Numerical Studies of Deep Convection in the Northwestern Mediterranean Sea Using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS^{TM})

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Abstract - **Deep convection in the Northwestern Mediterranean Sea is studied using COAMPS^{TM} for winters 1989/1999 and 1999/2000. Hourly surface forcing from COAMPS^{TM} atmospheric reanalyses are applied to the Navy Coastal Ocean Model (NCOM). Numerical studies have investigated the ocean response to the stronger Mistral year (1998/1999) and weaker Mistral year (1999/2000). Large differences in deep convection between the two winters are also investigated by analyzing the depth and temperature of the mixed-layer, the surface height, and the current structure. Interaction between local deep convection and advected Levantine Intermediate Water (LIW) is also presented in the simulated results.**

1. INTRODUCTION

The northwestern Mediterranean Sea (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 (the Mistral) over preexisting 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 [1][2][3]. It depends on the seasonal development of the surface buoyancy flux with respect to preconditioning and lateral advection in the ocean. The convection does not always penetrate to full depth (2000-2500m), in some instances it only reaches 1000 m or less. The uncertainty of the atmospheric forcing and the ocean environmental conditions complicates the formation of deep convection and results in interannual variability of deep convection [4]. Deep convection was observed in 1969 [1], in 1970, in 1975 [5][6], and in 1987 [2][7]. It did not occur in 1972 [5][6] and occurred only partially, rarely penetrating deeper than 1200 m, in 1991/1992 [8][9].

To accurately represent the effect of variability of atmospheric forcing on the deep convection in the Gulf of Lion region, high spatial and temporal resolution is necessary, since the area of deep convection can be fairly small and the Mistral winds have fairly short spatial and temporal scales. Earlier model studies of deep convection showed that high spatial resolution and temporal frequency were necessary [10][11]. A simulation of water mass transformation in a high-resolution model of the Labrador Sea [10] captured many features of deep convection. The model was driven by twice-daily surface fluxes taken from National Meteorological Center (NMC) analyzed fields. A study conducted by Castellari et al. [11] showed the influence of the frequency (monthly versus 12-hourly) of the atmospheric forcing for the period 1980-1988 on the interannual variability of water mass formation processes in the Mediterranean Sea. Deep convection in the western Mediterranean was not formed in any of the years for either of the atmospheric forcing frequencies. Only after a salinity enhancement in the Gulf of Lion during the preconditioning (in January) and strong mixing (in February and March) phases, were they able in some years to model the deep convection in this area. In another study of the role of Levantine Intermediate Water (LIW) in deep convection, Wu and Haines [12] simulated deep convection below 1500m in the Balearic-Ligurian Basin with coarse horizontal resolution ($0.25^0 \times 0.25^0$). However, they needed to use a relaxation scheme with a relaxation timescale of 2 hours for temperature and of 5 days for salinity to nudge surface properties of the water masses toward modified climatological values. The modification was to set the surface properties in winter to those of the known deep convection.

In this study, the atmospheric component of the US Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS^{TM}) is used to construct high-resolution reanalyses of surface fluxes over the Mediterranean Sea using all available observations. The period of the reanalyses is from October 1998 to September 2000. The high-resolution reanalyses are used to force the Navy Coastal Ocean Model (NCOM), which has been incorporated into COAMPS^{TM}. The response of deep-water convection and formation to high-resolution atmospheric forcing in the Gulf of Lion is investigated for the winters of 1998/1999 and 1999/2000.

II. MODEL DESIGN

NCOM was developed by Martin [13] for coastal and mesoscale ocean simulation and prediction. NCOM is designed to offer the user a range of numerical choices in terms of parameterizations, numerical differencing, and vertical grid structure. NCOM is based on the hydrostatic primitive equations, and has prognostic variables for the ocean currents, temperature, salinity, and surface height. An implicit formulation is used for the barotropic component. The equations are solved on a staggered C grid. NCOM uses a hybrid vertical coordinate system with

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sigma layers near the surface and z-levels below a user-selectable depth. For these simulations, a third-order upwind scheme was used for advection and vertical mixing was computed with the Mellor-Yamada 2.0 scheme [14].

The COAMPS^{TM} atmospheric reanalysis was conducted on an 81-km resolution grid over Europe with a nested grid of 27-km resolution over the Mediterranean. The reanalysis uses a 12-h analysis/forecast cycle in which analyses are done every 12-h using all available observed data and the previous 12-h atmospheric forecast as a basis field. These analyses are then used to initialize the next forecast. Atmospheric fields output at 1-h intervals are used to force NCOM.

A flux coupler has been developed to couple the COAMPS^{TM} atmospheric and ocean models through fluxes of heat, momentum, and moisture across the air-water interface. The forcing includes solar radiation, precipitation, and surface atmospheric pressure.

The ocean model is run on a domain of 576 × 288 grid points with a horizontal resolution of about 6 km covering the entire Mediterranean. The vertical grid is logrithemically 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 and there is a switchover from sigma to z-level vertical coordinates at about 100-m depth. The model topography is obtained by a cubic spline interpolation from the DBDB1 database for the Mediterranean developed by the Naval Oceanographic Office. The bathymetry in the Northwest Mediterranean Sea in the area of the Rhone Deep Sea Fan, which is important to the preconditioning phase of the deep convection [15], is shown in Fig. 1.

