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Intermediate water formation in the Ligurian Sea

Intermediate water
Hydrological data
ADCP measurements
Ligurian Sea

Eau intermédiaire
Données hydrologiques
Courantométrie acoustique Doppler
Mer Ligure

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ABSTRACT

Observations carried out in the Ligurian Sea in February 1969 during the MedOc experiment permitted the identification of a dense water formation episode. A new experiment was conducted in the same area during 1991 in the framework of the PRIMO programme. Water temperature, salinity and vertical velocities were measured using a CTD probe and ADCPs. The data have shown the formation of dense water with temperature and salinity properties significantly different from those found during the MedOc experiment. In 1969, strong cold winds caused the mixing and cooling of the water column to a depth of 1200 m. In 1991, the surface forcings were not strong enough to erode the stratification from the surface to the bottom, and the dense water formed found its equilibrium depth at an intermediate level. The differences between the 1969 and 1991 events are discussed as part of a more general interannual variability observed in the Ligurian Sea.

RÉSUMÉ

Formation de l'eau intermédiaire dans la mer Ligure.

La formation d'eau dense a été observée dans la mer Ligure en février 1969 au cours d'une expérience MEDOC. En 1991, au cours d'une nouvelle campagne effectuée dans le cadre du programme PRIMO, la température, la salinité et les vitesses verticales ont été mesurées à l'aide d'une sonde CTD et de courantomètres acoustiques Doppler. Les résultats montrent la formation d'une eau dense dont les caractéristiques (température et salinité) diffèrent de manière significative de celles trouvées pendant l'expérience MEDOC. En 1969 de violents vents froids ont provoqué le brassage et le refroidissement de la colonne d'eau jusqu'à une profondeur de 1200 m. En 1991, les forçages superficiels n'étaient pas assez forts pour effacer la stratification entre la surface et le fond, l'eau dense formée trouvant son équilibre à une profondeur intermédiaire. Les différences entre 1969 et 1991 sont discutées dans le cadre plus général de la variabilité interannuelle observée dans la mer Ligure.

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INTRODUCTION

The water of Atlantic origin (hereafter called Modified Atlantic Water - MAW) entering the Mediterranean through the Strait of Gibraltar is continuously transformed during its eastward and northward flow. Due to local climatic effects and mixing, the salinity of the surface water increases from about 36 in the Gibraltar Strait to 38 and 39 respectively in the northwestern and eastern ends of the basin. Strong changes in the physical properties occur in limited areas where intermediate and deep waters are formed during extreme meteorological conditions.

Deep water formation is one of the most dramatic air-sea interaction processes, the different phases of which have been described by many authors (*e.g.* Killworth, 1976; Gascard, 1978). In the western Mediterranean, deep convection may occur in some areas of the Liguro-Provençal basin. The main experimental efforts directed towards the study of dense water formation in the northwestern Mediterranean began at the end of the 1960s within the framework of an international cooperative programme entitled MedOc (an acronym for Méditerranée Occidentale). During the 1969 MedOc experiment, surface dense waters were observed in the Gulf of Lions and in the central part of the Ligurian Sea (MedOc Group, 1970). In the Gulf of Lions, deep convection has been observed on several occasions (*e.g.* Gascard, 1978; Schott and Leaman, 1991; Leaman, 1994). The deep water formed in the Gulf of Lions (Western Mediterranean Deep Water - WMDW) is characterized by a potential temperature of 12.7-12.9 °C, a salinity of 38.42-38.45 and a density of about 29.12 σ_θ units. It is situated below the Levantine Intermediate Water (LIW) and presents an inter-annual variability highlighted by Lacombe *et al.* (1985) and Leaman and Schott (1991).

It is generally thought that convective processes could also occur in the central part of the Ligurian Sea (Fig. 1), where surface dense waters and weak vertical stability are observed during winter. During the 1969 MedOc experiment (MedOc Group, 1970), dense water with characteristics between LIW and WMDW was observed in this area. However the data were not published and studies on the convective processes involved were never performed as intensively as in the Gulf of Lions.

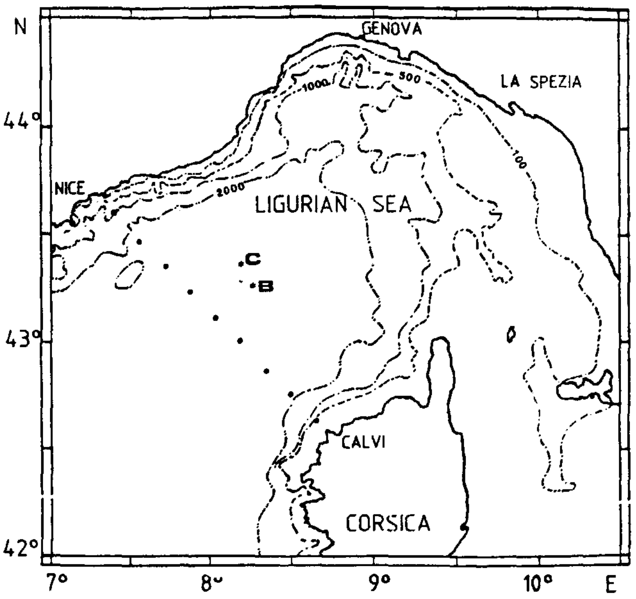

Figure 1

The Ligurian Sea, showing the positions of the moorings (indicated by the letters B and C) and the section Nice-Calvi.

In winter 1990-1991, two moorings composed of Acoustic Doppler Current Profilers and eulerian current meters (the latter equipped with pressure, temperature and conductivity sensors) were deployed in the central part of the Ligurian Sea in the area where surface dense waters had been observed during the 1969 MedOc experiment. Intense (5 to 7 cm/s) vertical movements related to sinking waters were detected by the current profilers in February 1991. The temperature and salinity of these sinking water masses were significantly different from those observed in 1969, and attained their equilibrium depth at an intermediate level.

In order to understand whether interannual variability of surface forcings would affect temperature and salinity characteristics, we analysed historical hydrological data from the Ligurian Sea and confronted our results with those reported by Garrett (1994) in his study of air-sea fluxes in the Mediterranean. In addition, we have focused particular attention on the meteorological conditions in 1969 and 1991.

The purpose of this paper is to advance the hypothesis that dense water is formed in the Ligurian Sea by presenting two data-sets showing convective processes:

- the 1969 MedOc data (never published in the open literature);
- the temporal evolution of temperature, salinity and vertical velocity during convective processes in February 1991 as shown by data collected during the PRIMO-0 experiment (UNESCO, 1988).

We also discuss the results of the above data analysis within the context of a more general interannual variability of the water properties that was observed when the historical hydrological data set was analysed.

MATERIALS AND METHODS

Comparison of data from different instruments requires great care.

In 1969, the hydrographic data were gathered by means of Nansen bottles and a Kieler Howaldst Werke CTD probe. The estimated precision of temperature, salinity and density associated with the bottle samples were 0.01 °C, 0.02 and 0.02 kg m^{-3} respectively. The precisions reported for the same parameters for the CTD probe were 0.05 °C, 0.1 and 0.1 kg m^{-3}.

