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Tornadoes and waterspouts in the Balearic Islands: phenomena and environment characterization

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Abstract

In the Balearic Islands, located in the Western Mediterranean, 27 tornadoes and 54 waterspouts have been recorded during the period 1989–1999. A climatology focusing, which focuses on path length, F-scale velocity, season and time of occurrence, is presented. September and October appear to be the months with the highest frequency of appearance. The environment in which thunderstorm producing tornadoes and waterspouts developed has been analysed. Main thermodynamic stability indices reveal that no specific conditions are required for the tornado and waterspout genesis. It is also found that these events form in air masses colder than that indicated by the climatology of the region. Analyses of helicity and CAPE demonstrate that, in most of the cases, the environments were not favourable for mesocyclone formation and supercell development. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Tornadoes and waterspouts are not an unknown phenomena in the Western Mediterranean, although this region is known in the world by its smooth climate and sunny weather. Particularly in the Balearic Islands, Spain (see Fig. 1 for the locations referred to in the text), more than 25 tornadoes and 50 waterspouts have been reported during the period from 1989 to 1999. Thus, these events have a considerable risk of damage due to

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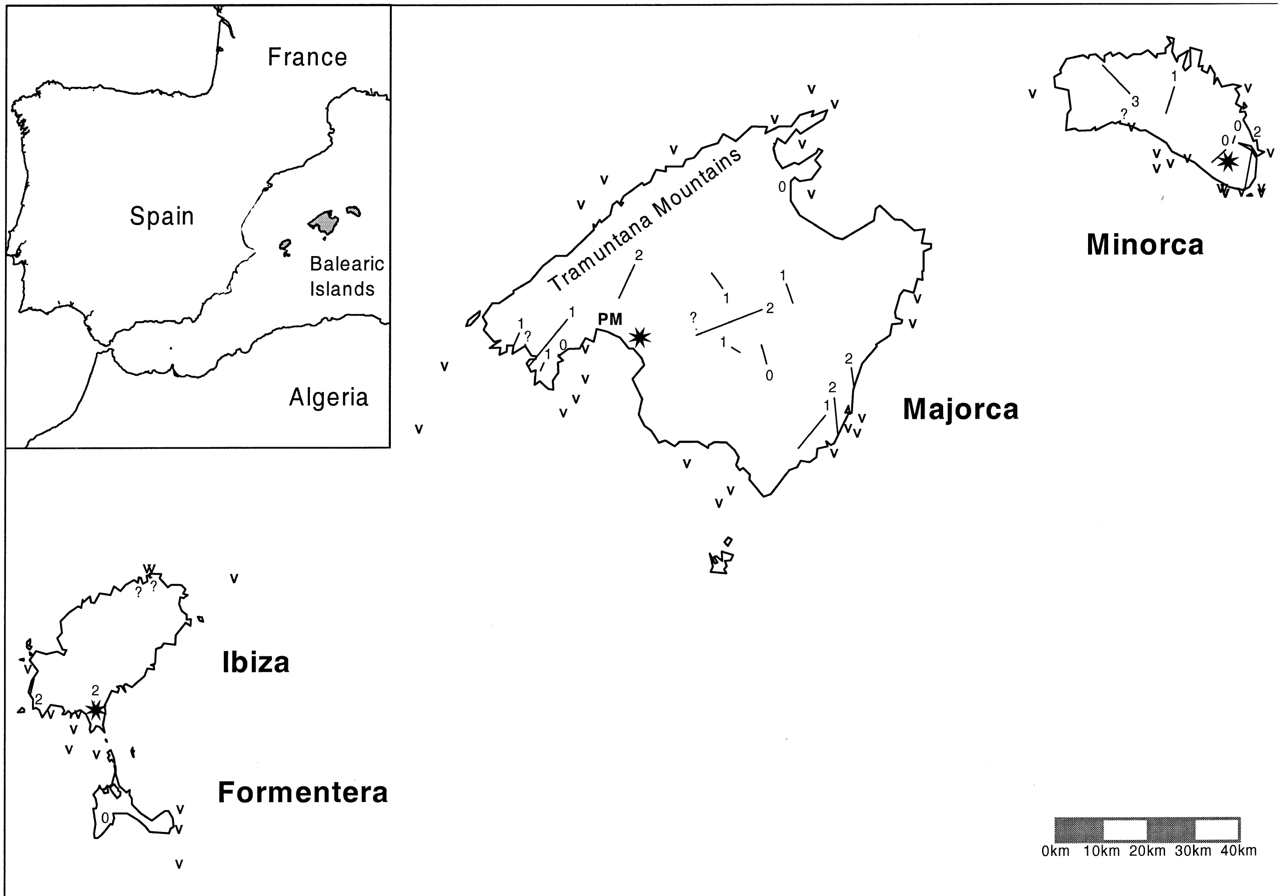

Fig. 1. Map of the Balearic Islands with damage path of the tornadoes (lines connecting beginning and ending points), and approximate location of waterspouts (V symbol). Fujita scale numbers are located on the lift off point. Symbol "?" indicates unknown path and strength; "PM", the radiosounding station in Palma. Stars indicate the location of airports.

the high population density of the Balearic Islands and their intense use for tourism (e.g. 10 millions tourists in 1999). Therefore, it is necessary to know under what meteorological conditions tornadoes and waterspouts form. This might be useful for an improved forecast of this severe weather.

