Numerical Simulation of Strong Wind Situations near the French Mediterranean Coast: Comparison with FETCH Data

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ABSTRACT

A detailed analysis is made of some typical strong wind situations near the French Mediterranean coast. Special attention has been paid to the wind from the north-northwest in the Gulf of Lion, also called the mistral. The analysis is made from both the synoptic and mesoscale point of view with the aid of numerical simulations carried out with the Regional Atmospheric Modeling System (RAMS) to study the main atmospheric, climatic, and meteorological characteristics of this wind in the Gulf of Lion. Simulations were made with this model during the periods of 20–22 March and 24–26 March 1998. Afterward, a comparison was made with the meteorological measurements collected during the international Flux, Etat de la Mer et Télédétection en Condition de Fetch Variable (FETCH) campaign (Gulf of Lion, March–April 1998). The comparison between the simulated wind fields and the values measured by the coastal meteorological stations, an oceanographic buoy, and the ship *Atalante* at sea help to give full understanding of the complicated physical processes that characterize strong wind situations in coastal zones.

1. Introduction

This research work was initiated to study the atmospheric transport of polluting agents along the coast, especially by designing models of air–sea–land exchanges. In fact, the generation of aerosols, and, thus, the origin of the possible polluting particles, can be schematically classified into two categories: direct emission at the boundaries of the atmospheric reservoir, mainly due to the mechanical effect of the wind on the sea surface (Resch and Afeti 1991; Afeti and Resch 1992), and indirect formation by gas–particle conversion, mainly due to the combined effect of relative humidity and solar radiation. Therefore, the aerosols can play a determining role in the coastal environment, leading to a continual exchange of matter between oceans and continents through the atmosphere (Resch 1982).

Various studies have shown that in zones particularly exposed to marine aerosols, the vegetation of the coastal regions has undergone conspicuous modifications and exhibits some characteristic signs of deterioration. In particular, in the San Rossore Park in Italy on the shores of the Tyrrhenian Sea the trees show symptoms of disease starting from around 1960. Gellini et al. (1983) point out that the bark of trees exposed to sea winds are the first to show signs of degradation. They pointed out the influence of the force and direction of the wind on the damage observed. Near the regions that are hit by this degradation, very often there are industrial and domestic water-discharge zones that transport polluting agents of a more or less toxic nature into the sea. The Morto River that flows through the San Rossore Park receives the waste waters of the city of Pisa and the surrounding districts in this way. After reaching the Tyrrhenian Sea, the polluting agents migrate to the north along the coastal zone. It is clear in this case that it is the polluted marine aerosols that damage the vegetation.

Along the French Mediterranean coast, particularly in the region of Marseilles and the Var coast, significant damage to the vegetation has occurred. Toward the end of the 1970s, a survey was conducted on the progression of the damage of the vegetation on the island of Port-Cros (Cheret and Bourrely 1985), where the vegetal growth exposed directly to the sea water has been particularly affected.

Based on just these few examples, the importance of the study of aerosol movement can be appreciated, especially in coastal zones and in regard to the importance of the interaction between air and the sea. In particular, the mistral influences the air–sea interactions in the

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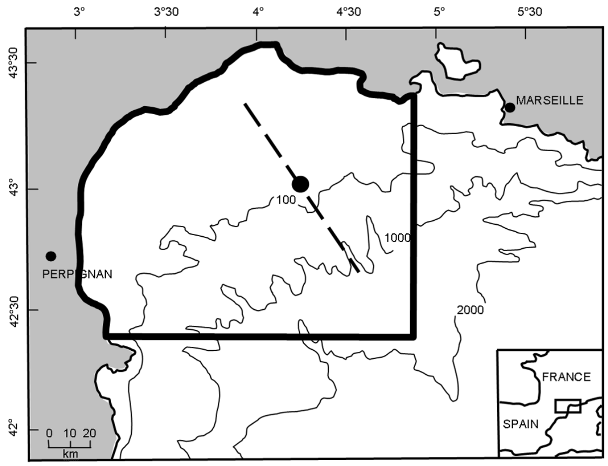


FIG. 1. Map for the FETCH campaign: the large black circle represents the position of the ASIS buoy, and the dashed line is the possible operational radius of the ship *Atalante*.

French Mediterranean coastal zone. The mistral is a north-northwest wind that originates in the polar cold front, coming from the Atlantic Ocean toward the Mediterranean Sea, which generates cumulus or cumulonimbus clouds and their associated storms. The front shifts in direction from the northwest to the southeast, and the wind veers to the right from the east-southeast to the north-northwest after the front crosses the coastal line. The wind blows continuously from inland to the sea, and, when the cold air meets the warm sea, it produces very unstable atmospheric conditions (Scorer 1997).

The characteristics of the sea state are influenced by these strong coastal winds. It is generally accepted that the significant wave height H_S is proportional to a power of U between 1 and 2 (Komen et al. 1996), where U is the surface wind velocity. Moreover, although an error of 10% in the evaluation of U may be acceptable to a majority of meteorologists, an error of 10%–20% for H_S, and consequently of 20%–50% for the energy of the waves, cannot be accepted by oceanographers.

For all of the above-cited reasons (sea state, ocean circulation, aerosol production, etc.) the main purpose of this present work is, therefore, to propose as precise a simulation as possible for the surface atmospheric structure in situations of strong coastal winds using the Colorado State University Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992). This model is especially suitable for coastal zones with complex topography (Cotton et al. 1994; Planchon and Cautenet 1997).

Wind fields in mistral conditions in the Gulf of Lion are presented and compared with those obtained by meteorological measurements collected during the international Flux, Etat de la Mer et Télédétection en Condition de Fetch Variable (FETCH) campaign (Hauser et al. 2000). The comparison between the simulated wind fields and the values measured by coastal and sea stations will help to fully understand the complicated physical processes that characterize the strong coastal wind situations. The final stage of this work is a study and analysis of the wind fields for atmospheric phenomena characterized by high instability with the wind coming mainly from land.

Indeed, the results of the model simulations will show that it is possible to obtain a realistic representation of the wind direction, at least when the mistral is fully developed; on the other hand, the calculated wind speed values are underestimated when compared with the measured values, especially on land and in the immediate neighborhood of the coast. These results confirm the studies of other authors who have simulated the strong wind events with mesoscale models (Reason and Steyn 1992; Cavaleri and Bertotti 1997; Guan et al. 1998; Colle and Mass 1998a,b; Jackson et al. 1999; Doyle et al. 2000; Reason and Jackson 2002).

2. FETCH campaign and characteristics of the studied zone

The FETCH campaign took place from 12 March to 16 April 1998 in the Gulf of Lion (see Fig. 1). The aims of the FETCH experiment (Hauser et al. 2000) were focused on the following: examination of physics of ocean–atmosphere interactions, aerosol cycles in coastal zones, coastal hydrodynamics, and use of observations based on remote sensing.

The experiment entailed a combination of measurements obtained by remote sensing and in situ measurements carried out from different platforms. In situations of wind coming from the land (limited fetch), the ship *Atalante* obtained headwind measurements over a radius of approximately 100 miles. Along these radii, stops were made at different points to obtain measurements in the atmosphere, in the ocean, and on the surface. Simultaneously, aircraft were requested to fly at various levels in which the flight axis was aligned with the direction of the wind. High-altitude routes (from 2500 to 6000 m) made it possible to collect observations by remote sensing (radar, lidar), whereas at low altitudes (from 100 to 300 m) the atmospheric boundary layer parameters were measured directly.

Beside the episodes of wind coming from the land, the FETCH experiment had to coordinate, in time and space, the in situ and aerial measurements with the observations of the second *European Remote Sensing Satellite* (*ERS2*) and Ocean Topography Experiment (TOPEX) satellites, data that can serve to determine the surface wind and the characteristics of the waves. Each time one of the satellites passed over the zone, the aircraft, the ship, and the buoys made simultaneous observations.

The French Mediterranean coast between the Spanish and Italian frontiers is characterized by a quite complicated topography. To allow for a good comparison between the simulated and measured values of direction and intensity of the wind, it was, thus, decided to use

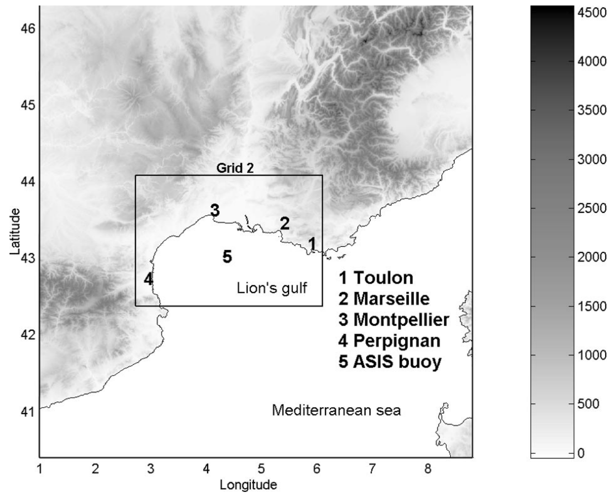


FIG. 2. Topography of the zone under study and the location of the meteorological stations used for comparison with the simulations.

the main stations located along the coast of the Gulf of Lion, the ship *Atalante*, and the Air–Sea Interaction System (ASIS) buoy (see Figs. 1 and 2). It can be seen that the meteorological station at Toulon represents the east sector of the Gulf of Lion, whereas the station at Marseille describes well the central-eastern zone. The central-western sector is monitored by the meteorological station at Montpellier, whereas the western zone of the Gulf of Lion is represented by the Perpignan measuring station. The ship *Atalante* and the ASIS buoy were found to be fundamental to the study of the meteorological conditions at sea.

According to Hauser et al. (2000), the balance of the observations shows that, at the beginning of the campaign (March), three mistral events were studied and documented, two of them in detail. After a period of 10 days with a weak wind coming from the southeast at the end of the campaign, many situations were observed with a gusty wind coming from the northwest associated with cold fronts. This wind is named ''tramontane.'' Two cases were selected (see Fig. 3) for detailed study (Lefèvre and Dandin 1998; Pezzoli 2001) from the 30 days of data from the FETCH campaign:

- case study 1: 20–22 March 1998 (winds from the north to the north-northwest on the Gulf of Lion and winds from the southeast at Toulon, starting from 21 March 1998), and
- case study 2: 24–26 March 1998 (winds from the north to the north-northwest with rotation to the southeast at Toulon only on 24 March 1998 at 1200 UTC).