In 1991, the hydrological measurements were carried out with a Neil Brown MKV CTD probe. The instrument was calibrated at the Saclant Centre (La Spezia) and estimated precisions are: 0.005 °C, 0.002 and 0.002 kg m^{-3} for the temperature, salinity and density respectively.

In November 1990, two current meter chains were moored in the Ligurian Sea, midway between Nice (France) and Calvi (Corsica), by the Stazione Oceanografica-CNR. The distance between the two moorings was about 15 km. The geographical positions and the arrangements of the moorings are reported in Table 1. The Aanderaa eulerian current meters were calibrated by Aanderaa Inc. and were equipped with temperature and conductivity sensors. The precisions for temperature and salinity estimated from *in situ* CTD measurements and analysis of water samples, were respectively 0.05 °C and 0.06.

Table 1

Geographical position and depth of the instruments moored in the central Ligurian Sea during winter 1990-91 and analysed for this paper.

Mooring B		Mooring C	
LAT 43 17 01 N LON 8 15 03 E		LAT 43 23 01 N LON 8 10 54 E	
Instrument	Depth	Instrument	Depth
ADCP	318	ADCP	349
AANDERAA	348	AANDERAA	379
AANDERAA	480	AANDERAA	509
		AANDERAA	809
AANDERAA	1440	AANDERAA	1469

In order to detect vertical velocities in the layers between 100 and 350 m, Acoustic Doppler Current Profilers (RD 150 KHz) were included in each mooring. These were arranged to obtain 30 bins of 8-metre vertical resolutions and a 20 min sampling interval. The ADCP data quality was assessed from echo amplitude (Schott, 1989).

The vertical stability of the moorings was checked using the Aanderaa pressure sensors which did not detect significant variations during the period covered by this paper.

The measurements were carried out by the Stazione Oceanografica-CNR, the Centro Ricerche Ambiente Marino-ENEA and the Saclant Centre. Meteorological data collected at Cap Bear during the experiment were kindly provided by the Service Météorologique Interrégional Sud-Est in Aix-en-Provence (France). The historical hydrographic data set was extracted from the ENEA-CRAM data bank which contains about 30 000 temperature and salinity profiles covering the entire Mediterranean Sea. All temperature data were converted to the corresponding potential temperatures before the analysis.

RESULTS

Climatological characteristics of the Ligurian Sea during winter

Many hydrographic data have been gathered in the Ligurian Sea. In particular, the Station Zoologique and the Laboratoire d'Océanographie Physique at Villefranche-sur-mer (Groupe Hydrokor, 1973; 1975) have routinely measured temperature and salinity along the section Nice (France) - Calvi (Corsica). In some years, vertically homogeneous high density water masses were found in the central part of the section. Hydrokor data and other measurements carried out along the section Nice-Calvi from 1950 to 1987 were used for the study of the mean hydrological characteristics. Maps of monthly mean climatological T-S distributions with a horizontal spatial resolution of 5 miles were produced (Brasey, 1992) by averaging data from vertical profiles. During winter, the atmospheric conditions cool the surface waters which mix with those of the lower layers and erode the seasonal thermocline. The vertical temperature gradient during February is extremely reduced (Fig. 2*a*): surface temperature reaches its minimum value of about 12.9 °C. Higher values (13.4 °C) can be found at about 300 m as a signature of the LIW. The salinity (Fig. 2*b*) exhibits a dome

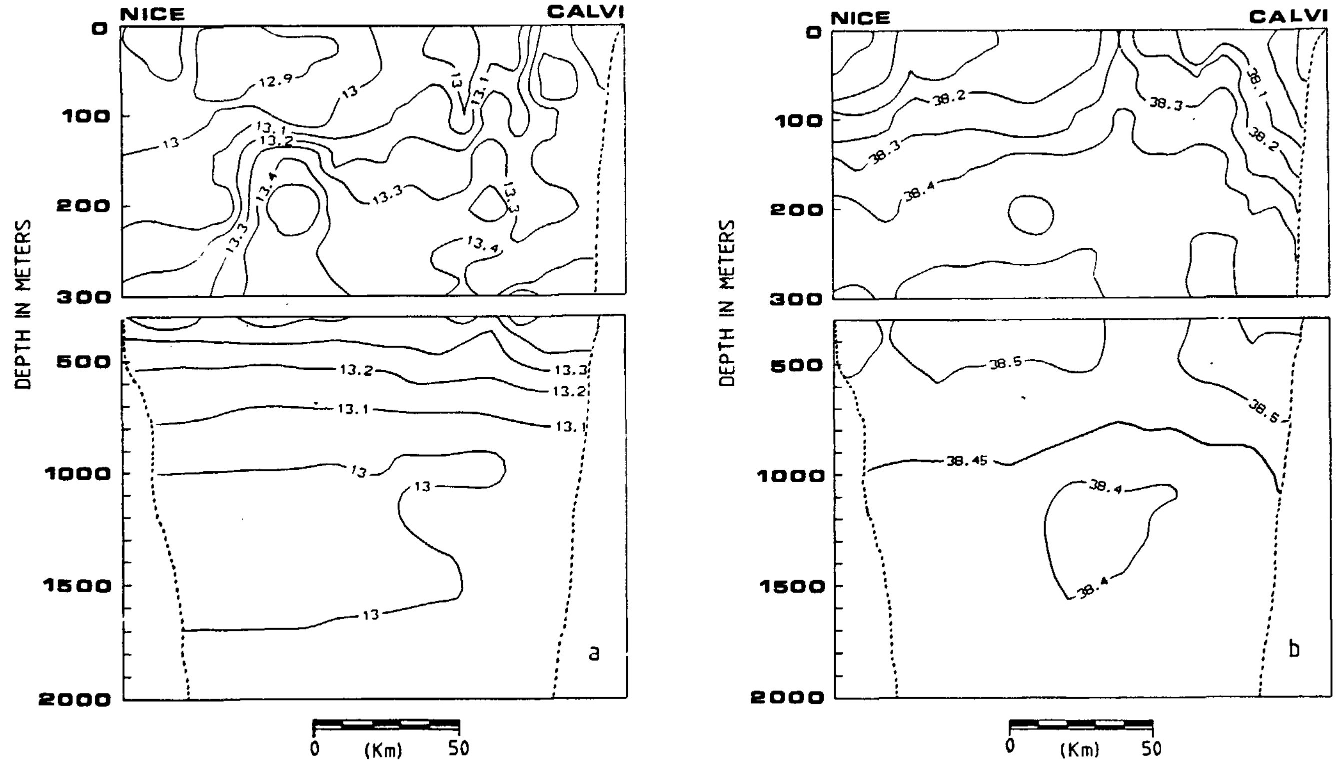

Figure 2

(a) Averaged temperature (contour interval = 0.1 °C) and (b) averaged salinity (contour interval = 0.1) along the section Nice-Calvi in February (data from 1950 to 1987).

