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Prediction of a Mesoscale Convective System over Catalonia (Northeastern Spain) with a Nested Numerical Model

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With 16 Figures

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Summary

A mesoscale convective system that affected Northeastern Spain on October 10, 1994, with rainfall amounts up to 400 mm, is simulated reasonably well by a nested 3-dimensional hydrostatic mesoscale model. Previous studies carried out in this region had already portrayed the main synoptic patterns that give rise to these devastating episodes. The present contribution takes a further step since it goes down to the mesoscale by means of a numerical model providing a more detailed representation not otherwise achieved by earlier analysis methods. Although the model was unable to forecast accurately the precipitation fields, it captured satisfactorily the framework in which the convective system originated and evolved.

1. Introduction

The Mediterranean basin of the Iberian Peninsula is frequently affected, especially during the fall season, by mesoscale convective systems (MCS) that are often associated with heavy rains (Llasat and Puigcerver, 1992; Riosalido, 1991) and, eventually, flash floods with loss of property and, in some cases, human casualties (Miró-Granada, 1974).

These systems are difficult to forecast because they have their own internal dynamics evolving on a small scale that is not conveniently reflected in the operational synoptic scale numerical models (Riosalido, 1990a). Within the last few years, a considerable effort has been devoted to the development of mesoscale numerical models capable of simulating convective processes that are essential in the life cycle of MCS (Rutledge, 1991).

So far radar and satellite imagery have been used to study and monitor these situations (Riosalido, 1990b, 1991). Other authors, like Ramis et al. (1994) and Rivera (1990), have paid attention to the synoptic features which are common in such events, as well as to the mesoscale and local factors that may contribute to their formation and evolution. More recently, few authors have carried out simulations with numerical models (Fernández et al., 1995).

Earlier studies point out that there are common elements among such situations that are very useful for diagnostic purposes. Thus, for example, a characteristic pattern (Riosalido, 1990a) involves a mid-level low pressure system centered aloft the SW of the Iberian Peninsula that slowly shifts eastwards originating southwesterly winds over the Mediterranean coast, often reinforced by an anticyclone in Central Europe. This low-level flow from North Africa and the Mediterranean sea advects warm and humid air towards the coast. In most cases, the birth and development of MCS is fueled by either the mechanical ascent of this potentially unstable air over the coastal ranges of the region, or the lifting induced by synoptic conditions.

This paper focuses in one of these episodes that took place between the 9th and 10th of October 1994 and affected Catalonia (the NE corner of the Iberian Peninsula) with heavy rains and local floods. It is the first time that a nested mesoscale numerical model is used to analyze the behavior of such a situation in this region. Section 2 gives an overview of the model, Section 3 describes the synoptic situation which preceded the development of the MCS, and Section 4 discusses the results of the model simulation.

2. Description of the Model

The model used in our simulations is an upgrade of the Mesoscale Atmospheric Simulation System, hereafter referred to as MASS, which is described in more detail by Kaplan et al. (1982), Koch et al. (1985), Zack et al. (1991) and Kaplan and Karyampudi (1992). MASS is a 3-dimensional hydrostatic primitive mesoscale model designed to be run with horizontal grid point resolutions of about 10 to 100 km, with 20 to 40 levels in the vertical. The model has the ability to perform nested simulations, i.e., simulations over areas enclosed in a larger simulation region which numerical output is used as first guess and boundary condition data for the smaller scale simulation.

The model incorporates a high resolution Blackadar type planetary boundary layer parameterization and detailed surface energy and moisture budgets that include the parameterization of surface hydrology and evapotranspiration. Both cloud water/ice and precipitation are included among the model forecast's variables, and their mutual interaction as well as the interaction with water vapor are parameterized. The effects of sub-grid scale cumulus convection may be handled by three different schemes (Kuo-Anthes, modified Kuo-Anthes and Fritsch-Chappell) that can be chosen depending on the model grid spacing. Longwave and shortwave radiation at the surface and within the atmosphere and their interaction with clouds and precipitation are included in the parameterization.

Most of these parameterizations require appropriate databases of surface characteristics, such as terrain elevation, normalized difference vegetation index NDVI, land-water boundaries, climatological sea surface temperature SST, land use and soil type. Since the simulation area is larger than the Catalonian region, for which high-resolution databases of those magnitudes are available, public-domain data sets are used for the whole area. In order to avoid inhomogeneities in the surface representation of the simulation domain, no attempt is made to merge both fine and coarse data sets. The terrain database is a U.S. Central Intelligence Agency 5 minute × 5 minute (about 9 km resolution) topographical database; land/water distinction comes from a U.S. Navy 10 minute resolution data set; NDVI is obtained from the Monthly Global Vegetation Index (GVI) from the Global Ecosystems Database CD-ROM at 10 minute resolution; the soil type database is a webb global soil texture class from the Global Ecosystems Database CD-ROM at 1 degree resolution; land use and land cover data are obtained from the Olson World Ecosystems Database CD-ROM at 30 minute resolution; climatological sea surface temperature is obtained from a bi-weekly U.S. Geological Survey SST climatology at 12 minute resolution.

MASS also contains a data preprocessor that can create a complete model initialization data set as well as boundary condition data from a variety of observational and gridded forecast data. The observational data is interpolated to a set of regularly spaced grid point by means of an optimum interpolation scheme.

The case under study covers the floods that affected Northeastern Spain on October 10, 1994. A 24-hour large scale simulation was run on a grid with 55 km grid-point spacing, 55 × 55 grid points in the horizontal, and 20 levels in the vertical, as shown in Fig. 1. It was initialized about 12 hours before the onset of the heavy rains, at 12 UTC 9 October. Synoptic surface and rawinsonde observations and first guess data from the 12-hour forecast of the U.S. National Meterological Center's Medium Range Forecast model (MRF) were incorporated in the initialization process. The MRF was also used to provide boundary conditions every 12 hours.

The nested simulation was initialized at 18 UTC 9 October and executed for 18 hours of simulated time on a grid with 10 km grid-point spacing, 55 × 55 grid points in the horizontal and 20 levels in the vertical, as depicted in Fig. 2. Major geographical reference points that are mentioned in the following discussions are repre-

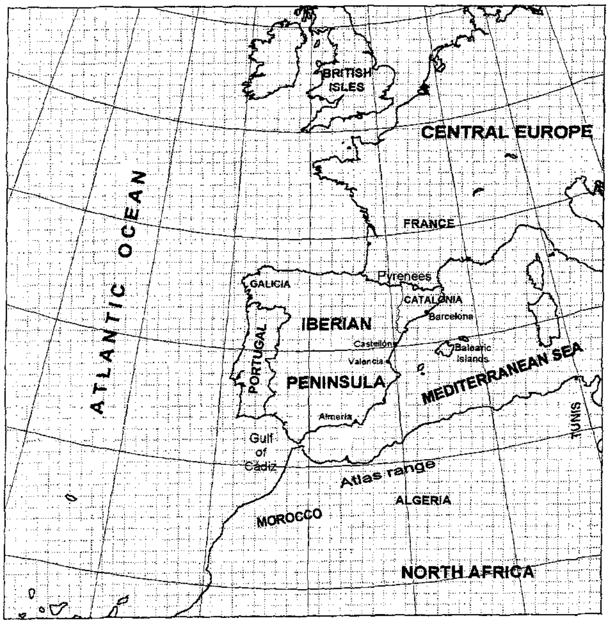


Fig. 1. Large-scale simulation area and 55 × 55 horizontal grid point distribution (grid interval 55 km)

Fig. 2. Nested simulation area and 55 × 55 horizontal grid point distribution (grid interval 10 km)

sented on the map. It becomes apparent that the finer mesh of the grid allows for a better representation of the Pyrenees and coastal ranges in the terrain field. This simulation was initialized by interpolating the output from the larger scale simulation, which was also used to provide boundary conditions every hour for the duration of the simulation.

