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**Pure and Applied Geophysics**

# Numerical Simulation of Deep-Water Convection in the Gulf of Lion

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*Abstract*—The unsteady-state process of deep-water convection in the Gulf of Lion has been observed and investigated in recent decades. However, the mechanisms of the uncertainty and irregularity of the deep-water convection in this region have not yet been fully understood. In this study, the effects of time variation of the surface buoyancy flux on the formation of the deep-water convection are examined. Numerical simulations using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) with the NRL Coastal Ocean Model (NCOM) as an oceanic component were conducted for the period from October 1998 to September 2000 to cover two winters, 1998–1999 and 1999–2000, over the Gulf of Lion region. The results show large differences in the deep-water convection between the two winters, even though the total surface heat fluxes during the two winter seasons are similar. The differences are related to the time variation of the surface buoyancy flux that causes large differences in the preconditioning and mixing stages of the convection.

**Key words:** Deep-water convection, Gulf of Lion, COAMPS, NCOM.

## 1. Introduction

The northwestern Mediterranean Sea (the Gulf of Lion) is one of the regions in the world where deep-water convection and formation are likely to occur during the winter season. The convection is strongly related to intense winter storms, which bring cold and dry air over pre-existing weakly stratified water in the northwestern Mediterranean Sea. Observations have revealed that the deep convection in this region is not a steady-state process that recurs every year with certainty and regularity (MEDOC GROUP, 1970; LEAMAN and SCHOTT, 1991; SCHOTT *et al.*, 1996). Numerical simulations also show that the variations in wind stress and heat fluxes can induce significant interannual fluctuations of not only upper ocean circulation (PINARDI *et al.*, 1997) but also deep-water formation (MERTENS and SCHOTT, 1998) in the Mediterranean Sea.

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Recent observations of currents and temperatures on the continental slope of the Gulf of Lion by BETHOUX *et al.* (2002) showed intense cascading of dense water in February 1999. This was one of four cascading events of dense water observed during the 1971–2000 period, which affected the hydrology of the basin and contributed to the formation of western Mediterranean deep water. Strong down-canyon current bursts on the continental slope of the Gulf of Lion in the winter of 1998–1999 resulted in a quasi-simultaneous temperature decrease at 500- and 1000-m depth, respectively, and the disappearance of the intermediate layer (characterized by higher temperature and salinity). BETHOUX *et al.* (2002) propounded that this dense water formation most likely occurred during the stormy period between January 26 and February 23, 1999. They also found that despite strong air-sea exchanges during the winter of 1999–2000, similar to those observed in the previous winter of 1998–1999, there was no evidence of an intense cascading of dense water. They attributed this absence of a cascading event to large freshwater inputs from the western coast of the Gulf in November 1999, which reduced the shelf salinity and limited the dense water formation.

In this study, numerical simulations using COAMPS (HODUR, 1997) with NCOM (Martin, 2000) as the oceanic component were conducted to investigate the mechanism of deep-water convection and formation in the Gulf of Lion during the winters of 1998–1999 and 1999–2000 and to reveal the reasons that led to the dissimilar characteristics of deep-water formation for these two winters. Section 2 describes the model and the design of the numerical simulation. Section 3 discusses the air-sea fluxes from the COAMPS atmospheric reanalyses for the winters of 1998–1999 and 1999–2000 and compares them with observations. Section 4 presents and discusses the model results for the deep-water convection and formation in the Gulf of Lion. Section 5 provides a summary.

## *2. Model Design*

The COAMPS atmospheric reanalyses were conducted on an 81-km resolution grid over Europe with a nested grid of 27-km resolution over the Mediterranean. The reanalyses used a 12-h analysis/forecast cycle in which analyses were done every 12 h using all available observed data and the previous 12-h atmospheric forecast as a background field. These analyses were then used to initialize the next forecast. Atmospheric fields output at 1-h intervals were used to force NCOM through fluxes of heat, momentum, and moisture across the air-water interface. The surface forcing also included solar radiation, precipitation, and surface atmospheric pressure.

The ocean model was run on a domain of 576 by 288 grid points with a horizontal resolution of about 6 km covering the entire Mediterranean. The internal Rossby radius in the Mediterranean Sea is of the order of 10 km. The

