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Numerical simulation and sensitivity study of a severe hailstorm in northeast Spain

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Abstract

During the afternoon of August 16th 2003 a severe hail event occurred in the town of Alcañiz in the Ebro Valley (Spain). This storm brought with it intense rain and hail precipitation that caused severe floods, damaged cars and street furniture. A diagnosis, using data from ECMWF, showed the presence of a mesolow at surface level centered over the Northeast of Spain, carrying winds from the Mediterranean Sea towards the Central Ebro Valley. At medium and high levels, a trough, whose axis extended over the Northwest of the Iberian Peninsula, moved eastwards preceded at 500 hPa by a thermal trough that caused increasing instability before the arrival of the geopotential trough.

A numerical study of this event has been carried out using the MM5 model with a double aim. On the one hand, it attempts to check whether or not the simulation reproduces the storm in Alcañiz. On the other hand, it carries out a sensitivity experiment in order to evaluate the contribution of two specific factors: topography and solar radiation. Compared with radar data, the control simulation reproduces the region affected by the storm reasonably well. The suppression of topography and/or solar radiation substantially modifies the surface mesolow and the spatial distribution of the precipitation. Neither of these factors, considered independently, reproduces the precipitation caused by the storm in Alcañiz. However, the results illustrate the importance of the synergic effect of these two factors on the spatial localization of the storm and on the intensity of the precipitation registered.

Keywords: Severe storm; Hail; MM5 simulation; Radar

1. Introduction

The Ebro Valley is located in Northeastern Spain and orientated NW–SE. This valley is bordered by the mountainous area of the Pyrenees to the north, the Iberian System to the southwest, and the Mediterranean Sea to the east (see Fig. 1). Due to its location, the Ebro Valley is a corridor for the entrance of air masses from the NW down the valley, and from the Mediterranean coast. In the latter case, warm and humid air is taken to the area known as the Central Ebro Valley. This peculiar topography, together with the high temperatures registered during the summer months, make hailstorms a frequent phenomena during these months. In fact, the Ebro Valley is one of the areas in Europe with the highest number of cases of severe convective phenomena. There are 20 thunderstorms per year in the southern

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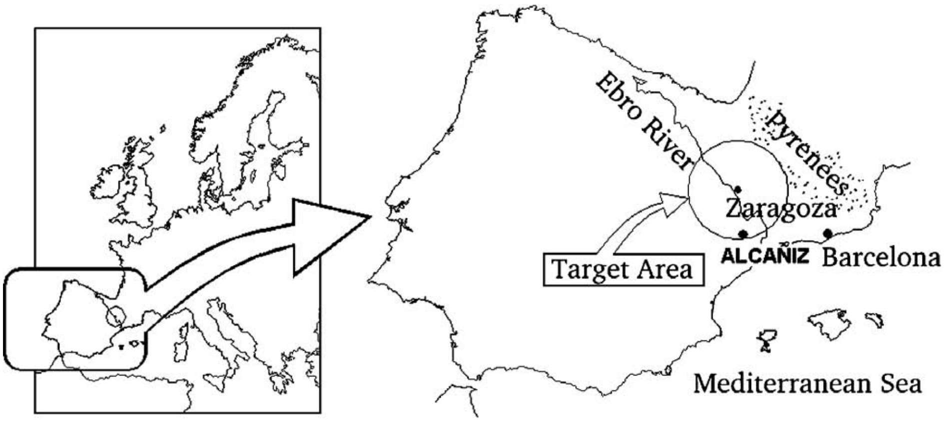

Fig. 1. Target area.

part of the Valley (Font, 1983). These storms are usually of the warm-based cloud type (Sánchez et al., 1999) and most of them can be classified as multicellular, whereas supercells only represent 3% of all cases (Castro et al., 1992).

Font (1983), basing his studies on the analysis of maps on a synoptic scale, attributes the development of thunderstorms to the release of latent instability by strong surface heating. This author claims that the topography plays a fundamental role in this development when there is cold air at medium and high tropospheric levels. However, more recent studies including numerical simulations of a mesoscale system, such as the one carried out by Ramis et al. (1999), demonstrate the importance of a thermal mesolow in a hail event in Cataluña. A similar mesoscale structure was the triggering factor in the catastrophic flash flood over the Spanish Pyrenees in the summer of 1996 (Romero et al., 2001). Tudurí et al. (2003) also conclude that the presence of a mesolow of thermal origin is a fundamental factor in the development of a chain of hailstorms in the Ebro Valley in the summer of 2001.

On August 16th 2003, between 1525 and 1820 UTC, a severe storm broke over the town of Alcañiz (41.02° N, 0.08° W), province of Teruel (in the Ebro Valley, Fig. 1). Rain gauges registered a maximum accumulated precipitation of 115 mm in slightly over 3 h. Within this time span, an intense hail fall affected the town and its surroundings for over half an hour, and hailstones of up to 12 cm were registered. Satellite images (not shown) provided information of the storms which originated over the Central part of the Ebro Valley and the existence of a mesoscale convective system generated over the Alborán Sea (southern part of the Spanish Mediterranean coast) that moved northwards. A C-band radar with a high time resolution was used to follow up the horizontal and vertical structure of the storm.

A number of numerical simulations were carried out in four domains that include synoptic, meso and microscales. The first aim of this study was to test whether or not the model could represent the conditions in which the severe storm in Alcañiz occurred, at both synoptic and mesoscale. Furthermore, it aims at studying whether or not the simulation at a higher resolution is capable of reproducing the event well enough. The information provided by the radar has been essential in order to locate the storm in time and space, and thus establish a comparison with the output of the model. Finally, the importance of topography and solar radiation has been studied in relation with the origin of this particular severe storm, considering not only their individual relevance, but also the contribution of the combination of both factors in locating the storm in time and space.

2. Observations

Infrared images from Meteosat show that by 1030 UTC a convective cloud mass started developing in the Central Ebro Valley, moving from NW to SE. Between 1530 and 1830 UTC the satellite images confirm that the cloud top temperature of the air mass over Alcañiz was between −60 and −65 °C. The cloud band associated to this air mass was subsequently pushed northwards by mid and high tropospheric winds, causing small disperse storms in the Pyrenees in the late evening. The 1200 UTC sounding in Zaragoza (Fig. 2) registered winds from the south at mid and high tropospheric levels. There is also a layer of instability in the lower first meters, and an area of conditional

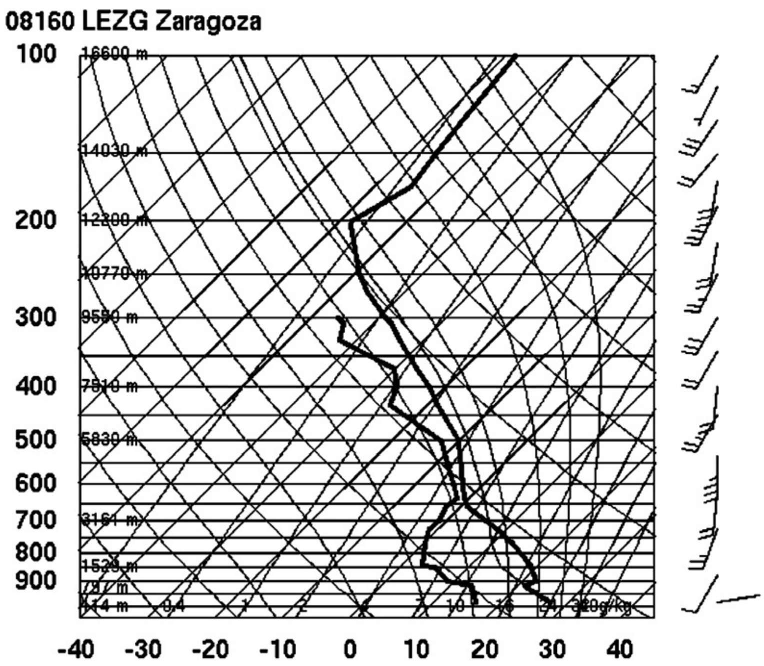

Fig. 2. Skew-T plot of the Zaragoza sounding on 16th August 2003 at 1200 UTC.

instability around 925 hPa, just before a layer of stability at 900 hPa. The Convective Available Potential Energy (CAPE) reveals favorable conditions for convective developments, going from 161.4 J kg^{-1} at 0000 UTC to 672.5 J kg^{-1} at 1200 UTC. In this same time interval, the Lifted Index went from −0.82 to −1.46.

