Nat. Hazards Earth Syst. Sci., 11, 1875–1883, 2011
www.nat-hazards-earth-syst-sci.net/11/1875/2011/
doi:10.5194/nhess-11-1875-2011

Natural Hazards and Earth System Sciences

Tornadoes and waterspouts in Catalonia (1950–2009)

M. Gayà[1], **M.-C. Llasat**[2], **and J. Arús**[3]

[1]Agencia Estatal de Meteorología, Delegació Territorial a les Illes Balears, Palma, Spain
[2]Department of Astronomy and Meteorology, University of Barcelona, Spain
[3]Agencia Estatal de Meteorología, Delegació Territorial a Catalunya, Barcelona, Spain

Received: 28 September 2010 – Revised: 8 May 2011 – Accepted: 12 June 2011 – Published: 8 July 2011

Abstract. This paper presents a preliminary climatology of tornadoes and waterspouts in Catalonia (NE Iberian Peninsula). A database spanning 60 yr (1950–2009) has been developed on the basis of information collected from various sources such as weather reports, insurance companies, newspapers and damage surveys. This database has been subjected to a rigorous validation process, and the climatology describes its main features: timing, spatial pattern, and trends in the tornado and waterspout distribution. Results show the highest concentration of tornadoes from August to October, the highest density in the heavily populated coastal areas and a growing positive trend that is likely more closely linked to an increase in observation and perception rather than a real climatic trend.

1 Introduction

Tornadoes and waterspouts are violent convective weather that has been documented unsystematically for centuries. However, in recent times, these vortices have had a much greater social repercussion than in the past. Indeed, although in past decades these phenomena were likely to have been at least as frequent as we currently observe them to be, it has been felt that they represent a phenomenon not only rare, but unusual (in the sense of alien). Therefore, they included adjectives such as "tropical", "small", "weak", and sometimes described events as cyclones, or hurricanes. Recently, an increase in use of the term tornado has occurred in the mass media, particularly in the press. The number of news items about tornadoes or waterspouts has increased along with items on other natural hazards in Catalonia (NE of the Iberian Peninsula) (Llasat et al., 2009a, b). This may be caused by the interest of its population in unusual phenomena, such as tornadoes. Indeed, this Spanish Mediterranean region is frequently affected by heavy rains and flooding, strong winds and sea storms and forest fires (Piñol et al., 1998; Camuffo et al., 2000; Llasat, 2009). However, in spite of tornadoes and waterspouts being less frequent and the area affected much smaller, the relative impact in the media (measured by the number of news items and the ratio between the number of headlines per event) is greater (Llasat et al., 2009b).

The selected study region is Catalonia (NE of Iberian Peninsula), because of it is one of the Spanish regions where the largest number of tornadoes has been recorded. It also has a very high population density: more than 7.5 million inhabitants in a region of 32 000 km^2, although more than 60 % of them live near the coast. A third factor in the selection of this region was that any detailed climatology of tornadoes and waterspouts for this region has been built now and it is presented here for the first time. This paper also presents the first analysis of this database that spans the period 1950–2009.

Prior to the period of study, some tornadoes and waterspouts were described by contemporary or subsequent narratives, including these phenomena within their accounts (i.e. Blokland, 1965). But, sometimes, they included a mythical or supernatural assessment, as in the case of a tornado near Montserrat presented by Hoinka and Castro (2005), or the severe whirl cited as a snake in the historical work written by Juan de Mariana (1737) as a "precursor" of the defeat of Hannibal against the Roman army around the mouth of the Ebro River (c. 205 BC).

New technologies applied to photography, telephony and document delivery have enabled a large number of cases that otherwise would have gone unnoticed and unrecorded, but are now taken into account. An interest in meteorological topics is manifesting itself by an increasing number of weather forums and websites on the internet. Also, many

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

Published by Copernicus Publications on behalf of the European Geosciences Union.

groups now exist for the purpose of chasing storms, with special attention to tornadoes, information about which is regularly posted on the internet. Usually they are made up of amateurs (i.e., not professional scientists) with various degrees of training and basic knowledge about the matter, so that the use of such information for scientific purposes requires some caution. Thus, information that some years ago was mainly from the press now comes from diverse channels. This wealth and variety of information sources also produces inhomogeneities in the database that have to be recognized and accounted for in any analysis of those data.

Most scientific work about tornadoes in Catalonia is devoted to the analysis of specific cases. Most of the papers on the phenomenon center on the meteorological factors that produced the tornadoes (see among others, Gayà and Redaño, 1996; Ramis et al., 1997; Homar et al., 2003; Aran et al., 2006; Bech et al., 2007). The oldest and most complete systematic work bringing together data about tornadoes in Spain refers to the Balearic Islands (Gayà et al., 2001), although data about tornadoes in Spain have also been collected and analysed (Gayà, 2005). All the databases show a positive increase in tornado frequency that is most likely more related to a change in the perception level of the population, rather than to actual climatic change. This is not a problem unique to Catalonia or Spain (see Doswell and Burgess, 1988; Brooks et al., 2003)

It can be difficult occasionally to separate the damage caused by a tornado itself from that caused by other associated hazards such as heavy rains, hail or windstorms. In some cases, tornadoes or waterspouts also occur during situations of mixed winds and torrential rain (Bech et al., 2007). That was the case, for instance, in the event of 12–15 September 2006, during which flash floods, hail, strong wind and tornadoes were recorded on the Catalan coast (Barnolas et al., 2008). Likewise, on some occasions, damage produced by a downburst can be confused with that produced by a tornado (Doswell, 2003).