It was decided to make the simulations with RAMS for these two meteorological situations.

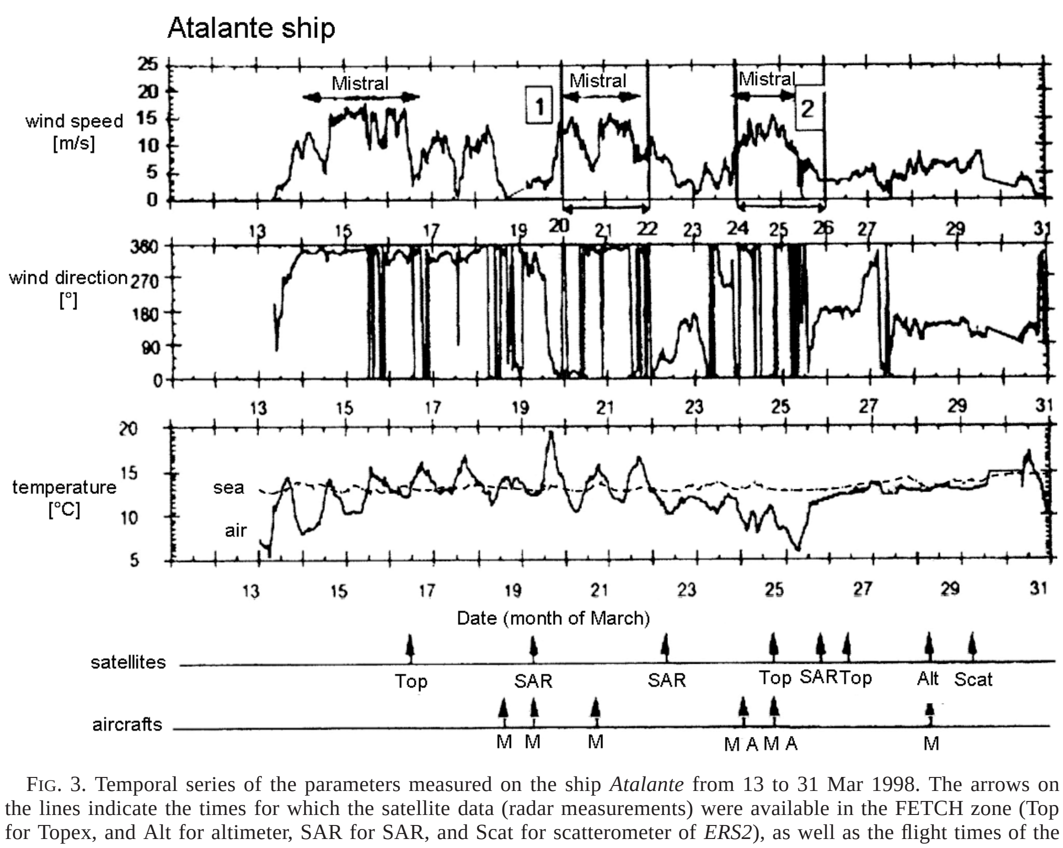


FIG. 3. Temporal series of the parameters measured on the ship *Atalante* from 13 to 31 Mar 1998. The arrows on the lines indicate the times for which the satellite data (radar measurements) were available in the FETCH zone (Top for Topex, and Alt for altimeter, SAR for SAR, and Scat for scatterometer of *ERS2*), as well as the flight times of the aircraft (M for Merlin, A for Arat, F for Falcon; after Hauser et al. 2000). The numbers 1 and 2 are used to specify, respectively, case study 1 (20–22 Mar 1998) and case study 2 (24–26 Mar 1998).

3. Model description and simulation conditions

A meteorological model must be used that responds to different criteria in order to study the state of the upper and lower atmosphere in cases of strong winds coming from land. In our study, the choice of this model was based on the fact that it was intended to model the mistral situations in the Gulf of Lion. In effect Pezzoli (1998) verified that

- the mistral is a meteorological phenomenon coming from the Atlantic Ocean, and as a consequence the mesoscale meteorological model must have the capability of ‘‘nudging’’ to take into account meteorological conditions outside the calculation grid (for this study the nudging was performed for the complete model domain);
- the mistral, being associated with a strong atmospheric instability, implies that the meteorological model must be mesoscale and nonhydrostatic, and must allow for the study of convective phenomena; and
- according to the case, the breeze effect (land or sea) can slow down or accentuate the mistral (consequently the meteorological model must be nonhydrostatic and mesoscale with a high-resolution grid).

As described by Pielke et al. (1992), RAMS is a versatile mesoscale model that has been used in a wide range of atmospheric applications. In particular, Cautenet (1988) has analyzed the interaction between the sea breeze and synoptic wind in the Gulf of Guinea; Cotton et al. (1994) have studied the surface wind fields in zones with complex topography; Sutton (1994) has analyzed the interaction between the sea breeze and synoptic wind in the Gulf of Auckland, which is also characterized by complex topography; Planchon and Cautenet (1997) have studied the case of a sea breeze along the southwest coast of France; and Edy (1997) designed a mesoscale model for the redistribution of chemical species in a tropical zone. Also, the Sahara dust, present in the Mediterranean, has been studied with RAMS (Cautenet et al. 2000).

In addition, Pastor et al. (1999) have analyzed with RAMS the role of the marine temperature variation in the formation of heavy rain in coastal zones (the region of Valencia, Spain). McQueen et al. (1999) have studied the wind fields and sea surface currents in the Chesapeake Bay with a grid resolution of 4 km. In this case, RAMS was compared with other atmospheric models: local effects were evaluated (sea breeze) using this model (wind fields, visibility, rain) and RAMS gave satisfactory results. Reason et al. (2000) have examined the dynamic influence of large valleys on the distribution of atmospheric flows in coastal zones. Reason and Jackson (2002) have also studied a coastal ridging event with strong wind over southeastern Australia.

We made a very detailed analysis of the various parameters in order to get a correct simulation of the different meteorological events from the point of view of atmospheric dynamics. In this study the simulations with RAMS were made under conditions of variable initialization and nudging every 6 h, including nonhydrostatic effects. The results of the simulations for the two different chosen events (20–22 and 24–26 March 1998) were compared with the data from the Météo-France measurement network, the measurements taken on the ASIS buoy, and the measurements of the ship *Atalante.* After studying the different results, the most suitable parameters were chosen for the simulations referred to in section 4 (see Table 1).

TABLE 1. Parameter values for initializing RAMS.

Constant data
Number of grid points for the studied zone (lon × lat) × vertical levels
Grid 1: 32 × 32 × 24, centered on (43°N, 5°E)
Grid 2: 62 × 38 × 24, centered on (43.27°N, 4.38°E)
Grid 1: DX = DY = 20 000 m
Grid 2: DX = DY = 5000 m
Increasing vertical steps, 12 levels from 0 to 1000 m, peak at 11 000 m
Time steps: 20 s
Topography: NOAA (30″ avg over 5 or 20 km)
Type of soil: sandy–clay–loam
Type of vegetation: crop/mixed farming
Soil level: 6, down to 0.21 m
Soil humidity profile: vertically variable with a value included between 0.3 and 0.2 (0.0 = dry soil, 1.0 = saturated soil)
Soil roughness: 0.1-m constant over land, computed from wind speed over water
Variable data
Analysis data of ECMWF
Sea surface temperature (OISST model)

The topographic grid was selected with a mesh of 5 km × 5 km for the second grid nested within a first grid of 20 km × 20 km (see Fig. 2). The topographic model used is the National Oceanic and Atmospheric Administration (NOAA) 30″ model averaged over 5 or 20 km, corresponding to the different grids.

RAMS is very sensitive to the sea temperature values (Pastor et al. 1999) to which special attention must be paid, particularly in cases of interaction between a coastal breeze and synoptic flow (Pielke 1981). In our case, the mistral tends to attenuate these local atmospheric circulations because it is usually stronger than the sea breeze as confirmed by numerical simulations carried out in section 4. Although, from an examination of the sea temperatures measured by satellite in the area of study (Slutz et al. 1985; Woodruff et al. 1993; Reynolds and Smith 1994) for the months of March for 4 yr in the period of 1990–96, it was observed that the mean sea surface temperature gradient is equal to 1.0°C, we chose to use a variable temperature for the sea in order to have the results of the simulations as realistic as possible. We used the optimum interpolation sea surface temperature analysis (OISST) model to determine the sea surface temperature during the month of March 1998.

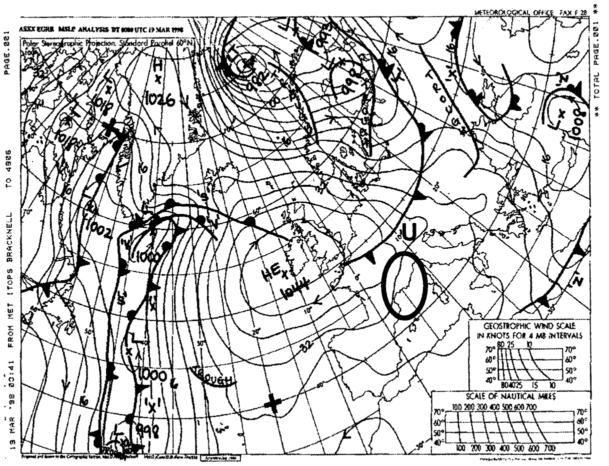


FIG. 4. Met Office synoptic surface analysis for 0000 UTC 19 Mar 1998. The study area is highlighted with a black oval.

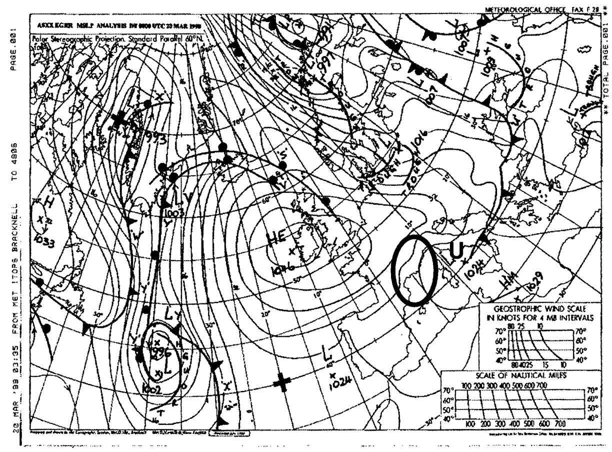


FIG. 5. Met Office synoptic surface analysis for 0000 UTC 20 Mar 1998. The study area is highlighted with a black oval.