A C-band radar with a high time resolution was installed close to Zaragoza, about 100 km from Alcañiz. This radar provided information on the horizontal and vertical structure of the storm with a spatial resolution of 1 km. The radar images show that the storm originated at approximately 1525 UTC. The radar echoes were almost stationary, indicating that the storm moved very little during its active life. At 1540 UTC, the maximum reflectivity factor of the storm reached 48 dBZ at an altitude of 11,000 MSL, with an echo top of 18 km. These values remained nearly unchanged for about an hour. At approximately 1650 UTC, the intensity of the storm decreased, but from 1710 UTC the storm gained renewed intensity, with a maximum reflectivity factor, Z_{max}, between 42 and 47 dBZ until 1740 UTC, when the storm started dwindling until it was completely dispersed by 1830 UTC. Rain gauges in Alcañiz registered a maximum accumulated precipitation of 115 mm in just over 3 h. In this time there was an intense hailfall in Alcañiz that lasted over half an hour, with hailstones between 5 and 12 cm.

3. Control simulation

3.1. Experiment description

Several numerical experiments were performed using the non-hydrostatic version of the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model MM5v3 (Dudhia, 1993; Grell et al., 1995). The multiple-nest capability of the model has been used in order to capture the synoptic scale evolution, the mesoscale and the microscale features of the episode with manageable computational cost. Four 151 × 151 grid domains, using Lambert's conformal projection, were set up to obtain the highest resolution over the area of interest (Fig. 3). The coarse domain has a resolution of 18 km, covering western Mediterranean areas, eastern mid-latitude Atlantic areas and the north of Africa (domain 1). The three other nested domains (domains 2, 3 and 4) are centered in the study area with a resolution of 6, 2 and 0.67 km, respectively. Vertically, 23 terrain-following σ-levels have been considered. The model output intervals used are 6, 3, 1 and 0.5 h, respectively. The four domains interact with each other through a two-way nesting strategy. Initial and boundary conditions for the coarse domain are constructed from the analysis of the ECMWF. The source data of the 25-category classified global coverage, with the resolution of 5 min (domain

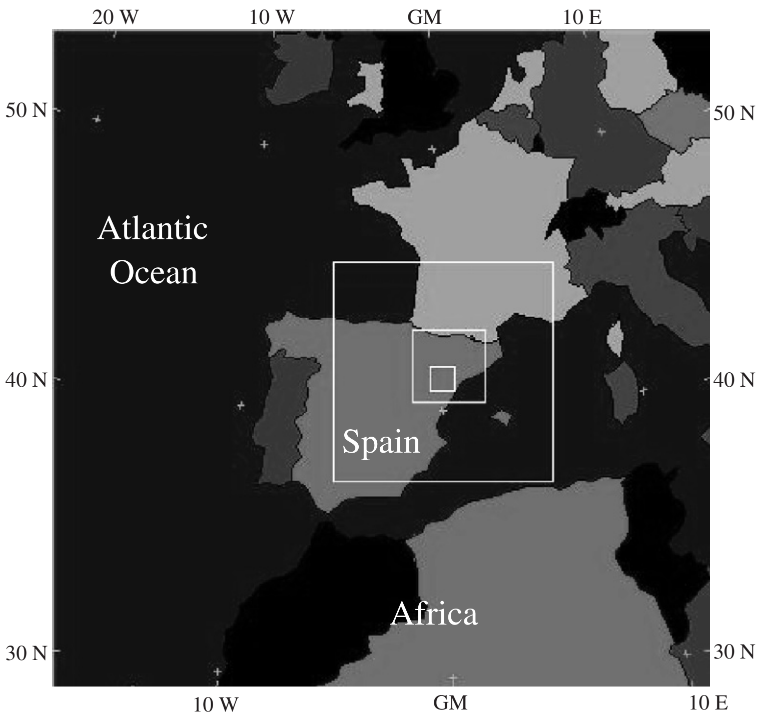

Fig. 3. The four domains used for numerical simulations.

1), 2 min (domain 2) and 30 sec (domains 3 and 4), were used to specify terrain elevation, land use, vegetation cover and land–water mask.

As for the period of time covered by the experiments, a 36-h long simulation was performed, from August 16th at 0000 UTC to August 17th at 1200 UTC, to ensure a stable behavior of the model during the time of the storm.

The MM5v3 model includes different physical parameterizations. For the present study, the Kain and Fritsch (1990) convective parameterization scheme was used for domain 1. In domains 2, 3 and 4, no convective scheme has been introduced and convective processes are fully explicit. The moisture scheme used was the Reisner graupel (Reisner et al., 1998) based on a mixed-phase scheme, but adding graupel and ice number concentration prediction equations. The parameterization scheme used to represent the planetary boundary-layer processes is the MRF scheme (Hong and Pan, 1996).

3.2. Model validation and diagnosis

The numerical study requires a control run that reproduces closely the observed meteorological aspects of the event. The model simulation must reproduce the observations for a run to be considered useful, keeping in mind the difficulty involved in achieving accuracy in the results when simulating an event on a convective scale with four domains, with the smallest one having a grid domain of only 0.67 km.

The simulation results show that the model reproduced reasonably well the evolution on a synoptic scale of the domains observed in the ECMWF analysis at all tropospheric levels. The simulation in domain 1 (Fig. 4) shows that at 300 hPa and at 1200 UTC there is a trough over the Iberian Peninsula with a low over Galicia moving eastward until 1800 UTC. As a result, an upper-level flow from S–SW is found over the study zone. A similar topography is observed at 500 hPa, with a cold air mass affecting the region of Aragón and the Mediterranean coast, with temperatures below −12 °C to the east of the geopotential trough moving eastward (Fig. 5). This cold air mass has to be taken into account, as it will cause increasing instability before the trough arrives.

On the other hand, Fig. 6 shows a strong temperature gradient over the Iberian Peninsula at 850 hPa moving NW–SE, with temperatures from 10 °C in the north Atlantic coast of Galicia to 19 °C in the Mediterranean coast, with a maximum of 22 °C to the south of Alcañiz.

