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The snow storm of 8 March 2010 in Catalonia (Spain): a paradigmatic wet-snow event with a high societal impact

M. C. Llasat[1], **M. Turco**[2], **P. Quintana-Seguí**[3], **and M. Llasat-Botija**[1]

[1]Department of Astronomy and Meteorology, University of Barcelona, Barcelona, Spain
[2]CMCC (Euro-Mediterranean Centre on Climate Change), Lecce, Italy
[3]Observatori de l'Ebre, Universitat Ramon Llull – CSIC, Roquetes, Spain

Correspondence to: M. C. Llasat (carmell@am.ub.es)

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Abstract. A heavy precipitation event swept over Catalonia (NE Spain) on 8 March 2010, with a total amount that exceeded 100 mm locally and snowfall of more than 60 cm near the coast. Unusual for this region and at this time of the year, this snowfall event affected mainly the coastal region and was accompanied by thunderstorms and strong wind gusts in some areas. Most of the damage was due to "wet snow", a kind of snow that favours accretion on power lines and causes line-breaking and subsequent interruption of the electricity supply. This paper conducts an interdisciplinary analysis of the event to show its great societal impact and the role played by the recently developed social networks (it has been called the first "Snowfall 2.0"), as well to analyse the meteorological factors associated with the major damage, and to propose an indicator that could summarise them. With this aim, the paper introduces the event and its societal impact and compares it with other important snowfalls that have affected the Catalan coast, using the PRESSGAMA database. The second part of the paper shows the event's main meteorological features and analyses the near-surface atmospheric variables responsible for the major damage through the application of the SAFRAN (Système d'analyse fournissant des renseignements atmosphériques à la neige) mesoscale analysis, which, together with the proposed "wind, wet-snow index" (WWSI), allows to estimate the severity of the event. This snow storm provides further evidence of our vulnerability to natural hazards and highlights the importance of a multidisciplinary approach in analysing societal impact and the meteorological factors responsible for this kind of event.

1 Introduction

On 8 March 2010, a heavy snowfall swept over a large proportion of Catalonia (NE Iberian Peninsula). It was an unusually severe weather event, characterized by high-intensity snowfalls that reached down to sea level, wind gusts that exceeded 90 $\mathrm{km\,h^{-1}}$ in some areas, and thunderstorms. The event occurred mainly on the northern coast, where snow depth was generally between 20 and 30 cm, although local depths reached 60 cm. As a consequence of the weight of the "wet snow" (Deneau and Guillot, 1984) and the strength of the wind, hundreds of trees were destroyed and, in some areas, the electricity networks collapsed. Its comparison with other events and the fact that this event was the first in Spain with a major echo in social networks allowed us to classify it as the first "Snowfall 2.0".

Snowfalls in Catalonia usually affect the mountain areas, mainly the Pyrenees region, and are generally associated with stratiform precipitation. Intense precipitation events are frequent in Catalonia and usually associated with convective precipitation (Llasat, 2001; Rigo and Llasat, 2004), producing frequent flash floods on the coast (Llasat et al., 2003; Llasat, 2009). They are mainly recorded in summer (local events) or autumn (more organized events), favoured by the warm sea water and strong instability. Generally, the presence of a near pressure low (Milelli et al., 2006; Rigo and Llasat, 2007; Campins et al., 2011) organizes the warm and moist flow at low levels or triggers the convection. The 8 March snowfall event would be a paradigmatic example of the combination of snowfall and thunderstorms in a low altitude Mediterranean region.

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However the case analysed here is also a good example of a "wet-snow" event. Wet snow occurs when surface temperatures are around 0 °C, humidity is high and winds are moderate, thus producing ice formations on structures and power lines. The density of these icing formations usually ranges from 0.3 to 0.8 kg dm^{-3}. Generally, in Mediterranean regions, the values range from 0.3 to 0.5 kg dm^{-3}. Although this phenomenon is frequent in other countries, such as France, it is quite unusual in Spain (Deneau and Guillot, 1984; Admirat et al., 1988; Bonelli and Lacavalla, 2009; Wakahama, 1979; Farzaneh, 2008).

The main objective of this paper is to analyse the reasons for the high societal impact of the snowfall of 8 March 2010. To do so, the paper starts by analysing the societal impact of the event and the role played by social networks, which were becoming mainstream at that time. Its main meteorological features are then described and a comparison with other snow events affecting the same area since 1960 is made, in order to show whether or not it was exceptional. To undertake this analysis, information from the press since 1960 was collected and analyzed following the methodology shown in (Llasat et al., 2009). Furthermore, to analyse the surface features favouring the production of wet snow and their hourly evolution, spatial data of screen level, temperature, humidity and wind speed are necessary. For this reason we used the SAFRAN (Système d'analyse fournissant des renseignements atmosphériques à la neige) meteorological analysis system (Durand et al., 1993; Quintana-Seguí et al., 2008) recently applied to this region (Quintana-Seguí et al., 2012). Finally, in order to summarise the severe surface weather conditions in an indicator that could be easily related to damages, an index to estimate the severity of the event at municipal scale has been introduced, by the application of GIS (geographical information system) tools, following examples of literature on societal impact (e.g. Amaro et al., 2010a; Petrucci and Pasqua, 2008; Dao and Peduzzi, 2004). The paper ends with the main conclusions.

2 Main precipitation features

Figure 1 shows the snow coverage the day after the event, over an area that includes parts of Catalonia, Spain, and the Midi-Pyrénées and Languedoc Roussillon, France. Weak precipitation started on the evening of 7 March in the southern part of the region, and near midnight snow coverage extended over most of the region. During that day the snow levels progressively decreased from 1000 to 700 m, and even to 400 m in some areas. The next morning, precipitation intensified in the northern part of the region, associated with thunderstorm activity. In the afternoon, the snow level reached sea level. The official precipitation data was provided by the rain gauge network of the Meteorological Service of Catalonia (SMC, Prohom and Herrero, 2008). Possible systematic underestimation of the amount of solid precipitation should be taken into account since generally only rain gauges placed at high altitudes are heated. However, while such an underestimation may introduce an additional uncertainty, we considered it negligible to describe the main precipitation features of this event. Figure 2 shows that the maximum precipitation amounts were recorded in the northeast of the region, with around 100 mm in 24 h of equivalent liquid precipitation (official recorded maximum value of 101.7 mm in Torroella de Montgrí), while the snow depth reached 60 cm in Girona (76 m a.s.l.) and 2–3 cm at sea level, covering large extensions of beaches along the coast.

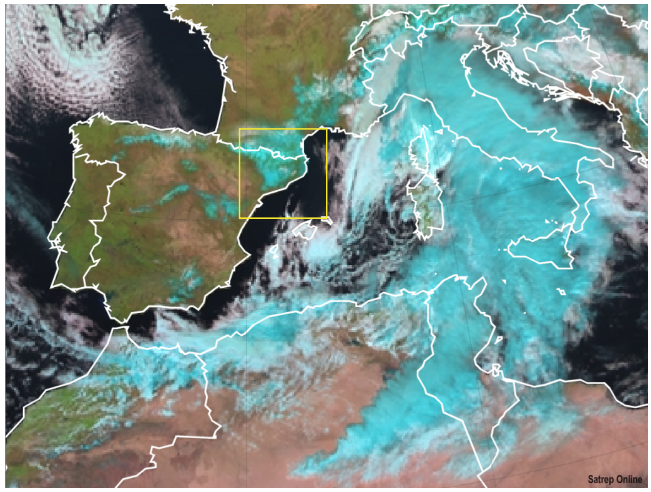

Fig. 1. Satellite image (natural colour RGB, channels NIR1.6; VIS0.8; VIS0.6) from the EUMETSAT Second Generation for 9 March 2010 at 12:00 UTC. Source: http://www.eumetrain.org/. The area of study is located within the yellow box.

