time of the survey, the lens centre was located at 32° 12'5 N, 28° 59'0 W (st. 42). To

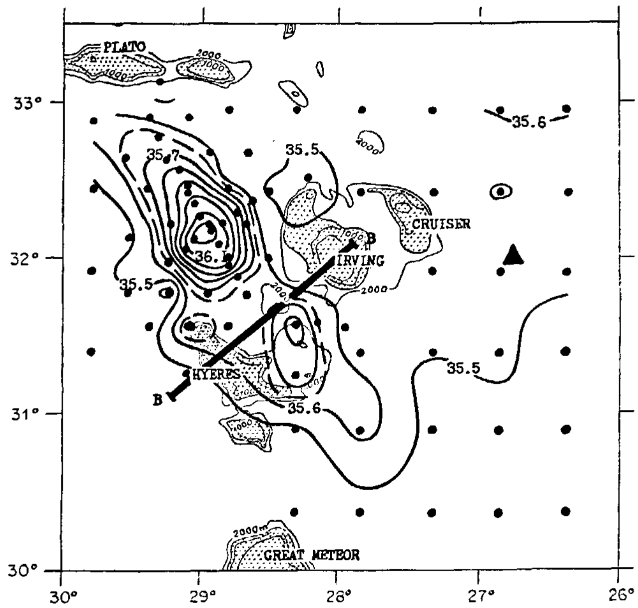


Figure 3

*Salinity maximum distribution in the layer of 900-1300 m depth. Contour intervals are 0.1 psu for solid lines and 0.05 psu for dashed lines. Bottom topography contour interval is 500 m. Areas shallower than 1500 are shaded.* **B-B** *shows the location of section presented on Fig. 6. Black triangle indicates the location of the lens center observed by Dykhno* et al. *(1991) on 31 October 1989.*

the southeast of the Meddy, a region of saline water was found which extended between Hyeres and Irving Seamounts. Two isolated patches of highly transformed Mediterranean Water were revealed inside this region southeast of the main lens, the first located in the eastern part of the passage between Hyeres and Irving Seamounts (st. 34, 31° 34' N, 28° 20' W) near an unnamed peak, and the second one near the northwestern slope of the Hyeres Seamount (st. 37, 31° 34' N, 29° 07' W) (Fig. 3). The main properties of Meddy "Irving" and two saline patches are listed in Table 1.

Vertically the Meddy had a bimodal structure (Fig. 4). At the lens centre, the upper and lower cores occupied the depth intervals of 690-980 m and 980-1355 m respectively. In the upper core the increase in salinity with depth was accompanied by the increase in temperature, whereas in the lower core it corresponded to uniform temperature. Fig. 4 also shows salinity and temperature profiles measured at the centre of the Meddy observed by Dykhno *et al.* (1991) on 31 October 1989 to the east of the top of the Irving Seamount, at 32° 00' N, 26° 43' W (black triangle in Fig. 3). There is good agreement between the profiles in the depth range of 800-1200 m. The extent of coincidence can be recognized by comparison with other lenses observed nearby. For example, Fig. 4 shows temperature and salinity profiles measured at the centre of the Meddy (at 28° 57' N, 28° 16' W) found by Maltsev *et al.* (1990). In this case, the difference in profiles is much greater. Combining these facts with the absence of Meddies in a large study area to the east of the chain of seamounts (Fig. 3), we can hypothesize that on January, 1990 we observed the same lens as Dykhno *et al.* (1991) on October, 1989. From this it follows that the lens moved generally westward between two identified locations.

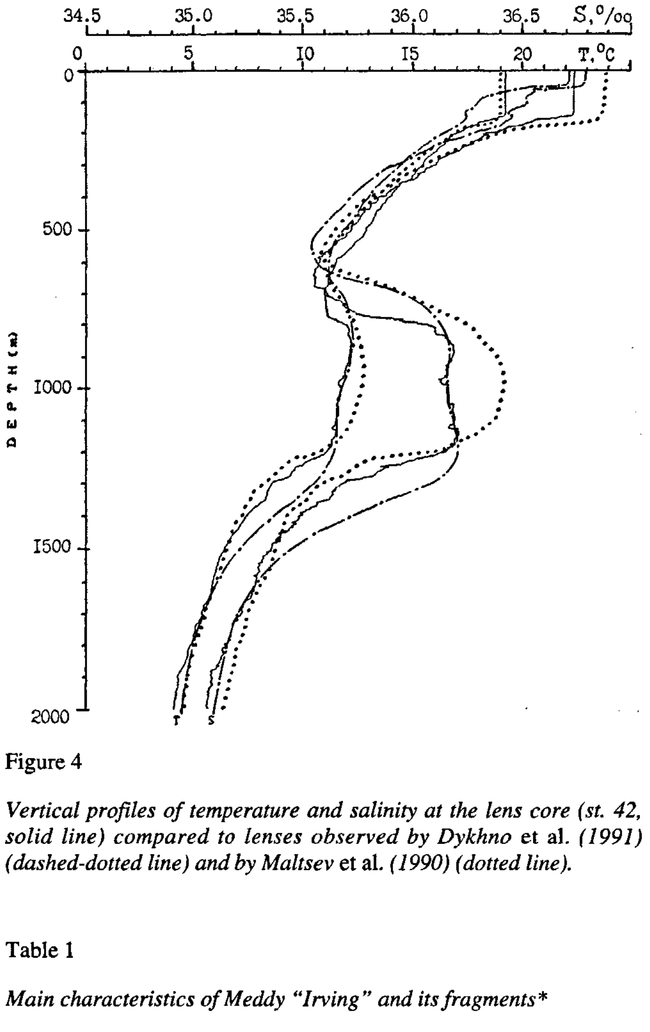


Figure 4

*Vertical profiles of temperature and salinity at the lens core (st. 42, solid line) compared to lenses observed by Dykhno* et al. *(1991) (dashed-dotted line) and by Maltsev* et al. *(1990) (dotted line).*