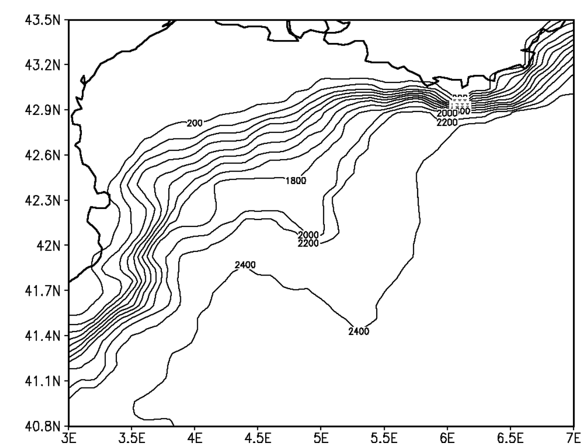

Fig. 1. Model bathymetry (m) for the Gulf of Lion area.

The surface heat flux for a 2-y run includes a relaxation to 12-hourly COAMPS^{TM} sea-surface temperature analyses with a rate of 4 md^{-1}. The surface salt flux includes a relaxation to monthly MODB [16] climatology with a rate of 0.1 md^{-1} to reduce the drift of the surface salinity.

The model is initialized from the annual mean MODB temperature and salinity climatology for the Mediterranean and then is then run for 10 years using monthly mean climatological wind stresses and heat fluxes [17] for the forcing. The period of spin-up is long enough to achieve a repeating seasonal cycle for the volume averaged kinetic energy (Fig. 2). Following this spin-up, the COAMPS^{TM} fluxes at hourly frequency are applied as surface boundary conditions for NCOM to continue the run for a 2-y period from October 1998 to September 2000. The investigation of the simulation over this 2-y period will be concentrated in the Northwest Mediterranean to study deep convection for the winters of 1998/1999 and 1999/2000.

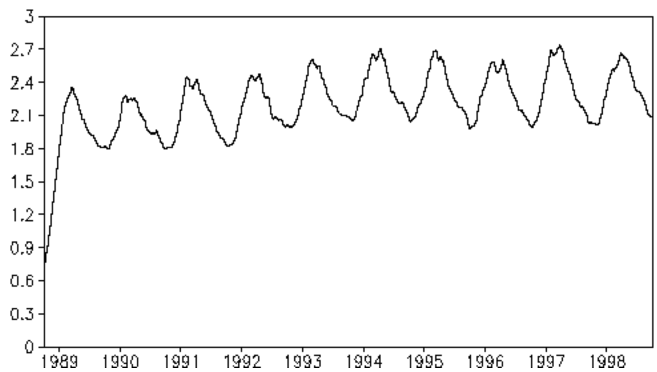

Fig. 2. Volume averaged kinetic energy (Jm^{-3}) from 10-year spin-up.

III. DISCUSSION

A. Air-Sea Fluxes for Winters of 1998/1999 and 1999/2000

Air-sea fluxes used in the model include wind stress, latent and sensible heat fluxes, long-wave radiation, solar radiation, precipitation and surface atmospheric pressure. Time series of time-integrated mean wind stress for each month over the Gulf of Lion area (41-43 ^{0}N and 3.5-7.0 ^{0}E) show the month of strongest wind stress forcing during the two-year period to be February 1999 (Fig. 3a). There are other significant differences between the two winters. The winter of 1998/1999 is characterized by moderate wind stress in the preconditioning months from October 1998 to January 1999. Of these months, the most Mistral events happen in December. There are relatively fewer Mistral events in January. The Mistral is reduced greatly in March after the strong forcing in February. However, there are still a few Mistral events during April 1999.

The wind stress in the winter of 1999/2000 is much different from the winter of 1998/1999. There are no significant Mistral events in October 1999, but a relatively large amount of wind stress is accumulated in November, compared to the amount in 1998 (Fig. 3b). For the months of December and January, wind stress is slightly less. There are substantial fewer Mistral events in February of 2000, which is usually the main time of 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 doesn’t appear very significant. The magnitude of the wind stress and buoyancy flux during this event are important for the deep convection as will be discussed in Section C.

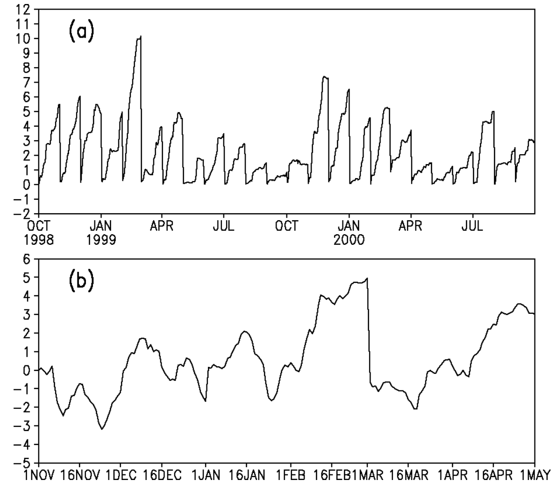

Fig. 3. (a) Area average of wind stress (Nm^{-2}) over the Gulf of Lion, time integrated over each month. (b) Difference of integrated wind stress between winters 1989/1999 and 1999/2000.