Very few work exists focusing on the study of tornadoes in Spain. Martín et al. (1995) presented the meteorological situation in which a strong tornado (F2 in the Fujita (1981) scale) developed above central Spain. In addition, Ramis et al. (1997, 1999) analysed a case of a tornado produced by an intense and rapid developing convective system to the northeast of Spain. A first tornado climatology of the Balearic Islands was presented by Gayà et al. (1997). It presents a description of the tornadoes' main characteristics using data from 1989 to 1996. In addition, a classification of the synoptic situations in which they developed is also shown. Such situations are mainly characterised at mid-tropospheric levels by a through or closed low over Spain producing southwesterly winds over the Western Mediterranean. The authors also indicate that these meteorological situations are very similar to those which produce heavy rain in the Spanish Mediterranean area. Homar et al. (2001) present a detailed synoptic and mesoscale diagnosis of a tornado outbreak in the Balearic Islands. Even if there are many mentions of the sighting of waterspouts in the Western Mediterranean (e.g. Cardona, 1920; Hurts, 1956; Affronti, 1966), as far as we know no studies on their characteristics have been done previously.

The aim of this paper is to present the main characteristics of the tornadoes and waterspouts in the Balearic Islands as derived from a data set, built from reports of collaborators in the Balearics. Arising from the fact that no evidences on the exact dynamics involved in the tornadogenesis are known, climatic studies for the region become more useful than usual since they supply a good observational summary that further theoretical works should take into account. Furthermore, a regional climatology, including the spatial and temporal distribution, as well as the strength and basic features of the tornadoes and waterspouts is important in order to classify and compare them to those that occurred throughout the world. On the other hand, the sounding data usually provide good information for the characterisation of the tornadogenetic environments. Their analysis through the use of thermodynamic indices is done. These statistics might be useful for forecasters to quantitatively diagnose tornadogenetic environments.

The main basic characteristics of the reported tornadoes and waterspouts are explained in Section 2. An analysis of the tornadogenetic environment, focusing on some general characteristics of the atmosphere, is presented in Section 3. The more relevant tornado and waterspout properties in the Balearics and the main conclusions are summarised in Section 4.

2. Climatology

A tornadoes and waterspouts database was started in the early 1990s. It records the most recent events from 1989, also including funnel clouds, downbursts and other damaging winds produced by thunderstorms. Unfortunately, the data set is not homogeneous due to intrinsic difficulties of data collection. Although most of the reported tornado cases could be surveyed a few days after the event, several cases had to be surveyed some weeks or months later, making it much more difficult to obtain reliable information on the path, strength, location and time of occurrence of the event. In addition, some records of the data set are incomplete due to the impossibility of reliably precise information related to the event. Further, waterspouts can only be observed during the daytime. Nevertheless, all events were taken into account in the total amounts, but some were not used in the detailed analysis. However, although significant conclusions on rare events in climatology need more than 30 years to stabilise (see Schaefer et al., 1993), and even more on an area as small as the Balearic Islands (about 5014 km^2 and 1239 km of coastline), some clearly common features of the tornadoes and waterspouts emerge from the considered period (1989–1999).

The number of collected tornadoes during the whole 11-year period has been 27 on 20 days and 54 waterspouts on 53 days. This indicates that more than five tornadoes were recorded per year and per 10,000 km^2 during the 1989–1999 decade. In spite of the limited period considered, the overall tornado occurrence relative to the area seems to be as high as in Oklahoma or Texas (Grazulis et al., 1993), and much higher than in other Mediterranean countries (Dessens and Snow, 1993). In addition, considering a coastal zone 5 km wide offshore, nearly four waterspout cases were collected per year and per 10,000 km^2. Fortunately, minor injures and no fatalities had directly occurred from these severe events though important economical damage was produced in either populated and unpopulated areas.

The spatial distribution of tornadoes and waterspouts during the whole 11-year period is presented in Fig. 1. Moreover, an estimation of the track and strength in the Fujita scale for each tornado is depicted. Distribution in Majorca shows only tornado reports to the centre and south of the Island. In addition, no tornado has been recorded over the 400-m height due to the lack of evidences that remain over the mountains. It is notable that about a half of all cases present the touchdown close to the coastline, suggesting that these tornadoes could have been a waterspout. On the other hand, waterspout reports appear concentrated near the most populated coastal areas. As an example, a large number of reports were given close to the airports of Minorca and Ibiza, where advises are usually made by meteorological service staff. The same happens close to the harbours, where detection is significantly high. Because of the uncertainty in the determination of the waterspout's position and movement, Fig. 1 presents an approximate estimation of the location of each event. An inspection of the tornado track direction reveals that, although cases occurred in most of the orientations, a predominant direction of their track from S–SW to N–NE emerges.

Referring to the longitude of the trajectories, Fig. 2 shows the distribution of the path length for 21 of the 27 tornadoes. Maximum track length was around 15 km but most cases were shorter than 4 km. The average length is 5.1 km, which is nearly a 75% of the length of the north American tornadoes' average (Grazulis et al., 1993). Contrarily, the median is 4.0 km, which is much higher than the north American median. When path length average for every F-scale class is compared with the north American values, no significant difference is found, especially on weak tornadoes.

