Advances in Geosciences, 7, 215–222, 2006
SRef-ID: 1680-7359/adgeo/2006-7-215
European Geosciences Union

Study of 11 September 2004 hailstorm event using radar identification of 2-D systems and 3-D cells

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Received: 7 October 2005 – Revised: 9 February 2006 – Accepted: 13 February 2006 – Published: 8 March 2006

Abstract. The most important hail event recorded in the region of the Ebro Valley (NE Spain) in 2004 was the 11 September episode. Large hailstones (some of them with a diameter of over 30 mm) caused important damages in agriculture and properties. The hail event affected an area of 3848 ha and was caused by several multicellular systems. The aim of this paper is the analysis of the associated convective structures using the meteorological radar as well as the MM5 mesoscale model, thermodynamic data and a hailpad network. To achieve this end, the new hailstorm analysis tool RHAP (Rainfall events and Hailstorms Analysis Program) has been applied. It identifies tracks and characterises precipitation systems and convective cells, taking into account 2-D and 3-D structures. The event has also been studied with the TITAN software (Thunderstorm Identification, Tracking, Analysis and Nowcasting) in an attempt to compare both methods. Results show that the episode had a strong convective activity with CAPE values over 4000 J/kg and with hail-forming cells characterised by VIL (Vertical Integrated Liguid) exceeding 40 kg/m^2, VILD (VIL density) over 4 g/m^3, HP (Hail Probability) of 100% and SHP (Severe Hail Probability) of over 75%. The hail cells evolved into multicellular systems that lasted between 70 and 90 min. Finally, the comparison of RHAP and TITAN has shown significant correlations between methods.

1 Introduction

The most important hail event in 2004 in the Ebro Valley (area of about 40 000 km^2), North-East of Spain (Fig. 1), occurred on 11th September 2004. The event affected a region of over 2500 km^2, 15% of which is covered by a hailpad network belonging to the ADV, "Associació de Defensa dels Vegetals" (Association for the Protection of Plants) in Lleida (Fig. 1). This network is formed by 170 hailpads and its density is close to 1 hailpad per 16 km^2 and provides, among other data, values of maximum hail size, ice mass, kinetic energy and number of impacts per m^2 (Schleusener and Jennings, 1960; López, 2003). A total of 19 hailpads were hit by hailstones during this event, damaging 3,848 ha of crops including apples of the Golden Delicious type, pears, peaches and nectarines. The largest hailstones were registered in the towns of Fraga and Alcarrás (Fig. 1), with a maximum hail size of 34.6 mm.

Summer storms are very frequent in the study zone, where an average number of 32 thunderstorm days per year have been registered in the south-western part, area of about 25 000 km^2, (Font, 1983). Previous studies (Pascual, 2000; López, 2003) have shown that the medium size of hailstones in this area is usually under 20 mm and this size is usually registered around 16:00 UTC, after the maximum irradiance value. From a mesoscale point of view, hailstorm events are associated with atmospheric instability, strong updrafts and highly organised convective systems (Ragette, 1973; Browning, 1977; Knight and Knight, 2001; Martín et al., 2001). López (2003) found that in this area an average CAPE (Convective Available Potential Energy) value of 1020 J/Kg is required to cause convective activity related with hail, while the Total of Totals index has an average value of 47.3. Various studies have been carried out in order to classify associated convective systems using the meteorological radar and taking into account 2-D and 3-D features (Fraile at al., 2001; Sánchez at al., 2003; Rigo, 2004; Rigo and Llasat, 2004).

These thermodynamic features together with the evolution of convective systems (2-D and 3-D) associated to the 11 September 2004 event are explored in this paper. To achieve this end, different meteorological data and hailpad data have been integrated using software developed by the University of Barcelona: RHAP (Rainfall events and Hailstorms Analysis Program). More detailed information about this software can be found elsewhere in this issue (Ceperuelo et al., 2005). The present paper starts with the description of the data base and the methodology employed. Then, the synoptic scale and mesoscale circulation obtained with the MM5

