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Proposal of three thermodynamic variables to discriminate between storms associated with hail and storms with intense rainfall in Catalonia

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Abstract

Between late spring and early fall, the development of storms is common in Catalonia. Despite the fact that they usually produce heavy showers of short duration, they can also involve severe weather with ice pellets or hail. While the latter usually affect inland regions, and there are numerous publications on these cases; the analysis of events affecting the coast and causing damage to public and private properties is not so well developed. The aim of this study is to provide additional thermodynamic indicators that help differentiate storms with hail from storms without hail, considering cases that have affected various regions of Catalonia, mainly coastal areas. The aim is to give more information to improve prognosis and the ability to detail information in these situations. The procedure developed involved the study of several episodes of heavy rainfall and hail that hit Catalonia during the 2003-2009 period, mainly in the province of Girona, and validated the proposal during the campaign of late summer and fall of 2009, as well as 2012. For each case, several variables related to temperature, humidity and wind were analyzed at different levels of the atmosphere, while the information provided by the radio sounding in Barcelona was also taken into account. From this study, it can be concluded that the temperature difference between 500 hPa and 850 hPa, the humidity in the lower layers of the atmosphere and the LI index are good indicators for the detection of storms with associated hail.

Key words: thermodynamic variables, intense rainfall, hail, coastal areas, Catalonia

1 Introduction

Every year, there are agricultural losses exceeding 650 million Euros in Spain, with Catalonia, specifically the northeast and west regions, being one of the areas where there are most hailstorms (Ceperuelo et al., 2009). The commonest time for them to occur is from April to October, a period in which there is also heavy rainfall and, therefore, there is often considerable difficulty in predicting the meteors associated with the expected storms.

There are several studies dealing with hail in Catalonia. In essence, they can be grouped into three types: specific case studies, those on the Ebro valley and Lleida plain, and those that span all Catalonia. Among the former, there are those by Ceperuelo et al. (2006) on the episode of September 11, 2004, or by Farnell et al. (2009) and Pineda et al. (2009) on the episode of September 17, 2007. With regard to longer periods, there are those by Pascual (2002), who conducted a study of hailstorms on Lleida plain, and by Ceperuelo et al. (2009), which presented a technique for improving the identification of hail in the Ebro valley area using radar observations, an area also referred to in the unpublished study by Merino (2009) on thermodynamic characterization, or Aran et al. (2011), who relates different atmospheric circulation patterns with episodes of hail in Lleida. Finally, among those referring to all Catalonia and covering relatively longer periods, we find the unpublished research developed within the SEVERUS project of the CICYT, by Boshoms (2008) and Bernal (2008), which shows a temporal and spatial analysis of hailstorms in Catalonia in the period between 1996 and 2006, and the reference to the evolution of hailstorms in the context of climate change (Llasat and Corominas, 2010).