A classification of the tornadoes by its maximum velocity using the Fujita scale (Fujita, 1981) is presented in Fig. 3. For 4 of the 27 tornadoes, the maximum velocity

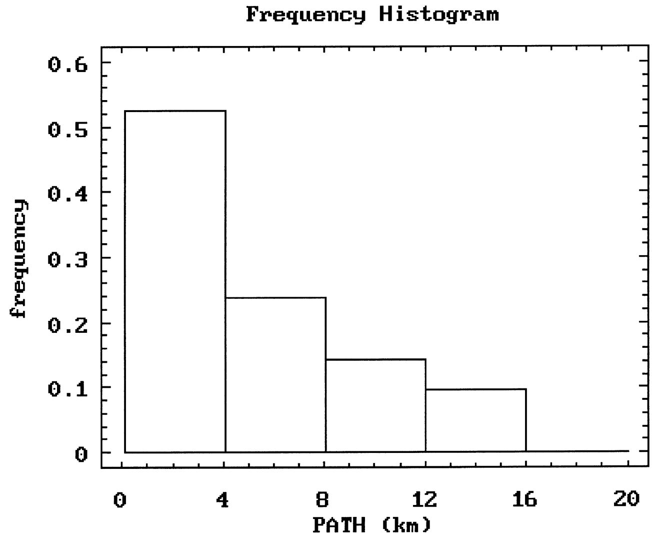

Fig. 2. Path length distribution of 21 tornadoes during the 11-year period 1989–1999.

could not be trustworthily determined. Weak tornadoes (F0 or F1) occurred on more than 60% of the cases, and about 30% were strong (F2 or higher). An extraordinary case 1 km wide, which affected a forested and unpopulated area in Minorca Island, was rated F3. Perhaps the lack of reports of weak tornadoes and the lax classification that derives from the application of F-scale, might be responsible for the lack of F0 tornadoes in the

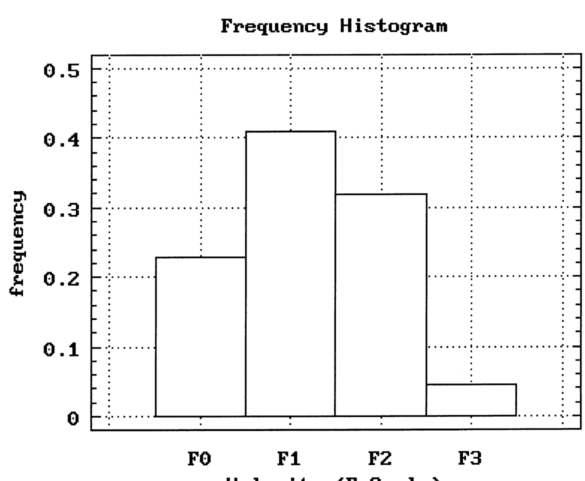

Fig. 3. Maximum velocity distribution of the 23 tornadoes after the Fujita scale during the 11-year period 1989–1999.

database as well as for the differences on the velocity distribution shape with respect to the American one given by Grazulis et al. (1993).

Fig. 4 presents the monthly distribution of thunderstorm, tornado and waterspout days in the Balearic Islands. There is a marked tornado occurrence tendency for the months of September and October, which present almost the 60% of the total cases. Similarly, waterspouts occur during the whole year and the highest concentration appears also in September and October. Defining the vortex season as the shorter period that covers 75% of waterspout and tornado days, this starts late July and finishes on early December. With the same criteria, tornado season starts on mid-September and finishes on early December. This period, centered in the autumn season, contrasts with that presented by Biddle (1998) for violent tornado season in North America: March 11 through June 20. The percentage of thunderstorm days during the study period (1989–1999) is also presented in Fig. 4. This shape distribution suggests that thunderstorms are necessary to generate or maintain these vortices. A thunderstorm day was considered when any of the approximately 200 observers in the Balearics recorded a thunderstorm during the period from 0800 UTC to 0800 UTC next day. Almost 50% of the waterspout cases have appeared without any cloud to ground stroke inside a radius of 30 km waterspout's area in the closest hours. A day is defined a thunderstorm day when there is a lightning report from an observer; only 25% of all waterspout cases took place on a no stormy day. Contrarily, almost all tornado cases occurred on a thunderstorm day.

In order to determine the possible influence of the diurnal cycle on the tornado and waterspout occurrence, Fig. 5 presents the events distribution along the normalised day. For 26 of the 27 tornadoes, time of occurrence could be determined. Most of them happened during late afternoon and evening, when surface temperatures are usually high. The notable number of tornadoes in the first 6 h of the day is mainly due to an outbreak case, which produced five tornadoes early in the morning well before sunrise