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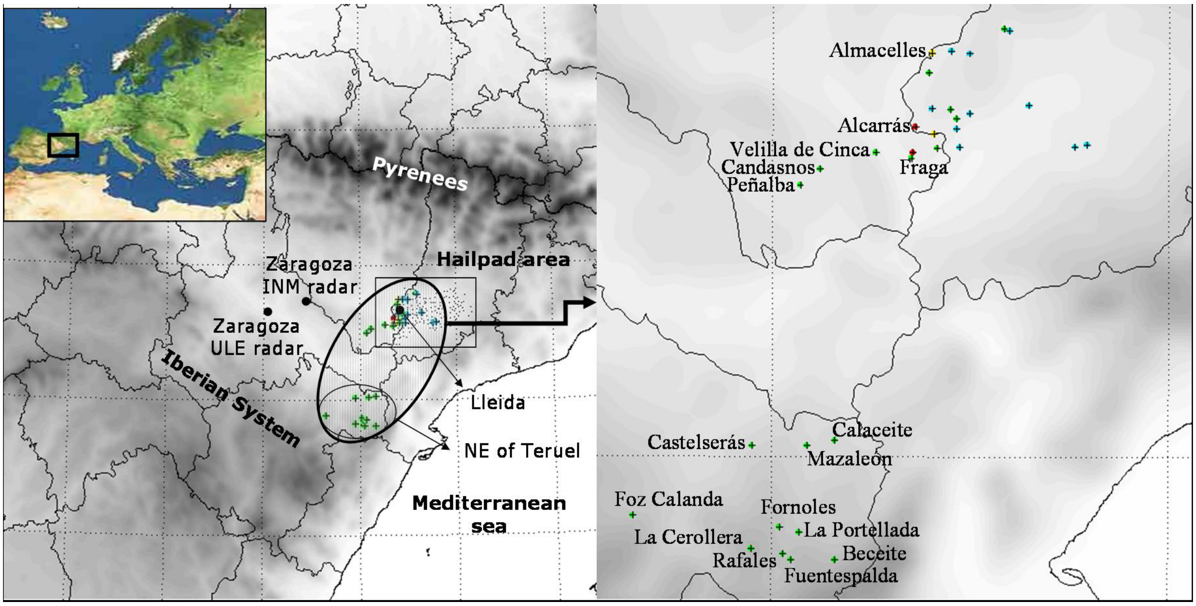

Fig. 1. Study area and locations.

Table 1. University of Leon radar and INM radar features.

Feature	INM radar	ULE radar
Beamwidth	0.9°	1.65° max
Frequency	5600–5650 MHz	5485–5600 MHz
Pick power	250 kW	250 kW
Pulse width	2 μs	2 μs
PRF	250 Hz	250 Hz

meteorological model and the upper-air soundings are explained. The next section includes the radar characterisation and the tracking of 3-D cells and precipitation systems that produce hailstones. The results in the analysis of hail cells obtained using RHAP and using TITAN are then compared. Finally, conclusions are presented.

2 Database and methodology

To study the 11th September 2004 hail event, a wide range of data have been used: radar data, upper-air sounding data, hailpad data and MM5 model outputs. First of all, ground observations provided by the ADV hailpad network and meteorological observers were obtained. These data have been analysed and verified using radar data. Thermodynamic data were obtained from the 12:00 UTC Lleida radiosounding.

The meteorological radars used (Fig. 1) were the Zaragoza radar from the Spanish National Institute for Meteorology (Instituto Nacional de Meteorología, INM) and the Zaragoza radar from the University of León (ULE), Spain. The main radar features are shown in Table 1, and the main radar difference is that the time step of the ULE radar is 3 min, whereas in the case of the INM radar it is 10 min.

The 11th September 2004 event has been studied focusing on the Zaragoza INM radar and the radar parameters used for characterising the event were: VIL "Vertical Integrated Liquid" (Greene and Clark, 1972), VILD "VIL density" (Amburn and Wolf, 1997), VOD "VIL of the Day" (San Ambrosio, 2005; Paxton and Shepherd, 1993), H45 "Waldvogel Parameter" and HP "Hail Probability" (Waldvogel et al., 1979), SHP "Severe Hail Probability" (Witt et al., 1998), MEHS "Maximum Expected Hail Size" (Witt et al., 1998), kinetic energy (Waldvogel et al., 1978 and Witt et al., 1998) and ECHOTOPS of 20, 30 and 40 dBZ. The objective of combining all of these parameters is to produce a good indicator of hail evidence. For example, VIL is an approximation of vertical liquid content and VOD is an empirical index of hail presence that can be used to establish a threshold of hail and no hail evidence. In the case of VOD, HP, H45, MEHS and SHP, thermodynamic data from an upper-air sounding are required.

On the other hand, data from the Mesoscale Meteorological model MM5 have been used in order to obtain wind fields at four different levels (925, 850, 700 and 500 hPa) to carry out the 3-D-cells tracking of the hail event. The initial and boundary conditions come from the FNL/NCEP analyses (1° latitude $\times$ 1° longitude, every 6 h), and the model parameterisation applied here is shown in Table 2).

All these data have been integrated using RHAP software (Ceperuelo at al., 2006). The RHAP techniques used for identifying and characterising 3-D cells are an improved version of the SCIT algorithms (Johnson et al., 1998; Rigo and Llasat, 2004) and an improved version of the 3-D tracking method in TITAN (Dixon and Wiener, 1993). The 3-D cells

Table 2. MM5 parameterisations.