The surface buoyancy flux is the major source of the hydrostatic instability that induces deep convection in areas of weak static stability. The total buoyancy flux is calculated from the model output as the sum of the contributions from the thermal flux (Q_{Bh}) and the haline flux (Q_{Be}) [8] [17]:

$$Q_B=(g\alpha/c_w)Q_{hl}+g\beta S_{sl}(P-E)= Q_{Bh} + Q_{Be}$$

where Q_{hl} is the net heat flux at the ocean surface, including the sensible and latent heat fluxes, short wave radiation and long wave radiation, P is the precipitation, $E=Q_l/L_v$ is the evaporation calculated from latent heat flux Q_l, c_w is the specific heat of water, α is the thermal expansion coefficient of seawater, β is the corresponding coefficient for salinity, L_v is the latent heat of vaporization, and S_s is the sea surface salinity from the model output.

Area averages of the thermal and haline contributions to the surface buoyancy flux over the Gulf of Lion, time integrated over each month, are shown in Fig. 4a for the 2-y period from October 1998 to September 2000. The features for the buoyancy fluxes in Fig. 4a are similar to those for integrated wind stress in Fig 3a. The maximum monthly thermal and haline buoyancy fluxes occurred in February 1999, with comparable fluxes during the preconditioning phase from October 1998 to January 1999. The buoyancy fluxes decreased after February. The pattern for the difference of the total integrated buoyancy flux between the winters of 1998/1999 and 1999/2000 (Fig. 4b) is also similar to that for the integrated wind stress. There was more buoyancy flux for November 1999, but slightly less for December and January of 1999. The significant difference of the buoyancy flux for February was consistent with the difference in the wind stress, indicating stronger cold and dry Mistral events in February 1999. Over all , the contribution of the haline flux to the buoyancy flux is about 10% that of the heat flux. However, the haline flux plays an essential role in determining the stability as indicated in [8].

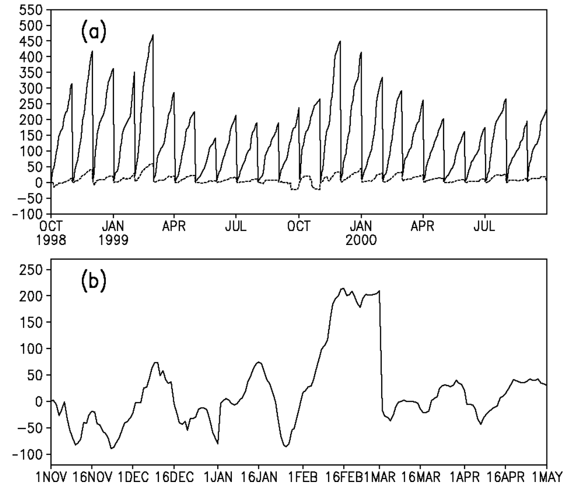

Fig.4 (a) area average of surface buoyancy thermal (solid line) and haline (dashed line) fluxes, time-integrated over each month. (b) difference of integrated total buoyancy fluxes between winters 1989/1999 and 1999/2000.

B. Winter of 1998/1999

1) The Preconditioning Phase

In the ocean simulation, cyclonic circulation dominated in the Gulf of Lion during the winter preconditioning phase for December 1999. The monthly mean surface current streamline is shown in Fig 5a. The center of the main cyclonic gyre was slightly east of its classic location at 42 ^{0}N and 5 ^{0}E [1]. However, in the future the location of the gyre needs to be further compared with observations (if available) for this particular period. The surface height shown in Fig. 5b indicates that the depression has a maximum of 28 cm in the center of the gyre. The diameter of the gyre is about 100 km. There is another cyclonic circulation in the south Balearic Sea. Low temperature (and high salinity and density, figures are not shown) extend in a strip with two centers cross the Gulf (Fig. 5c), corresponding to the cyclonic Lion gyre area. The stability of the surface layer and the reserve of buoyancy in the center of the gyre is reduced by the cold and dry Mistral wind prior to the violent mixing phase. The cyclonic Lion gyre uplifts the isopycnals in an elongated dome (Fig. 5d). In the center of the dome, the LIW salinity maximum is brought into depths shallow enough to be exposed to entrainment with the mixed layer [19]. 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 [20]. Slightly less dense water than the observed was presented for the LIW in the simulation. This is primarily due to lower salinity in the model simulation with an average of 38.35 psu (the observed was about 38.5-38.6 psu [3][12]). With the entrainment of proper LIW, the convection can deepen since it will increase density at the surface and thus decrease the stability.