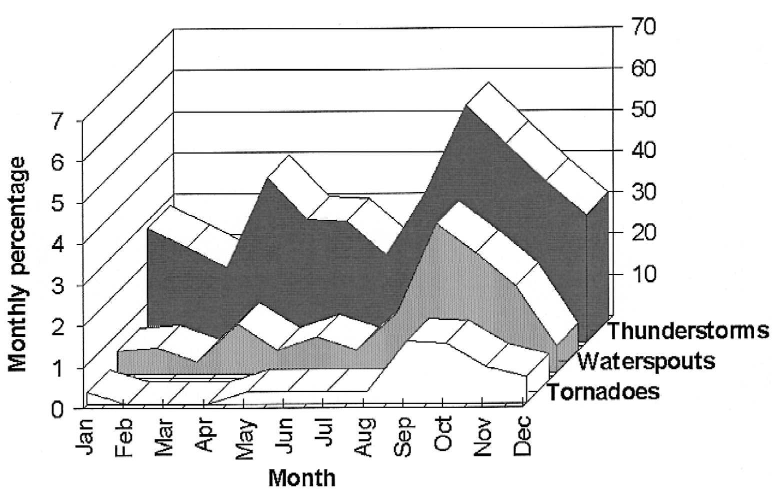

Fig. 4. Monthly percentage of event days during the 11-year period 1989–1999. Tornado and waterspout on the left scale and thunderstorm on the right scale.

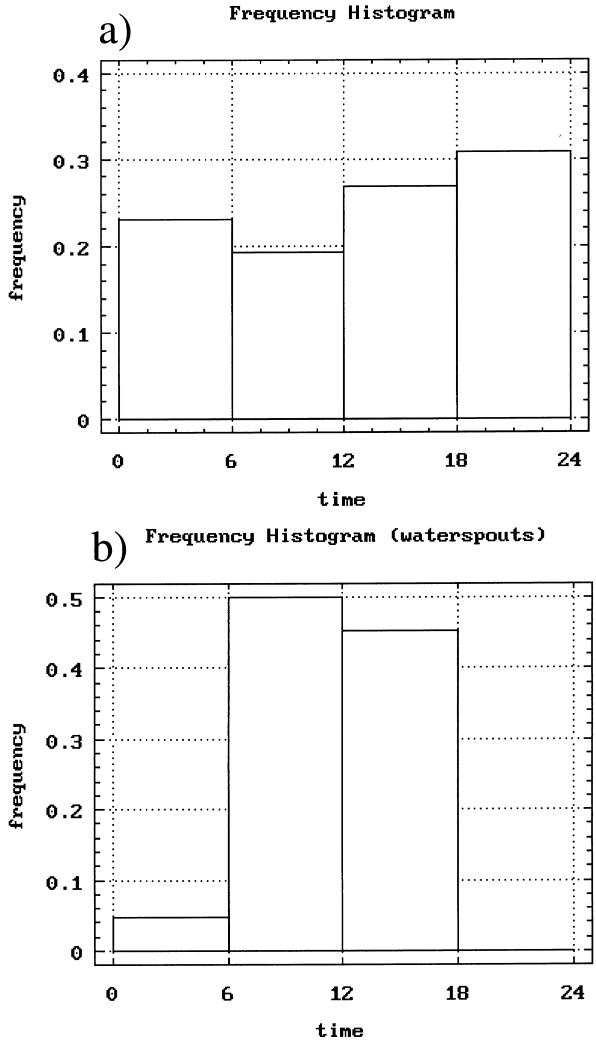

Fig. 5. Time distribution of: (a) 26 tornadoes and (b) 44 waterspouts during the 11-year period 1989–1999.

(Homar et al., 2001). Waterspout distribution does not show any significant information since all 44 events were obviously seen when sunlight was present. The only case before 06 UTC took place just before sunrise whereas all the others are similarly distributed into the two diurnal periods.

3. Environmental characteristics

As pointed out by Gayà et al. (1997), the synoptic meteorological situations in which tornadoes develop in the Balearic Islands are very similar to those that produce heavy rain in the Spanish Mediterranean area. Actually, notable rainfall fell during tornado days. In fact, in 90% of all tornado days the meteorological situation produced rainfall larger than 35 mm in 24 h somewhere in the Balearic Islands. In 30% of the cases, precipitation was higher than 75 mm. When waterspouts are considered, the meteorological situation generally becomes less active. That is, only 59% of all waterspout situations were able to generate amounts over 35 mm. In addition, only in 17% of the cases was a precipitation of 75 mm achieved somewhere in the Balearics. One of the reasons for this difference could come from the observational problems that obviously exist related to the rain detection over the sea in the Balearic Islands area, since no meteorological radar station exists. Consequently, a waterspout has more than a half of its surrounding area in which no rainfall detection is possible.

The main thermodynamic features of the environment in which tornadoes and waterspouts occurred have been studied using the sounding data, at 0000 and 1200 UTC, from the Palma station (PM in Fig. 1). In order to obtain conclusions as reliable as possible, some criteria for the selection of the significant soundings have been applied. A sounding has been used for the analysis only if the event occurred during a period of 3 h before and after the sounding release. All events that occurred in the Balearic Islands were considered since the farthest point is 150 km away from the sounding station. This criterion is much more permissive than that used by Kerr and Darkow (1996) for a proximity sounding. Even that, only 11 tornado cases and 20 waterspout events could be analysed.

Some stability indices as Total Total's (TTI), K Index (KI), Lifted Parcel (LP), Lifted Index (LI), Showalter (SH), Wet Bulb Potential Index (PI) and Windex (WI) have been calculated (see Tudurí and Ramis, 1997 for a review on the indices). Figs. 6 and 7 present the mean and extreme values for tornado and waterspout events. They show a large dispersion of their values in both kind of events. Nearly all indices have less dispersion in tornado cases than in waterspout ones, especially KI, TT, and LI. However, Figs. 6a and 7a show that LP, PI and TTI indices present mean values that indicate high probability of convective thunderstorms.