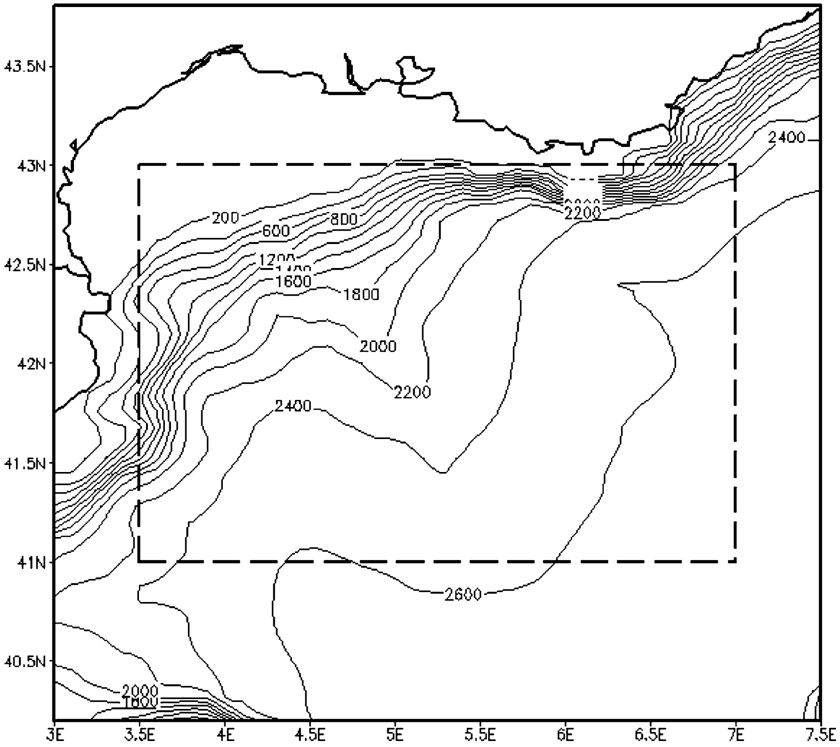

Figure 1
Model bathymetry (m) for the Gulf of Lion area. The area within the dashed-line is used for calculating area average.

vertical grid is logarithmically stretched from the surface downward with an upper-layer thickness of 2 m and a maximum depth of 4000 m. There are a total of 40 layers with a switchover from sigma to z-level vertical coordinates at about 100-m depth. The model topography was obtained by a cubic spline interpolation from the 1/60°–resolution U.S. Navy Digital Bathymetric Database 1 (DBDB1) developed by the Naval Oceanographic Office. The bathymetry of the northwest Mediterranean Sea including the area of the Rhône Deep Sea Fan, which is important to the preconditioning phase of the deep convection (Hogg, 1973), is shown in Figure 1.

The model was initialized by annual mean temperature and salinity from the Mediterranean Oceanic Data Base (MODB) and was then run for 10 years using monthly-mean climatological wind stresses and heat fluxes (May, 1986) for the atmospheric forcing. This period of spin-up is long enough to achieve a repeating seasonal cycle for the volume-averaged kinetic energy (not shown). Following this spin-up, the COAMPS atmospheric fluxes at hourly frequency were applied as surface boundary conditions for NCOM to continue the run for a 2-year period from October 1998 to September 2000. The investigation of the simulation over this 2-year period will be concentrated in the Gulf of Lion to study the deep-water convection and formation for the winters of 1999 and 2000.

## *3. Air-Sea Fluxes for the Winters 1998–1999 and 1999–2000*

### *3.1. COAMPS Atmospheric Reanalyses*

Air-sea fluxes used in the model include wind stress, latent and sensible heat fluxes, long-wave radiation, solar radiation, evaporation and precipitation, and surface atmospheric pressure. Time series of the area-mean and time-integrated wind stress over each month from the hourly outputs for October 1998 to September 1999 are shown in Figure 2a. The area used to calculate the means covers the Gulf of Lion area (41–43°N and 3.5–7.0°E) and is shown in Figure 1.

The winter of 1998–1999 is characterized by moderate wind stress (about 5–6 N-day-m$^{-2}$) in the preconditioning months from October 1998 to January 1999. During these months, most of the Mistral events happen in December. (The Mistral refers to a violent winter outbreak, in which a strong, cold northwesterly wind system blows from Southern France into the Gulf of Lion.) There are relatively few Mistral events in January. The largest wind stress for the two-year period (about 9–10 N-day m$^{-2}$) is in February 1999, implying strong Mistral events. The Mistral is greatly reduced in March 1999 after the strong forcing in February. However, there are still a few weak Mistral events during April 1999.

The wind stress in the winter of 1999–2000 is quite different from the previous winter. There are no significant Mistral events in October 1999, but a relatively large amount of wind stress accumulated in November 1999 compared to the amount in November 1998 (Fig. 2a). For the months of December 1999 and January 2000, the wind stress is slightly less. There are substantially fewer Mistral events in February of 2000, which is usually the main period of the year for deep convection and deep-water formation. The strongest Mistral for the winter of 1999–2000 occurred on 23 January, although the accumulated wind stress for this month does not appear very significant.