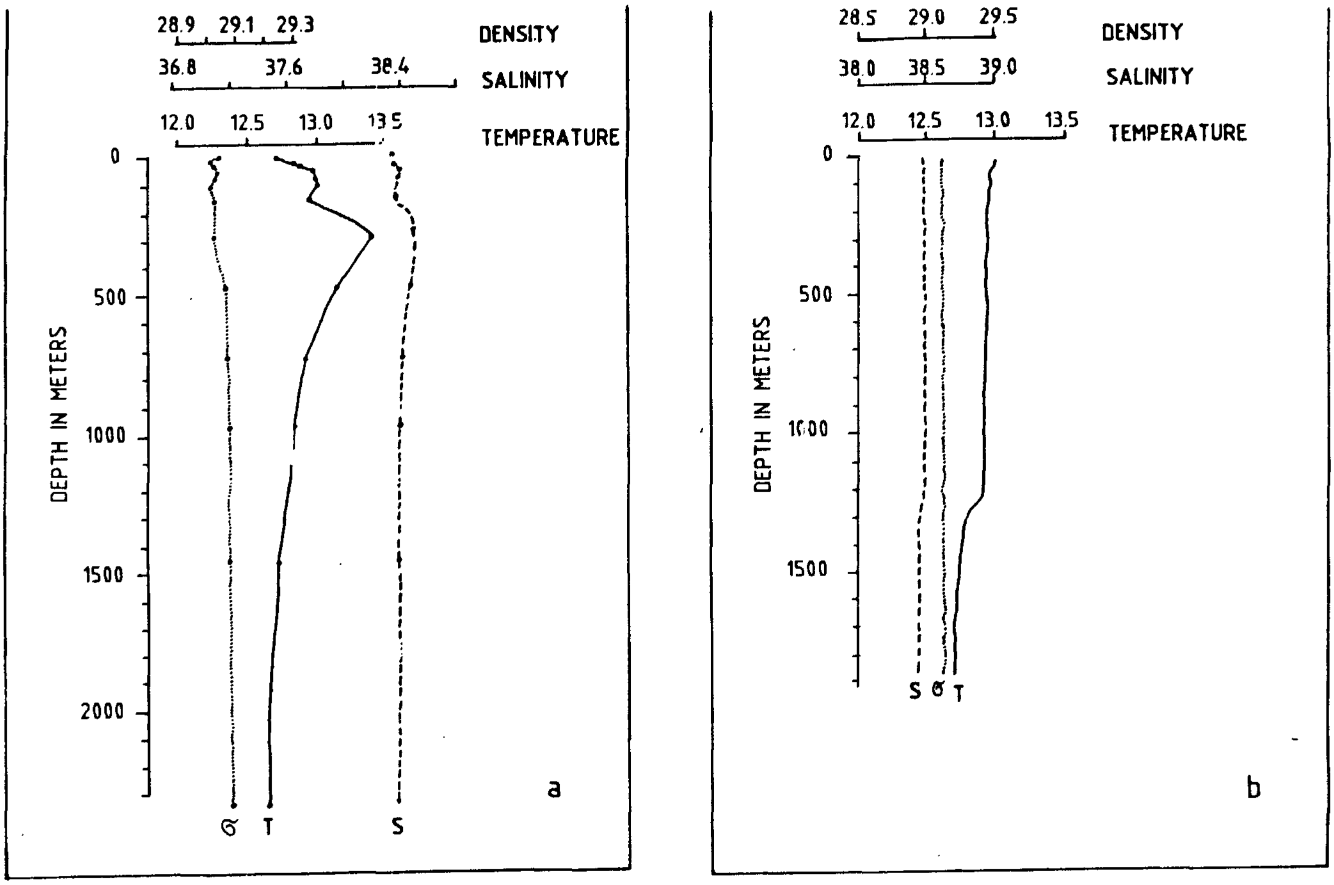

Figure 3

Vertical profiles of temperature (°C), salinity (ppt) and density (σ_θ units) at 43° 17' N, 8° 18' E (a) before (7 February 1969) and (b) after (18 February 1969) the storm event.

structure with the 38.3 isohaline reaching the surface. The maximum salinity associated with the LIW (about 38.5) is found at 250-350 m. In the central area, there is a nearly homogeneous water mass characterized by a quasi-constant salinity from the surface to about 700 m. This central zone, where a cyclonic circulation is always present, extends about 30 km laterally and possesses a weak vertical stability which can permit convective movements in the presence of strong atmospheric forcings at the surface.

First evidence of deep convection in the Ligurian Sea: the 1969 MedOc experiment

During the "classical" MedOc experiments from 1968 to 1975 in the Gulf of Lions, concurrent observations were carried out in the Ligurian Sea by Frassetto and co-workers who produced horizontal surface maps of temperature, salinity and density on a large grid (MedOc Group, 1970) for the region. More accurate measurements were then taken in those areas where the surface density was higher than 29.08 σ_θ units. These measurements showed a scenario similar to "the plumes when they assume the shape of narrow columns of lifting air over flat lands due to irregular heating from the sun" (Frassetto - pers. comm.).

During the period 3-10 February 1969, hydrological measurements allowed the definition of a three layer system as evidenced in the profiles of Figure 3*a*:

- a MAW surface layer about 200 m deep with low salinity (about 38.3), low temperature (12.7-13.0 °C) and a density of about 29.0 σ_θ units;

- a LIW layer about 600 m thick, characterized by higher values of temperature and salinity with maxima (13.40 °C and 38.48) at about 300 m, and a density of 29.01 σ_θ units;

- a deeper layer with a salinity of about 38.38, a temperature of about 12.72 °C and a density of 29.07 σ_θ units.

A violent storm interrupted the measurements (see Bunker, 1972, for a description of the overall meteorological conditions). New hydrological casts were carried out from 18 to 27 February 1969, revealing small areas characterized by vertically homogeneous temperature (12.93 °C) and salinity (38.48) from the surface to 1200 m. Below this depth, a small jump was detected both in temperature (12.72 °C) and salinity (38.45). The density was homogeneous over the entire water column with a value of 29.12 σ_θ units (Fig. 3*b*).

The first idea to arise from the analysis of these historical data was that, in the Ligurian Sea, formation of dense water may occur. These water masses have densities lower than that of the WMDW and therefore they cannot reach the deepest levels: "As it turned out, this smaller, eastern (Ligurian Sea) patch (of dense water) never did evolve into a very deep convective region" (Stommel *et al.*, 1971).