A modified Kuo-Anthes convective parameterization scheme was employed for the large scale simulation. However, since it was realized that this scheme tended to overestimate convection in mountainous areas, a Fritsch-Chappell scheme was chosen in the nested simulation.

3. Analysis of the Synoptic Situation

The synoptic charts for October 9 at 12 UTC feature a deep north-south trough at 250 hPa (Fig. 3), closing a 10520 m low pressure area above Portugal and Galicia. At this level, the maximum values of the wind are located in the southwesterly flow over the Atlas range. At 500 hPa (Fig. 4), the trough is less pronounced and its center is found west of Portugal. The axis of the ridge east of the low-pressure extends SE-NW, from Tunis to the British Isles. The wind is from the SW over the northwest of Africa, but turns southerly over the Iberian Peninsula. Since the temperature and geopotential fields are similar but slightly shifted, the warm advection is most important between the SE of the Iberian Peninsula and North Africa. From the synoptic point of view, the situation is favorable to the ascent of the air in the area between trough and ridge at these levels.

At 850 hPa the low-pressure center is located above the Atlantic, over the SW of the Iberian

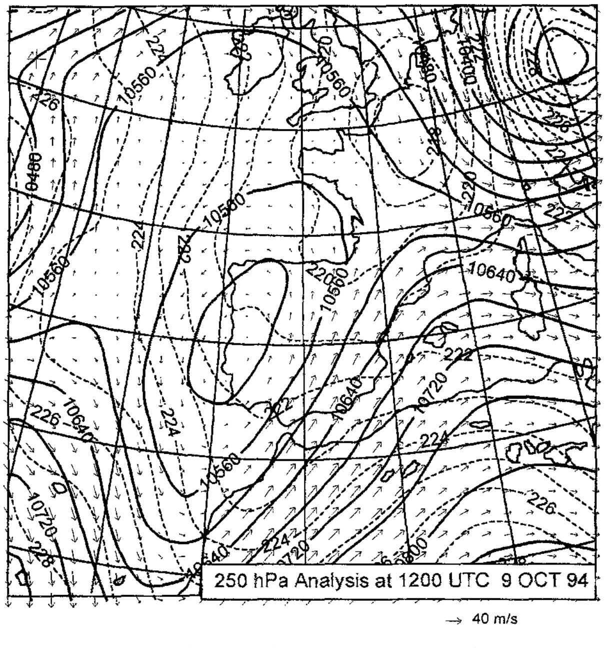


Fig. 3. MASS 250 hPa analysis at 1200 UTC 9 October 1994. Solid lines: geopotential height (in meters); dashed lines: isotherms (in K); arrows: wind speed and direction

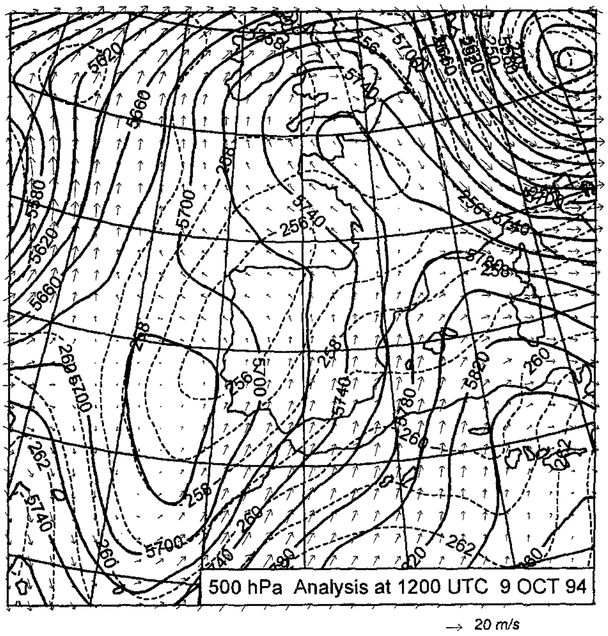


Fig. 4. As Fig. 3 but for 500 hPa

Peninsula (Fig. 5). Above the Mediterranean sea the wind is from the south, and exhibits the maximum velocities between the Iberian Peninsula and northern Africa over the 0° meridian. A marked thermal ridge points towards the coast of Catalonia with its axis oriented NW to SE, from the Balearic Islands to Algeria. Over the eastern Iberian Peninsula there is a cold air mass with a minimum temperature of 9 °C very close to the Mediterranean coast. Above the Balearic sea, the temperature of the warm air mass is 13 °C, and 19 °C over the Algerian coast. Therefore, the maximum warm advection is found at this time between Valencia and Almería. On the other hand, the path of the air masses coming from North Africa is the longest for those reaching the coast between Valencia and Catalonia. The interaction between this low-level southeasterly warm and humid jet and the mid-level southwesterly flow generates strong ascending vertical motion in all this region.

At the surface, the low pressure area is located on the gulf of Cádiz (Fig. 6), while a 1024 hPa high pressure area extends over central Europe; the wind on the Mediterranean coast of the Iberian Peninsula is, therefore, from the east, between 10 and 25 kt.

In this synoptic framework, rainfall amounts about 50 mm were collected in the eastern part of the Iberian Peninsula between 06 UTC 9 October and 18 UTC 9 October (62 mm/12 h in Castellón). Within this period, weak or moderate rains affected southern Catalonia, with 15 mm/12 h collected in the south of Tarragona. After 18 UTC the precipitations spread and gained intensity in Castellón and Tarragona, and about 02 UTC

