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PART I

Some aspects of time variability of the Mediterranean Water off south Portugal

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Abstract

Mediterranean Water contributes significantly to the hydrological properties and circulation of the intermediate layers of the North Atlantic, yet the temporal variability of the Mediterranean Undercurrent is still not well understood, even at intra-annual time scales. The present study addresses the evolution of the temperature field in the layers of Mediterranean Water off south Portugal during one year (July 1993–July 1994), obtained with an almost weekly repetition of a high-resolution expendable bathythermograph (XBT) section in the vicinity of Portimão Canyon, during the AMUSE experiment. The information obtained with this set of data was complemented by velocity observations of the Mediterranean Undercurrent with RAFOS floats launched simultaneously with the XBT lines. The typical structure of the Mediterranean Undercurrent along the slope of the Gulf of Cadiz, consisting of a westward jet associated with the cores of the thermohaline structure, was observed in almost 60% of the 24 repetitions of the XBT section. The results show that this typical structure in the velocity was not always accompanied by a typical thermal structure. Anomalous behaviour of the Undercurrent – southward or southwestward flow or local recirculation – occurred only in winter and corresponded to some anomalies in the thermal field associated with the Mediterranean Water. The occurrence of warm features offshore of and separated from the main body of warm water found against the slope off south Portugal seemed to be connected with episodes of changes in direction and speed of the Undercurrent. Several scales of time variability within the Mediterranean Water layers were identified ranging from a week to a month. A possible seasonal trend in the temperature of these layers was apparent in the XBT data and seemed also to be found in time series obtained with moored current meters. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Mediterranean Water, characterized by anomalously high salinities and temperatures, strongly influences the hydrology and the dynamics of the northeast Atlantic. The salinity anomaly associated with this water mass spreads as a tongue into the North Atlantic and is detected to the west of the mid-Atlantic ridge, well to the north of Cape Finisterre (northwest Spain) and far south of the Canary Islands (e.g., Reid, 1994; Lozier et al., 1995). The spreading of this thermohaline anomaly is much reinforced by the action of submesoscale eddies that detach from the Mediterranean Undercurrent. These meddies seem to play an important role, not only in the dispersion of Mediterranean Water in the Atlantic (Armi and Stommel, 1983; Armi and Zenk, 1984; Armi et al., 1989; Richardson et al., 1989; Ahran et al., 1994), but also as carriers of particulate and dissolved matter (Abrantes et al., 1994).

As the Mediterranean Outflow leaves the Strait of Gibraltar, it descends towards the Gulf of Cadiz, while being deflected to the right due to the Coriolis effect. The gradual attenuation of its anomalously high thermohaline properties and the corresponding decrease of its density is a consequence of the entrainment and mixing with the surrounding fresher and colder Atlantic Water (Price et al., 1993; Price and Baringer, 1994). At about 8°W the Mediterranean Outflow reaches quasi-equilibrium as a density current but flows as a wall-bounded current – the Mediterranean Undercurrent.

One of the singular aspects of the Mediterranean Outflow in the NE Atlantic is its subdivision into two main cores (e.g., Siedler, 1968; Madelain, 1970; Zenk, 1970; Ambar and Howe, 1979a, b), which closer to the Strait of Gibraltar are hard to distinguish but further downstream are easily identifiable by separate maxima of temperature and salinity, centered respectively, at depths of about 800 m and densities around $\sigma_\theta = 27.6$ (upper core), and 1200 m and $\sigma_\theta = 27.8$ (lower core). This double layer structure is coincident with a general westward flow following the bottom contours along the northern continental slope of the Gulf of Cadiz. Previous observations of the thermohaline field have shown that the Mediterranean Outflow does not always cling to the slope but is strongly influenced by the presence of submarine valleys and canyons, which divert the flow and induce meandering and offshore extensions (e.g. Ambar and Howe, 1979a; Zenk and Armi, 1990). Besides the two "classical" main cores of Mediterranean Water, there is evidence of a third, less conspicuous, core at shallower depths, i.e. around 400–600 m, which was found off the southern coast (Zenk, 1975; Ambar, 1983) and also off the western coast (Ambar, 1983; Hinrichsen and Rhein, 1993) of Portugal, not extending further offshore than about 50 km, hereafter referred as the shallow core.

An important issue that needs further investigation is the temporal variability of the Mediterranean Outflow. Time series of hydrology and current measurements obtained in the Strait of Gibraltar have shown the tidal and internal wave activity dominating the high frequency variability (Lacombe and Richez, 1982; Armi and Farmer, 1985). The changes of the cross-channel slope of the sea surface, apparently related to atmospheric pressure fluctuations over the western Mediterranean Sea, seem to be the important factor at low (subinertial) frequencies (Bormans et al., 1986; Candela et al., 1989; Bryden et al., 1994).

In the Gulf of Cadiz, there have been only a few investigations of low frequency variability in the Mediterranean density current (Stanton, 1983; Zenk, 1975; Gründlingh, 1981; Thorpe, 1976), and the time-dependent behaviour of the Mediterranean Undercurrent is still an unclear subject, even at intra-annual time scales. Further investigation is needed based on direct observations of the temporal evolution of the hydrology and the dynamics. A field program called "A Mediterranean Undercurrent Seeding Experiment" (AMUSE) was carried out over a one year period in 1993-94 (Bower et al., 1995; Bower et al., 1997a, b; Hunt et al., 1998). The main objectives of this experiment were to observe directly the formation of meddies and the spreading of the Mediterranean Water off the Iberian Peninsula, based on the tracking of subsurface RAFOS floats deployed sequentially over a 10-month period at the level of the lower core of Mediterranean Water. The hydrological setting, in terms of the vertical distribution of temperature across the undercurrent, was obtained by a high-resolution expendable bathythermograph (XBT) line repeated each time the RAFOS deployments were performed. Additional XBT lines were also carried out to complete a one-year sampling.

The choice of the experiment site was based on several requirements, the most important being a location in the Mediterranean Undercurrent downstream of the region where the Mediterranean Water sinks to its level of neutral buoyancy but upstream of all the proposed meddy formation sites. To comply with these requirements, an analysis was made of previous observations (Ambar and Howe, 1979a, b) and of those obtained during a CTD campaign in the Gulf of Cadiz aboard the *R/V Oceanus*, between 30 April and 14 May 1993 (*Oceanus* 258 cruise), in the framework of AMUSE (Bower et al., 1997a).

This paper concerns mainly the detailed analysis of the XBT observations, complemented by other direct observations of the temperature and current field, such as those obtained by the RAFOS floats (Bower et al., 1997b) and by recording current meters moored on the Portuguese continental slope. The methodology adopted for the data collection and processing is given in the following section. The main results of the observations are presented in Section 3. Finally, the integrated analysis of the results is discussed in Section 4.

2. Measurements

2.1. Location and time period of the XBT measurements

The observational strategy of AMUSE consisted of weekly deployment from a chartered vessel – *Kialoa II* – of two RAFOS floats ballasted for depths within the lower core of the Mediterranean Water (1100–1200 m), complemented by a high resolution XBT section across the main flow. The total of 44 floats deployed in this way were tracked acoustically for a period of up to 11 months (Bower et al., 1997b). After the float deployments had finished (March 1994), the XBT program was continued in order to complete the annual cycle, at least on a monthly basis; this led to four more repetitions of the same line, aboard another chartered vessel, the *Monara*.

During *Oceanus* 258, the deployment of the three sound sources needed for the tracking of the floats was made, as well as the first launch of one RAFOS float. The examination of the temperature and salinity distributions along the sections conducted during this cruise and the above-mentioned considerations led to the final selection of the site for the RAFOS deployments – one float as close to the slope as possible and the second some kilometers offshore – and for the complementary XBT line. This main XBT line (line K), whose portion between stations 03 and 09 was coincident with the *Oceanus* section C (stations 107–113, 11 May 1993), is shown in Fig. 1, the offshore part of it intersecting the Portimão Canyon, the main local bathymetric feature.

The systematic launching of floats and the simultaneous high-resolution XBT lines started on 5 July 1993. The XBTs used in this experiment were of the types T-4 (maximum depth of about 500 m), T-7 (800 m) and T-5 (2000 m) depending on the depth of the site where they were launched. The spacing between stations was 1.5 nautical miles (about 2.8 km), but in the neighborhood of the sites where the RAFOS floats were deployed (i.e. between stations 05 and 08) the resolution was increased by introducing one station at half distance; these extra stations were designated 5a, 6a and 7a.

As the observational program developed, there was a need to extend, both inshore and offshore, the initial XBT line in order to observe the shallow core and the whole offshore extent of the Mediterranean main cores (upper and lower). In the first K section (K01, 5 July 1993), 14 XBT stations (stns. 01 to 14) were performed; in the second K section (K02, 15 July 1993), 6 extra inshore stations were added (stns 0 to -06) and maintained throughout the whole program; beginning with the tenth K section (K10, 13 November 1993), the observed increase in the lateral extension of the Mediterranean layers required the offshore addition of 3 more stations. This offshore extension was maintained or even increased (up to 7 more stations) according to the situation found at the time of sampling.

A second XBT line (line 2K, see Fig. 1), downstream of the Portimão Canyon and having with line K a common end point at the offshore edge, was later (13 November 1993) added. The purpose of this line was to observe the temperature structure and any eventual alterations due to the presence of the canyon and was repeated 10 times (until 13 February 1994). The spacing between stations in line 2K was 2 nautical miles (about 3.7 km). Table 1 gives summarized information on both XBT lines (K and 2K).

The more or less regular weekly observational programme that lasted from July 1993 until March 1994 suffered interruptions, of about one and one and a half months, during August and October 1993, due to technical problems with the floats (Hunt et al., 1998). From March 1994 until July 1994, the main section (K) was repeated monthly. Fig. 2 illustrates the schedule of the repetitions of the XBT lines.