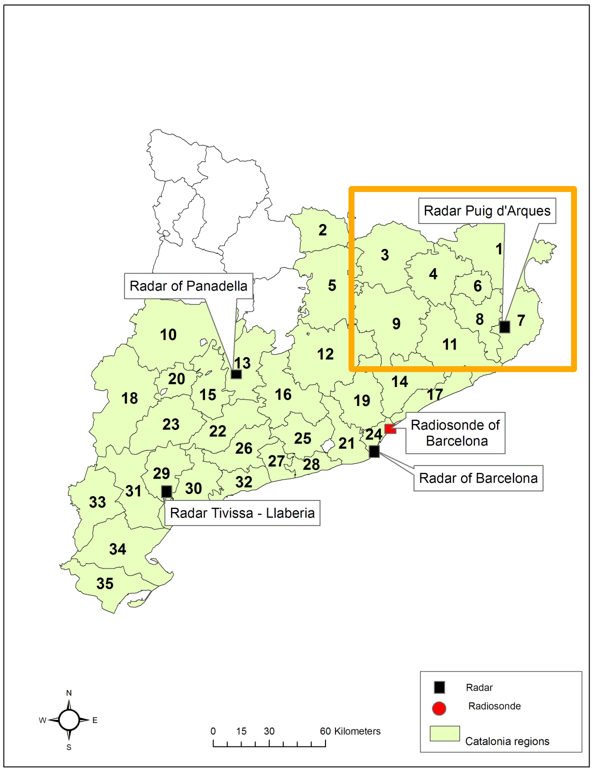

Figure 1. Location of 4 radars of the SMC network (la Panadella, Puig d'Arques, Vallirana i Tivissa-Llaberia) and Barcelona radiosonde station, represented by a red dot. Location of the study area and the north-east sector (box). In green are the regions affected by episodes analyzed and mentioned in Tables 1, 2 and 3. 1 Alt Empordà; 3 Ripollès; 2 Cerdanya; 4 Garrotxa; 6 Pla de l'Estany; 7 Baix Empordà; 8 Gironès; 11 La Selva; 9 Osona; 5 Berguedà; 12 Bages; 14 Vallès Oriental; 17 Maresme; 24 Barcelonès; 19 Vallès Occidental; 21 Baix Llobregat; 28 Garraf; 25 Alt Penedès; 16 Anoia; 13 Segarra; 15 Urgell; 20 Pla d'Urgell; 10 Noguera; 23 Garrigues; 18 Segrià; 22 Conca de Barberà; 26 Alt Camp; 30 Baix Camp; 32 Tarragonès; 29 Priorat; 31 Ribera d'Ebre; 33 Terra Alta; 32 Baix Ebre; 35 Montsià.

Despite the extensive aforementioned literature, there are hardly any works on ice pellets in the coastal areas of Catalonia. That is why the aim of this work is to analyze some episodes of hail and heavy rain that occurred in the northeast of Catalonia with the aim of providing simple criteria that help to distinguish the possibility of storms with or without hail, which can be very useful to complement other procedures that are discussed below. Indeed, unlike the Lleida plain and the Ebro Valley, where most storms produce hail, on the coast they tend to produce heavy rain, and to a lesser extent, rain with ice pellets, or ice pellets or hail without rain.

Deep convection is necessary for the formation of hail. We understand deep convection as a region in which there are strong updrafts (> 10 m s^{-1}), which spread out to most of the troposphere and have diverse phenomena associated with them, such as: hail, tornadoes, strong winds, heavy rainfall and/or electric discharge (Weisman and Klemp, 1986). The effects produced on the surface are divided according to the severity and intensity of rainfall and the type of precipitation. The National Weather Service (NWS) defines severe storm as a storm that contains one of these phenomena: hailstones of 2 cm or more in diameter, wind gusts of more than 50 kt or tornadoes. This method is also used by the Spanish Meteorological Agency (AEMET) and the Meteorological Service of Catalonia (SMC).

There are different tools and methodologies to estimate the likelihood of deep convection, or to analyze it. One possibility is the use of weather radar and, in the case of hail, the use of variables such as the density of VIL (the amount of vertically integrated liquid in a column), daytime VIL or Hail Probability Observation (San Ambrosio, 2001; Aran et al., 2007), or the algorithm proposed by Witt et al. (1998). López (2003) defines some indicators to discriminate cells with hail or without hail based on VIL, DVIL, maximum and average reflectivity, cloud ceiling, maximum reflectivity height, volume, mass, speed of the storm, or variation of some variables (cloud top height, volume, etc.) per time unit. Later, Ceperuelo et al. (2009) applied the analysis of the main component technique and reduced the 25 radar parameters to five new variables that explain the physical characterization of the convective cell through 3D observation. These five variables are: i) Intensity; ii) Physical dimensions of the cell; iii) Fusion and cooling level of the convective cell; iv) State of the life cycle of the cell; v) Reflectivity and system organization.

Another possibility, which essentially complements the previous one, is based on the thermodynamic and mesoscale analysis, as in the work of Sánchez et al. (2003). In this case, the necessary factors for the formation of storms and the factors that discriminate between storms and severe storms should be known. The common factors are humidity in lower layers, convective instability and forcing mechanisms (McGingley, 1986). In both cases the presence of intense updrafts is required. Some of the discriminatory factors, which are only formed in severe storms, are the presence of a dry layer at middle levels and wind shear (McGingley, 1986). In addition, there are several factors to consider for the formation of hail: long duration organized structures, height of freezing level and isotherms of -5°C and -10°C (Pascual, 2002), height of the cloud basis (Martín et al., 2007) and cloud top height (Pascual, 2002). The thermodynamic indexes that must be kept in mind are CAPE (Convective Available Potential Energy), the LI (Lifted Index), the TTI (Total Totals Index), the Tc (Convection temperature) and the CCL (Convective Condensation Level). These indexes have also been used in the studies by Rigo (2004), López (2003), Brooks and Craven (2002), Mitzeva et al. (2007) and Kunz (2007).