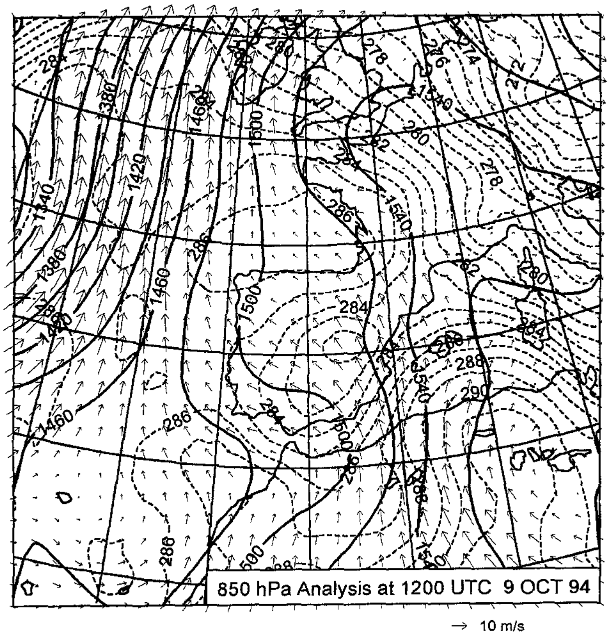


Fig. 5. As Fig. 3 but for 850 hPa

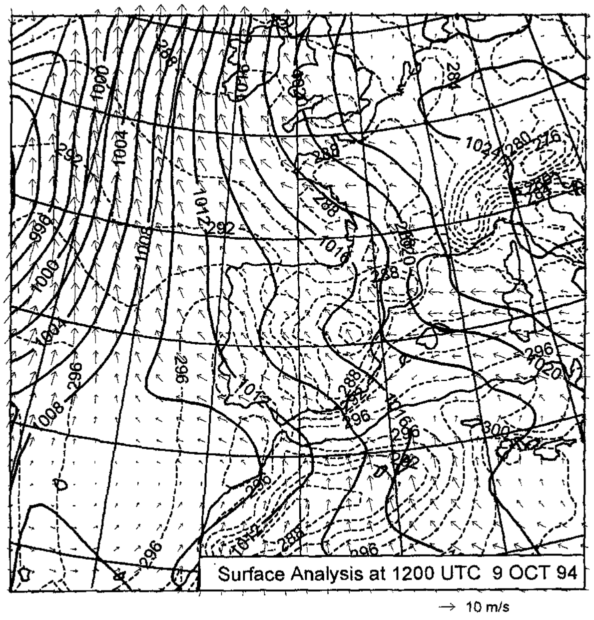


Fig. 6. As Fig. 3 but for surface level. Solid lines are now isobars in hPa

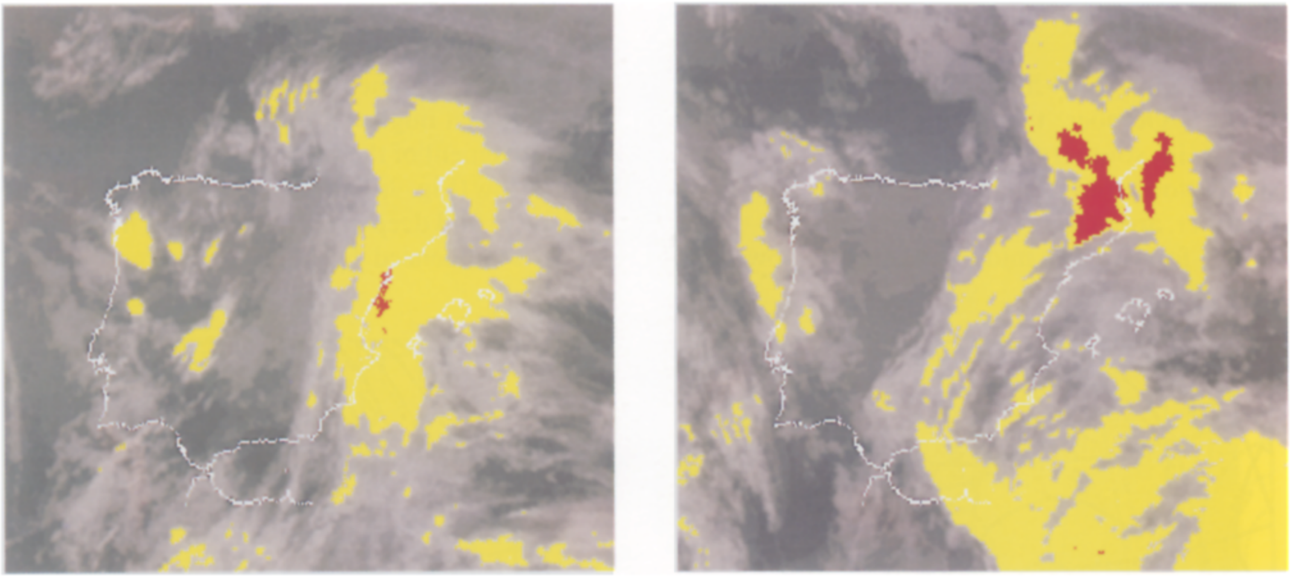


Fig. 7. METEOSAT enhanced infrared imagery for 18 UTC 9 October (left) and 06 UTC 10 October (right). Yellow: $-52 < t < -32\,°C$; red $t < -52\,°C$

a convective system developed in this area, strongly affecting a mountainous area around Alforja (the precipitation collected at this site throughout the whole episode exceeded 400 mm in 2 days). In the following hours, several precipitation areas developed along the coastal ranges, from SW to NE, affecting the provinces of Barcelona and Girona. That displacement and intensification of the precipitation areas along the coast, from S to N, is also reflected in the evolution of cloud tops (Fig. 7). The total precipitation collected in Catalonia in October 9 and 10 is depicted in Fig. 8. The maximum located over the east of the Girona province took place during the afternoon of October 10 (at Girona airport, 93 mm were collected between 18 UTC and 06 UTC 11 October).

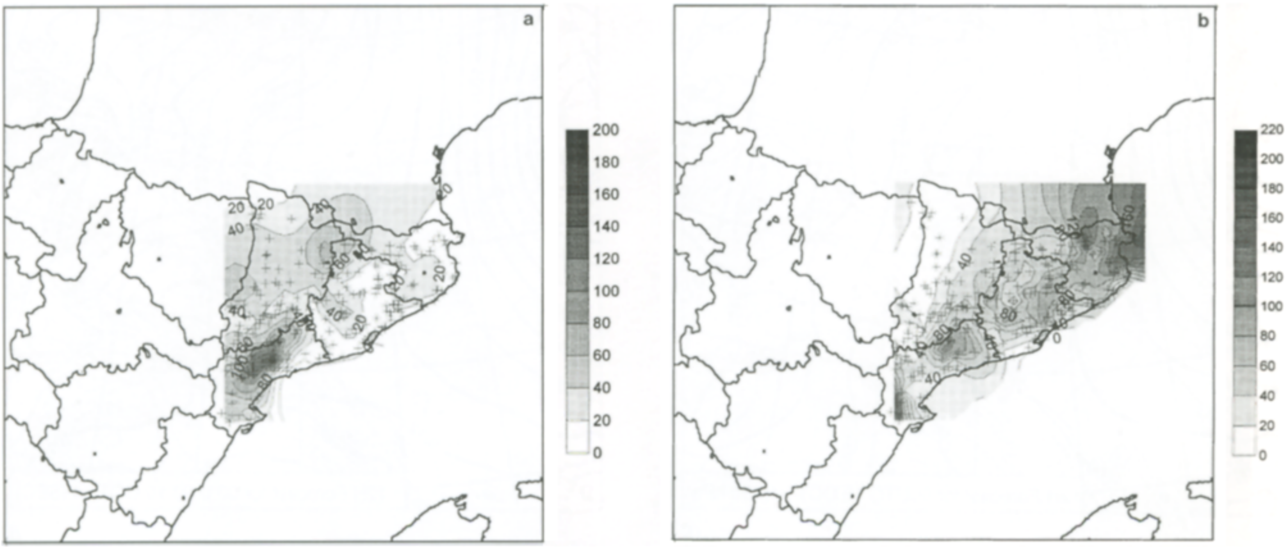


Fig. 8. Observed precipitation, in mm, between (a) 08 UTC 9 October and 08 UTC 10 October, and (b) 08 UTC 10 October and 08 UTC 11 October. Data from the Spanish Weather Service regional precipitation network

4. Results of the Model

The results of a 24-hour simulation starting at 12 UTC 9 October, twelve hours before the first floods in southern Catalonia, and the nested simulation from 18 UTC through 12 UTC 10 October, are presented in this section.

