8.8 OBSERVATIONS AND FINE-GRID SIMULATIONS OF AN OROGRAPHICALLY-INITIATED CONVECTIVE EVENT IN NORTHEASTERN SPAIN

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1. INTRODUCTION

Ordinary convective cells develop almost every afternoon during summer in northeastern Spain over the elevated terrain of the Pyrenees and Iberic System (Fig. 1). These storms are normally the result of the intense solar heating, which destabilizes the boundary layer, activates upslope and valley wind systems and the inflow of maritime air through breeze circulations, and modulates an otherwise suppressive synoptic environment by means of a quasi-permanent thermal low over the dry Iberian plateau (Alonso et al. 1994).

When synoptic conditions are more supportive, as with cold air aloft, short-wave troughs moving over the region at upper levels, or when influenced by a passing cold front, convection can become more intense and extensive (as well as more organized and long-lasting), and move well into the adjacent lowlands. During the evening of 7 August 1996 a convective storm that developed in the Biescas zone (Huesca; see Fig. 1) produced more than 200 mm of rainfall between 15 and 18 UTC **, causing a severe flash flood which killed 86 people in a camping site.

The storm at Biescas was only a small-scale component of a widespread convective development that affected several provinces of northeastern Spain. Several convective systems coexisted in time. These systems generally exhibited differential movement speeds and directions, and some of them even interacted with each other. This paper provides a depiction and physical interpretation of the mesoscale processes that evolved in the convective environment of 7 August 1996, based on both observations and output from fine-grid mesoscale numerical simulations.

2. OBSERVATIONAL ASPECTS OF THE EVENT

An analysis of the observed rainfall between 07 UTC 7 August and 07 UTC 8 August (Fig. 2) displays a peak value in the Biescas area. By using radar-derived amounts corrected with local rainfall registers, Riosalido et al. (1998) estimated that the actual maximum likely exceeded 250 mm, with 225 mm accumulated between 15 and 18 UTC and 150 mm between 16 and 17 UTC. As reflected in Fig. 2, rainfall greater than 5 mm was widespread in the northeastern provinces.

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** Local time during summer corresponds to UTC+2 hr.

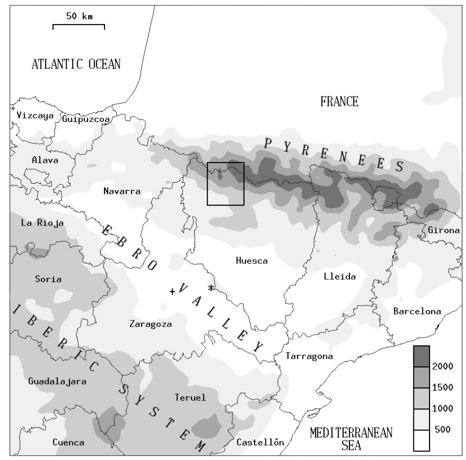

Figure 1. Depiction of northeastern Spain. The scale for the orography is expressed in m. The locations of the radar and radiosounding sites in Zaragoza are indicated by the asterisk and cross symbols respectively. The Biescas zone, where the flash floods occurred, is demarcated by the interior rectangle.

The episode began at about 12 UTC (Fig. 3), suggesting that diurnal heating could be an important factor. The convection started on the slopes and peaks of the Pyrenees and Iberic System and was initially confined around these zones (Fig. 3a). Convective systems S1 and S2 progressed eastward from their initial locations over the mountains (Fig. 3b). About 15 UTC, the convective development that was to affect Biescas was already visible at the western extreme of the chain of convective cells attached to the Pyrenees (B in Fig. 3b). Unlike the bigger systems S1 and S2, B remained basically stationary during the subsequent hours, gaining in intensity and areal extent and extending downslope from its genesis area on the mountain peaks of the Spain-France boundary.

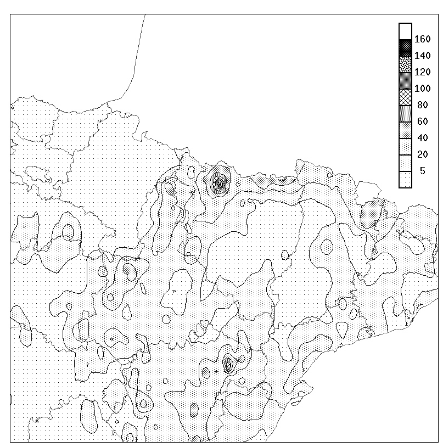

Figure 2. Analysis of the observed rainfall (mm) in northeastern Spain from 07 UTC 7 August to 07 UTC 8 August 1996.