Based on the geomorphological and pedological studies of the region carried out by Duclos (1994), it was decided to select a ''crop/mixed farming'' type of vegetation and a sandy–clay–loam type of soil. Both are taken as constant in the zone under study. The roughness length over land, generated by the model using the crop/mixed-farming option, is equal to 0.06 m. Nevertheless, in the area of study, we have a large percentage of the zone that is covered with shrubs and trees. For this reason we have chosen to select the roughness length over land larger at 0.1 m. The roughness length over water is computed from wind speed.

The determination of the ''soil model'' parameters must be precise (level of soil depth, initial humidity profiles, and temperature of soil). Six levels were considered, starting from ground surface down to a depth of approximately 0.2 m. The initial soil moisture was chosen to be vertically variable. For the temperature profiles, reference was made to the thermal variation cycle (Musy and Soutter 1991); the daily and yearly cycles were combined to obtain the initial thermal profile of the soil.

We used the synoptic analysis of pressure data [supplied by the European Centre for Medium-Range Weather Forecasts (ECMWF) during the FETCH campaign] for the variable initialization and for the Newtonian nudging every 6 h. The RAMS outputs were recorded every hour.

4. Results of numerical simulations

The aim of the study is to analyze the variation of the mistral in time and space and to compare the calculated values with the measurements. For this reason, we chose to present only the wind fields at 10 m. For the two simulations, the validity of the results were checked, calculating for each measuring point the mean absolute error (MAE) for the speed and the direction of the wind at 10 m (Wilks 1995),

$$\mathrm{MAE} = \frac{1}{n}\sum_{k=1}^{n} |y_k - o_k|, \tag{1}$$

where y_k represents the calculated k values and o_k are the measured k values.

Note that a vertical scale from $-90°$ to $270°$ was chosen for presenting the wind direction (see Figs. 8–13 and 18–23) to be able to better represent the results for winds in the northwest and northeast sectors.

a. Case study 1: 20–22 March 1998

The case studied—north-northwest wind—in this section was characterized by a rapid passage of a cold front coming from the North Sea that was located over central Europe (0000 UTC on 19 March 1998), generating a flow from the north. The front, denoted by the letter U (see Fig. 4), moved during the subsequent 24 h (see Fig. 5) over central Italy following a north to south direction. The formation of a trough at high altitudes and a depression at sea surface level, initially located on the Ligurian Gulf, created a strong wind flow from the north-northwest over the Gulf of Lion and a cyclonic circulation on the east side of the French Mediterranean coast. The low pressure located in the Ligurian Gulf moved subsequently toward the south.

The analysis made with RAMS helps us to understand the correct phenomenology of this type of atmospheric event. Referring to Figs. 6a–d, representing the wind fields at 10 m for grid 1 (20 km) for 20 and 21 March 1998 at 0600 and 1500 UTC, it can be seen how the passage of the cold front over northern Italy corresponds to a rapid formation of strong winds from the north on the Gulf of Lion and a depression vortex having its center in the northwest of Corsica.

In this first initial phase, the zone surrounding Toulon (see Fig. 2) was characterized by a wind coming from the east that afterward rotated to the northern quadrants (northwest–north-northwest), remaining very unstable

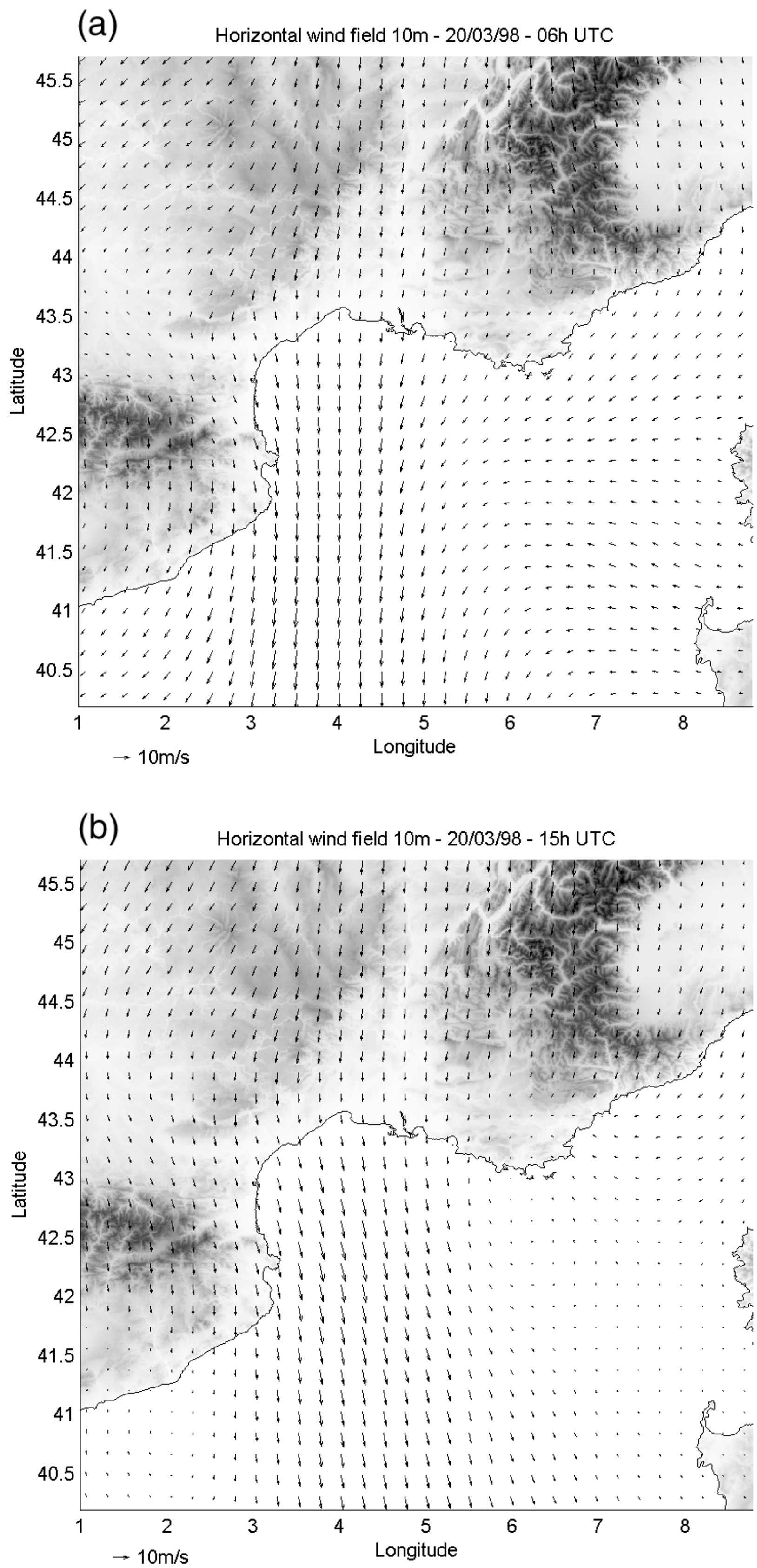


FIG. 6. Wind field at 10 m for grid 1 (20 km) for the case study at (a) 0600 and (b) 1500 UTC 20 Mar and (c) 0600 and (d) 1500 UTC 21 Mar 1998.

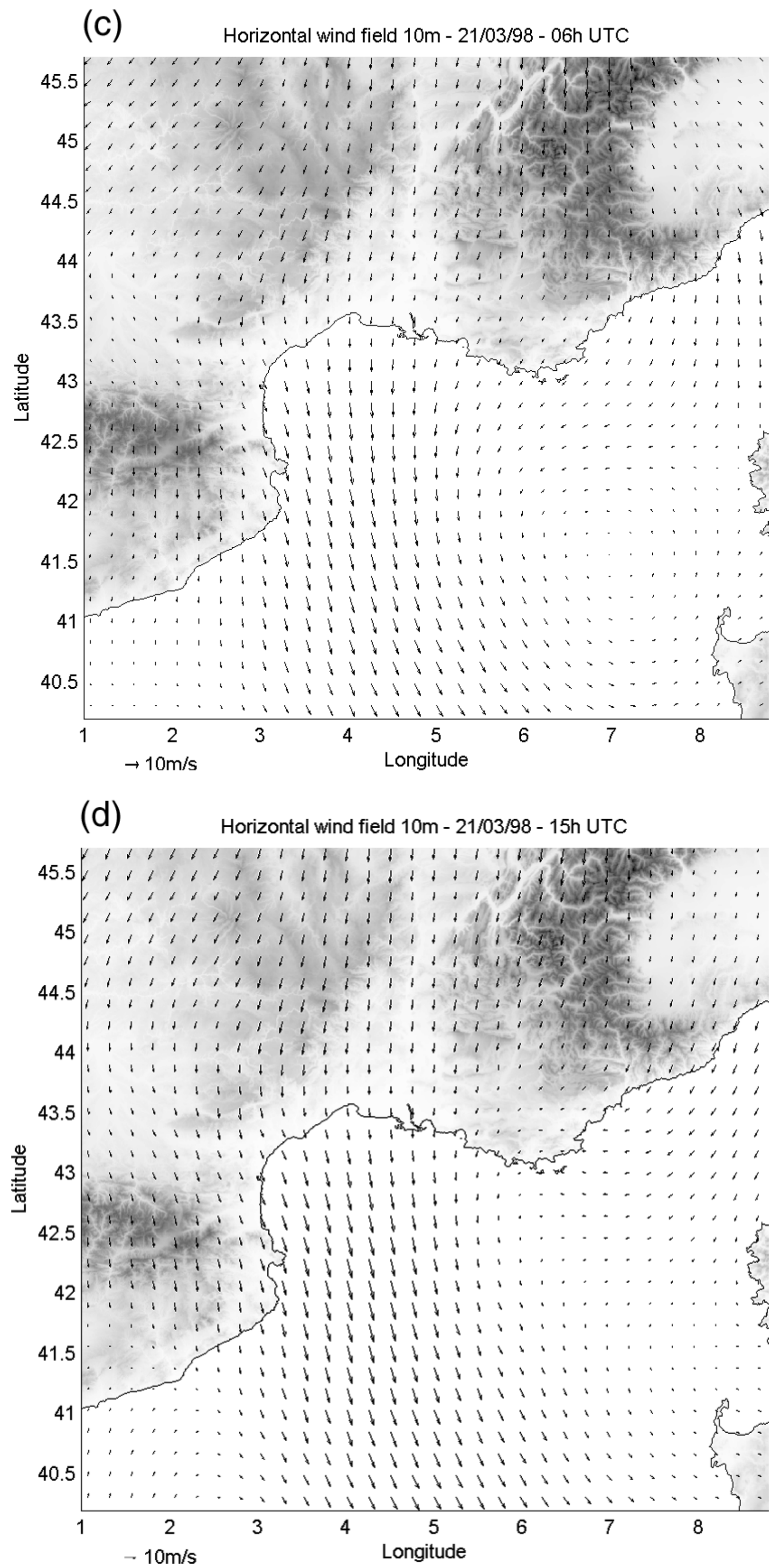


FIG. 6. (*Continued*)