Before processing the data obtained with the XBTs, there was the need to establish the exact depth to which the temperature profile should be considered for the stations

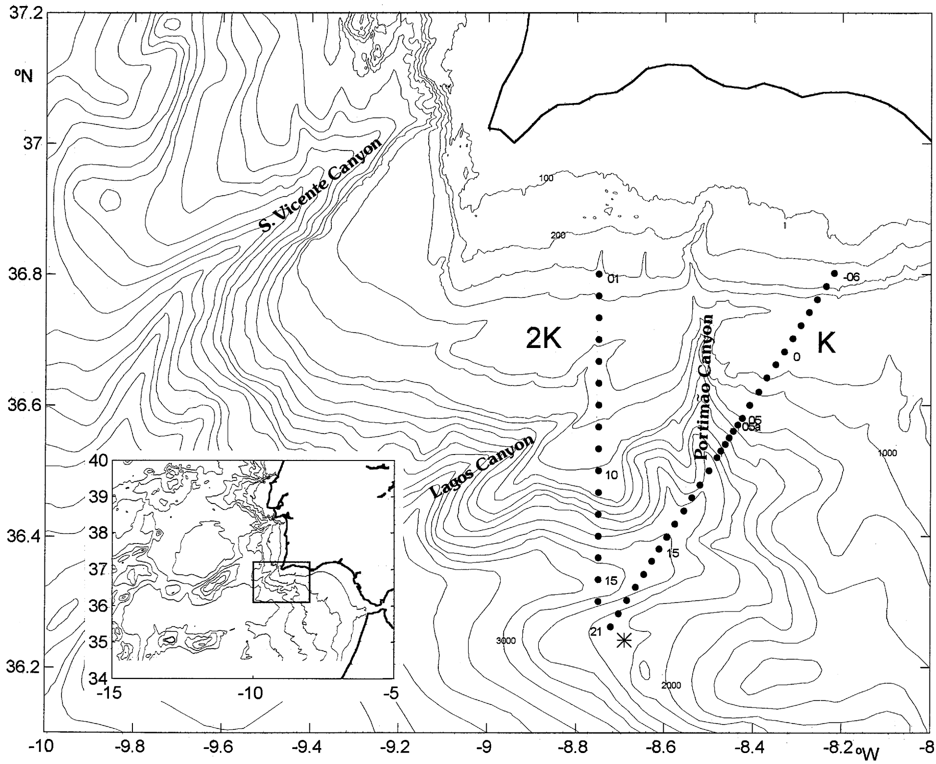

Fig. 1. Location of the XBT stations along the lines repeated during AMUSE: line K, from May 1993 until May 1994, and line 2K, from November 1993 until February 1994. Also indicated (by a star) is the site of the current meter mooring deployed during the CORAL project. Bathymetric contours are shown for 100 m, 200 m and then every 200 m. Inset: General area of interest.

shallower than the maximum depth attainable by the instrument, in order to detect where the influence of the sediments or of hard bottom had started. The bottom profile that was chosen for sections K and 2K corresponds to the most frequently observed depths at each XBT station.

2.2. Main bathymetric features of the area

The XBT and the current meter observations off the coast of Algarve were made in the region where the Mediterranean Undercurrent first encounters a large system of submarine canyons – the Portimão Canyon and the Lagos Canyon (Fig. 1). The head of the Portimão Canyon crosses the border of the continental shelf, which, in this region, is relatively wide (about 30 km) and gently slopes until its edge, defined by the 200 m isobath (Vanney and Mougenot, 1981). The lower part of this canyon constitutes a complex system subdivided into two main branches oriented to the north and

Table 1
Summary of information on the XBT lines during AMUSE, with the dates and stations

XBT line	Date	Vessel	Station numbers
K01	05 Jul 93	*Kialoa II*	1 to 14, and 5a, 6a and 7a
K02	15 Jul 93	*Kialoa II*	-06 to 11 and 5a, 6a and 7a
K03	21 Aug 93	*Kialoa II*	-06 to 14 and 5a, 6a and 7a
K04	28 Aug 93	*Kialoa II*	-06 to 14 and 5a, 6a and 7a
K05	04 Sep 93	*Kialoa II*	-06 to 14 (except -01, 9, 11, 12) and 5a, 6a and 7a
K06	11 Sep 93	*Kialoa II*	-06 to 14 and 5a, 6a and 7a
K07	18 Sep 93	*Kialoa II*	-06 to 14 and 5a, 6a and 7a
K08	26 Sep 93	*Kialoa II*	-06 to 14 and 5a, 6a and 7a
K09	09 Nov 93	*Kialoa II*	No useful data
K10	13 Nov 93	*Kialoa II*	-06 to 17 and 5a, 6a and 7a
2K01			1 to 16
K11	20 Nov 93	*Kialoa II*	-06 to 14
K12	04 Dec 93	*Kialoa II*	-06 to 17 and 5a, 6a and 7a
2K02			1 to 16
K13	11 Dec 93	*Kialoa II*	-06 to 16 and 5a, 6a and 7a
K14	20 Dec 93	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K03			1 to 16
K15	04 Jan 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K04			1 to 16
K16	08 Jan 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K05			2 to 16
K17	15 Jan 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K06			1 to 16
K18	22 Jan 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K07			1 to 16
K19	29 Jan 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K08			1 to 16
K20	05 Feb 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K09			1 to 16
K21	13 Feb94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
2K10			1 to 16 and 9a
K22	19 Feb 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
K23	26 Feb 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
K24	05 Mar 94	*Kialoa II*	-06 to 18 and 5a, 6a and 7a
M01	23 Apr 94	*Monara*	-06 to 21
M02	21 May 94	*Monara*	-06 to 19
M03	18 Jun 94	*Monara*	-06 to 18
M04	16 Jul 94	*Monara*	-06 to 19

to the northwest and another one pointing southeastwards. The continental slope is cut by the above mentioned canyons, inducing a very complicated bottom topography pattern with almost meridional bathymetric lines in the upstream region and almost zonal lines between the two canyons.

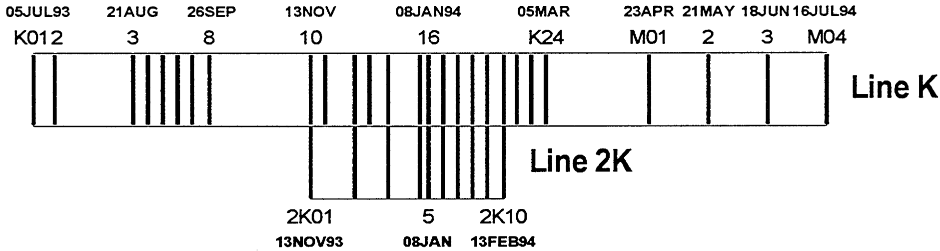

Fig. 2. Chronogram of the repetitions of lines K and 2K.

3. Observations and analysis

3.1. Mediterranean Undercurrent structure

The canonical structure of a steady Mediterranean Undercurrent is a wall-bounded current that hugs the continental slope and is in clear association with the cores of the thermohaline structure that characterizes the Mediterranean Water (high temperatures and salinities). Along the northern margin of the Gulf of Cadiz, this Undercurrent flows in a generally westward direction, and its offshore extent is approximately the radius of deformation associated with the mid-depth pressure perturbation of the undercurrent. This can be considered as the "typical" structure of the Undercurrent off south Portugal, and examples can be found in the hydrological and current meter observations reported by Zenk (1974), Thorpe (1976), Ambar and Howe (1979a, b) and Howe (1984).

This same typical Undercurrent structure was found in the present observations and can be illustrated using the CTD data collected on section C of *Oceanus* 258 for representing the thermohaline vertical distribution (Fig. 3a and 3b). The associated geostrophic currents calculated relative to the 400-dbar level (Fig. 3c) and the trajectory of the RAFOS float (Fig. 3d) that was deployed on station 110 at about 1200 m are shown. The temperature section (Fig. 3a) shows values exceeding 12°C at the level of the Mediterranean upper core (about 800 m) and lower core (about 1200 m). The salinity section (Fig. 3b) shows higher salinities, over 36.6, in the lower core as compared with the upper, where the maximum did not exceed 36.3, this being expected from previous knowledge of the differences in the thermohaline characteristics of the two main cores. The geostrophic velocity across the section and within the Mediterranean Water layers indicates a westward component close to the continental slope, with a maximum centered at about 1000 m ($>50\ \mathrm{cm\,s^{-1}}$) and a slower ($<30\ \mathrm{cm\,s^{-1}}$) eastward flow in the outer part of the section. The RAFOS float track (Fig. 3d) showed southwestward movement at the level of the lower core and a mean speed of $22\ \mathrm{cm\,s^{-1}}$ (with maxima reaching $40\ \mathrm{cm\,s^{-1}}$) for the first 3 days after launching, confirming the results obtained with the geostrophy in both the westward component of the velocity and the order of magnitude of the speed (about $20\ \mathrm{cm\,s^{-1}}$) at the site of the RAFOS deployment (station 110, at about 1200 m).

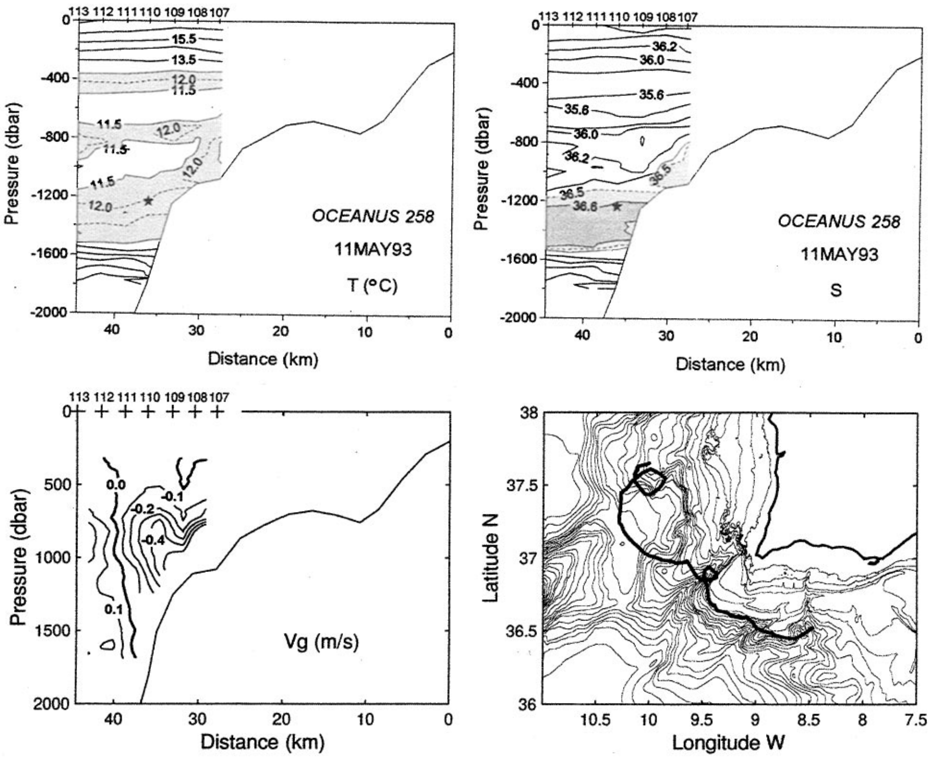

Fig. 3. Typical Mediterranean Undercurrent structure as shown in the vertical distribution for section C of *Oceanus* 258 cruise (coinciding with XBT line K between stns. 03 and 09; see Fig. 1 for location): (a) temperature (°C), (b) salinity, and (c) geostrophic velocity (m s^{-1}) across the section and relative to 400 dbar (negative values correspond to a westward component of the current); (d) trajectory of the RAFOS float deployed during the cruise, showing the westward flow associated with the Undercurrent. The station and depth where the float was launched are indicated by a star in the thermohaline vertical sections (a and b).