Parameterisation	D1	D2	D3
Moisture scheme	Reisner2	Reisner2	Reisner2
Cumulus scheme	BM	KF	Non
PBL scheme	MRF	MRF	MRF
Radiation scheme	Cloud	Cloud	Cloud
Soil scheme	5-Layer	5-Layer	5-Layer
Shallow convection	No	No	No

tracking algorithm uses the mean wind grid point nearest to the cell centroid to extrapolate the current cell position to the previous position. The mean wind has been obtained using 925, 850, 700 and 500 hPa. After the position extrapolation, the cell in the previous radar image that satisfies the TITAN condition (the closest and the most similar cell) is searched in order to assign it as a tracked cell. Moreover, RHAP also enables us to identify, characterise and track the precipitation system. The classification of precipitation systems is made on the basis of the proposal by Rigo and Llasat (2004) and includes: mesoscale convective system (MCS), isolated convection (ISO), multicellular (MUL), convective precipitation embedded in stratiform precipitation (EST-EMB) and stratiform precipitation (EST). The classification takes into account the size and duration of the system, as well as the contribution of convective precipitation and stratiform precipitation. For each identified precipitation system it is possible to obtain, among other data, the type of the 2-D system and its size, the percentage of convective precipitation, the maximum reflectivity and the centroid position, the maximum axis, and the 3-D cells involved in the system. For each 3-D cell the following parameters were used: maximum and mean reflectivity, echotop and base mean values, and maximum VIL and VILD values.

3 Meteorological situation

The synoptic situation observed on 11th September 2004 at 12:00 UTC showed a thermal depression over the Iberian Peninsula and a cold front in north-western Spain. A trough with a northeast-southwest axis was identified at high levels, 500 hPa (Fig. 2a) and caused a south-west flow over the Iberian Peninsula. The thermal anticyclone situated over North Africa and the Azores high-pressure system were responsible of this situation. A thermal trough was also observed in the northwest of the Iberian Peninsula. This trough was contrasted with the presence of the African continental air mass over the eastern part of the Iberian Peninsula from surface level to 850 hPa (Fig. 2b). This fact and the cold air mass at high levels were the factors that favoured the thunderstorms formed in the study area. This high instability was detected in the thermodynamic analysis, where the hail event was characterised with high values of the instability indices

Table 3. Radiosonde parameters of 11 September 2004 hail event.

Radiosonde Parameter	Value
Lifted Index	−6.3
Showalter Index	−0.8
K Index	23.4
Total of Totals Index	51.4
SWEAT index	231.2
Wind Shear 0–6 km (m/s)	9.4
Wind Shear 0–1 km (m/s)	4.5
CAPE (J/kg)	4322.3
VIL of the Day: VOD "Lewis III" (kg/m^2)	48.4
VOD "Paxton and Shepherd" (kg/m^2)	39.1
W_{max} (m/s)	93.0
0°C height (m)	4223.7
−20°C height (m)	6864.0
Precipitable water: SFC-850 (kg/m^2)	14.4
Precipitable water: 850–700 (kg/m^2)	7.6
Precipitable water: 700–500 (kg/m^2)	2.7
Precipitable water: SFC-300 (kg/m^2)	25.7

(Table 3), with values of CAPE and TTI of 4322.3 J/kg and 51.4 respectively.

The convergence zones were located at the South-West of Lleida (Fig. 3) due to low-level wind perturbations caused by the mountains of Iberian System, with heights around 1700 m (Fig. 1). The low-level wind reanalysis showed a moisture advection over the convergence zones, behind a dry layer at mid-levels (850–700 hPa) with only 7.6 kg/m^2 of precipitable water mass that favoured triggering convection and hail production, as shown in Fig. 3. This figure shows how the convective cells nest zones obtained with radar data agree with the convergence zones obtained with the MM5 meteorological model.

4 Meteorological Radar and tracking of precipitation systems and 3-D cells

The radar analysis has shown that the maximum convective activity appeared between 17:00 UTC and 18:00 UTC (Fig. 4) with some values of VIL over 40 kg/m^2, VILD over 4 g/m^3, HP of 100% and SHP with values over 75%. Hail observations were registered between 15:00 UTC and 19:00 UTC associated to high values of radar parameters (Z_{max}>50 dBz) in some places. Meanwhile, the maximum hailstone size was registered at the moment of maximum convective activity, with 62.0 dBZ (Fig. 5).

The VOD value using Lewis III was 48.4 kg/m^2 and the VOD value using Paxton and Shepherd (1993) was 39.1 kg/m^2. These high values showed that only cells with high vertical developments could produce hail in this event.

