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A methodology to conduct wind damage field surveys for high impact weather events from convective origin

Oriol Rodríguez[1], Joan Bech[1], Juan de Dios Soriano[2], Delia Gutiérrez[2], and Salvador Castán[3]

[1]Department of Applied Physics - Meteorology, University of Barcelona, Barcelona, 08028, Spain
[2]Agencia Estatal de Meteorología, Sevilla, 41092, Spain
[3]Agencia Pericial, Cornellà de Llobregat, 08940, Spain

Correspondence: Oriol Rodríguez (orodriguez@meteo.ub.edu)

Abstract. Post-event damage assessments are essential to document the effects of high- impact weather events such as floods or strong wind events. Moreover, evaluating the damage and characterizing its extension and intensity can be helpful for further analysis such as completing a diagnostic meteorological case study. This paper presents a methodology to perform field surveys of damage caused by strong winds of convective origin, i.e. tornado, downburst and other types of convective winds. It is based on previous studies and also on 136 fieldworks performed by the authors in Spain from 2004 to 2018. The methodology includes the systematic collection of pictures and records of damages on man-made structures and on vegetation, as well as collection of any available Automatic Weather Station data, witness reports and images of the phenomenon and their location and orientation. Three final deliverables are proposed to synthesize the data recorded: (i). A summary of the fieldwork; (ii). A table consisting of detailed geolocated information about each damage, and (iii). A map or a .kml file containing the previous information ready for graphical display and further analysis. This methodology has been applied by the authors in the past, sometimes only a few hours after the event occurrence and, in many occasions, when the type of convective phenomenon (e.g. tornado, downburst) was uncertain. In the latter case the information resulting from this methodology has proofed very useful to discern the phenomenon type, based on the damage patterns particularly if no witness reports were available. The application of systematic methodologies as the one presented here is necessary in order to build homogeneous databases of severe weather cases and high impact weather events.

1 Introduction

Meteorological phenomena associated with strong surface winds from convective origin, which include tornadoes, downbursts and other types of convective winds, can cause important disruption to socio-economic activity, including injuries or even fatal victims despite their local character compared to larger scale mid-latitude synoptic wind storms. For example, from 1950 to 2015 tornadoes in Europe caused 4,462 injuries, 316 fatalities and economic losses of at least €1 billion (Antonescu et al., 2016, 2017). Due to their economic and social impact, a large number of previous studies have been devoted to study these phenomena both from the point of view of their consequences (as in Strader et al., 2015) or specifically from a meteorological point of view (see for example Taszarek et al., 2017; Miller and Mote, 2018 or Rodríguez and Bech, 2018).

Natural Hazards and Earth System Sciences
Discussions
Open Access

Analysing damage using the information gathered during a strong-convective wind survey assessment can be essential to determine which phenomenon took place (Bunting and Smith, 1993; Doswell, 2003), for instance, estimating the wind field from the fallen trees direction (Hall and Brewer, 1959; Holland et al., 2006; Bech et al., 2009; Beck et al., 2010; Rhee and Lombardo, 2018). When these phenomena affect a sparsely populated area, or they occur in a low visibility environment due to night darkness or intense precipitation, there is usually a lack of direct witnesses and recorded images. In that case the task of assessing the damage intensity and discriminating if it was caused by a tornado, a downburst or other type of convective winds can be rather challenging.

Despite the recent progress on assessing wind damage using high resolution radar observations (see Wurman et al., 2013 or Wakimoto et al., 2018), the systematic elaboration of fieldworks is still the standard way to evaluate the damage caused by these meteorological phenomena (Marshall, 2002; Marshall, 2012; Zanini et al., 2017), similarly to field surveys of hailstorms (Farnell et al., 2009) or floods (Molinari et al., 2014; Li et al., 2018). A detailed damage analysis makes possible to characterize strong-convective wind phenomena (see for example Burgess et al., 2014; Meng and Yao, 2014), estimating damage path length and width, and wind maximum intensity, which can be done using the Fujita scale (Fujita, 1981), the Enhanced Fujita scale (EF-scale, WSEC, 2006) or some other wind damage scales as mentioned in Sect. 3.