From that time (Figs. 3c to e), the evolution of the convective systems changed significantly, probably as a consequence of the complex disruption of the flow by the convection itself. While system S2 continued its eastward movement until its dissipation about 19 UTC, system S1 started to exhibit a northeastward movement (S1n) at the same time that other active cells developed on the southwestern part of the convective band over southern Zaragoza (S1s). After 17 UTC, the system S1n merged with the convective storms of the Pyrenees, losing its elongated structure with time and undergoing a gradual dissipation. In particular, precipitation rates in the Biescas zone decayed rapidly after the interaction of the storm B with the system S1n at 18 UTC. Meanwhile, the system S1s also decayed, whereas the nearby system S3 grew and intensified very rapidly, dominating the situation as a squall line by 21 UTC (Fig. 3e).

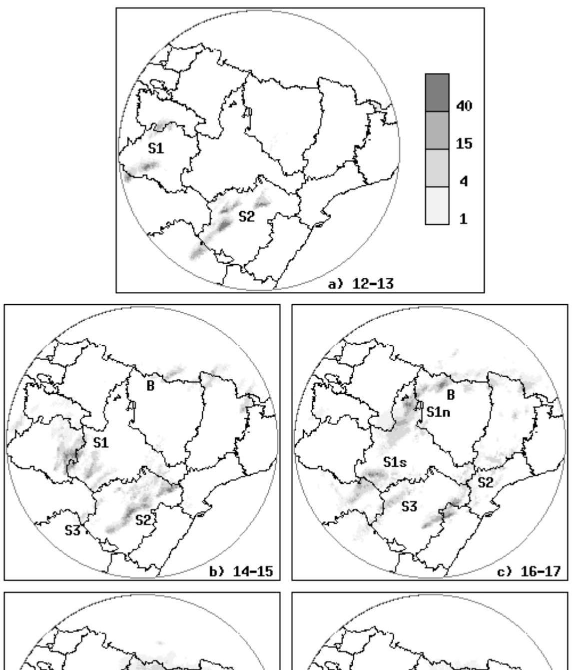

Figure 3. Sequence of hourly rainfall estimates (mm) by the radar of Zaragoza (Fig. 1) from 12 UTC 7 August to 21 UTC 7 August 1996, every 2 hr. Convective systems described in the text are indicated.

The synoptic situation at mid-tropospheric levels (Fig. 4) was characterized by the advance of a trough and cold front. This favored an increase of potential instability and a general pattern of upward quasi-geostrophic forcing over the eastern half of the Iberian Peninsula. At 12 UTC, the observed sounding at the Zaragoza station (Fig. 5) reflects a significant steepening of the middle and upper tropospheric lapse rates and relatively weak winds around 500 hPa, associated with the approach of the synoptic-scale trough. The precipitable water (PW) is 37 mm and the stability indices indicate probability of convection (LI, -2; K, 35; TT, 55; and CAPE, 945 J kg^{-1}). However, convective inhibition (CIN) was 165 J kg^{-1} as a consequence of the stable layer next to the ground. Therefore, significant lifting was necessary for the surface parcels to reach their level of free convection. In addition to a favorable synoptic-scale context, mesoscale lifting mechanisms are normally required to initiate and sustain deep convection (Doswell 1987).

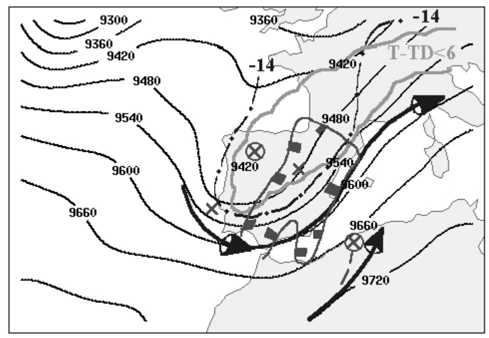

Figure 4. Synoptic composite chart on 12 UTC 7 August 1996 for mid- and upper-tropospheric levels (from Riosalido et al. 1998), showing geopotential height at 300 hPa, jet streaks (arrows), the area with upward quasi-geostrophic forcing at 500 hPa (contour with squares), curvature and shear vorticity maxima at 500 hPa (crosses with and without circle, respectively), area with dew point depressions at 500 hPa less than 6 degrees (scalloped contour) and the -14 ^{0}C isotherm at 500 hPa (dot-dashed line).