Fig. 7 corresponds to domain 2 and shows a thermal mesolow at 1200 UTC over the Central Ebro Valley. This low becomes more marked in the study

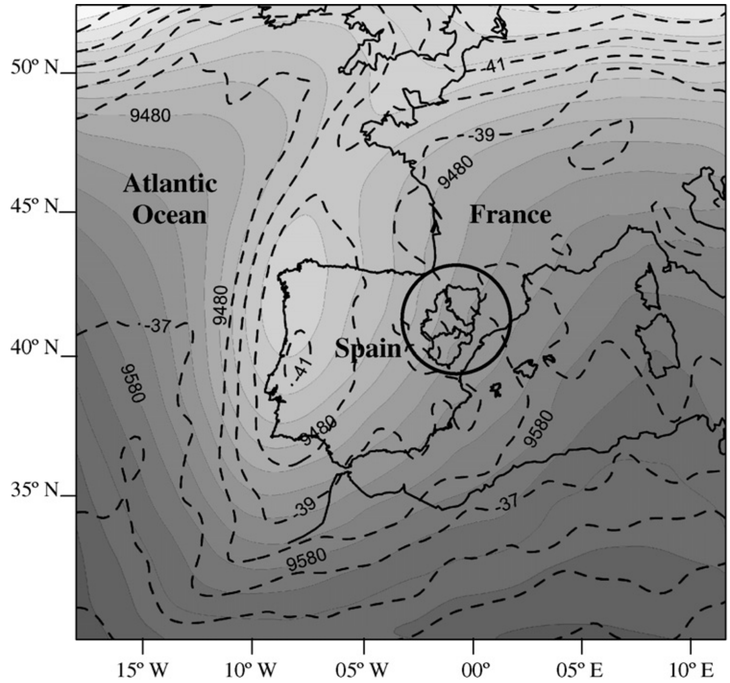

Fig. 4. Geopotential height (gpm, shaded areas) and temperature (°C, dashed line) at 300 hPa at 1200 UTC on 16th August 2003, as simulated by the model (domain 1). The circle comprises the area of study.

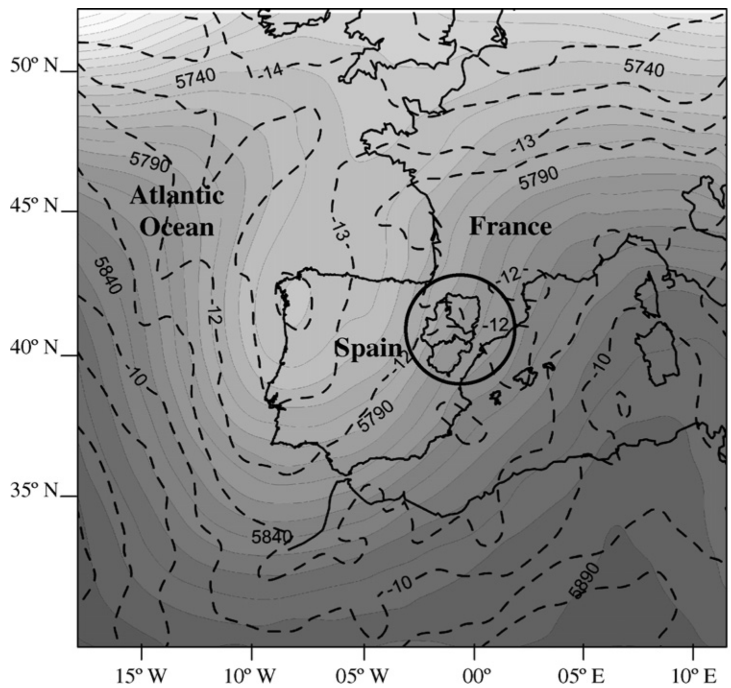

Fig. 5. Geopotential height (gpm, shaded areas) and temperature (°C, dashed line) at 500 hPa at 1200 UTC on 16th August 2003, as simulated by the model (domain 1). The circle comprises the area of study.

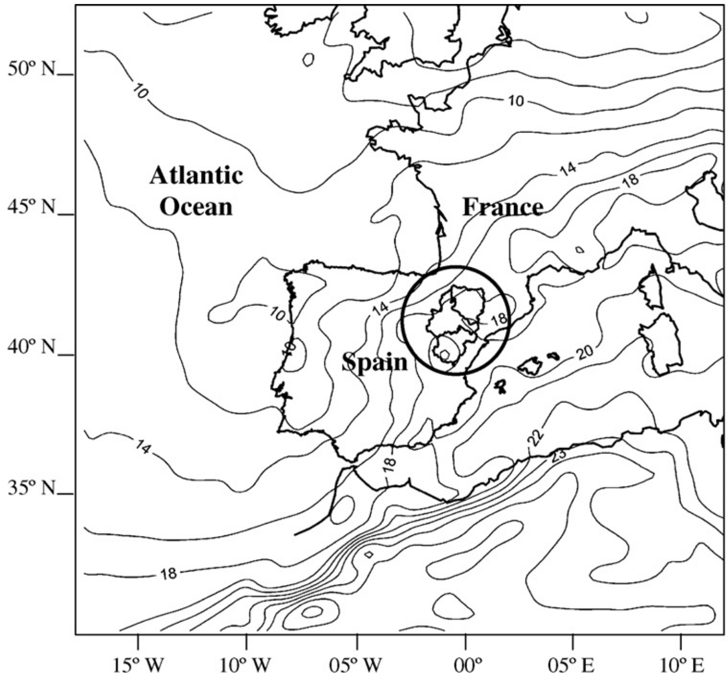

Fig. 6. Temperature (°C) at 850 hPa at 1200 UTC on 16th August 2003, as simulated by the model (domain 1). The circle comprises the area of study.

zone. The figure highlights that the area of Alcañiz registers temperatures of over 31 °C. Between 1200 and 1500 UTC there is a strong increase in the relative surface humidity in the study zone (not shown), soaring from 40% to over 75%. Fig. 8 corresponds to domain 3 and shows the surface wind field from the

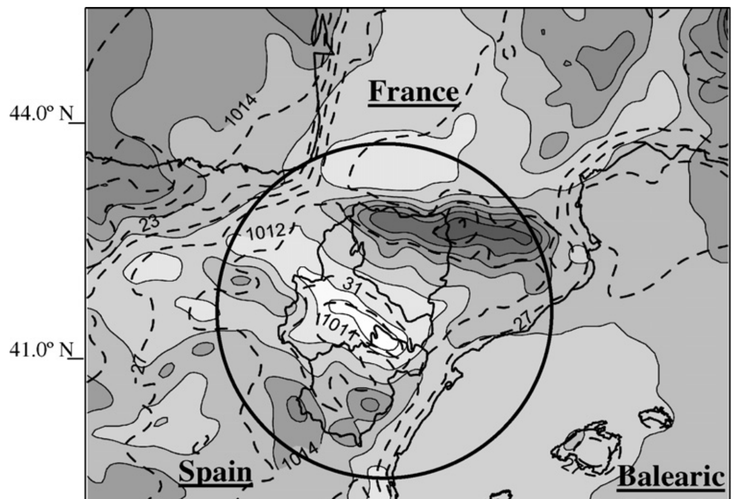

Fig. 7. Sea level pressure (hPa, shaded) and surface temperature (°C, dashed line) at 1200 UTC on 16th August 2003, as simulated by the model (domain 2). The circle comprises the area of study.

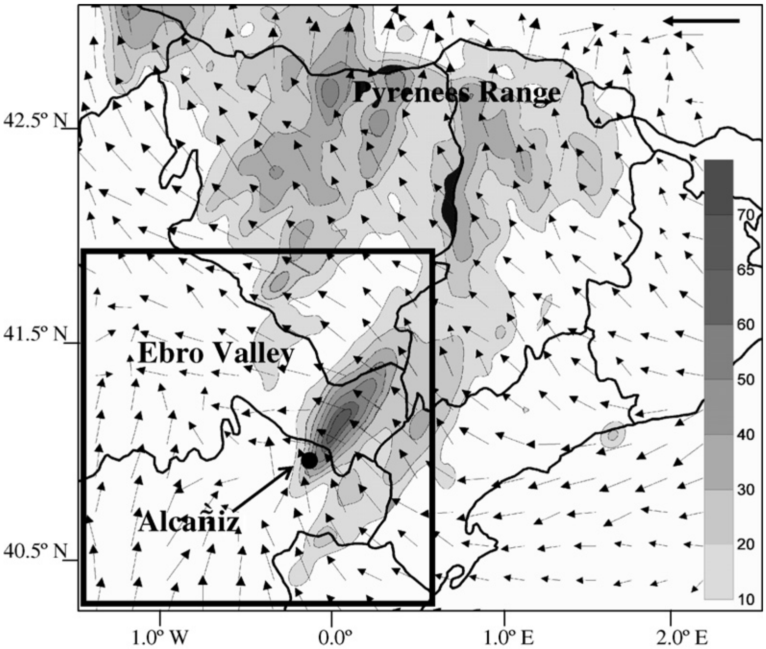

Fig. 8. Simulated surface wind field at 1200 UTC. Arrow on upper right-hand corner corresponds to 12 ms^{-1}. Simulated precipitation field (control simulation) recorded from 00 UTC to 19 UTC on 16th August 2003. Precipitation is in mm. (domain 3). The box in the lower left is shown enlarged in Fig. 9.