In order to assess the spatial and temporal distribution of tornadoes, a high quality, systematic database about tornadoes is necessary. Unfortunately, this kind of database is not easy to obtain, because it requires detailed information about damage, meteorological observations and tornado reports that must be subjected to stringent quality control. The goal of this paper is to develop and present such a climatology of tornadoes and waterspouts in Catalonia and the surrounding sea. Following a description of the process of building the database, the paper focuses on the resulting temporal and spatial distributions of the phenomena and some of its characteristics, as well as offering possible processes that can account for the observed variations in temporal and spatial distributions over the last decades.

Fig. 1. Example of the impacts produced by a downburst: diffluent damages to trees caused by a microburst (a small downburst) embedded in a wide downburst produced on 9 September 1992, in Ciutadella de Menorca (Spain), and seen from helicopter survey (photo © Miquel Gayà)

Fig. 2. Example of the impacts produced by a tornado: collapsed farm caused by a tornado in Espluga de Francolí (Spain), on August 31, 1994 (photo © Miquel Gayà).

2 Database and criteria

Tornadoes and downbursts are distinctly different phenomena, but are not always easy to distinguish when they have not been observed directly by an expert. Effects on the ground are usually quite different, but in some cases small damage over restricted areas may not be sufficient evidence to distinguish between them (Figs. 1 and 2). Another difficulty in classifying this kind of severe weather (when tornadoes and waterspouts are distinguished) is when a waterspout arrives at the coast and becomes a tornado; in this case it could be classified as tornado or as waterspout. Those facts, as well as the potential simultaneous occurrence of tornadoes with other hazards (i.e. downburts, floods, Fig. 3), must be taken into account in construction of the database.

Fig. 3. Example of simultaneous occurrence of tornadoes during an event that also recorded heavy rainfalls and floods (Barcelona Airport, Spain).

The database has the following characteristics and criteria:

1. The complete database includes tornadoes, waterspouts, funnel clouds, and all phenomena that can be confused with the former. However, the data used in this work contains only tornadoes and waterspouts that have been checked and can be confidently classified as such.

2. The period covers 1950–2009.

3. The geographical area of study is Catalonia (NE of Spain)

4. The first 30 yr of the database have been compiled primarily from information consulted in weather and historical archives and newspaper collections (Spain's National Library, National Library of Catalonia, etc.). The field surveys to clarify the type of phenomenon involved and their relevant characteristics intensified over the period 1980–2009, and especially since 1990. Bearing in mind that this can lead to some inhomogeneities, some analyses have been developed only for this second period.

5. Each event has been characterized by the date, UTC time, latitude and longitude of the touchdown and lift-off points (tornadoes), town or locality affected closer to the path, trajectory, intensity value assigned according to the Fujita scale, and other information on the impacts, such as casualties and damage cost. It also includes narrative descriptions or key words used to characterize the atmospheric phenomenon and other subjective assessments provided by the source of the report.

6. If a waterspout touches the shore, the event is considered only as a tornado. If several waterspouts have been observed in the same event and in the same area, they have been recorded as one unique waterspout event. On the other hand, each tornado has been recorded individually in such multiple tornado events.

7. The geographical coordinates of the waterspouts are approximate, except in very specific cases in which they were located by triangulation of images taken from different locations. For tornadoes whose damage was not investigated on the ground, or in cases where the journalist's description is not sufficiently clear, the coordinates that have been assigned are those of the urban center closest to the trajectory.

Table 1. Number of tornadoes and waterspouts (and number of days in which one or more tornadoes and waterspouts have been observed) for the two subperiods considered.

	1950–1979		1980–2009		TOTAL	
	Cases	Days	Cases	Days	Cases	Days
Tornadoes	13	13	84	67	97	80
Waterspouts	6	5	56	53	62	58

With these conditions, the final database used in this paper contains 97 tornadoes and 62 waterspouts events sufficiently referenced and checked. Consequently, from a total of 159 vortex events recorded over or near Catalonia, 39 % of them are produced over the sea and never touch the shore. It is important to clarify that the complete database contains 243 phenomena. Although this is the best database available for Catalonia, it could be affected by the intrinsic problems discussed in Doswell (2007).

3 Temporal distribution

In order to recognize the geographical distribution of risk and the representativeness of the available database, two periods of thirty years each have been considered: 1950–1979 and 1980–2009. The great increase in number experienced in the second period (Table 1) may be very much influenced by improvements in observation and identification.