A double-core structure is more evident at the lens periphery. On vertical salinity profiles, the maximal excess over the local minimum located between the cores was 0.08 psu at the lens centre (st. 42) and reached 0.20 psu at st. 44 (32° 12' N, 29° 16' W), 26 km from the centre. Fine-scale thermohaline structure was practically absent below the Meddy (Fig. 4) in contrast to the Mediterranean Water tongue observed in the eastern part of the survey. The density stratification in the upper core $\gamma = \partial\sigma_\theta/\partial z = 0.6 \cdot 10^{-3}$ kg·m$^{-4}$ (800-900 m layer) was about two times less than in the background water column, whereas in the lower core it was $\gamma = 0.4 \cdot 10^{-3}$ kg·m$^{-4}$ for the 1100-1200 m layer, *i.e.* approximately equal to the background value. This means that the available potential energy was mainly concentrated in the upper core.

The bimodal vertical structure of the lens is probably caused by its place of origin near Cape St.Vincent in the Gulf of Cadiz, where a double maximum is typical in temperature and salinity profiles. Meddy "Irving" was identified at a distance of 2000 km southwest of Cape St.Vincent. With the average drift velocity of 2÷4 cm·s$^{-1}$ (Richardson *et al.*, 1989) the life time of the Meddy observed is about 1.5÷3 years. Another possible reason for formation of a double core structure is the poloidal circulation caused by the friction between a lens and ambient water. In a three-layer model, the radial velocities are directed from the periphery to the centre at the neutral density depth level (Shapiro, 1987). According to this circulation pattern, the background or highly transformed water from the periphery could penetrate toward the lens centre. Anomalies of salinity ΔS and temperature ΔT as compared to back-

Table 1

*Main characteristics of Meddy "Irving" and its fragments**

| Characteristic | Main lens (st. 42) | Patch 1 (st. 34) | Patch 2 (st. 37) |
|---|---|---|---|
| Smax (psu) | 36.21 (1145) | 35.82 (885) | 35.71 (1005) |
| Tmax (°C) | 12.16 (885) | 10.85 (810) | 9.97 (900) |
| ΔSmax (psu) | 0.75 (1145) | 0.31 (1085) | 0.22 (1005) |
| ΔTmax (°C) | 3.76 (1145) | 1.81 (1085) | 0.86 (1005) |
| Depth range (m) | 750-1295 | 725-1215 | 870-1035 |

* The outer borders of salty patches are assumed to be isohalines: 35.70 psu for the main lens, and 35.60 psu for both fragments. Numbers in brackets indicate the depth of observation in metres.

ground st. 38 (31° 34' N, 29° 25' W) are shown in Table 1 at several depth levels.

Horizontal distribution of the salinity maximum calculated for the layer of 900-1300 m depth is shown in Fig. 3. Meddy "Irving" had an elliptical shape in the horizontal plane. Its major diameter (bounded by the isohaline 35.7 psu) was 100 km from northwest to southeast and the minor one was 60 km from northeast to southwest. Since the lens observations were completed within a 5-day period, the movement of Meddy could not seriously alter its shape. The inner core of the Meddy with salinity exceeding 35.9 psu was near-circular (Fig. 3). The salty wake bounded by 35.6 psu and elongated from nortwest to southeast was identified near the lens. According to Fedorov and Paka (1988), a moving Mediterranean lens generates a salty wake behind it. Therefore, the salty wake shown in Fig. 3 can be used to trace the lens trajectory.

On the salinity and temperature sections along the major lens axis (Fig. 5*a,b*) one can see wave-like disturbances in the frontal part of the lens and in one of the salty patches behind the lens. On the perpendicular section, the lens is bounded by smooth isolines (Figs. 5*c,d*). Assuming that inside isohaline 35.7 psu the Meddy is a triaxial ellipsoid with semi-axes $H = 275$ m, $L_L = 50$ km, $L_S = 30$ km (Fig. 5) we get the value for its volume $V = 4/3\ \pi H L_L L_S = 1.7 \cdot 10^3$ km$^3$.

Another approach to determining the lens boundary is based on calculation of isopycnal anomalies of temperature $T'_\rho$ and salinity $S'_\rho$. Taking $S'_\rho = 0.08$ psu as the outer boundary value for the Meddy (Koshliakov and Panteleev, 1988) we obtain for semi-axes $H = 450$ m, $L_L = 65$ km, $L_S = 40$ km. Fig. 6 shows the isoline $S'_\rho = 0.08$ psu on cross-sections along major and minor lens axes superimposed on the bottom topography section between Hyeres and Irving Seamounts marked by **B-B** on Fig. 3. The width of the passage is 90 km at 1000 m depth. Below 1460 m it is subdivided into two parts by an unnamed peak, which is high enough to contact with the moving Meddy and