The radar images from the Meteorological Service of Catalonia (Fig. 3) show the formation of convection embedded in stratiform precipitation (Rigo and Llasat, 2004), with maximum reflectivities and tops mostly below 40 dBZ and 4 km (Bech et al., 2012). Convective cells, occurring mainly in the north, were favoured by the wet Mediterranean air advection that lasted more than 3 h. This stationarity of the system allowed the accumulation of high quantities of rain and snow. The occurrence of thunderstorms is confirmed by the lightning activity that affected this region: 101 CG (cloud-to-ground) flashes (231 strokes) and 169 IC (intra-cloud) flashes, mainly recorded from 12:20 to 17:40 UTC (Bech et al., 2012).

3 Societal impact of the event

The Meteorological Service of Catalonia issued the first meteorological warning three days before the event, as well as two special press releases to inform the public (Vilaclara et al., 2010). The government activated "NEUCAT", the emergency plan for snow (http://tinyurl.com/cgvocdl). In spite of these measures, the event had a major

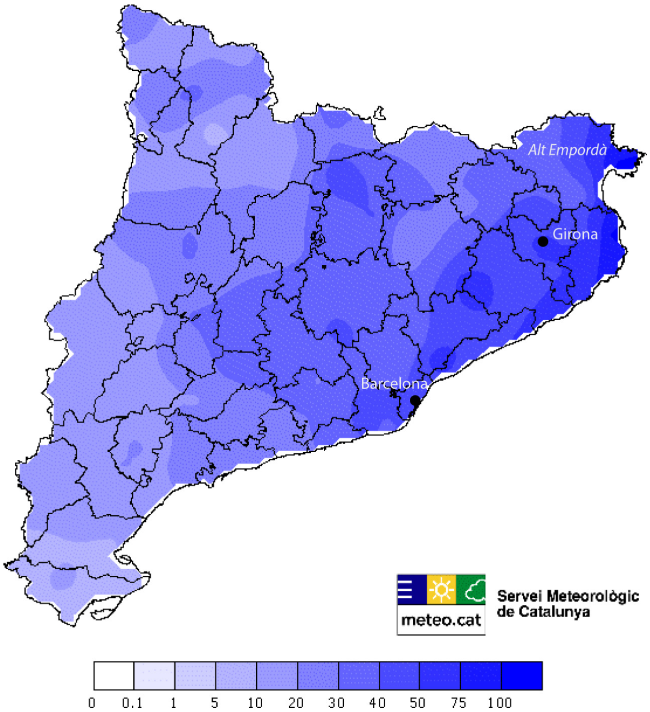

Fig. 2. Accumulated precipitation between 7 (00:00 UTC) and 10 March (00:00 UTC) 2010. Source: www.meteo.cat.

Table 1. Main damages as a consequence of the snow event of 8 March 2010 in Catalonia (M: million).

Deaths	2
High-voltage power-transmission towers affected	36
Customers affected by power outages	450 000
Cost of recovery works of electric company	EUR 60 M
Forest area affected	150 000 ha
Losses in agriculture and forestry	EUR 35.68 M
Forest cleanup operations	EUR 23.5 M
Roads and highways	180 affected, 34 closed
Students without classes	215 623
Hours of work estimated as lost	5 M
Estimation of total damages	EUR 90 M

societal impact in Catalonia. This was mainly due to its exceptionality: the large amount of wet snow and precipitation and wind, as well as the fact that it affected the most densely populated city in Catalonia, Barcelona (nearly five million inhabitants in the metropolitan area) with 3 cm of snow near the sea and 20 cm at the Fabra Observatory (415 m a.s.l.).

This event surpassed the threshold for consideration as a heavy rainfall event of 60 mm/24 h set by the MEDEX (Mediterranean Experiment) project (Homar et al., 2007), thus allowing application of the methodology developed in Amaro et al. (2010a) to analyse requests received by the SMC for information and certificates. Nearly one hundred requests were received, 70 % asking for snow information and 30 % for data about the rainfall event, a far higher number than the average number of requests (fewer than twenty) received by the SMC in the month of March (Amaro et al., 2010b). The main interests were to justify absence from work, to calculate the overload on infrastructures due to the snow, and to evaluate and justify damage.

Besides this information, the impact of the event was analyzed with information from newspapers and reports (Table 1). A total of 36 high-voltage power-transmission towers were damaged by snow and wind (Fig. 4a). As a consequence, more than 450 000 customers were affected by power outages over the following days and the electricity company spent EUR 60 million on repairs. The damage to forests was substantial, affecting 150 000 ha (Fig. 4b), while fallen branches and trees affected infrastructure such as roads and made access to residential areas more difficult. Losses in agriculture and forestry were estimated at EUR 35.68 million. The main problems after the event lay in clearing these forests, fallen trees and wood in order to open pathways, restore gardens and houses affected by the damage and also to prevent an increase of wildfire risk, since dead wood is a key factor in wildfire severity (Turco et al., 2012). The Catalan Regional Government approved funds of EUR 23.5 million to mitigate the damage caused by this event (mainly for forest clearing operations). The Decree 43/2010 of 23 March of the Government of Catalonia (DOGC, 2010) approved the adoption of urgent measures to alleviate the damage and reduce the risks to the environment as a result of the snowstorm of March 2010. As Fig. 5 shows, the major damage in forestry municipalities occurred near the coast, in the littoral range, which has maximum altitudes of less than 700 m, as a consequence of a combination of snow accretion and strong winds. Following this decree (no information from insurance companies is available), Fig. 6 shows the municipalities in which more than 25 % of the population was affected by power cuts for more than 24 h; it refers only to the aid received by the council, with a maximum value of 70 073.75 in Girona (the capital of the northern Catalan region). Figure 6 was built using a geographical information system (GIS) software in order to calculate simple correlations with variables like the number of inhabitants, information given by IDESCAT (Institut d'Estadística de Catalunya (Statistical Institute of Catalonia), 2010). It has been found that the distribution of subsidies was mainly proportional to the number of inhabitants in the municipality (correlation, $r = 0.94$), more than to the estimated total public and private damage. This fact shows the great importance of the population density as an indicator of the potential cost for the administration.