An analysis of the vertical temperature profile has been done by calculating the mean anomalies of the measured temperature at the standard levels for each tornadic and waterspout day with respect to a climatic sounding for the same day of the event. The climatic sounding for each particular day has been calculated by linear interpolation between the monthly mean sounding (Ramis, 1976), assigning the monthly mean values to the central day of the month. The mean dew-point depression at low and mid levels has also been calculated in order to examine humidity environmental tendencies during a tornado or waterspout event. A first significant conclusion which emerges from Fig. 8a is that tornadogenesis occurs in environments colder than the mean at low and mid levels. Especially, the mean temperature anomaly for the tornadic events at 700 hPa is about 3 K colder than the climatic average. Referring to the humidity vertical profile, some indication of a dry layer is found at 850 hPa, with a mean dew point depression of 7 K. Although a high dispersion is obtained at mid levels, dry values are obtained for levels higher than 650 hPa. Furthermore, referring to the waterspouts, the mean temperature deviations is even lower than in the tornado sample (Fig. 8b), the greater deviation being found at 800 hPa and 4 K colder than the average. For the waterspout

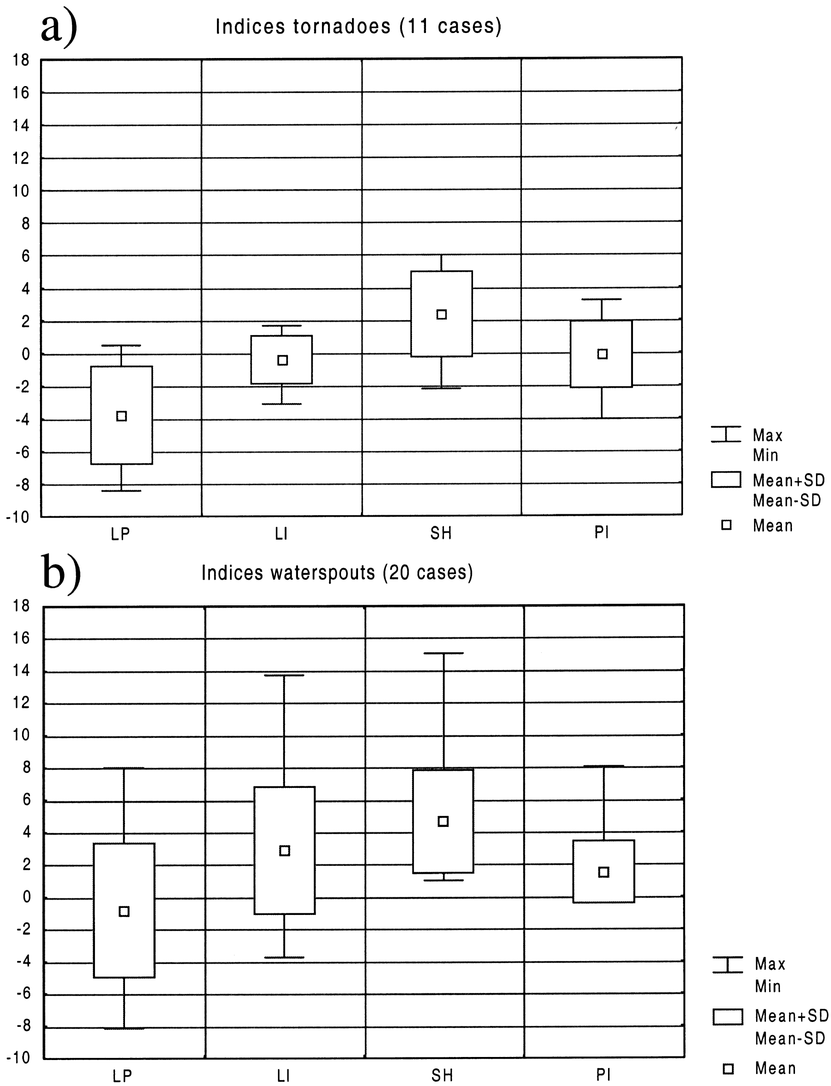

Fig. 6. Mean and extreme values of LP, LI, SH and PI for: (a) tornadoes and (b) waterspouts.

cases (Fig. 9b), the humidity profile shows an unusually dry air at low levels and a mostly standard profile at mid levels.

The supercell is probably the most commonly known tornado producing system. Lilly (1986), beside others, noted the importance of helicity (H) on rotating thunderstorm, and Davies-Jones et al. (1990) introduced the idea of storm relative helicity (SRH) in order to measure the potential of an environment to generate and maintain mesocyclones. Storm relative helicity is very useful when the storm evolution can be followed with radar data, and a reliable storm velocity can be determined. As no radar images are