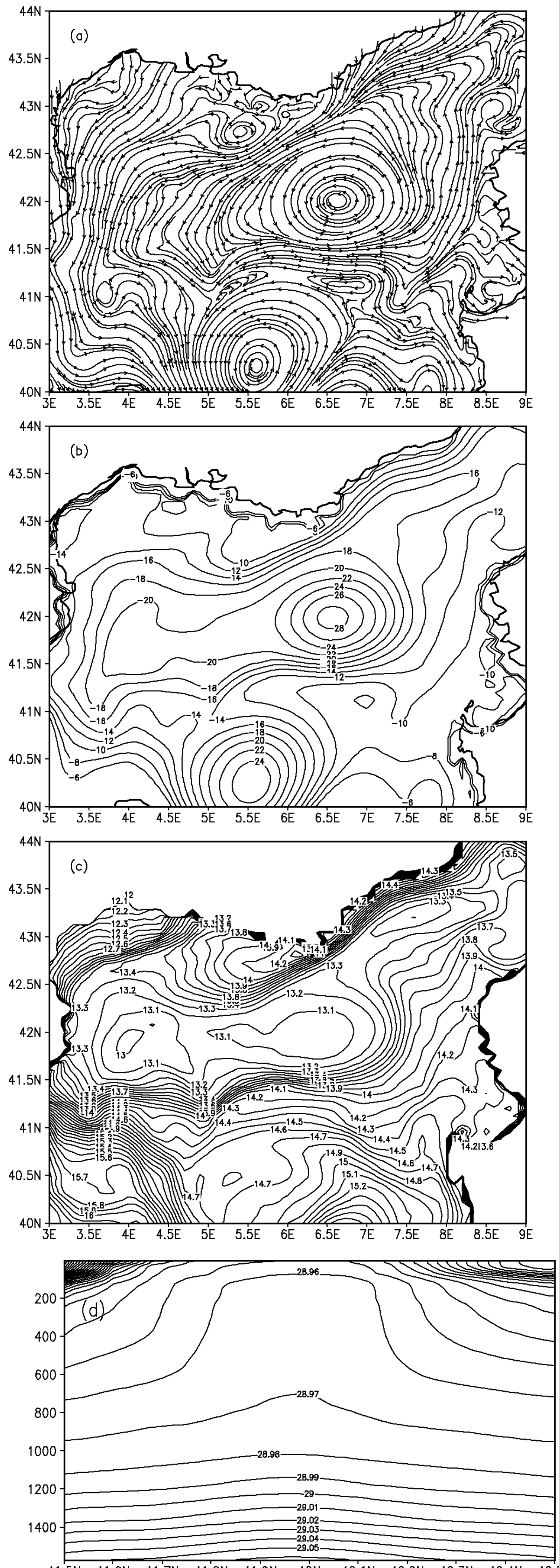

Fig. 5. Monthly mean (a) ocean current streamline, (b) surface elevation (cm), (c) surface potential temperature, (d) potential density along the center of the gyre at 6.5 ^{0}E for December 1998.

2) Deep Convection

The atmospheric reanalyses show that several Mistral events occurred during the winter of 1998/1999 as indicated by peak wind stresses and large buoyancy fluxes in Fig. 6, they were averaged in the area of 41-43 ^{0}N and 3.5-7.0 ^{0}E over the Gulf of Lion. There was a substantial strength Mistral event in early December 1998, resulting in the stability being greatly reduced and creating favorable conditions for deep convection. The Mistral events were much weaker and fewer in number in January. However, several subsequent Mistral events occurred in February. The strongest winter storm passing through the northwestern Mediterranean Sea for the winter of 1998/1999 was on 11 February 1999. This intense Mistral with a maximum wind stress over 1.8 Nm^{-2} induced a total buoyancy flux loss of over 9×10^{-4} $Nm^{-2}s^{-1}$ over the Gulf of Lion. Strong surface cooling and evaporation with highly favorable preconditioning trigger deep convection after the 11 February Mistral (Fig. 7a). A mixed-layer depth (defined by uniform properties in the water column) of over 800 m covered much of the area in the Gulf of Lion (Fig. 7c). The simulation generated four convective centers with eddy sizes under 100 km and with mixed-layer depth over 1200 m. The maximum mixed-layer depth was greater than 2000 m.

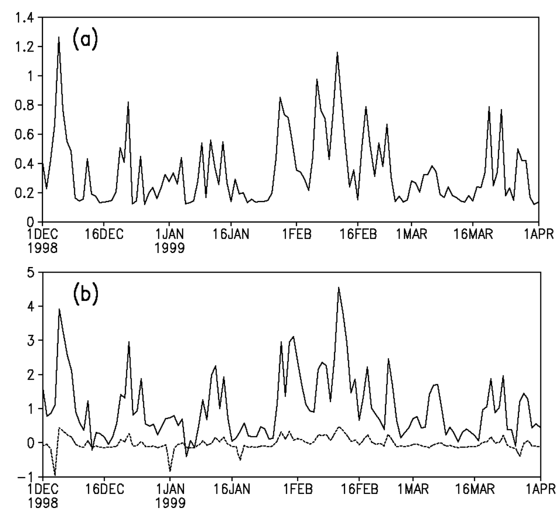

Fig. 6. Area average of (a) wind stress and (b) buoyancy thermal (solid line) and haline (dashed line) fluxes for winter 1998/1999. The area ranges from 41 to 43 ^{0}N and from 3.5 to 7 ^{0}E.

The hierarchy of convective processes and scales involved in the deep convection after the severe Mistral of 11 February is evident in Fig. 7b and Fig. 7c. Enhanced gradients and strong currents indicate vigorous baroclinic instability. The rim current that developed around the large convective patch in Fig. 7b was supported by baroclinic instability. As convective deepening proceeds, horizontal density gradients at the edge of the forcing region support a geostrophic rim current, which develops growing meanders through baroclinic instability. Eventually finite-amplitude baroclinic eddies sweep stratified water into the convective region at the surface and transport convected water outward and away below, setting up a steady state in which lateral buoyancy flux offsets buoyancy loss at the surface [21].