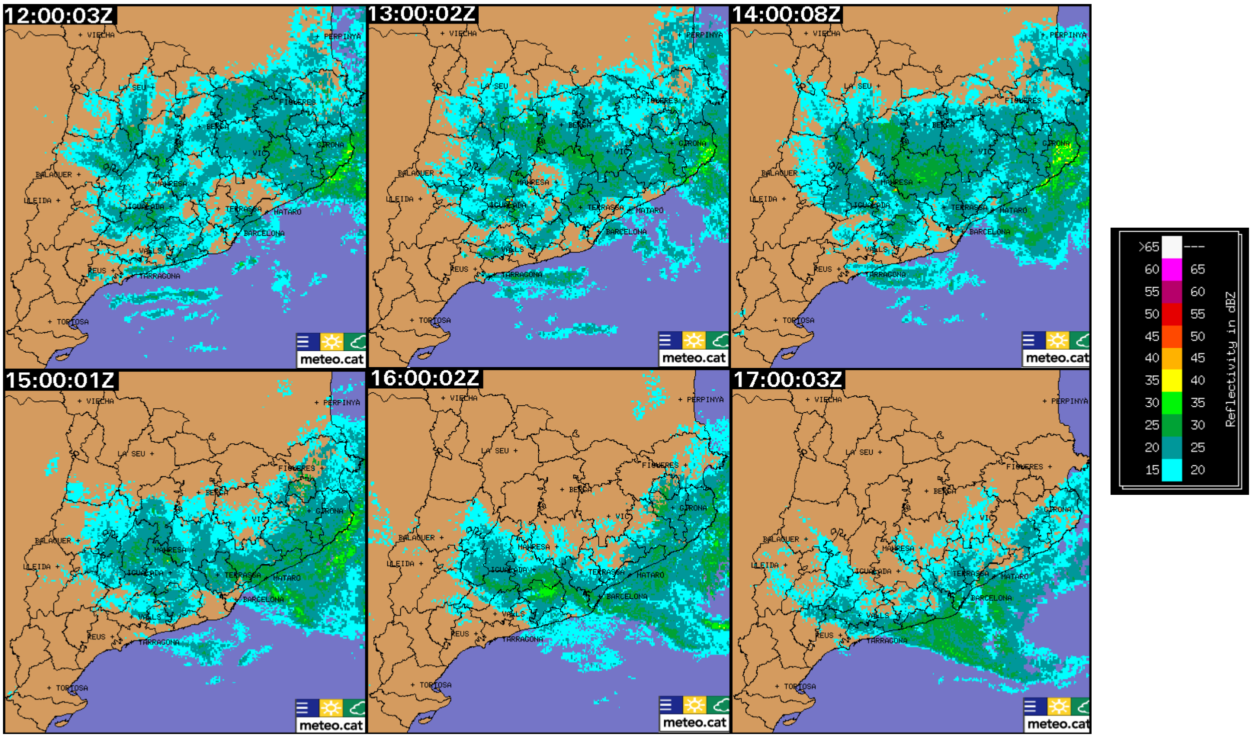

Fig. 3. Composite radar imagery over Catalonia showing the first CAPPI, from 12:00 to 17:00 UTC, 8 March 2010. Source: www.meteo.cat.

Fig. 4. (a) High-voltage power-transmission tower destroyed near France (Port-Bou) by wind and the weight of the wet snow. Source: www.elperiodico.com. **(b)** Fallen trees due to the effect of snowfall and wind (Les Gavarres, Girona). Source: www.elperiodico.com.

Previous work on the estimation of societal impact and the perception of natural hazards in Catalonia through the press (PRESSGAMA database) for the period 1982–2007 (9428 newspapers) showed that snow events have the highest number of news items per event, probably due to their low frequency in the region (Llasat, 2009). So for floods (the main natural hazard in Catalonia), the average number of headlines per event is 5.5, while for snow events it is 6. These figures may change over the years, depending on the presence of such high impact events. In 1985, five snow events made 102 headlines, although 96 concerned the snowfall of 5 January (Table 2). In the case of March 2010, considering the period 8 March–23 April 2010, 210 news items were published in the newspaper taken as a reference (*La Vanguardia*), 194 of them in March. The news in the press about this issue disappeared abruptly after the eruption of the Eyjafjalla Volcano.

Besides the PRESSGAMA database built after systematic research in each newspaper (Llasat, 2009), information on snow events affecting the coastal region since 1960 was sought in specific newspapers. According to this information, the March 2010 snow event had the most press reports in the history of that newspaper, followed by the 1962 event, which also affected the city of Barcelona, with more than 50 cm of snow and the unusual sight of people skiing in the city centre. Table 2 shows the events that recorded more than 40 cm of snow in the province of Girona. Looking at the evolution of the more severely affected economic sectors in these 50 yr,

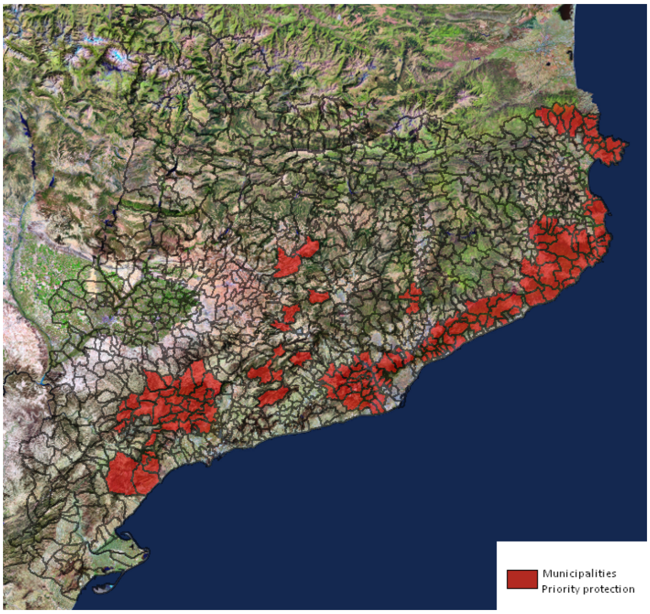

Fig. 5. Map showing the municipalities within the priority forestry protection perimeters established by Decree 43/2010 of 23 March (DOGC, 2010).

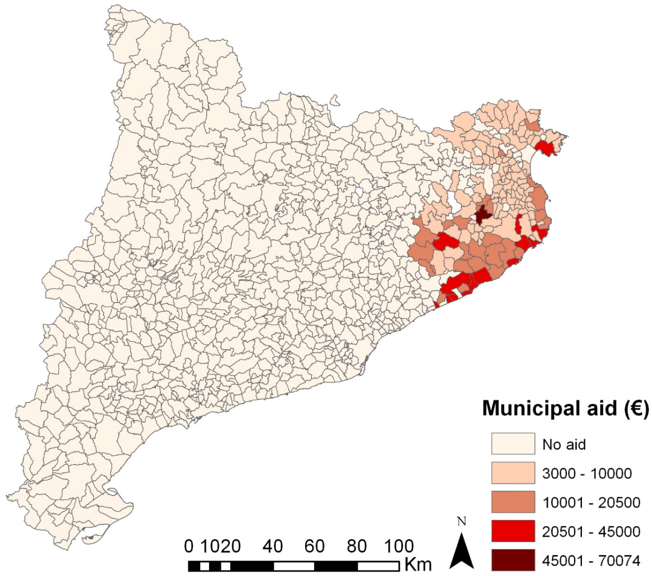

Fig. 6. Municipalities that received special grants for payment of costs occasioned because of snowfall (Decree 43/2010 of 23 March, DOGC, 2010).

while in the first decades the main damage was in agriculture, with the most recent events, the service sector came first in the ranking. The supply of electricity was, however, damaged in all cases. In terms of comparison, although the event of 2001 also had a substantial societal impact and damage was very high due to roads and highways being blocked, there was considerably less damage (for more information on this event, see Pascual et al., 2003). However, as a consequence of the 2001 event and the evident difficulties in emergency management, the Government launched the "NEUCAT" program, which was operative during the 2010 snowfall event and prevented greater damage. A final observation on news coverage shows a change in sociopolitical reaction: while the events in the sixties saw newspapers praising the authorities and emergency management, in recent decades, reporting has, in the main, been severely critical.

