Synoptic Patterns of Severe Hailstorm Events in Spain

F. de Pablo Dávila\textsuperscript{a*}, L.J. Rivas Soriano\textsuperscript{a}, C. Jiménez Alonso\textsuperscript{b}, M. Mora García\textsuperscript{c}

J. Riesco Martín\textsuperscript{b}

1. Departamento de Física Fundamental, Universidad de Salamanca, Salamanca, Spain.

2. Agencia Estatal de Meteorología, (AEMet), Málaga, Spain

3. Agencia Estatal de Meteorología, (AEMet), Valladolid, Spain

* Corresponding author address:

Dr. Fernando de Pablo

Departamento de Física Fundamental

Facultad de Ciencias. Universidad de Salamanca

Pl. de la Merced s/n

37008 Salamanca (Spain)

e-mail: fpd123@usal.es

ORCID: 0000-0003-4859-4613
ABSTRACT

A study of severe hailstorm (with size ≥ 3cm) over Spain has been conducted using 8 years (2012–2019) of data. The 73 events of heavy hail selected were classified using the moisture flux at the 850 hPa pressure level (qv) and the lifted index (LI) as variables and a principal component analysis, coupled with a K-means clustering, as statistical technique. The application of this procedure provided four groups with their respective final cluster center. We took as the salient pattern of each cluster the case closest to each final cluster center. It was found that high values of low levels moisture flux (~ 89 g m/kg s on the average) are accompanied by static instability (SBCAPE ~ 600 j/kg and average LI ~ -4). The temperature values exceeded 20 °C at the 850 hPa pressure level and range between -8°C and -20°C at the 500 hPa pressure level. The most typical configuration corresponded to geopotential and thermal trough at mean levels of the troposphere and low pressure at low levels. Likewise, high values of precipitable water (> 35 kg/m²) have been detected and the presence of storm relative helicity and shear was moderate or strong in all cases.

Keywords: Severe hailstorms. Stability index. Cluster analysis. Spain.
1. Introduction

Hail is a meteorological phenomenon that consists of a type of precipitation made up of ice particles with a diameter equal to or greater than 5mm. Hail occurs in many areas of our planet and thus frequent severe hailstorms take place over most of Europe, causing considerable damage to buildings. This is equally the case with agricultural crops or cars, generating great economic losses. In the work of Punge and Kunz (2016) an extensive review of the characteristics of hail is carried out, with observations of Europe in recent decades. There, it is shown how, for instance, two supercells that occurred on July 27/28, 2013 activated in the vicinity of Andreas low pressure system caused insured damages of 2.800 million euros in Germany. Thus, it became the most costly event of insured losses during 2013 worldwide (SwissRe, 2014).

A year later, hailstorms associated with the Ela episode that occurred between June 8-10, 2014, were responsible for insured damages of € 2.3 billion in France, Belgium and Germany. Zimmerli (2005) estimated that the potential insurance damage caused by hailstorms across Europe, with a return period of 200-300 years, may be around € 4 billion. Regarding the Iberian Peninsula, hail can be observed in any area of it and Spain is among the countries with the highest associated losses within the agriculture sector. According to Porras et al., (2013) the annual average of insurance compensation in the agricultural sector is around 240 million euros for the period 2001-2009. The hail map, based upon the damages produced in agriculture, shows the areas of maximum intensity in the Pyrenees and NE of the Iberian System (Burgaz, 2004) as well as on the east coast of the Iberian Peninsula (Saa Requejo et al., 2011).

Among the first works that identify these regions as the Spanish areas most affected by hail are those carried out by Font (1983). In them it was observed that in certain areas of the Ebro valley the frequency of storms reaches the value of 32 days of
storm per year. Similarly, the work carried out by Pascual (2002) evinces an average hailstorm frequency of 9.4 hail per year between the months of May and September in the same region of the Ebro valley. More recent articles such as those of García Ortega et al., (2014) using radar observations in the central area of the Ebro valley (∼60.000 km²) detect an annual average of 32.6 days of hail for the period 2001-2010. In the province of Lleida (Spain), over an area of 3500 km², 12 hail days per year were observed during the period 1995-2007 (Pascual, 2002; Farnell et al., 2009). In the Lleida observatory, a frequent place for hail episodes, Sousa (1987) estimated values of 1.4 days per year throughout the period 1953-1980. Bernaldo (2009) related hail days observed in different places and damage caused in agriculture in the provinces of Burgos, Cuenca, Valladolid and Zaragoza. While in Zaragoza, in the Ebro valley, the highest annual percentages of losses with 2.3% were detected, following an interval of 8 days of hail, the province of Burgos, in the north of Castilla y León and with a similar number of stations, there were average losses of only 1.85% albeit being distributed over 54 hail days. In Portugal, large hailstorms are a rare phenomenon, mainly due to the prevalence of westerly winds from the Atlantic Ocean. In its state observation network, only 7 days with hail of size of 2 cm or larger are referenced over a period of 10 years, and yet values of 5 days per year of small hail (presumably including graupel) are observed in elevated areas of the north of the country (Font Tullot, 2000).