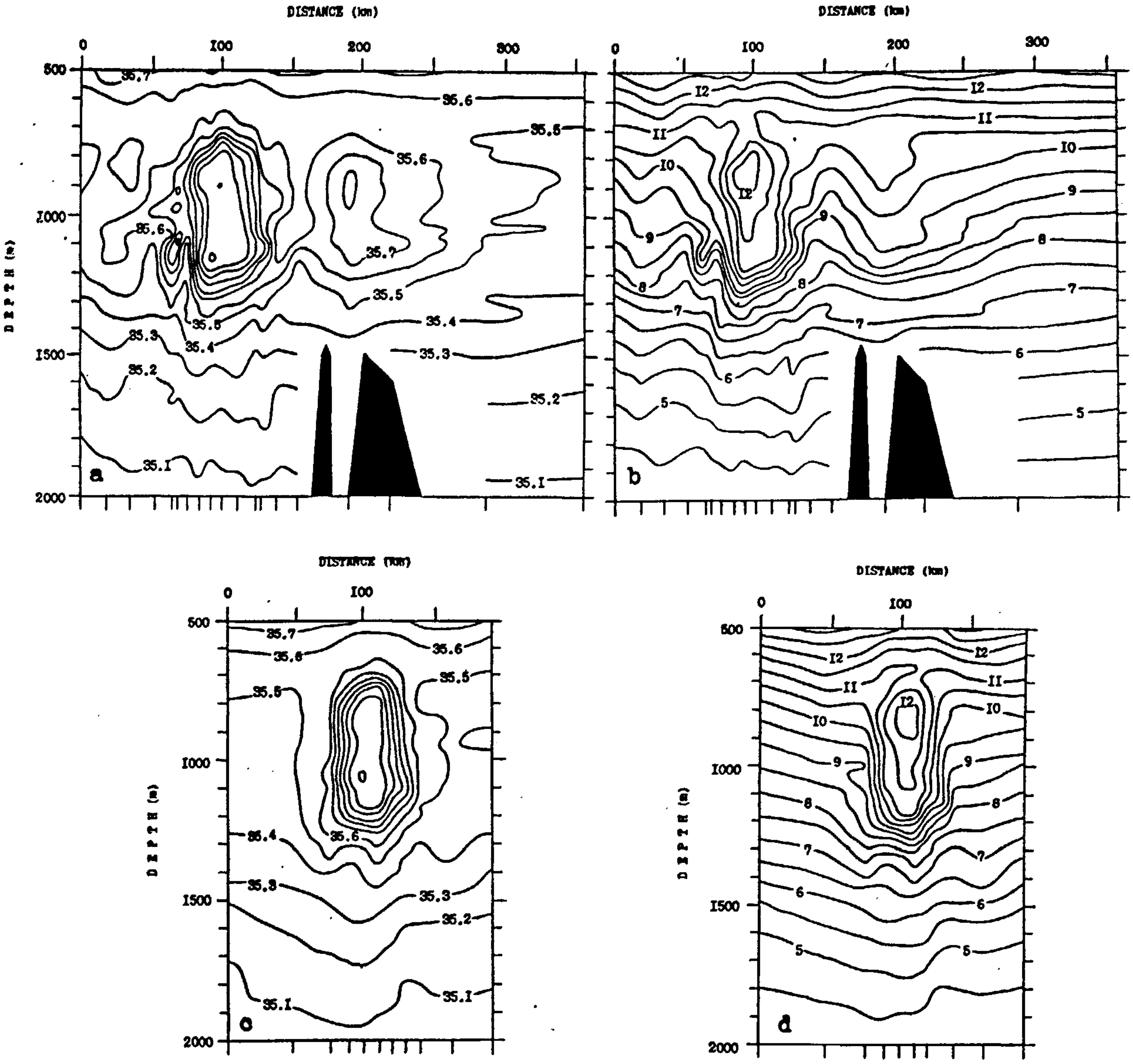


Figure 5

*Salinity and temperature cross sections for the major (a,b) and minor (c,d) axes of Meddy "Irving". Location of CTD stations is shown by tics at the bottom.*

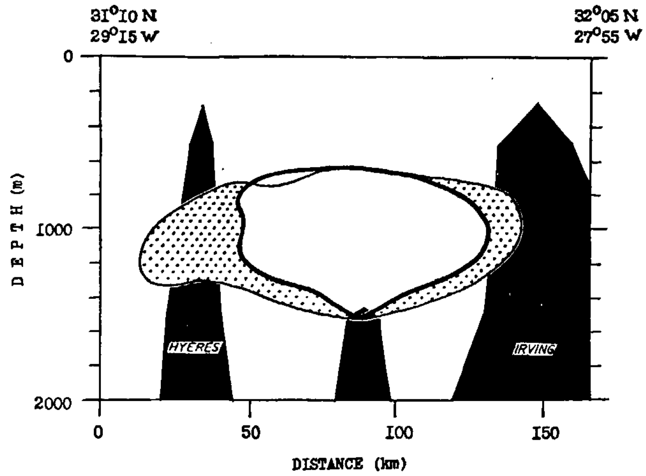


Figure 6

*The cross section through Meddy "Irving" along major (light curve) and minor (heavy curve) axes superimposed on bottom topography section marked by* **B-B** *on Fig. 3. The lens is delineated by isopycnic salinity anomaly of* $S_p' = 0.08$ *psu.*

deform it. The major lens axis is too large to fit between peaks, whereas the minor axis is approximately equal to the width of the gap between the seamounts. This would be explained by the fact that the initially circular lens "Irving" (see Dykhno *et al.*, 1991) was not only vertically deformed by bottom topography, but also horizontally squeezed in the passage by the impact of seamounts.

At the salty patch 2 (st. 37, 31° 34' N, 29° 07' W), the salinity anomaly was found only above 1050 m and the salinity maximum was less than at salty patch 1 (st. 34), see Table 1. One possible reason for this is that the patch at st. 34 had not passed through the passage and therefore was less disturbed by the impact of topography. The

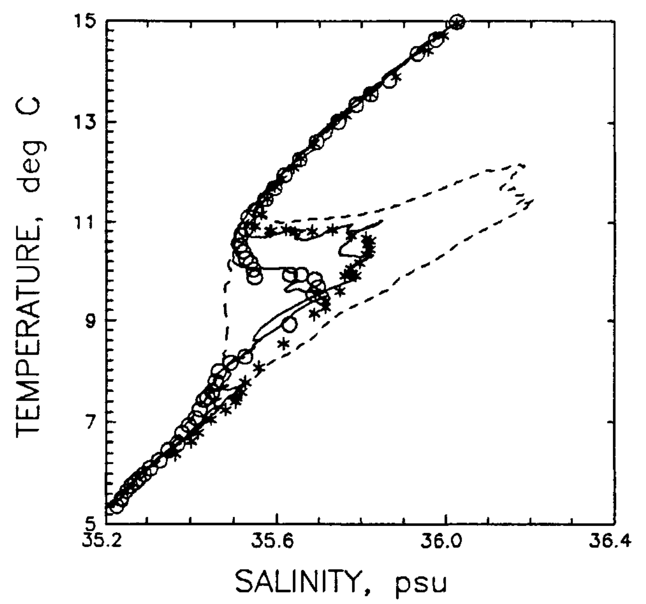


Figure 7

*Salinity-temperature diagrams for salty patch one (st. 34, marked by stars) compared to st. 66 in the lens (solid line) and salty patch two (st. 37, marked by circles) compared to st. 68 in the lens (solid line). Dashed lines show the data for the Meddy centre (st. 42) and background water (st. 38).*