Clarifying the origin and characterizing damaging strong-convective winds phenomena is not only important for scientific reasons. In Spain, for example, there are also economical motivations, as current legal regulations set different insurance compensations for tornadic and non-tornadic cases: in order to be compensated the latter require a wind speed threshold exceedance while the former do not. This factor, together with the fact that high-densely populated coastal areas are among the regions most affected by tornadoes in Spain (Bech et al., 2007, 2011; Mateo et al., 2009; Gayà et al., 2011; Sánchez-Laulhé, 2013; Riesco et al., 2015) –as in other Mediterranean countries (see Matsangouras et al., 2014; Miglietta and Matsangouras, 2018 or Renko et al., 2018)– contribute to the motivation of this study.

The objective of this paper is to propose a methodology to conduct wind-field damage assessments of convective-driven events in a systematic way, to contribute to the creation and maintenance of homogeneous databases. This methodology is based on previous studies (Bunting and Smith, 1993; Marshall, 2002; Doswell, 2003; Gayà, 2018) and also on 136 fieldworks performed in Spain from 2004 to 2018 by the authors (Figure 1), especially in Catalonia and Western Andalusia, and can be readily applied elsewhere. The proposal includes the systematic collection of pictures and records of damage on man-made structures and on vegetation, as well as any available Automatic Weather Station (AWS) data, witness reports and images of the phenomenon together with their location and orientation. Three final deliverables are suggested to synthesize the data recorded: (i). A summary of the fieldwork; (ii). A table consisting of detailed geolocated information, iii). A map or a .kml (Keyhole Markup Language) file containing the previous information ready for graphical display and further analysis.

The present article is organized as follows. In Sect. 2 the field survey methodology proposed is explained in detail. Section 3 discusses specific limitations of its application. Section 4 illustrates the methodology with two recent tornadic case studies and Sect. 5 presents a summary and final conclusions.

https://doi.org/10.5194/nhess-2019-294
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Natural Hazards and Earth System Sciences
Discussions

2 METHODOLOGY

The main goal of a strong-convective wind damage survey is to collect as much information as possible about the relevant consequences of the phenomenon and to geolocate the damage (Bunting and Smith, 1993; Doswell, 2003). Later on, processing this information will make possible a further detailed analysis of the event.

The methodology to carry out fieldworks must be efficient, making possible to visit all the affected area as soon as possible. It is also be easily reproducible and its results should be accurate. Geolocating damage using pictures or videos recorded with smartphones, or cameras with a Global Navigation Satellite System such as GPS fulfils these conditions (Edwards et al., 2013). Nevertheless, as it happens with other types of damage assessments, there are inherent uncertainties that should be taken into account when analysing field data (Beven et al., 2018), like possible GPS location errors or EF-scale limitations, which are discussed on Sect. 3.

During the second decade of the XXI century, mass media and social networks have become increasingly important sources of information about severe weather and particularly strong-convective wind events (Hyvärinen and Saltikoff, 2010; Knox et al., 2013; Kryvasheyeu et al., 2016). Citizen science collaborative platforms covering different geographical domains such as the European Severe Weather Database (ESWD, Dotzek et al., 2009)the severe weather database from the Spanish Meteorological Agency (SINOBAS, Gutiérrez et al., 2015) and the meteorological spotters platform from the Meteorological Service of Catalonia (XOM, Ripoll et al., 2016), are also important sources of tornado and downburst reports.

Those reports can typically contain: (i). Image and/or information from direct witnesses of the phenomenon (i.e. actual tornado picture) and damage, (ii). Image and/or information from direct witnesses of damage, but not of the phenomenon, and (iii). Image and/or information from direct witnesses of the phenomenon, but not of damage. In cases (i) and (ii), it should be relatively straight-forward to find the damage location with the information provided by direct witnesses and image authors, and using also available weather observations (radar, AWS, etc.) and GIS tools. However, in case (iii) the procedure is different. Firstly, the coordinates of the point and the orientation from which the image was taken must be estimated. Then, using these data and also weather observations and GIS tools it should be feasible to delimitate the possible affected area.

Once damage location or the possible affected area is known, fieldwork should start as soon as possible. Nevertheless, in case (iii) it is possible that no damage is found, either due to the lack of man-made structures or trees in the potentially damaged area, or because the observed tornadic funnel cloud may have not actually touched down.

On the following subsections specific guidelines are given for survey planning, tasks to be performed on the field, and preparation of the final deliverables summarizing the field survey.