3.2. *Identification of time scales of variability*

Before focusing on the Mediterranean Undercurrent variability, a brief description is now given of some general aspects shown by the sequence of XBT data throughout the observational period. The vertical temperature distributions along the main XBT line (K01 to K24 and M01 to M04) are shown in Fig. 4. The positions of the RAFOS floats deployed at each repetition of the XBT main line are marked by a star in the K sections of that figure.

The near surface layer presented the classical evolution during the year of observations, with a seasonal thermocline occupying the first 50 m from July 1993 (Section K01) until September 1993 (section K08), when it began to dissipate and was replaced by a mixed layer that reached depths of more than 200 m at the offshore stations in February 1994 (section K22). Subsequently, the gradual formation of a new seasonal

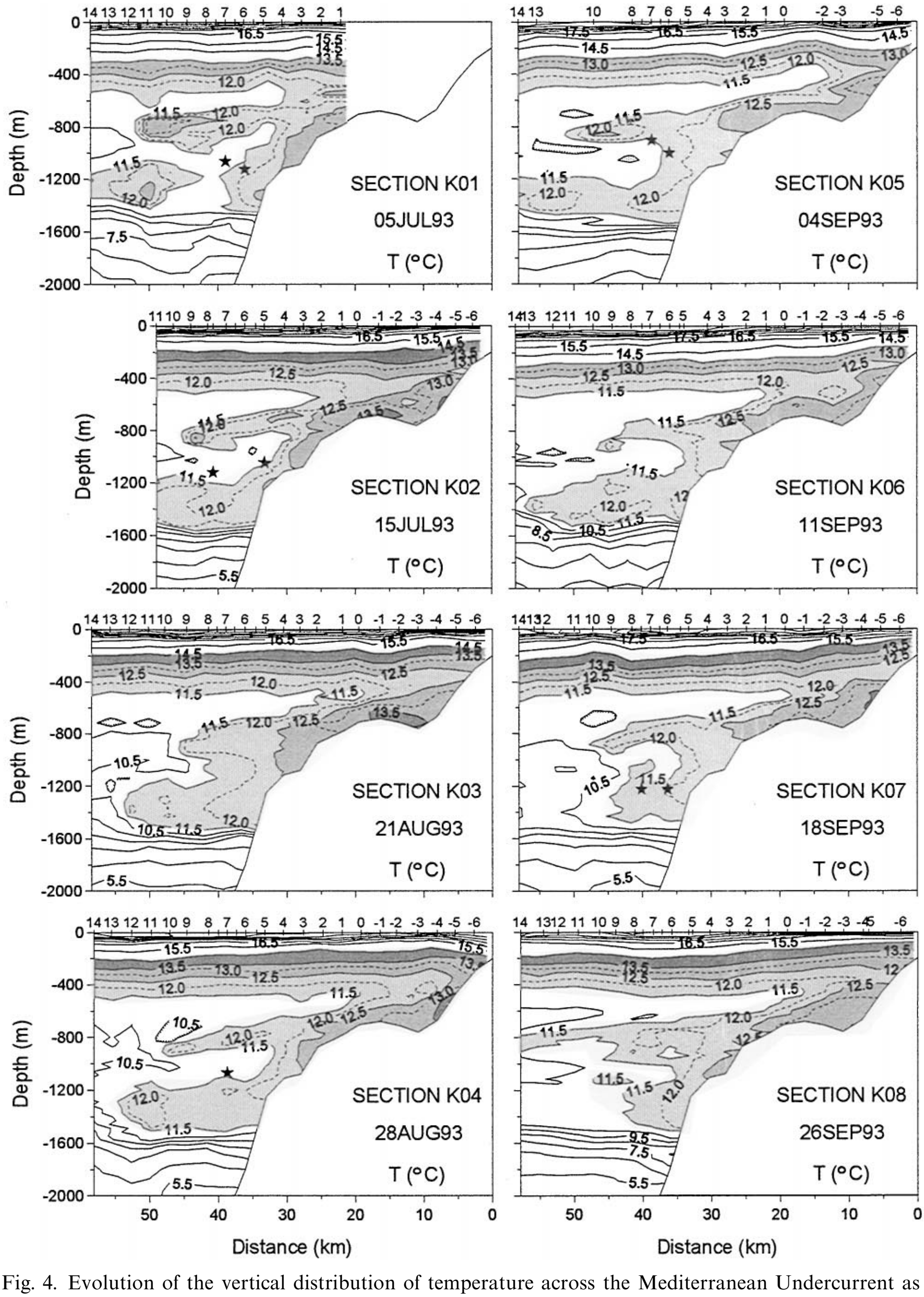

Fig. 4. Evolution of the vertical distribution of temperature across the Mediterranean Undercurrent as obtained with the sequential repetition of line K (K01–K24, M01–M04) between 5 July 1993 and 16 July 1994. Distances (km) are relative to the shelf edge (200-m bottom contour). The stars shown in the sections represent the site and depth of deployment of the corresponding RAFOS floats.

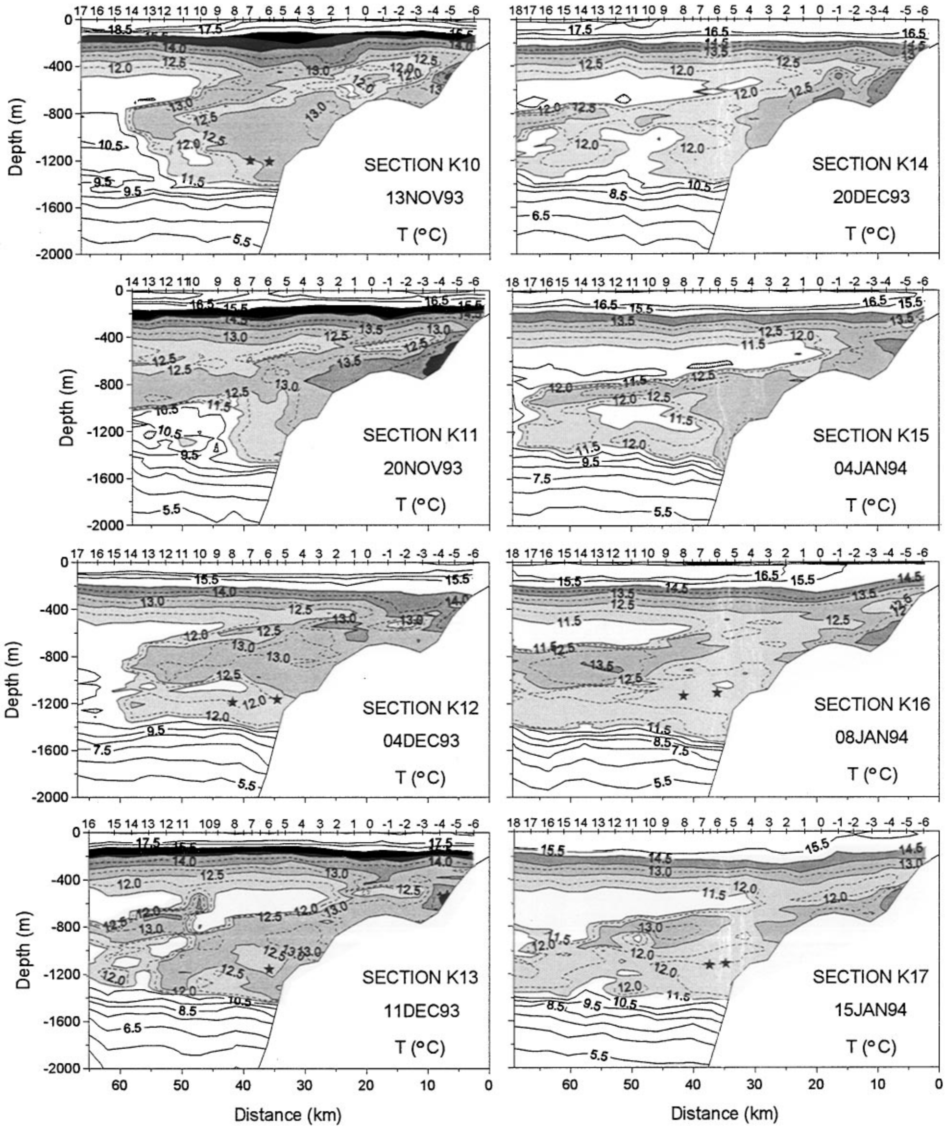

Fig. 4. (*continued*).

thermocline started, and four months later, in June 1994, there was again a 50 m upper layer of strong temperature gradient.