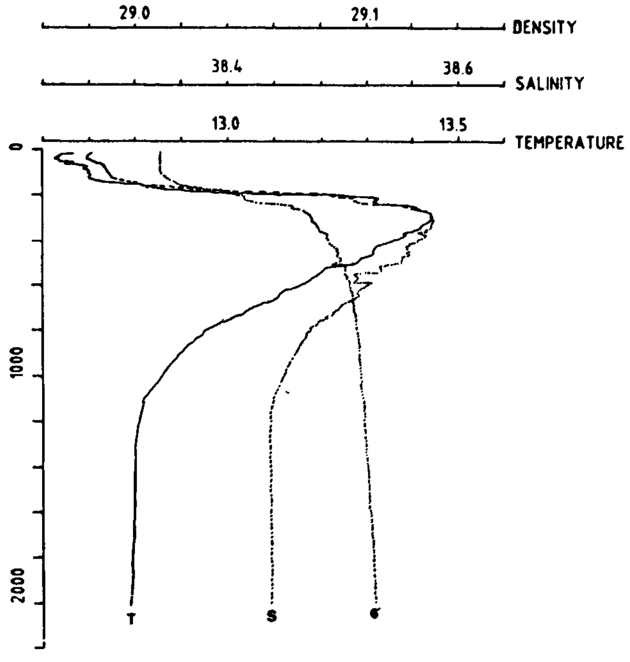

Figure 4

Vertical profiles of temperature (°C), salinity (ppt) and density (σ_θ units) on 6 February 1991 from SaclantCen CTD cast close to mooring B (43° 16' N, 8° 14' E).

The 1991 PRIMO-0 experiment

New measurements were carried out in the same area in 1991 during the PRIMO-0 experiment. In this paper, the data analysis is limited to the month of February when significant vertical movements were detected by the ADCPs.

At the beginning of February, a few CTD measurements were taken by the Saclant Centre in positions very close to the moorings. The situation in the intermediate and deep layers was rather different from the 1969 case, presenting the stratification shown in Figure 4:

- a MAW layer about 200 m deep with low salinity (38.28-38.29), low temperature (12.55-12.67 °C) and a density of 29.0-29.02 σ_θ units;
- a LIW layer 600 m thick, characterized by higher values of temperature (13.43 °C) and salinity (38.58) at about 300 m, and a density of 29.079 σ_θ units;
- a deeper layer with a salinity of 38.44, a temperature of 12.8 °C and a density of 29.10 σ_θ units.

The Aanderaa sensors detected the highest salinity values at 480 m in position B (38.57) and at 379 m in C (38.56). Corresponding temperatures and densities were 13.42 °C and 29.074 in B and 13.38 °C and 29.05 σ_θ units in C.

The wind regime, as detected at Cap Bear during February 1991, was characterized by a succession of Mistral events. In the periods 5-6 and 12-15 February, the Mistral daily mean speed value exceeded 14 m/s (Fig. 5). The air temperature was relatively high (about 8-9 °C) until 5 February, when it began to drop, reaching a minimum value of 3.5 °C on 6 February. Successively, the air temperature increased to about 8.5 °C and dropped again around 10 February. From 11 to 15 February there was a relatively long cold period (about 4 °C). During the last part of this month, the wind intensity decreased drastically and the air temperature increased to about 12 °C.

The meteorological data indicate that there were two important events: the first, characterized by a strong wind and a relatively high air temperature, occurred during 5-6 February; the second, characterized by a strong Mistral wind and a low air temperature, occurred during 11-15 February.

Mooring B

The analysis of ADCP data from the same period showed both daily vertical oscillations due to plankton migration and significant downward movements (of about 4-5 cm/sec) on 6-7 February (Fig. 6). The latter, observed between 100 and 270 m, lasted for a few hours and were

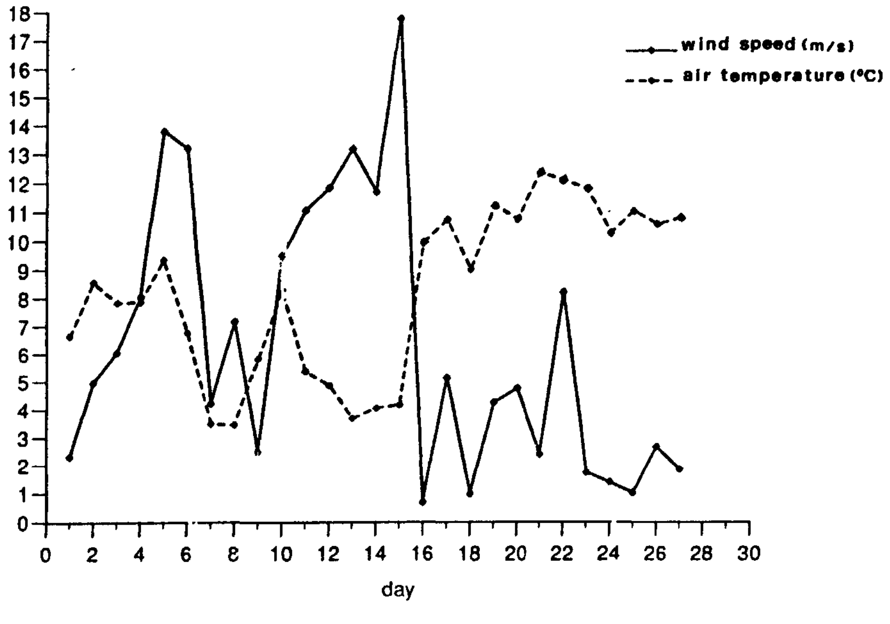

Figure 5

Wind intensity and air temperature measured at Cap Bear during February 1991.

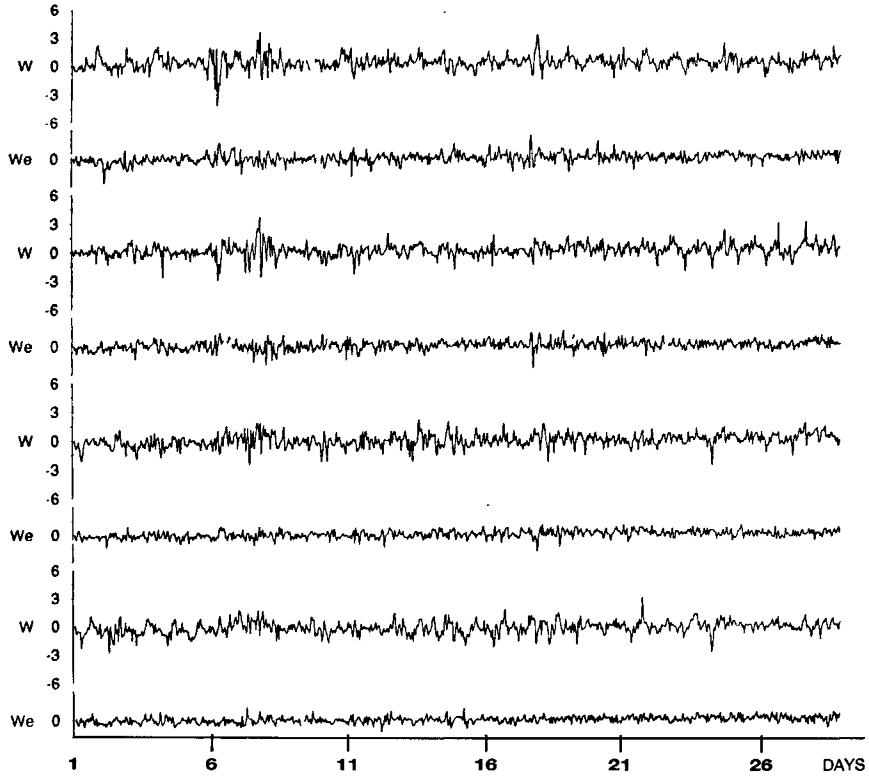

Figure 6

Vertical velocities (W) and error velocities (We) in cm/sec from the ADCP in position B, at selected depths (110 m, 174 m, 238 m, 302 m) during February 1991. Data smoothed with a Hanning filter.

due to a meteorological forcing in the form of strong Mistral winds and a relatively high air temperature. The events exceeded the error velocities (as also shown in Fig. 6). The sensors located at 350 m detected significant changes both in temperature and salinity which dropped from 13.42 °C to 13.2 °C and from 38.57 to 38.50 respectively, with a corresponding density decrease from 29.074 to 29.066 σ_θ units.