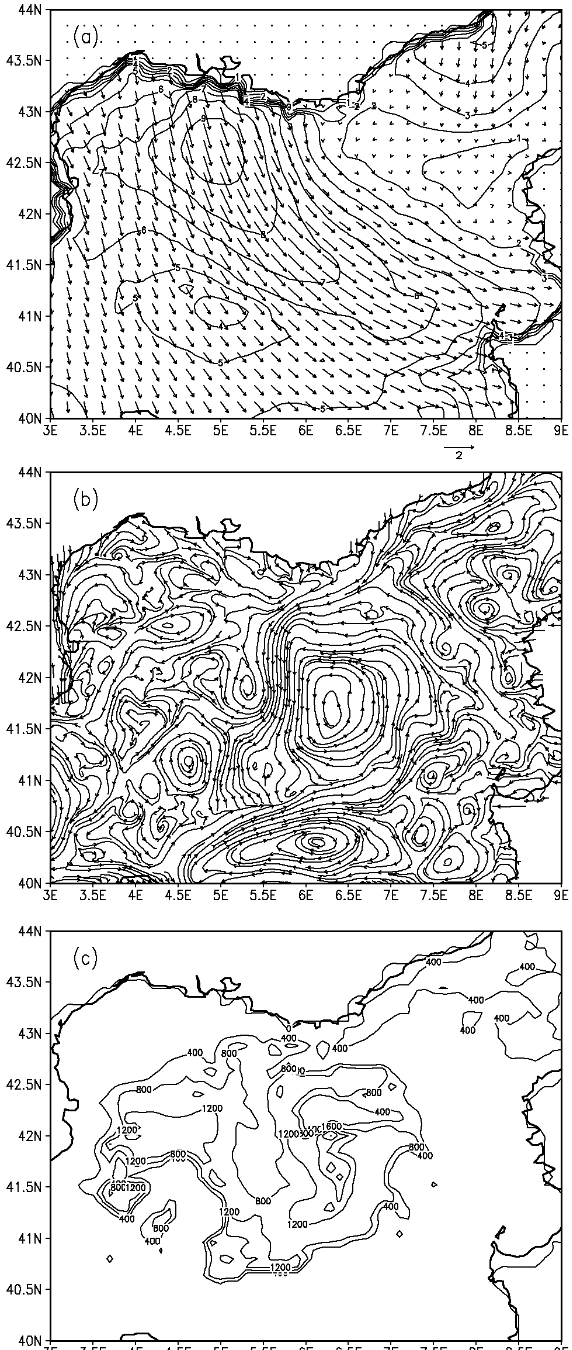

Fig. 7. (a) wind stress (vector) and buoyancy fluxes (contour) on 11 Feb, 1999. (b) current streamline on 16 Feb. 1999. (c) mixed-layer depth on 18 Feb. 1999.

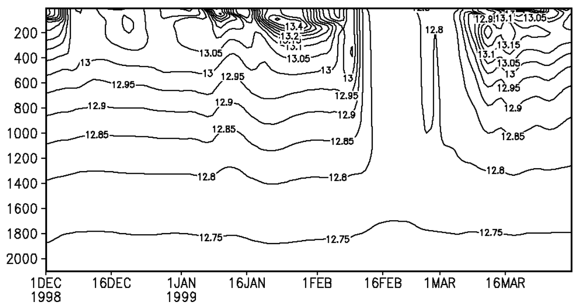

Fig. 8. Time series of potential temperature at point 41.8 ^{0}N and 6.2 ^{0}E for winter 1998/1999.

The time series of potential temperature at the center of convection in Fig. 8 shows vertical penetration of the cooling from the surface. The deepening of the mixed-layer consistently reflects the Mistral events. The strong Mistral in December eroded the surface stratification and mixed down to 500 m. Three weaker Mistral events followed in January and then the mixing was interrupted with a capping of warm surface water. After that, active Mistral events in February mixed the water down to 1800 m. The vertically well-mixed column of water was maintained until early March by subsequent Mistral events. This continued mixing is enhanced by LIW when the initial mixing brought up the subsurface LIW to the surface. Wu and Haines [12] indicated that without the entrainment of LIW the convection would not be so deep, even though the strong relaxation of surface temperature produced sufficient heat loss for the deep convection in their simulation. Deep convection could only occur when the large-scale circulation was correctly established. In Fig. 8, distinct LIW characterized by a warm temperature anomaly from surrounding had advected into the area in mid-March.

C. Winter of 1999/2000

1) The preconditioning Phase

As discussed in the previous section, for the winter of 1999/2000, more Mistral events occurred during November and December than February (Fig. 3 and Fig. 4). Although a larger buoyancy flux was lost during November and December, the induced density instability in the upper layer was not enough to overturn the thick warmer layer beneath during this period. More small-scale cyclonic circulations with diameters under 100 km occupied in the Gulf of Lion (Fig. 9a). The Lion gyre was not as well organized as in December 1998. The surface depression from the simulation has two centers with maxima of 28 and 24 cm, respectively, and with an elevation trough between them (Fig. 9b). The monthly mean fields of potential temperature indicated a warmer preconditioning phase for December 1999 (Fig. 9c), compared to that of December 1998 (Fig. 5c). Less baroclinic instability in the preconditioning phase resulted in a less favorable situation for deep convection. Doming of the isopycnals for December of 1999 (Fig. 9d) was not as significant as that for December of 1998 (Fig. 5d). Lower density existed in the upper layer for 1999 than for 1998.