Within the extensive set of existing references about the relationship between hail episodes and associated synoptic situations, it is worth mentioning: Sioutas and Flocas (2003) study hail days in northern Greece over a period of 26 years (1976-2001), extracting and analyzing the most pivotal synoptic modes that generate hail in that area, finding that a short wave trough was the dominant situation in the generation of the phenomenon. Schemm et al., (2016) analyze hail data observed in Switzerland over a
12-year period (2002-2013). They conclude that the occurrence of hail in Switzerland is
associated with the existence of a cold front at an atmospheric level of 700 hPa. Li et al.,
(2016) study hails episodes that occurred in central China between 1960 and 2012,
using reanalysis data provided by NCEP/NCAR. They analyzed the atmospheric
circulation patterns that generated these hail episodes and defined five synoptic patterns
that explained the occurrence of hail in the area. These deduced patterns were deep
trough at 500 and 850 mb and thermal low pressure at sea level. Aran et al., (2011),
using as variables the average atmospheric pressure at sea level and the geopotential
height at 500 hPa level, classify and group the synoptic patterns causing hail in Lleida
(Spain). Researchers such as Simeonov and Giorgiev, 2003; Garcia-Ortega et al., 2007;
Huth et al., 2008; Kunz et al., 2009; Philipp and Bartholy, 2010; Twardosz, 2010; Saa
Requejo et al., 2011; Johnson and Sugden, 2014; Wapler and James, 2014; Melcón et
al., 2017 and Slahi et al., 2018 have used various statistical tools to analyze and classify
the most frequent atmospheric patterns that generate hail in different places and periods.

The main objectives of this study are, first and foremost, to obtain, through the
combined use of the techniques of Principal Component Analysis (PCA) and Cluster
Analysis (CA), those synoptic patterns that bring about episodes of severe hail (> 3 cm)
in Spain. Secondly, the results obtained in the previous stage are employed to showcase
the synoptic analysis of representative cases with their most pronounced meteorological
characteristics.

2. Data sets and methods

Hail observation in Spain is carried out directly and continuously (24 hours) in a
few observatories from the main network of the State Meteorological Agency (AEMet)
that have its own trained staff. The rest of the network makes general observations from
06 to 18 UTC, with some singular exceptions, such as the case of airports, which extend
observations beyond 18 UTC trough with variable hours and depending on the time of
year. This network is complemented by the secondary network, made up of
collaborators who altruistically make climatological observations and whose data is not
subject to the same quality controls as data from observatories with AEMet personnel,
which causes great uncertainty in the data. To this, it must be added that during the
summer months, some observatories of the secondary network cannot guarantee their
activities due to the vacation periods. The aforementioned evidence indicates that
analyzing hail data from the national observation network is a complex task both
spatially and temporally, especially considering that given the brevity of the
phenomenon, its ongoing observation becomes paramount.

In 2012, AEMet develops a Singular Atmospheric Observations Notification
System (SINOBAS in Spanish) capable of collecting and making available to citizens
information about the occurrence of certain phenomena that have been called
singular. Among them are included intense wind phenomena (tornadoes,
waterspouts, vortices streak, etc.), precipitation phenomena (hailstorms, singular
snowfalls, sudden precipitation) or other particular phenomena such as
avalanches, breaking waves or transitory variations in sea levels. All of them are
characterized by being local, infrequent, of significant intensity and capable of
causing high social impact. Through this database, created in line with the concepts
of crowdsourcing or citizen science, AEMet collects information provided by any
citizen about the occurrence of meteorological phenomena. Due to their scale, they
may go unnoticed by conventional observation networks and remote sensing
systems, but which have meteorological relevance and may cause a significant
impact upon the population. SINOBAS (https://sinobas.aemet.es) has been
operational since April 2013, although it allows reporting not only recent events, but also historical episodes of interest, making it feasible to find records even before the release date. It is a consolidated tool for AEMet, which provides, thanks to citizens’ collaboration, valuable information that could otherwise be lost. It likewise establishes a connection between those interested in the area that concerns the monitoring of weather and atmospheric phenomena. AEMet technicians subsequently validate all the information entered into the system. That being so, it is gradually becoming a valuable database of unique meteorological phenomena that would otherwise be difficult to pinpoint and locate.