The forecast for midnight (Fig. 9) shows that the center of the low-pressure area in the upper-levels (250 hPa) shifts slightly to the north, towards the NW of the Iberian Peninsula, whilst the axis of the jet migrates to the Mediterranean sea. The movement of the wave at this level makes the surface low (Fig. 9d) propagate towards the Mediterranean and deepen in the following hours. The latter is influenced by both the decrease of the

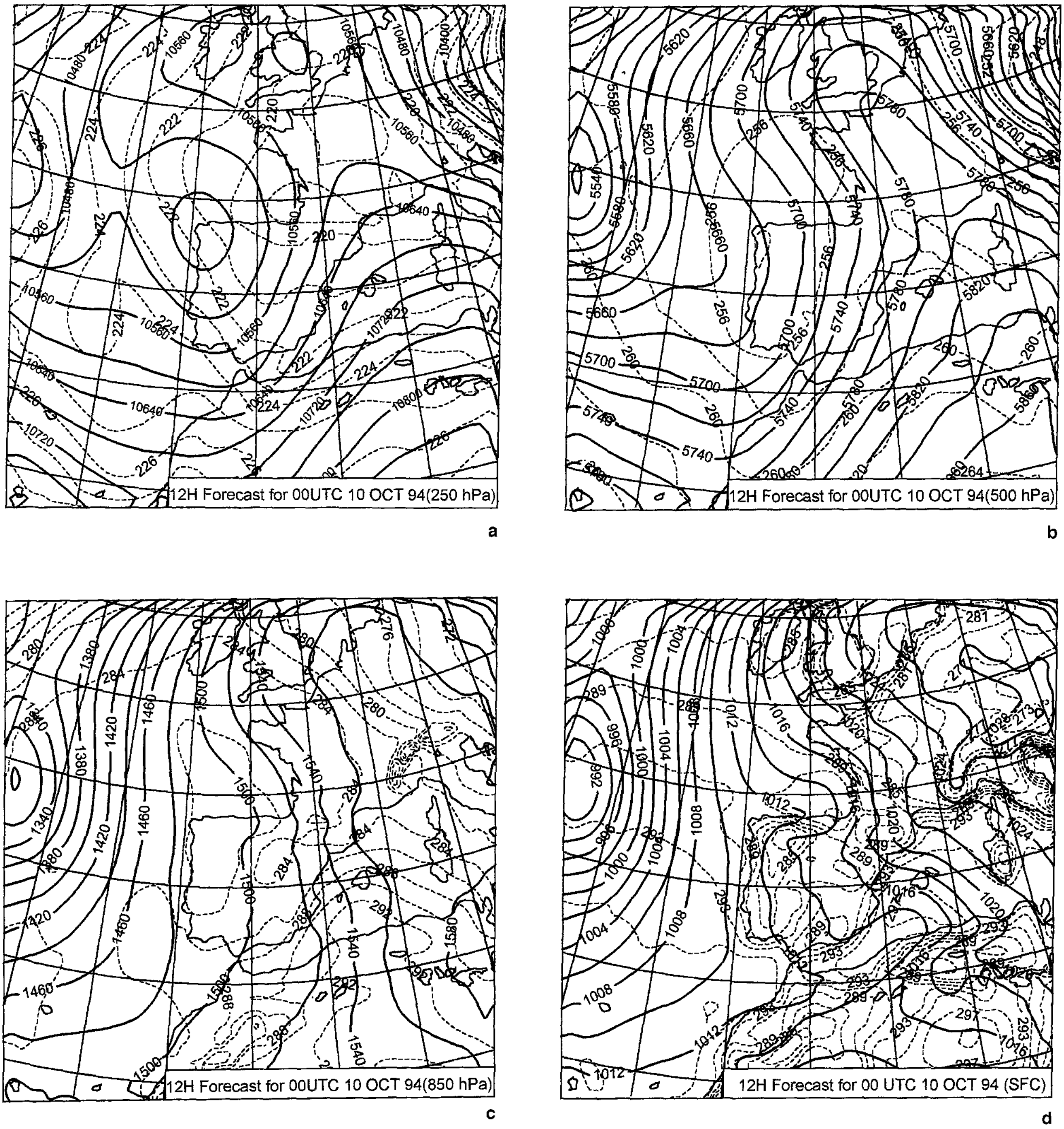


Fig. 9. MASS large-scale 12 h forecast at indicated levels. Solid lines: geopotential height in meters (isobars, in hPa, in the surface chart); dashed lines: isotherms (in K)

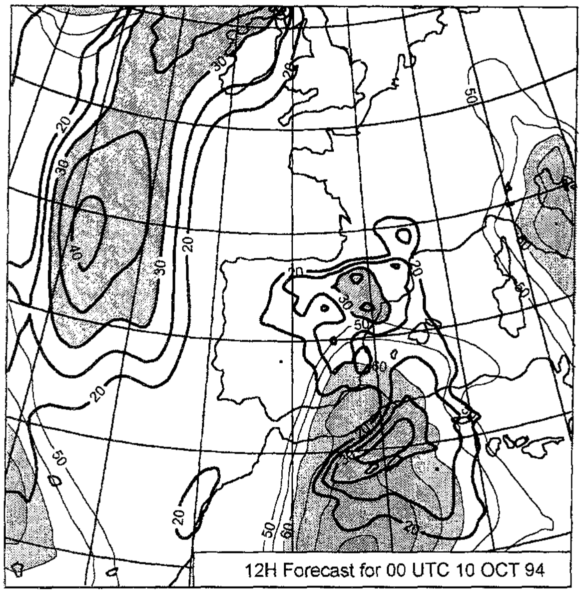
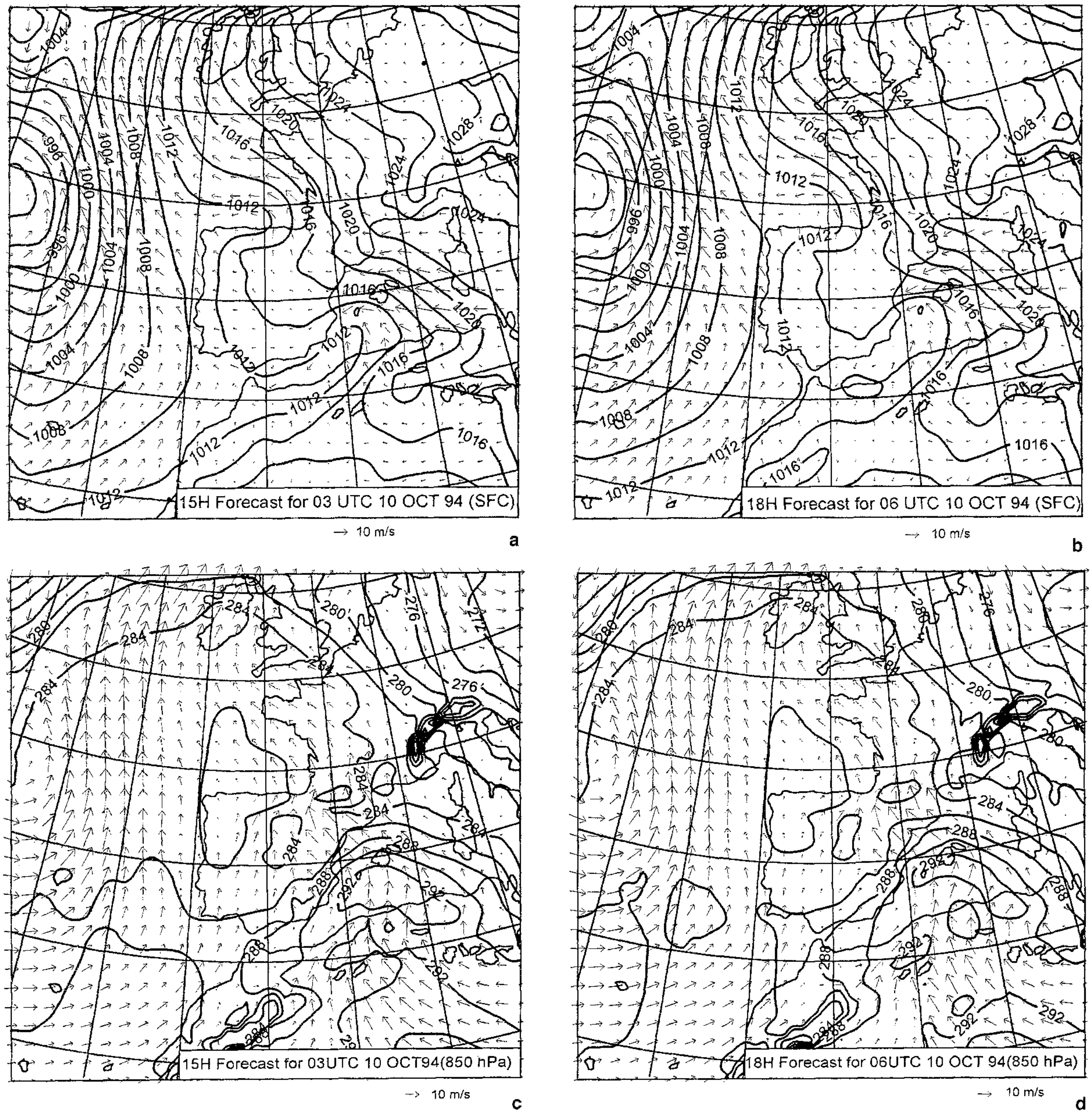