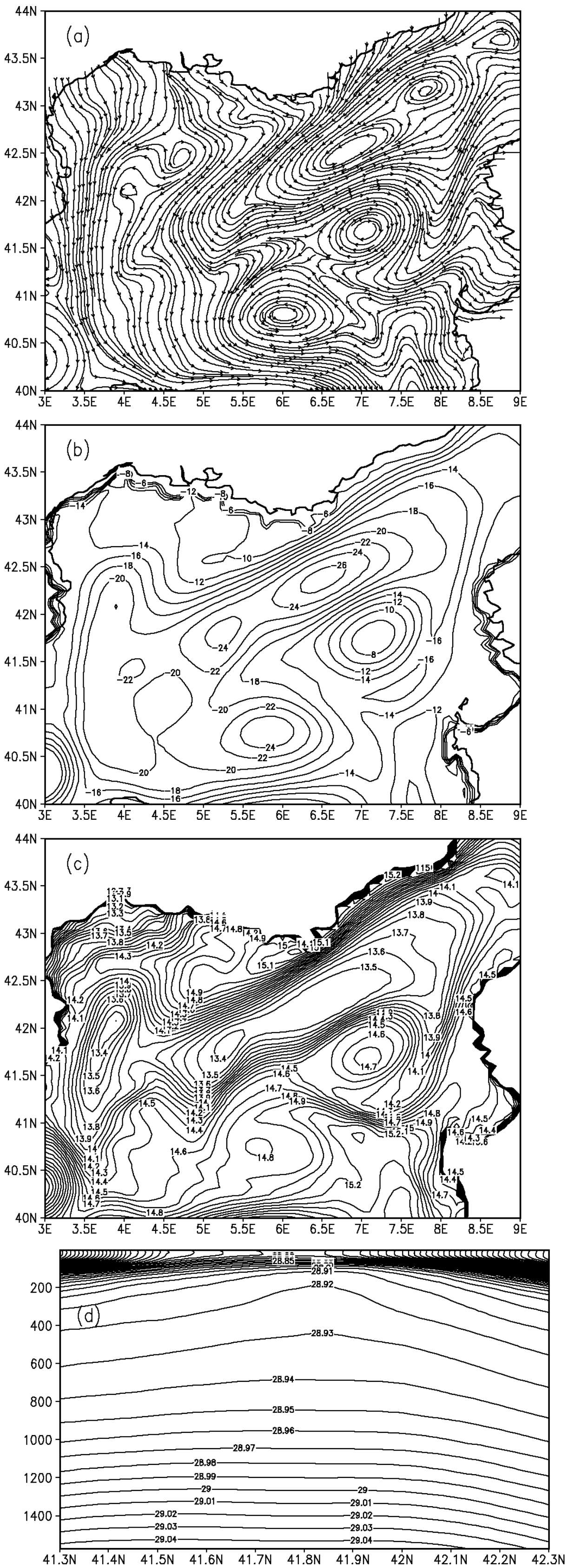

Fig. 9. Monthly mean (a) ocean current streamline, (b) surface elevation (cm), (c) surface potential temperature, (d) potential density along the center of Lion gyre (5.2 ^{0}E) for December 1999.

2) Deep Convection

Area averages of wind stress and buoyancy flux for the winter of 1999/2000 are shown in Fig. 10. A few relatively weak, short Mistral events occurred in December 1999. Higher frequency changes of wind stress and buoyancy flux for December in Fig. 10 denoted short periods of each Mistral events. With a calm period in early January, stronger Mistral events happened for the second half of January 2000. There were much weaker Mistrals in February 2000, than in February 1999, as shown in Fig. 3 and Fig. 4.

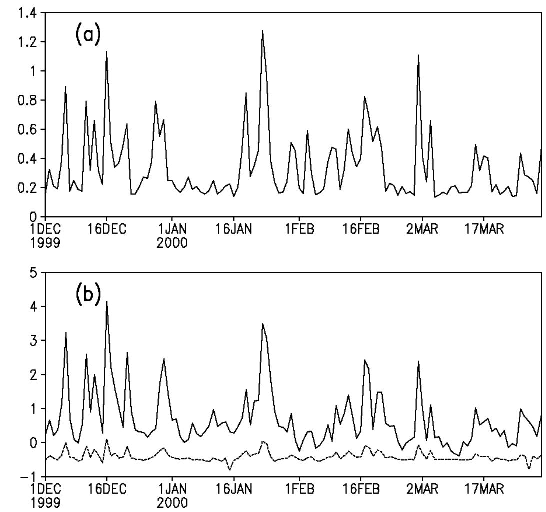

Fig. 10. Area average of (a) wind stress and (b) buoyancy thermal (solid line) and haline (dashed line) fluxes for winter of 1999/2000. The area ranges from 41 to 43 ^{0}N and from 3.5 to 7 ^{0}E.

The strongest Mistral for the winter of 1999/2000, which occurred on January 23, is shown in Fig. 11. The maximum wind stress was over 1.4 Nm^{-2} and the surface buoyancy flux was over 6×10^{-4} Nm^{-2} s^{-1}. The magnitudes for both wind stress and buoyancy flux were smaller than those from the strongest event in the winter of 1998/1999. Smaller cyclonic gyres than those in Feb. 1999 (Fig. 7) developed in the convective area. The mixing area, depth and period were also smaller for this winter. The mixed-layer depth of 800 m covered about half of the Gulf of Lion and extended toward the Ligurian Sea (Fig. 11c). There were two major convective centers, one in the Gulf of Lion and another one between the Gulf of Lion and Ligurian Sea. The second convective center had deeper mixed-layer depth with a maximum over 1400 m. It was about 22% shallower than the maximum in Fig. 7c. Overall, the deep convection was weaker for the winter of 1999/2000 than for the winter of 1998/1999.