Mooring C

More interesting were the events detected in position C between 15-20 February during which the vertical velocity reached 6-7 cm/sec (at least four times the associated error velocities, see Fig. 7). Each event lasted for about two hours and affected the entire water column covered by the ADCP measurements (from about 100 to 350 m). Also, in

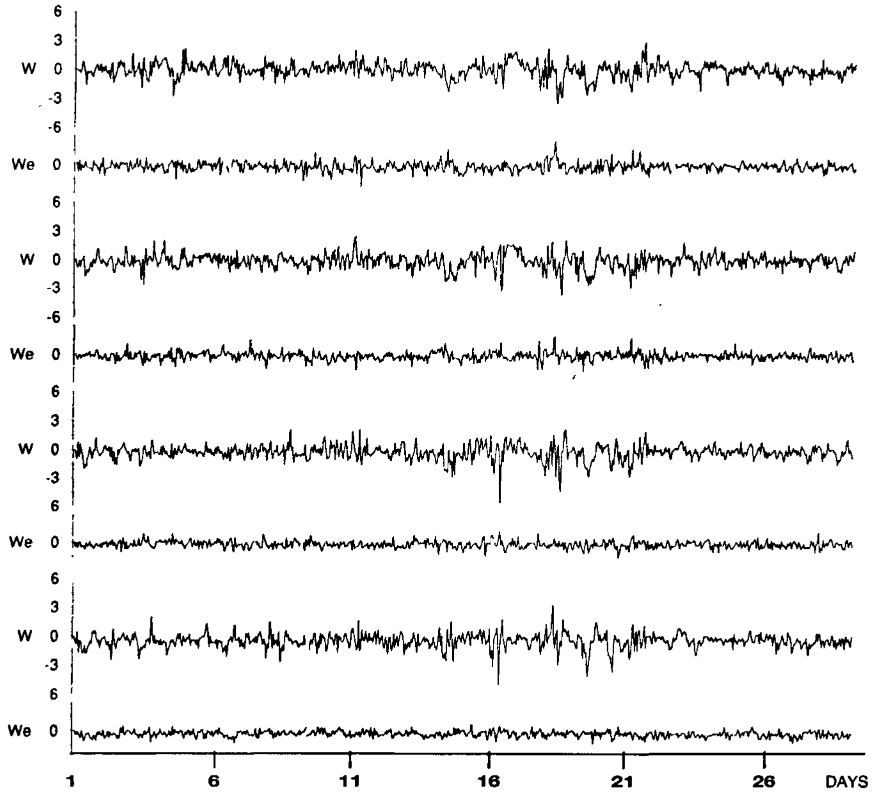

Figure 7

Vertical velocities (W) and error velocities (We) in cm/sec from the ADCP in position C, at selected depths (141 m, 205 m, 269 m, 333 m) during February 1991. Data smoothed with a Hanning filter.

this case, the temporal evolution of both temperature and salinity was characterized by an abrupt diminution of the values from 10 to 22 February at 379 m and from 11 to 13 February at 509 m. At 379 m, the temperature decreased from 13.38 to 12.85 °C while salinity fell from 38.56 to 38.40. These values corresponded to a small density increase from 29.075 to 29.077 σ_θ units. At 509 m, the temperature dropped to 13.01 °C and the salinity to 38.48, a value close to that found at 809 m; density increased from 29.08 to 29.09 σ_θ units. At greater depths, both temperature and salinity showed higher values which remained rather constant (Fig. 8).

Horizontal current analysis

The horizontal currents in the period 1-28 February 1991 show a high temporal variability both in position B and C, indicating an intense mesoscale variability. The data show a significant spatial shear, as previously found by Taupier-Letage and Millot (1986).

The currents are vertically similar at least in a 100-500 m layer. A complex EOF analysis gave a first mode that accounted for 91 % of the total variance in position B and 87 % in position C. These values indicate a dominant barotropic structure. The amplitude and direction of the eigenvectors are similar from the uppermost level to a depth of 350-400 m. The amplitudes are significantly reduced in the lower layers.

The salient features of the horizontal current characteristics in our observations, namely, intense mesoscale variability, predominant barotropic structure and small horizontal correlation, are typical for homogeneous winter stratification (Taupier-Letage and Millot, 1986).

Representative progressive vector diagrams, shown in Figure 9, indicate a general westward motion of water masses but deflections from this direction are observed