In the cases discussed below, the previous methodologies have been taken into account, although the focus was put on synoptic, mesoscale and thermodynamic analysis in order to find simple discriminatory policies that helped improve prediction in Catalonia. With this in mind, this article

Table 1. Episodes studied with the time, hour, place, phenomena, duration and damage produced. The name of the affected region has a number that refers to its location in Figure 1.

	Starting time	Place	Phenomena and observations	Duration	Damage
20/08/2003	18 h	Garrotxa (4), Pla de l'Estany (6)	Hailstone: tennis balls; intense rain; strong wind	30 min	Broken trees; damaged cars and houses; foxtail millet crops destroyed
16/06/2006	14 h	Pla d'Urgell (20) and Urgell (15)	Hailstone of 4 cm; heavy rain; small tornado; lightning 35,000	10-30 min	Destroyed crops; destroyed houses and sheds; lifted roofs
18/10/2006	12 h	Girona regions (1-4, 6-8, 11) and Barcelona (5, 9, 11, 12, 14, 16, 17, 19, 21, 24, 25, 28)	Intense rainfall (100 mm 30 min^{-1}); one tornado	During the afternoon	Flooded basements, fallen trees, evacuated schools
11/09/2008	12 h in the Pyrenees; at 15 h in Girona and at 17 h in Lleida	Alt Empordà (1), Pla de l'Estany (6), Garrotxa (4) i Ripollès (3), Lleida regions (10, 13, 15, 18, 20, 23)	Hailstone; rain; strong wind; thunder and lightning	15 min	Crop losses, especially apples and peaches; trees fallen due to the wind; firemen called out for floods; road landslides at Port Ainé (Pallars Sobirà)
05/07/2009	Early afternoon	Pla de l'Estany (6) i Gironès (8)	Hailstone of 4 cm, golf balls; rain and wind	30 min	Fallen trees due to the wind; flooded streets; crops affected by hailstones
09/07/2009	12 h	Barcelona regions (5, 9, 11, 12, 14, 16, 17, 19, 21, 24, 25, 28)	Intense rainfall	3 hours	The most intense were in the Barcelona regions. They coincided with the Tour of France
04/09/2009	Mid-afternoon	Girona regions (1-4, 6-8, 11) and Barcelona (5, 9, 11, 12, 14, 16, 17, 19, 21, 24, 25, 28)	Intense rainfall	During the afternoon	A river in Rupit burst its banks. Flooded streets

is distributed as mentioned below. After this introduction, section two presents the study area. The third point explains the cases that have been studied and the sources of information. Section four explains the methodology used and the fifth point offers the results obtained. Finally, the sixth section gives the conclusions.

2 Study area and sources of information

The studies are focused on Catalonia, in the north-east of the Iberian Peninsula (Figure 1). This region is surrounded by the Pyrenees to the north and the coastal and pre-coastal mountain ranges. The Mediterranean Sea lies to the east, and to the west the Lleida plain along with the continuation of the pre-coastal and coastal mountain ranges and the Pyrenees. This highly complex terrain favors the formation of hail, mostly in the summer months, and heavy rain, which causes flooding, especially during the fall months. We analyzed several episodes that have affected this area and, in particular, the province of Girona.

Information from the C-Band Doppler radar network of the SMC and the SMC radio sounding launched daily from the University of Barcelona at 00:00 UTC and 12:00 UTC was used for the analysis of the episodes. Indirectly, the information analyzed in the MONEGRO (REN2003-09617-C02-02), SEVERUS (CGL2006-13372-CO2-02) and FLASH (Framework Programme European Commission, project no. 036,852) projects, and information from the network of 172 hailstone gauges installed in the Lleida area (Ceperuelo et al., 2009), from the network of 126 rain gauges of the SAIH network of the Catalan Water Agency and from the network of automatic weather stations of the SMC, XEMA (Atencia et al., 2011), was also used to identify the characteristics of the hail surface and precipitation. Data

Table 2. Episodes analyzed from March to September 2012. The starting time, place and phenomena are shown. The name of the affected region has a number that refers to its location in Figure 1.