The area averages of the thermal (heat) and haline (salt) contributions to the surface buoyancy flux over the Gulf of Lion, converted to buoyancy flux and time integrated over each month, are shown in Figure 2b for the 2-year period from October 1998 to September 2000. The temporal variability of the calculated surface buoyancy flux is similar to that of the wind stress. The buoyancy flux is considerably larger for February 1999 than for February 2000. This may contribute to the cause of the difference in the generation of deep-water convection for the two winters.

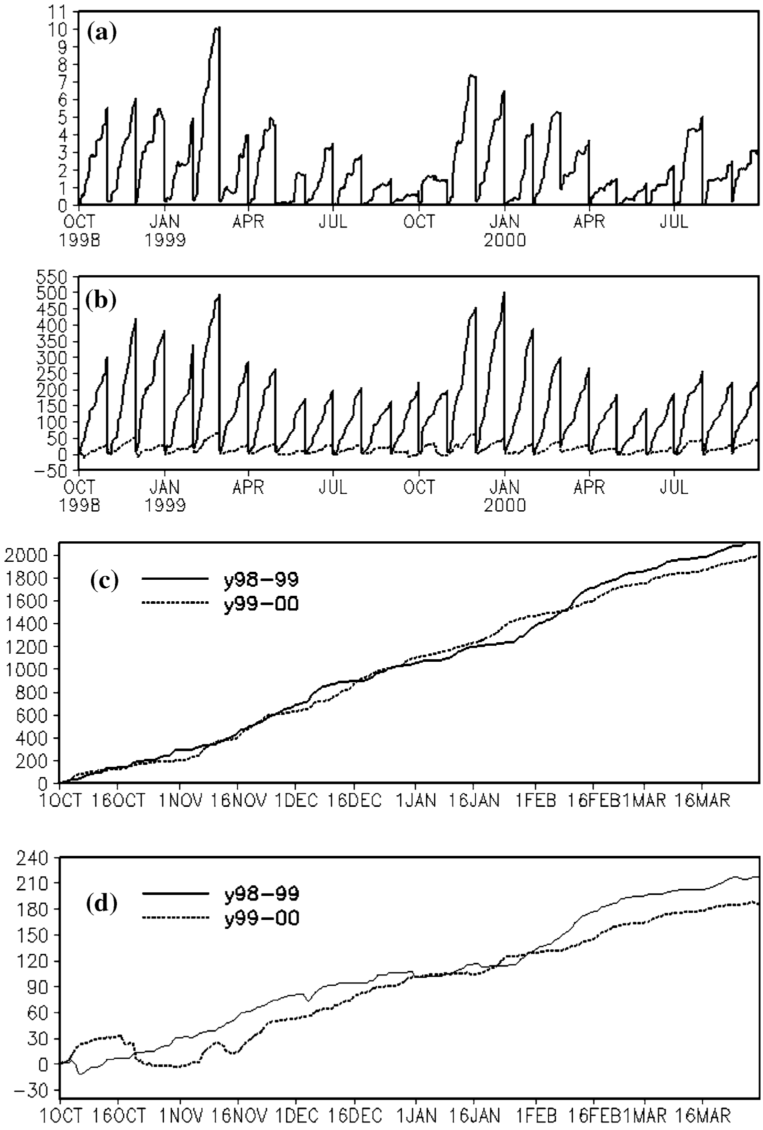

Figure 2

Gulf of Lion area-averaged and time-integrated COAMPS surface fluxes. (a) Wind stress (N-day $m^{-2}$) and (b) surface thermal (solid line) and haline (dashed line) buoyancy fluxes ($Nm^{-2}$) are integrated over each month. Surface (c) thermal and (d) haline buoyancy fluxes are integrated over six months. The area used to calculate the average is 41 to 43°N and 3.5 to 7°E as shown in Figure 1.

The surface haline flux is usually about 10% of the thermal flux. As discussed by GAILLARD *et al.* (1997), this haline flux, even though small, can affect vertical mixing. The haline flux in Figure 2b is mostly positive and contributes to

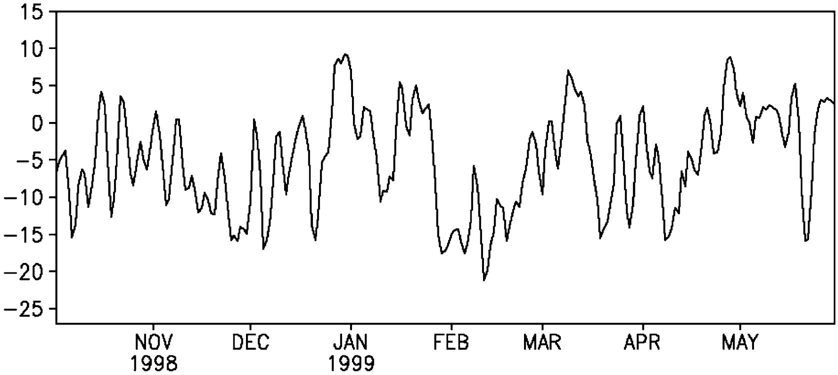

Figure 3
Time series of NW-SE wind speed (m s$^{-1}$) from COAMPS reanalyses at Cape Béar Station corresponding to the same period and location as observed.

de-stabilizing the upper ocean. However, a noticeable period of small negative haline flux (about 5–10 Nm$^{-2}$) in October and November 1999, during which precipitation exceeded evaporation, tends to increase the stratification and stabilize the surface during the preconditioning stage.