second patch (st. 37) was found at the exit from the passage and could have been damaged by the unnamed peak and the slope of Hyeres Seamount (Fig. 3).

At the periphery of the main lens, the salinity-temperature diagrams (st. 66, 17 km from the lens centre, and st. 68, 42 km) coincide well with the data in the salty patches (Fig. 7). This supports the hypothesis that salty patches have been split from the main lens.

Putting together all the above we can suppose the following scenario. Meddy "Irving" moved southwest to the western edge of the Canary Basin and then passed between Hyeres and Irving Seamounts. It was partially damaged due to the impact of seamounts. As a result of the collision, two salty patches were detached containing water from the sides of the lens. In front of the lens wave-like disturbances were generated. A part of the mother lens water was lost while passing between the seamounts, mixed with surrounding water, and formed a salty wake.

## Dynamic topography

Maps of geopotential relative to 1900 m show high dynamic activity at depths from the surface down to 1600 m in the region where Meddy "Irving" was found (Fig. 8*a,b*).

The position of the anticyclonic baroclinic vortex (the Meddy itself) coincides with the position of the salty lens at depth range from 700 to 1400 m (Figs. 3, 8*b*). The calculated orbital velocities in Meddy "Irving" reached 24 cm·s$^{-1}$ at 1100 m. An adjoining anticyclonic vortex was revealed above the salty lens top at 50-600 m depth (Fig. 8*a*). Typical values of geostrophic velocity at 400 m depth were 6-10 cm·s$^{-1}$. The formation of the shallow eddy can be attributed to squeezing the vortex lines in the water column over the lens while penetrating into surrounding water.

Two fragments of Meddy "Irving" centred at stations 34 and 37 (Table 1) are located in the area of weak vortex activity and, in contrast to the main lens core, are practically invisible in the map of geopotential at 1100 m (Fig. 8*b*).

Anticyclonic eddies to the west of Irving Seamount (st. 54, 31° 59' N, 28° 32' W) and to the northwest of Hyeres Seamount (st. 39, 31° 07' N, 29° 16'5 W) are traced on maps of geopotential from the depth of 1000-1200 m to the surface. They have common isolines with Meddy "Irving" at 1100 m (Fig. 8*b*), but they are formed by different waters. In contrast to Meddy "Irving" which has an excess of salinity, the anticyclonic rotation of the eddies centred at st. 39 and st. 54 is caused by a salinity (and density) deficit up to 0.07-0.1 psu compared to background waters. Salinity profiles inside these eddies are less disturbed by fine structure than at neighbouring stations outside them. On the 400/1900 m map (Fig. 8*a*) there is a zone of low geopotential values which separates the shallow vortex over the top of the Meddy from anticyclones centred at st. 39 and st. 54 which seem to be topographically induced. They are located to the right relative to seamount peaks (viewing down along the main southward flow) whereas open streamlines deviate to the left over Irving Seamount forming a clockwise gyre. These facts are in agreement with the theory and

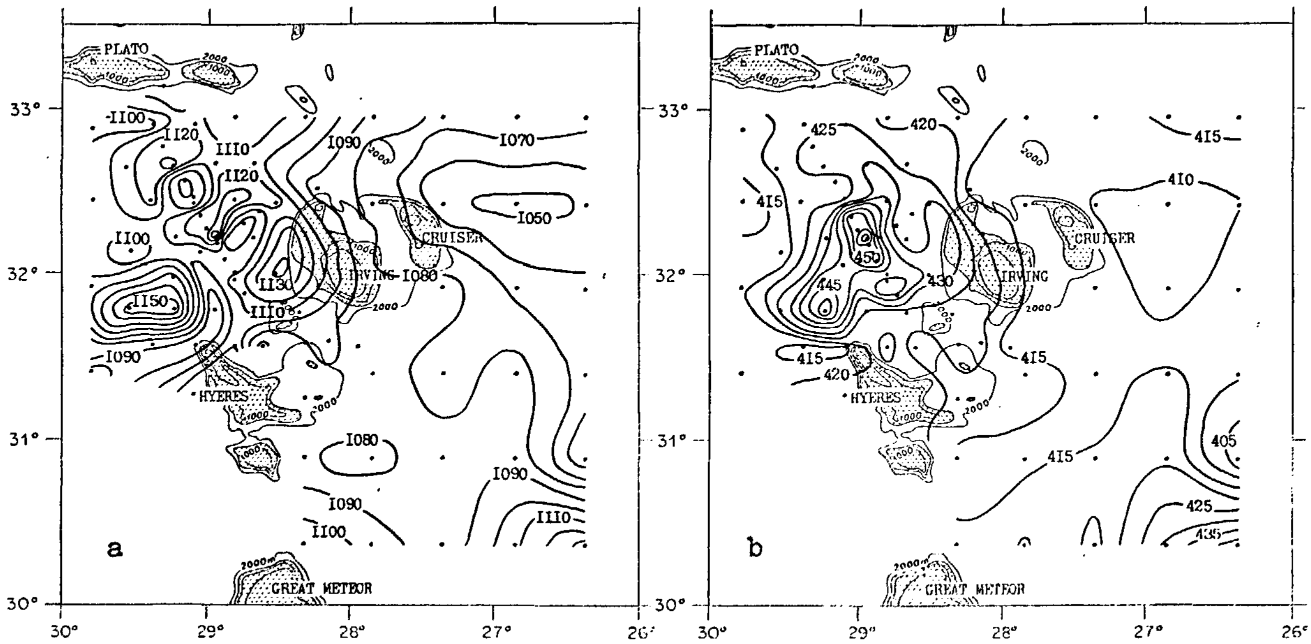


Figure 8

*The map of geopotential ($10^2$ $m^2 \cdot s^{-2}$) for 400 m (a) and 1100 m (b) relative to 1900 m.*

numerical simulation of topographically induced eddies (Huppert and Bryan, 1976).