Time (UTC)		Place	Phenomena
12/09/2009	16:00	Garrotxa (4); Anoia (16); Pla d'Urgell (20)	Hail; ice pellets
13/09/2009	12:00	Baix Camp (30)	Showers with storm; hail; ice pellets
14/09/2009	13:30	Barcelonès (24)	Intense showers with storm and ice pellets
17/09/2009	From 17:00	Barcelona regions (5, 9, 11, 12, 14, 16, 17, 19, 21, 24, 25, 28) and Tarragona (22, 26-35)	Intense rainfall
18/09/2009	00:00 h	Girona regions (1-4, 6-8, 11)	Intense rainfall

from automatic weather stations have also been used for monitoring the events in the validation period.

From the point of view of the weather models, we have worked with: i) the NCEP reanalysis; ii) the MM5 mesoscale maps run by the GAMA group from the UB, according to the parameterizations and explained annually by Barrera et al. (2007).

3 Selected case studies and information sources

3.1 Selected case studies

The case studies were selected based on four criteria: i) Affected area: sites susceptible to flooding and hailstorms were sought; ii) hail diameter > 2 cm, as in this case significant damage occurs not only to agriculture but also to infrastructures and vehicles, in addition to direct personal injury; iii) High average intensity of rainfall; iv) significant damage.

The cases were selected after a systematic search in the press database developed by the GAMA group, PRESSGAMA (Llasat et al., 2009); the INUNGAMA flood database (Barnolas and Llasat, 2007) according to the homogeneity of the available meteorological information and, finally, the study periods covered by the MONEGRO, SEVERUS and FLASH projects. In all, seven cases included in the 2003-2009 period were selected, focusing on the period of hail tracking campaigns, from May to September, with special emphasis on cases that hit the coast. Some more recent cases, which occurred during the summer of 2009 and during the spring and summer of 2012, have been added to these to validate the findings. Some cases that affected inland areas have been included in order to make a comparison.

Table 1 shows the different episodes studied, the areas most affected, the synthetic description of the phenomena and the damage that they caused. The ANELFA classification was used to classify the hail according to its size (Dessens et al., 2007).

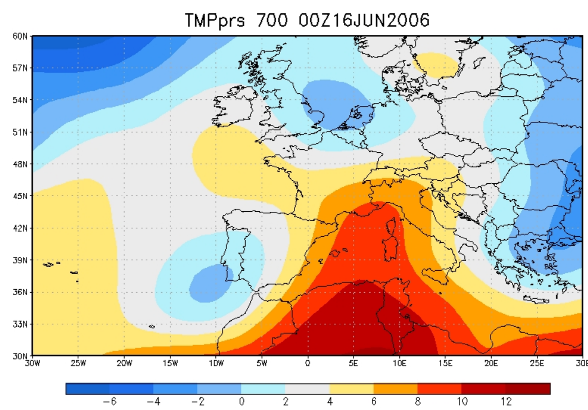

Figure 2. Temperature analysis at 700 hPa on 16 June 2006 at 00:00 UTC.

Five more studies were done later to validate the method (Table 2) and 21 more, three years later (Table 3). The advantage is, that the criteria proposed based on previous analyses on the prediction could be applied, and real-time monitoring of these events was done. The monitoring was done through the various sources explained in section 2 and the results of these analyses can be seen in detail in the results. In this case there was a distinction between ice pellets (< 10 mm diameter) and hailstones (> 10 mm diameter).

4 Methodology

The work began by analyzing hail and heavy rain episodes in Table 1. Through these analyses, the selection

Table 3. pisodes analyzed from March to September 2012. The starting time, place and phenomena are shown. The name of the affected region has a number that refers to its location in Figure 1.