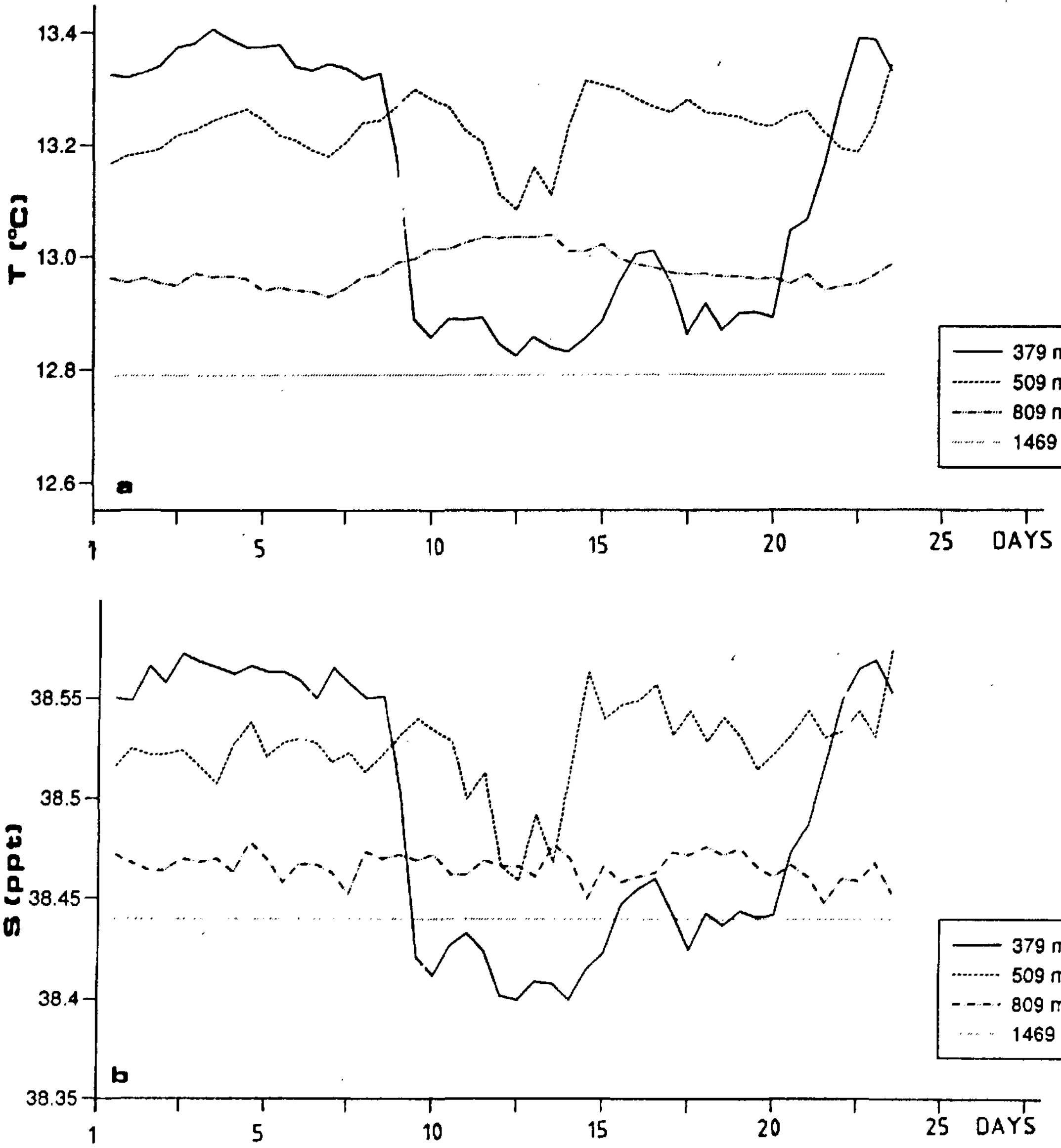

Figure 8

Temporal variability of temperature (a) and salinity (b) from Aanderaa sensors in position C during February 1991. Hourly averaged data.

both in B and C. In particular, in mooring C, corresponding to the lowering of the temperature and salinity between 10 and 20 February, a cyclonic movement of water can be noted. This cyclonic circulation can be alluded to an eddy having a diameter of about 20 km.

During the period 15-20 February, density increases, ranging from 0.01 to 0.05 kg m^{-3}, are observed during sinking events. At the same time, the horizontal currents show a marked short term variability with direction inversions. Figure 10 shows a selected period, when the strong vertical velocities are associated with small-scale anomalies which are super-imposed on a mean south-eastward flow. From the data, it is not easy to ascribe the current anomalies to vortex-like features advected past the observation site, as was done by Schott and Leaman (1991). The anomalies in the currents are often so frequent that more than one small-scale rotating feature seemed to be detected by the current meters within a period comprising only a few hours.

Scaling analysis

A view of the synoptic situation could not be obtained because of the absence of CTD casts after these events and the limited coverage of the ADCPs and the Aanderaa current meters. Also, as a result of the lack of appropriate measurements, the fate of these newly formed water masses could not be followed. Nevertheless, a scaling analysis of events associated with sinking can give an idea of the length scale involved in open-ocean convective processes (Marshall *et al.*, 1994).

For a time scale $t << 1/f$ (where f is the Coriolis parameter), the effect of the earth's rotation on convection is negligible and the length scale L can be computed from the relationships:

$$u \sim w \sim \sqrt{Bt} \tag{1}$$

$$L \sim \sqrt{Bt^3} \tag{2}$$

where B is the buoyancy flux, L is the horizontal or vertical length scale, u and w are the horizontal and vertical velocity scales and t is the time.

With a t of about 2 hours and a velocity of the order of 6 cm/sec, we obtain a value for $B \approx 5 \cdot 10^{-7}$ m^2 s^{-3} by inverting (1) and consequently $L \approx 450$ m from (2).

The cooling rate W can be calculated from B by using the formula:

$$W = \frac{\rho c_w}{g\alpha} B \tag{3}$$

where:

$\rho = 10^3$ kg m^{-3} is the sea water density;

$c_W = 4 \cdot 10^3$ J kg^{-1} K^{-1} is the specific heat;

$\alpha = 2 \cdot 10^{-4}$ K^{-1} is the thermal expansion coefficient of water;

$g = 9.81$ m s^{-2} is the gravity.

For $B \approx 5 \cdot 10^{-7}$ m^2 s^{-3}, we obtain a cooling rate $W \approx 1000$ W m^{-2}.

The length scale we found is in agreement with the one computed by Schott *et al.* (1994) for the Gulf of Lions.