Mediterranean Sea entering the Ebro Valley, and reaching Alcañiz by 1200 UTC. This wind field associated with the thermal mesolow supplies warm air from the Mediterranean Sea, which had in those days temperatures higher than average in that time of the year, with a high content of water vapor. The

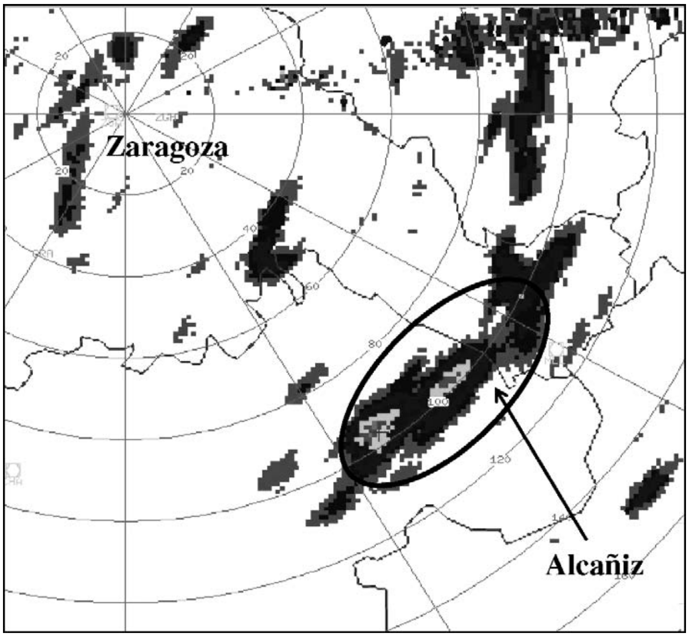

Fig. 9. Accumulated precipitation areas provided by the C-band radar in Zaragoza recorded from 00 UTC to 19 UTC on 16th August 2003. The highlighted area indicates the zone affected by the severe storm. The picture corresponds to the boxed region in the Fig. 8.

surface inflow, the convergence area shown in Fig. 8 around Alcañiz, and the thermal mesolow, overlapping on a favorable synoptic environment, with a deep trough and a cold front arriving from NW, are enough to trigger convection.

Fig. 8 also shows the total precipitation field. This field comprises, on the one hand, the northern part of the domain until the Pyrenees, and on the other hand, the Ebro Valley near Alcañiz. The shaded areas over Alcañiz indicate the highest intensity in precipitation.

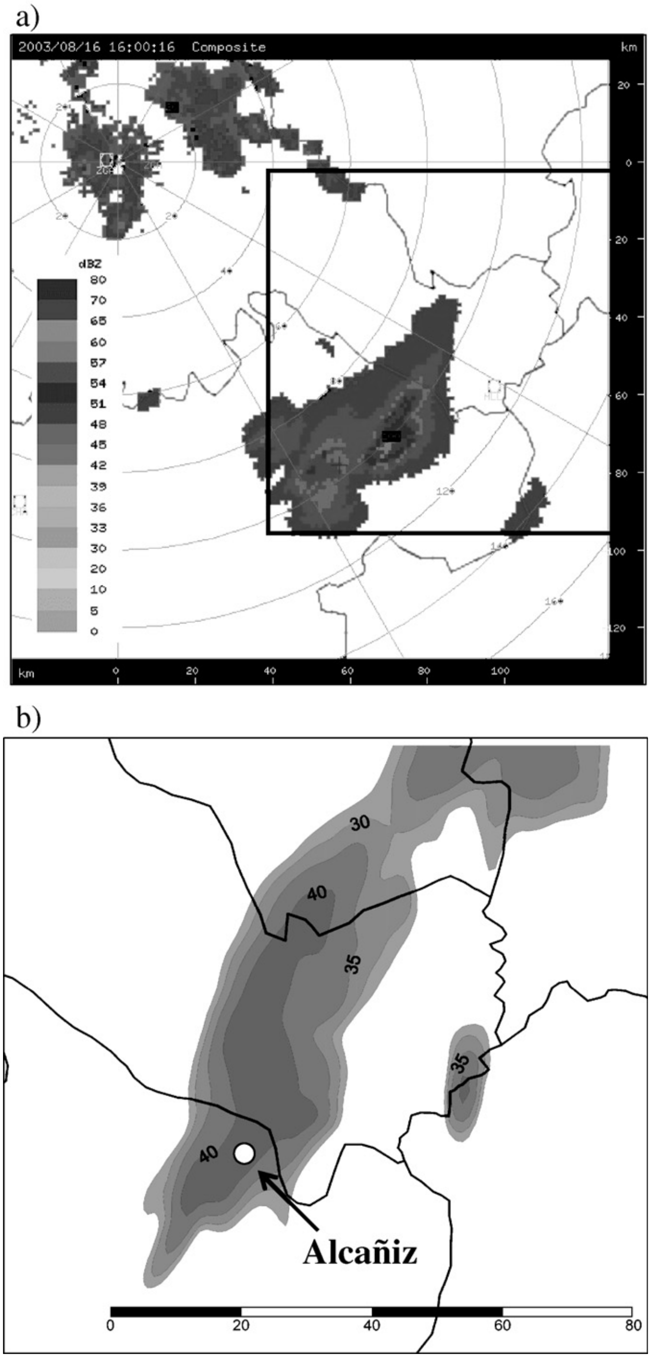

Fig. 10. a) Composite reflectivity factor (dBZ, according to the scale) provided by the radar at 1600 UTC. b) Zoom to the box in Fig. 10a showing the simulated reflectivity factor averaged between 1530 and 1600 UTC (domain 4).

As far as precipitation in the Pyrenees is concerned, there were some isolated storms, but the radar range and the mountainous profile of this area have hindered the gathering of additional information about this fact. If we compare the results of the simulation with the actual study zone, according to the radar data (Fig. 9) it may be stated that the simulation reproduces quite closely the area affected by the severe storm. The point that establishes the maximum precipitation estimated by the radar moves only 15 km to the SW of the maximum precipitation point, according to the model. However, the maximum precipitation recorded by the rain gauges

a)