2.1 SURVEY PLANNING

A detailed planning is necessary to optimize the time and resources to carry out a damage survey. Firstly, preliminary information about damage location and images available on the media and social networks should be gathered. That information can be used to decide where to start the survey. It is recommended to contact with authors of pictures to get more information about where they were taken. Emergency services and local authorities can also be a valuable source of information, because may provide detailed damage data, especially if an urban area is affected. Occasionally, they may take damage aerial recordings, which can be very useful to complement the damage survey assessment.

Analysis of satellite and weather radar imagery is required to estimate the approximate timing of the event and the movement of the convective parent storm that may have produced the phenomenon. That information should be considered, in order to extend the initial evidences of a damage path (looking for possible initial or ending points) and also to assess the consistence of reports by direct or indirect eyewitnesses.

Smartphone or cameras with GPS image geolocation and orientation (azimuth pointing) capabilities provide essential data to carry out a fieldwork in order to geolocate damage, as discussed previously. Moreover, a compass and a tape measure are also highly recommended, as well as a hand counter device to count uprooted or snapped trees and, ideally, a portable suitcase balance to weigh wind-borne debris. As it is indicated in Bunting and Smith (1993), water, food, comfortable footwear, rain jacket, spare clothes and a mobile phone spare battery are recommended, because affected areas may be far away from inhabited locations. As the affected area can require surveyor displacements longer than a few kilometres, a well-equipped, preferably all terrain, car is necessary to save time between points-of-damage analysis. Nevertheless, difficult access areas may be found along the track, because of mudded roads and fallen trees or because of the absence of roads. Especially in these cases, and also to study in detail damaged areas, walking is the other basic way to perform the field survey.

It is strongly recommended to start damage surveys as soon as possible, especially if urban areas have been affected. Emergency and clearing services use to start repairing tasks only a few hours after the event (Figure 2), which can alter the quality and quantity of information gathered during the survey. For this reason, if a large area is affected, the fieldwork should preferably start on urban areas. In the case that damage is repaired (for example streets cleared of debris or fallen trees) before the survey team visits the zone, it would be very helpful to gather photos taken by neighbours or authorities and geolocate them. After that, it is recommended to visit damaged electrical transmission or telecommunication lines, industrial parks and urban parks. Forest and other surrounding areas should be the last priority.

Finally, despite this may not be always feasible, it would be ideal to have a multidisciplinary damage survey team formed by meteorologists, insurance inspectors, forestry engineers and architects experienced on damage assessments, at least familiar with damage reporting systems such as the EF-scale. This facilitates a deep analysis of the damage and the phenomenon intensity.

2.2 SURVEY TASKS

2.2.1 PREVIOUS CONSIDERATIONS

Knowledge of the wind climatology from the studied area is highly recommended, particularly in windy regions (either because of the orography or the prevailing synoptic conditions). In that case, man-made structures and forests are adapted to resist strong winds –sometimes from specific directions– and wind speed damage thresholds may be higher than in non-windy regions. It must be kept in mind that if a weak tornado or microburst affects a windy region, it is possible that not much damage is reported. This must also be taken into account when rating the phenomenon using a wind damage scale.

In some occasions, the studied area may have been affected recently by another damaging wind storm or by a heavy snowfall that may have produced widespread damage in forests (for example with heavy wet snow as described in Bech et al., 2013 and Llasat et al., 2014). In those cases, the data collection process may be hampered by possible overlapping damage and, consequently, great care must be taken to identify the most recent one and to avoid mixing recent with previous damage. A possible way to mitigate this problem is asking locals about previous events and paying attention to the dryness from affected trees and broken branches, which can indicate if forest damage is recent or not.

Automatic weather stations can contribute to determine the phenomenon type and estimate the wind strength (Letchford, 2002; Karstens et al., 2010. Therefore, it is strongly recommended to search and locate all weather stations in the area of study, requesting the data with the maximum temporal resolution (see Figure 3 as an example), and performing basic quality control (time consistency and comparison with official observations) before use.

2.2.2 MAN-MADE STRUCTURES DAMAGE ASSESSMENT

Man-made structural damage is essential to estimate the phenomenon intensity using the EF-scale. As explained in WSEC (2006), the Enhanced Fujita scale considers several Degrees of Damage (DoD) from a total of 23 Damage Indicators (DI) related to constructions and 3 DI from other man-made structures that can be used to determinate the 3-seconds wind gust speed associated to these damages.