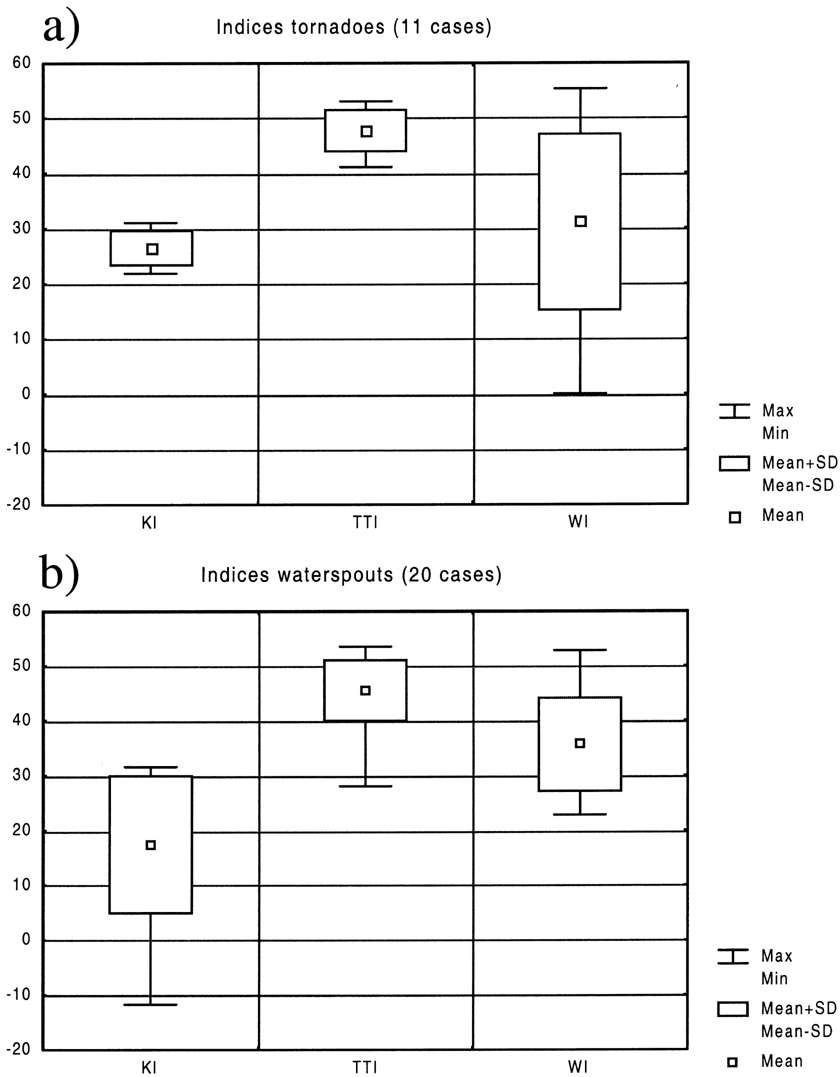

Fig. 7. Mean and extreme values of KI, TI and WI for: (a) tornadoes and (b) waterspouts.

available in most of the data set events, we have used the rule suggested by Davies and Johns (1993) to estimate the storm velocity from the vertical wind profile. It consists in reducing the mean velocity of the lower 3000 m to 75% and veering it 30° clockwise (30R75). Fig. 9 presents the values of SRH vs. H. Even all tornado cases present larger SRH values than H ones (Fig. 9a), although there are some events with negative values of SRH. One case reached SRH value as large as 380 m^2 s^{-2}, which corresponds to the tornado of 3 December 1998, with a path length not longer than 4 km and F1 strength. Referring to the waterspout producer environments (Fig. 9b), the low dispersion that it