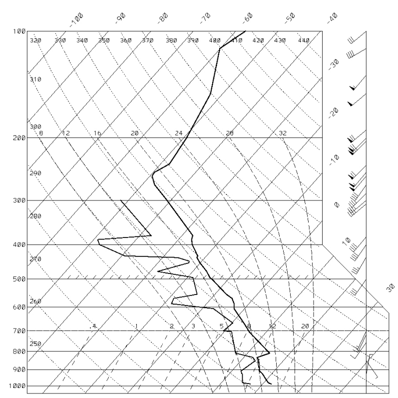

Figure 5. Radiosounding at Zaragoza (Fig. 1) on 7 August 1996 at 12 UTC. Full wind barb is 5 m s^{-1}.

Mesoscale ingredients for this event appear to be related with the organization of the low-level flow and with the orography (Fig. 6). The upper part of the Ebro valley was affected by cool northwesterly winds associated with a cold front, whereas the general flow was from the southeast, directly from the Mediterranean waters. The streamlines were deflected toward the slopes of the Pyrenees and Iberic System, probably as a result of the diurnal heating. A SW-NE oriented deformation zone was positioned across western Zaragoza and western Huesca, sustaining south-

southwesterly upslope winds in the Biescas area. An intensifying mesolow in the Ebro valley during the afternoon of thermal origin (as suggested by its warm core), as well as the slow down-valley progression of the cold front, combined to enhance the inflow and convergence towards northern Zaragoza and western Huesca. Presumably, the convectively-generated cold pools and outflow boundaries also conditioned the subsequent evolution of the convective systems in a complex way.

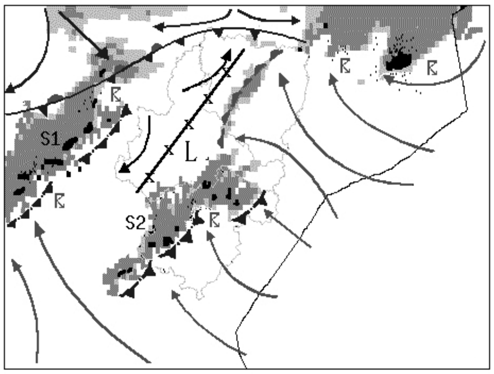

Figure 6. Surface mesoscale composite chart on 7 August 1996 at 12 UTC (from Riosalido et al. 1998). The chart shows streamlines, deformation zone represented by the dilatation axis, cold cloud tops as indicated by infrared channel of Meteosat (light and dark shaded), intense radar echoes (black areas), lightning activity (conventional symbol and black dots), front, outflow boundaries, warm boundary, and the mesolow developed in the central and upper portions of the Ebro valley (L). The provinces of Huesca, Zaragoza and Teruel are included as reference.

3. SIMULATIONS AND DISCUSSION

For the purpose of better identifying and evaluating the mesoscale processes that governed the particular mode of initiation and evolution of the convection, a simulation of the event was designed using the non-hydrostatic version of The Pennsylvania State University-National Center for Atmospheric Research mesoscale model (Grell et al. 1994). Since the present study requires a sufficiently high grid resolution for an adequate representation of the convective systems and proper incorporation of the terrain features, three sucessively nested domains with horizontal grid spacings of 36, 12 and 4 km were considered. The simulation presented extends 24 h, starting at 00 UTC on 7 August 1996.

In terms of the forecast rainfall field (Fig. 7), the primary simulation appears to be sufficiently validated (compare with the observed spatial structure of this field; Fig. 2). The major deficiencies occur along the Mediterranean coastal provinces, where the simulation indicates either no precipitation or too little precipitation owing to some difficulties of the model in maintaining the activity of the mature convective systems that enter those provinces from the west. Interestingly, the model locates very accurately a precipitation center at Biescas, with a moderate peak amount of 85 mm.

The capability of the model to capture the timing of the event is certainly remarkable, as can be verified by comparing the observed sequence of hourly rainfall (Fig. 3) with the same field computed from the simulation (shaded areas in Fig. 8).