Of all the phenomena referenced in SINOBAS, we have selected the phenomenon of hail for it presents great economic and social impact, in addition to having associated peculiar atmospheric characteristics. From 2012 to 2019, 256 singular hailstorms were reported in SINOBAS by private citizens and subsequently validated by AEMet technicians. Of all of them, we have selected those hailstorms where the size of the hail was equal to or greater than 3 cm, as they constitute the events with the greatest environmental impact. Hence, a sample of 73 events has been obtained (from April to October as it is the annual period with the highest convective activity), something considered highly reliable.

In Figure 1, we can observe the spatial distribution of the 73 analyzed events and it is necessary to indicate that the areas or places where no event is referred do not depend upon the absence of hail possibility, but rather on the absence of information provided by citizens, thus highlighting the areas and places where the citizens’ interest in these phenomena is most pronounced.

The atmospheric variables used, both to classify and group the 73 selected episodes and to identify the characteristics and independent patterns or modes of
variability of set of data, were obtained by ERA-5 reanalysis by European Centre for Middle Range Weather Forecasting (ECMWF) (Dee et al., 2011).

The methodological approach employed in this study consisted of applying Principal Component Analysis (PCA) coupled with Cluster Analysis (CA) as other authors have done (Richman, 1986; Yarnal, 1993). To apply these statistical techniques in a spatial domain it is necessary to use a continuous variable that provides the main dynamic and thermal structures. So, two indices were selected: a) one associated with the moisture flux at the 850 hPa pressure level, \((qv)_{850}\) (calculated by multiplying the mixing ratio and the wind intensity, units g m/kg s), and b) the lifted index (LI) (Galway, 1956), computed taking 500 hPa as the upper limit. These parameters were chosen because the supply of moisture at low levels and static instability are two key factors in the generation of heavy hail, (as commented in the Introduction). Consequently, they significantly explain the characteristics of the selected episodes in the sample of the 73 events. In any case, it should be taken into account that there are other relevant factors in the determination of the final amount of hail and its location, such as orography and low-level convergence. The 850 hPa pressure level was selected because it is representative of low levels and in general without being subject to local effects except in some reduced areas of the domain studied. As Huth et al., (2008) indicate, the use of PCA in the classification of synoptic patterns is twofold. In our analysis, PCA is used prior to CA, so it cannot be considered a classification tool because the posterior CA accomplishes this aim. The PCA is only used as an intermediate tool for the data dimension reduction.

The PCA was applied to the covariance matrix of these indices, and the resulting empirical orthogonal functions/patterns (EOF) were of unit variance and, also, were not
rotated. It should be noted that there is a little correlation between the two parameters ($r^2 = 0.01$), and they can therefore be regarded as linearly independent. Accordingly, only one principal component was retained, which explained 62.7% of the total variance.

Later, CA is applied to the factor scores resulting from the PCA. The clustering algorithm used is the non-hierarchical K-means method. For this algorithm the number of the groups is required beforehand. This can be decided by taking into account the results of a procedure called “jump method”. This procedure is calculated from a hierarchical clustering algorithm and using the Ward Method as an agglomeration technique. The coefficient given in the agglomeration schedule turns out to be the within-cluster sum of squares at each step. The number of groups is estimated detecting the greater distortion between the coefficients in two consecutive steps. Finally, the K-means method is used without iterative steps. These approaches have been widely applied in atmospheric studies and are described in minute detail in many textbooks (e.g. Wilks, 2006). The application of this procedure gave 4 groups with their respective final cluster center, which represents for each case, the final cluster assignment made from the Euclidean distance between the case and the cluster center used to classify the case. We take as the characteristic pattern of each cluster, the case closest to each final cluster center.