Underneath this seasonally variable near surface layer, the presence of the main water masses for this region of the northeast Atlantic (Ahran et al., 1994; Fiúza et al., 1998) was evident: the Eastern North Atlantic Central Water (ENACW), extending to depths of 400–500 m and corresponding to the permanent thermocline, the

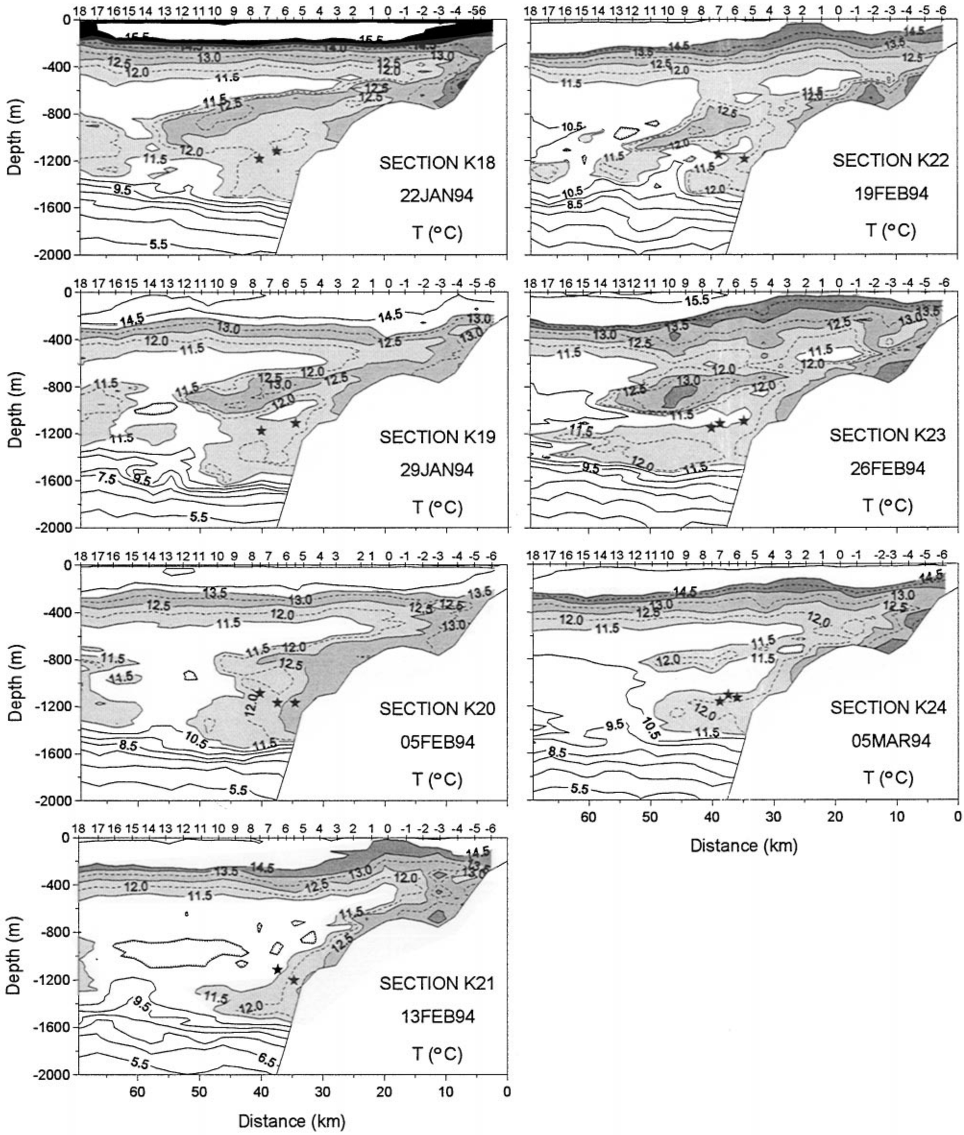

Fig. 4. (*continued*).

Mediterranean Water (MW), occupying the intermediate levels from about 500 m down to 1200–1400 m, and the North Atlantic Deep Water (NADW) underneath, corresponding to a decrease in both temperature and salinity with depth. The ENACW and NADW showed very little variation throughout the year compared to the MW.

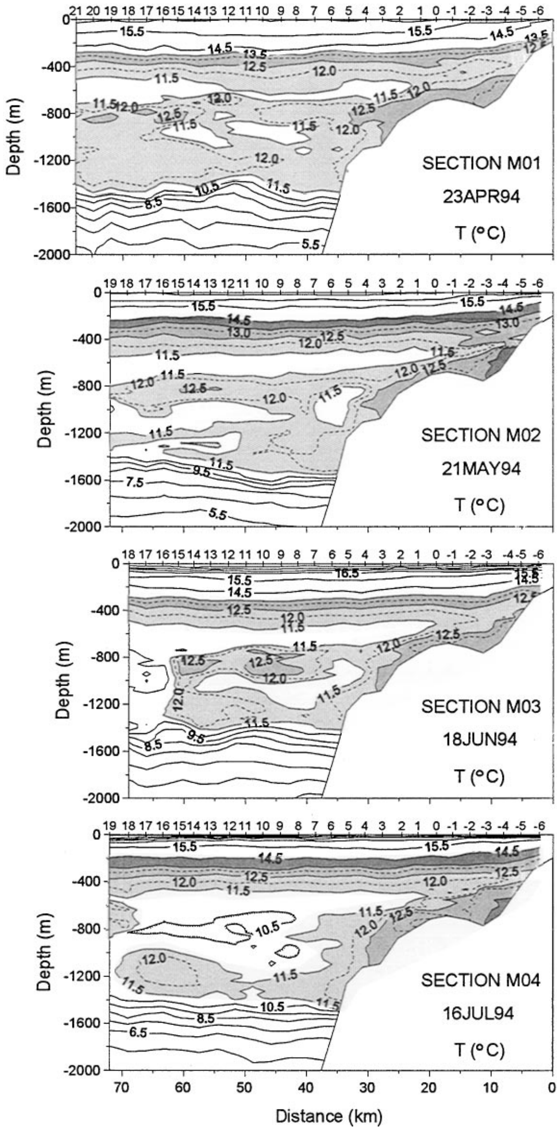

Fig. 4. (*continued*).

The Mediterranean Water layer was found against the continental slope and also extending offshore. There was evidence of the presence of the upper and the lower cores, centered at about 800 and 1300 m, and also of the shallow core lying on the bottom of the upper slope stations, at depths centered at 500 m. The temperature of the upper core reached values slightly higher than 13.5°C (e.g. in Section K23), but that of the lower core never exceeded 13.0°C and rarely was higher than 12.5°C. The shallow core always had temperatures above 13.0°C and even reaching 14.5°C (e.g. in Section K11).

In the sequence corresponding to line K (Fig. 4), several examples of the "typical" hydrological structure associated with the Mediterranean Undercurrent can be identified, such as in sections K01, K02 and K21. In contrast, sections like K13, K16 or M01 show an atypical structure, with a very wide layer of Mediterranean origin extending off the continental slope, with a diffuse, ill-defined outer boundary.

The existence of offshore features enclosed in isotherms with high temperatures was sometimes detected in line K and also in 2K, especially in January and February. They could be associated either with the presence of locally detached blobs of warm water or with meandering filaments. The most conspicuous examples of these features are those centered at station 13 of section K16 and at station 9 of section K23, where values above 13.5°C were attained at the level of the upper core; coincidently or not, they were found at stations localized on the axis of the two main indentations of the complex system of Portimão Canyon (Fig. 1), and, considering that such high values of temperature were normally found only on the bottom of shallower stations near the head of the canyon (inshore of station -01 on line K), a possibility exists that these structures were in fact detached from the main body at the head of the canyon and eventually became meddies. However, the present data do not allow any final conclusions regarding this process.

An approximate measure of the width of the Mediterranean layer and its variations during the period of observations (July 1993 to July 1994) was obtained through the offshore distance along the section reached by its outer edge at the levels corresponding to the upper core (at about 800 m) and to the lower core (at about 1200 m). The outer edge was considered here as represented by the 11.5°C isotherm, and the offshore distance was obtained relative to the 800-m isobath for the upper core and to the 1200-m isobath for the lower core. The inshore separation of these isobaths is about 8 km for line K. Some caution should be taken when considering these offshore distances, since the local bathymetry is very irregular and the XBT line, especially in its outer half, is not perpendicular to a straight boundary. The distances along line K are shown for the upper core (Fig. 5a) and for the lower core (Fig. 5b). There were some cases in which the XBT line was too short to reach the outer edge of the Mediterranean layer as defined by the 11.5°C isotherm, and this is indicated in the figures by the dots at the extremity of the respective line. The comparison of these extensions shows that, in most cases, at the level of the upper core they reached distances from the slope of about 5–15 km further than at the level of the lower core, but that is not surprising, since the upper core is on average warmer and therefore the 11.5°C isotherm represents for it a much outer edge than for the lower core.

The upper core in line K (Fig. 5a) extended to distances of about 25 km, with small oscillations, from July 1993 (K01) until September 1993 (K07); then it started increasing its extension and reached about 40 km in December 1993 (K13) and apparently more than 45 km in January 1994 (e.g., K16). This extreme situation was followed by the appearance of a separated, warm feature around the end of January (K19), its offshore progression during the next two weeks and the simultaneous regression of the part that stayed against the slope to extensions of about 5 km (K21). In February (K22

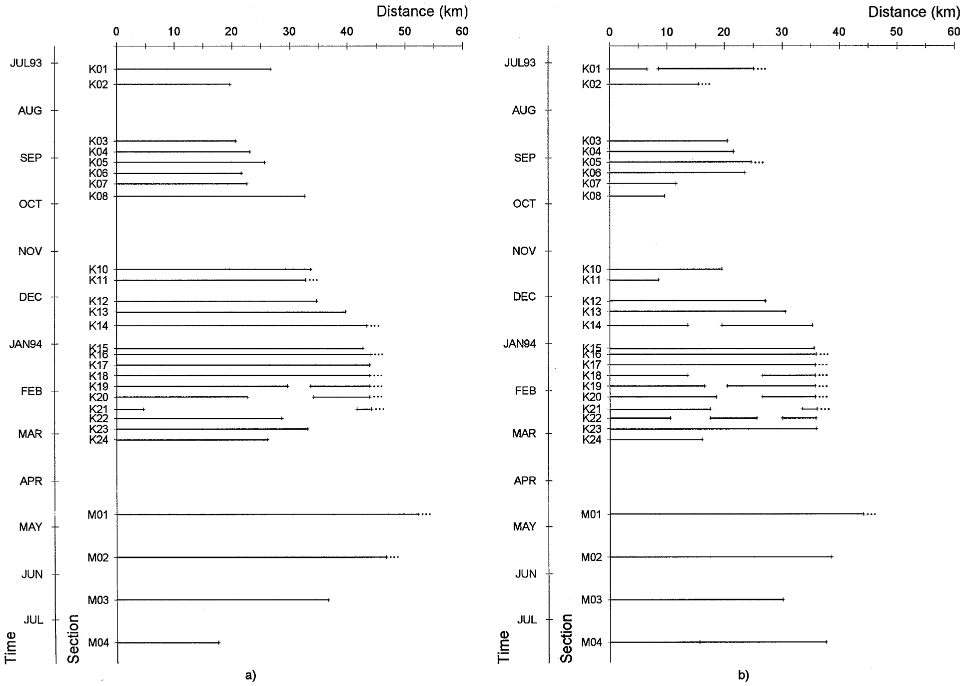

Fig. 5. Time evolution of the offshore extension (in line K) of Mediterranean Water (a) for the upper core, at about 800 m depth, as given by the distance (km) of the 11.5°C isotherm to the 800-m isobath, and (b) for the lower core, at about 1200 m depth, as given by the distance (km) of the 11.5°C isotherm to the 1200-m isobath. The presence of offshore structures is shown by separated line segments. Dots at the outer extremity of a line mean that the XBT line was too short to reach the offshore end of the 11.5°C isotherm.

and K23), the offshore presence of a very warm structure, which might have originated upslope as already mentioned, makes difficult the evaluation of the extension of the upper core, but in March 1994 (K24) it was again at about 25 km. Then, a month later (April 1994, M01), the data showed that there had been a great increase in the extension to values exceeding apparently much more than 55 km, followed by a progressive decrease until July 1994 (M04) to values of about 20 km, similar to those found a year before (July 1993).