Figures 2c and 2d show area averages of the surface thermal and haline buoyancy fluxes integrated over the six-month period from October to March for the winters of 1998–1999 and 1999–2000. Although the time variations of the thermal fluxes for the two winters are much different, the area-averaged and time-integrated thermal fluxes over the two winter periods are very similar, which reach 2134 and 1994 Nm$^{-2}$ on March 31 of 1998–1999 and 1999–2000, respectively. The integrated thermal flux for the winter of 1998–1999 is 7% more than for the winter of 1999–2000. The integrated haline flux for the winter of 1998–1999 is about 17% more than for the winter of 1999–2000.

### *3.2. Comparison with Observations*

Observations from the meteorological station at Cape Béar (a rather windy cape near the border between Spain and France) showed very strong and prolonged northwest-southeast (NW-SE) winds during February 1999 (Fig. 5a in Bethoux *et al.*, 2002). Before this period it was fairly calm from December 8, 1998 to January 26, 1999 with only twelve short Mistral events. It became stormy from January 26 to February 23, 1999 with wind speed frequently larger than 25 ms$^{-1}$. This stormy period was followed by a rather calm period again from February 24 to March 17, 1999. Time series of NW-SE wind speed from the COAMPS reanalyses at the location of Cape Béar station (Fig. 3) show a variability consistent with the meteorological records from the station. However, the magnitudes of the COAMPS wind speed are smaller than observed, which implies that the reanalyses may need even higher resolution in the future to better represent extreme wind events.

## *4. Discussion of Model Results*

Results from the 2-year model simulation with hourly COAMPS atmospheric forcing are analyzed with special attention for the deep convection for the winters of 1998–1999 and 1999–2000 in the Gulf of Lion area. The study includes the preconditioning phase, when the winter surface cooling reduces the stability of the surface layer and leaves very little reserve buoyancy in the center of the area, and the deep convection (violent or strong mixing) phase, in which a rather narrow region of deeply penetrative convection occurs in the preconditioned area (MEDOC GROUP, 1970).

### *4.1. Winter 1998–1999*

#### *4.1.1. Preconditioning phase*

Results from the simulation show that cyclonic circulation dominates in the Gulf of Lion (Fig. 4a) during the winter preconditioning phase for December 1999, when the integrated thermohaline forcing is not yet able to induce deep convection. There are two cyclonic gyres. The center of the main cyclonic gyre is slightly east of its normal location at 42°N and 5°E (MEDOC GROUP, 1970). This so-called Lion gyre is about 100 km in diameter and usually exists in the Gulf of Lion every winter, when the stability of the surface layer and the reserve of buoyancy in the center of the gyre are reduced by the cold and dry Mistral wind prior to the strong mixing phase. There is another cyclonic gyre in the south Balearic Sea. The cyclonic Lion gyre uplifts the isopycnals in an elongated dome (Fig. 4b). In the center of the dome, the salinity maximum in the Levantine Intermediate Water (LIW) is brought into depths shallow enough to be exposed to entrainment with the mixed layer (NARDELLI and SALUSTI, 2000). This leads to a favorable condition for deep convection since the surface water stays in the same place and gets more exposure to evaporation and cooling instead of passing quickly through (SWALLOW and CASTON, 1973). The LIW in the simulation in the area of the Gulf of Lion is slightly less dense than observed (29.08–29.1 $\sigma_\theta$ units). This is primarily due to the lower salinity in the initial condition of the model simulation with an average of only 38.35 psu, while the observed salinity is about 38.5–38.6 psu as described in SCHOTT *et al.* (1996) and WU and HAINES (1996). The less saline LIW may reduce the enhancement of the surface instability by the entrainment of the LIW and thus the deepening of the convection may be less than expected (WU and HAINES, 1996).