3. Results and discussion

The spatial distribution of the 73 hail events with size $\geq 3$cm is evinced in Figure 1. Most of observed cases were associated with mountain ranges, especially the Sistema Iberico. This fact was also reported by García Ortega et al. (2012) and it is due to the flow perturbations caused by the mountain, since the upslope flow contributes to trigger and maintain deep convection (de la Torre et al., 2015). The impact of orography in hail
was regarded all over the world (for example Punge et al., 2014 in the Massif Central in
France, de la Torre et al., 2015 in Los Andes; Nisi et al., 2016 in the Alps). Figure 1
also elucidates that areas close the North and East coasts presented high density of
severe hail events. This is in agreement with the outcome provided by Sánchez et al.,
(2003). The presence of moisture at low levels becomes a staple ingredient for deep
convection (Markowski and Richardson, 2010) and, consequently, moisture flux from
the Cantábrico and Mediterranean seas favour the development of hailstorm.

Table 1 shows that ~ 74% of the severe hail events considered in this study
occurred between July and September. Most of studies in Europe reported that hail is
observed namely between April and September (see Punge and Kunz, 2016 and
references herein). The high surface temperature during the warm season provides an
appropriate thermodynamic atmospheric background for convection. Hailstorm
formation need high static instability and sufficient moisture supply at low levels
(Markowski and Richardson, 2010). As expected, both requirements were met in the
hail events considered in this study. The average values of moisture flux and LI were
66.8 g m/kg s and – 3.6 respectively.

The application of the procedure indicated in the item 2 gave 4 groups or
clusters. The case closest to each final cluster centre was taken as the characteristic of
each cluster. As expected, the four cluster centers presented values of moisture flux and
LI greater than average (see Table 2).

Group 1 (13 cases. Cluster centre : Alagón, 31/07/2015)

A geopotential and thermal trough at the 500 hPa pressure level (Fig. 2a) with
axis over Portugal was going through the Iberian Peninsula (IP). The pattern at sea level
showed the Azores anticyclone over the Atlantic ocean with a low over the IP. Low
level flow was from SE in the east IP. Temperature was high, ~ 24ºC at 850 hPa (Fig.
Moreover, the water content in the IP was high, especially eastern IP with ~ 45 kg/m² in the zone of the cluster center (Fig. 3a). This synoptic environment was favorable for deep convection. As a result, severe hail was mainly reported on the east face of Sistema Ibérico. The model sounding (Fig. 3b) for the cluster center conveyed high values of surface-based CAPE (SBCAPE = 563 J/kg) and great thickness for convection (more than 10000 m). The sounding gave high values of shear, storm relative helicity (~ 240 m²/s²), and precipitable water. The satellite and radar images (Fig. 4a and b) manifested organized convection in the SW-NE direction, probably due to forcing associated with the 500 hPa trough. The cold tops of cumulonimbus (CB) indicated deep convection and reflectivity values 54 dBz, which were representative of large hail.

Group 2 (18 cases, cluster center: Tineo, 22/6/2016)

A geopotential and thermal trough at 500 hPa were seen entering the northwestern IP (Fig 5a). Low pressure was over the IP at the sea level, with flow from SW in the east half of the IP. Temperature at 850 hPa was high: ~24°C in the central IP (Fig. 5b). There was a lot of water content, peaking over the north IP (Fig. 6a). These synoptic conditions were appropriate for deep convection to develop. Severe hail associated with this group tended to be found south of the mountains. The model sounding for the cluster center (Fig. 6b) reveals high static instability (SBCAPE = 627 J/kg). There was a small inversion at the surface, so some forcing as heating of wind convergence was necessary to trigger convection. In this case the thickness for convection was 12000 m. Shear was high, but storm relative helicity was moderate (66 m²/s²). The satellite image (Fig. 7a) exposed deep convection that seem to be organized as a mesoscale convective system. Reflectivity values were > 54 dBz, even over 60 dBz in some zones, which were values compatible with large hail (Fig. 7b).
Group 3 (6 cases, cluster center: La Paúl, 13/9/2019)

A trough affecting the NW of the IP was seen at the 500 hPa pressure level. There was also cold air at mean and high levels over the northwestern IP, with temperature of ~ -20°C at 500 hPa (Fig. 8a). A low pressure centered over the SW of France affecting the northern IP appeared at the surface level. Temperature at low levels was high: 20°C at the 850 pressure level (Fig. 8b). High water content appeared over the northern and eastern IP, with values ~ 35 kg/m² in the zone of the cluster center (Fig. 9a). Low level flow was from W/NW. This was the group with the fewest number of severe hail cases detected, all of them in the east half of the IP. The model sounding (Fig. 9b) revealed high static instability (SBCAPE = 642 J/kg), great thickness for convection (10500 m), and high values of shear and storm relative helicity (191 m²/s²).