The hailstones registered in the Lleida region were produced by two different cells. The cell that produced the maximum hail size at surface (34.6 mm in diameter) was the

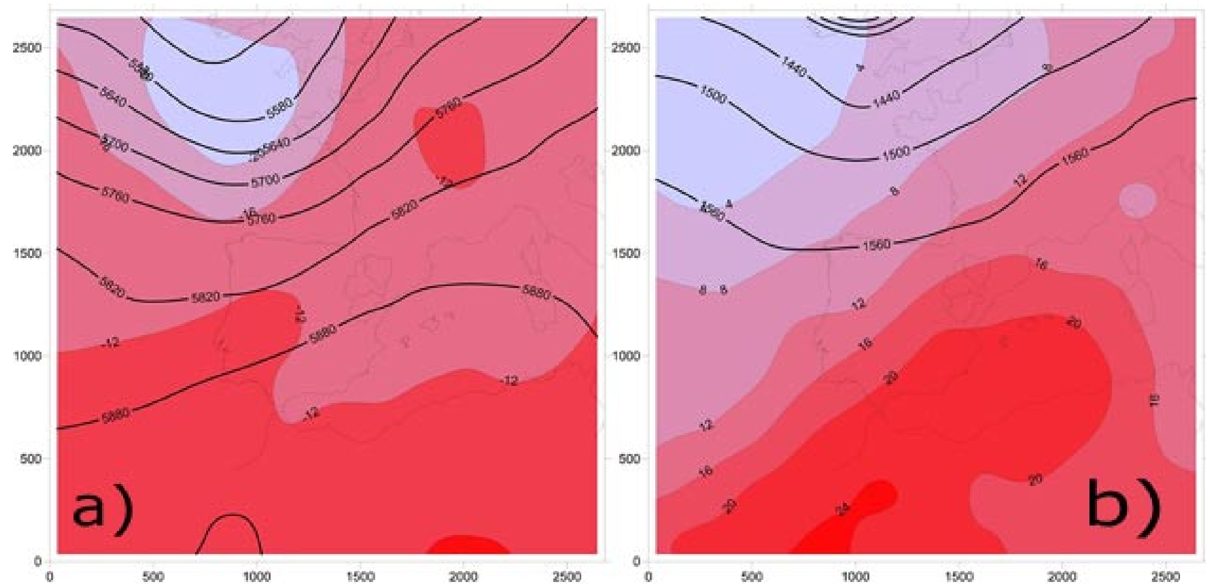

Fig. 2. Geopotential height (contour lines) and temperature (shaded areas) at 500 Pa **(a)** and 850 hPa **(b)**.

Table 4. Radar parameters of the 11 September 2004 hail cells at the moment of maximum convective activity: Maximum reflectivity (Z_{max}), Mean reflectivity (Z_{mean}), Vertical Integrated Liquid (VIL), VIL density (VILD), Kinetic energy (KE), Hail probability (HP), Severe hail probability (SHP) and Maximum expected hail size (MEHS).

	Hailpad area			Non-hailpad area			
Cell	Fraga and Alcarrás cell	Almacelles cell	Foz de Calanda cell	La Cerollera, Rafales, Fuentespalda and Beceite cell	Castelleserás, Mazaleón and Calaceite cell	Fornoles and La Portellada cell	Candasnos, Peñalba and Velilla de Cinca cell
Hail size	31–45 mm	21–30 mm	Chickpea	Walnut	Walnut	Chickpea	Walnut
Time (UTC)	17:30	17:20	15:20	16:10	17:30	18:10	18:40
Latitude	41.591	41.736	40.917	40.861	41.042	40.882	41.539
Longitude	0.348	0.411	−0.299	0.025	0.138	0.026	0.162
Z_{max} (dBZ)	56.8	54.8	55.2	55.2	56.8	56.0	60.0
Z_{mean} (dBZ)	47.8	42.2	44.0	48.4	47.4	49.2	50.0
VIL (kg/m^2)	38.8	11.7	26.1	45.6	35.9	19.1	63.5
VILD (g/m^3)	3.7	2.3	3.7	3.6	4.2	3.2	6.0
KE (J/m^2)	976.4	266.3	683.4	973.0	970.4	748.3	1776.2
HP (%)	100	48.9	75.5	100	88.8	100	100
SHP (%)	73.3	29.6	58.5	78.1	68.3	64.6	85.8
MEHS (mm)	70.9	12.5	39.3	85.9	58.0	50.1	116.1

Fraga and Alcarrás cell at 17:30 UTC, with a VIL value of 38.82 kg/m^2, and a VILD value of 3.7 g/m^3 (case 1). These values are close to the empirical value to obtain hail at surface level (VOD). The SHP showed a value of 73.3%, which points to a high likelihood of severe hail at surface level. In non-hailpad-covered areas the hailstones were traced back to 5 different cells, but the problem of this area is that no hail size information is available. However, if we were to compare the values obtained for hail cells in non-hailpad-covered areas to hail cells in hailpad-covered area, we could expect sizes larger than walnuts (>34 mm) in the latter region. This was the case of the cell that affected Candasnos-Peñalba-Velilla de Cinca (Table 4) and recorded the most intense values of the event, with maximum VIL value of 63.5 kg/m^2, maximum SHP of 85.7% and MEHS of 11.7 cm. These values were higher than those from cells of the hailpad-covered area. In conclusion, we could expect larger hailstones. This hypothesis was confirmed by the meteorological observers.