It was probably the anticyclonic eddy to the west of Irving Seamount that dragged the Meddy into the passage. The other anticyclonic eddy, located behind Hyeres Seamount, acts to keep the lens out of the passage. It is somewhat stronger but more distant from the assumed lens trajectory, so that its influence is lower.

## Heat and salt content of Meddy "Irving"

The integral heat $Q$ and salt $M$ content of Meddy "Irving" were calculated using formulae (A1)-(A6) derived in Appendix. Profiles at st. 76 (31° 58' N, 29° 34' W) were chosen as background and the value of isopycnal salinity anomaly $S'_\rho = 0.08$ psu was chosen to mark the lens border. Maximum values of heat $q_0$ and salt $m_0$ content anomalies were obtained at st. 64 (32° 10' N, 28° 58' W), *i.e.* 6 km away from the lens centre (st. 42). According to formulae (A1) and (A2) for st. 64 we have $q_0 = 7.23 \cdot 10^9$ $J \cdot m^{-2}$, $m_0 = 400$ $kg \cdot m^{-2}$ with $H_1 = 640$ m, $H_2 = 1500$ m. Local isopycnal anomalies of temperature $T'_\rho$ and salinity $S'_\rho$ reached the values of 3.35 °C and 0.73 psu respectively at density level $\sigma_t = 27.64$ (st. 64).

Both $q$ and $m$ were calculated for all stations located along main axes of Meddy ($\varphi_1 = 0,\pi$; $\varphi_2 = \pm\pi/2$) and then $q(r,\varphi)$ and $m(r,\varphi)$ were approximated by Gaussian curves (A3). Distances of "e"-fold decrease were found to be the same for $q$ and $m$ but different along major and minor axes. We obtained $L_a = 30$ km for major ($\varphi = 0,\pi$) and $L_b = 20$ km for minor ($\varphi = \pm\pi/2$) axes, and $\varepsilon^2 = 0.51$ for the eccentricity of Meddy "Irving".

The integral heat and salt contents of the lens "Irving", according to formulae (A5)-(A6), are $Q = 1.31 \cdot 10^{19}$ J and $M = 7.18 \cdot 10^{11}$ kg, respectively. For the whole lens volume we have from (A7)-(A8) the same value of $V = 1.7 \cdot 10^3$ $km^3$ as in Section "CTD observations of Meddy Irving" based on the location of the isohaline 35.7 psu. The volume-averaged isopycnal anomalies of temperature $\langle T'_\rho \rangle$ and salinity $\langle S'_\rho \rangle$ are 1.88 °C and 0.41 psu.

The same procedure was applied to estimate the heat and salt content of both fragments of the Meddy. For the first fragment (st. 34) $Q = 2.74 \cdot 10^{18}$ J, $M = 1.11 \cdot 10^{11}$ kg and $L_b = 14$ km, $\varepsilon = 0$. For the second one (st. 37) we have $Q = 0.78 \cdot 10^{18}$ J, $M = 0.32 \cdot 10^{11}$ kg and $L_b = 14$ km, $\varepsilon = 0$. It means that, in total, both fragments contain 27 % of Meddy heat content and about 20 % of its salt content.

## Chemical data

The complexity of dynamic structure of the region, thermohaline contrasts caused by presence of warm and salty (relative to the surrounding water) Meddy and its fragments, and the influence of seamounts result in a very mixed picture of chemical element distribution. However, the basic coherent structures can also be traced on maps of chemical elements.

Background distributions of all chemical elements are characterized by a meridional orientation of isolines coinciding with the general direction of geostrophic flow in the study area.

Distribution of phosphates at the depth of 1000 m (Fig. 9*a*) is the most representative: the position of the Meddy and its fragments is marked by local areas with minimum phosphate concentration of 24 $\mu g \cdot l^{-1}$ (the Meddy core, st. 42), 28 $\mu g \cdot l^{-1}$ (first fragment, st. 34) and 26 $\mu g \cdot l^{-1}$ (second fragment, st. 37). The influence of the Meddy core can be traced at depths from 600 m to 1200 m. The fragments of