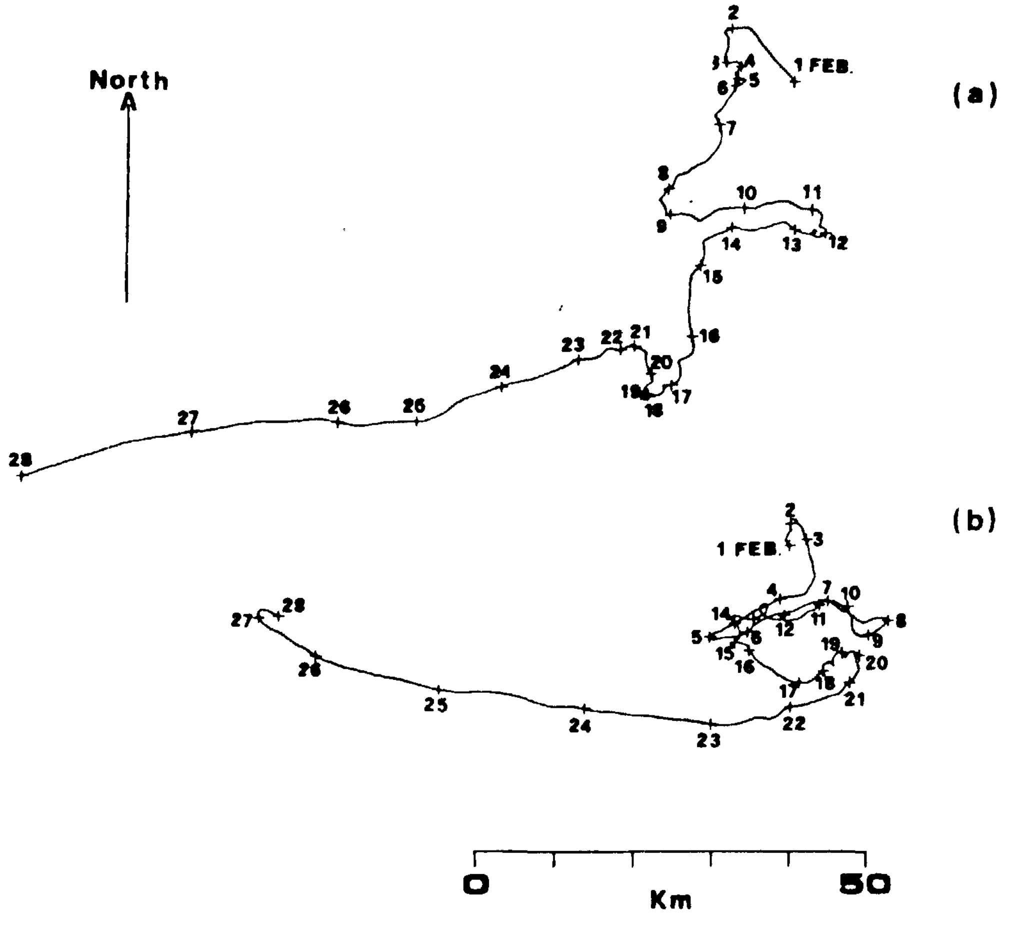

Figure 9

Progressive vector diagrams computed from horizontal currents measured at 94 m in position B (a) and at 117 m in position C (b) from 1 to 28 February 1991.

INTER-ANNUAL CHANGES IN THE LIGURIAN SEA

The cyclonic circulation of the Ligurian Sea is subjected to seasonal and inter-annual changes that can be related to water mass modification (Astraldi and Gasparini, 1992; Béthoux *et al.*, 1982) and/or to the wind regime (Heburn, 1987). The possible relationship between preconditioning and large-scale circulation has been described by Schott *et al.* (1994). Changes in the intensity of the cyclonic circulation would be reflected in the convective processes.

Several studies on climatic variations in the Mediterranean Sea have been carried out in the past decade. Sparnocchia *et al.* (1994) found that the LIW temperature and salinity core properties in the Ligurian Sea increased (on an average) by 0.1 °C/decade and 0.02 ppt/decade. Investigations on WMDW temperature and salinity changes have shown differences of 0.07 °C and 0.05 (Leaman and Schott, 1991; Rohling and Bryden, 1992) or 0.11 °C and 0.03 (Béthoux *et al.*, 1990) between 1955 and the present. Changes in the deep water properties were observed also by Lacombe *et al.* (1985). Béthoux *et al.* (1990) ascribed the observed temperature increase of the WMDW to global climatic changes. Rholing and Bryden (1992) deduced that the reduced runoff due to the construction of dams was responsible for the increase in temperature and salinity of the deep layers from 1950 till the present.

The variations reported by the different authors are significant and it appears from data that, in the Western Mediterranean, the Ligurian Sea changes are the strongest (Sparnocchia *et al.*, 1994).

The data examined in this paper show that, during the preconditioning phase, the water mass characteristics were different. In particular, the LIW salinity was greater by 0.1 in February 1991 than in February 1969.

To better understand the observations, hydrographic data gathered in the Liguran Sea from 1950 to 1987 were analysed. About 4400 temperature and salinity profiles from the ENEA-CRAM data bank in La Spezia (Picco, 1990) were examined. All data were reduced to standard levels and were spatially averaged in order to obtain time series representing the monthly evolution of the salinity and temperature. The results could be affected by uncertainties due to the uneven spatial and temporal coverage. However, they are in agreement with those obtained by other authors using methods of analysis quite different from ours.

In Figure 11, the inter-annual variability of the mean January, February and March temperatures from 1950 to 1987 at a depth of 50 m are shown. The same trend is observed at the surface and at lower levels although in the latter case, it is more smoothed. The curves show some common features: several minima around 1970 and two distinct maxima around 1960 and 1977. Salinity data were also analysed but they do not show the clear inter-annual variability demonstrated by the temperatures.

Sea surface temperatures in the Mediterranean were analysed by Garrett (1994), who reported a minimum during 1975 and a value close to the average in 1970.

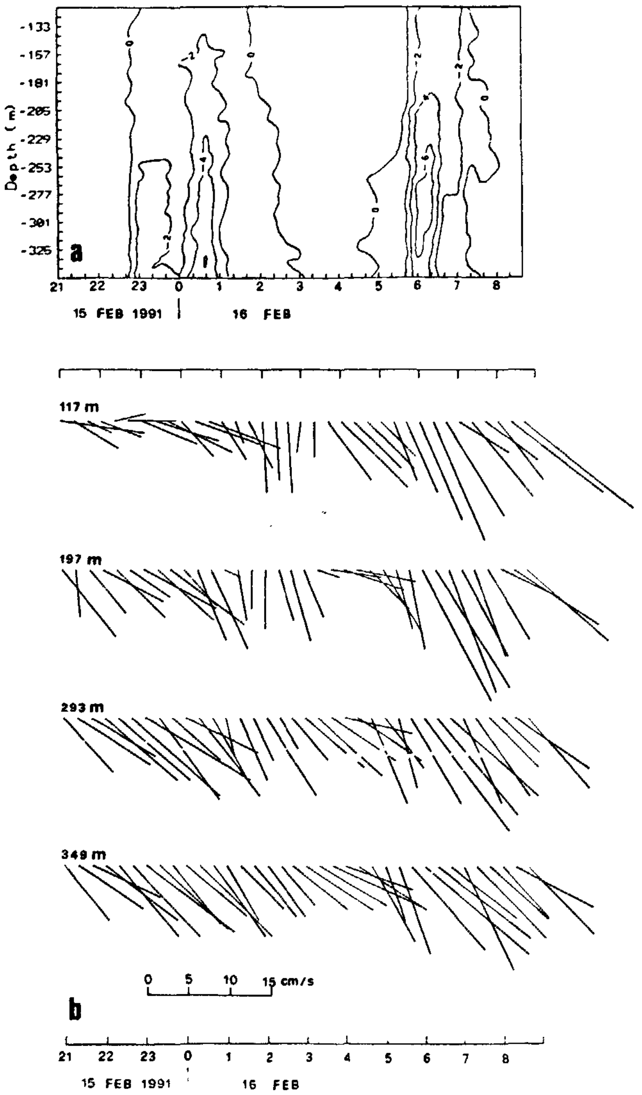

Figure 10

(a) Time-depth contours of vertical velocity at C between 21:00 hours on 15 February and 8:40 hours on 16 February in the depth range 117-349 m (time interval = 20 minutes). (b) Current vector plots of several ADCP bins during the same period.

DISCUSSION AND CONCLUSION

Temperature and salinity data gathered during February 1969 allowed the reconstruction of the density fields before and after a storm in the Ligurian Sea. Meanders and areas of relatively dense water were observed during the first days of February. After the storm, the meanders still existed, the surface density increased and patches of very dense water were observed. The patterns observed in the Ligurian Sea resemble the numerical results of Madec *et al.* (1991) who, while investigating deep water formation forced by heat and salt fluxes in a rectangular basin, obtained meanders which induced strong horizontal and vertical mixing. Dense water sank and spread at the peripheries of the area defined in the model while lighter peripheral waters flowed into it. This constitues a non-penetrative baroclinic adjustment process which does not entail very deep convection as it is triggered by strong surface thermohaline fluxes.