This snowfall event could be classified as the first "Snowfall 2.0". Between 9 March and 23 April 2010, a search with the Spanish term "*nevadas marzo 2010*" (snowfalls March 2010) led to 81 600 results on Google, 132 on Facebook and 750 amateur videos on YouTube. Most results related to personal experiences during the event and included text and pictures. Twenty-four hours after the event started, the number of fans, friends or likes of Facebook members, groups or pages about the snow event had reached 72 000. On the one hand, Facebook and YouTube were used as venues to share experiences related to the snowfall, and there were even competitions to find the best photographs. On the other hand, Twitter acted as a warning channel during the event and the following days, although we found no posts discussing what could be done better to prepare for this kind of event or improve resilience capabilities.

4 Meteorological analysis

Looking at Table 2, the 8 March event was the last snowfall event of the year (they are usually recorded in December and January). It was characterized by the presence of a deep cold low (COL) at high levels, mainly over Catalonia, with a wet advection from the south (Fig. 7), while at low and middle levels there was a northeasterly–easterly wet advection due to the presence of a mesoscale low over the Catalan-Balearic Sea (Fig. 8a). This low was a consequence of the upper level cold trough which favoured a rapid cyclogenesis over the Mediterranean. The position of the COL, embedded in a deep trough that crossed France, allowed the entrance of very cold ($-30\,^{\circ}$C) and dry continental air at 500 hPa, and the development of instability in middle and high levels. A key factor was the advection of very wet air at 700 and 850 hPa from the east, which affected the Girona area and favoured the feed of humid air at middle levels (Fig. 8b), and, consequently, the development of wet snow. The westward movement of this low marked the end of the precipitation event the next day over Catalonia, although the low temperatures still remained, freezing the snow that had fallen the day before.

The surface mesoscale low organized the flow at low levels over the Catalonian coast, and its location and role were similar to those of other heavy rainfall events (e.g. the floods of June 2000, Milelli et al., 2006). It favoured the advection of moist and relatively warmer air from the Mediterranean,

Table 2. Number of news items published by *La Vanguardia* newspaper about the worst snow events that have affected Girona and the surrounding area (in brackets the number of news items published during the first 10 days is shown) and the main material damage and human injury in Catalonia (in brackets the inflation-adjusted losses to 2011 Euro values; ESP: Spanish peseta). All the events recorded more than 40 cm of snow in this province (exception: the 1964 event that is included due to having occurred in March).

Event	Snow depth (cm) (min–max)	News items in *La Vanguardia*	Material damages (M: million)	Deaths
25 Dec 1962	10–88	(115)	> ESP 320 M (64.3)	2
1 Feb 1963	12–100	(14)	> ESP 236 M (43.3)	0
7 Mar 1964	2–25	(9)	Not known	0
5 Jan 1985	13–40	96 (61)	> ESP 4000 M (64.7)	38
30 Jan 1986	6–40	46 (42)	> ESP 4000 M (59)	2
23 Jan 1992	2–68	(12)	Not known	0
1 Mar 1993	3–30	25 (23)	Not known	0
14 Dec 2001	20–40	89 (70)	> EUR 3.5 M (4.5)	9
8 Mar 2010	25–59	210 (194)	EUR 90 M (92.8)	2

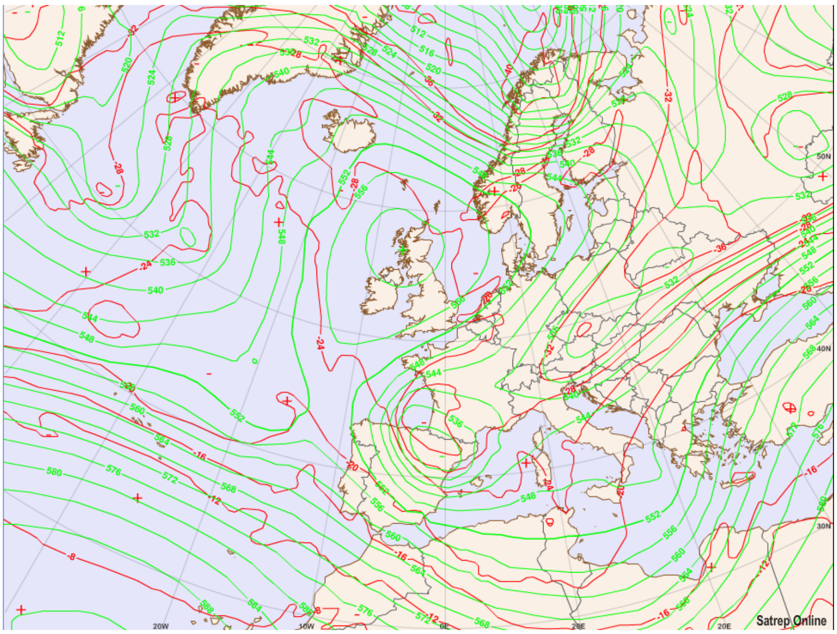

Fig. 7. Temperature and geopotential analysis at 500 hPa at 12:00 UTC, 8 March 2010. ECWMF Model. Source: http://www.eumetrain.org/.

the convergence of water vapour, and the flow from the east that impinged nearly perpendicularly to the electricity network (favouring a major momentum) extending near the coast from southwest to northeast. Both the low and the littoral mountains triggered convective instability and the development of thunderstorms. Indeed, radio-sounding analysis over Barcelona showed high values of precipitable water mass (9.31 mm) and TT index (total index, 49), indicating a high probability of thunderstorms (Fig. 9). Instability indexes such as CAPE (convective available potential energy) and LI (lifted index), however, showed no particular feature. This was one of the main differences in comparison with the usual heavy rainfall events occurring in Catalonia in summer or autumn, when potential instability is concentrated at the lowest levels due to the advection of very warm and wet air and a strong gradient of equivalent potential temperature (Llasat, 2009).

The comparison of the main synoptic features that characterized the snow events included in Table 2, shows a similar surface pattern for all the events, with low pressures over the Iberian Peninsula and the entrance of cold air from eastern Europe (as an example, only the reanalysis of the most representative events is shown, Fig. 10). At 500 hPa, the presence of cold air from the northwest over Catalonia is also common, although a cut-off low has been identified only on a few occasions (Fig. 11). Within this synoptic pattern

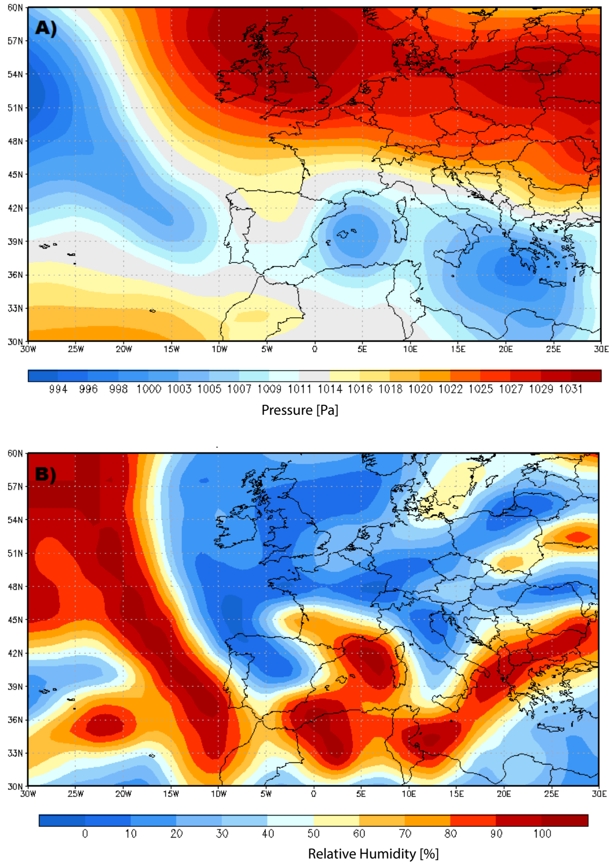

Fig. 8. (a) Sea level pressure analysis, at 12:00 UTC, 8 March 2010. **(b)** Analysis of moisture at 700 hPa, at 12:00 UTC 8 March 2010. (NCEP model. Source: http://nomad2.ncep.noaa.gov).