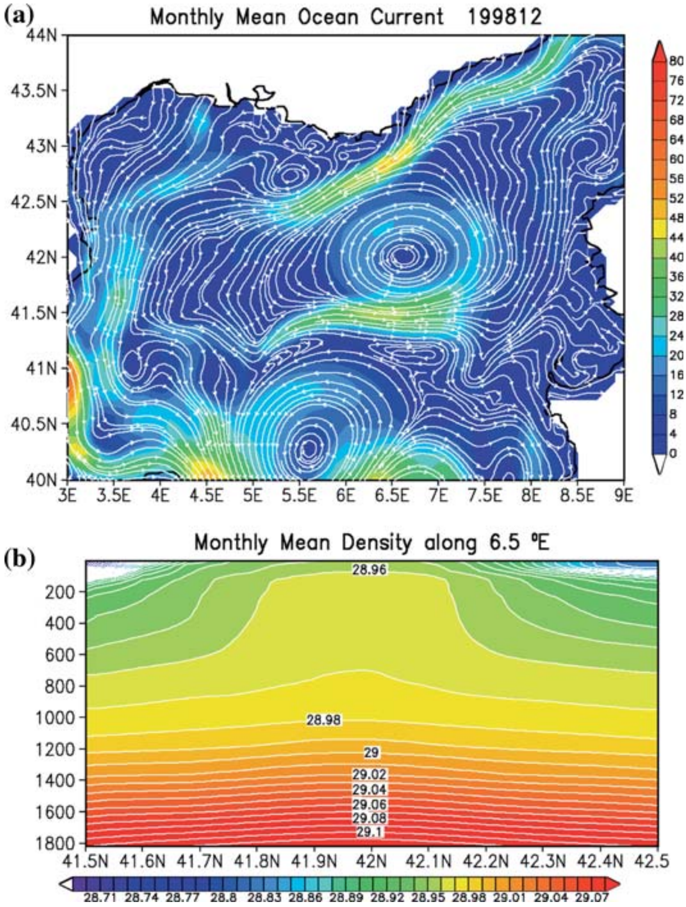

Figure 4

NCOM monthly mean (a) ocean current streamlines and (b) potential density along the center of the Lion gyre at 6.5°E for December 1998.

### *4.1.2. Deep convection*

The strongest winter storm for the winter of 1998–1999 passed through the northwestern Mediterranean Sea on 11 February, 1999. This intense Mistral with a maximum wind stress over 1.8 $\mathrm{Nm}^{-2}$ induced a total buoyancy flux loss surpassing $9 \times 10^{-4}\,\mathrm{Nm}^{-2}\mathrm{s}^{-1}$ over the Gulf of Lion. This buoyancy flux loss was substantial compared to that observed during the 1991–1992 winter Mistral periods (GAILLARD *et al.*, 1997), which was about $4 \times 10^{-4}\,\mathrm{Nm}^{-2}\mathrm{s}^{-1}$. The strong surface cooling and evaporation with highly favorable preconditioning triggered deep convection after the 11 February Mistral (Fig. 5a). A mixed-layer depth (defined by uniform properties in the water column) of over 800 m covered much

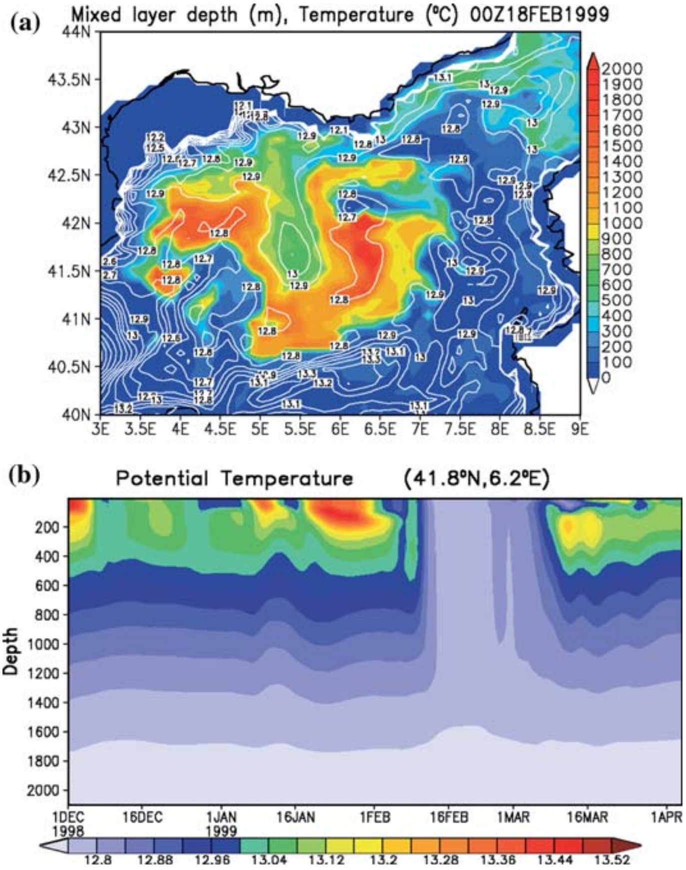

Figure 5

NCOM (a) mixed-layer depth on February 18, 1999 and (b) time series of potential temperature at location 41.8°N and 6.2°E for winter 1998–1999.

of the area in the Gulf of Lion. The simulation generated four convective centers with eddy sizes under 100 km and mixed-layer depth over 1200 m. The maximum mixed-layer depth was greater than 2200 m in a couple of small areas on 18 February, 1999. There was a hierarchy of convective processes and scales involved in the deep convection as shown in Figure 5a.