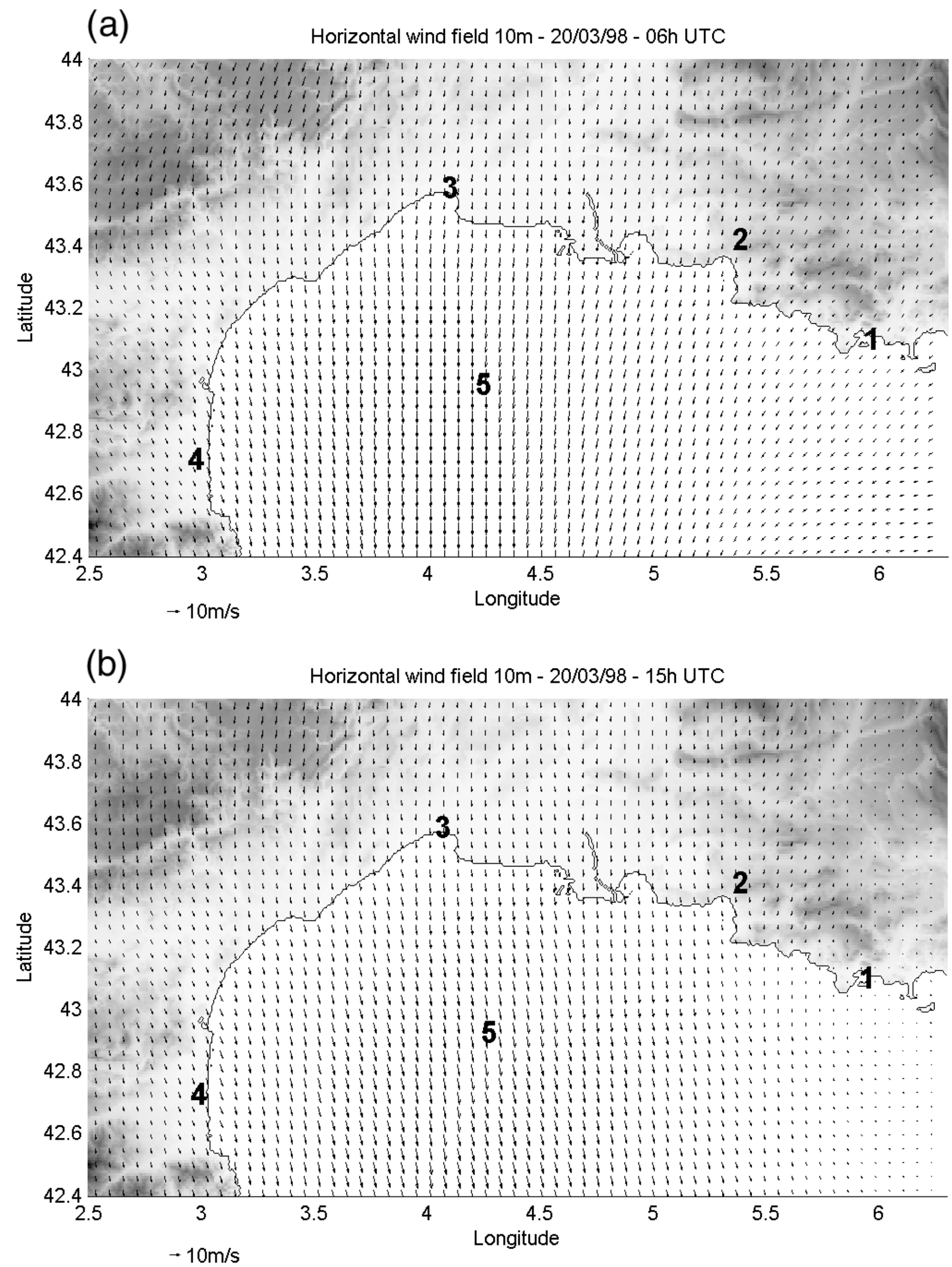


FIG. 7. Wind field at 10 m for grid 2 (5 km) for the case study of (a) 0600 and (b) 1500 UTC 20 Mar and (c) 0600 and (d) 1500 UTC 21 Mar 1998 at 1: Toulon, 2: Marseille, 3: Montpellier, 4: Perpignan, and 5: ASIS buoy.

and fluctuating for at least the first 30–36 h (see Figs. 7a–d). Toulon's zone is a critical geographical area because it plays the role of a "frontier" between the Gulf of Lion and the "French Riviera–Gulf of Genoa" area. In fact the atmospheric model shows major discrepancies with MAE for wind speed of 1.69 m s^{-1} and an MAE for direction of 93.6° (see Fig. 8). This is the only case where the MAE for the wind speed can be considered quite acceptable, in contradiction to the MAE of the wind direction. However, it should be kept in mind that the measurement at the meteorological station is made at a point, whereas with RAMS the mean wind is estimated over an area of approximately 25 km^2. Nevertheless, the results of the numerical simulations follow with a certain fidelity the general "trend" in the direction and the speed of the wind. These results are in agreement with those obtained by McQueen et al. (1995).

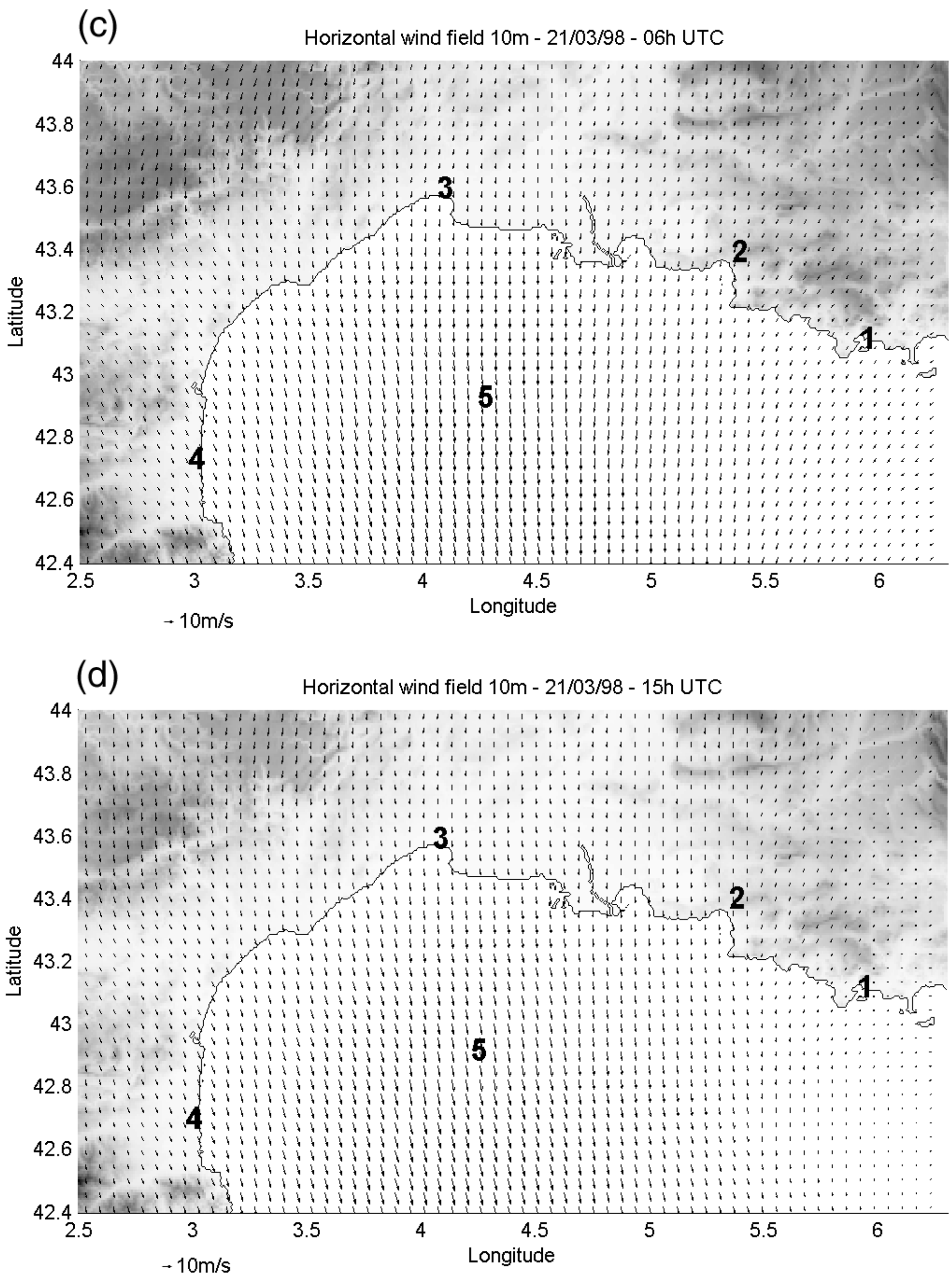


FIG. 7. (*Continued*)

With the use of nested grids it is possible to have a realistic representation of the wind fields in the area between the high and the low pressure zones. Besides, as already indicated, the final goal of this work is to study and analyze wind fields for atmospheric phenomena characterized by high instability and with the wind coming mainly from inland. For this reason it becomes necessary to model the atmospheric phenomena over a large area (see Figs. 6a–d). Clearly it is possible, with the use of a nested grid of higher resolution (see Figs. 7a–d), to understand the effect of the topography on the formation of the so-called wind channels. It is, therefore, possible to affirm that the choice of the topographic grid with a mesh of 5 km × 5 km for the second grid nested with a first grid of 20 km × 20 km (see Fig. 2) is in this case the better solution in terms of computational efficiency and representation of the event.