The number of reported waterspouts and tornadoes has increased over the past 60 yr (Fig. 4). In fact, the period 1980–2009 shows a significant increase. After the mid'-90s, the major interannual variability observed could be the typical kind associated with rare events. The distribution shows an average of one tornado per year in the period 1950–1980, increasing to 1.4 cases per year in the period 1980–2009. However, the number of tornadoes increased to about 5 cases per year in the early interval of 1995–2009, a value that would be above the two tornadoes over land, in average per year,

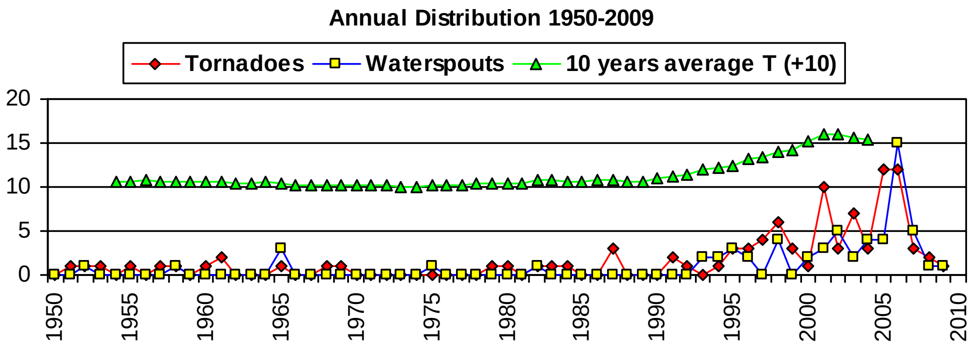


Fig. 4. Temporal evolution of the annual number of tornadoes and waterspouts recorded in the period 1950–2009.

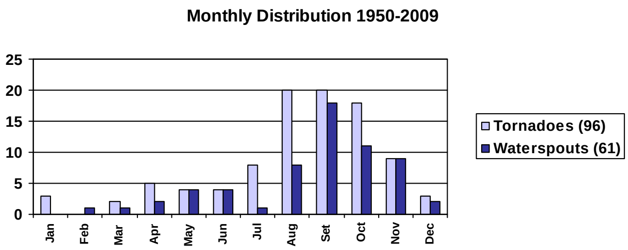


Fig. 5. Monthly distribution for tornadoes and waterspouts in the complete period 1950–2009 in Catalonia. One tornado and one waterspout from the total sample cannot be classified due to the lack of information.

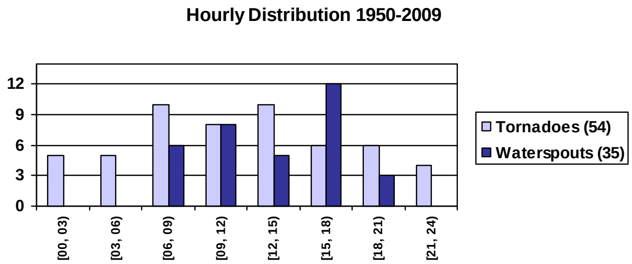


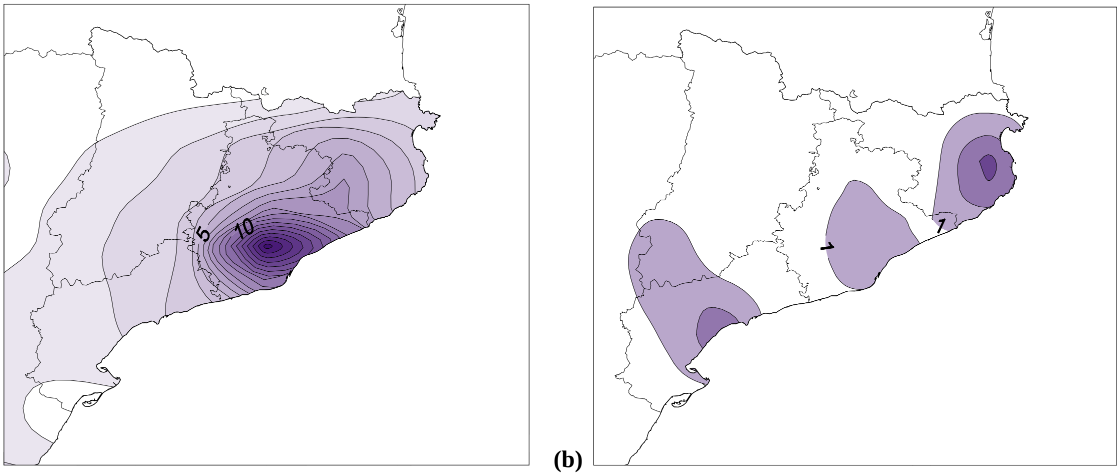
Fig. 6. Hourly distribution of tornadoes and waterspouts for which this information is available (1950–2009).

suggested by Dotzek (2003). This increase is not necessarily associated with a true increase in tornadic activity, however, but rather represents an increase in the detection and recording of tornadoes in Catalonia. As already mentioned, new technologies applied to photography, mobile communications, and the internet have allowed detection of a large number of cases that in the past, likely would have gone unreported and undocumented. This consideration is especially notable in the case of waterspouts.

Figure 5 shows that the 96 tornadoes and 61 waterspouts recorded during the period 1950–2009 in Catalonia were mainly concentrated in the months of August, September and October. This seasonal distribution shows a shift towards summer in comparison with the autumn-winter distribution obtained for the Eastern Mediterranean (Sioutas et al., 2005; Sioutas and Keul, 2007). If we define the tornado season as that which includes 66 % of all cases, the tornado season would start on 12 August and end on 15 November, with a duration of 96 days (period 1980–2009). When waterspouts cases are taken into account, the waterspout season would last 89 days, starting on August 16 and ending on 12 November. If the period considered were 1950–1979, then in spite of the smaller number of cases (13), the season would be longer (113 days), starting on 29 May and ending on 19 September. This implies a major dispersion of the interannual distribution of tornadoes and a shift towards the spring. However this result is not representative, owing to the underestimation of tornado frequency in the first 30 yr of the series.