In the present methodology it is proposed to geolocate every damaged structure on the affected area. It is also convenient to take one or more photos from each damaged building, both general and detailed views that may be of interest to evaluate the damage intensity (Marshall, 2012; Roueche and Prevatt, 2013).These images can be useful when a deeper analysis is required to study which type of strong convective wind phenomenon caused the damage. The way how debris is spread or how a roof is collapsed or lifted can indicate winds with either a rotation and upward pattern, or with a diverging and downward pattern –see for example Rhee and Lombardo (2018). It is highly recommendable to document also the maintenance status of the man-made structures to facilitate the intensity determination. The absence of anchors or the presence of rust makes a roof weaker, and it has to be taken into account when a damage scale is applied. It is proposed to take photos of these details together with damage pictures. The distance of wind-borne debris displacement, as well as its size and weight, also provide valuable information to estimate wind velocity associated to the studied phenomenon so, whenever possible, characteristics of flying objects should be determined and documented.

2.2.3 FOREST DAMAGE ASSESSMENT

In Sect. 1 it is explained that the average wind field pattern (direction and intensity) associated with a strong convective wind can be estimated using the approximation that fallen trees indicate the wind direction. Therefore, if damaged trees are available, a detailed forest damage study can be performed, which is especially useful for cases without recorded images. Tasks include taking and geolocating photos of damaged trees, fallen trees direction (with a compass) recording and noting debarked or snapped trees trunk diameters. As there may be a large number of damaged trees in a forest area, it is advisable to collect data from the most representative ones (for example, where tree fall direction changes or converges, which may mark the centre of a tornado damage track). Nevertheless, it is necessary to notice that the falling direction of a tree may be induced by the local terrain. A steep slope close to a tree or another close tree falling first can alter the tree direction with respect to the dominant wind. So, in these cases it is recommendable not to consider the fall direction.

Damage in forest areas can be also useful to evaluate the phenomenon intensity. The EF-scale (WSEC, 2006) describes different wind velocity ranges for five Degrees of Damage (DoD), namely small limbs broken, large branches broken, trees uprooted, trunks snapped and trees debarked with only stubs of largest branches remaining. However, the health of trees, the forest tree density and the damage ratio are aspects that must be taken into account to enhance the wind intensity estimation (Feuerstein et al., 2011; Godfrey and Peterson, 2017). Moreover, soil characteristics can alter tree stability; in case of very moist soil or thin or rocky subsoil, trees can be uprooted more easily, as it is shown in Figure 4a. Wind effect on trees also depends on the tree species (Foster, 1988). Figure 4b shows an example of a mixed Mediterranean forest affected by a tornado in Catalonia, on 7 January 2018; most pines are blown down or snapped, whereas for cork oaks only some large branches are broken.

As in Spain around 75 % of tornado identified tracks are shorter than 5 km (Gayà, 2018),a deep forest damage analysis is usually possible. However, in cases where damage is widespread, a complete detailed analysis may not be feasible. To solve that, it is recommended to study discontinuous segments every 250-500 metres along the estimated damage path. This allows taking the path width and looking for the damage continuity. In addition, aerial images taken by a helicopter or a drone, can enhance the forest damage analysis, especially in case of large damage swaths, and difficult access areas (Karstens et al., 2013). Alternative approaches to widespread forest damaged areas are satellite image processing as recently reported by Shikhov and Chernokulsky (2018) and Shikhov et al. (2019).

2.2.4 WITNESS ENQUIRIES

Direct witnesses, if available, are an important source of information often essential to determine which type of strong convective wind phenomenon occurred. Witnesses experience of the event and their possible knowledge of other witnesses in nearby damaged locations can be very useful to complement a damage survey. In Bunting and Smith (1993) and Gayà (2018) it is noted that a direct witness may have been emotionally or physically affected by the phenomenon (for example private property damaged or close persons injured) so it is necessary to be respectful and careful during the enquiry.

It is important to let witnesses explain with their own words their experience of the event, and interviewers should avoid using key words such as tornado, downburst or gust front, particularly in those cases when the phenomenon type is not known yet. The terms used by the witness may provide useful clues about what happened. In addition, it is necessary to consider that media can alter the explanation of witnesses; for example if the event has been described as a tornado in the media, even if evidences of rotation are not found in the damaged area, people will probably say that a tornado has occurred.

A brief and concise inquiry, with specific questions but allowing open answers that may unveil relevant information, is proposed. Recommended questions are shown in Table 1.

In some occasions, a direct witness may have taken photos or videos of the phenomenon that can be helpful for the study. When available, they should be treated as described at the beginning of this section.