In Fig. 9 is shown the comparison between the measurements made by Marseille's meteorological station and the relevant values calculated with RAMS. This result, together with those observed at the stations of

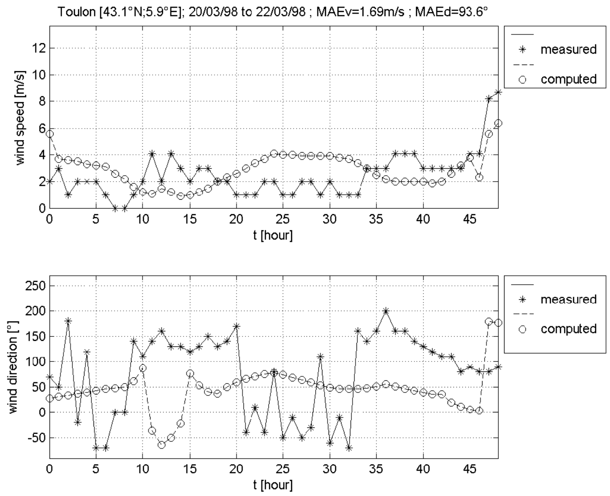


FIG. 8. Comparison between wind (top) intensity and (bottom) direction measured at the Toulon station (continuous line with asterisks) and those calculated by RAMS (dashed line with circles).

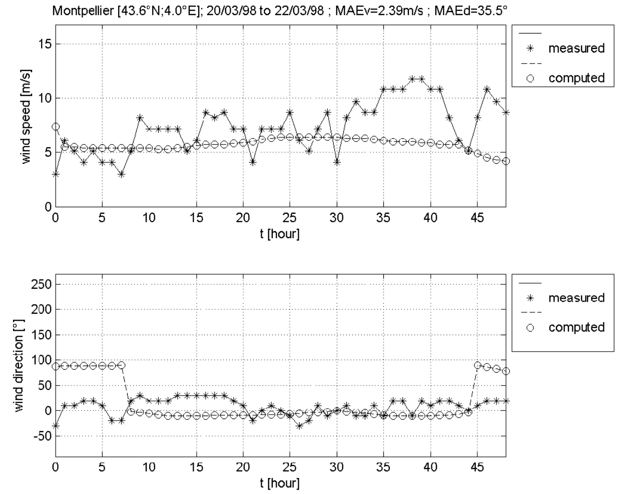


FIG. 10. Same as Fig. 8, but for the Montpellier station.

Montpellier (see Fig. 10) and Perpignan (see Fig. 11), shows how the mesoscale nonhydrostatic atmospheric models underestimate the wind speed on land and in the immediate neighborhood of the coast, even when the mistral is fully developed.

At sea, on the other hand, with the ASIS buoy and the ship *Atalante* we note a correct representation of the phenomena (see Figs. 12 and 13), particularly regarding the direction of the wind with an MAE of approximately 22°. When rapid rotations of the wind are created by a particularly unstable atmospheric condition, a good representation of the direction of the wind and its space–time variations is fundamental in obtaining a correct estimation of a zone wherein the fetch is constant. Note also that the MAE of wind speed for the ASIS buoy is equal to 2.29 m s^{-1}. There is good agreement between the calculated and measured data for the phase and amplitude of the wind direction and for the wind speed on the ASIS buoy and for the ship *Atalante*. Last, Figs. 12 and 13 show how the mesoscale nonhydrostatic atmospheric models can now be considered to be valid tools for both the study and analysis of particular atmospheric conditions in zones characterized by a complex topography (Pezzoli 2001).

b. Case study 2: 24–26 March 1998

The case study for the mistral in this section is characterized by a large difference between the temperature of the air and the temperature of the sea, the latter being higher than the temperature of the air by approximately 3°–4°C during the entire period under study. This is one of the major characteristics of the north-northwest wind in the Gulf of Lion, and it should be noted that in the mistral situation, the atmosphere is especially unstable in its most superficial layer (Monahan 1971).

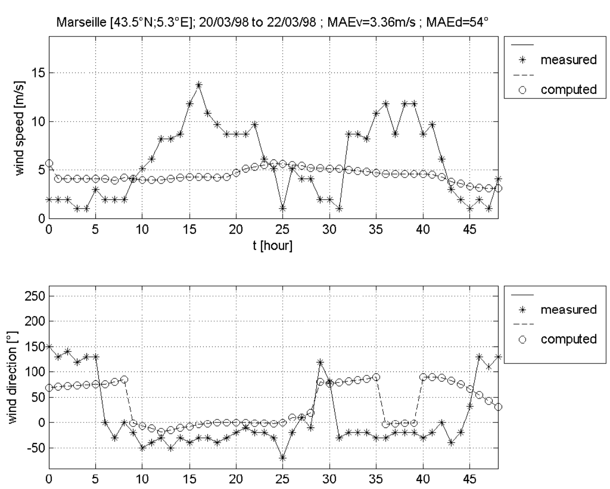


FIG. 9. Same as Fig. 8, but for the Marseille station.

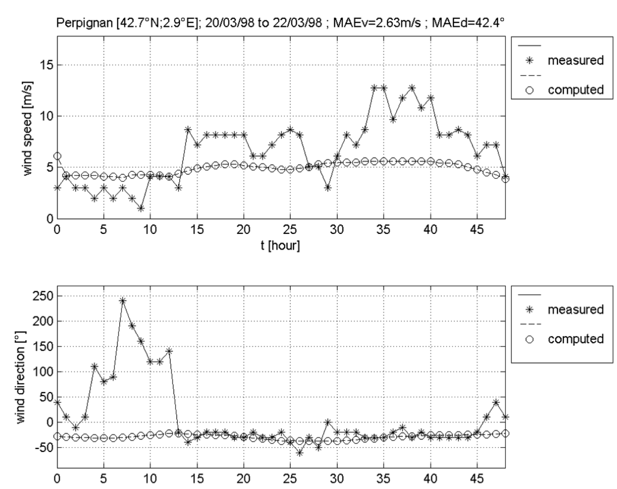


FIG. 11. Same as Fig. 8, but for the Perpignan station.

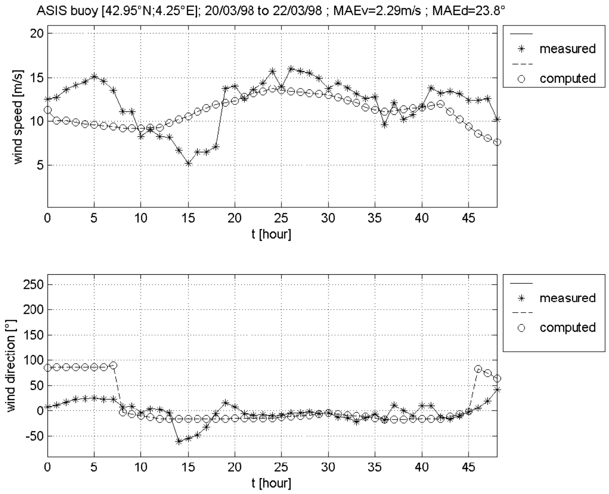


FIG. 12. Same as Fig. 8, but for the ASIS buoy.

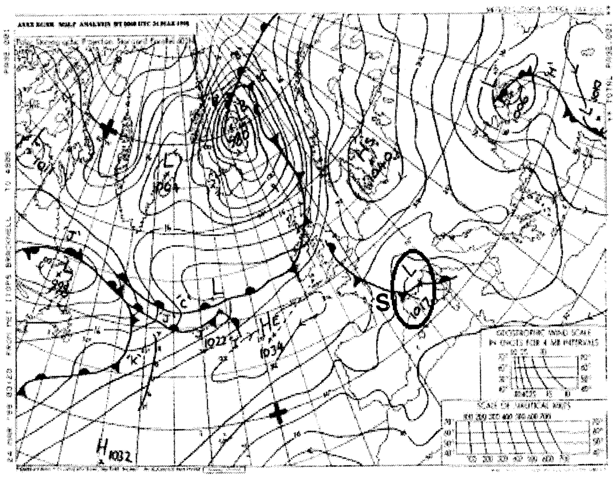


FIG. 14. Met Office synoptic surface analysis for 0000 UTC 24 Mar 1998. The study area is highlighted with a black oval.

In this specific case, the mean sea level pressure distributions were characterized by a trough of low pressure that, on 24 March 1998, rotates from the Alps to the Mediterranean, isolating the minimum temperature values over Corsica and therefore leading to a rain zone. To the northwest, a ridge approached that caused a subsidence effect and noticeable drop in the relative humidity values. On the surface, the Brittany region of France was under the influence of the front (denoted *S* on the map of Fig. 14), while the rest of France was under a field of high pressure (see Fig. 14). During the night the French Riviera was subjected to passing rain at the same time as Corsica. The sky of the French Mediterranean coast cleared during this day while the mistral was reaching very high wind speed values. On 25 March 1998 the high pressures dropped slightly in the northwest, allowing the penetration of the warm zone of the front *S* and announcing the return of a temperature air flow of oceanic origin over the whole country. The low pressure that was positioned over Corsica during 24 March moved toward Italy and Greece (see Fig. 15). The mistral, still moderate during the morning, calmed down in the afternoon.

Considering the results of the simulations made with RAMS (see Fig. 16a–d and Figs. 17a–d), it can immediately be noted how the evolution of the phenomenon is developed with a correct timing of the different phases. In fact, from Figs. 16a and 17a, we can see that on the morning of 24 March 1998 the wind from the northwest was already well established on the Gulf of Lion, whereas a depression vortex was still present over the Gulf of Genoa. In the afternoon (see Figs. 16b and 17b), at the same time as the depression moved toward southern Italy, the wind turned to the north in the Gulf of Lion and to north-northeast of Toulon. These wind directions are characteristic and very frequent during the cases of mistral where the atmosphere is very unstable (Ascensio et al. 1987, 1988; Coppeaux et al. 1992). In the afternoon of 25 March 1998 (see Figs.