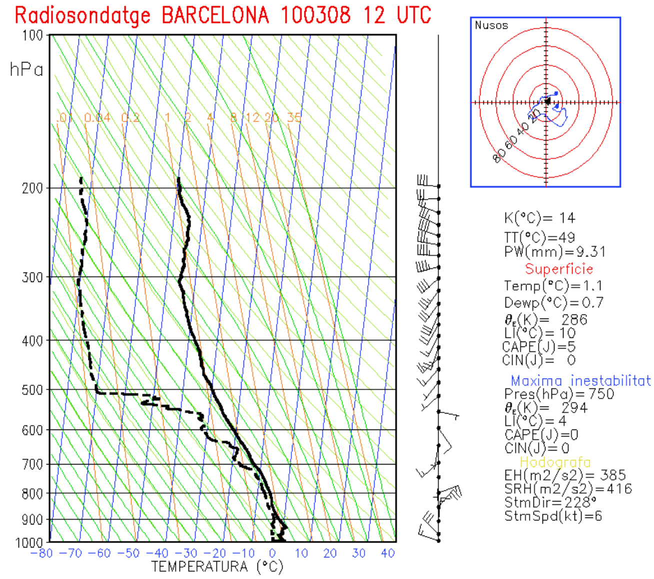

Fig. 9. Radio-sounding analysis over Barcelona at 12:00 UTC, 8 March 2010. Source: www.meteo.cat.

characterized by the entrance of cold, continental air from the northeast, the main synoptic differences can be found in the humidity field at 700 hPa, which on some occasions does not reach 60 % (i.e. March 1964, January 1985), and which appeared to be a determinant factor in the March 2010 event (Fig. 12).

5 Surface analysis

As discussed in the introduction, the formation of wet snow requires temperatures close to 0 °C, high humidity values and moderate winds. In order to obtain a regional analysis of the hourly evolution of these variables, we used the SAFRAN analysis (Durand et al., 1993; Quintana-Seguí et al., 2008). SAFRAN is a mesoscale atmospheric analysis system for screen-level variables. By means of optimal interpolation, it produces a meteorological hourly analysis of temperature, precipitation, wind speed, relative humidity and cloudiness using all available ground data observations and the outputs of a meteorological model. One of its main features is that it is based on climatically homogeneous zones (areas where spatial gradients of meteorological variables are not very relevant) and is able to reliably take vertical variations into account. SAFRAN is currently operational at Météo-France and has been widely used in different contexts, for example, to force land surface and hydrological models (Habets et al., 2008; Quintana Seguí et al., 2009) or as an observational database for climate downscaling studies (Quintana Seguí et al., 2010; Vidal et al., 2010; Quintana-Seguí et al., 2011). Currently, the SAFRAN analysis system is being implemented in the northeast of the Iberian Peninsula (SAFRAN/NEIP), in collaboration with AEMET (Agencia Estatal de Meteorología, the Spanish Meteorology Agency), which provides data from their synoptic and climatological networks and the outputs of the HIRLAM HNR meteorological model, to be used as a first guess (Quintana-Seguí et al., 2012). We used the same grid as HIRLAM (5 km of resolution). The first prototype of the system was implemented for the hydrological year September 2009–August 2010, and it was thus possible to apply it to the case of 8 March 2010. Over Catalonia (defined by the box within 0 and 3.4° E and 40.5° N and 42.9° N), the analysis includes data from 217 precipitation stations and 29 stations which measure the rest of the variables (mainly pressure, temperature, relative humidity and wind). SAFRAN reads and analyses the observed data every 6 h (0, 6, 12, and 18:00 UTC), except for precipitation, which is provided daily. These analyses are interpolated onto the hourly time step. In the case of precipitation, relative humidity is used to establish the hourly distribution of precipitation (Quintana-Seguí et al., 2008).

The added value of the application of SAFRAN to this event is to provide mesoscale analysis of near-surface

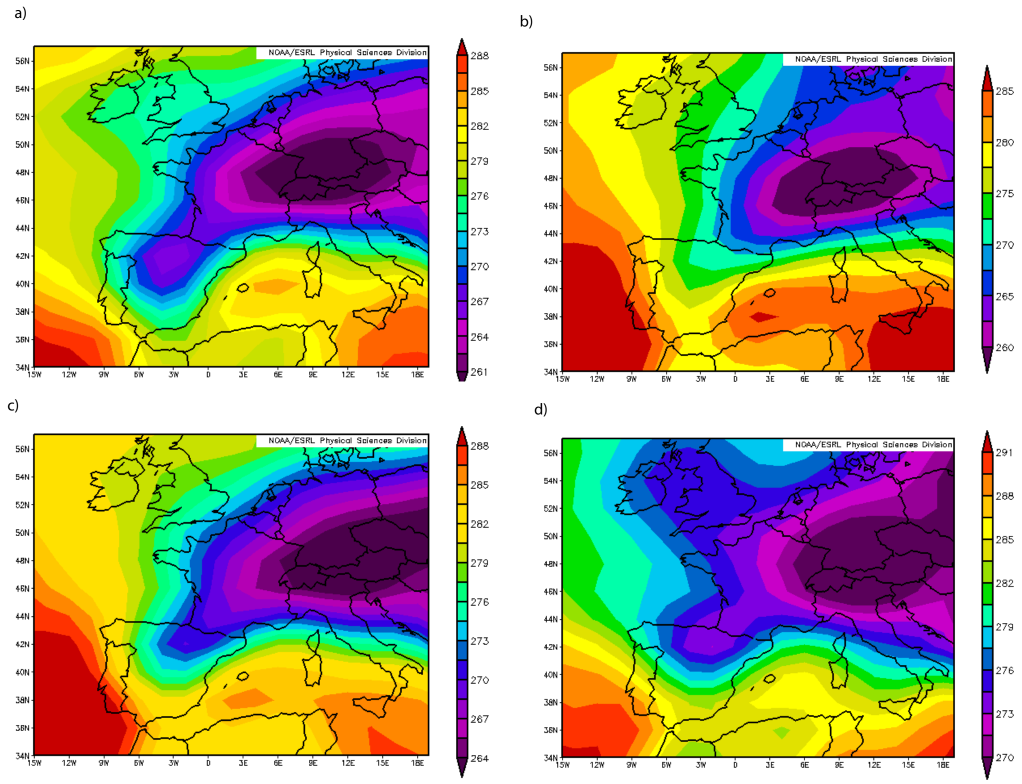

Fig. 10. Reanalysis showing the mean surface air temperature: **(a)** 25 December 1962; **(b)** 5 January 1985; **(c)** 14 December 2001; **(d)** 8 March 2010. Source: 20th Century Reanalysis, NOAA/ESRL.