2.3 DELIVERABLES

In order to present the data described above in a clear way to facilitate its interpretation and use, three final synthesis deliverables are proposed: (i). A summary of the damage survey (text and graphical support), (ii). A detailed table of geolocated information, and (iii). A data location map.

2.3.1 DAMAGE SURVEY SUMMARY

The summary of the damage survey should contain the following items:

- Name and email from the members of the damage assessment team
- Sources of information about the studied event (media, social networks, citizen science platforms, private pictures or messages, direct witnesses, etc.)
- Date of the damage survey
- Type of phenomenon reported or inferred
- Affected municipalities
- Day and timing of the event
- Duration of the phenomenon at a specific location according to witness inquiries
- Weather conditions before, during and after the strong convective wind event (e.g. if it was raining, hailing or thundering)
- Brief explanation of the damage observed
- Estimation of the fieldwork coverage over the total affected area
- Name list and relevant information from the inquiry

The remaining information (pictures, videos, complete inquiries, etc.) should be properly archived.

2.3.2 GEOLOCATED DAMAGE TABLE

A table of geolocated information given in a standardized way is proposed containing six different location types (see Table 2). Moreover, for each of the first three damage location types should contain the following additional information:

- Photograph
- Falling tree direction, if it exists
- DI and DoD from EF-scale
- A brief explanation of the observed damage
- Other data of interest (broken trunk diameter, previous weaknesses, etc.)

2.3.3 DATA LOCATION MAP

A map or a file in .kml format containing the information described in the previous subsection is produced in order to allow further graphical analysis, for example using Google Earth software (Gorelick et al., 2017). Each of the previous six location types are represented with a different icon, with a specific colour depending on its intensity using the EF-scale.

As an example, Figure 5 shows part of the data location map of the damage survey carried out on 25 March 2012 to study the EF1 tornado that affected the municipalities of Castellnou de Seana and Ivars d'Urgell (Catalonia) on 21 March 2012 (Bech et al., 2015). It also shows the information about a damaged tree location and the Ivars d'Urgell AWS location.

3 DISCUSSION

Some limitations of the methodology proposed such as difficult access areas or very large survey areas have already been commented. Specific comments about three additional challenges (geolocation accuracy, intensity rating and phenomenon type determination) are given below.

Geolocation accuracy of points-of-damage depends on a number of factors including local terrain geometry, quality of the receiver antenna system or number of satellites observed. Photo cameras and smartphones have location errors usually ranging from 5 to 20 meters, typically being greatest in deep valleys, or close to large buildings blocking satellite signals. To minimize geolocation errors it is recommended to check the accuracy with manually selected reference locations and, if necessary, to correct damage locations on the summary map. This is feasible in urban or periurban areas, where buildings or other elements are easily identifiable using ortophotos, but not in forests or other natural areas without evident references where this verification maybe not possible.

Another challenge of the methodology presented is damage rating. Despite the progress made introducing the more detailed EF-scale (WSEC, 2006) compared to original and simpler Fujita scale (Fujita, 1981),its practical application has some limitations detected years ago (Doswell et al., 2009). The Enhanced Fujita scale, developed in the USA, is mainly based on the damage caused by wind on standard US buildings and elements (schools, hospitals, automobile showrooms, etc.), so-called Damage Indicators (DI). When applied to areas outside the USA many DI may not exist, hampering its application as discussed in detail Feuerstein et al. (2011). Moreover, there may exist (for example in Europe) similar elements to those included on the EF-scale, such as traffic signals, walls and fences, trash bins and vehicles, but with different characteristics. Possible solutions to this problem include considering specific studies reporting strong wind effects, for instance, on vehicles (Paulikas et al., 2016; Haan et al., 2017), proposals to introduce new DI to the EF-scale (Mahieu and Wesolek, 2016) or adapt them to typical man-made structures from other countries (Environment Canada, 2013; Japan Meteorological Agency, 2015). Nevertheless, there exists the necessity to develop a standardized International Scale, as proposed in Groenemeijer et al. (2018).

Finally, in some cases the information gathered in a fieldwork may not be sufficient to clarify which phenomenon (like tornado or downburst) caused the damage. This is especially critical in weak events that affect a small area, from which there are neither images nor direct witnesses. In these cases, damage may be sparse, scattered, and unconnected which makes unidentifiable any damage pattern consistent with a tornado, a microburst, etc., not allowing further detailed damage swath analysis (as in Bech et al., 2009 or Rhee and Lombardo, 2018). For example, 7 % of the 136 fieldworks carried out in Spain since 2004 by the authors lead to inconclusive results about the phenomenon type.