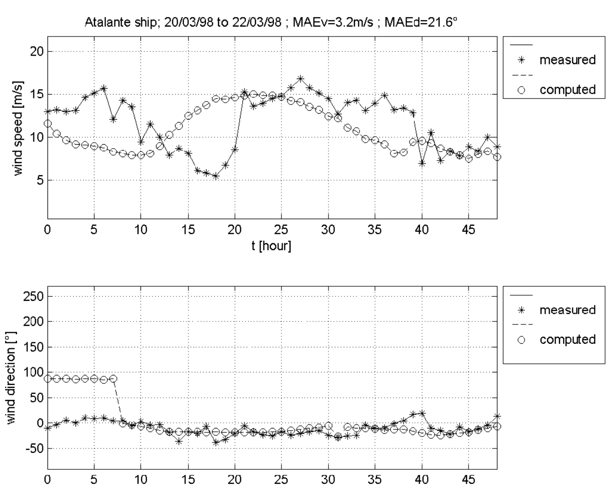


FIG. 13. Same as Fig. 8, but for the ship *Atalante.*

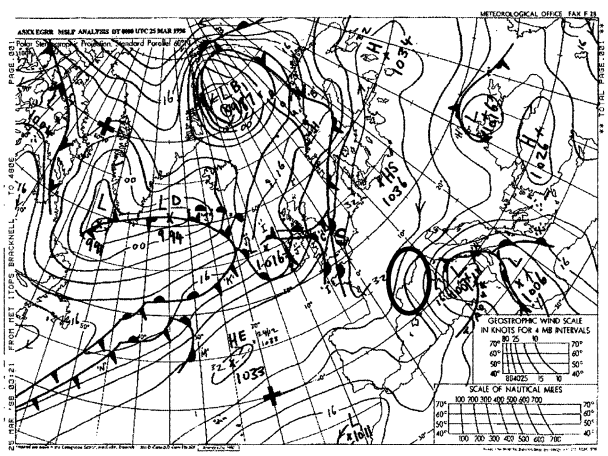


FIG. 15. Same as Fig. 14 but for 25 Mar 1998.

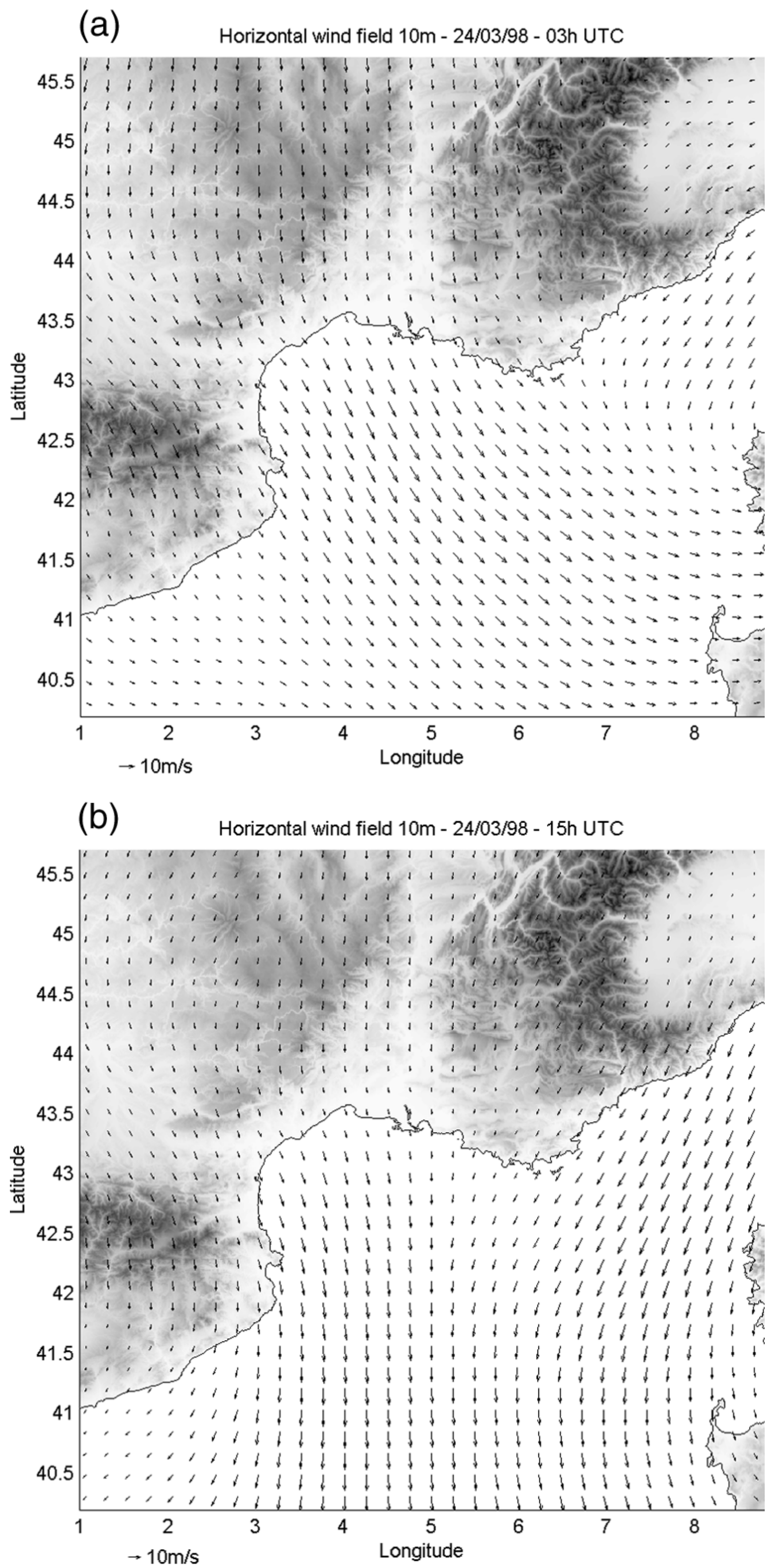


FIG. 16. Wind field at 10 m for grid 1 (20 km) for the case study at (a) 0300 and (b) 1500 UTC 24 Mar and (c) 0600 and (d) 2100 UTC 25 Mar 1998.

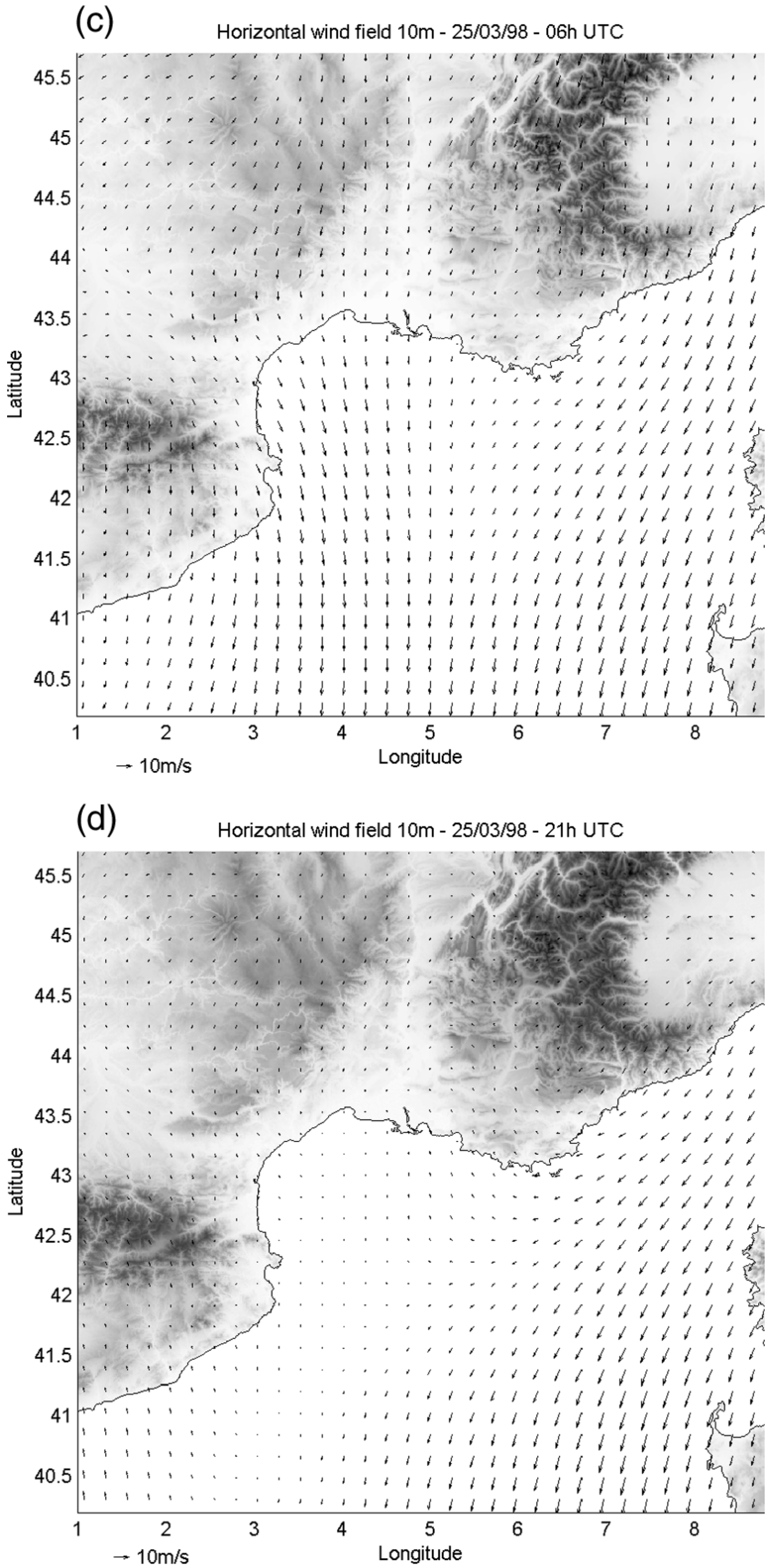


FIG. 16. (*Continued*)