	Hour (UTC)	Place	Phenomena
19/3/2012		Osona (9)	Ice pellets
26/3/2012	Afternoon	Segrià (18)	Ice pellets
3/4/2012	Afternoon - evening	Pla d'Urgell (20)	Ice pellets
6/4/2012	Afternoon	Interior Tarragona regions (22, 26-35)	Ice pellets
12/5/2012	Afternoon	Pyrenees, Pre-Pyrenees, Girona regions (1-4, 6-8, 11)	Ice pellets
13/5/2012	Afternoon	Maresmes; Osona (9, 17)	Ice pellets
19/5/2012	Afternoon	Franja de Ponent (10, 18, 31, 33)	Ice pellets
20/5/2012	Morning	Urgell, Pla d'Urgell, Segrià, Garrigues (15, 18, 20, 23)	Ice pellets
	Afternoon	Mollet del Vallès (19)	Ice pellets
		Eastern half of Catalonia	Intense rainfall
27/5/2012	Afternoon	Planes d'Hostoles Tordera (4, 17)	Ice pellets
12/6/2012	Afternoon	Pyrenees, Pre-Pyrenees, Girona regions (1-4, 6-8, 11)	Intense rainfall; storms
19/6/2012	Early morning	Palau d'Anglesola (20)	Ice pellets
1/7/2012	Afternoon	Vilafranca del Penedès; Badalona (24, 25)	Ice pellets
5/7/2012	Afternoon	Pla Urgell; Segrià; Urgell; Berguedà; Bagès; Serra de l'Obach (5, 10, 12, 15, 18, 20)	Hail
27/7/2012	Afternoon	Segrià (18)	Hail, ice pellets
28/7/2012	Matí	Aldea; Valentins del Montsià (35)	Hail
5/8/2012	Afternoon	Segrià; Noguera (10, 18)	Hail, ice pellets
30/8/2012	Morning	General throughout Catalonia	Intense showers
9/9/2012	Afternoon	Prat Lluçanès, Castellar del Riu (5, 9)	Hail
	Afternoon	St Vicenç de Torelló; Rierades Gironella (9)	Ice pellets
10/09/2012	Afternoon	Berguedà (5)	Hail, intense rainfall
	Afternoon	Alfès (18)	Ice pellets
12/9/2012	Afternoon	Girona regions(1-4, 6-8, 11)	Intense rainfall

of some discriminating factors between rainfall and hail was made. These were examined during two experimental campaigns, which were carried out in September 2009 and during the spring and summer of 2012. The analysis performed includes the steps below.

4.1 Analysis at a synoptic scale

Table 4 shows the variables and factors studied for each episode at 00:00 UTC, 06:00 UTC, 12:00 UTC and 18:00 UTC, from the NCEP analysis. First of all, the factors that favor the formation of thunderstorms were taken into consideration (McGingley, 1986; Martín et al., 2007): i) Humidity at medium and low layers, ii) Convective instability, iii) Forcing mechanisms (orographic effects, thermal and humidity boundary, microfronts on a gust, low level jet). Factors discriminating between storms and severe storms were also analyzed (McGingley, 1986; Martín et al., 2007): i) dry layer at middle levels ii) wind shear. It should be noted that the vertical shear with respect to direction favors the deepening and organization of convection. According to López (2003), a very intense shear, especially between 500 and 200 hPa, inhibits convection.

The temperature at upper layers was also observed. According to Martín et al. (2007), , clouds generating hail must have their peak at between -20°C and -40°C (5 to 10 km altitude). Finally, the presence of a close depression is also an important factor to consider, especially due to the convergence that it can create and the organization of the airflow (Rigo and Llasat, 2007).

4.2 Mesoscale analysis

The following mesoscale fields, at different levels of the atmosphere (surface, 850 hPa, 700 hPa, 300 hPa and 500 hPa), were analyzed at 00:00, 12:00 UTC and 18:00 UTC, from the outputs of the MM5: i) Temperature, ii) Relative humidity, iii) Wind direction and speed, with special emphasis on areas of convergence. According to Martín et al. (2007), these factors can also behave as forcing mechanisms at mesoscale level. The parameterization and initialization of MM5 used are listed in Barrera et al (2005), but are mainly based on the Kain-Fritsch scheme (Kain and Fritsch, 1993).

4.3 Thermodynamic and radar analysis

Different factors and thermodynamic indexes have been analyzed through the Barcelona radio soundings of 00:00 UTC and 12:00 UTC, i) Presence of intense updrafts. The intensity of these drafts is determined by the available convective potential energy, CAPE (Weisman and Klemp, 1986) and the maximum vertical velocity, VMAX (Martín et al., 2007); ii) freezing level height and freezing level of the wet-bulb thermometer (López, 2003; Martín et al., 2007);

Table 4. Factors analyzed at a synoptic scale for each episode.