Satellite image (Fig. 10a) showcased cloud bands in front of the low in northern Spain and southern France. The most salient convective development was perceived in Aragon and Navarra. Reflectivity values (Fig. 10b) were > 60 dBz in the zone of the cluster centre.

Group 4 (36 cases, cluster centre: Castellfort, 29/7/2015)

Zonal flow over the north half of the IP and high pressures on the SW of the IP were scrutinized at the 500 hPa, with temperatures ~ -8°C in the study area (Fig. 11a). Two high pressure centres were observed on the Atlantic Ocean and the Cantábrico Sea at surface level, with relative low pressures in the east half of the IP. Low level temperature was high (~ 28°C at the 850 hPa pressure level) (Fig. 11b). The water content was also high, with values > 40 kg/m² in the study area (Fig. 12a). Low level flow was from SW. This was the cluster presenting the highest number of reported events of severe hail. Most of them were located at the north and east of the IP. The model sounding (Fig. 12b) revealed noticeable static instability (CAPE = 2385 J/kg).
and thickness for convection (12500 m). Moreover, the values of shear and helicity were high. Satellite image (Fig.13a) conveyed convective development over the Mediterranean coast. It is remarkable the mesoscale convective system over the cluster centre. Reflectivity values were > 60 dBz in that zone (Fig. 13b).

The aforementioned synoptic conditions associated with severe hail in Spain encountered in this study are in accordance with those reported in sundry regions and countries in Europe: trough at mean levels of the atmosphere and low pressure and fronts with warm and moist air at low levels (for example Aran et al., 2011; Twardosz et al., 2010; Garcia Ortega et al., 2011; Kapsch et al., 2012; Berthet et al., 2013). Many studies have suggested that hail occurrence is related to high CAPE values and moderate or strong shear and substantial storm relative helicity (Craven and Brooks, 2004; Groenemeijer and van Delden, 2007; Půčik et al., 2015; Kunz et al., 2017). This is also found in the cases of severe hail in the IP.

4. Conclusions

In this study, 73 events of severe hail (size ≥ 3 cm) - observed in Spain in the period 2012 to 2019 – have been analyzed. Most of these events tend to be concentrated in mountainous areas, markedly on mountainside terrain facing the Mediterranean and Cantábrico seas from July to September. The 73 episodes were classified relying upon a Principal Component Analysis (PCA) coupled with K-mean clustering and four synoptic types were distinguished. Two indices were employed to carry out this classification: moisture flux at the 850 hPa pressure level and the Lifted Index and the characteristic patterns of each group are represented by the patterns of the cluster centers. These two variables, uncorrelated with one another, have a strong influence on heavy hailstorm, although the final amount is modulated by certain factors, some of
them with very local influences, such as mechanisms of convergence at low levels, orographic interaction, and the persistence of a proper flow. The importance of the propagation characteristics of precipitating systems, due to various meso and microscale factors, should also be emphasized.

The ensuing main conclusions are to be extracted from the meteorological conditions associated with each cluster:

(i) In the sample of the 73 cases studied, high values of low level moisture flux (~ 89 g m/kg s on the average) were seen accompanied by static instability (SBCAPE ~ 600 J/kg and average LI ~ -4).

(ii) The most typical configuration correspond to geopotential and thermal trough at mean levels of the troposphere and low pressure at low levels.

(iii) The temperature values exceed 20 °C at the 850 hPa pressure level and range between -8°C and -20°C at the 500 hPa pressure level.

(iv) High values of precipitable water have been detected (> 35 kg/m²).

(v) The presence of storm relative helicity and shear was moderate or strong in all cases.

Information on hail events (with size ≥ 3cm) characteristics from SINOBAS data set (AEMet) has been evaluated with the objective to present an overview of knowledge on severe hailstorms across Spain. It is worth mentioning here that the observed meteorological conditions are in line with those uncovered in other studies in Europe and dissimilar regions.