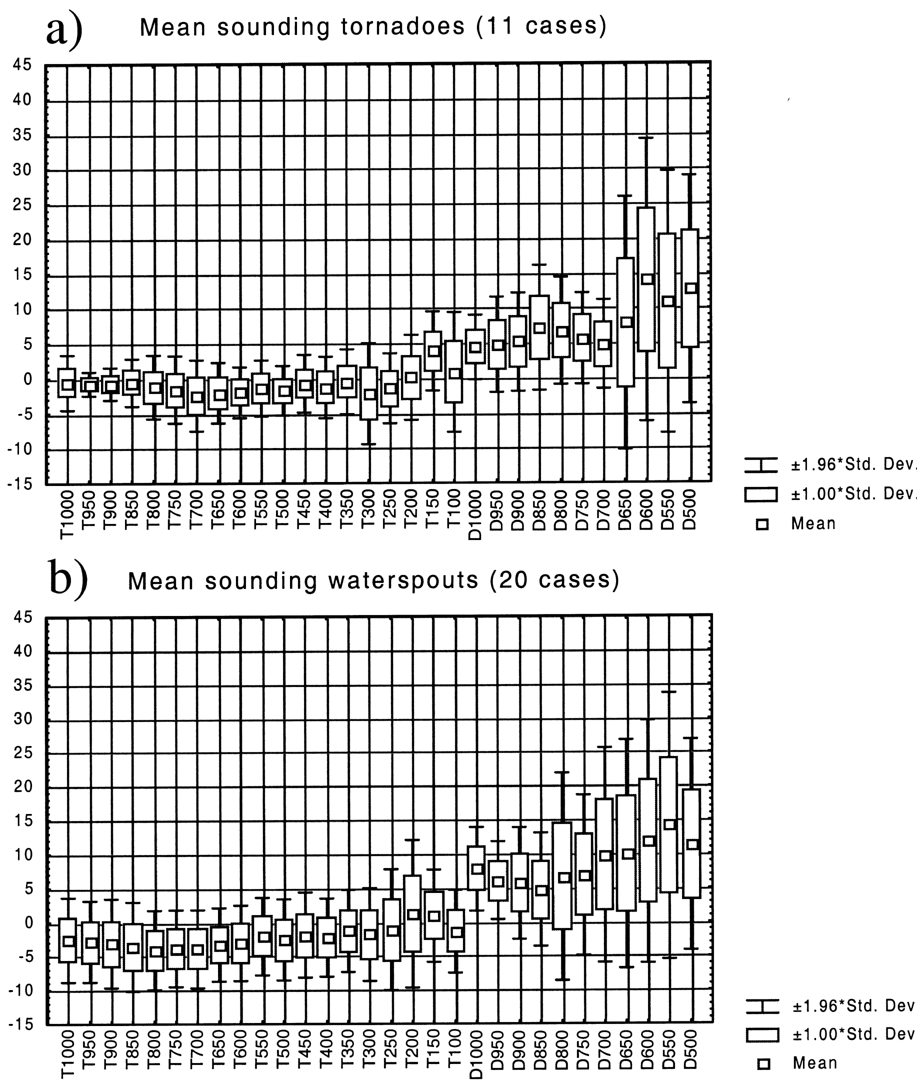

Fig. 8. Mean temperature deviations (T) and mean dew point depression (D) at the standard levels (in hPa) for: (a) 11 tornadic and (b) 20 waterspout soundings.

shows, as well as the similarity of SRH values to the H ones, is notable. In most cases, SRH is positive and always lower than 80 m^2 s^{-2}. These values, both in tornado and waterspout cases, are far from the thresholds found by Davies-Jones et al. (1990).

Significant values of Convective Available Potential Energy (CAPE) seems to be necessary for a supercell thunderstorm development, but as suggested by Doswell et al. (1990), no large values are strictly necessary. CAPE has been calculated by lifting the parcel from surface level. The obtained values have a notably high dispersion, both in

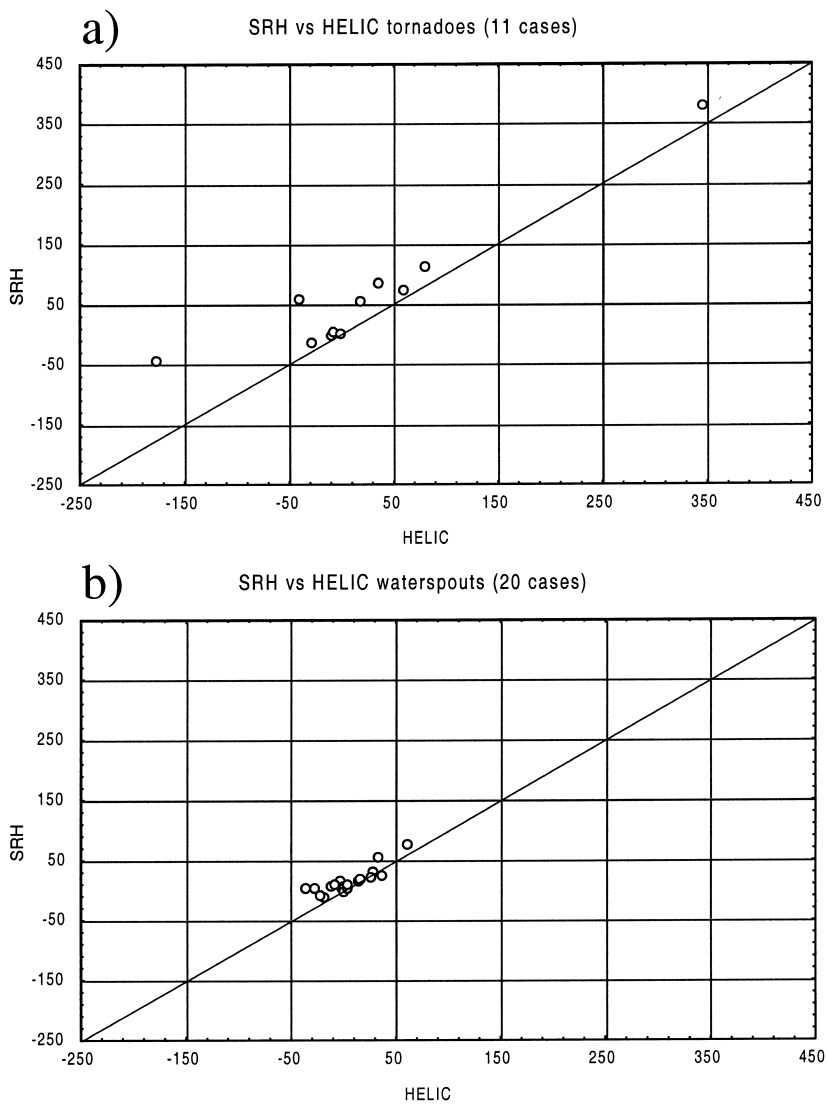

Fig. 9. SRH vs. H (m^2 s^{-2}) for: (a) 11 tornado and (b) 20 waterspout cases.