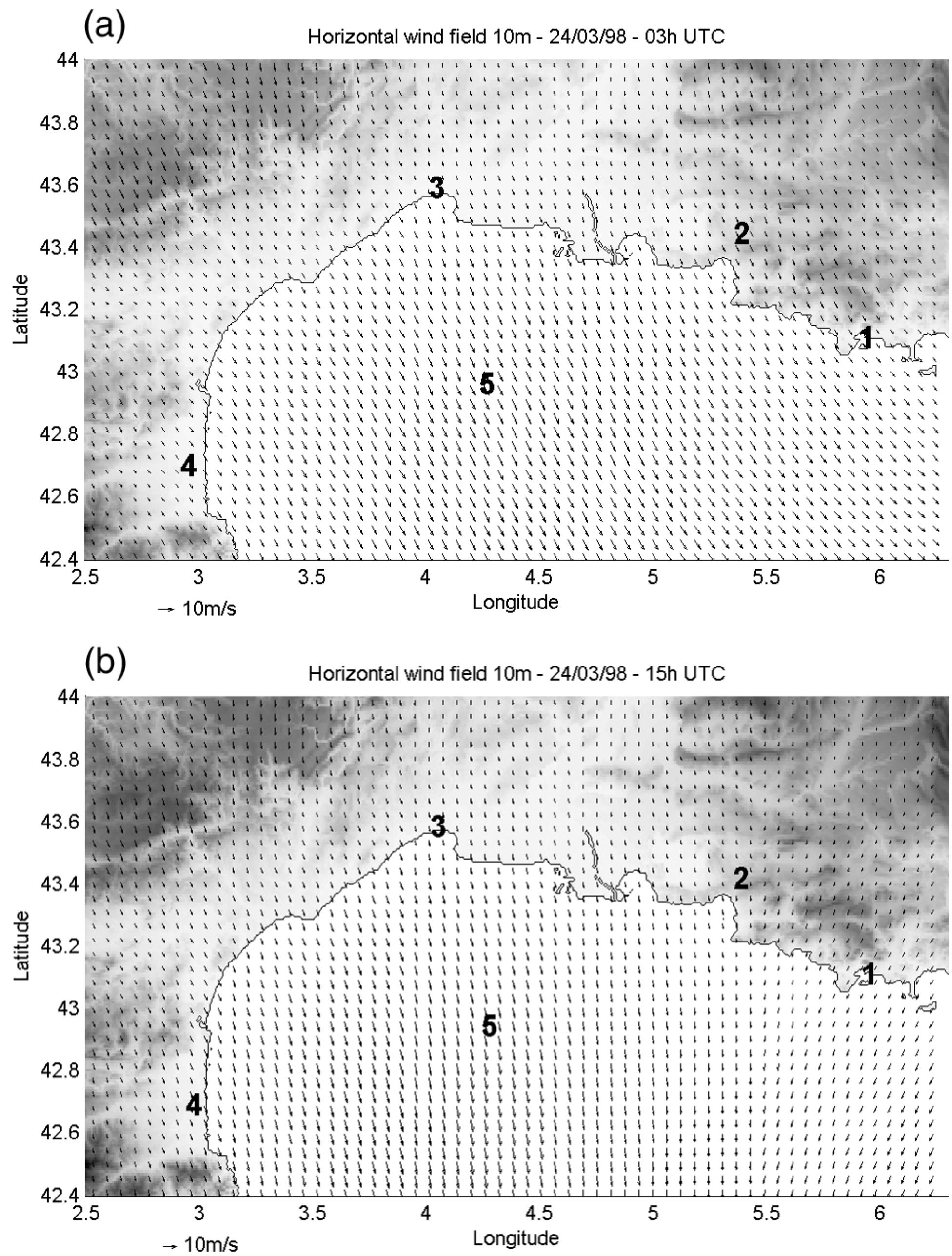
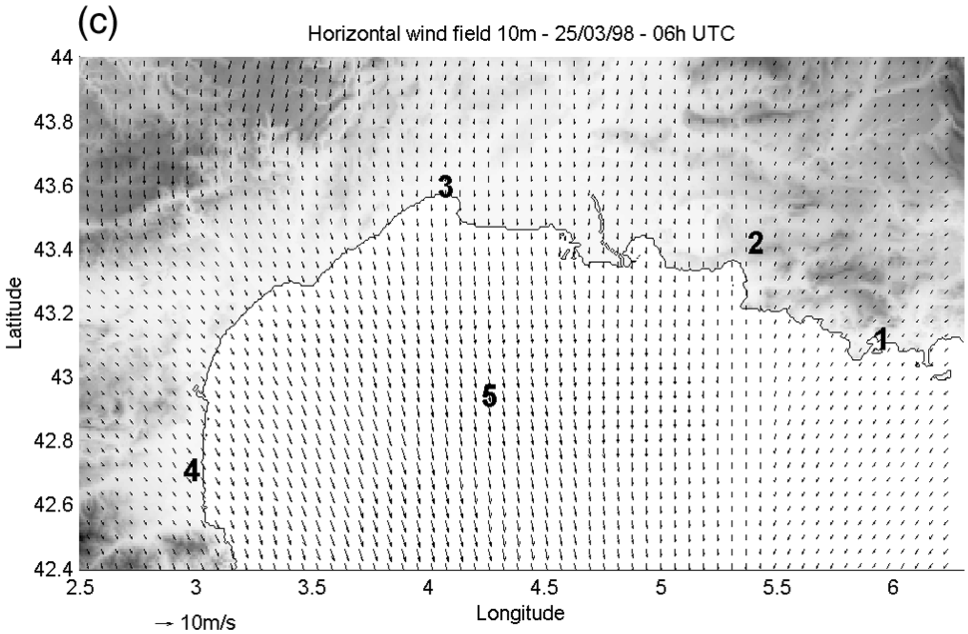


FIG. 17. Wind field at 10 m for grid 2 (5 km) for the case study of (a) 0300 and (b) 1500 UTC 24 Mar and (c) 0600 and (d) 2100 UTC 25 Mar 1998 at 1: Toulon, 2: Marseille, 3: Montpellier, 4: Perpignan, and 5: ASIS buoy.

16d and 17d) there was a final drop in the intensity of the wind, confirmed by the measurements taken at the ground stations during this period.

In fact, from Fig. 18, showing the comparison between the wind direction and speed values measured at the station of Toulon and calculated by RAMS, it can be noted how after 25 h from the start of the simulation, the trend of the wind speed and wind direction variations tend to decrease. Meanwhile the wind direction oscillates between the southern quadrants during the day and the northern quadrants during the night following the thermal cycle. The variations in the wind speed and rotations are both damped in the model but, in any case, are in agreement with the measurements.

This rotation of the wind, associated with the drop in intensity, becomes even more evident when observing the measured values at the station of Marseille (see Fig. 19). For this reason it is concluded that the area around Marseille is very important for predicting the phenomenon of the mistral. The measurements made along the



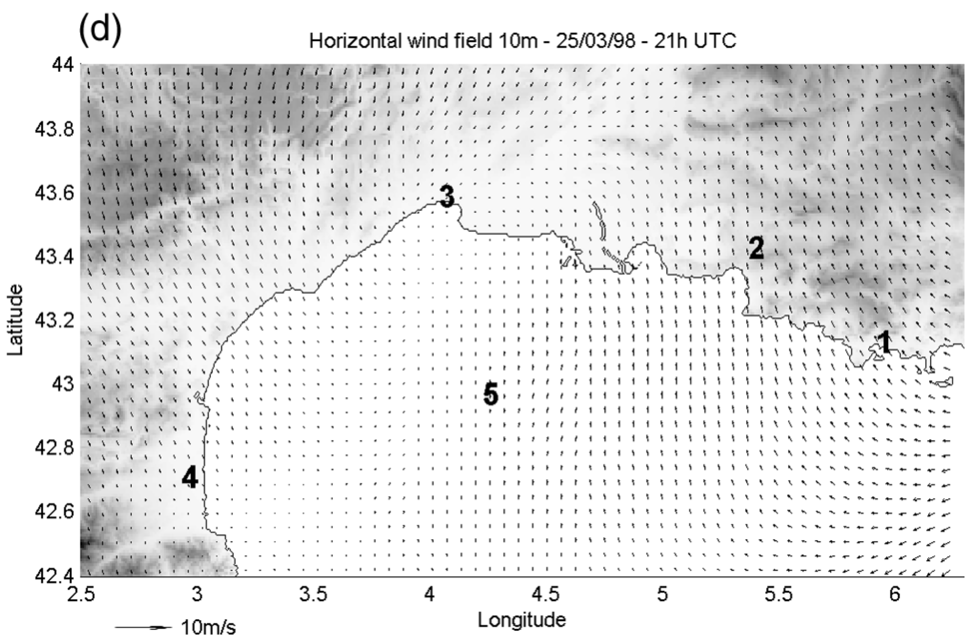


FIG. 17. (*Continued*)

coastal zone and in the immediate Marseille area become fundamental for nowcasting. From Fig. 19 it can be seen how, after 15 h from the start of the simulation, the measured values of the wind speed show a decreasing trend with a gradual shifting of the wind direction from the north-northwest to east-southeast. Also in this case the results of the model for Marseille's station are close to the actual situation for the wind direction, but the model underestimates the actual wind speed. For the station of Montpellier (see Fig. 20) and Perpignan (see Fig. 21), the same scheme appears as already has been demonstrated during the analysis of the case study of 20–22 March 1998.

Nevertheless, the comparison between wind intensity and direction values measured at the location of the ASIS buoy, by the ship *Atalante,* and those calculated by RAMS (see Figs. 22 and 23) confirm that the representation of the wind direction and speed by the model can be considered to be close to reality, although the wind speed values in most cases are slightly underestimated when compared with the measured values. In particular, the underestimation of the wind speed cal-

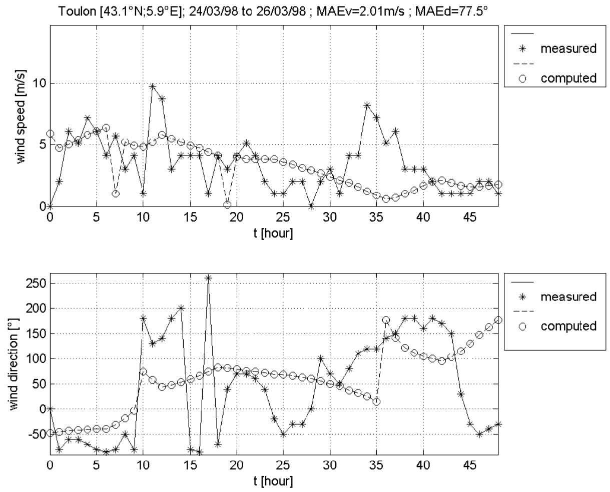


FIG. 18. Comparison between wind intensity and direction values measured at the Toulon station (continuous line with asterisks) and those calculated by RAMS (dashed line with circles).