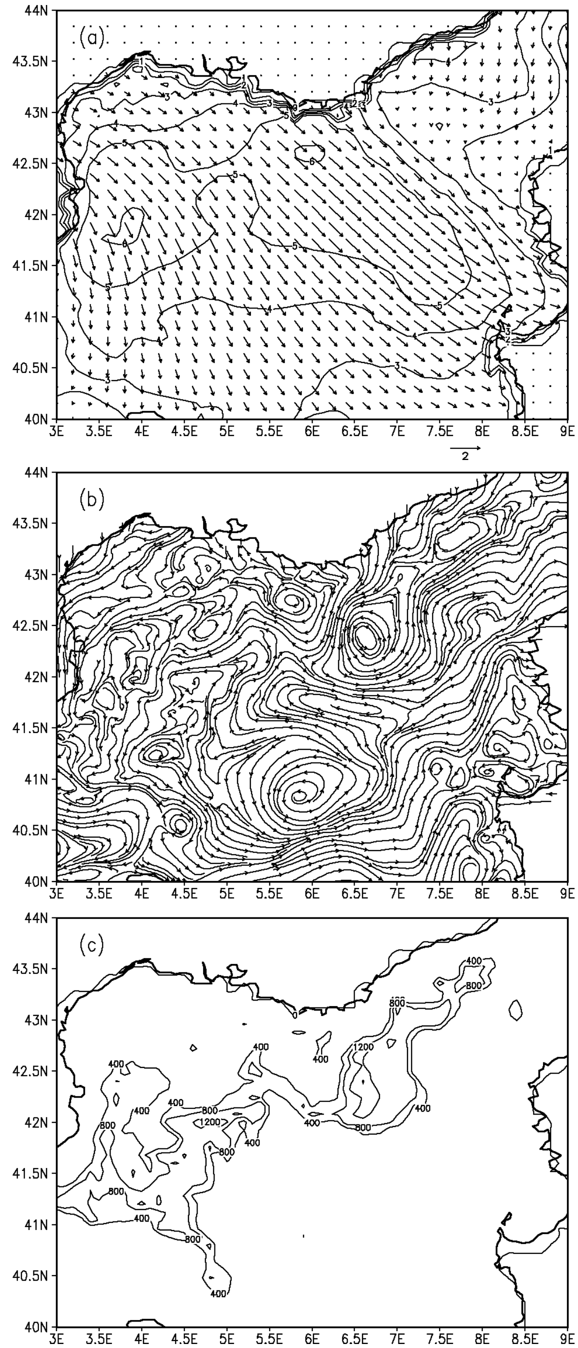

Fig. 11. (a) wind stress (vector) and buoyancy fluxes (contour) on 23 Jan. 2000. (b) current streamline on 28 Jan. 2000. (c) mixed-layer depth on 28 Jan. 2000.

A time series of potential temperature versus depth at 41.8 ^{0}N and 6.2 ^{0}E for the winter of 1999/2000 is shown in Fig. 12. It shows the deepening of the mixed-layer 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, the strongest Mistral occurred during this winter. Temperature decreased and salinity increased less significantly, resulting in shallower winter convection. The deepest mixing reached 1400 m after the strongest Mistral. The vertically well-mixed column of water was re-stratified in a few days. The LIW advected into the site in early March.

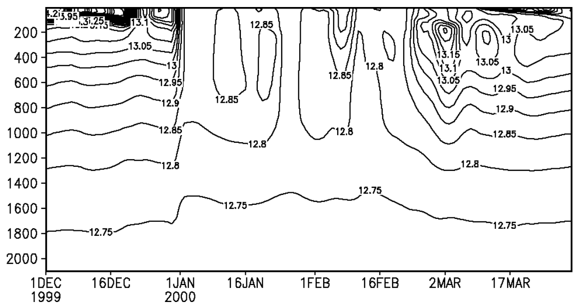

Fig. 12. Time series of potential temperature at point 42.5 ^{0}N and 6.7 ^{0}E for winter 1999/2000.

IV. SUMMARY

Model-simulated ocean deep-water convection forced by COAMPS^{TM} hourly high-resolution atmospheric reanalyses showed significant interannual variability for the winters of 1998/1999 and 1999/2000. The differences were related to variations in the strength of the surface forcing applied to the ocean with preconditioning providing favorable weak stratification for deep convection.

During the winter of 1998/1999, there were several Mistral events. However, the strongest vertical mixing occurred after the strongest forcing event on 11 February 1999. The mixed-layer depth reached 1400 m over a large area and was greater than 2000 m in a few small areas. The vertically well-mixed column of water had temperature of 12.75 ^{0}C and was preserved for more than 20 days by subsequent Mistral events.

During the winter of 1999/2000, there were relatively weaker Mistral events as compared to the winter of 1998/1999. The preconditioning showed strong stratification, which was less favorable for deep convection, although the integrated buoyancy flux was larger in January of 2000 than in January 1999. The resulting vertical mixing extended over a smaller area with a mixed-layer depth range of about 400-1400 m. The maximum mixed-layer depth of 1400 m lasted for only a few days. It was about 22% shallower than the winter of 1998/1999. Overall, the deep convection was weaker for the winter of 1999/2000 than for the winter of 1998/1999.