The evolution of the upper core extension in line 2K for the period when XBT data was collected there (November 1993 – February 1994) was very similar to that shown in line K.

Comparing the general time evolution of the two cores (Fig. 5), it is obvious that they show similar patterns, with the offshore extension gradually increasing from September 1993 and reaching the largest values in November 1993–February 1994 and in April 1994, and again regressing in May 1994. At both core levels, the occurrence of detached bodies or meandering filaments was noticed mainly from December to February (K14–K23), although more frequently at the level of the lower core. From July to September 1993 (K01 to K06), and considering only the undercurrent closer to the slope, the 11.5°C isotherm at the level of the upper core (800 m) reached about the same distances off slope as at the level of the lower core (1200 m), from then until December (K14) it reached further offshore, and from December 1993 until July 1994 (M04) there was no obvious dominance of either of the two cores.

Besides the fluctuations in the offshore extension, there were fluctuations also in the temperature reached by the Mediterranean Water. In order to evaluate the associated scales of variability, a time series of the vertical temperature distribution at selected stations was drawn for the whole period of observations. The stations were selected from those where no intermittence in the Mediterranean Water presence occurred during that period: stations 04 of line K and station 03 of line 2K for the shallow core (Fig. 6), and station 05 of line K and 10 of line 2K for both the upper and lower cores (Fig. 7). For the whole period of observations seen here (Fig. 6a and Fig. 7a), only monthly data are used, whereas Fig. 6b and Fig. 7b, which include only the period in which both lines K and 2K were done (13 November 1993–13 February 1994), make use of the weekly data.

The analysis of Fig. 6 (a and b) shows that the shallow core, centered between 400 and 500 m, generally maintained temperatures above 12.5°C in both lines K and 2K. The comparison between these lines (Fig. 6b) shows a similar pattern of time evolution of the thermal structure of the shallow core. The period from November 1993 until the end of January 1994 corresponded to higher temperatures ranging from 13.5°C to over 14.5°C on line K and from 13.0°C to over 14.0°C on line 2K (Fig. 6b). The highest temperatures were found in November for line K (K11) and December for line 2K (2K02).

Fig. 7 shows the time evolution of the temperature at the levels of the upper core, centered at 800 m, and of the lower core, centered at 1200 m, at station 05 of line K (Fig. 7a and in the upper part of Fig. 7b) and at station 10 of line 2K (lower part of Fig. 7b). It indicates that these two cores generally maintained temperatures above 11.5°C but not exceeding 13.5°C. On line K (see Fig. 7a), temperatures higher than 12.5°C (reaching just over 13.0°C) were consistently present in the period between mid-October and mid-December 1993, then more intermittently until mid-February 1994; similar high temperatures were again found in April 1994 on line K (M01) but only at the level of the upper core. The comparison between lines K and 2K (Fig 7b) shows that the presence of Mediterranean Water at the stations located offshore of the 1200 m isobath (like stations 05 of line K and 10 of line 2K) is more intermittent downstream of the canyon (line 2K) than upstream (line K), especially at the level of the lower core. If this implies local meandering or offshore deviation of part of the outflow, the present data do not provide an answer.

Some of the aspects of the intra-annual variability shown in the XBT observations of the Mediterranean Undercurrent are also apparent in the time series of the temperature obtained with an Aanderaa current meter at the depth of about 1300 m (corresponding to the lower core of Mediterranean Water) on a mooring off the south coast of Portugal (36°14.48′N, 8°41.39′W), in the framework of the research project "The Mediterranean Current Off Algarve – CORAL". The current and temperature

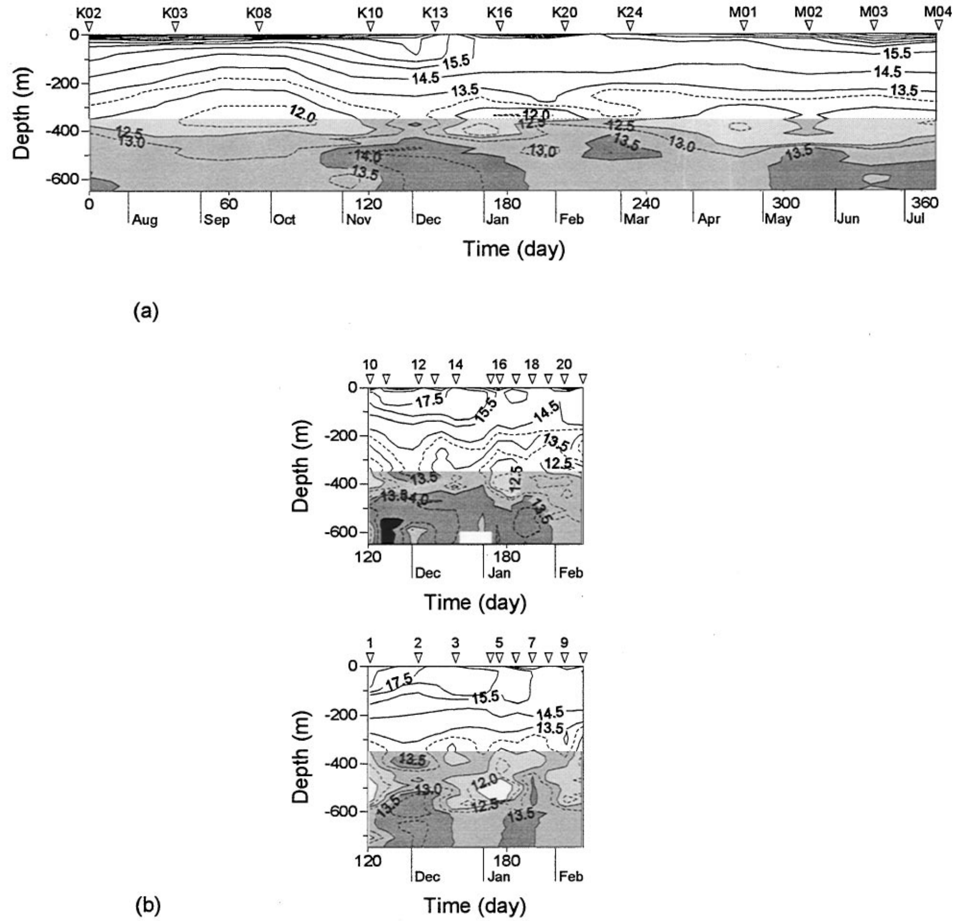

Fig. 6. Time evolution of the vertical temperature distribution at a station where the shallow core of Mediterranean Water was permanently present: (a) monthly data between 15JUL93 and 16JUL94, at station -04 of line K, and (b) weekly data between 13NOV93 and 13FEB94, at station -04 of line K and at station 03 of line 2K.

data correspond to the period between 11 September 1992 and 4 August 1993, thus coinciding for about 1 month (July 1993) with the XBT observation period, and the mooring site is about 5 miles offshore relative to station 18 of line K (see Fig. 1). As these records correspond to about 11 months of observations, they allow a better insight on the intra-annual variations of the Mediterranean Undercurrent than the short term (no longer than 1 month) current meter observations obtained previously in the Gulf of Cadiz (e.g. Zenk, 1975; Thorpe, 1976; Stanton, 1983).

The analysis of the time evolution of the temperature recorded at 1300 m (Fig. 8a) seems to confirm some of the aspects described above based on the observations with the XBT repeated profiles. Some caution should be taken in the interpretation of this