Atmospheric levels	300 hPa	500 hPa	700 hPa	850 hPa	925 hPa	Surface
Pressure						X
Wind maximum	X					
Wind speed		X	X	X	X	
Wind direction	X	X	X	X	X	
Groove		X				
Vorticity		X				
Thermal dorsal			X			
Thermal advection			X	X		
Temperature	X	X	X	X		X
Humidity		X	X	X	X	X

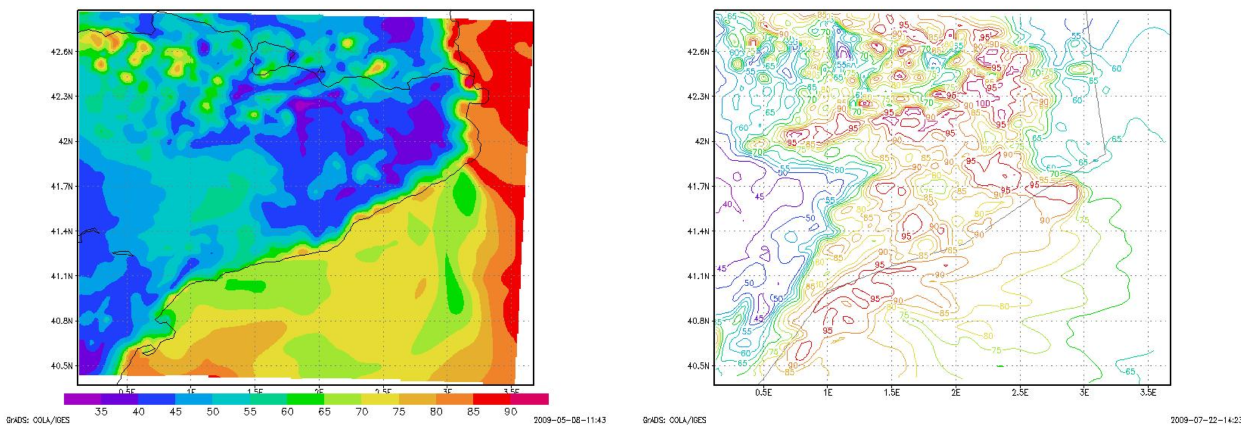

Figure 3. Mesoscale humidity maps at 12:00 UTC. At left (a), hail episode on 11/09/2008. At right (b), rainfall episode of 09/07/2009.

iii) Height of isotherms at -5°C, -10°C, -20°C (Martín et al., 2007); iv) LI (Galway, 1956); v) Total totals index, TTI (Miller et al., 1972); vi) Lifted condensation level, LCL; vii) Convective condensation level, CCL; viii) Precipitable water mass, PWM.

The radar images were used to follow the evolution of storms and to locate the areas affected by each of them. Subsequently the damage in each of the zones was observed.

5 Results

5.1 Mesoscale and synoptic analysis

In all cases, whether associated with heavy rain or hail, at 300 hPa the temperature is between -38°C and -42°C, without any discriminating difference being found between the two types of episodes. Also, the wind blows from the southwest at this level, with a maximum speed that is between 15 and 20 m s^{-1} in all cases.

Circulation at 500 hPa and 700 hPa is not always well defined. In most episodes, the grooves identified are secondary and their vorticity is small or negligible. However, there are two episodes (16/06/2006 and 18/10/2006), which affected the Lleida and Girona areas, respectively, where a cold closed depression or a deep groove at 500 hPa were found, west of the region. The prevailing wind in the storm front was west or southwest with a speed of between 15 and 20 m s^{-1}. In the first of these cases, which affected the province of Lleida, a noticeable south warm air inlet to middle and high levels was observed (Figure 2), placing the affected area in the field of the thermal ridge input. The humidity was below 60% in all cases except the 09/07/2009 episode of rain that hit the province of Barcelona, where it was 90%.

At 850 hPa, the difference in humidity between the hail and rain episodes was marked. In the case of hail, the humidity was below 70%, while in rainfall episodes it exceeded 80%. The common feature was the existence of a small cold air intake, which lowered the temperature between 1 and 2°C. The wind, also in all cases, was weak and no dominant direction was found.

At 925 hPa, the difference in humidity between episodes associated with hail and rain continued to be notable. In the first ones, the humidity was below 70%, whereas in the case of rain the humidity was above 90%. The wind was still very similar to that at 850 hPa, being weak and without a dominant direction.

Table 5. Thermodynamic index for each episode (RDS 12 UTC). The abbreviations are defined in the text.