Natural Hazards and Earth System Sciences
Open Access
Discussions

4 CASE STUDIES

In this section, two case studies (Table 3) are analyzed using the proposed methodology. The first one is a multi-tornado event in Menorca (Balearic Islands), from 1 April 2017. The second one is a tornado case that affected a coastal area of Catalonia the early morning of 15 October 2018.

4.1 CASE 1: 1 APRIL 2017, MULTI-TORNADO EVENT IN MENORCA (BALEARIC ISLANDS)

During this episode, two tornadoes hit the western part of Menorca Island and at least one waterspout was observed in the same area. Ciutadella de Menorca, the second most populated town on the island, was hit by one of them. The first tornado formed over the Mediterranean Sea at 11.15 UTC. It moved onshore at Punta Nati (see Figure 6), an uninhabited and deforested area in north-west Menorca. When the field survey was carried out in this zone, no significant damage was found. Nevertheless, as the visibility was very good and the phenomenon took place at midday (when typically many people are outdoor) there exist several images from the event. That helped to locate the tornado track, despite the absence of damage in the initial part.

Images indicated a condensation funnel cloud moving north to south, affecting a photovoltaic solar park, where some of the 20 kg weigh solar panels were lifted up and displaced up to 150 m. Later, in the port of Ciutadella de Menorca, a boat which was out of the water was tipped over. Finally, the tornado dissipated south of the town (Figure 7a). Just at the end of the damage track, an AWS located about 160 meters from the estimated tornado position centre, registered a maximum wind gust of 29.2 m/s.

In general, there was only minor damage in urban areas because the tornado was weak and, also, because this area of the island is used to strong northerly synoptic winds. Some traffic signals were blown down, a metal fence was damaged, several roof tiles were removed and some tree branches were broken. However from the DI available on the EF-scale, only vegetation elements in this case could be used to rate the tornado intensity. This illustrates the limitations of the above mentioned scale, as discussed in the previous section.

The second tornado formed around 11.30 UTC. It touched down in a crop field area located 7.5 km SE of the Ciutadella de Menorca town centre (see Figure 7b). It moved to the south-east, crossing an uninhabited zone with a large pine-forest extension, which was visibly damaged. That enabled to gather useful information to analyze the phenomenon, although there were very few direct witnesses and images recorded. The tornado also affected Cala Galdana village outskirts, which is located in Ferreries municipality (see Figure 7b). After that, it moved over the sea crossing the bay and moved onshore again. Then, some houses and trees were affected and, finally, the tornado dissipated when it went offshore again.

Damage survey tasks revealed hundreds of damaged pines, with a trunk perimeter between 100 and 250 cm on average. Most of them were uprooted, and in some cases the trunk was snapped. Following Sect. 2.2.3., several locations with substantial tree damage and the most representative predominant fall tree direction were recorded in order to estimate the maximum wind field pattern. It was also calculated the ratio of affected trees in one of the most damaged forest areas, close to Cala Galdana. In this section of the track around 65-70 % of pines were uprooted or its trunk was snapped, which would be compatible with EF2

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

damage, according to Godfrey and Peterson (2017). To complete this study, aerial images taken during a helicopter flight by the Balearic Institute of the Nature from the Balearic Islands Government were also used.

The fieldwork was carried out on the 3, 4 and 13 April 2017 and concluded that the damage track length of the first tornado was 5.9 km, its maximum path width 50 m and the maximum intensity was at least in the upper bound of EF0. The second tornado damage track was 5.9 km long, its maximum width was 280 m and the maximum intensity was EF2.

4.2 CASE 2: 15 OCTOBER 2018, TORNADO IN MALGRAT DE MAR (CATALONIA)

This event affected some villages located about 55 km NE Barcelona at 01:45 UTC of 15 October 2018. As the phenomenon occurred during the night, there were few witnesses to confirm the possible existence of a funnel cloud or any type of surface vortex. Damage was reported west of the coastal village of Malgrat de Mar, and also in another area 6.5 km north, near the village of Tordera. Moreover, an AWS located north of Tordera registered a maximum wind gust of 30.3 m/s at 01:55 UTC and its surroundings exhibited some damage. Initially, it was not known if both areas were damaged by the same event nor if it was a tornado or a microburst.