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REFERENCES


Johnson, A.W., Sugden, K.E., 2014. Evaluation of sounding derived thermodynamic and wind-related parameters associated with large hail events; EJSSM 9(5) 1–42.


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<th>2012</th>
<th>2013</th>
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<th>2016</th>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.37</td>
<td></td>
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<tr>
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<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>0</td>
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<td>4</td>
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% annual 2.73 8.22 9.59 24.65 4.12 23.29 21.91 5.49

Table 1. Annual and month percentages of the 73 selected hail events between April and October 2012–2019.
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<th>Month</th>
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<th>Longitude (E)</th>
<th>Altitude (m)</th>
<th>$(q_v)_{850}$ [g kg$^{-1}$ m s$^{-1}$]</th>
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<td>31</td>
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<td>22</td>
<td>Tineo (Asturias)</td>
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Table 2. Characteristics and location of the cluster centers selected by the PCA and CA statistical analysis.
**Figure captions.**

Figure 1. Geographical characteristics and location of the 73 hail events with size ≥ 3cm used in this study, indicating (star) the cluster centers.

Figure 2. Weather charts for group I (Cluster centre: Alagón, 31/07/2015, 13 UTC): (a) geopotential height (m) and temperature (°C) at the 500 hPa pressure level; (b) mean sea-level pressure (hPa) and temperature (°C) at the 500 hPa pressure level.

Figure 3. Weather charts for group I (Cluster centre: Alagón, 31/07/2015, 13 UTC): (a) Total column water (kg/m²); (b) Soundings interpolated by the deterministic model of the ECMWF for the cluster centre.

Figure 4. 31 July 2015: (a) Mesoscale convective system seem by Meteosat (IR chanel), 12 UTC. (b) Radar image (dBz) plan position indicator (PPI) over zone by AEMet, 13 UTC.

Figure 5. Weather charts for group II (Cluster centre: Tineo, 22/06/2016, 17 UTC): (a) geopotential height (m) and temperature (°C) at the 500 hPa pressure level; (b) mean sea-level pressure (hPa) and temperature (°C) at the 500 hPa pressure level.

Figure 6. Weather charts for group II (Cluster centre: Tineo, 22/06/2016, 17 UTC): (a) Total column water (kg/m²); (b) Soundings interpolated by the deterministic model of the ECMWF for the cluster centre.

Figure 7. 22 June 2016: (a) Mesoscale convective system seem by Meteosat (IR chanel), 17 UTC. (b) Radar image (dBz) plan position indicator (PPI) over zone by AEMet, 17 UTC.

Figure 8. Weather charts for group III (Cluster centre: La Paúl, 13/09/2016, 15 UTC): (a) geopotential height (m) and temperature (°C) at the 500 hPa pressure level; (b) mean sea-level pressure (hPa) and temperature (°C) at the 500 hPa pressure level.
Figure 9. Weather charts for group III (Cluster centre: La Paúl, 13/09/2016, 15 UTC): (a) Total column water (kg/m²); (b) Soundings interpolated by the deterministic model of the ECMWF for the cluster centre.

Figure 10. 13 September 2016: (a) Mesoscale convective system seen by Meteosat (IR channel), 15 UTC. (b) Radar image (dBz) plan position indicator (PPI) over zone by AEMet, 15 UTC.

Figure 11. Weather charts for group IV (Cluster centre: Castellfort, 29/07/2015, 15 UTC): (a) Geopotential height (m) and temperature (°C) at the 500 hPa pressure level; (b) Mean sea-level pressure (hPa) and temperature (°C) at the 500 hPa pressure level.

Figure 12. Weather charts for group IV (Cluster centre: Castellfort, 29/07/2015, 15 UTC): (a) Total column water (kg/m²); (b) Soundings interpolated by the deterministic model of the ECMWF for the cluster centre.

Figure 13. 29 July 2015: (a) Mesoscale convective system seen by Meteosat (IR channel), 15 UTC. (b) Radar image (dBz) plan position indicator (PPI) over zone by AEMet, 15 UTC.
FIGURE 1
FIGURE 2

(a)

(b)
FIGURE 4

(a)

(b)
FIGURE 5

(a)

(b)
FIGURE 7

(a)

(b)
FIGURE 8

(a)

(b)
FIGURE 10

(a)

(b)
FIGURE 11

(a)

(b)
Declaration of interests

X The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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