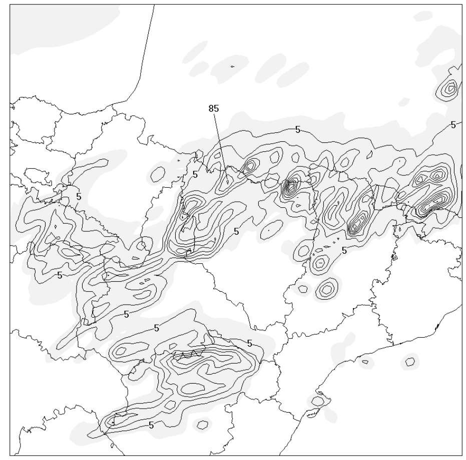

Figure 7. Forecast total precipitation. Contour interval is as in Fig. 2, with the shaded areas indicating rainfall in excess of 1 mm.

3.1 *Evolution of the convection and governing mesoscale processes*

Figure 8 summarizes the evolution of the simulated convective event from its beginning at noon until 21 UTC, when most of the inland convection started to dissipate. The triggering of the first convection (Figs. 8a and b) is certainly rooted in the appreciable lifting provided by the slopes of the Pyrenees and Iberic system. General upslope wind flows are simulated in agreement with the surface composite chart (Fig. 6). Further, the deformation zone observed across western Zaragoza and western Huesca is very well captured by the simulation, being most clear at 15 UTC (Fig. 8b). Another important feature that conditioned the low-level flow, the mesolow in the Ebro valley (L), is properly developed in the simulation. The mesolow deepens appreciably between 12 UTC and 15 UTC, the period in which the ground temperatures on the dry lowlands of the Ebro valley are the highest. The deepening of the mesolow is noted in the intensification of the southeasterly and northwesterly winds towards the center of Zaragoza, where the mesolow is located. Other remarkable and persistent features of the sea level pressure field are the blocking high pressure areas found along the north-facing flanks of the Pyrenees (H1) and Iberic system (H2), against which the cold front is trapped (Fig. 6).

The simulated convective systems S1 and S2 move from their genesis areas to the east/southeast in the same way as observed (Figs. 3a and b), approximately following the topography of the Iberic system. This movement appears to be regulated by the generation of new cells that are due to lifting provided by the upslope winds along the range, probably enhanced by the action of the outflows from previous convective areas. In fact,