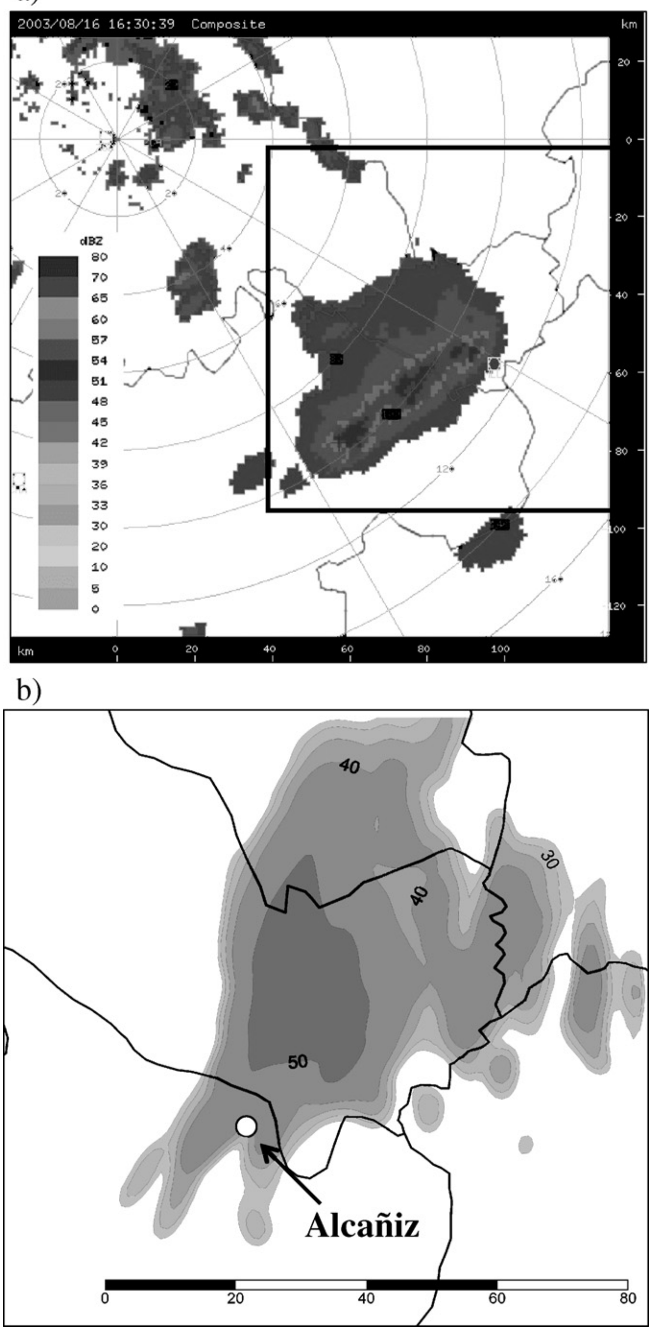

Fig. 11. a) Composite reflectivity factor (dBZ, according to the scale) provided by the radar at 1630 UTC. b) Zoom to the box in Fig. 11a showing the simulated reflectivity factor averaged between 1600 and 1630 UTC (domain 4).

in Alcañiz was 115 l m^{-2}, whereas the model gives a maximum precipitation value of 85 l m^{-2}.

In addition, the model simulates reasonably well the environment and the convective activity causing the severe hail event in the area of Alcañiz. The model locates very precisely the area with the most intense precipitation, although it underestimates the amount registered. Taking into account that the present study is focused on one single severe storm, and considering the difficulty of reproducing these

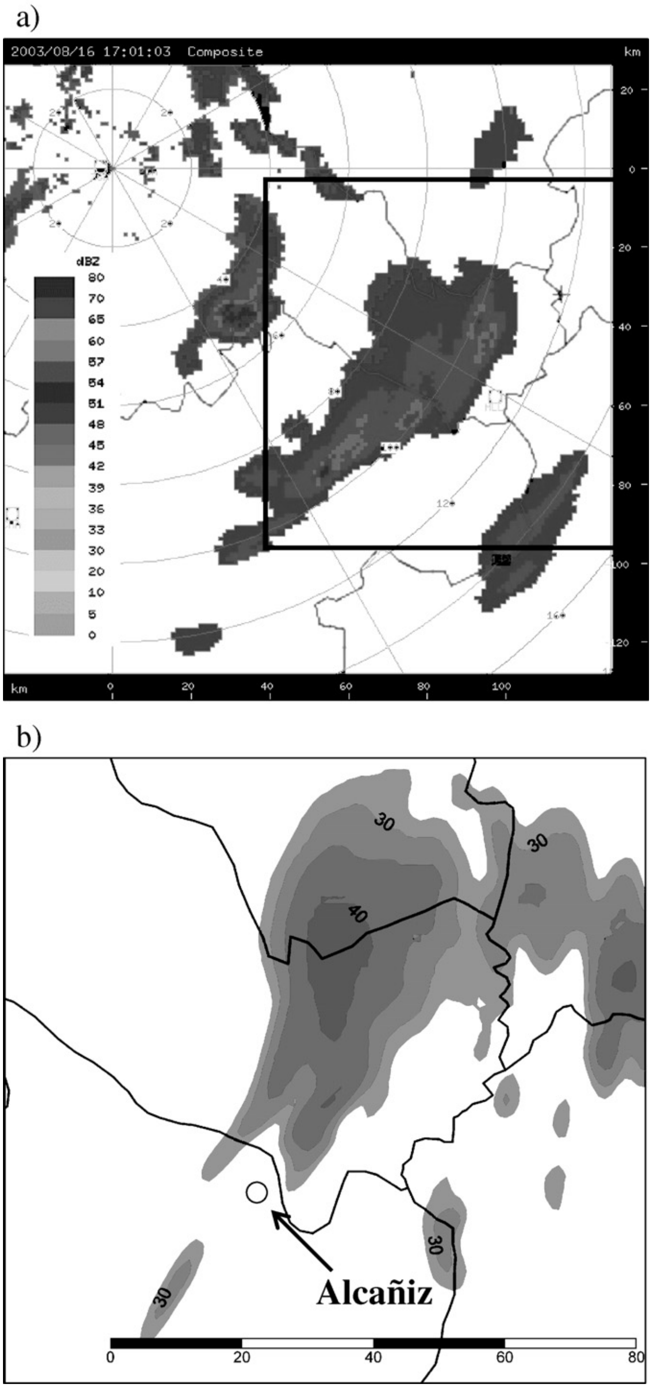

Fig. 12. a) Composite reflectivity factor (dBZ, according to the scale) provided by the radar at 1700 UTC. b) Zoom to the box in Fig. 12a showing the simulated reflectivity factor averaged between 1630 and 1700 UTC (domain 4).

events on a convective scale, the results found are so satisfactory that the authors consider carrying out a more in-depth analysis of the causes of the event to use this simulation as a control simulation for a sensitivity study.

3.3. Radar vs. simulation

The radar was simulated on domain 4 between 1530 and 1830 UTC to analyze whether or not the model was capable of reproducing the spatial and temporal