This concentration in late summer and autumn has also been observed in Italy (Giaiotti et al., 2007) and Portugal (Leitão, 2003), in contrast to a spring frequency maximum in United States and other European countries such as France (Paul, 2001), Germany (Dotzek, 2001) or Ireland (Tyrrell, 2003). This seasonal concentration is most likely due to the inertia of sea surface temperature in the Mediterranean, in conjunction with the changes in the latitude of strong westerlies and the track of travelling synoptic-scale cyclones, and coincides strongly with the seasonal flash-floods distribution in the region (Llasat et al., 2010).

Most tornadoes occur in the hours when the development of convection is at its peak (Fig. 6), in the early afternoon (between 12:00 and 15:00 UTC), with a secondary maximum between 06:00 and 09:00 UTC. This result matches that obtained for the time distribution of hail events in Catalonia (Ceperuelo et al., 2009) and Mesoscale Convective Systems (Rigo and Llasat, 2007). However, it is somewhat anomalous when compared with other countries as Germany (Dotzek, 2001) and the rest of the Iberian Peninsula and the Balearic Islands (Gayà et al., 2001), where the maximum tends to occur later in the afternoon.



(a) (b)

Fig. 7. Contours of tornado occurrence density for the periods 1980–2009 **(a)** and 1950–1979 **(b)**. The interval contours are 1 case/0.5° × 0.5° latitude longitude.

Waterspout records (Fig. 6) show an obvious preference for the daytime, and they are most frequent late in the afternoon. Only a few cases were observed in twilight time or in low light or special conditions, and none at night. This may simply be an observational bias, of course.

4 Geographical distribution

The distribution of tornado density in Catalonia for the period 1980–2009 (Fig. 7a) is based on the number of tornado touchdowns in each 0.5° × 0.5° latitude/longitude box, assumed to apply at the box centroid. Figure 7b shows the same kind of distribution for the period 1950–1979. In order to have a good representation of the tornado density near the borderlines, data from the rest of Spain were deemed to include Portuguese cases (P. Leitão, personal communication, 2009) but not cases in France. Thus, the contouring avoids crossing the Pyrenees, although the density is known along the French border next to the sea.

The observed geographical distribution is strongly influenced by two very different factors: proximity to the sea and population density. These two factors combine in the area near the city of Barcelona, so this region has the maximum density of tornadoes in Catalonia. By contrast, areas ”free” of tornadoes are located inland, and mainly near the Pyrenees. The fact that the minimum density of tornadoes is in the Pyrenees and surrounding areas could actually be a lower frequency, but low population density may be an important factor. If a tornado occurs well away from an urban area, there is a high likelihood it will not be reported and documented. This tornado distribution is very similar to the flood spatial distribution obtained by Barnolas and Llasat (2007) for the 20th century (Fig. 8), but there are some subtle differences, the most important of which is the absence of tornadoes in the western Catalan part of the Pyrenees, probably due to its orography and its continental climate. The comparison shows that a secondary maximum in flood distribution observed in the Northeastern part of Catalonia, where the highest precipitations amounts are also recorded, is not observed in the case of tornadoes for the period 1980–2009.

The waterspout distribution shows the highest density located near the populated areas of Barcelona (Fig. 9) during the period 1980–2009. Similarly, the few waterspouts recorded in the period 1950–1979, are scattered near the coastline. Note that the contours in the waterspout distribution near the bottom of the figure are influenced by the numerous cases near the Balearic Islands (located about 250 km to the South-East). Since the number of waterspouts sighted from remote parts of the coast is very low, the maximum observed frequency remains close to the Catalan coast. As with tornadoes on land, the condition of being “observed” apparently plays a major role in the waterspout distribution. However, there is a difference between both distributions that merits a comment. The maximum frequency of observed waterspouts is south of Barcelona, whereas the maximum of tornadoes is north of the city. This difference cannot be explained by the population distribution and sea activities (fisheries, sportive, commercial and so on), and it may reflect an actual characteristic of the spatial distribution. Similarly, we have classified those phenomena that do not end as tornadoes as waterspouts; this difference could be due to a minor number of tornadoes starting in the sea and ending inland or an absolute major number of waterspouts.

If instead of distinguishing by the type of severe weather (tornado or waterspout), we combined both the tornado and waterspout databases (Fig. 10), the location of the maximum density of convective vortices would be better detected. In any case, the region to the southwest of Barcelona is the peak in the spatial distribution. In effect, although this is a “sensitive” area because the existence of