Fig. 10. MASS large-scale 12 h wind speed (kt) forecast at 850 hPa (thick lines) and 250 hPa (thin lines)

wave amplitude in the upper-levels and the cyclogenetic effect produced by the southerly flow crossing the Atlas range (Jansà, 1987; García-Moya et al., 1989). The forecasted strong advection of warm air at 850 hPa over the Mediterranean coast is a key factor to the further development of the MCS (Fig. 9c). Figure 10 depicts the isotachs at this level and at 250 hPa, making apparent the wind shear above the Mediterranean at both levels which also contributes to the destabilization of this region.

According to the model, between midnight and 06 UTC, the surface low (Fig. 11a and b) moves to the north and the wind direction in the Catalan coast turns easterly, with high speeds that rapidly

Fig. 11. MASS large-scale 15 h and 18 h forecasts at indicated levels. Solid lines are isobars (in hPa) in the surface chart and isotherms (in K) in 850 hPa; arrows show wind direction and speed



decrease inland. During these hours, in which the MCS developed, the advection of temperature at 850 hPa was maximum over this area (Fig. 11c and d) and a slight shift to the NE of the jet's axis at this level was forecasted by the model. Given the maritime origin and the high temperature of the air at low levels, a large amount of moisture was expected to feed the MCS. Figure 12 shows the evolution, as forecasted by the model, of the mean relative humidity between the surface and 500 hPa, with maximum values (greater than 90%) located over Catalonia between 00 and 06 UTC.

The nested simulation allows for a detailed analysis of some determining elements in the formation of the MCS, and to assess the performance of the model through the forecasted evolution of the precipitation fields. The forecasted fields of surface wind and pressure (Fig. 13) show a reinforcement of the easterly flow between 21 and 00