The time series of potential temperature at the center of the convection in Figure 5b shows the vertical penetration of the cooling from the surface. The deepening of the mixed-layer is consistent with the Mistral events. The strong Mistral in early December eroded the surface stratification and mixed the water down to 500-m depth. Although this was a relatively strong Mistral, the high stability inhibited convective deepening during this period. After a calm period, there was another weaker Mistral in late December. The mixing from this Mistral reached down to 500-m depth as in the previous Mistral because of the weakened stratification. Warm surface water recapped the area afterwards. Three weaker Mistral events followed in January and then the mixing was interrupted with a capping of warm surface water. After that, the strong Mistral events in February mixed the water down to 1800 m starting on 13 February, 1999. The well-mixed vertical column of water had a temperature of 12.75°C and was maintained for 15–20 days until early March by subsequent Mistral events. The minimum mixed-layer temperature reached 12.6°C in one of the well-mixed vertical columns (Fig. 5a). This continued mixing was enhanced by the LIW when the initial mixing brought the subsurface LIW to the surface. WU and HAINES (1996) indicate that without the entrainment of the LIW, the convection in the Gulf of Lion would not be so deep, even though the strong relaxation of the surface temperature produced a sufficient heat loss for deep convection in their simulation. In Figure 5b, distinct LIW, distinguished from the surrounding water by a warm temperature anomaly, had again advected into the area in early March.

### *4.1.3. Comparison with observations*

The observations of BETHOUX *et al.* (2002) show that deep-water current and temperature anomalies occurred from February 14 to March 12, 1999 on the

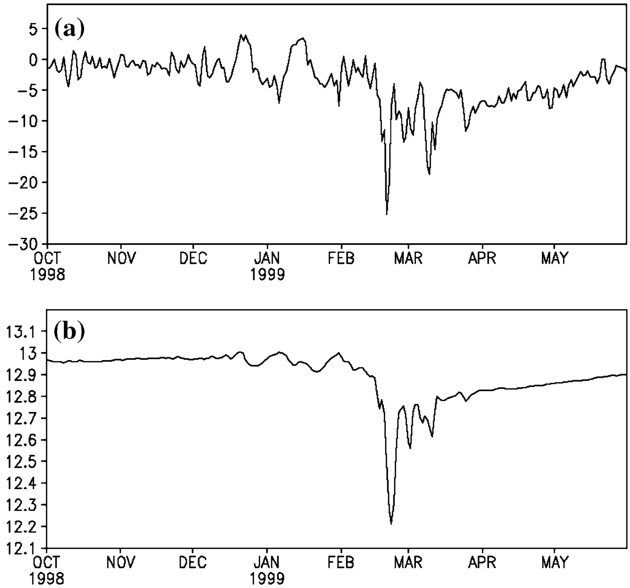

Figure 6
NCOM time series of (a) north-south current velocity and (b) potential temperature at 42.3°N, 3.7°E at 880-m depth from October 1998 to May 1999.

continental slope of the Gulf of Lion. These were the first such anomalies since October 1993. Near-bottom current velocities at 1000-m depth increased from a few cm $s^{-1}$ to 60 cm $s^{-1}$ in the Lacaze-Duthiers canyon (Fig. 5b in BETHOUX *et al.*, 2002) in correspondence with the very strong and prolonged wind period from January 26 to February 23, 1999 (Fig. 3). The strong, down-canyon current bursts were associated with quasi-simultaneous temperature decreases between 0.5 and 1°C at 500 m and 1000 m depth. The *in situ* temperature anomalies remained between 11.8 and 12.9°C at 1000 m and between 12.5 and 13.2°C at 500 m (Fig. 6 in BETHOUX *et al.*, 2002). From the model simulation, the north-south current at 880 m indicated a similar rapid increase during the same time period (Fig. 6a). The current speed increased from about 2–3 cm $s^{-1}$ up to 27 cm $s^{-1}$. The temperature anomaly was also present in the model simulation, where the temperature at 880 m abruptly dropped from 12.9°C to 12.1°C, a change of 0.8°C (Fig. 6b). The current increase and temperature decrease in the Lacaze-Duthiers canyon indicated the cascading of dense water from the shelf down the slope. This dense water most likely formed during the stormy period from January 26 to February 23, 1999.