	Hailstone				Rainfall		
	16/06/2006	05/07/2009	11/09/2008	20/08/2003	09/07/2009	04/09/2009	18/10/2006
CCL (m)	2660	2223	1685	2223	463	1129	1000,9
LCL (m)	1705	909	892	1292	500	446	704
Freezing level	3872	4050	4392	3952	3812	4393	3258
LI	-2.3	-8	-4.7	-3.3	5.2	-6.2	-1.2
TTI	52.2	51	46	45.6	40.3	47	51.8
CAPE	283	2457	1960	788	0	2291	233
PWM	3.46	3.26	3.61	2.81	4	3.48	3.6
Tc	33.2	34.6	32	37.8	23	28.2	19.6
T850-T500	32.6	28.3	28.1	37.2	23.0	25.9	19.0

Table 6. Humidity (%) at different levels of the atmosphere in the rainfall episodes. The numbers in italics indicate low humidity ($< 60\%$), while the numbers in bold indicate humidity $> 90\%$. The value of the LI index is also indicated as well as the temperature differences between 850 and 500 hPa.

Episodes	Humidity (%) at diferent atmospheric levels					Thermodynamic indexes	
	500 hPa	700 hPa	850 hPa	925 hPa	1000 hPa	LI	T850-T500
09/07/2009	82	**97**	**95**	89	85	5.2	23
04/09/2009	*44*	*20*	81	**95**	65	-3	28.2
18/10/2006	69	**98**	**100**	86	85	-1.2	19.6

In the mesoscale analysis on surface, differences between episodes of hail and rain were perceived. In the episodes of hail, humidity was below 67%, except in the episode of 16 June 2006 when it was 78% (Figure 3). In the rainfall episodes, humidity was over 85% except for the episode of September 4, 2009 when it was 65%.

5.2 Thermodynamic indexes

Table 5 shows a summary of the results of the thermodynamic study from Barcelona radio sounding. The analysis of the temperature difference between 500 hPa and 850 hPa showed that in hail episodes it was over 28°C, in case of rain, the difference was less than 26°C.

Another indicator that showed differences between the episodes was the convective condensation level (CCL). According to Pascual (2002), if the CCL is too high the updrafts cannot be developed with enough power or may not be developed at all. In all hail cases studied here, the CCL was above 1600 m, while in rainfall episodes it was below 1100 m.

If the Tc is too high, the convection might not even happen (Pascual, 2002). In the analysis done for the different episodes it was found that in hail episodes, the Tc was higher than 32°C, and in the rainfall episodes it was less than 23°C, except for the episode of 04/09/2009 that had a convection temperature of 28°C. Therefore, they are temperatures that are found in summer.

In cases of hail, the LI presented low values and in general allowed differentiating cases of hail and rain. In the episodes of hail it had a value of less than -2. In the cases of rain, it was higher than -1, except for the episode of 04/09/2009 containing a value of -6.

The CAPE, TTI and freezing level indexes are good indicators of unstable weather but they are not enough to differentiate cases of hail from those of rain, since the differences between them are poorly marked.

5.3 Selection of the more discriminant variables

In the previous section, for each of the cases mentioned, nine variables between 300 hPa and 1000 hPa and 10 indexes calculated from radio soundings were analyzed. Tables 6 and 7 seek to synthesize the most representative variables and the ones that indicated differences between the episodes of hail and those of rain.

In the analysis of the maps, a single significant difference was observed, humidity at low levels. To work with this variable more accurately, the humidity values at different levels were taken from the radio soundings at 00:00 and 12:00 UTC. It was observed that in the rainfall episodes the humidity was above 95% between 850 hPa and 925 hPa (Table 6). However, in hail episodes the humidity was below 85% and 100% humidity was never reached (Table 7).

In the thermodynamic analysis, the temperature difference between 500 hPa and 850 hPa and the LI index are good indicators. This difference was higher than 28°C in hail episodes and below this threshold in rainfall episodes. The LI index was less than -2 in hail episodes, and higher than -1 in rain episodes. In some way, these results are consistent with those obtained by Gibergans-Bàguena and Llasat (2007) after analyzing 2393 (00:00 UTC) and 2265 (12:00 UTC) ra-

Table 7. Humidity (%) at different levels of the atmosphere in hail episodes. The numbers in italics indicate low humidity (< 60%), while the numbers in bold indicate humidity > 90%. The value of the LI index is also indicated as well as the temperature differences between 850 and 500 hPa.

Episodes	Humidity (%) at diferent atmospheric levels					Thermodynamic indexes	
	500 hPa	700 hPa	850 hPa	925 hPa	1000 hPa	LI	T850-T500
16/06/2006	*38*	83	61	*56*	78	-2.3	33.2
05/07/2009	*44*	*43*	83	74	*55*	-4.8	34.6
11/09/2008	*28*	71	63	76	67	-5.6	31.5
20/08/2003	*22*	*50*	*28*	*47*	*52*	-3.3	37.8

Table 8. Factors and indexes analyzed to corroborate or reject the hypothesis. The numbers in italics indicate low humidity (< 60%), while the numbers in bold indicate humidity > 90%. The value of the LI index is also indicated as well as the temperature differences between 850 and 500 hPa.