Following the proposed methodology, the fieldwork started only a few hours after media reports and the visits to urban and periurban areas were prioritized. It was found a damage swath starting at the beach in Malgrat de Mar and apparently finishing 1 km to the north-west, where there is a hilly area with tops 350 m high. Tordera damage path was also aligned with it. Afterwards, it was analyzed the hilly-forest area located between Malgrat de Mar and Tordera, where vegetation damage was found. Because of the length of the track and the difficult access to some zones, discontinuous damage segments every 250-500 meters were analyzed. The damage path continued to the north-west affecting the municipalities of Fogars de la Selva and Massanes, where no more wind damage was found (Figure 8a).

A poplar forest located between Fogars de la Selva and Massanes, next to a highway, was severely damaged. Most of the trees, which were young specimens with a trunk diameter between 15 and 30 cm, were uprooted. This area was surveyed in detail with the aim to estimate the wind field of the phenomenon. A convergent fallen tree damage pattern was found (Figure 8b), which is compatible with a rotating vortex in motion as discussed in Bech et al. (2009).

Damage in tiles and asbestos cement roofs, brick walls and greenhouses were observed. Trash bins were displaced several meters from their initial location and even two gas station pumps were overthrown. In contrast to the previous case study, several DI from the EF-scale were found, which were very useful to estimate the phenomenon intensity: trunks of softwood and hardwood trees were snapped, fascia material from a service station canopy was blown down, a flag pole was bent and there was some damage in an electrical transmission line (see Figure 9). Moreover, a camper van was shifted laterally, which is compatible with a rating of EF1 or higher, according to Paulikas et al. (2016).

According to the information gathered during the damage survey carried out on 15, 19 and 24 October 2018, it can be concluded that a waterspout moved onshore in Malgrat de Mar, affecting the municipalities of Palafolls, Tordera, Fogars de la Selva and Massanes. The damage path was 14.7 km long, which is unusual in this area: according to Gayà (2018), only 7 % of identified tornado tracks in Spain are longer than 10 km. The maximum swath width was 150 m, and the intensity was rated as EF1.

5 Summary

Damage survey assessment data are used to study the consequences of natural hazards, which include floods or strong-convective winds. Specifically, the latter can be characterized carrying out fieldworks, estimating damage path length and width, and also the intensity of the event. Moreover, they are also useful to clarify which phenomenon caused the damage (tornado, downburst or other convective winds) in case neither images nor direct witness reports exist.

The purpose of the presented methodology is to provide guidelines for gathering pictures and locations of damage on man-made structures and on vegetation, using smartphones or photo cameras with geolocation capability. Complementary data from AWS close to the affected area and witness reports should be gathered if available. With all this information, three final deliverables are generated (a summary of the fieldwork, a table consisting of detailed geolocated points-of-damage, and a map or file in .kml format containing all of them). The whole data set gathered allows for further analysis and archive purposes.

This methodology is based on previous studies and has been refined during the elaboration of 136 strong-convective wind damage surveys carried out in Spain between 2004 and 2018. Known limitations of its application include geolocation errors of damage, applicability of the EF-scale outside the USA and inconclusive determination of phenomenon type (like tornado or downburst) in weak events, low visibility cases or low density population affected areas. In any case, the field survey data obtained are valuable for further analysis, complementing meteorological detailed case studies based on operational remote sensing, surface observations and NWP standard fields. Moreover, the methodology proposed may contribute to standardize detailed field surveys which are essential to build up and maintain robust databases of severe weather phenomena.

Data availability. The data used in this paper is available from the authors upon request.

Appendix A: Geolocated videos from 1 April 2017 Menorca multi-tornadic event

Table A1 lists the location (latitude and longitude) and the link of several videos, accessible on 3 September 2019, of Menorca multi-tornadic event from 1 April 2017.

Competing interests. The authors declare that they have no conflict of interest.