The life cycle of the different radar parameters has been calculated in order to know the life cycle of the hailstorms, distinguishing between precipitation systems and 3-D cells. The hail system that produced the largest hailstone (34.6 mm) in the hailpad-covered area, Alcarrás and Fraga cell (case 1), and the hail system that produced hail in the longest-life cell of the non-hailpad-covered area, La Cerollera-Rafales-Fuentespalda-Beceite cell (case 2), have been only studied:

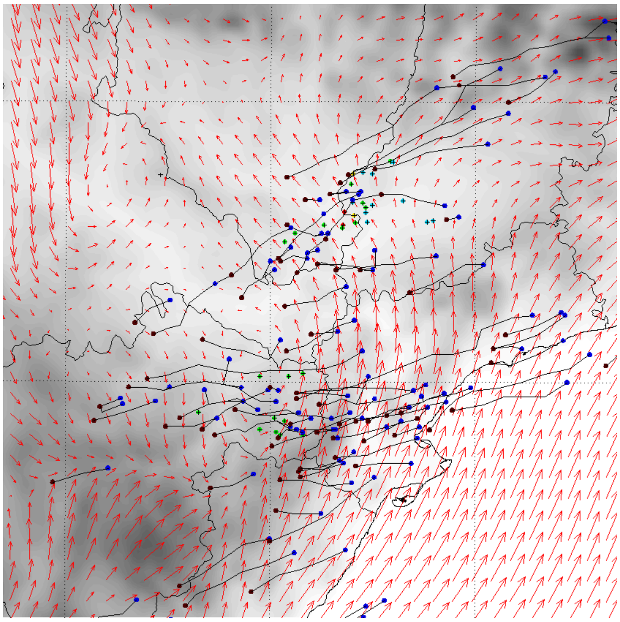

Fig. 3. Trajectories of all the 3-D cells (black lines) of the event and 925hPa wind field obtained with the MM5 meteorological model at 18:00 UTC (red arrows). Black points are the beginning of the 3-D cells and blue points are the end of the 3-D cells.

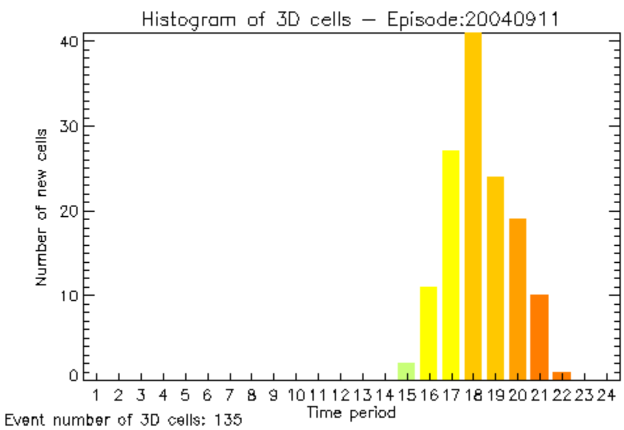

Fig. 4. Histogram of the number of new 3-D cells formed with time resolution of one hour.

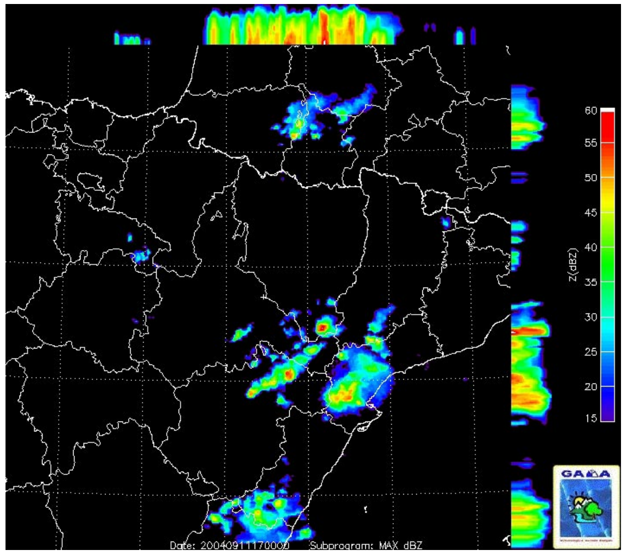

Fig. 5. Maximum reflectivity product of 11 September 2004 hail event at 17:00 UTC (maximum reflectivity value of 62.0 dBZ).