### *4.2. Winter 1999–2000*

#### *4.2.1. Preconditioning phase*

Although a larger buoyancy flux was lost during November and December 1999, the induced density instability in the upper layer was not enough to overturn the thick layer of warmer water lying beneath during this period. This was because a negative haline flux input, due to large rainfall during late October and early November 1999 (Fig. 2b), decreased the shelf salinity and increased its stability. The seasonal accumulated haline flux is also significantly less than that of the previous year during the preconditioning stage (Fig. 2d). More small-scale cyclonic circulations with diameters less than 100 km occurred in the Gulf of Lion (Fig. 7a). The Lion gyre was not as well organized as in December 1998. Doming of the isopycnals in December of 1999 (Fig. 7b) was also not as significant as that in December of 1998 (Fig. 4b), as indicated by the lower density in the upper layer in December 1999.

#### *4.2.2. Deep convection*

The mixing area and depth of the deep-water convection were less for the winter of 1999–2000. The maximum mixed-layer depth occurred on January 2000, when water with a mixed-layer depth of 800 m covered only a portion of the Gulf of Lion and extended toward the Ligurian Sea (Fig. 8a). There were two major convective centers, one in the Gulf of Lion and the other between the Gulf of Lion and the Ligurian Sea. The second convective center had a deeper mixed-layer depth with a

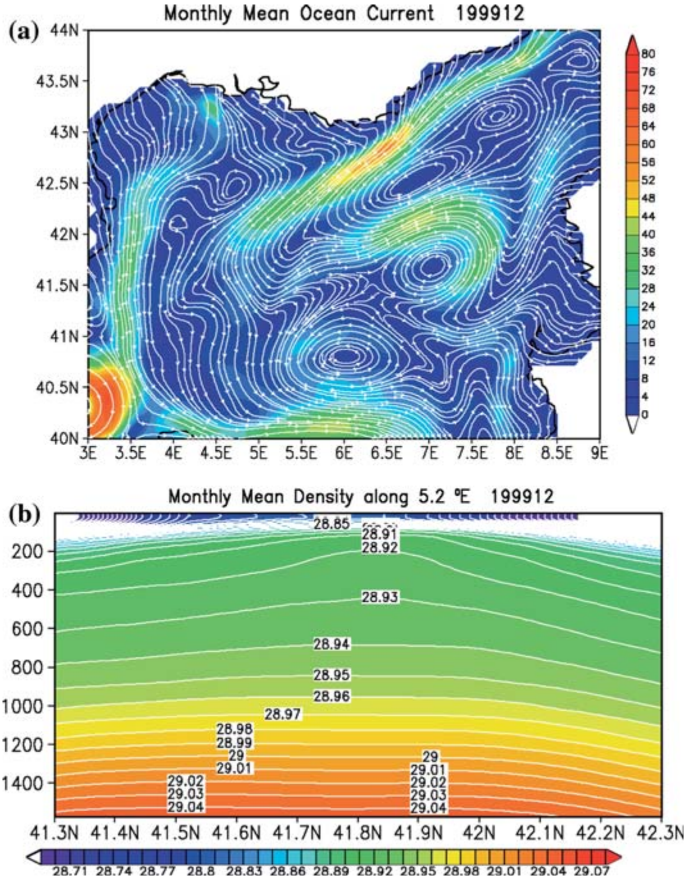

Figure 7
NCOM monthly mean (a) ocean current streamlines and (b) potential density along the center of the Lion gyre (5.2°E) for December 1999.

maximum depth of 1400 m, which was about 22% shallower than the maximum for February 1999 as shown in Figure 5a.

The time series of potential temperature versus depth at 41.8°N and 6.2°E from December 1999 to March 2000 (Fig. 8b) shows that the deepening of the mixed-layer was caused by the surface forcing. Surface cooling and vertical mixing did not erode the surface-layer stratification until the end of December. The larger ocean response corresponds to the 23 January event, which was the strongest Mistral that occurred during that winter. Temperature decreased and salinity increased less significantly, resulting in shallower winter convection. The deepest mixing reached 1400 m after the strongest Mistral. The well-mixed vertical column of water was re-stratified in a few days. The LIW advected into the site near the end of February, which was earlier than during the previous winter.