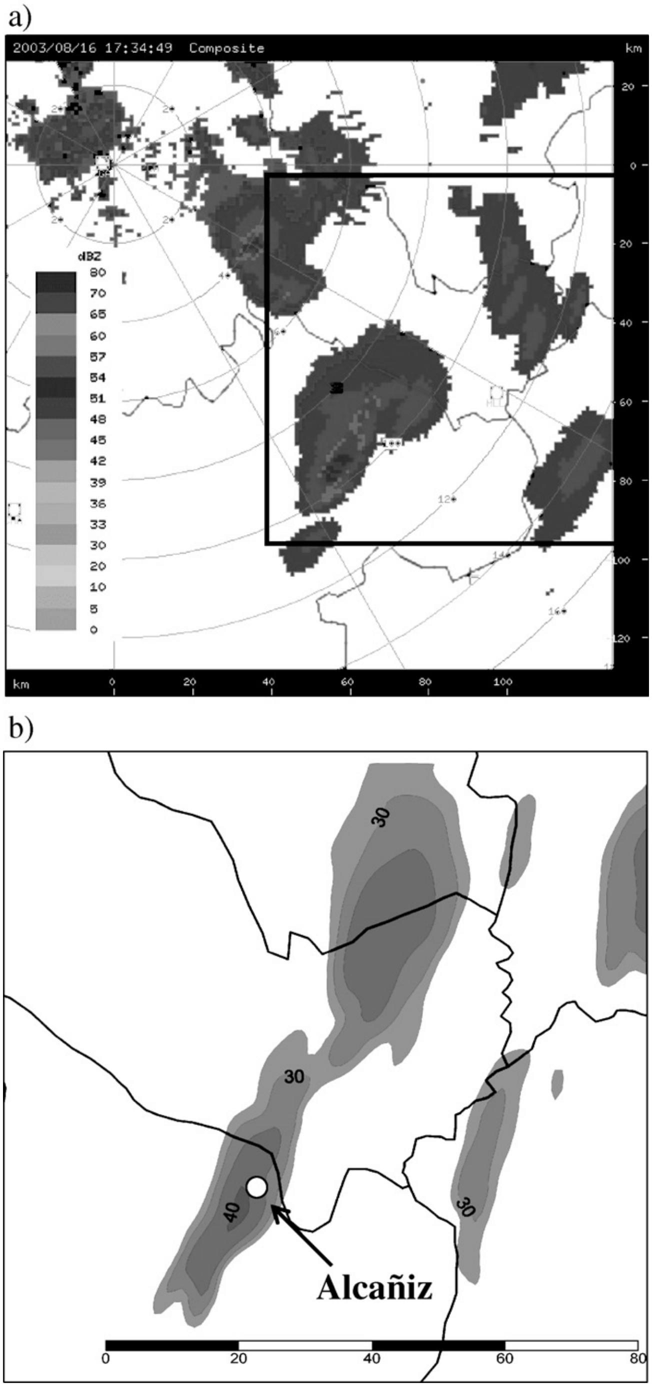

Fig. 13. a) Composite reflectivity factor (dBZ, according to the scale) provided by the radar at 1730 UTC. b) Zoom to the box in Fig. 13a showing the simulated reflectivity factor averaged between 1700 and 1730 UTC (domain 4).

evolution of the storm. Radar data are supplied every 3.5 min approximately, while the model output interval in domain 4 is 30 min. Because of this, a statistical comparison was carried out. The average values of the radar reflectivity factor were calculated at intervals of 30 min, and the data were compared to the simulation of the radar reflectivity factor averaged every 30 min.

In reference to spatial evolution, it is interesting to observe (Figs. 10–14) that there is quite a high degree of similarity. Between 1530 and 1700 UTC the radar

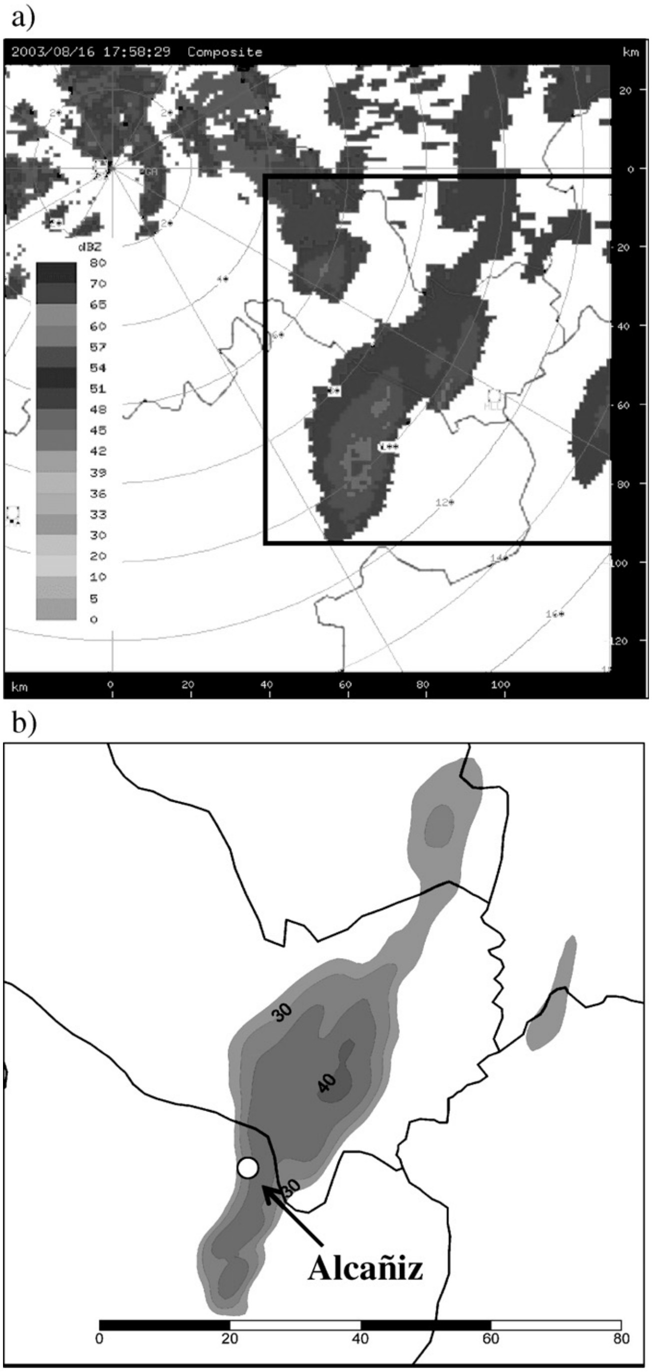

Fig. 14. a) Composite reflectivity factor (dBZ, according to the scale) provided by the radar at 1800 UTC. b) Zoom to the box in Fig. 14a showing the simulated reflectivity factor averaged between 1730 and 1800 UTC (domain 4).

shows how the storm moves slowly towards the NE. The same behavior is observed in the simulation. The radar images show that around 1700 UTC the storm starts dissipating in its central and northeastern parts, whereas the southwest regains activity, although to a smaller extent. Similarly, the simulation shows a decrease in the intensity of the storm, followed by a renewed activity in the SW of domain 4. The intensity of this new nucleus increases between 1700 and 1730 (Fig. 13).

The most intense hail event occurred between 1600 and 1630 UTC. The maximum value of the maximum radar reflectivity factor, $Z_{max}=54$ dBZ, was registered at 1613 UTC (not shown). The simulation shows that the intensity of the storm reaches its maximum values between 1600 and 1630 UTC, coinciding with the data from the radar.

4. Sensitivity experiments

Once the most relevant synoptic and mesoscale-scale components in the development of the episode have been diagnosed, and once the satisfactory performance of the model in the simulation of the storm has been confirmed, it would be interesting to determine which factor has the strongest impact on the formation of the storm.

As mentioned above, the occurrence of a thermal mesolow is a feature common to various cases of severe convective phenomena studied in the Ebro Valley, and it was also present in the storm in Alcañiz. The peculiar topography of Alcañiz, to the south of a valley that forms a corridor to the Mediterranean Sea between the Pyrenees and the Iberian Mountains, fosters the inflow of warm and humid air from the sea and the lifting of low-level parcels. In other words, the topography induces changes in the low-tropospheric wind field. The high temperatures of the summer (solar radiation) influence the development of the thermal mesolow and play a fundamental role in the convective episode. These two factors, topography and solar radiation, have been studied with respect to the effects they may have on the formation of the mesolow, as well as on the spatial distribution and the intensity of the precipitation.

The factor-separation technique by Stein and Alpert (1993) has been used in order to determine the quantitative effects of topography and solar radiation. The factor-separation technique is a method for calculating the contributions of various physical processes, as well as their mutual interactions. If the synergistic contributions are not calculated and separated, the comparison among factors may be misleading. The method allows for a quantitative isolation of the effects due to different factors. Once the important agents acting on a system are identified, this technique determines unambiguously their joint and mutually independent effects (Alpert et al., 1995).