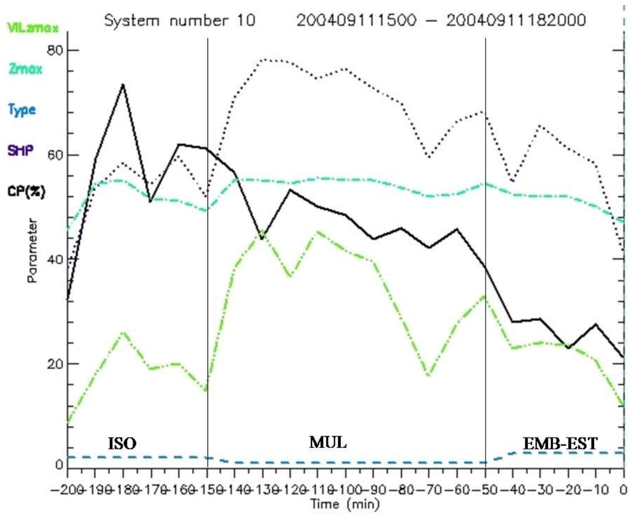

Fig. 6. Time evolution of the precipitation system parameters of the biggest system over the non-hailpad covered area that has produced hail. Time period: from 15:00 UTC to 18:20 UTC. Solid line shows the convective precipitation percentage evolution (%), dotted line shows de SHP (%) evolution, dashed line shows the evolution of the type of system, dash-dot line is the evolution of maximum reflectivity (dBZ) and dash-dot-dot line is the time evolution of VIL Z_{max} (kg/m^2).

4.1 Precipitation systems

In case 1 the precipitation structure started at 16:40 UTC as an EST-EMB system. Then it rapidly changed to an ISO system at 16:50 UTC, which lasted 30 min. At 17:30 UTC the system evolved to a MUL system with an area of 992 km^2 and eight 3-D cells (four of them over 50 dBZ) and a percentage of convective precipitation of 56%. At 17:40 UTC the MUL system merged with a southern MUL system to develop a bigger MUL system with twelve 3-D convective cells. At 18:00 UTC this bigger system split into two different MUL systems. The northern one remained a MUL system until 18:30 UTC.

The system of case 2 began as an ISO type at 15:00 UTC and lasted until 15:50 UTC. At 16:00 UTC it evolved to a MUL system until 17:30 UTC, when hail precipitated (from 16:00 to 16:40 UTC). Then the system changed to an EST-EMB system until its disappearance. Figure 6 shows the time evolution of the type of system, Zmax, convective precipitation percentage, VILZ and SHP. The area covered by the precipitation system and the biggest hail cell is shown in Fig. 7.

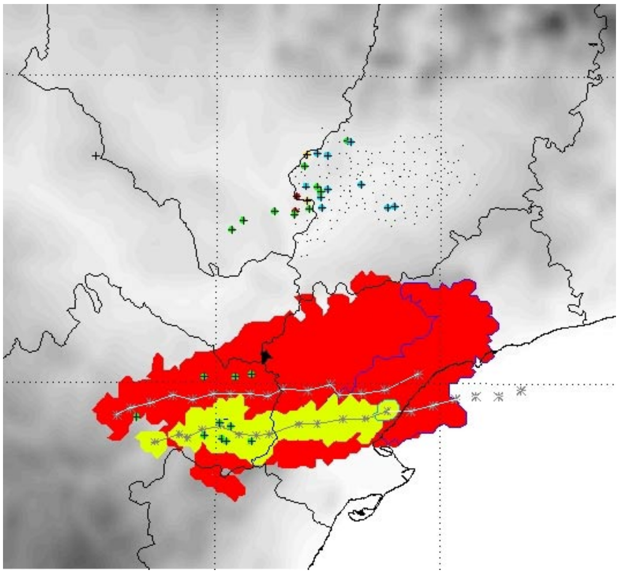

Fig. 7. Trajectory, area covered (15:30–17:30 UTC) and nowcast (60 min) of the La Cerollera-Rafales-Fuentespalda-Beceite cell (case 2), and trajectory and area covered (15:00–17:30 UTC) by the associated precipitation system (red area). Ground hail observations are also shown.

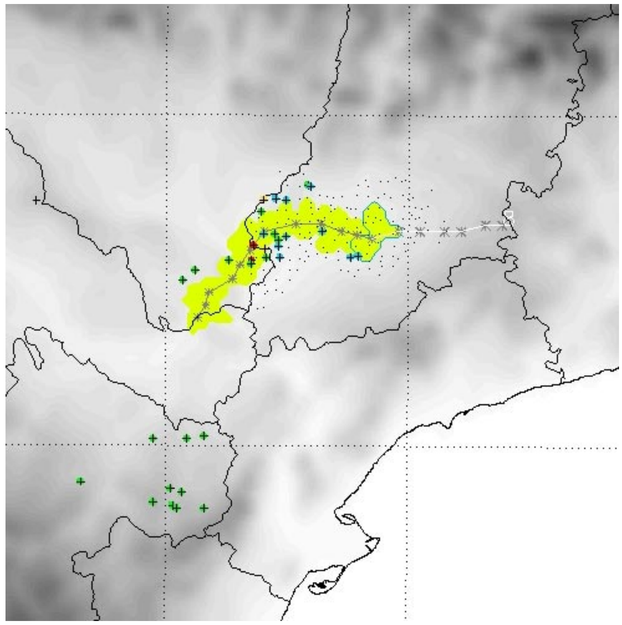

Fig. 8. Trajectory, area covered (16:40–18:30 UTC) and nowcast (60 min) of the Fraga and Alcarrás cell (case 1). Ground hail observations are also shown.