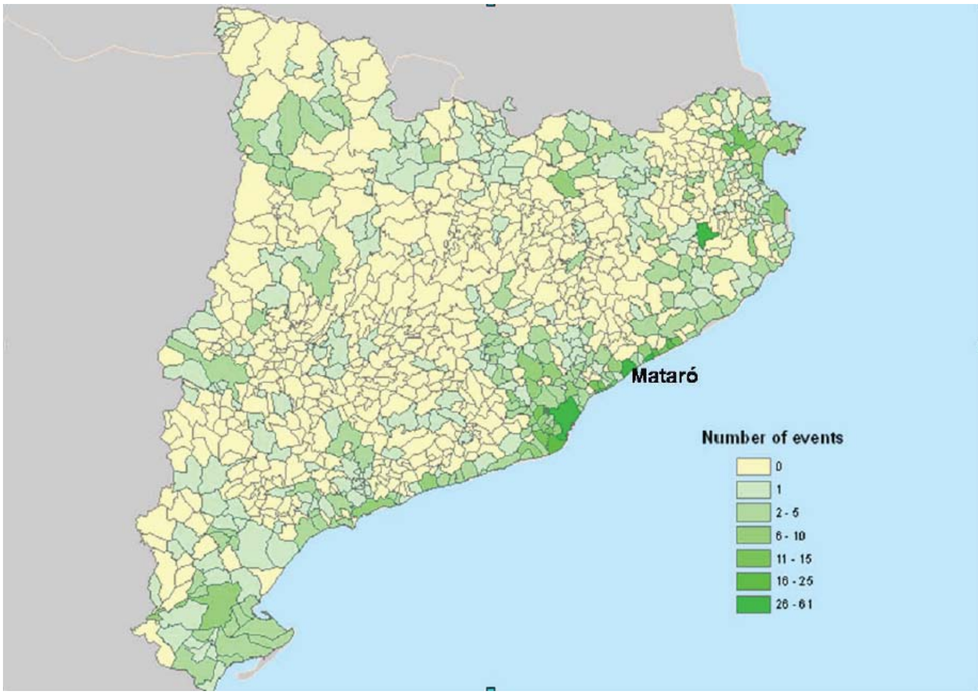


Fig. 8. Number of flood events by municipality for the period 1901–2000 (Barnolas and Llasat, 2007).

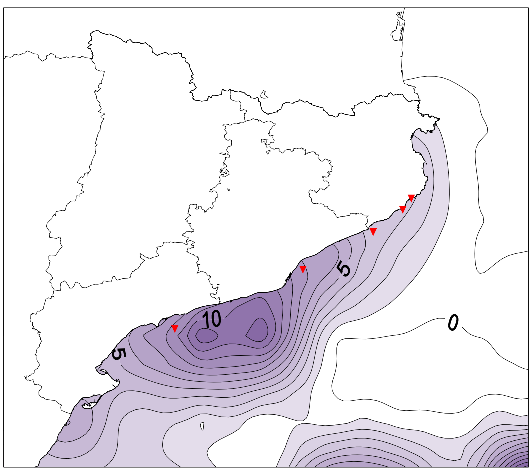


Fig. 9. Waterspouts occurrence density contours in the period 1980–2009. Red inverted triangles are the plotted waterspout in the period 1950–1979. The interval contours are 1 case/0.5° × 0.5° latitude longitude.

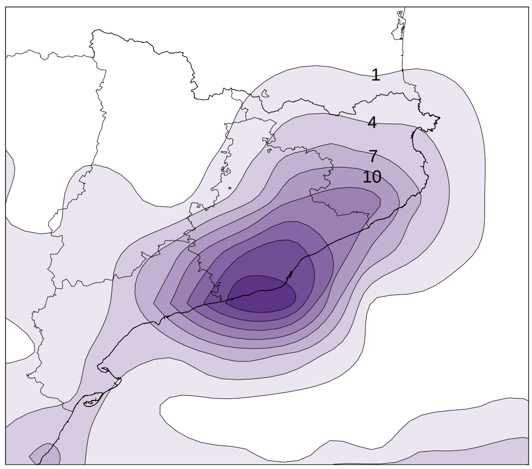


Fig. 10. Density contours of vortex events (tornadoes and waterspouts) for the period 1980–2009. The interval contours are 1 case/0.5° × 0.5° latitude longitude.

the Barcelona airport (Fig. 3), and industrial and technological clusters and residential areas are located in it, the northern part is also very vulnerable, owing to the high population density and industrial activity. Then, some factors related to the tornado hazard should be considered.

5 Tornado characteristics

During the period 1950–1979, the tornado path length was not given in newspaper reports. Although locations (or municipalities) affected by the tornado were occasionally referenced, this deficiency in the information doesn't permit a value to be assigned to the length for this period. Therefore, Fig. 11 has been prepared solely from the information derived from field surveys or reliable descriptions of the route

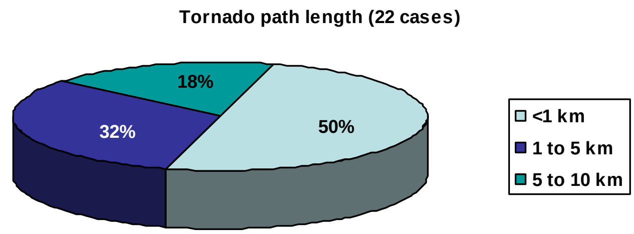


Fig. 11. Tornadoes path length distribution (1980–2009). Only those cases with reliable information sources have been considered.

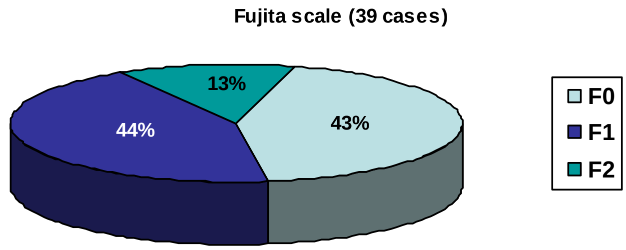


Fig. 12. Distribution of tornadoes recorded in Catalonia (1950–2005) following the Fujita scale.

followed by the vortex. Thus, the number of cases with available data is small (22 instances), which means any statistical analysis of the data can not be considered reliable.