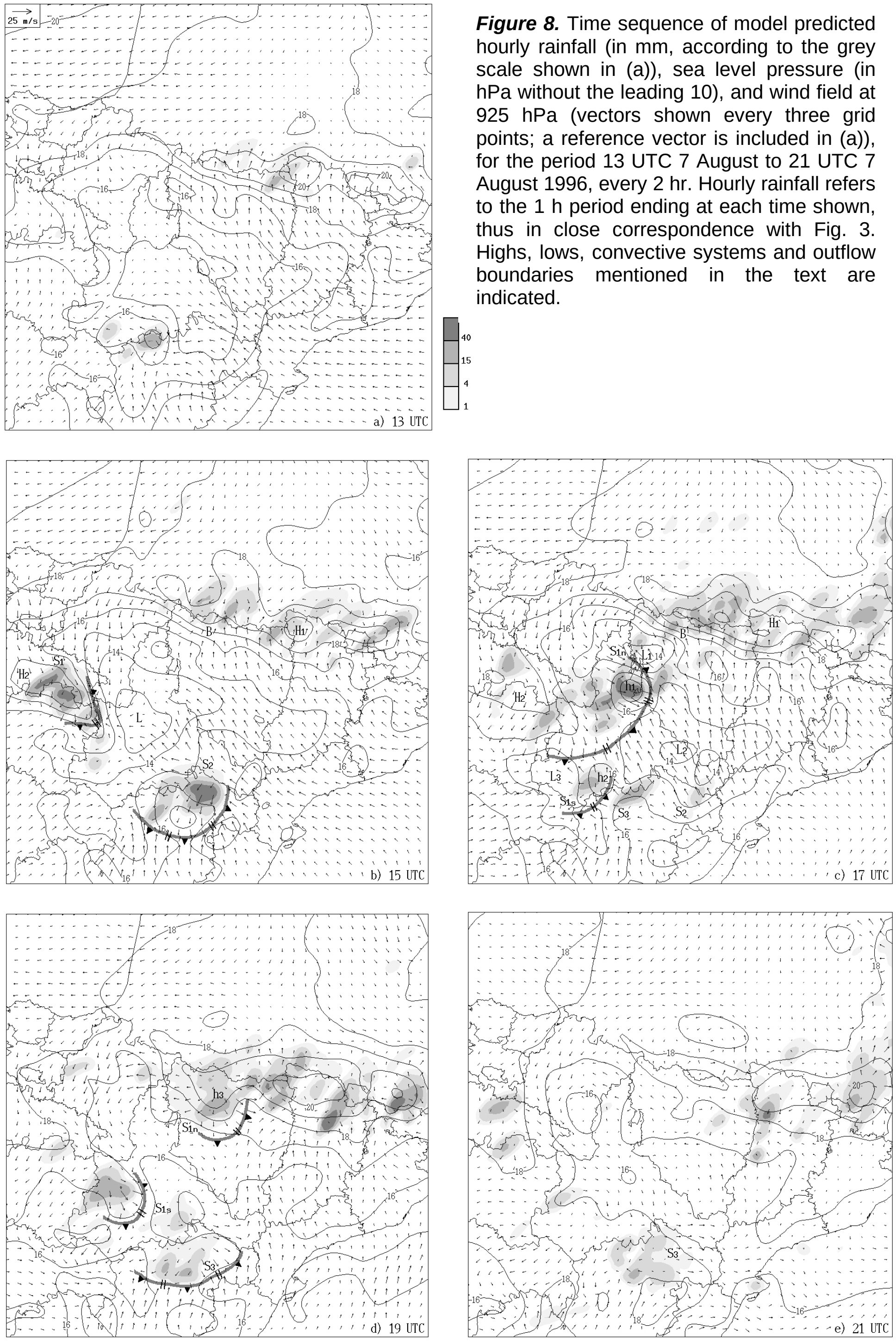

Figure 8. Time sequence of model predicted hourly rainfall (in mm, according to the grey scale shown in (a)), sea level pressure (in hPa without the leading 10), and wind field at 925 hPa (vectors shown every three grid points; a reference vector is included in (a)), for the period 13 UTC 7 August to 21 UTC 7 August 1996, every 2 hr. Hourly rainfall refers to the 1 h period ending at each time shown, thus in close correspondence with Fig. 3. Highs, lows, convective systems and outflow boundaries mentioned in the text are indicated.

convective outflows due to S1 and S2 are evident at 15 UTC (Fig. 8b), with the position of the outflow boundaries closely following the observations (Fig. 6).

From 15 UTC, the low-level flow pattern becomes very complex as a consequence of the disruption produced by the convectively-generated cold pools and outflows interacting with the complex terrain. These features are probably influential in the evolution and propagation of convection very strongly. The different movement of the convective systems S1 and S2 between 15 and 19 UTC noted on the radar images (Fig. 3) is also indicated by the simulation (Fig. 8). On one hand, system S2 continues its movement eastwards, although the simulated system dissipates too quickly compared with the observations. On the other hand, system S1 acquires a northeastward movement and therefore progresses well into the Ebro valley and towards the Pyrenees (S1n). Such movement results from the generation of new convection in northern Zaragoza and northwestern Huesca along areas with strong low-level convergence that appears to be connected with inflows into the mesolow and outflow winds arriving from S1 and S2. At 19 UTC the most important convection is affecting the northwestern quadrant of Huesca, and the connection between system S1n and the storm of Biescas (B) has already occurred (Fig. 8d). In addition, the other convective systems developed in southern Zaragoza and northern Teruel (S1s and S3, respectively) have grown in size and moved to the east during the 15-19 UTC time period. During the last hours of 7 August, the simulated convective event departs appreciably from the observed characteristics.

Of particular interest is the evolution of the convection in the Biescas area (storm B). Although the rainfall rate of the simulated storm is far below the actual value (225 mm in 3 h), the simulated spatial localization and life cycle of the storm as function of time are remarkably good (compare Figs. 3 and 8). The southward extension and gain in intensity of the storm between 15 and 17 UTC are well captured. The interaction of the storm with the larger system S1n approaching from the southwest after 17 UTC, the slight extension of the merger toward the east and its gradual dissipation, are equally correct. Such a convective sequence results from the characteristics of the low-level wind in the Biescas zone and how it evolves. Observe that sustained southerly winds impinging against the southern slopes of the mountains are predicted until 17 UTC (Figs. 8a-c). After the interaction with the convective system S1n, convective outflows begin to dominate in northwestern Huesca, so the low-level convergence shifts to the east and by 19 UTC the convective mesohigh (h3) and low-level divergence are evident in the Biescas zone (Fig. 8d). Under these conditions, the system quickly dissipates (Fig. 8e).