4.2 3-D cells

In case 1 a long lived cell of 120 min was identified (Fig. 8). However, after applying the RHAP reanalysis, based on the strong oscillations of VIL, it is possible to see this long lived cell was three consecutive different cells. The first one was active over the non-hailpad covered area and no hail observations were available. Probably, this cell produced severe hail (hailstones of over 35 mm) due to the high values of the different radar parameters: Z_{max}=62.0 dBz, VIL=54.1 kg/m^2, VILD=5.1 g/m^3 (Table 5). The second cell affected the hailpad covered area with hailstones of over 30 mm. It produced hail during thirty minutes with VIL values up to 35 kg/m^2, SHP over 70% and Z_{max} over 55 dBZ. Finally, the third cell was weaker than the other ones, with high reflectivity values, but small values for VIL and SHP due to the lower values of the tops of the cell.

Case 2 was a long lived cell of 130 min. As in the previous case, this “cell” was composed by two consecutive cells. The first one lasted 100 min (Table 6) producing hail during 50 min with VIL values over 35 kg/m^2, SHP over 70% and Z_{max} over 54 dBZ.

Comparing the two analysed cases, the same hail conditions (VIL$>$35 kg/m^2, SHP$>$70% and $Z_{max}$$>$54 dBZ) were generally fulfilled.

Finally, after analysing these two cases, a comparison between the two different methods of identifying and tracking 3-D cells (TITAN and RHAP) was carried out. The radar from the University of León located in Zaragoza was used for the TITAN method. The most important difference found between the two identification methods was that TITAN uses only one threshold value (30 dBZ) to identify the cell, whereas the RHAP algorithm uses 7 reflectivity thresholds (30, 35, 40, 45, 50, 55, 60 dBZ). Consequently, where the TITAN identifies one only structure, the RHAP can distinguish between two or more cells (from a spatial point of view as a MUL system and from a temporal point of view following the life cycle of the cells). For this reason, the best correlation between both methods was obtained when the hail was produced by a main cell. The correlation coefficients of reflectivity, tops and volume for the non-hailpad covered area cell have been statistically significant at the 95% confidence level, largely explaining the variability (Table 7).

5 Conclusions

Using the meteorological model results and sounding parameters, we conclude that the convective activity in the 11th September 2004 event was triggered by the synergy of multiple factors: zones of wind convergence, high values of the instability indices, moisture advection at low levels and dry layer at mid-levels (850–700 hPa) with 7.6 kg/m^2 of precipitable water. After the initiation of convection at 14:00 UTC, the maximum convective activity has been registered from 17:00 to 18:00 UTC with the maximum number of new cells, maximum reflectivity (62 dBZ) and maximum hailstone diameter (34.6 mm).

The application of the meteorological radar has allowed identifying and tracking two main systems: one related with the largest hailstone (34.6 mm) in the hailpad-covered area (case 1) and the other one related to the longest life cell of the

Table 5. Life time evolution of radar parameters of 11 September 2004 Alcarrás-Fraga cell (16:40 UTC – 18:30 UTC): Maximum reflectivity (Zmax), Mean reflectivity (Zmean), Vertical Integrated Liquid (VIL), VIL density (VILD), Kinetic energy (KE), Hail probability (HP), Severe hail probability (SHP) and Maximum expected hail size (MEHS).

Time (UTC)	Hail	Longitude	Latitude	Z_{max} (dBZ)	Z_{mean} (dBZ)	VIL (kg/m^2)	VILD (g/m^3)	KE (J/m^2)	MEHS (mm)	SHP (%)
1830	No data	0.851	41.627	52.4	41.5	14.3	2.4	296.5	18.33	39.2
1820	Yes	0.788	41.639	49.2	43.7	14.7	1.7	202.2	26.66	48.7
1810	No data	0.724	41.649	51.2	42.2	13.6	1.6	205.4	18.81	39.9
1800	Yes	0.639	41.672	54.0	42.5	18.4	2.2	323.0	37.86	57.5
1750	No data	0.537	41.672	50.0	42.5	12.7	1.8	192.0	19.88	41.3
1740	Yes	0.404	41.648	56.8	45.3	39.8	3.8	988.8	64.41	70.9
1730	Yes	0.348	41.591	56.8	47.8	38.8	3.7	976.4	70.89	73.3
1720	Yes	0.304	41.547	58.0	46.0	35.3	3.4	822.5	64.30	70.9
1710	No data	0.273	41.505	52.0	42.1	8.5	1.9	140.0	41.82	60.0
1700	No data	0.177	41.464	62.0	50.4	54.1	5.1	1724.8	81.46	76.8
1650	No data	0.164	41.423	53.2	42.6	20.3	2.4	401.9	46.68	62.8
1640	No data	0.130	41.388	35.6	33.0	0.7	0.3	0.0	0.00	0.0