The majority of this small sample of Catalonian tornadoes has a path length <5 km. In fact, half of the cases were less than one km (Fig. 12). Moreover, the direction of these trajectories shows a tendency to move westwards. Indeed, for most tornadoes in Spain, the predominant direction is from the SW, as in most countries of the Northern Hemisphere. However, in the case of Catalonia, the majority of tornadoes (75 %) have a trajectory from south to north and southeast to northwest. This suggests that low levels of the atmosphere mainly determine the direction of tornado movement. Accordingly, if atmospheric instability comes from situations with westerly or southwesterly flow at middle and upper levels (guided, for instance, by a trough or depression over the Iberian Peninsula), the induced low-level flows set in Catalonia tend to be from the south through the east. This synoptic-scale flow, moreover, is the thread that affects the sea breeze on the Catalan coast. This conjunction could be also an ingredient that promotes the helicity of the lower atmospheric layer.

As regards the intensity of tornadoes in Catalonia, only 39 cases have been classified. The majority of tornadoes are weak (Fig. 12) and only 13 % can be characterized as F2. In the studied period, no F3 or greater tornado affected Catalonia.

Radar imagery has been available since 1996. Nowadays the region is covered by a network of four C-band meteorological radars from the SMC (Meteorological Service of Catalonia) and one radar from AEMET (Spanish Meteorological Service), but none of these radars has Doppler capability. Consequently, these images do not allow direct recognition of supercellular signatures in those thunderstorms that generated tornadoes or waterspouts. Only a few hints in a few cases have been identified (Bech et al., 2007, 2011), showing that the vortex was associated with a multicellular storm, an observation corroborated by the visual analysis of other events. This would indicate that most of the tornadoes were generated by non-supercell storms. Also, the short path lengths, and the fact that more than 30 % of 1980–2009 tornadoes in the region were the result of waterspouts that reached the coast, would suggest that the tornadogenesis mechanism for most of the recorded events is that proposed by Wakimoto and Wilson (1989) and Brady and Szoke (1989).

6 Conclusions and discussion

A database containing 97 tornadoes and 62 waterspouts that affected Catalonia over the period 1950–2009 has been built up and analysed. It is the first climatology of tornadoes and waterspouts for such a long period in this region. This database has been subjected to strict quality control.

The main conclusions show that the region with a higher frequency of tornado events is located close to the metropolitan area of Barcelona. The higher frequency of waterspout events is detected near the coast placed at the SW of Barcelona. Tornadoes and waterspouts are more frequent from middle August to middle November. The diurnal distribution is somewhat anomalous when compared to other countries and the rest of Spain, because most tornadoes occur in the early afternoon, with a secondary maximum between 06:00 and 09:00 UTC. Usually they are weak tornadoes and only 13 % of all cases can be considered as F2. The majority of tornadoes recorded in Catalonia have a path length less than 5 km.

The variations observed in the temporal and spatial distributions do not appear to be caused by the effects of climatic changes. Rather, these changes are most likely the result of a change in the social uses of space, and above all, changes in communication and the presentation of information to the public. The attention of newspapers is usually focused on stories of interest to readers. As most of those readers are urban residents, the news contains information with a marked urban character. Obviously, when the atmospheric phenomenon is remarkable, very violent, or has caused casualties or major damage to human structures, the media pay more attention to it than in cases with no casualties and little damage. For the years 1950–1979, the information came mainly from the press, so the reports are few in number. As attention to severe storms has increased with time, the number of stories about such storms has increased as well. Since the 1990s, and especially since the presence of the internet, the news has taken on a remarkable immediacy. Internet users post news very quickly and, furthermore, these items remain posted for a considerable time, allowing for comments and changes, something that rarely happens in more traditional media.

But this significant increase in the news does not mean that *all* such events are being reported and documented today. In fact, internet users are mostly urban. The most densely populated areas, most notably near the city of Barcelona, generally have the majority of recorded events,. The frequency of reported events has increased considerably beyond the frequencies over the period 1950–1979, and sightings have also been reported in the large cities of the other three provinces (Girona, Tarragona and Lleida). In more sparsely populated areas of the Pyrenees, there are no records of tornadoes in either of the periods. Virtually uninhabited or used as industrial land in the first half of the twentieth century, the coast has experienced strong urban and tourist pressure beginning the 1970s. This fact implies a vulnerability increase and also an enhanced likelihood for tornados and waterspouts to be observed and reported. It is difficult to detect possible effects of climate change among all these complicating factors. However, a comparison with precipitation and flash floods evolution in the studied region underlines the potential large impact of the societal factors in the observed increase. It is noteworthy that no trend in heavy rainfall distribution has been detected, despite a positive trend in flash flood frequency (Llasat et al., 2010).

Although the influence of human presence seems to be an important factor in the increase in sightings of these vortices, we do not believe it to be the only factor in the particular geographical distribution observed in Catalonia. In effect, some geographical areas have features that allow a wind field with sufficiently low level of helicity (a measure of the amount of rotation found in a storm's updraft air) to favour tornado formation. The orography and changes in intensity or in wind direction at lower levels of the atmosphere, among other factors, may cause a substantial increase in helicity (Maddox, 1993). Probably the sea breeze with a wind from the S or SE plays an important role in combination with a situation of atmospheric instability and SW flow in middle and upper levels. The zones with high vortex frequency are determined by dynamically favorable meteorological conditions in conjunction with low-level air having a long trajectory over the warm western Mediterranean (Doswell and Bosart, 2001), especially in autumn.