Episodes	Hour (UTC)	Humidity (%) at diferent atmospheric levels					Thermodynamic indexes	
		500 hPa	700 hPa	850 hPa	925 hPa	1000 hPa	LI	T850-T500
12/09/2009	12	72	65	*48*	*53*	*50*	-1.4	30
13/09/2009	00	67	90	*47*	65	*56*	-1.1	28.5
	12	*58*	85	75	**100**	72	-1.1	28.5
14/09/2009	00	80	**92**	61	80	72	-1.7	26,6
	12	67	*55*	88	73	**94**	2,9	24.1
17/09/2009	12	65	**93**	75	65	60	0	24.5
18/09/2009	00	64	83	76	75	**91**	-1.43	26.4

dio soundings in Palma de Mallorca for the 1975-1989 period, and searching among 22 thermodynamic parameters, the most discriminated ones on the rainfall in Catalonia. Of the seven indexes obtained, LI and relative temperature at 850 hPa were two of them.

The rain episode of 4th September 2009 was studied more thoroughly, as during the analysis it was observed that the values obtained for different indexes the CCL and Tc, were close to the values of the hail cases, and the LI index obtained an equal value. The question is, why was there no hail? While this study cannot give a conclusive answer, it is possible to observe that below 850 hPa, the humidity was above 90%.

5.4 Hypothesis validation

In September 2009, there was a monitoring campaign to corroborate or refute the hypotheses developed in the previous analysis. We analyzed five episodes of heavy rain and/or ice pellets or hailstones (Table 2). The factors analyzed in these episodes were humidity ranging from the 500 hPa and 1000 hPa levels, the thermodynamic index LI, and the difference between the temperature of 500 hPa and 850 hPa. Table 8 shows how the humidity at 850 hPa was below 50% in only two cases where there were hailstones, and in the cases where rain prevailed, it was over 75% at this level. The detailed study of all levels between 850 hPa and the surface showed that it was over 95% in the cases dominated by rain.

Regarding the thermodynamic index, it was observed that the lifted index was less than -1 in cases dominated by hail, in which the difference of temperature between 500 hPa and 850 hPa was below 28°C (Table 8).

During 2012, there was a second experimental campaign held between March and September (Table 3), taking episodes of heavy rain, ice pellets and hailstones. Of the 21 case studies that were selected, hailstorms were recorded in only six of them, and heavy rains and/or hail in the rest of them. Of those six episodes and attending to radio soundings in Barcelona and Zaragoza, they all showed values of LI < -3, humidity below 80% (5 of them below 70%) and the temperature difference in the middle levels was above 28°C. However, in none of the other cases in which there was either rain or rain accompanied by ice pellets, were these three conditions met.

6 Conclusions

From the meteorological analysis of 33 cases of storms with rain and thunderstorms with hail that happened between 2003 and 2012, through 9 variables and 10 thermodynamic indexes, we conclude that there are three thermodynamic indexes that can help differentiate storms with hail from storms without hail. Thus, values of LI < -2, differences in temperature between 850 hPa and 500 hPa over 28°C and humidity between the surface and 850 hPa below 70%, are the main indicators. In contrast, in rainfall episodes the LI is usually higher than -1, humidity at low levels exceeds 85% and the average temperature gradient at middle levels is considerably lower than in the case of ice pellets.

This result is consistent with the production of severe storms as opposed to storms with intense rain in the study area. In the case of hailstorms, it shows the significant instability in middle levels, which in the case of rainfall is concentrated mainly at low levels, as well as the requirement for higher humidity in the latter cases. In the study of Gibergans-Bàguena and Llasat (2007) about discriminated thermodynamic factors of heavy rainfall in Catalonia, from the radio soundings made in Mallorca, the importance of high values of precipitable water mass between 700 and 500 hPa and high temperatures at low levels were already detected. Moreover, the synoptic situation shows similar characteristics associated with spring, summer and early fall storms in both types of cases, with the presence of a trough to the west, or a close depression, the intake of warm air at low levels. The marked temperature gradient observed in hail cases suggests a relatively cold air intake on middle levels.

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