The factor-separation technique requires 2^n experiments, where n is the number of considered factors. Apart from the control simulation (S_C), three additional experiments have been carried out. By means of the algebraic combination of the model output fields it is possible to isolate the effects due to the individual selected factors and their mutual interactions. Thus, if 2 factors are considered and they can be turned on and off, four experiments are required. In order to study the effects of solar radiation (first factor) and topography (second factor) in different study fields, the following simulations have been carried out: a control simulation (S_C), a simulation without solar radiation (S_2), a flat terrain simulation (S_1), and a simulation with neither solar radiation nor topography (S_0). The factor-separation method is used to isolate the study field (for example, total precipitation) induced by solar radiation ($\bar{f}_1$), by topography ($\bar{f}_2$), by the synergic effect of solar radiation and topography ($\bar{f}_{12}$), and by neither of the two ($\bar{f}_0$):

$$\bar{f}_1 = S_1 - S_0$$

$$\bar{f}_2 = S_2 - S_0$$

$$\bar{f}_{12} = S_C - (S_1 + S_2) + S_0$$

$$\bar{f}_0 = S_0$$

The experiment with neither solar radiation nor topography S_0 (not shown) shows no precipitation at all in Northeastern Spain, with only a maximum of 10 mm in a very small area over the Mediterranean Sea.

If solar radiation is left out (experiment S_2, Fig. 15), the mesolow is less intense than in S_C. The temperature in the area of Alcañiz at 1200 UTC is only 24 °C (compared to 33 °C in the control simulation). As far as topography is concerned, it clearly influences the form of the mesolow along the Ebro Valley. As a result, the total precipitation field induced by topography ($\bar{f}_2$, Fig. 16) is substantially different from the one obtained in the control simulation, with less precipitation in the Pyrenees. In addition, no precipitation occurs in the area of Alcañiz and it is limited to only a small area of the Mediterranean coast, where the temperature is

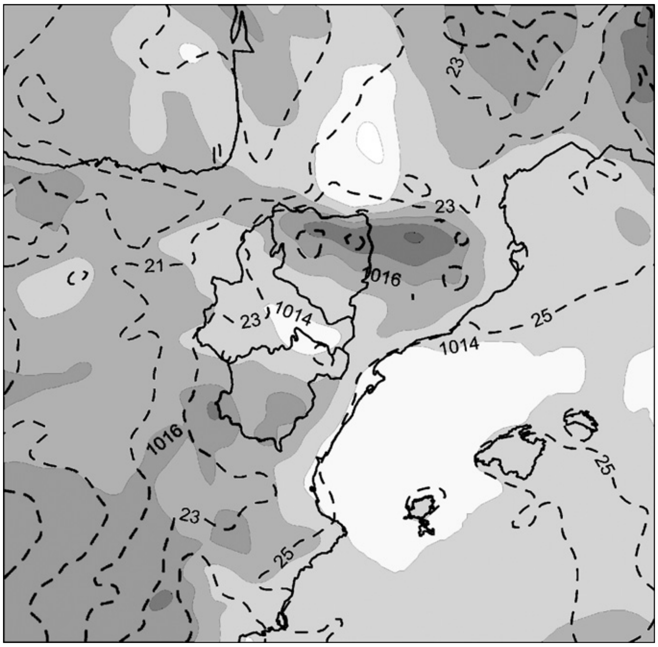

Fig. 15. Sea level pressure (hPa, shaded) and surface temperature (°C) at 1200 UTC on 16th August 2003, as simulated by the no-radiation experiment S_2 (domain 2).

higher. This precipitation starts at a later time than in the control simulation, at 1800 UTC, coinciding with the arrival of a high cold front.

In the simulation with flat terrain (experiment S_1, Fig. 17) the mesolow spreads in all directions, since its geometry is not conditioned by the valley. The temperature in Alcañiz is somewhat lower than in the control simulation, reaching $T = 30$ °C, and the low-level inflow from the Mediterranean Sea is not present. Consequently, the total precipitation field induced by solar radiation ($\bar{f}_1$, Fig. 18) comprises a larger area than in $\bar{f}_2$, drawing a map similar to the

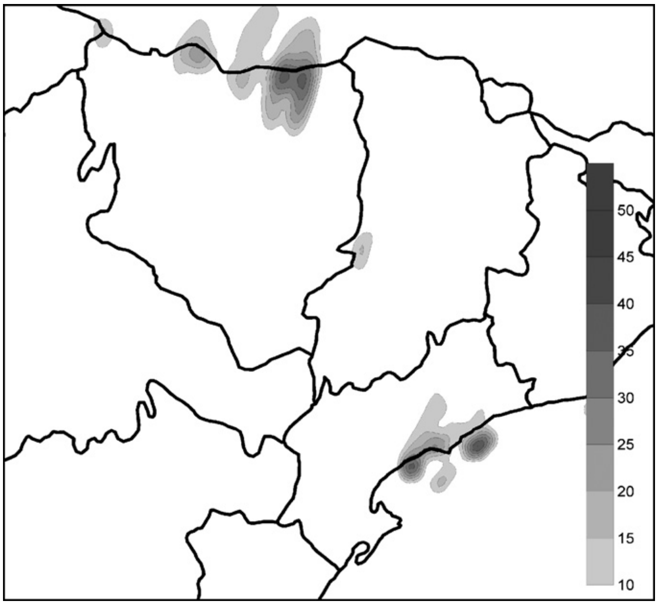

Fig. 16. Simulated precipitation field induced by terrain ($\bar{f}_2$) from 00 UTC to 19 UTC on 16th August 2003. Precipitation is in mm (domain 3).

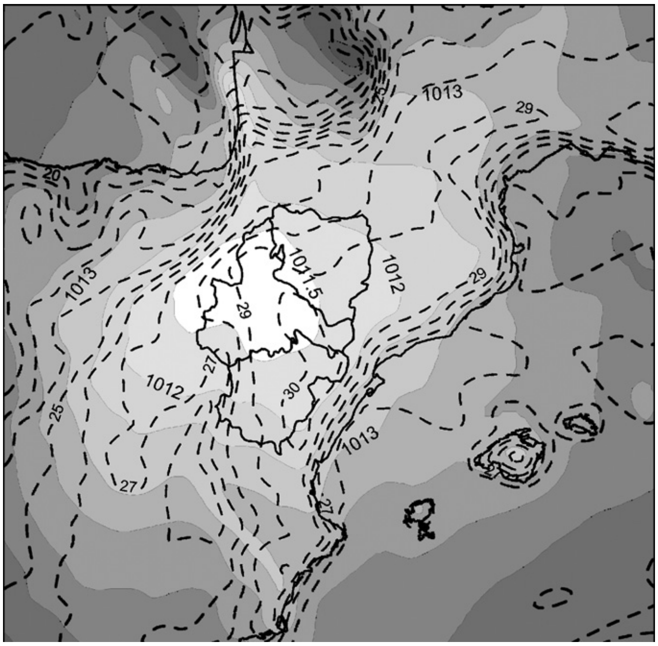

Fig. 17. Sea level pressure (hPa, shaded) and surface temperature (°C) at 1200 UTC on 16th August 2003, as simulated by the flat terrain experiment S_1 (domain 2).

control simulation in the Pyrenees, but with lower precipitation rates, and affecting Alcañiz only to a small extent with 10-15 mm.

These results show that neither of the two factors in isolation can explain the precipitation caused by the severe storm in Alcañiz. Therefore, synergic effects of the two factors have been studied. The interaction of topography and solar radiation is essential to determine the places where rain actually fell and those where it did not fall.