Gayà et al. (1997) identified four relevant configurations at 500 hPa, when Balearic events were considered. In all cases, a cut-off-low or a deep trough was present. These meteorological situations can usually produce heavy rainfall somewhere in the western Mediterranean. A similar synoptic pattern was also described by Martínez et al. (2008) in their classification of intense rain episodes. The maximum located near Barcelona city, mainly towards the South, coincides with the region with the maximum yearly contribution of convective precipitation (Llasat et al., 2005), a factor that is not related to the population distribution. In this region, the precipitation recorded between May and November has a convective contribution of above 50 %, value that decreases to less than 40 % in Pyrenees region. It is worth noting that the coast, and particularly the region near Barcelona, also records the maximum flash-flood frequency (Barnolas and Llasat, 2007; Llasat et al., 2010). The presence of two mountain ranges almost parallel to the coast can release the potential instability, and the feeding of warm and humid Mediterranean is a key factor in producing severe weather in Catalonia. The ingredients of deep moisture convection can be focused synergistically when the low flow impinges perpendicularly to the Catalan ranges (Doswell and Bosart, 2001; Llasat, 2009).

Future research on relevant configurations at synoptic and mesoscale factors that produce tornadoes in Catalonia will be developed. Finally, it is important to add that this database is not finished; new findings could drive the introduction of new tornado events.

Acknowledgements. This database could not have been drawn up without the collaboration of many people – professional meteorologists, amateur meteorologists and the occasional meteorologists – who reported and sent information in a nonobligatory manner. We note particularly the contributions made by Salvador Castán, Crispin Parra, Manel Conde and Manel Dot. Our thanks go to Ruth Romero for picture 3. We also appreciate the collaboration of the TV3 channel and its team of meteorologists in sending on the information submitted by their viewers. We acknowledge Ch. Doswell III and the second review for their careful revision and comments that have contributed a lot to the better quality of this paper.

Edited by: A. Mugnai
Reviewed by: C. Doswell III and another anonymous referee

References

Aran, M., Amaro, J., Arús, J., Bech, J., Figuerola, F., Gayà, M., and Vilaclara, E.: Synoptic and mesoscale diagnosis of a tornado event in Castellcir, Catalonia, on 18th October 2006, Atmos. Res., 93, 1–3, 147–160, 2006.

Barnolas, M. and Llasat, M. C.: A flood geodatabase and its climatological applications: the case of Catalonia for the last century, Nat. Hazards Earth Syst. Sci., 7, 271–281, doi:10.5194/nhess-7-271-2007, 2007.

Barnolas, M., Atencia, A., Llasat, M.C. and Rigo, T.: Characterization of a Mediterranean flash flood event using rain gauges, radar, GIS and lightning data, Adv. Geosci., 17, 35–41, 2008, http://www.adv-geosci.net/17/35/2008/.

Bech, J., Pascual, R., Rigo, T., Pineda, N., López, J. M., Arùs, J., and Gayà, M.: An observational study of the 7 September 2005 Barcelona tornado outbreak, Nat. Hazards Earth Syst. Sci., 7, 129–139, doi:10.5194/nhess-7-129-2007, 2007.

Bech, J., Pineda, N., Aran, M., Amaro, J, Gayà, M., Arús, J., Montanyà, J., and Van der Velde, O.: A Mediterranean nocturnal heavy rainfall and tornadic event. Part I: Overview, damage survey and radar Analysis, Atmos. Res., 5th ECSS Special Issue, Atmos. Res., 100, 4, 621–637, 2011.

Blokland, D. E.: En imposante hoos aan de Costa Brava. An impressive waterspout at Costa Brava, Hemel en Dampkring, 63, 12, 348–349, 1965.

Brady, R. H. and Szoke, E. J.: A case study of non mesocyclone tornado development in northeast Colorado: similarities to waterspout formation. Mon. Weather Rev., 117, 843–856, 1989.

Brooks, H. E., Doswell III, C. A., and Kay, M. P.: Climatological estimates of local daily tornado probability for the United States, Weather Forecast, 18, 626–640, 2003.

Camuffo, D., Secco, C., Brimblecombe, P., and Martín-Vide, J.: Sea storms in the Adriatic Sea and the western Mediterranean during the last millennium, Climatic Change, 46, 209–223, 2000.

Ceperuelo, M., Rigo, T., Llasat, M. C., and Sánchez, J. L.: Improving hail identification in the Ebro valley region using radar observations: probability equations and warning thresholds, Atmos. Res., 93, 474–482, 2009.

Doswell, C. A. III and Burgess, D. W.: On some issues of United States tornado climatology, Mon. Weather Rev., 116, 495–501, 1988.

Doswell, C. A. III and Bossart, L.: Extratropical Synoptic-Scale Processes and Severe Convection. Severe Convective Storms, Meteorol. Monogr., 28, N 50 Am. Met. Soc., 27–69, 2001.

Doswell, C. A. III: A Guide to F-Scale Damage Assessment, U.S. Dept. of Commerce, NOAAA/NWS, 94 pp., 2003.