Table 6. Life time evolution of radar parameters of 11 September 2004 La Cerollera-Rafales-Fuentespalda-Beceite cell (15:30 UTC – 17:30 UTC): Maximum reflectivity (Zmax), Mean reflectivity (Zmean), Vertical Integrated Liquid (VIL), VIL density (VILD), Kinetic energy (KE), Hail probability (HP), Severe hail probability (SHP) and Maximum expected hail size (MEHS).

Time (UTC)	Hail	Longitude	Latitude	Z_{max} (dBZ)	Z_{mean} (dBZ)	VIL (kg/m^2)	VILD (g/m^3)	KE (J/m^2)	MEHS (mm)	SHP (%)
1730	No data	0.766	40.910	44.0	36.0	0.0	0.0	6.0	7.43	16.5
17200	No data	0.668	40.886	52.0	42.1	20.1	1.9	362.9	27.83	49.8
1710	No data	0.567	40.884	52.0	44.0	17.0	2.8	390.7	41.01	59.5
1700	No data	0.453	40.868	53.6	46.1	28.9	2.8	603.1	61.38	69.7
1650	No data	0.374	40.867	55.2	49.4	39.5	3.8	962.5	68.84	72.6
1640	Yes	0.239	40.835	55.2	47.8	41.5	3.3	859.2	80.20	76.4
1630	Yes	0.181	40.831	55.6	48.2	45.2	3.6	1052.4	74.47	74.6
1620	Yes	0.104	40.832	54.4	49.2	36.6	3.5	717.9	84.09	77.6
1610	Yes	0.025	40.861	55.2	48.4	45.6	3.6	972.9	85.87	78.1
1600	Yes	−0.058	40.850	55.2	48.2	38.5	3.1	831.9	64.10	70.8
1550	No data	−0.124	40.821	48.0	42.0	5.6	1.6	84.8	30.41	52.0
1540	No data	−0.160	40.832	47.6	44.7	1.8	1.8	45.4	0.00	0.0
1530	No data	−0.269	40.808	48.8	38.2	7.7	1.3	85.3	9.38	22.4

non-hailpad-covered area (case 2). The evolution has shown the systems started as isolated convection that lasted around 40 minutes. Then, they developed into a multicellular system and the largest hailstones were produced. As a multicellular system they lasted around 1 and 1.5 h. In some occasions, if VIL oscillations are considered, it is possible to conclude that more than one cell was developed along the track. Hail-producing cells have been characterised by the high values of radar parameters: VIL, VILD, HP, SHP, KE, Zmax, Zmean, etc. Generally values of VIL, VILD, HP, SHP and Zmax are above 35 kg/m^2, 7 g/m^3, 100%, 70% and 54 dBZ, respectively

The comparison of TITAN and RHAP methods has shown similar results when the hail was associated to a main cell. On the contrary, if hail could be associated to different cells into a MUL system the RHAP methods would be more useful

Table 7. Pearson, Kendall's τ_b and Spearman's ρ correlation coefficients between TITAN and RHAP track methods for the Cerollera, Rafales, Fuentespalda and Beceite cell.

	Correlation coefficients		
Variable	Pearson	Kendall's τb	Spearman's ρ
Top TITAN/Top RHAP	0.684**	0.478*	0.641*
Volume TITAN/Volume RHAP	0.744**	0.513*	0.720**
Z(dBZ) TITAN/Z(dBZ) RHAP	0.693**	0.521*	0.719**

* The correlation is significant at the 95% confidence level.
** The correlation is significant at the 99% confidence level.

because it could distinguish the internal system structure and its life cycle.

Further studies will be based on this kind of analysis to characterise hail phenomena and will improve the nowcasting of radar parameters of 3-D cells and precipitation systems.

Acknowledgements. The authors thank the MONEGRO (REN2003-09617-C02-02) Spanish project for enabling the drawing up and presentation of this contribution. Our thanks to the *Associació de defensa dels Vegetals*, Maite Torà and Marta Masot,to the Meteorological Service of Catalonia of the *Generalitat de Catalunya* and to the *Instituto Nacional de Meteorología* for the hailpad data, radiosonde data and radar data. And, finally, thanks to the University of León and the observers of Aragón for ground truth data.

Edited by: V. Kotroni and K. Lagouvardos
Reviewed by: T. Karacostas

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