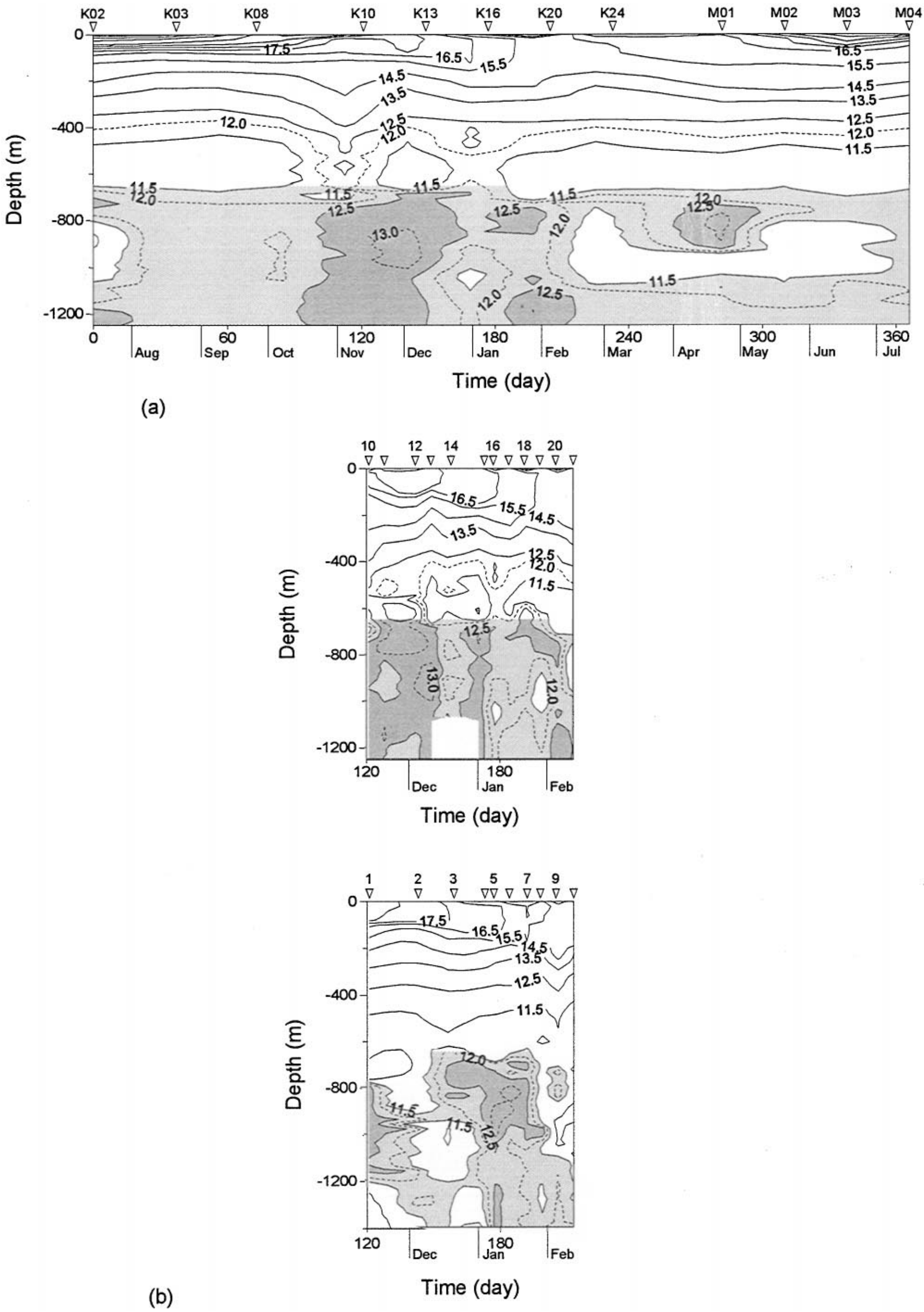

Fig. 7. Time evolution of the temperature vertical distribution at a station where the upper and lower cores of Mediterranean Water were permanently present: (a) monthly data between 15JUL93 and 16JUL94, at station 05 of line K, and (b) weekly data between 13NOV93 and 13FEB94, at station 05 of line K and at station 10 of line 2K.

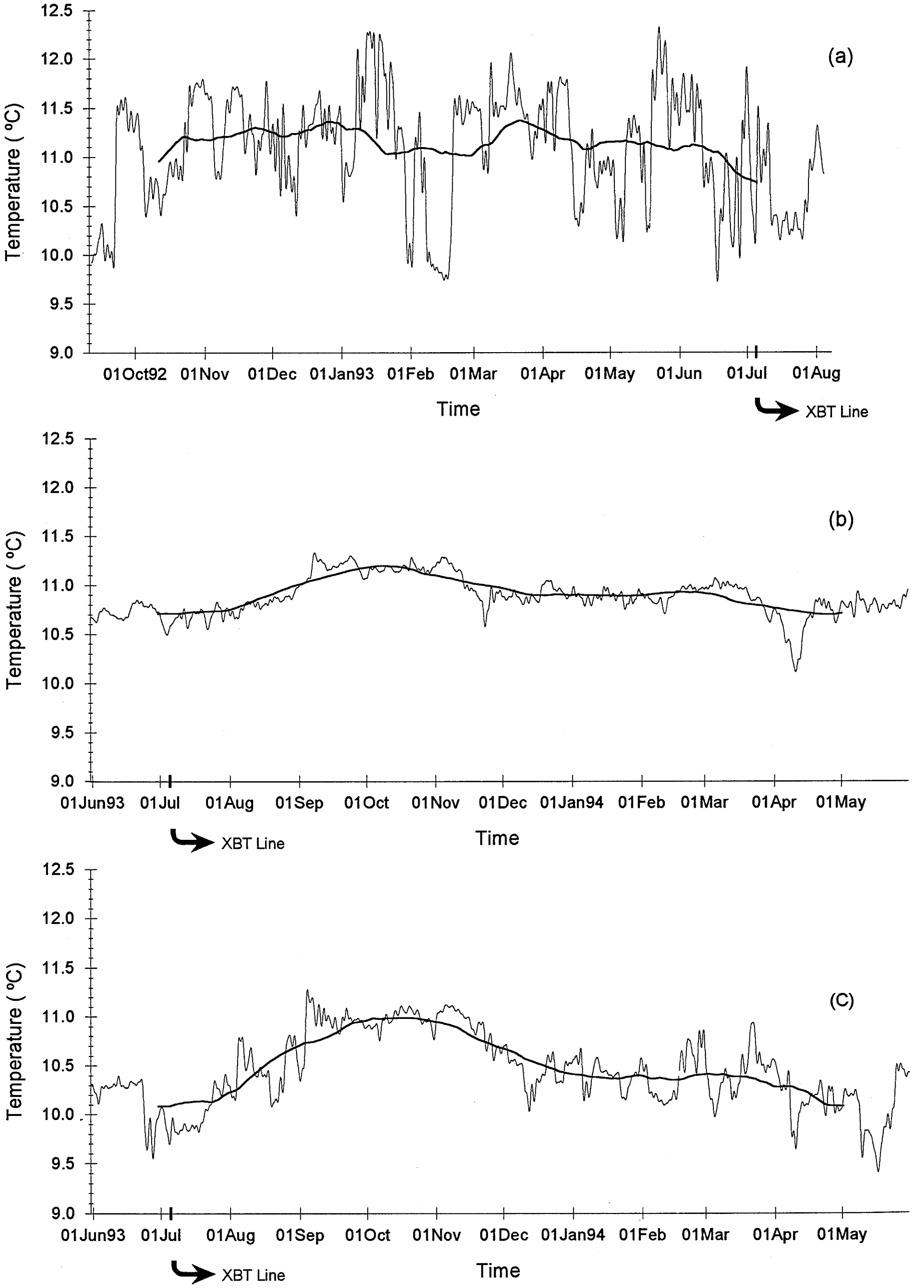

Fig. 8. Time series of low-pass (cut-off period: 40 h) values of temperature (°C) as recorded by current meters (a) at 1300 m offshore of the Portimão Canyon (see Fig. 1 for location); (b) at 1200 m at mooring A of the MORENA Project, on the continental slope off the west coast of Portugal (40°59.93′N, 9°28.49′W); (c) at 1200 m at mooring B of MORENA Project, on the continental slope off the west coast of Portugal (41°00.16′N, 9°44.91′W). Superimposed on the temperature graphs are the 60-day running mean curves. The start of the AMUSE XBT line K is indicated on the time axis for reference.

set of current meter data since the site of the mooring (Fig. 1) was such that it is not always certain that the Mediterranean Undercurrent reached it; this is illustrated with the very low values of temperature (9.5–10.0°C) found in September, February and June (Fig. 8a), which were most certainly associated with the absence of the Undercurrent at the mooring location due to a smaller offshore extension of it, rather than with an actual decrease in its temperature.

Superimposed on the temperature record, the 60-day running mean in Fig. 8a helps one to visualize a positive trend from September 1992 (when the recording started) and a negative trend from mid-March until August 1993 (when the recording ended). In addition to these general tendencies, there were bursts of high temperature with time scales of about 6 days and reaching, in some cases (January and May 1993), values above 12°C. This could be associated either with meandering of the Undercurrent or with the passage through the mooring site of warmer structures such as meddies. The analysis of the time series of the current speed corresponding to these warm episodes has shown that they generally coincided with peaks in the speed with the same time scale.

The apparent seasonal trend of the temperature at the levels of the Mediterranean Water could also be detected in other data sets obtained with current meter moorings located on the continental slope off the northern coast of Portugal at about 41°N (mooring A: 40°59.93′N, 9°28.49′W, total depth: 1293 m; mooring B: 41°00.16′N, 9°44.91′W, total depth: 2500 m), between 31 May 1993 and 31 May 1994, in the framework of the research project MORENA. The period during which these data were collected coincided for about 11 months (July 1993–May 1994) with the XBT collection period. On both moorings, but more clearly on mooring B, the temperature time series at the level of the upper core (800 m) and of the lower core (1200 m, Figs. 8b and 8c) showed a gradual increase from June 1993 until October–November 1993 followed by a gradual decrease until May 1994, when the moorings were recovered (Fiúza et al., 1996). The differences in the mean temperature between June and October reached about 0.5°C at 1200 m on mooring A and at 800 m on mooring B, and about 1°C at 1200 m on mooring B.

The results in this section indicate that the intra-annual time variability of the temperature at the levels of the Mediterranean Water has several scales ranging from the week to the month and, perhaps, a seasonal fluctuation.

3.3. *Westward current*

As referred to above, the typical structure of the Mediterranean Undercurrent along the slope of the Gulf of Cadiz corresponds to a westward jet, which is usually associated with a core of relatively high velocities and a more diffuse edge of about the same width. The present observations obtained with the RAFOS floats show that this model can explain about 60% of the cases.

The velocity of the Undercurrent in the vicinity of the XBT lines was estimated by considering the trajectory of the floats, calculating for each the mean velocity components (zonal and meridional) corresponding to the first 3 days of data and composing the respective mean velocity vector. Fig. 9 shows the time evolution of the

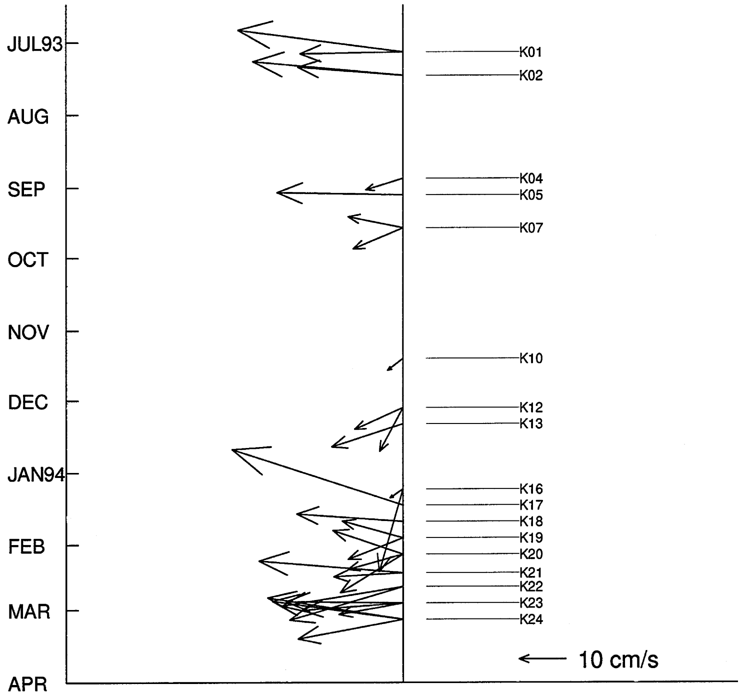

Fig. 9. Mean velocity vector corresponding to the Mediterranean Undercurrent immediately downstream of line K (obtained from the RAFOS float positions for the first three days of data), expressed as a function of the time and of the corresponding line K repetition. Only the floats deployed at the levels of the lower core (1100–1200 m) were considered here.