3.2 Importance of the diurnal forcing

Both the observations and the previous simulation suggest that diurnal forcing could have been an important factor for this event. Day-time diabatic heating in the boundary layer is typically very strong over the Iberian peninsula during summer as a consequence of the intense insolation and the very dry conditions of the semiarid terrain. The explosive character of the convection after noon would indicate that vertical destabilization in the boundary layer was necessary for the outbreak of the convection. Moreover, determinant features of the low-level flow, such as the mesolow in the Ebro valley and the sustained upslope winds, appear to be linked to the diurnal cycle. Therefore, it is worthwhile to investigate explicitly the role of the diurnal forcing for this case study. With this aim, another numerical simulation was performed, identical to the previous one but excluding solar radiation from the model physics.

Obviously, the importance of insolation for the boundary layer destabilization is well-known. A selected model sounding from Zaragoza (Fig. 9) is quite illustrative. A convective, well-mixed boundary layer develops in the full simulation (Fig. 9a), whereas the boundary layer is much cooler and more stable without solar radiation (Fig. 9b), resulting in very large amounts of CIN for the near-surface parcels to overcome.

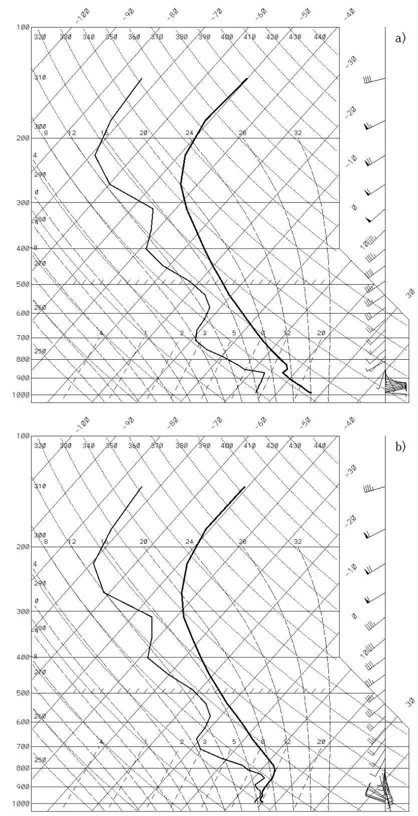

Figure 9. Model-predicted vertical soundings at Zaragoza on 13 UTC 7 August 1996 by (a) the full simulation, (b) the simulation without solar radiation. Full wind barb is 5 m s^{-1}.

The strong diurnal dependence of the low-level flow can be appreciated by comparing the results of the present simulation (Fig. 10) and the full simulation (Fig. 8a). It can be observed that without diurnal heating, the pressure gradient is much weaker and the mesolow of the Ebro valley does not develop. This supports the hypothesis that the mesolow has a thermal origin. Further, the widespread upslope wind systems obtained in the full simulation do not develop in this case either; the winds are generally weaker and rather parallel to the Pyrenees and Iberic ranges.

As expected, without the diurnal effects, the convection develops later and farther east, along a broad band extending between northeastern Huesca and the Mediterranean waters (Fig. 11). Presumably, most of the warm season convection that regularly affects northeastern Spain depends critically on diurnally-forced features of the flow for its initiation and spatial localization.

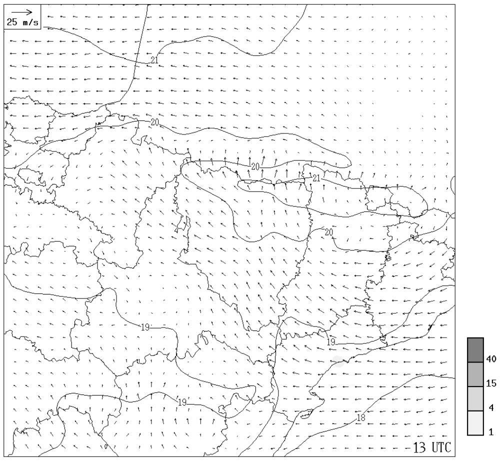

Figure 10. As in Fig. 8, except for the simulation without solar radiation and for 13 UTC 7 August.

Figure 11. As in Fig. 7, except for the simulation without solar radiation.

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