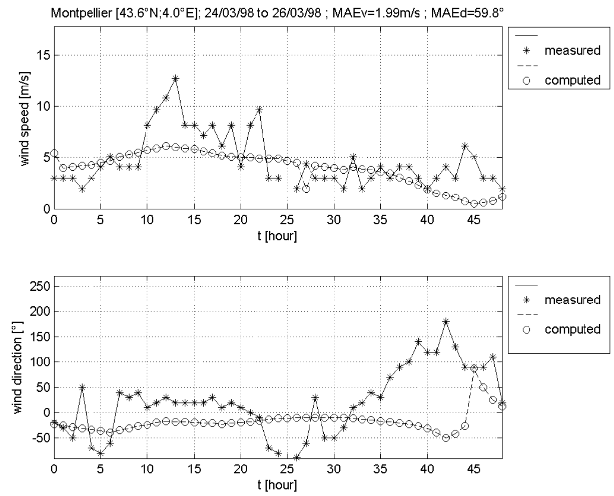


FIG. 20. Same as Fig. 18, but for the Montpellier station.

culated by the model increases when the mistral is fully developed between 1600 UTC 24 March 1998 and 0300 UTC 25 March 1998.

This is a common occurrence in the application of atmospheric models in cases of strong winds coming from the land with an unstable atmosphere (Cavaleri and Bertotti 1997; Pezzoli 1998; Bao et al. 2000) and in a complex topography (Pielke 1985). The models are able to simulate the phenomena but often underestimate the wind speed. It is for this reason that it becomes essential, during the final nowcasting phase, to compare the measurements with the calculated values. This consideration helps us to understand how important it is to be able to have reliable measurements distributed over the whole territory using remote measuring methodologies for meteorological parameters (Powers et al. 1997; Liu and Rabier 2002).

One possibility related to this deficiency is the initialization and the Newtonian nudging with the synoptic analysis of pressure data by the ECMWF model. In effect, Cavaleri and Bertotti (1997) have shown that the ECMWF model underestimates the wind field in the Adriatic Sea. They have suggested that the surface drag and the modeling of the surface layer at sea could be responsible for the underestimation. Surely this possible error of the ECMWF model has repercussions in the analysis made by a mesoscale model, such as RAMS. Certainly, the initialization of the mesoscale model by the surface observations and the four-dimensional data assimilation could, in the near future, bring about a considerable improvement in the obtained results. For example, in the nonhydrostatic mesoscale models currently used in forecasting mode (Davis et al. 1999; Roebber and Eise 2001; Pielke 2002), among which there is also RAMS (McQueen et al. 1997; McQueen et al. 1999), it is possible to introduce data initialization

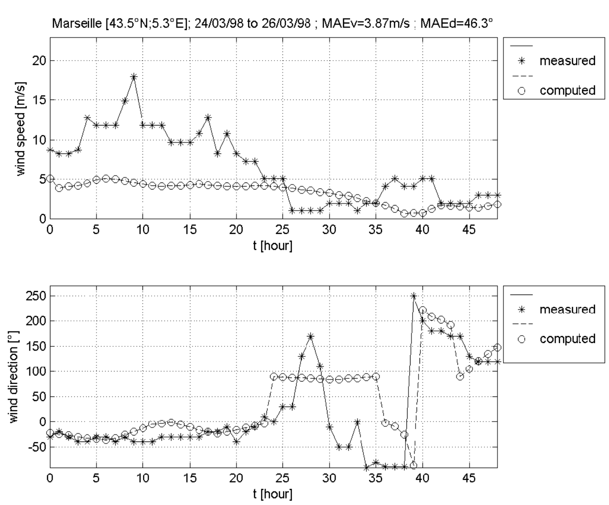


FIG. 19. Same as Fig. 18, but for the Marseille station.

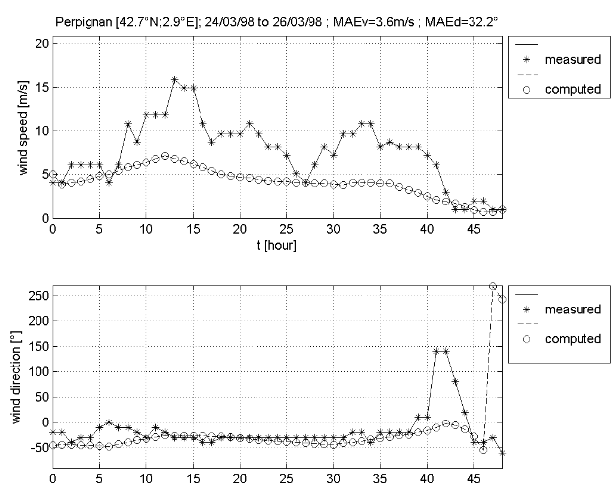


FIG. 21. Same as Fig. 18, but for the Perpignan station.

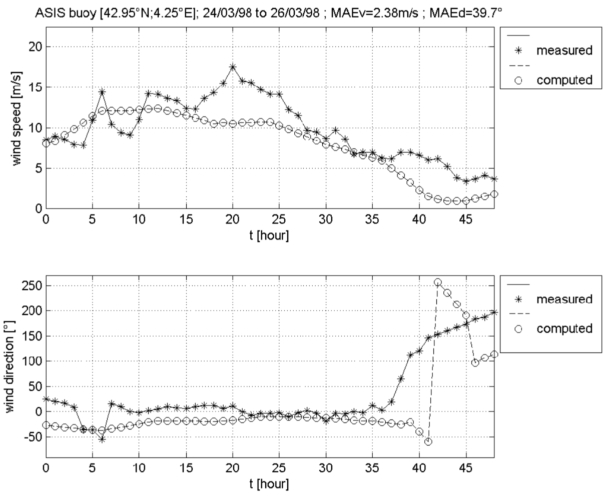


FIG. 22. Same as Fig. 18, but for the ASIS buoy.

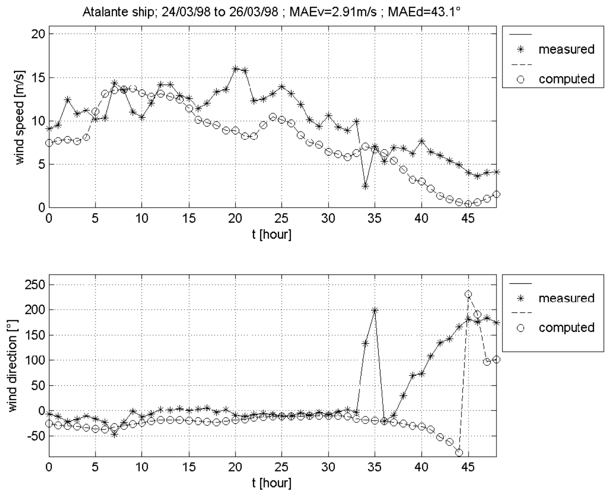


FIG. 23. Same as Fig. 18, but for the ship *Atalante.*

directly from the surface measurements. It is also possible to perform a variable assimilation of the same measurements (Guo et al. 2000; Pu and Braun 2001).

5. Conclusions

The results set out in the previous section illustrate the complexity of the atmospheric phenomena characterized by a high atmospheric instability. Furthermore, the topography that distinguishes the Gulf of Lion considerably influences the atmospheric flow in the lower layers. In fact, the simulations executed with RAMS have shown a space–time variability of the wind fields during cases of the mistral.

From the values measured by the stations of the Météo-France network and those simulated by RAMS, it can be noted how in a coastal zone between Toulon and Perpignan, separated by approximately 280 km, the direction of the wind varies considerably. For example, it can be seen that for the first station the wind has a prevalent direction from the east, veering suddenly to the west-northwest, while for the second station the northwest direction remains almost constant, varying gradually and only at the final stage of the event.

In analyzing the phenomenon of the mistral on a synoptic scale or on a high mesoscale (10–100 km), note that the Toulon area is to be considered as a transition zone between winds from the east that characterize the eastern coast of France and the Ligurian Gulf, and the northwest winds that are typical of the Gulf of Lion. These results are also confirmed by the detailed statistical–climatological analysis made by Ascensio et al. (1987, 1988) and by Coppeaux et al. (1992), where it is demonstrated that at the station at Perpignan the predominating direction is between 300° and 320° for a total annual frequency percentage of 50.9%. On the other hand, for the station of Toulon for the direction between 280° and 300° the total annual frequency percentage is 28.7%, and for the direction between 60° and 80° there is a total annual frequency percentage of 12.2%.

These considerations show how the results of simulations in analysis mode, made with nonhydrostatic mesoscale atmospheric models, can also be used to study the climatic conditions of a well-defined area (McDavitt 1997; Pielke et al. 2001). In this case there is the definite advantage of not having to refer exclusively to local values measured by the meteorological stations, but also to wind fields that give a representation distributed over the area involved. In addition, it is possible to study areas not covered by regular and constant measurements such as, for example, the marine zone of the first coastal strip where synthetic aperture (SAR) or altimeter radar satellite measurements still contain errors (Queffeulou 1999; Weinreich et al. 1999; Queffeulou et al. 2000). This remark seems valid even if the computed values in this area are underestimated compared with the actual situation.

Obviously the same type of model can be used in forecasting mode, taking full advantage of the potential offered, for example, operating with topographic grids of less than 1 km (Bidet 2001). A further refinement in the topographic grid may lead to a better representation of the wind speed, which, in our case, has been underestimated, especially on land and in the immediate neighborhood of the coast. In this specific case the extreme importance of a faithful representation of the surface wind fields over limited zones must be emphasized to obtain a correct assessment of the fetch and, therefore, an even more precise calculation of the wave characteristics at sea (Komen et al. 1996). In fact the effective variability of the mistral can really be observed by scrutinizing the wind fields at sea obtained by RAMS with the higher-resolution grid (shown in Figs. 7a–d and 17a–d), together with the relevant comparative analysis of the wind direction and intensity values measured by the

ASIS buoy and the ship *Atalante*. In particular, under unstable atmospheric conditions, the wind rapidly changes direction and intensity from the coast toward the open sea.

As a result, the wave fetch cannot be considered as constant in space for the wind coming from inland in coastal zones, as recommended by the parametric model (Carter 1982). This latter consideration is particularly important because the parametric equations that give the significant wave height and wave period are based on the hypothesis of a constant fetch and completely neglect the atmospheric stratification effect of the boundary layer (Donelan 1980; Bishop 1983; Smith 1991; Hershberger and Ting 1996).

Therefore, it could be interesting to analyze in future research the possibility to introduce corrections into these equations. These corrections could be based on the thermal parameters of the boundary layer that can be deduced by in situ measurements, or, as would seem more promising, by data obtained by simulations with atmospheric mesoscale models.

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