This study showed the importance of strong surface forcing, i.e., Mistral events and preconditioning, on generating deep winter convection. In order to simulate the deep-water convection over the northwestern Mediterranean Sea, we need to have accurate high-resolution atmospheric forcing and a skilful ocean model capable of generating favorable preconditioning with correct position for the cyclonic circulation in the Gulf of Lion. It is very important to notice that all the results were from numerical simulation without ocean data assimilation. Therefore, in the future we need to validate all the results with available observation to gain confidence on the model performance. In further study, we should perform ocean data assimilation to combine all available observed data with information from predictive model to give the best possible estimate or analysis of the ocean state at a given time.

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REFERENCES

[1] MEDOC GROUP, "Observation of formation of deep water in the Mediterranean Sea, 1969," *Nature*, Vol. 227, pp. 1037-1040, September 1970.

[2] K. Leaman, and F.A. Schott, "Hydrographic structure of the convection regime in the Gulf of Lions: winter 1987,"*J. Phys. Oceanogr.*, vol. 21, pp. 575-598, April 1991.

[3] F. Schott, M. Visbeck, U. Send, J. Fischer, L. Stramma, and Y. Desaubies, "Observations of deep convection in the Gulf of Lions, Northern Mediterranean, during the winter of 1991/1992," *J. Phys. Oceanogr.*, Vol. 26, pp. 505-524, April 1996.

[4] C, Mertens, and F. Schott, "Interannual variability of deep-water formation in the Northwestern Mediterranean," *J. Phys. Oceanogr.*, Vol. 28, pp. 1410-1424, 1998.

[5] J.-C. Gascard, "Vertical motions in a region of deep water formation," *Deep-Sea Res.*, Vol. 20, pp. 1011-1027, 1973.

[6] J.-C. Gascard, "Mediterranean deep water formation, baroclinic instability and oceanic eddies," *Oceanol. Acta*, Vol. 1, pp. 315-330, 1978.

[7] F. Schott, and K.D. Leaman, "Observation with moored acoustic Doppler current profiles in the convection regime in the Golf of Lion," *J. Phys. Oceanogr.*, Vol. 21, pp. 558-574, April 1991.

[8] F. Gaillard, Y. Desaubies, U. Send, and F. Schott, "A four-dimensional analysis of the thermal structure in the Gulf of Lion," *J. Geophys. Res.*, Vol. 102, pp.12515-12537, June 1997.

[9] F. Gaillard, J.-C. Gascard, and P. Klein, "A methodology for assessing the postconvection mesoscale dynamics in the Gulf of Lion from composite datasets," *J. Phys. Oceanogr.*, Vol. 30, pp. 3113-3133. December 2000.

[10] LabSea Group, "The Labrador Sea Deep Convection Experiment," *Bull. Am. Meteorol. Soc.,* Vol. 79, 2033-2058. 1998.

[11] S. Castellari, N. Pinardi, and K. Leaman, "Simulation of water mass formation processes in the Mediterranean Sea: influence of the time frequency of the atmospheric forcing," *J. Geophys. Res.,* Vol. 105, pp. 24157-24181, October 2000.

[12] P. Wu, and K. Haines, "Modeling the dispersal of Levantine Intermediate Water and its role in Mediterranean deep water formation," *J. Geophys. Res.*, Vol. 101, pp. 6591-6607, 1996.

[13] P. Martin, "Description of the Navy Coastal Ocean Model Version 1.0," Naval Research Laboratory, NRL/FR/7322—00-9962, pp. 1-42, December 2000.

[14] G.L. Mellor, and Yamada, "Development of a turbulence closure model for geophysical fluid problems," Geophys. And Space Phys., Vol. 20, pp. 851-875., 1982.

[15] N.G. Hogg, "The preconditioning phase of MEDOC 1969-II. Topographic effects," *Deep-Sea Res.*, Vol. 20, pp. 449-459, 1973.

[16] P. Brasseur, J.M. Beckers, J.M. Brankart, and R. Schoenauen, "Temperature and salinity fields in the Mediterranean Sea: Climatological analyses of an historical data set," *Deep-Sea Res.*, Vol. 43, pp. 159-192, 1996.

[17] P.W. May, "A brief explanation of Mediterranean heat and momentum flux calculations, *NORDA Rep. 322*, Naval Oceanogr. And Atmos. Res. Lab., Stennis Space Center, Miss., 1986.

[18] S. Sathiyamoorthy and G.W.K. Moore, "Buoyancy flux at ocean weather station Bravo." *J. Phys. Oceanogr.*, Vol. 32, pp. 458-474, 2002.

[19] B.B. Nardelli and E. Salusti, "On dense water formation criteria and their application to the Mediterranean Sea." *Deep-Sea Re.*, Vol. 47, pp. 193-221, 2000.

[20] J.C. Swallow, and G.F. Caston, "The preconditioning phase of MEDOC 1969-I. Observations," *Deep-Sea Re.,* Vol. 20, pp. 429-448, 1972.

[21] M. Visbeck, J. Marshall, and H. Jones, "Dynamics of Isolated convective regions in the ocean." *J. Phys. Oceanogr.*, Vol. 26, pp. 1721-1734, 1996.