Undercurrent velocity vector during the period when there were simultaneously XBT lines and deployments of RAFOS floats (K01–K24). Only the floats that stayed at depths corresponding to the lower core (1100–1200 m) were considered for the construction of this figure; those that were launched at the levels of the upper core during lines K3, K5, K6, K14, K15 are not shown.

Fig. 9 indicates that the 3-day mean velocities corresponding to the Mediterranean Undercurrent during the period of observations showed consistently a westward component (the general direction was kept between 190°T and 290°T) and speeds ranging from about 10 to almost 40 cm s^{-1} (daily means reached in some cases 50 cm s^{-1}), their fluctuations with time scales from about 1 week to larger periods. We note that floats that drifted rapidly downstream ($>$ 25 cm s^{-1}) in general had an average heading of west or slightly north of west (270–290°T) as, for example, in K01, K05, K17 or K24, while those moving more slowly had an average heading directed more toward the south of west (190–240°T), as in K10, K12 or K16, reflecting the orientation of the local bathymetry. These cases of lower speeds occurred within the period of warm episodes referred to above – November to January – but it is hard to attribute a causal relation between the two situations using only the present data set.

Selecting a few examples in which the Mediterranean Undercurrent presents a "normal" behaviour, i.e., a generally westward flow, we now examine the thermal structure associated with these situations. Fig. 10 shows the trajectories for the first 10 days of data collected by the RAFOS floats (on the left of the figure) and the corresponding vertical structure of the temperature field across the stream (on the right of the figure) in four cases for which the velocities of the Undercurrent were westward and higher than 25 cm s^{-1} (K02, K17, K21 and K23).

As already mentioned, some caution should be taken in the interpretation of the temperature distribution in XBT line K, since it crosses the axis of the canyon near station 09, and it is difficult to distinguish structures that have separated completely from the boundary and those that are flowing around the border of the canyon. The examples of K02 and K21 in Fig. 10 illustrate a generally confined Mediterranean Undercurrent, with the main core against the continental slope. The other two cases shown (K17 and K23) are examples of a much more diffuse body of Mediterranean Water, with a less defined structure and a more active interleaving at its boundary. This means that a "typical" Undercurrent in terms of velocity is not always "typical" in terms of the thermal structure.

3.4. Examples of anomalous behaviour

In this section we show a few examples obtained from the RAFOS float observations in which the Mediterranean Undercurrent, instead of the predominantly westward flow mentioned in the previous section, has evidenced an anomalous behaviour, like flow to the south- or southeastward and, in some cases, circling around in the interior of the Portimão Canyon. Only a few of these anomalous cases were detected in the analysis of the tracks of the RAFOS floats in the vicinity of the launching site. They all occurred in winter (November, December and January), and Fig. 11 illustrates them. The float tracks for the first 10 days of data recording are shown (on the left of the figure), and the vertical distribution of the temperature that was contemporaneous with the float deployment is also shown in the same figure for line K (on the right of the figure) and for line 2K (on the center of the figure).

The first example of the float tracks in Fig. 11 (left side) corresponds to line K10 (13 November 1993) and shows a cyclonic motion of the float in the interior of the canyon, which could be followed only for about 4 days. The contemporaneous XBT section K10 (Fig. 11, right side) shows a large body of Mediterranean Water with temperatures in excess of 11.5°C (reaching values over 13°C in the upper core) extending out of the slope, and on the offshore side a front-like structure is apparent at the levels of the upper core with a thickness of about 200 m. The temperature distribution on line 2K (Fig. 11, center) exhibits a much shorter offshore extension than on line K, but the frontal structure at the level of the upper core is even thicker ($\sim$400 m), whereas the presence of the lower core is almost negligible and confined in depth.

The second example of anomalous behaviour shown in Fig. 11 corresponds to line K12, in which the two launched floats followed a southwestward path down the canyon along the K line. The contrast between section K12 and the contemporaneous

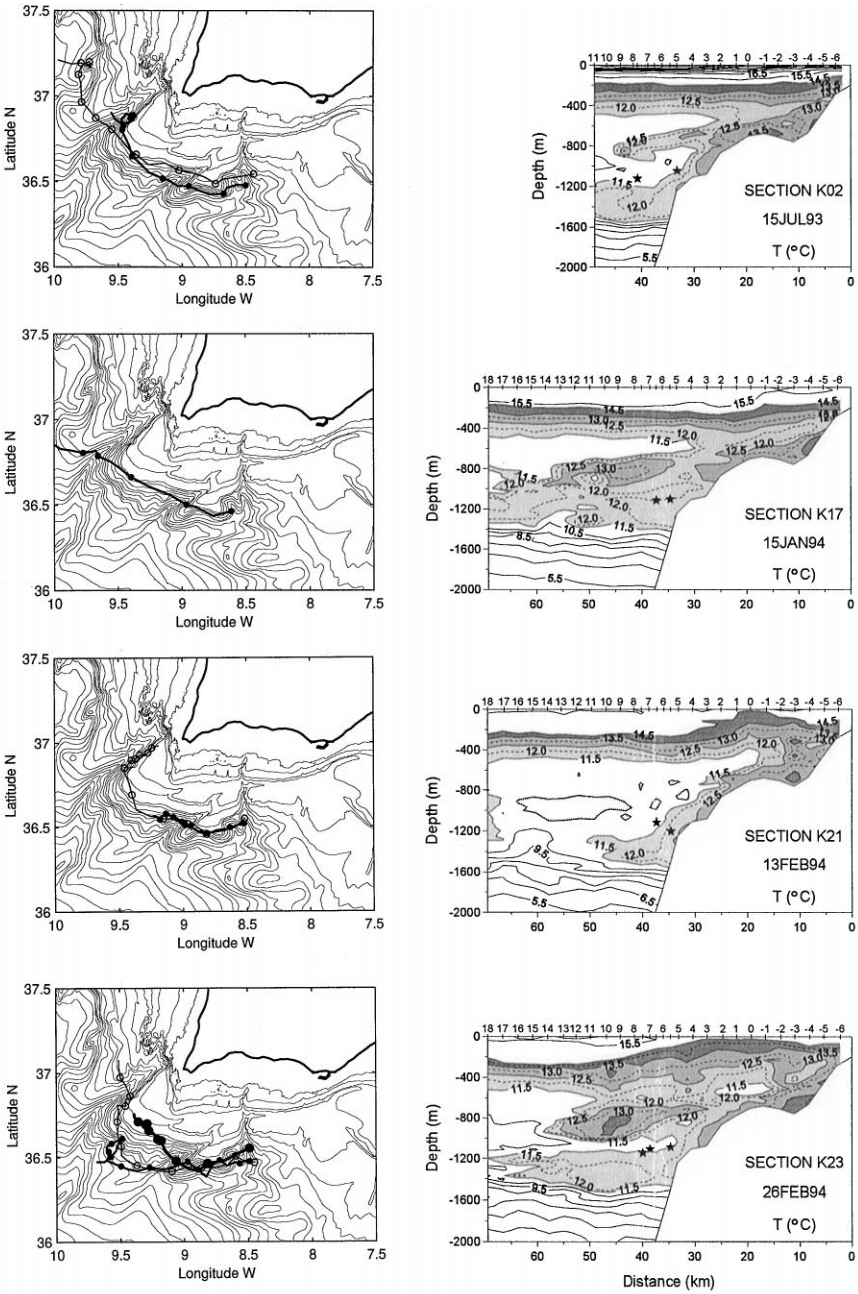

Fig. 10. Examples of normal behaviour of the Undercurrent in terms of velocity: the trajectories of the RAFOS floats for the first 10 days are represented on the left (circles along the float tracks indicate daily positions); bathymetric contours are shown for 100, 200 m and then every 200 m. The corresponding temperature distributions along XBT line K (K02, 15JUL93; K17, 15JAN94; K21, 13FEB94; K23, 26FEB94) are shown on the right.