tornado and waterspout cases: from almost zero CAPE until values higher than 5400 J kg^{-1} for tornadoes and 4000 J kg^{-1} for waterspouts. That was the case in the aforementioned tornadic event of 8 August 1995. CAPE is depicted vs. H in Fig. 10, which shows that points representing tornadic environments present a greater dispersion than those representing waterspouts ones. Our H values are lower than those obtained by Johns et al. (1993) or by Brooks et al. (1994) for cloud environments. Energy–Helicity Index (EHI; Davies, 1993) values show that two tornado events exceeded the value

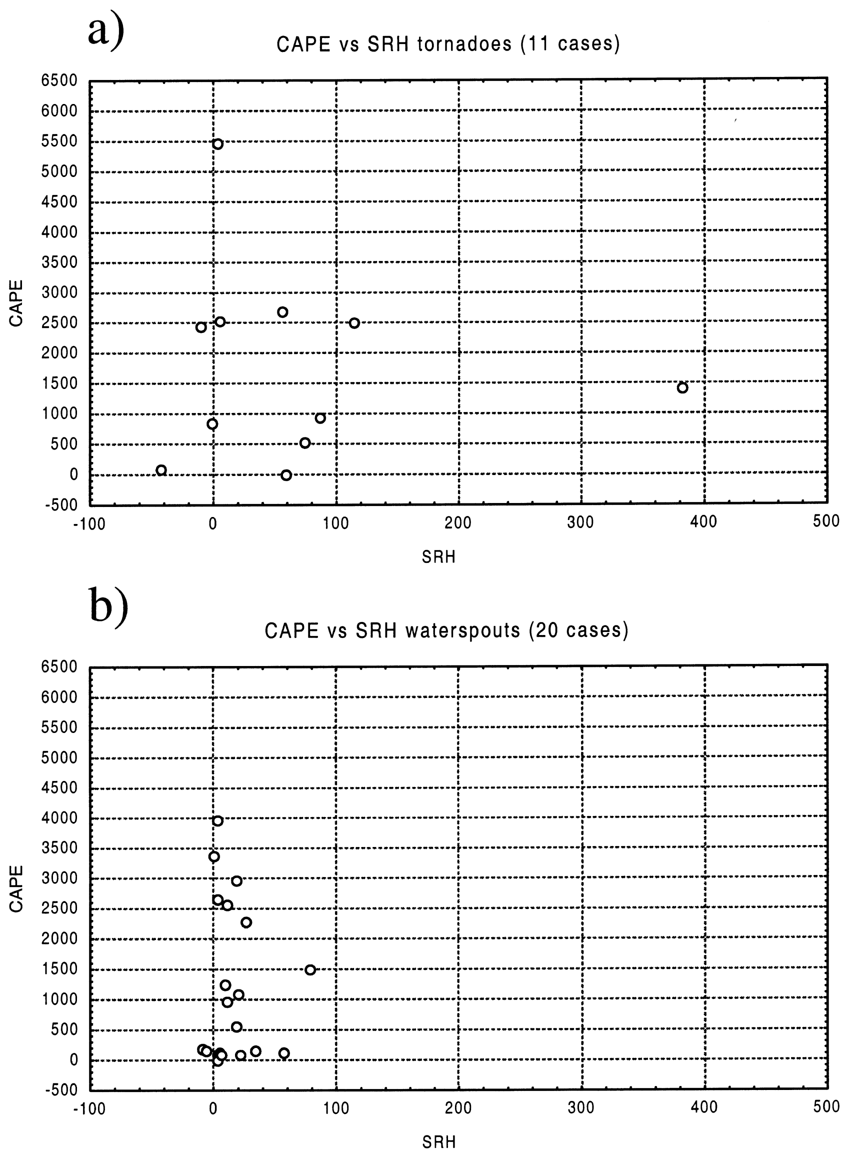

Fig. 10. CAPE (J kg^{-1}) vs. SRH (m^2 s^{-2}) for: (a) 11 tornado and (b) 20 waterspout cases.

of 1.5, one of them being higher than 2.5. On the other hand, no waterspout cases have an EHI value greater than 0.8. EHI is a fine tool for identifying environments that support mesocyclones but does not discriminate tornadic and non-tornadic ones (Brooks et al., 1994). Thus, the environment that has produced tornadic (or waterspout) thunderstorms in the Balearics does not seem to be able to support supercell.

4. Conclusions

The Balearic Islands is a region that reveals a significant presence of tornadoes and waterspouts. Having a limited database, it can be summarised that the typical reported tornado has a track length of less than 4 km, with a northeastwards direction of movement, maximum velocity F1 or F2 and occurring between the afternoon and the evening. Seasonal distribution shows a higher occurrence in autumn when thunderstorm days are more probable.

The mean values of the Lifted Parcel, Wet Bulb Potential and Total Total's I indices indicate a high probability of convective thunderstorms, especially in the tornadic cases. The environment in which tornado and waterspout thunderstorms form is colder than the climatic mean. A slight indication of a dry layer at about 850 hPa has been found in the vertical humidity profile for days with a tornado.

Although some visual evidences invite the belief that at least three tornado cases could be produced by supercell thunderstorm, no radar pictures are available to confirm it. Parameters such as Storm Relative Helicity, Convective Available Potential Energy or Energy Helicity Index do not offer a discriminate rule for waterspout cases but could be a good index for tornadic ones.

Future efforts will be necessary to grow the database, increasing sample and improving all statistical results.

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