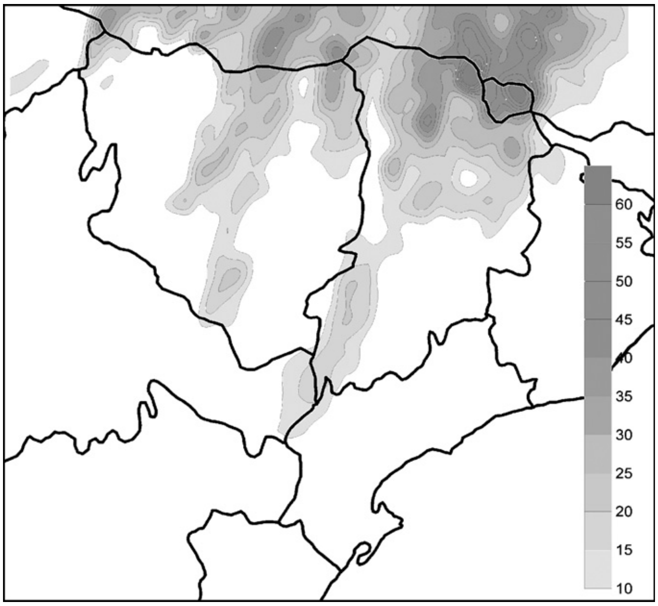

Fig. 18. Simulated precipitation field induced by solar radiation ($\bar{f}_1$) from 00 UTC to 19 UTC on 16th August 2003. Precipitation is in mm (domain 3).

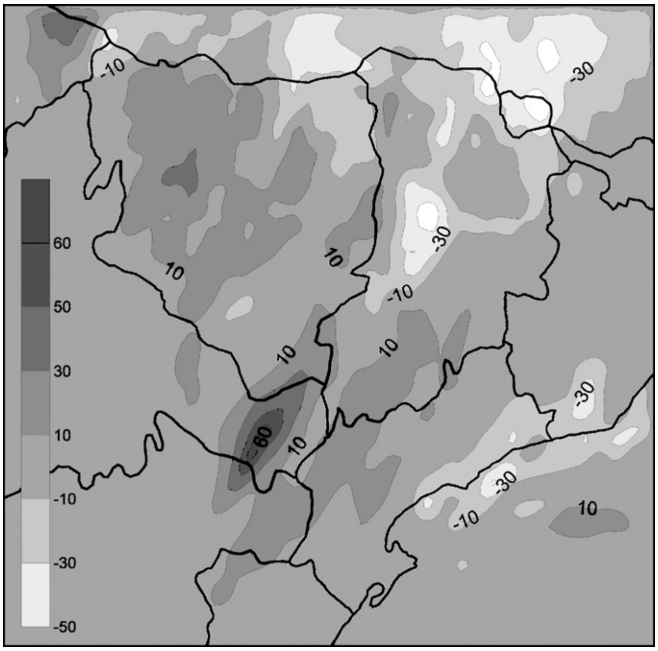

Fig. 19. Simulated precipitation field induced by the interaction between topography and solar radiation ($\bar{f}_{12}$) from 00 UTC to 19 UTC on 16th August 2003. Precipitation is in mm (domain 3).

In Fig. 19 we see that positive values correspond to a positive contribution to the total precipitation field. It is precisely in the area where the model locates the storm in Alcañiz that the combined effects of topography and solar radiation are more important (darker shaded areas). In contrast, the interaction of these two factors causes the opposite effect in other areas of Northeastern Spain, as shown in Fig. 19 shaded in light grey.

This case study leads to the conclusion that the mesoscale synoptic situation seems to have a rain potential by itself, but the thermal low of the valley causes an inflow of moist air from the Mediterranean Sea and updrafts in the area, occasionally generating convective clouds. The topography, together with solar radiation, contributes to highly localized and intense precipitation in the study zone.

5. Conclusions

This paper is focused on a numerical study of a severe storm event that occurred on August 16th 2003 in Northeastern Spain. Maximum precipitation amounts of 115 mm were registered in the rain gauges of Alcañiz, the most affected town. Hailstones of up to 12 cm were registered and the town was declared a disaster zone, claiming losses of over 10 M€. A C-band radar with a high temporal resolution made it possible to follow up the storm activity.

The event was characterized by a trough at mid to upper tropospheric levels. The arrival of a cold front from the NW of the Iberian Peninsula moving eastward caused high-altitude cooling. Numerical simulations were performed to examine the accuracy of the model in reproducing the severe storm of Alcañiz. The control run shows the presence of a thermal mesolow favoring the entrance of warm and humid air from the Mediterranean Sea all the way up the Ebro Valley. The total precipitation field indicates that the most intense precipitation fell in the study zone, coinciding to a great extent with the radar data. The radar simulation carried out with the model proves that, even though MM5 underestimates the maximum precipitation registered, it does reproduce the spatial and temporal evolution of the storm quite closely. On a convective scale, the result of the simulation can be considered to be very satisfactory.

Besides, a numerical sensitivity study was carried out as well to analyze the factors contributing to the localization of the intense precipitation. The roles played by topography and solar radiation were also examined, since these factors have previously been identified as relevant in severe storms in Northeastern Spain. In fact, the experiment carried out with no solar radiation shows a weakening effect on the mesolow and a reduction of the instability in the low troposphere. This hinders the activity of mechanisms triggering convection and inhibits precipitation, limiting it to small areas of the Pyrenees and the Mediterranean coast. In the experiment with flat terrain the corridor effect of the Ebro Valley on the mesolow disappears, as well as the low-level warm inflow from the Mediterranean Sea. The results conclude that the separate effects of either solar radiation or topography are not decisive by themselves in accounting for the intense precipitation caused by the severe storm of Alcañiz. However, the synergic effect of the two factors combined is fundamental for the spatial and temporal localization of the storm, and has an inhibiting effect in other areas of Northeastern Spain.

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References

Alpert, P., Tsidulko, M., Stein, U., 1995. Can sensitivity studies yield absolute comparisons for effects of several processes? J. Atmos. Sci. 52, 597–601.

Castro, A., Sánchez, J.L., Fraile, R., 1992. Statistical comparison of the properties of thunderstorms in different areas around the Ebro Valley (Spain). Atmos. Res.

Dudhia, J., 1993. A nonhydrostatic version of the Penn State/NCAR mesoscale model: validation tests and simulation of an atlantic cyclone and cold front. Mon. Weather Rev. 121, 1493–1513.

Font, I., 1983. Climatología de España y Portugal. Instituto Nacional de Meteorología, Madrid. 269 pp.

Grell, G.A., Dudhia, J., Stauffer, D.R., 1995. A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR. 117 pp.

Hong, S.-Y., Pan, H.-L., 1996. Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Weather Rev. 124, 2322–2339.

Kain, J.S., Fritsch, J.M., 1990. A one-dimensional entraining/detraining plume model and its application in convective parameterization. J. Atmos. Sci. 47, 2784–2802.

Ramis, C., López, J.M., Arús, J., 1999. Two cases of severe weather in Catalonia (Spain): a diagnostic study. Meteorol. Appl. 6, 11–27.

Reisner, J., Rasmussen, R.J., Bruintjes, R.T., 1998. Explicit Forecasting of Supercooled Liquid Water in Winter Storms Using the MM5 Mesoscale Model.

Romero, R., Doswell III, C.A., Riosalido, R., 2001. Observations and fine-grid simulations of a convective outbreak in northeastern Spain: importance of diurnal forcing and convective cold pools. Mon. Weather Rev. 129, 2157–2182.

Stein, U., Alpert, P., 1993. Factor separation in numerical simulations. J. Atmos. Sci. 50, 2107–2115.

Sánchez, J.L., E. García, E., Marcos, J.L., Dessens, J., 1999. Formation of big and giant drops inside Mediterranean convective cells. Proc. of the EGS Plinius Conf. Maratea, Italy. Eur. Geophys. 57–65.

Tudurí, E., Romero, R., López, L., García, E., Sánchez, J.L., Ramis, C., 2003. The 14 July 2001 hailstorm in northeastern Spain: diagnosis of the meteorological situation. Atmos. Res. 67–68, 541–558.