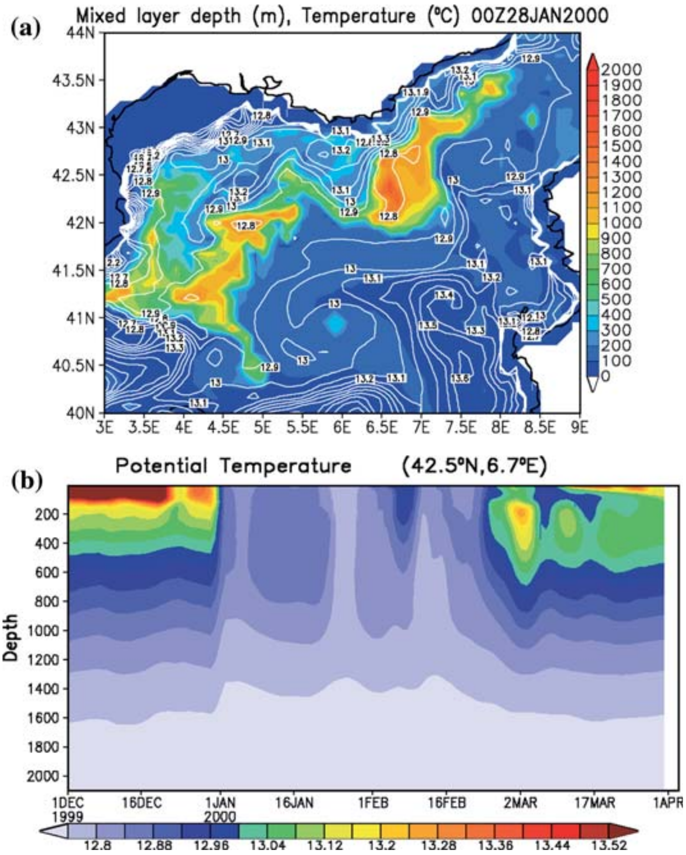

Figure 8

NCOM (a) mixed-layer depth on January 28, 2000 and (b) time series of potential temperature at 42.5°N, 6.7°E for winter 1999–2000.

### *4.2.3. Comparison with observations*

Observations showed no evidence of intense cascading of dense water in the winter of 1999–2000, despite the total amount of air-sea exchange being close to that observed in the previous winter (Bethoux *et al.*, 2002). Bethoux *et al.* (2002) indicated that the massive rainfalls and floods that occurred on the western coast of the Gulf in November 1999 resulted in more freshwater in winter 1999–2000 than in winter 1998–1999 and could linger long enough to limit the dense water formation. This was consistent with the small, area-averaged and time-integrated negative haline fluxes during late October and early November from the COAMPS reanalyses (Fig. 2b), which corresponded to large and prolonged negative surface haline fluxes in a large area of the Gulf of Lion. This condition resulted in a less favorable preconditioning for deep-water convection. Although the total amounts of winter heat fluxes were similar for the winters of 1998–1999 and 1999–2000 (Fig. 2c), their temporal distributions were different, which was important for generating favorable preconditioning and deep-water formation. In the winter of 1998–1999, a considerable amount of wind stress and thermahaline flux during the preconditioning phase (Fig. 2a and 2b) apparently produced a weaker stratification and favorable conditions for deep-water convection in the Gulf of Lion. In addition, very strong and prolonged Mistral events from January 26 to February 23, 1999 exerted a large forcing in the area with favorable preconditioning and then induced deep-water formation for a long period. In the winter of 1999–2000, however, the less favorable environment during the preconditioning phase, plus weaker surface forcing during the normally strong-mixing phase limited the dense water formation even though the total amount of winter heat flux was not small.

## 5. *Summary*

The time variation of atmospheric forcing is important in determining convective preconditioning and later in generating deep-water convection according to the study reported in this paper. COAMPS with NCOM as the oceanic component was used for numerical simulation of the Gulf of Lion region during the winters of 1998–1999 and 1999–2000. The mechanism of deep-water convection during these two winters was investigated. The results revealed possible reasons for the major discrepancy of deep-water convection between the two winters.

During the winter of 1998–1999, there were very strong and prolonged Mistral events. The strongest vertical mixing in the ocean occurred after the strongest atmospheric forcing event on February 11, 1999. The mixed-layer depth reached 1200 m over a broad area and was greater than 2200 m in a couple of small areas. The well-mixed vertical column of water had a temperature of 12.75°C and was preserved for 15–20 days by subsequent and prolonged Mistral events. The minimum mixed-layer temperature reached 12.6°C in one of the well-mixed vertical columns.

The total amount of surface thermal flux for the winter of 1999–2000 was comparable with that for the winter of 1998–1999. However, the temporal distribution of the surface thermal flux for both winters was different. In addition, there was significantly less accumulated haline flux for the winter of 1999–2000. This resulted in the deep-water convection in the winter of 1999–2000 being less significant than in the winter of 1998–1999. Strong stratification remained after preconditioning although the integrated thermal flux was larger in January 2000 than in January 1999. The resulting vertical mixing extended over a smaller area than in the previous winter, with a mixed-layer depth range of 400 to 1400 m. The maximum mixed-layer depth of 1400 m lasted for only a few days.

The results from both the COAMPS atmospheric reanalyses and the NCOM model simulation are comparable with the findings of BETHOUX *et al.* (2002). The COAMPS reanalyses of the high-frequency atmospheric forcing is capable of reproducing the strong (1999) and moderate (2000) Mistral events with a temporal variation similar to that observed. These similarities enabled us to use the model simulation to study the mechanisms that resulted in the difference in deep-water convection.

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