Doswell, C. A. III: Small Sample Size and Data Quality Issues Illustrated Using Tornado Occurrence Data, E-Journal of Severe Storms Meteorology, 2, 5, 2007.

Dotzek, N.: Tornadoes in Germany, Atmos. Res., 56, 233–251, 2001.

Dotzek, N.: An updated estimate of tornado occurrence in Europe, Atmos. Res., 67–68, 153–161, 2003.

Gayà, M.: Tornados en España: distribución temporal y espacial, Revista de Climatología webs.ono.com/reclim/reclim05b.pdf (1987–2005), 1578–8768, 5, 2005 (in Spanish).

Gayà, M. and Redaño, A.: El tornado de L'Espluga de Francolí, Medidas de campo y digitalización de imágenes, Proceedings IV Simposio de Predicción del Instituto Nacional de Meteorología, INM Madrid, 345–350, 1996 (in Spanish).

Gayà, M., Ramis, C., and Doswell III, C.: Tornadoes in the Balearic Islands (Spain): Meteorological Setting, Proceedings INM/WMO International Symposium on Cyclones and Hazardous Weather in the Mediterranean, 525–534, 1997.

Gayà, M., Homar, V., Romero R., and Ramis, C.: Tornadoes and Waterspouts in the Balearic Islands: phenomena and environment characterization, Atmos. Res., 56, 253–267, 2001.

Giaiotti, D. B., Giovanni, M., Pucillo, A., and Stel, F.: The climatology of tornadoes and waterspouts in Italy, Atmos. Res., 83, 534–541, 2007.

Hoinka, K. P. and de Castro, M.: A renaissance depiction of a Tornado, BAMS 86, 4, 543–552, 2005.

Homar, V., Gayà, M., Romero, R., Ramis, C., and Alonso, S.: Tornadoes over complex terrain: An analysis of the 28th August 1999 tornadic event in eastern Spain, Atmos. Res., 67–68, 301–317, 2003.

Leitão, P.: Tornadoes in Portugal, Atmos. Res., 67–68, 381–390, 2003.

Llasat, M. C., Barriendos, M., Barrera, A., and Rigo, T.: Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records, J. Hydrol., Applications of palaeoflood hydrology and historical data in flood risk analysis, 313, 32–47, 2005.

Llasat, M. C.: Chapter 18: Storms and floods, in: The Physical Geography of the Mediterranean basin, edited by: Woodward, J., Oxford University Press, ISBN: 978-0–19-926803-0, 504–531, 2009.

Llasat, M. C., Llasat-Botija, M., Barnolas, M., López, L., and Altava-Ortiz, V.: An analysis of the evolution of hydrometeorological extremes in newspapers: the case of Catalonia, 1982–2006, Nat. Hazards Earth Syst. Sci., 9, 1201–1212, doi:10.5194/nhess-9-1201-2009, 2009a.

Llasat, M. C., Llasat-Botija, M., and López, L.: A press database on natural risks and its application in the study of floods in Northeastern Spain, Nat. Hazards Earth Syst. Sci., 9, 2049–2061, doi:10.5194/nhess-9-2049-2009, 2009b.

Llasat, M. C., Llasat-Botija, M., Rodríguez, A., and Lindbergh, S.: Flash floods in Catalonia: a recurrent situation, Adv. Geosci., 26, 105–111, 2010, http://www.adv-geosci.net/26/105/2010/.

Maddox, R. A.: Diurnal Low-Level Wind Oscillation and Storm-Relative Helicity, The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Church, Burgess, Doswell, and Davies-Jones, Geophys. Monograph, 79, Am. Geophys. Union, Washington, DC, 591–598, 1993.

Mariana, J.: Historia General de España, Tomo I., Printed by Marcos-Miguel Bouchet, Antwerp, 520 pp., 1737.

Martínez, C., Campins, J., Jansà, A., and Genovés, A.: Heavy rain events in the Western Mediterranean: an atmospheric pattern classification, Adv. Sci. Res., 2, 61–64, 2008.

Paul, F.: A developing inventory of tornadoes in France, Atmos. Res., 56, 269–280, 2001.

Piñol, J., Terradas, J., and Lloret, F.: Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain, Climatic Change, 38, 345–357, 1998.

Ramis, C., Arús, J., López, J. M., and Mestres, A.: Two cases of severe weather in Catalonia (Spain). An Observational study, Met. Applications, 4, 207–217, 1997.

Rigo, T. and Llasat, M. C.: Analysis of mesoscale convective systems in Catalonia (NE of Spain) using radar for the period 1996–2000, Atmos. Res., 83, 458–472, 2007.

Sioutas, M., Doe, R., Michaelides, S., Christodoulou, M., and Robins, R.: Meteorological conditions contributing to the development of severe tornadoes in southern Cyprus, Weather, 60, 1–7, 2005.

Sioutas, M. V. and Keul, A. G.: Waterspouts of the Adriatic, Ionian and Aegean Sea and their meteorological environment, Atmos. Res., 83, 542–557, 2007.

Tyrrell, J.: A tornado climatology for Ireland, Atmos. Res., 67–68, 671–684, 2003.

Wakimoto, R. M. and Wilson, J. W.: Non-supercell Tornadoes, Mon. Weather Rev., 117, 6, 1113–1140, 1989.