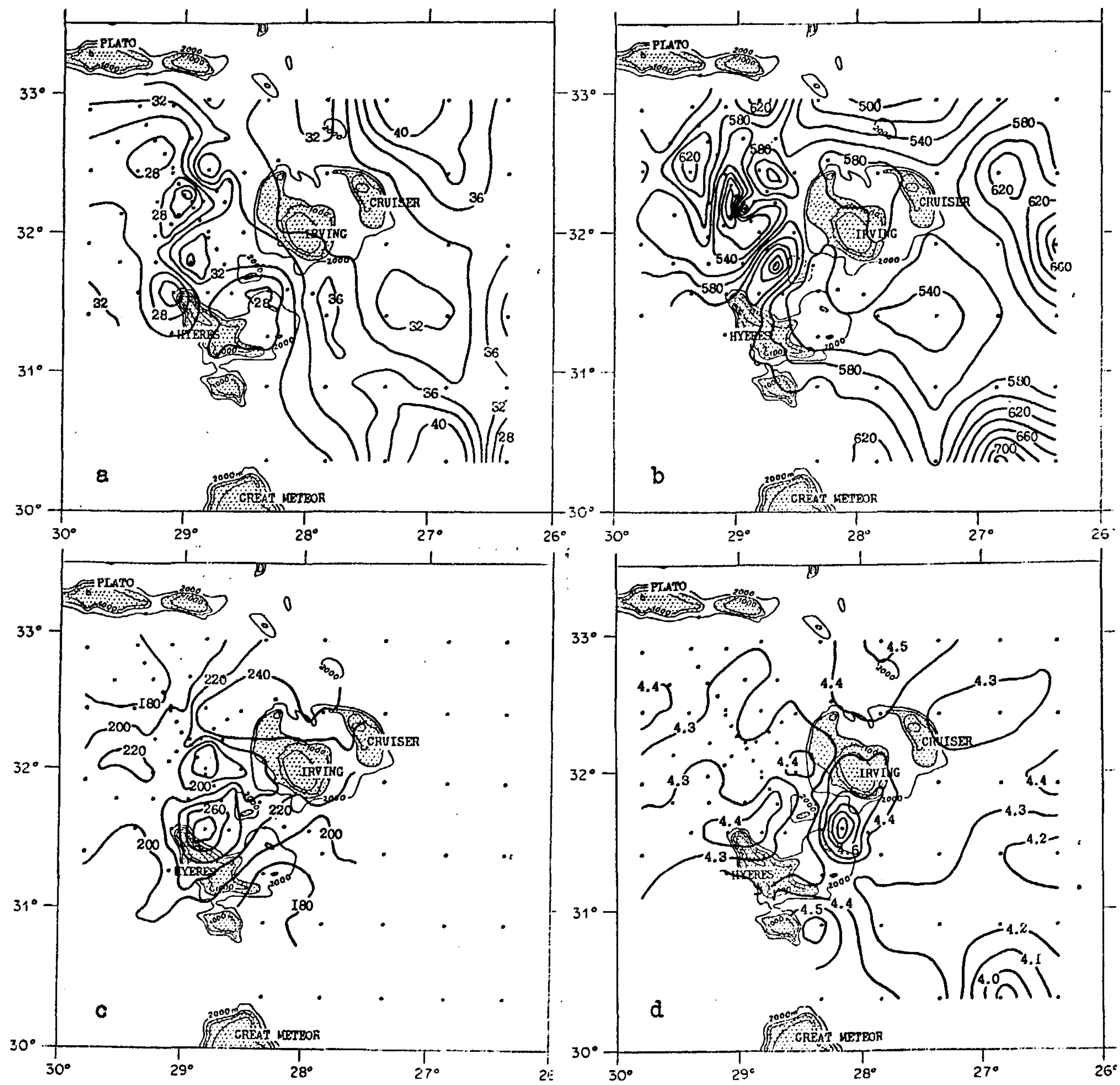


Figure 9

*Distributions of chemical elements at 1000 m: (a) - phosphates (μg·l⁻¹); (b) - silicates (μg·l⁻¹); (c) - nitrates (μg·l⁻¹); (d) - dissolved oxygen (μl·l⁻¹).*

the Meddy are evident in the depth range from 800 m to 1200 m. The anticyclonic vortex to the west of the Irving Seamount is characterized by a small region of slightly lower phosphate content (32 $\mu g \cdot l^{-1}$) as compared to the background (34 $\mu g \cdot l^{-1}$) in the layer of 600-1200 m.

At the depth of 1000 m (Fig. 9*b*) there is a limited region of low silicates concentration (450-500 $\mu g \cdot l^{-1}$) as compared to the background (580-600 $\mu g \cdot l^{-1}$). This region corresponds to the Meddy and can be traced in the depth range from 800 m to 1000 m. The Meddy fragments and the anticyclone to the west of the Irving Seamount are not pronounced in the field of silicates. In the vicinity of st. 60 there is a local area of high silicate content (640-650 $\mu g \cdot l^{-1}$) which is clearly traced in the layer of 1000-1200 m. This area corresponds to sharp depth increase in the passage between the Irving and Hyeres Seamounts.

As follows from Fig. 9*c*, the Meddy core is characterized by low nitrate concentration (< 200 $\mu g \cdot l^{-1}$). Regions of high nitrate concentration (260-280 $\mu g \cdot l^{-1}$) coincide with western spurs of the Irving and Hyeres Seamounts. They are traced in the layer of 1000-1100 m and are, probably, also caused by the effects of bottom topography.

According to the distribution of dissolved oxygen at the depth of 1000 m (Fig. 9*d*), Meddy "Irving" is characterized by a local minimum (< 4.4 $ml \cdot l^{-1}$) of concentration as compared to the background (> 4.4 $ml \cdot l^{-1}$). As Mediterranean Water propagates in this region below the layer of oxygen minimum, the contrasts in the distribution of dissolved oxygen at 1000 m are small.

Thus, both the Meddy and its fragments are characterized by local areas with minimum contents of phosphates, silicates and nitrates, and have low values of dissolved oxygen.

Concentrations of heavy metals in the lens are 5-35 times as high as the background values. The following concentrations were observed in the Meddy core: copper - 1.7 $\mu g \cdot l^{-1}$, cobalt - 0.5 $\mu g \cdot l^{-1}$, manganese - 4.9 $\mu g. l^{-1}$, whereas the background values were 0.35, 0.09 and 0.14 $\mu g \cdot l^{-1}$ respectively. This can be the result of pollution of the Mediterranean Water. Heavy metals are chemically conservative ingredients and can serve as a good indicator of the Mediterranean Water. Concentration of chromium has an unexplainable minimum of 0.20 $\mu g \cdot l^{-1}$ in the lens centre *versus* 0.83 $\mu g \cdot l^{-1}$ in the surrounding water. At vertical cross-sections, isolines of heavy metals concentration (except chromium) repeat the shape of the lens obtained from CTD data.