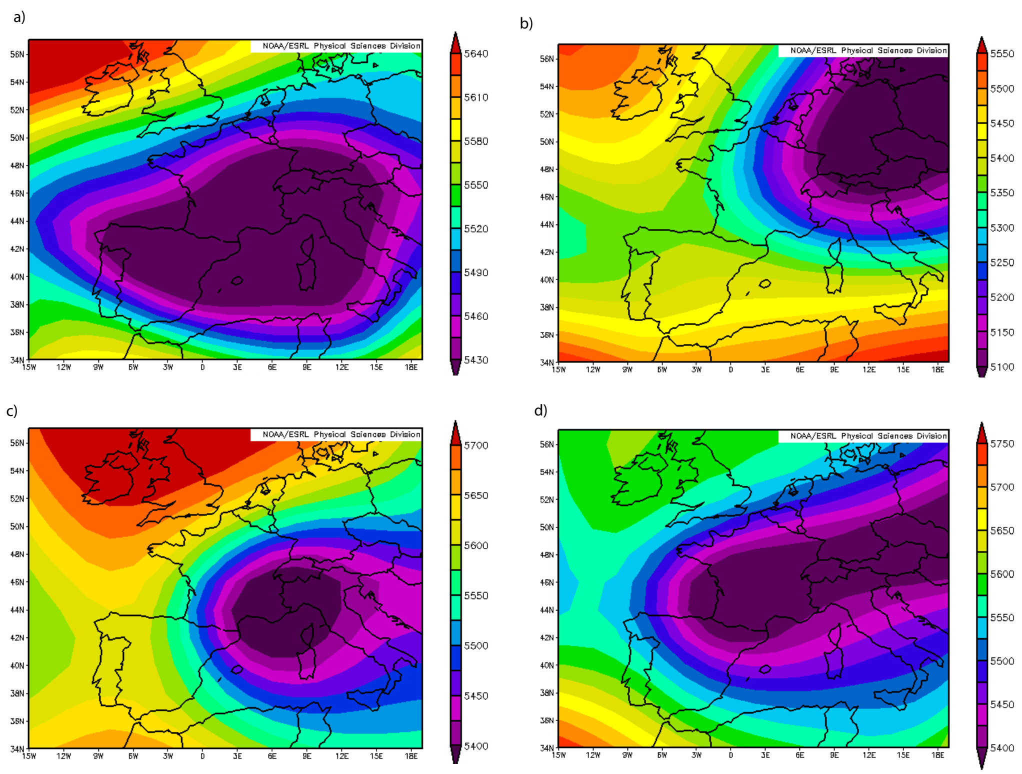

Fig. 11. Reanalysis showing the mean geopotential at 500 hPa: **(a)** 25 December 1962; **(b)** 5 January 1985; **(c)** 14 December 2001; **(d)** 8 March 2010. Source: 20th Century Reanalysis, NOAA/ESRL.

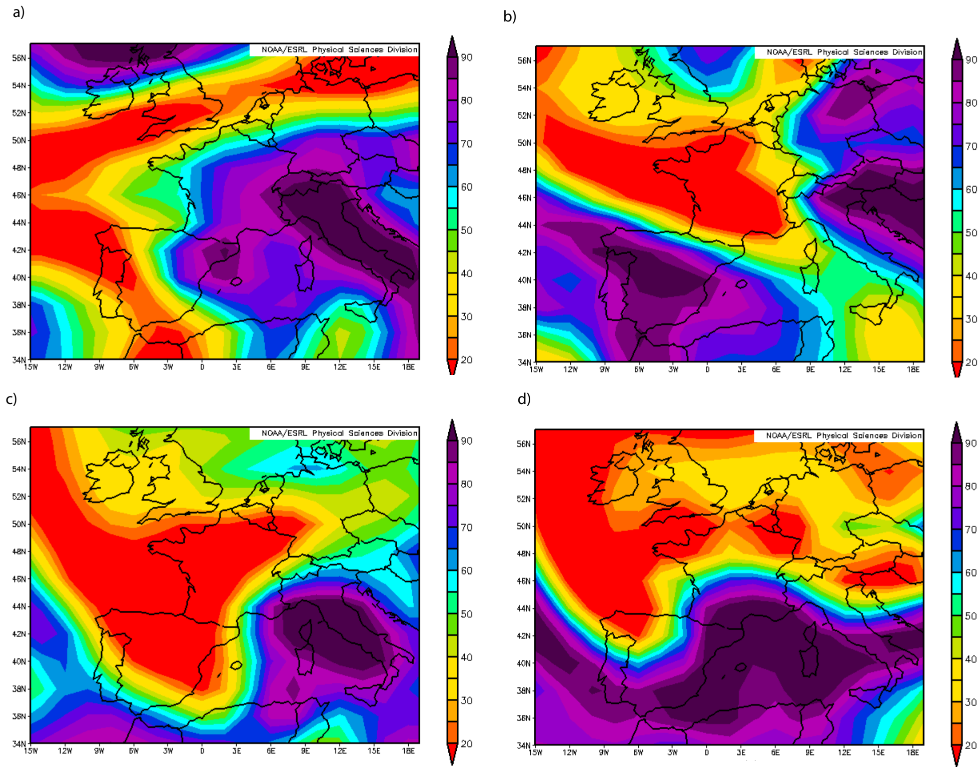

Fig. 12. Reanalysis showing the mean relative humidity at 700 hPa: **(a)** 25 December 1962; **(b)** 5 January 1985; **(c)** 14 December 2001; **(d)** 8 March 2010. Source: 20th Century Reanalysis, NOAA/ESRL.

atmospheric variables in which the observations are checked for their quality and that the variables are consistent with each other, in order to show the main factors responsible for the wet snow. Figures 13 and 14 show the evolution of the mean hourly values of relative humidity, temperature and wind at the surface over Catalonia from 12:00 UTC 7 March to 18:00 UTC 8 March. These variables are the most closely related to the production of wet snow and the associated damage. At 12:00 UTC on 7 March, the surface humidity field did not exceed the value of 60 %, with some peaks around 70 % over the south of the region and at some points of the Pyrenees, where some precipitation occurred in the evening. However, by 18:00 UTC, humidity values were higher than 60 % over the entire region and higher than 90 % at 00:00 UTC on 8 March. At 06:00 UTC on 8 March, the maximum values moved towards the northeast and a wide region registered values near 100 % from 10:00 until 19:00 UTC. On the following day, maximum values of relative humidity were recorded inside the region.

Surface temperature was very low the days before the snow event, and the 0 °C level reached the south of Catalonia. However, during the morning of 7 March, warm air was advected over the country, displacing the icing level back to the Pyrenees, with temperatures on the Girona coast above 12 °C. As a consequence of the arrival of a cold front, temperatures decreased markedly on 8 March: the northwest part of the region and Pyrenees dropped below −6 °C, and the coast recorded values ranging between 0 and 2 °C. These low temperatures persisted in the north of the region until 10 March.

A weak wind field dominated the entire region on 7 March, with hourly velocities of less than 1 m s^{-1}. However, at 22:00 UTC, the situation changed completely, and easterly winds with average hourly values above 3 m s^{-1} started to affect the entire coast, with maxima above 7 m s^{-1} in some areas. On the afternoon of 8 March, the presence of a region with weaker hourly winds gave way to a discontinuous distribution, broken on the Girona coast, where values were less than 2 m s^{-1}. This discontinuity disappeared some hours later when the strongest winds affected the entire coast. Weak precipitation started on the night of 7–8 March, and relatively heavy precipitation was recorded at 07:00 UTC 8 March, with hourly intensities near 8 mm h^{-1} on the Girona coast.