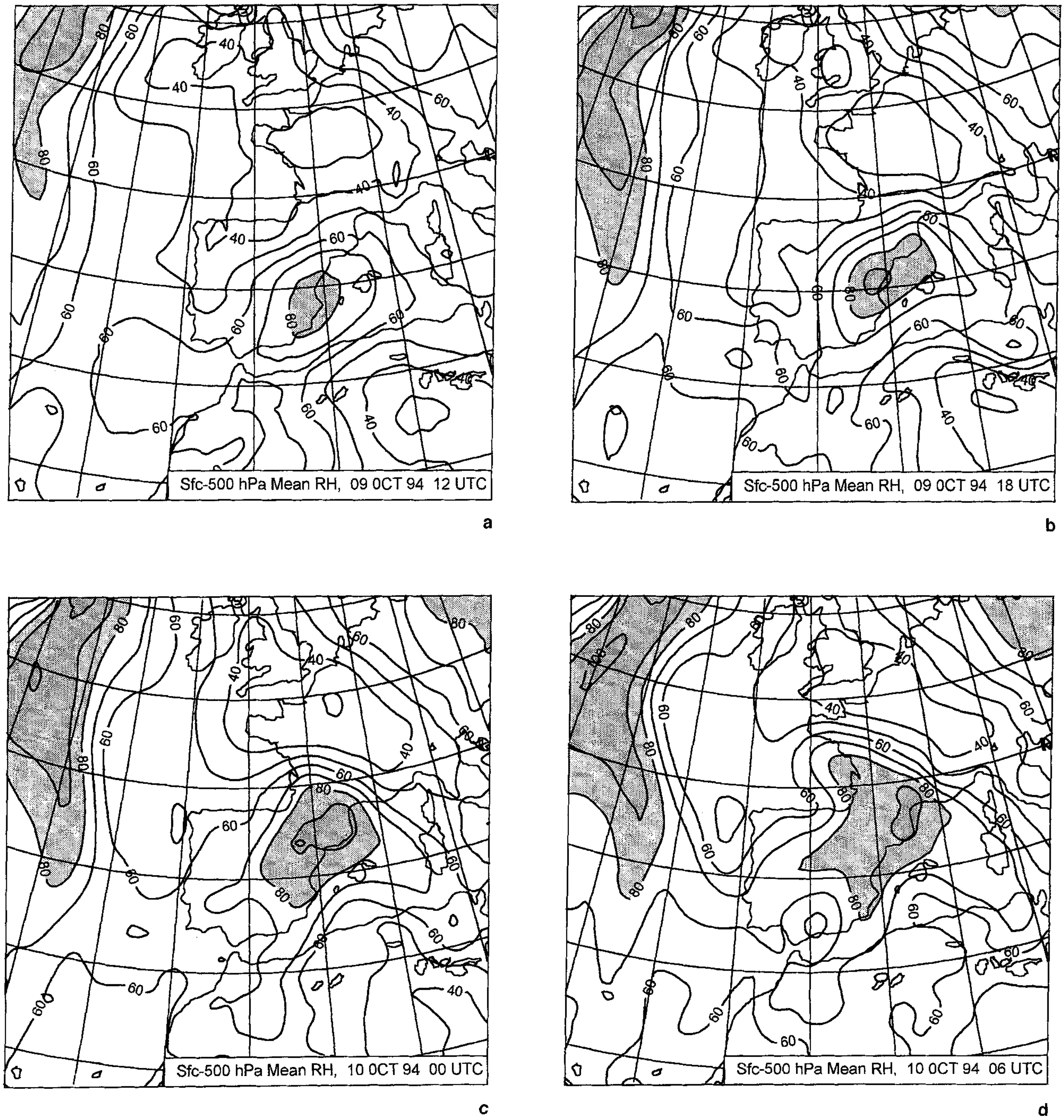


Fig. 12. Large-scale surface – 500 hPa mean RH forecasts (in %) at 6 h intervals

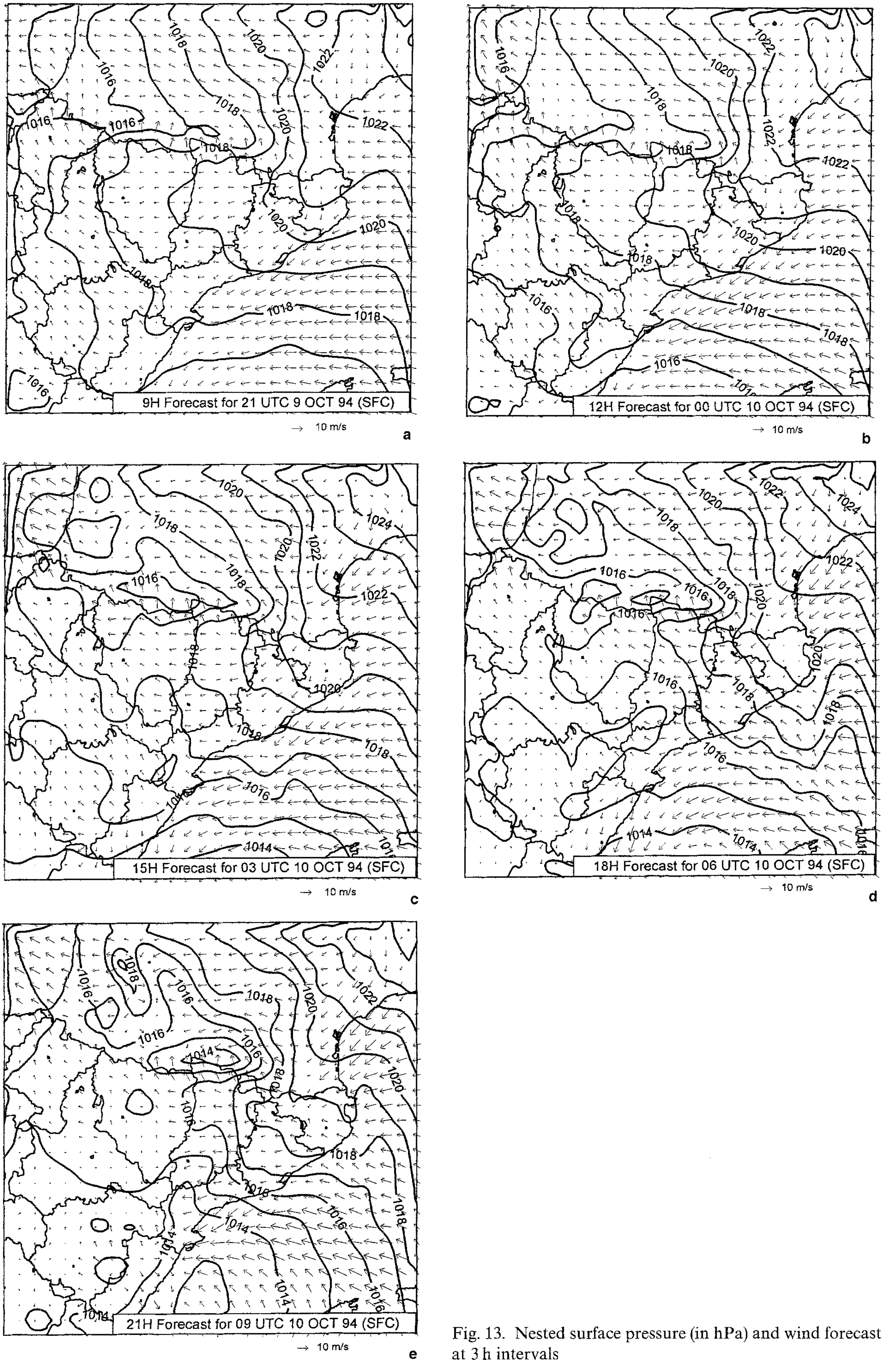


Fig. 13. Nested surface pressure (in hPa) and wind forecasts at 3 h intervals

UTC 10 October, blowing perpendicular to the coast near the Ebro delta. From midnight on, the meso-high pressure area develops over the south of Tarragona, and intensifies within the following three hours causing a wind convergence along the coast. In the next 6 hours (same figure) the low over the Mediterranean moves to the NE turning the wind easterly, blowing first perpendicular to the coast of Barcelona, and later of Girona; the convergence persists along the shoreline all the time.

On the other hand, the nocturnal cooling over land and the continued advection of warm and humid air from the sea creates a meso-front along the coast as can be seen in the temperature forecast (Fig. 14). This favors the ascent of air already stimulated dynamically by the convergence of the

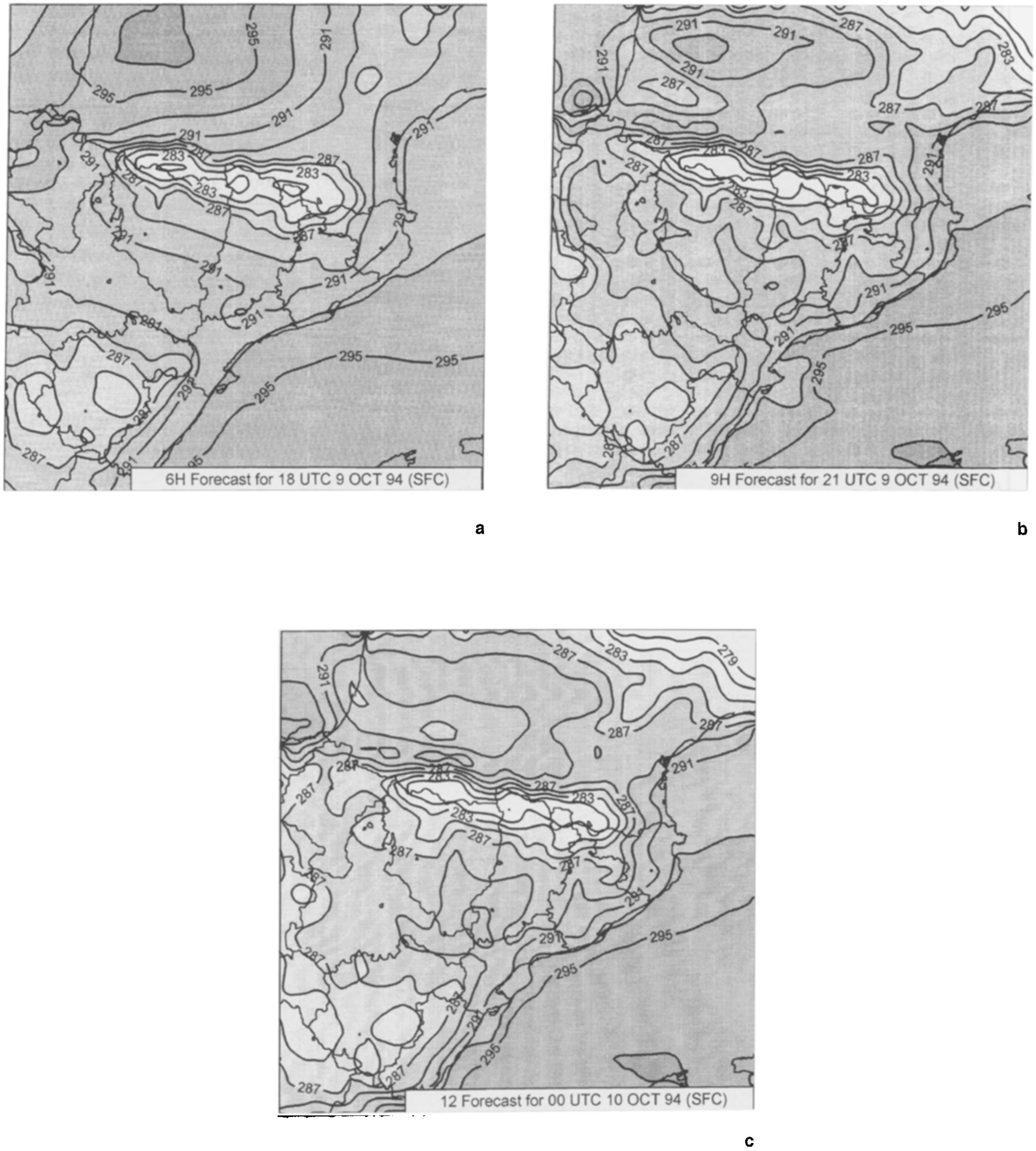


Fig. 14. Nested surface temperature forecasts (in K)