## CONCLUSIONS

We surveyed the Meddy "Irving" in January 1990 approximately 100 km to the west of the Irving Seamount. Two months before, an intense Meddy with the same *T,S*-characteristics was observed by Dykhno *et al.* (1991) to the east of the Irving Seamount. Combining this fact with the absence of Meddies in a large study area to the east of the Irving Seamount in January 1990, we can hypothesize that we observed the same lens as Dykhno *et al.* (1991). The lens moved generally westward between two identified locations.

The salty wake, elongated from northwest to southeast, was identified near the lens, in the passage between Hyeres and Irving Seamounts. Two isolated patches of saline water with *T,S*-characteristics close to the same parameters of the Meddy periphery were found inside the wake southeast of the Meddy. According to Fedorov and Paka (1988), a moving lens generates a wake of saline water behind it. Therefore, the salty wake traces the trajectory of Meddy "Irving" movement, and salty patches inside the wake have been split from the lens.

The Meddy "Irving" had an elliptical shape in horizontal plane. The major lens axis was too large to fit between Irving and Hyeres Seamounts, whereas the minor axis was approximately equal to the width of the gap between the peaks. This would be explained by the fact that the initially circular Meddy was horizontally squeezed in the passage by the impact of seamounts.

Putting together all the above, we can suppose the following scenario. Meddy "Irving" moved southwest to the western edge of the Canary Basin and then passed between Hyeres and Irving Seamounts. It was partially damaged due to the impact of seamounts. As a result of the collision, two salty patches were detached containing water from the sides of the lens. In front of the lens, wave-like disturbances were generated. A part of the mother lens water was lost while passing between the seamounts, mixed with surrounding water, and formed a salty wake.

We can conclude that at least some Meddies can overcome the chain of seamounts at the western edge of the Canary Basin, keeping their individual features and transporting their physical and chemical anomalies further to the west. It can be also supposed that the Mid-Atlantic Ridge is not an insurmountable barrier for westward propagation of Meddies.

## APPENDIX

### Computation of heat and salt content of Meddies

We introduce the isopycnal anomaly of temperature $T'_\rho$ as the difference between temperatures of water in the core of a Meddy and outside it at the same density level $\sigma_t$; the isopycnal anomaly of salinity $S'_\rho$ is defined similarly. Isopycnal anomalies of heat and salt content integrated over the lens thickness for each hydrographic station in the lens are calculated as

$$q = C_P \cdot \rho_0 \int_{H_1}^{H_2} T'_\rho \; dH \quad (\mathrm{J \cdot m^{-2}}) \qquad \text{(A1)}$$

$$m = 10^{-3} \cdot \rho_0 \int_{H_1}^{H_2} S'_\rho \; dH \quad (\mathrm{kg \cdot m^{-2}}) \qquad \text{(A2)}$$

where $C_P = 3935$ J·(kg·°C)$^{-1}$ is the heat capacity of sea water at the typical depth of Meddies; $\rho_0 = 1030$ kg·m$^{-3}$ is the background density; $H_1$ and $H_2$ are the depths of upper and lower borders of the lens *i.e.* depths where $T'_\rho$ and $S'_\rho$ go to zero (practically we used $S'_\rho = 0.08$ psu as the boundary condition).

We parameterize $q(r,\varphi)$ and $m(r,\varphi)$ distributions by Gaussian formulae

$$\begin{aligned} q(r,\varphi) &= q_0 \cdot \exp\left[-\frac{r^2}{L^2(\varphi)}\right] \\ m(r,\varphi) &= m_0 \cdot \exp\left[-\frac{r^2}{L^2(\varphi)}\right] \end{aligned} \qquad \text{(A3)}$$

where $r$, $\varphi$ are polar coordinates measured from the lens centre, $\varphi = 0$ corresponds to the major lens axis, $q_0$ and $m_0$ are anomalies calculated at the lens centre, $L(\varphi)$ is the variable lens radius. In accordance with the results of measurements we suppose the lens to have an elliptical shape from the top view. Hence, $L(\varphi)$ is determined as

$$L^2(\varphi) = \frac{L_b^2}{1 - \varepsilon^2 \cdot \cos^2(\varphi)} \qquad \text{(A4)}$$

where eccentricity $\varepsilon$ is given by the expression $\varepsilon^2 = 1 - (L_b/L_a)^2$ and the values of $L_a$ and $L_b$ are the approximation parameters, which are calculated by the best fit of the curves (A3) to the observational data.

For the integral heat and salt content anomalies over the whole lens volume we obtain using (A3)-(A4):

$$Q=4\int_0^{\pi/2} d\varphi \int_0^{\infty} q(r,\varphi) r dr = \frac{\pi}{\sqrt{1-\varepsilon^2}} \cdot q_0 \cdot L_b^2 \quad \text{(A5)}$$

$$M = \frac{\pi}{\sqrt{1-\varepsilon^2}} \cdot m_0 \cdot L_b^2 \quad \text{(A6)}$$

Similarly we approximate the lens thickness $h(r,\varphi)$ by Gaussian distribution:

$$h(r,\varphi) = h_0 \cdot \exp\left[-\frac{r^2}{L^2(\varphi)}\right] \quad \text{(A7)}$$

where $h_0 = H_1 - H_2$ is the thickness of a Meddy in its center, and $L(\varphi)$ is determined by (A4). Then the whole volume of a Meddy is

$$V=4\int_0^{\pi/2} d\varphi \int_0^{\infty} h(r,\varphi) r dr = \frac{\pi}{\sqrt{1-\varepsilon^2}} \cdot h_0 \cdot L_b^2 \quad \text{(A8)}$$


## Acknowledgements

We wish to express our gratitude to Dr. A.G. Zatsepin for helpful discussions, to Dr. N.N. Osipov and his group for carrying out chemical measurements, and to Kathy Schultz Tokos and Elena Krepkogorskaya for improving the English version of the manuscript. This work was partially supported by Russian Fund of Fundamental Research under grant 94-05-17302*a* and ISF grant No. IG7100.