The differences between the Ligurian Sea and the Gulf of Lions are important from many points of view. In the Gulf of Lions, the bottom topography is a preconditioning element in deep convection processes. In the Ligurian Sea, there are no topographic features which can significantly affect the water movements. The Ligurian Sea observations are in agreement with the Madec *et al.* (1991) model results which demonstrated that convective events could also be generated in a flat basin.

Data gathered in the central portion of the Ligurian Sea have shown the formation of water types having significantly different temperature and salinity properties in 1969 and 1991. These waters were locally produced under different meteorological forcings in these two years: in February 1969, the wind was stronger (about 21 m s^{-1} against 18 m s^{-1}) and the air temperature colder (about 1.5 °C against 4 °C) than in February 1991. The water type formed in the Ligurian Sea was denser (29.12) in 1969 than in 1991 (29.077).

During the MedOc experiment, while the surface water temperature and salinity were more or less equal to those observed in 1991, the salinities of the intermediate and deep waters were lower. The stronger and colder wind blowing in 1969 caused the mixing and cooling of the water column upto a depth of 1200 m. Conversely, the water type formed during 1991 was slightly warmer, saltier and less dense; surface forcings were not strong enough to erode the stratification from the surface to the bottom. The water type formed in 1991 was thus unable to reach great depths and found its equilibrium level at an intermediate depth. The amount and the characteristics of the dense water are subject to changes in climatic conditions. The events in 1969 occurred in a "cold" period, while those in 1991 took place during a "generally warmer" period. The analysis of the hydrographic data from 1950 till the present has shown inter-annual variability in the Ligurian Sea, with two temperature maxima in 1960 and 1977, and a pronounced minimum around 1970. The data existing in the ENEA-CRAM data bank do not make it possible to determine whether such a cycle is common to the entire Mediterranean. Garrett (1994), using COADS climatological data, obtained a quite different cycle for the sea surface temperature in the Mediterranean Sea. A minimum temperature value was computed for 1975, the years around 1970 being closer to the average value. Lacombe *et al.* (1985) noted that, while the winters of 1969, 1970, 1974 and 1975 were characterized by strong meteorological forcings, those of 1972 and 1973 were milder. The discrepancies between the data presented in this paper and those reported by Lacombe *et al.* (1985) and Garrett (1994) do not have a definitive explanation, and could be due to the lack of an adequate data set.

Figures 8*a* and 8*b* show a decrease in temperature and salinity above 500 m from 10 to 22 February, 1991. The decrease could be due to horizontal advective processes on which surface thermohaline fluxes are superimposed during the Mistral events (Madec *et al.*, 1991). Two horizontal scales could be deduced from our data: a chimney scale to which may be associated a cyclonic eddy with a diameter of about 20 km that persisted during the period when strong vertical movements were detected by the ADCPs; a smaller scale characterized by little convection cells advected past the site of observation. A scaling analysis provided an estimate of about 450 m for the length of these cells.

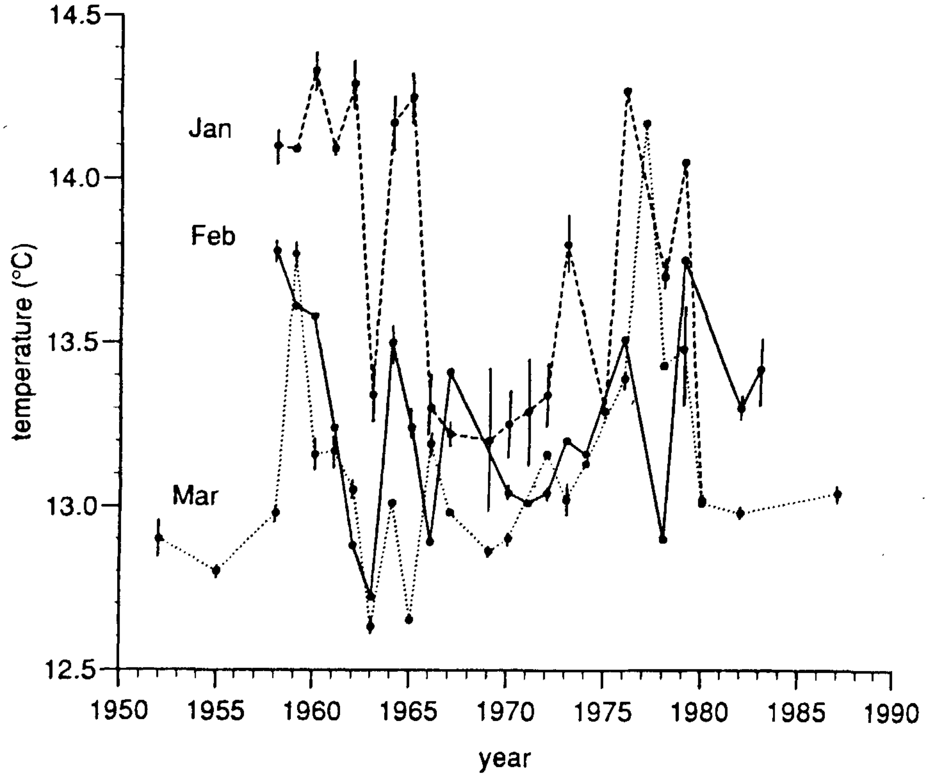

Figure 11

Interannual variability of winter temperature at 50 m in the Ligurian Sea obtained from monthly averaged data (1950-1987).

Finally, there could be a connection between the variability of the large-scale circulation and the dense water formation in the Ligurian Sea. The major large-scale hydrodynamic feature of the Ligurian Sea is a well-defined cyclonic circulation involving all the water masses. The transport due to this circulation system exhibits a seasonal variability. A winter maximum is associated with the increased transport from the Tyrrhenian Sea to the Ligurian Sea through the Corsica Channel (Béthoux *et al.,* 1982). Astraldi *et al.* (1994) suggest that the increased winter transport through the Corsica Channel reintegrates the heat lost by the Liguro-Provençal Basin to the atmosphere and replaces the volume of the surface water involved in the dense water formation processes. Transport values reported by Astraldi *et al.* (1994) show that from 1986 to 1988 the MAW winter transport through the Corsica Channel diminished from an average of 1.3 Sv to 0.8 Sv. The 1991 MAW winter transport was even lesser (about 0.5 Sv; Astraldi and Gasparini, pers. comm.).

Because of the inter-annual preconditioning processes, the large-scale convection processes and the changes in the atmospheric forcings, it is not surprising that, while intermediate water can be formed in some years, convection can be deeper in others. The Ligurian Sea, where the convective plume did not reach the sea floor even during a year (1969) of relatively strong heat and salt fluxes at the sea surface, contributes to the formation of dense water of a somewhat warmer and saltier variety that could be called (following Carmack and Killworth, 1978) "not-quite-deep water".

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