flow on the coast and the ranges parallel to the shoreline. Moreover, the flux of warm and humid air from the Mediterranean in the lower troposphere that is required for the development of convective instability, is reflected in the 850 hPa forecasted maps between 00 and 09 UTC 10 October (Fig. 15), which display the formation of a southeasterly jet. The wind blows perpendicular to the isotherms and the warmest air advects towards the coast of Catalonia. It is also apparent that the displacement to the NE of the low pressure center within these hours causes the wind to flow perpendicular to the coast of Tarragona first (Fig. 15a), then to Barcelona (Fig. 15b and c) and to the coast of Girona later, after 09 UTC 10 October (Fig. 15d). This is indeed the movement exhibited by the MCS which agrees, as is expected for this kind of phenomena, with the dominant wind direction in the mid and upper troposphere (Fig. 9a and b).

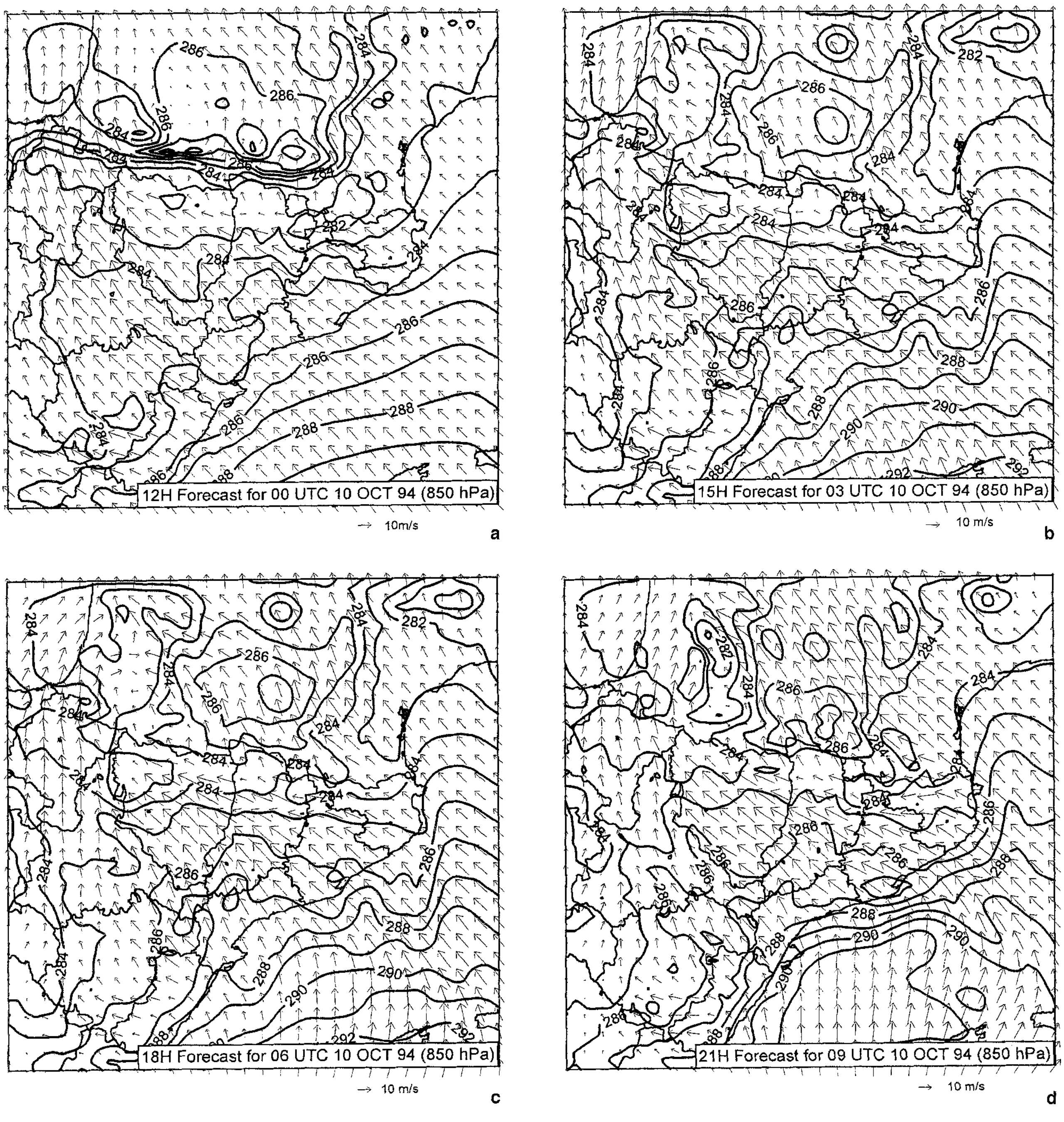


Fig. 15. Nested 850 hPa temperature (in K) and wind forecasts

This is confirmed by the forecasted precipitation fields. Thus, between 21 UTC 9 October and 03 UTC 10 October, the major rainfalls were expected in the south of Tarragona where the axis of the warm and humid 850 hPa jet was located at this time, and the surface convergence was the largest. Between 03 and 06 UTC 10 October, the rain spread to other areas close to the Catalan coast (Fig. 16c) and, concurrently with the displacement to the north of the jet axis, between 06 and 09 UTC the area of heavy precipitation moved towards the province of Girona (Fig. 16d), and became stronger 3 hours later in the north of this province (Fig. 16e).