## REFERENCES


**Armi L., H. Stommel** (1983). Four views of a portion of the North Atlantic Subtropical Gyre. *J. Phys. Oceanogr.* **13**, 828-857.

**Armi L., W. Zenk** (1984). Large lenses of highly saline Mediterranean Water. *J. Phys. Oceanogr.* **14**, 1560-1576.

**Armi L., D. Hebert, N. Oakey, J.F. Price, P.L. Richardson, H.T. Rossby** (1989). Two years in the life of Mediterranean salt lens. *J. Phys. Oceanogr.* **19**, 354-370.

**Belkin I.M., M.V. Emelianov, A.G. Kostianoy, K.N. Fedorov** (1986). Thermohaline structure of intermediate waters of the ocean and intrathermocline eddies. In: *Intrathermocline eddies in the ocean*, edited by K.N. Fedorov. P.P.Shirshov Institute of Oceanology, Moscow, 8-34 (in Russian).

**Csanady G.T.** (1979). The birth and death of a warm core ring. *J. Geophys. Res.* **84**, 777-780.

**Dykhno L.A., E.G. Morozov, S.V. Nikitin, B.N. Filyushkin, I.A. Shilov** (1991). On Mediterranean Water lens destruction due to interactions with bottom topography. *Okeanologija* **31**, 55-61 (in Russian).

**Fedorov K.N., V.T. Paka** (1988). On the thermohaline trace of an intrathermocline eddy in the ocean. *Doklady Akademii Nauk SSSR*, **301**, 1206-1209 (in Russian).

**Flierl G.R.** (1984). Rossby wave radiation from a strongly nonlinear warm eddy. *J. Phys. Oceanogr.* **14**, 47-58.

**Hebert D.L.** (1988). *A Mediterranean salt lens.* Ph.D. Thesis. Dalhousie University, Halifax, Nova Scotia, 187 p.

**Huppert H.E., K. Bryan** (1976). Topographically generated eddies. *Deep-Sea Res.* **23**, 655-679.

**Käse R.H., W. Zenk** (1987). Reconstructed Mediterranean salt lenses trajectories. *J. Phys. Oceanogr.* **17**, 158-163.

**Kamenkovich V.M., M.N. Koshliakov, A.S. Monin** (1987). *Synoptic Eddies in the Ocean.* Gidrometeoizdat, Leningrad, 512 p. (in Russian).

**Koshliakov M.N., G.G. Panteleev** (1988). Thermohaline characteristics of a Meddy in tropical zone of North Atlantic. In: *Hydrophysical investigations on the MEZOPOLYGON program*, edited by V.G. Kort. Nauka, Moscow, 46-56 (in Russian).

**Kostianoy A.G., G.I. Shapiro** (1989). On the forecast of lens-like eddy trajectories in the ocean. *Doklady Akademii Nauk SSSR*, **309**, 1219-1222 (in Russian).

**Maltsev N.E., K.D. Sabinin, A.V. Furduev** (1990). An acoustic-oceanologic experiment at the lens of Mediterranean waters in the Atlantic Ocean. *Akusticheskij Zhurnal* **36**, 86-93 (in Russian).

**McWilliams J.C.** (1985). Submesoscale, coherent vortices in the ocean. *Reviews of Geophysics* **23**, 165-182.

**Nof D.** (1982). On the movement of deep mesoscale eddies in the North Atlantic. *J. Mar. Res.* **40**, 57-74.

**Osipov N.N., A.V. Koleganov, T.R. Eremina, G.M. Kuchuk** (1991). On the chemical composition of the lens of Mediterranean water. In: *Lens-like eddies and fronts in North-East Atlantic Ocean*, edited by V.N. Pelevin. P.P. Shirshov Institute of Oceanology, Moscow, 41-47 (in Russian).

**Pingree R.D., B. Le Cann** (1993). A shallow Meddy (a Smeddy) from the secondary Mediterranean salinity maximum. *J. Geophys. Res.* **98**, 20169-20185.

**Richardson P.L., D. Walsh, L. Armi, M. Schröder, J.F. Price** (1989). Tracking three Meddies with SOFAR floats. *J. Phys. Oceanogr.* **19**, 371-383.

**Richardson P.L., M.S. McCartney, C. Maillard** (1991). A search for meddies in historical data. *Dyn. Atmos. Oceans.* **15**, 241-265.

**Shapiro G.I.** (1984). The structure of a mesoscale vortex lens in the ocean thermocline. *Doklady Akademii Nauk SSSR*, **276**, 1477-1479 (in Russian).

**Shapiro G.I.** (1987). To the theory of quasigeostrophic motions of finite amplitude in the viscous stratified ocean. *Okeanologija* **31**, 18-24 (in Russian).

**Shapiro G.I.** (1989). On the dynamics of lens-like eddies. In: *Mesoscale/synoptic coherent structures in geophysical turbulence*, edited by J.C.J. Nihoul and B.M. Jamart. Elsevier, Amsterdam, 783-796.

**Williams R.T., J.L. Sarmiento, P. Rhines, W.M. Smethie Jr., C.G.H. Rooth, R.M. Key, T. Takahashi, C. Collins** (1986). *Transient tracers in the ocean. Tropical Atlantic study, 1 December 1982 - 18 February 1983. Shipboard physical and chemical data report*, Scripps Institution of Oceanography *Tech. Rep. Ref.* 86-16, 310 p.

**Zatsepin A.G., M.V. Emelianov, Yu.E. Scherbakov** (1991). Some results of front observations in the Azores frontal zone. In: *Lens-like eddies and fronts in north-east Atlantic ocean*, edited by V.N. Pelevin. P.P. Shirshov Institute of Oceanology, Moscow, 136-149 (in Russian).