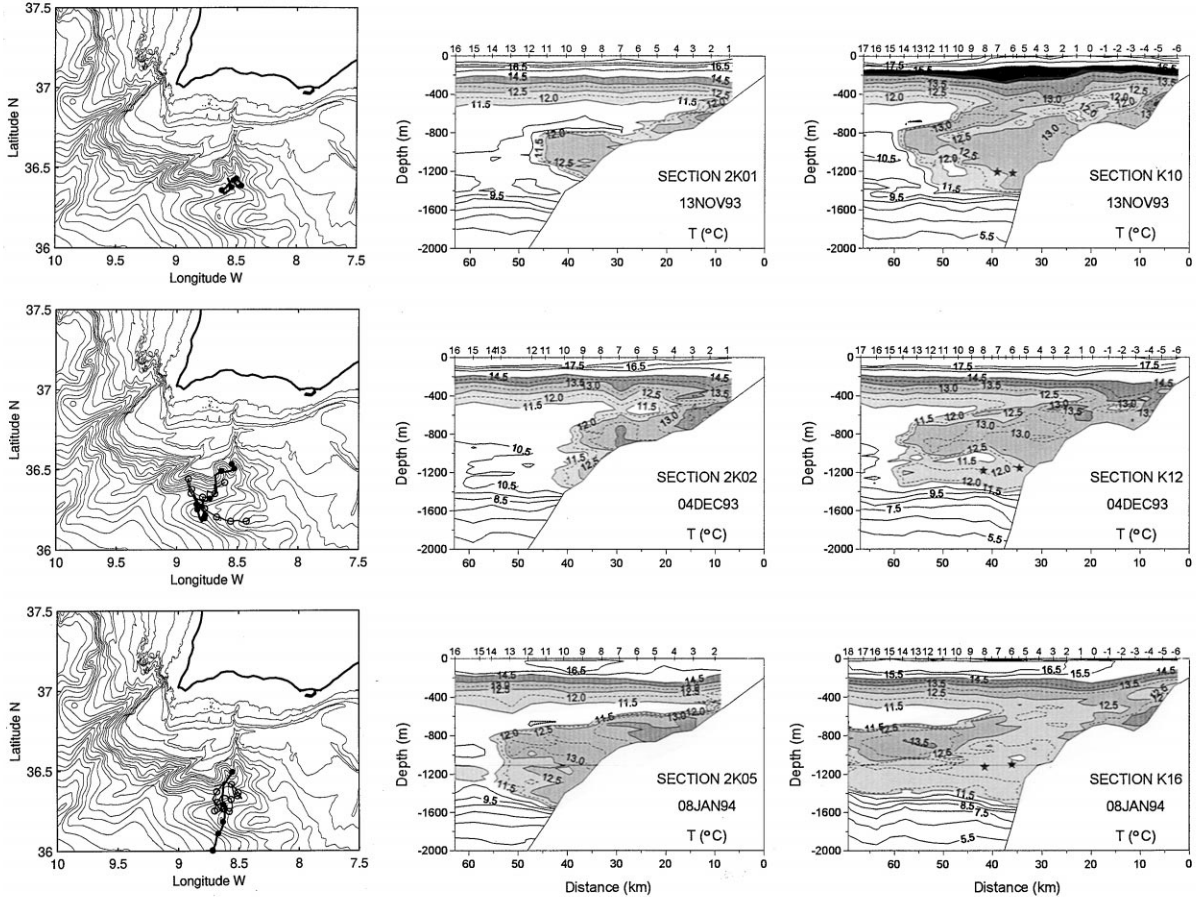

Fig. 11. Examples of anomalous behaviour of the Undercurrent: trajectories of the RAFOS floats for their first 10 days of data recording are represented on the left (circles along the float tracks indicate daily positions); bathymetric contours are shown for 100 m, 200 m and then every 200 m. The corresponding temperature distributions in lines 2K and K (2K01 and K10, 13NOV93; 2K02 and K12, 04DEC93; 2K05 and K16, 08JAN94) are represented on the center and on the right, respectively.

section 2K02 is evident, with a much larger extent of the Undercurrent in the upstream section at the levels of both the upper and the lower cores.

In the third example of Fig. 11, the two floats that were deployed went down the canyon, one straight south and the other making a few cyclonic loops. The corresponding XBT lines were K16 and 2K05, and again they show a contrasting appearance. The upstream section evidences a very large offshore extension and the presence of a patch of water with temperatures higher than 13.5°C, centered at station 13 (at about 55 km from the shelf edge) at the level of the upper core ($\sim$900 m); this same structure is present also at the levels of the lower core but with lower temperatures (just above 12.0°C), as expected. Along section 2K the whole body of high temperatures was found closer to the slope, and there was no sign of any prominent offshore structure similar to that found on section K, thus opening the possibility that it might be an isolated feature such as a meddy.

It is interesting to notice that the comparison of sections K with the corresponding sections 2K for the entire period in which this downstream line was repeated shows that they look similar in both extension and patterns of temperature distribution, except in four cases – K10, K12, K15 and K16. Three of these cases are exactly those referred to above as corresponding to a southward Undercurrent (Fig. 11); in the other case – K15 – there was no float launched at the lower core depths, but, at least at the level of the upper core, it corresponded to a rather sluggish (around 10 cm s^{-1}) southwestward flow. These observations indicate that an anomalous direction of the Undercurrent seems to be reflected in the lack of spatial coherence of the thermal structure between the upstream and the downstream sides of the canyon, showing that part of the Undercurrent was directed away from the continental slope along the axis of the canyon, either in the form of a meander or of a meddy.

4. Discussion

The main conclusion to be drawn from the analysis of the present data is the evidence of strong intra-annual time variability at the levels of the Mediterranean Undercurrent in scales ranging from a few days to a possible seasonal signal. These variability scales are present not only in the lateral extension of the Undercurrent and in its temperature field, but also in the velocity regime.

Looking back into previous work reporting short-term current meter data in the Gulf of Cadiz, both upstream and downstream of the site of the present observations, there is some evidence of temperature fluctuations with time scales of the order of a few days similar to those found here with the XBT lines. Close to the Strait of Gibraltar, at about 7°30′W, Stanton (1983) found low frequency variability in the range between 2 days and 2 weeks in current meter data; he recorded an event corresponding to an increase in temperature (of the order of 1°C in 4 days) simultaneous with a rise in the velocity, and another event where a sharp decrease in current speed (70 cm s^{-1} in 5 days) was associated with a decrease in temperature and a 45° downslope directional change in the current. He concluded that wind stress forcing was not a likely mechanism for the relatively rapid changes that were recorded in it, but that barometric pressure differences between the Gulf of Cadiz and the western Mediterranean could be responsible for some of these fluctuations. Also Gründlingh (1981), analysing hydrographic and current meter data from several moorings in the northern slope of the Gulf of Cadiz, between about 7° and 8°W, examined a solitary event in the Mediterranean Undercurrent, whose manifestation was a sudden temperature increase (order of 1°C) lasting for about 3–4 days, which was in some places accompanied by an increase in current velocity. He suggested that it was associated with atmospheric forcing, namely the wind stress, in the western Mediterranean. Thorpe (1976), comparing temperature and velocity time series obtained with current meters at the levels of the Mediterranean Undercurrent for a 20-day period in the northern slope of the Gulf of Cadiz near 8°W (about 35 miles upstream of line K of the present study), found evidence of changes in the thermal structure, which lasted for about 5 days, preceded by changes in the current regime. The abrupt increase in the temperature and salinity, which occurred near the site of the current meters, seemed linked to a disturbance of the westward flowing Undercurrent, which began flowing southwards off the slope and then completed a cyclonic eddy-like motion. The occurrence of these sudden disturbances in the Mediterranean current was associated with the arrival of denser near-bottom water. Howe (1984) presented results on short-term (2–3 days) variations of the jet-like flow at the levels of both the upper and lower cores of Mediterranean Water, which were observed with current meter moorings located for a 12-day period at 9°05′W (about 35 miles downstream from line K of the present study). The fact that most of the events previously reported were observed upstream of the site of the present XBT observations indicates that they are likely to be generated by disturbances during the early stages of the descent of the Mediterranean Undercurrent in the Gulf of Cadiz or even at the crossing of the Strait of Gibraltar.

The occurrence of warm structures offshore relative to the continental slope-bounded current is another important aspect revealed by this study and also mentioned in previous work (Ambar and Howe, 1979a). The present observations seem to indicate a possible connection between the existence of these structures, corresponding to isolated or semi-isolated bodies or to filaments of the Undercurrent, and episodes of changes in direction or speed of the Undercurrent. This is illustrated by the following similar sequences observed through the repetition of the XBT line (Fig. 4) and the complementary RAFOS float data, where the information on the mean velocity for the first 3 days after launching (considered as representative of the Undercurrent velocity at the site of the XBT lines) is given not only by the floats that were deployed in the Mediterranean lower core (as used in Fig. 9) but also by the few floats that stayed at the levels of the upper core (case of K14 and K15):

(i) weak flow (K10, K12: southward, 5–10 $\mathrm{cm\,s^{-1}}$; no float deployed in line K11; K13: westward, $\sim 15\ \mathrm{cm\,s^{-1}}$), followed by strong flow (K14: westward, 20–30 $\mathrm{cm\,s^{-1}}$) and isolated structure offshore.

(ii) weak flow (K15, K16: southwestward and southward, 10–15 $\mathrm{cm\,s^{-1}}$), followed by strong flow (K17, K18: westward, 30–40 $\mathrm{cm\,s^{-1}}$) and isolated structure offshore.

(iii) weak flow (K19, K20: southwestward, $\sim 15\ \mathrm{cm\,s^{-1}}$), followed by strong flow (K21, K22: westward, 30–35 $\mathrm{cm\,s^{-1}}$) and isolated structure offshore.

So these observations show a correspondence between the temperature field fluctuations and the velocity field, as Thorpe (1976), Gründlingh (1981) and Stanton (1983) have already shown, raising the hypothesis of a dynamical atmospheric forcing. There is also the possibility that these offshore structures constitute meddies formed in the Canyon of Portimão by instability mechanisms or by generation of anticyclonic vorticity in the frictional boundary layer (Bower et al., 1997), but the present data does not allow us to verify this hypothesis, since no RAFOS floats were locally deployed or entrained in these features.

Regarding the existence of a seasonal signal, and despite the fact that the XBT observations lasted only one year (and the last quadrimester was sampled only monthly), there seems to exist an indication of a trend in the temperature at the levels of the Mediterranean Water with a time scale of seasonal amplitude. Similar seasonal-like trends were also evidenced in the temperature time series obtained with a current meter mooring off south Portugal, very close to the XBT lines, and with two current meter moorings off the northwest coast of Portugal, at about 41°N. The XBT lines showed that the larger lateral extensions combined with the highest temperatures were found at the levels of all three Mediterranean Water cores (shallow, upper and lower) between November 1993 and mid-February 1994 and again in April–May 1994. In the current meter data obtained off the south coast of Portugal, there was also a positive trend of the temperature from September 1992 until January 1993 followed by a negative trend from mid-March until August 1993. Superimposed on this, there were bursts of high temperature with time scales of about 1 week (the largest ones were in January 1993 and May 1993). In the current meter data off the northwest coast of Portugal, again there was an indication of a positive trend in the temperature from June 1993 to November 1993 and a negative trend from then until the end of the record (May 1994). The hypothesis raised by Bormans et al. (1986) and also referred to in Garrett et al. (1990) of a seasonal control of the depth of the interface between the Atlantic Water and the Mediterranean Water in the Strait of Gibraltar associated with the replenishment of the reservoir of outflowing water in late February – early March, could perhaps explain the larger offshore extension and the higher temperatures found in winter with the present observations. It was also in winter that the lower speeds, the down-slope direction or even recirculation of the Undercurrent and the possible formation of meddies in the region of the Portimão Canyon were found with the RAFOS float data. All this and the existence of seasonal fluctuations of the Mediterranean Outflow, maybe connected to larger scale fluctuations within the Mediterranean or the North Atlantic basins, is still a subject that needs further long term observations and a modelling contribution.

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