Lack of mesoscale meteorological observations for this region did not allow us to carry out a suitable quantitave validation of our forecast. The only available variable measured at this scale is precipitation. Since a reasonable representation of the precipitation field should imply that the model captured the essence of the dynamics of the event, we have used this variable to verify our simulation. Within this episode, the total precipitation forecasted by the model between 00 and 12

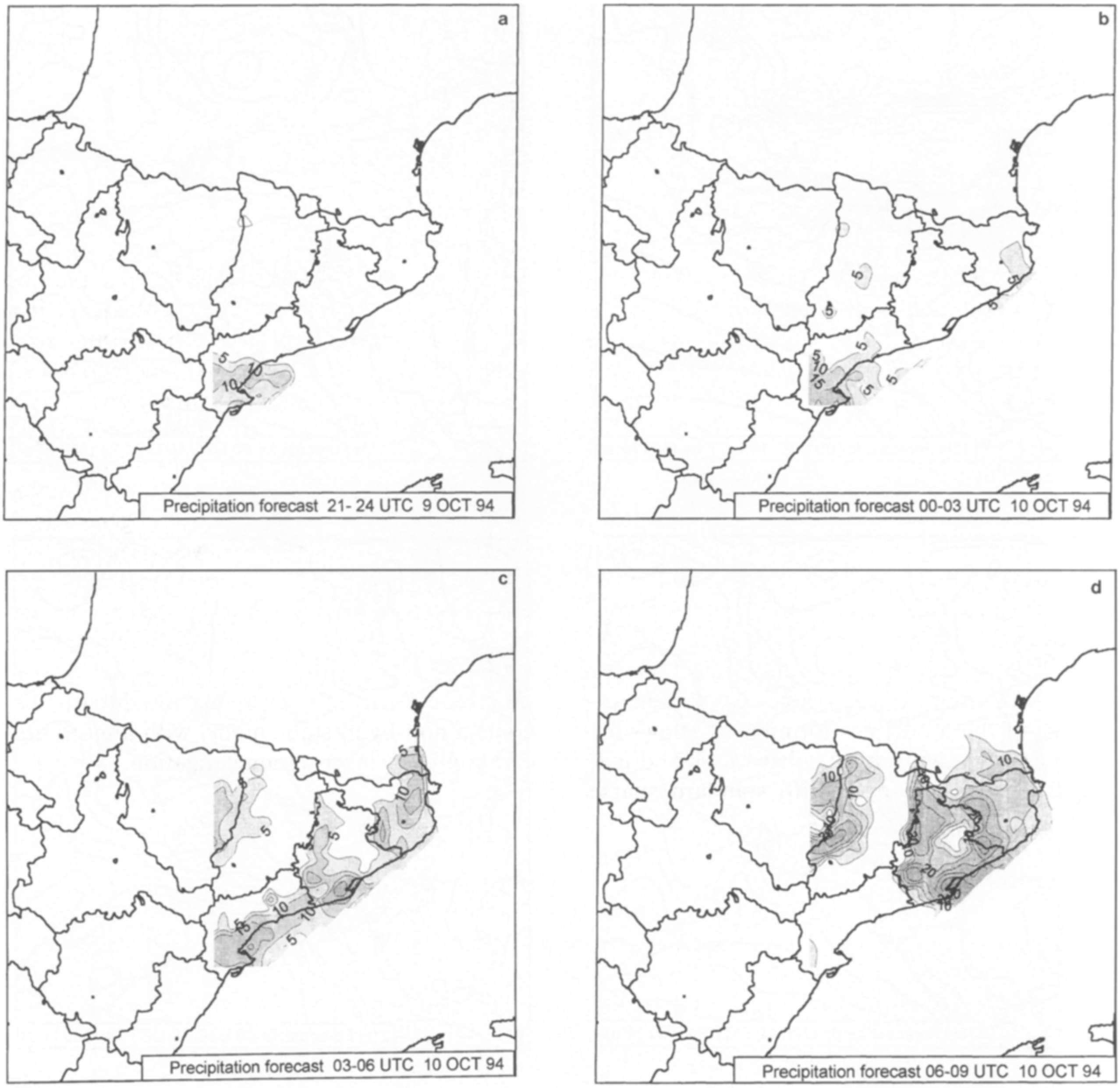


Fig. 16. (*Continued*)

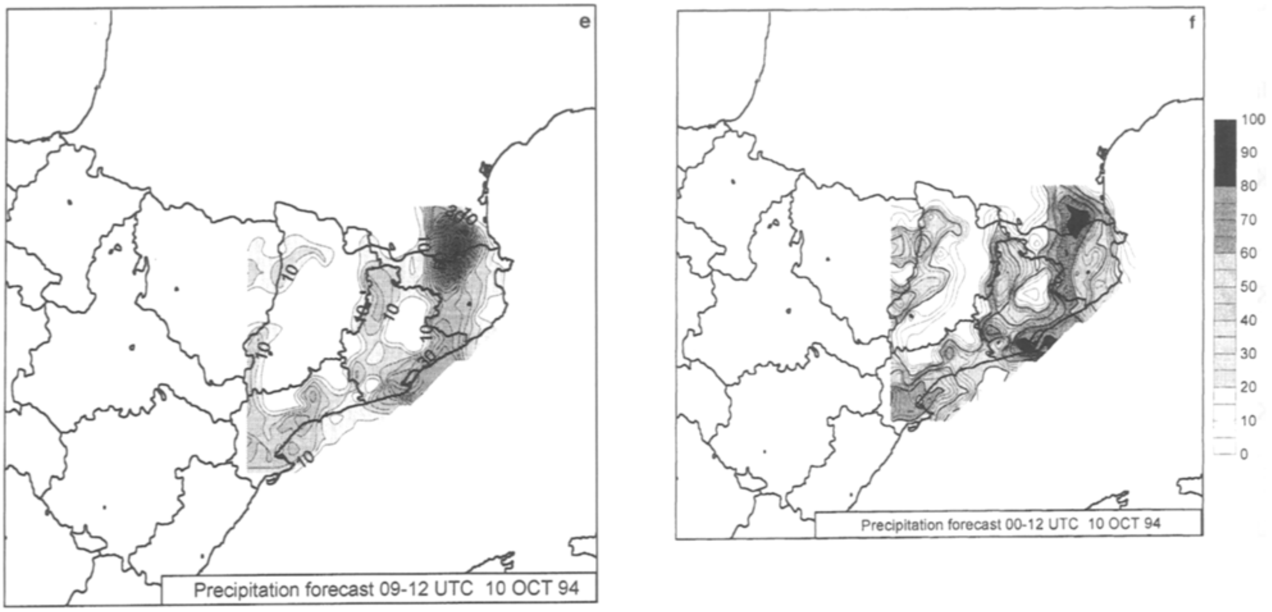


Fig. 16. Total precipitation forecasts (in mm) at indicated intervals

UTC 10 October (Fig. 16f) exceeds 100 mm in several places and, in spite of being certainly lesser than the collected precipitation, the isohyets delineate with a very good approximation the areas affected by floods.

5. Conclusions

The use of a mesoscale model to predict a convective system over NE Iberian Peninsula has proven to be quite satisfactory. Several things can be highlighted from our first attempt to employ such a model to gain more insight over these episodes that adversely affect that region. First of all, the resolution at which the equations and parameterizations of the model are formulated allows for a very accurate analysis of subsynoptic and mesoscale circulations, even with standard sparse synoptic and radiosonde observations. The simulation confirms the results of other authors who stress the role of the Atlas and Pyrenees ranges in stimulating an eastern circulation over the Catalan shore, and the coastal mountains which trigger the destabilization of warm and humid air from the sea. Finer details of the event are achieved through the nested simulation, like the displacement of the main precipitation areas at the same pace as the 850 hPa jet. Although the heavier precipitation was forecasted approximately at the right location, the precipitation totals were considerably less than observed. Obviously, one cannot expect to resolve the small scale and unusual precipitation peaks recorded in that event with a 10 km resolution model grid.

Further work has to be undertaken to give conclusive results. First of all, more episodes of this nature have to be gathered to see whether these preliminary results can be generalized. Moreover, a comparison between satellite and radar imagery with forecasted humidity and liquid water content fields and outgoing infrared irradiance at the top of the model should be done to provide a more rigorous verification. On the other hand, MASS is currently rewritten to become a non-hydrostatic model with a more precise boundary layer parameterization.

Acknowledgements

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