The configuration of the total precipitation field did not change until 16:00 UTC (Fig. 15), and then the hourly maximum values moved to the central part of the region. The first snowfalls started inland on the night of 7 March, and by 06:00 UTC they had already reached the sea south of Barcelona. From 10:00 until 16:00 UTC, maximum snowfall intensity was recorded over the Girona coast (Fig. 16), and, locally, liquid precipitation was also recorded. This combination facilitated the heavy density of the snow and the damage it caused to the electricity network and trees.

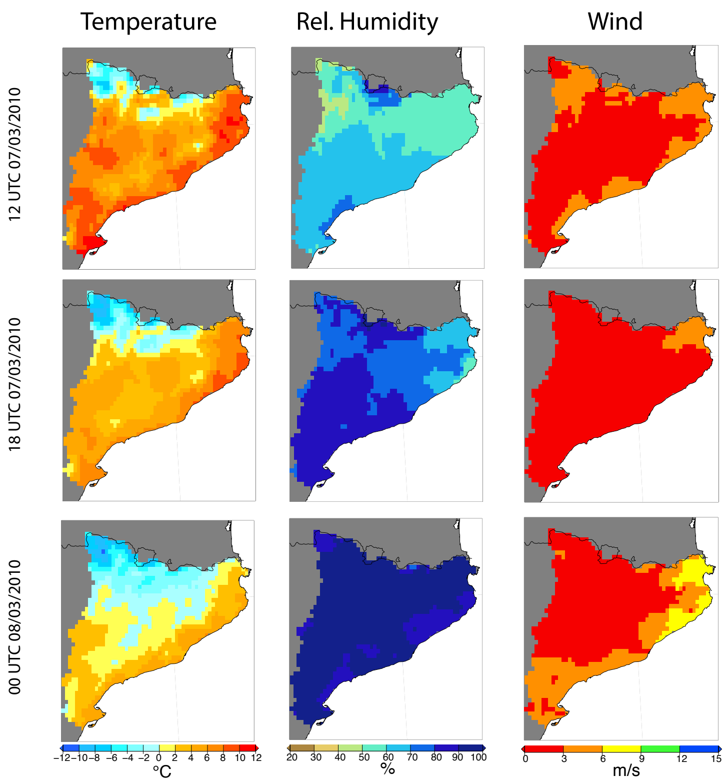

Fig. 13. Evolution of mean hourly values of temperature, relative humidity and wind at the surface over Catalonia from 12:00 UTC on 7 March to 00:00 UTC on 8 March. The analysis has been obtained from the SAFRAN analysis with a resolution of 5 km.

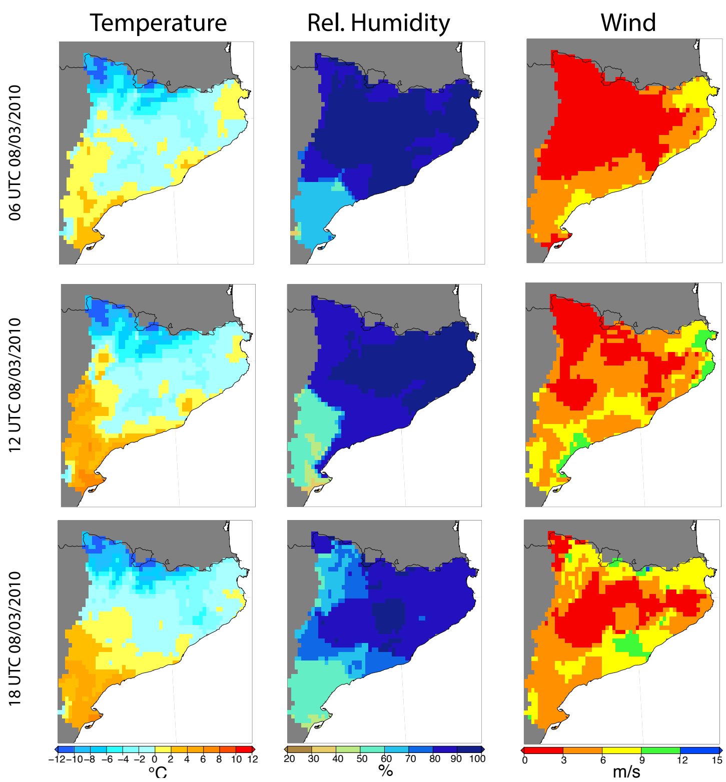

Fig. 14. Evolution of mean hourly values of temperature, relative humidity and wind at the surface over Catalonia from 06:00 to 18:00 UTC 8 March. The analysis has been obtained from the SAFRAN analysis with a resolution of 5 km.

Fig. 15. Hourly evolution of precipitation from 04:00 to 19:00 UTC on 8 March, obtained from the SAFRAN analysis with a resolution of 5 km.

In conclusion, the most affected areas were characterized by values of relative humidity near 100 %, surface temperatures between 0 and 2 °C, and intense snowfalls also accompanied by rainfall, which favoured the formation of wet snow. The weak wind during the central part of the event allowed accretion of the snow, but the increase in wind velocity afterwards led to the breaking of power lines and uprooting of trees because of the accumulated ice-weight and/or the momentum created by the wind. In other coastal areas, where wet snow was not so important, the wind also uprooted trees and partially destroyed some forest areas. Although the perturbation was displaced to the east on the following day, the low temperatures and consequent frosts and the strong winds increased the damage.

Finally, the risk of damage due to strong wind and wet snow has been estimated using a meteorological indicator of severity that we called “wind, wet-snow index” (WWSI). This indicator, which is a first approximation, summarizes wet-snow production and strong wind and it is obtained following a simple approach and combining those variables that played an important role in this event, that is, precipitation, surface temperature, and wind. Higher values of the index are associated with higher snow intensity, higher wind, and temperature values in a more favourable range to produce wet snow. The thresholds defining the different ranges agree with the studies of Wakahama (1979), Deneau and Guillot (1984), and Bonelli et al. (2011).

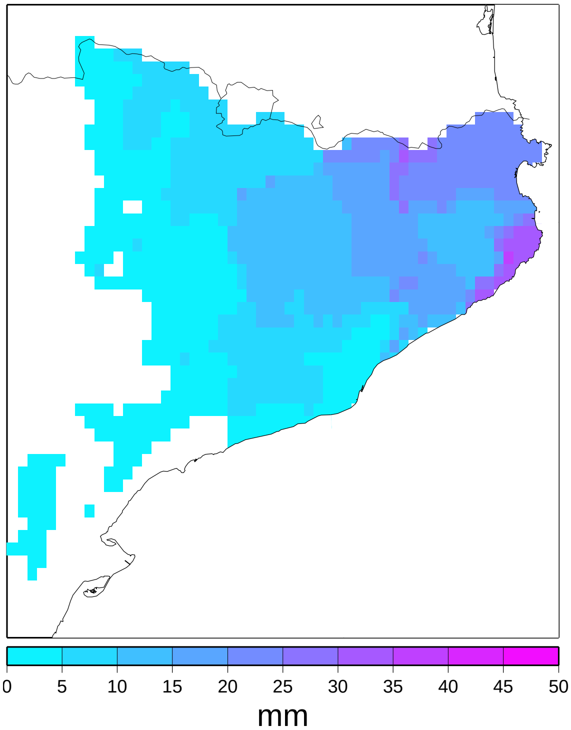

Fig. 16. Total snow recorded between 10:00 and 16:00 UTC on 8 March, obtained from the SAFRAN analysis with a resolution of 5 km.

First an hourly index ($WWSI_h$) is calculated as follows:

$$WWSI_h = SNOW \cdot TEMP \cdot WIND, \tag{1}$$

where

- $SNOW = 1$ (if snow intensity $\geq 0.1\,\text{cm}\,\text{h}^{-1}$),
  2 (if snow $\geq 0.2\,\text{cm}\,\text{h}^{-1}$),
  3 (if snow $\geq 0.4\,\text{cm}\,\text{h}^{-1}$),
  4 (if snow $>= 0.6\,\text{cm}\,\text{h}^{-1}$);

- $TEMP = 0$ (if $T < -4$ or $> 4\,^\circ\text{C}$),
  1 ($-4 \leq T < -1$ or $2 < T \leq 4$),
  2 (if $-1 \leq T < 2$);

- $WIND = 1$ (if $W < 15\,\text{km}\,\text{h}^{-1}$),
  2 (if $15 \leq W < 30$),
  3 (if $W \geq 30\,\text{km}\,\text{h}^{-1}$).

Then, a daily (WWSI) index is calculated as follows:

$$WWSI = 100 \cdot \sum_{i=1,24} \frac{WWSI_{hi}}{576}, \tag{2}$$

where 576 is the maximum daily possible score (24 × 24). Thus, the scale of the WWSI index goes from 0 to 100.

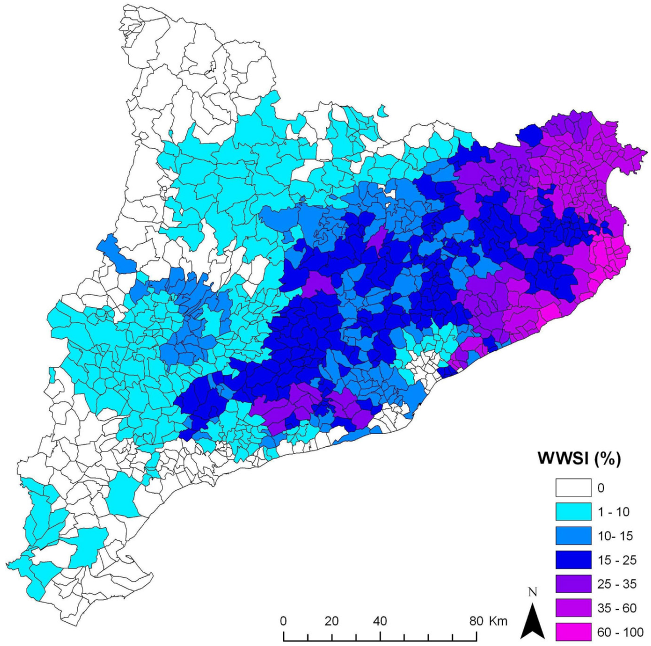

Fig. 17. Distribution of the wind, wet-snow index (WWSI) for Catalonia on 8 March 2010, calculated from SAFRAN analysis fields.

Figure 17 shows the WWSI index for 8 March 2010. This indicator tells us which were the areas with wet snow and strong wind, which gives us a good approximation of the probability of suffering damage as a consequence of the hazard and therefore allows us to estimate its geographical distribution (see Figs. 5 and 6). However, it cannot be directly correlated with the governmental subsidies at a local level, due to the complexity of the factors involved – not only in terms of vulnerability and exposure – but also because of sociopolitical decisions, as we commented previously. In addition, the impossibility of having complete information about the evaluation of total damage prevents finding any quantitative metric or spatial similarity.

This approach is an example of a simple application that highlights the importance of having mesoscale reanalysis fields, such as those provided by SAFRAN, to calculate an aggregated index that summarizes important aspects related to the atmospheric events.

6 Conclusions

The snowfall and heavy precipitation event of 8 March 2010 in Catalonia (NE Spain) was analyzed. It could be considered an exceptional severe snowfall event. Its exceptionality was due to four factors: (i) it was unusual for the time of the year; (ii) it affected mainly the coastal region, the most populated area; (iii) it was accompanied by thunderstorms; and (iv) it produced wet snow and strong winds that caused substantial damage.

Since it affected the most populated region in Catalonia through the breakage of power lines (as a consequence of the wet snow and the wind), the event caused damage exceeding EUR 90 million (the highest cost of a snow event in the last 50 yr), high numbers of injured people and two deaths. It was the snow event with the highest number of press reports (210 news items), and the first recorded in Spain after the emergence of Web2.0 (it was called "Snowfall 2.0"). There was a consequent strong impact on social networks and the Internet, with more than 81 600 inputs (in Spanish) on Google, 132 groups and pages on Facebook and 750 amateur videos on YouTube. However, these were mainly devoted to sharing amusing experiences, to damage-related claims (mainly due to power cuts) and to showing eye-catching pictures. Unfortunately, the population showed little interest in improving its role in prevention and resilience for future events.

This event was unusual from a meteorological point of view as well. A mesoscale low over the Catalan-Balearic Sea and humid and warm advection at low levels is typical of heavy precipitation events in Catalonia. The presence of a trough at high levels, associated with a very cold low, with cold air advection over northern Catalonia, is typical of snowfall events. The singularity of this event lies in the combination of these factors. Indeed, there was a moist advection in the middle and lower troposphere (below 500 hPa), which fed the convection and produced intense precipitation. Due to low temperatures, this precipitation was solid (snow), with a high water content, which is very unusual. The mesoscale low was responsible for organizing the flow and triggering convection. Its position caused heavier precipitation in Girona. Thunderstorms were produced by convection embedded in stratiform rainfall, with cloud tops of 8 km. The stationarity of the thunderstorms allowed the accumulation of high quantities of rainfall and snow.

The application of the SAFRAN analysis, which in this case provided hourly data with around 5 km of resolution, made it possible to follow the evolution of the event at the surface and search for the meteorological causes of the main damage. The most affected areas were characterized by values of relative humidity near 100 %, surface temperatures between 0 and 2 °C, and intense snowfalls also accompanied by rainfall, which favoured the formation of wet snow. The weak wind velocity during the central part of the event allowed the accretion of wet snowflakes on power lines, although the increase in wind velocity afterwards favoured the interruption of electricity networks and the uprooting of trees.

In this paper we discuss a meteorological indicator of severity that combines wet-snow production and strong wind, due to their important role in this event. This indicator, which we called the wind, wet-snow index (WWSI), is a first approximation. It is obtained following a simple approach, considering higher values of the index associated with higher snow intensity, higher wind, and temperature values in a more favourable range to produce wet snow (according to Wakahama, 1979; Deneau and Guillot, 1984; Bonelli et al., 2011). Given the limitations of the data available (SAFRAN is available in the NE of Spain, only for the hydrological year 2009–2010), it is not possible to carry out an extensive validation of this index, thus making it just qualitative. Further investigation is needed to understand the applicability of this index to other cases and regions. For example, it would be interesting to assess statistically, using linear multiregression, the significance of different meteorological variables, like snow intensity, temperature or wind speed, related to the estimated damage/impact of wet snow. In that case it could be possible to find a hierarchy amongst the parameters, assessing which are the most important with respect to the others, instead than deciding subjectively the weight of meteorological variables. Besides this, future work points to the definition of a risk, wind and wet-snow index, that also considers aspects related with vulnerability and exposure, like population density, concentration of vulnerable structures and so on.

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