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Preprint. Discussion started: 17 September 2019

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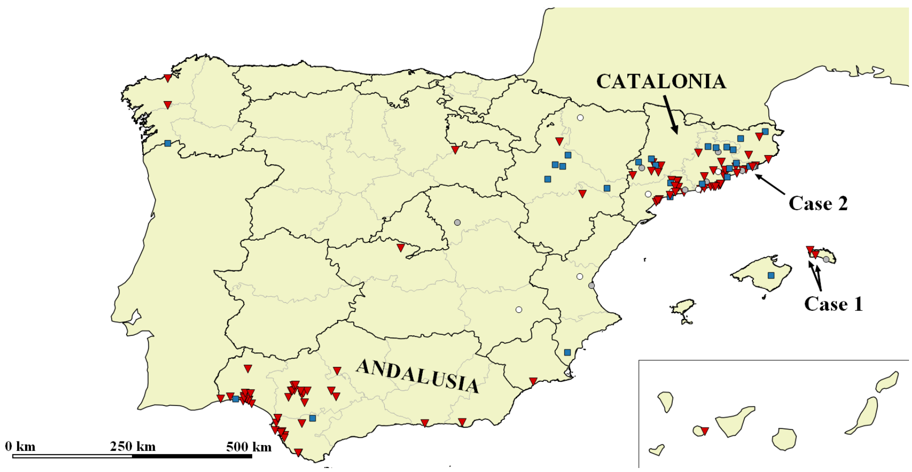

Figure 1. Location of 136 analysed events using the proposed methodology between 2004 and 2018, mostly concentrated in Andalusia and Catalonia. Red triangles are tornadoes, blue squares are downbursts, grey circles are undetermined phenomena and white circles are other phenomena (as gust fronts, funnel clouds which did not touch down, or dust devils). The two case studies analyzed in section 4 are indicated on the map.

https://doi.org/10.5194/nhess-2019-294
Preprint. Discussion started: 17 September 2019

Natural Hazards and Earth System Sciences
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Discussions

Figure 2. Clearing service of Zaragoza (NE Spain) removing broken branches after the 11 July 2018 downburst.

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Preprint. Discussion started: 17 September 2019

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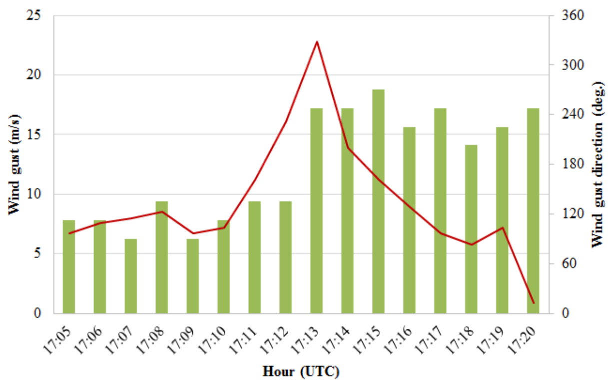

Figure 3. Wind gust (red line) and wind gust direction (green bars) registered by an AWS in Mataró (Catalonia) with 1-minutal resolution data. It is located 240 m to the left of the estimated centre of the EF0 tornado track, on 23 November 2016. Data source: Meteomar, Consell Comarcal del Maresme.

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Preprint. Discussion started: 17 September 2019

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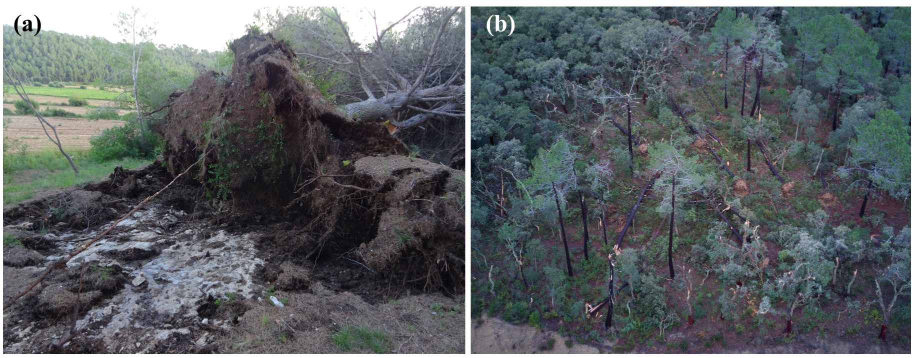

Figure 4. (a) Pine blown down by a weak tornado in Els Pallaresos (Catalonia) in a very thin, moist soil area, on 14 October 2018. Source: Oriol Rodríguez. (b) Drone image of a mixed Mediterranean forest in Darnius (NE Catalonia) where most of pines were blown down whereas cork oaks were only slightly affected with broken branches by a tornado, on 7 January 2018. Source: Jonathan Carvajal.

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Preprint. Discussion started: 17 September 2019

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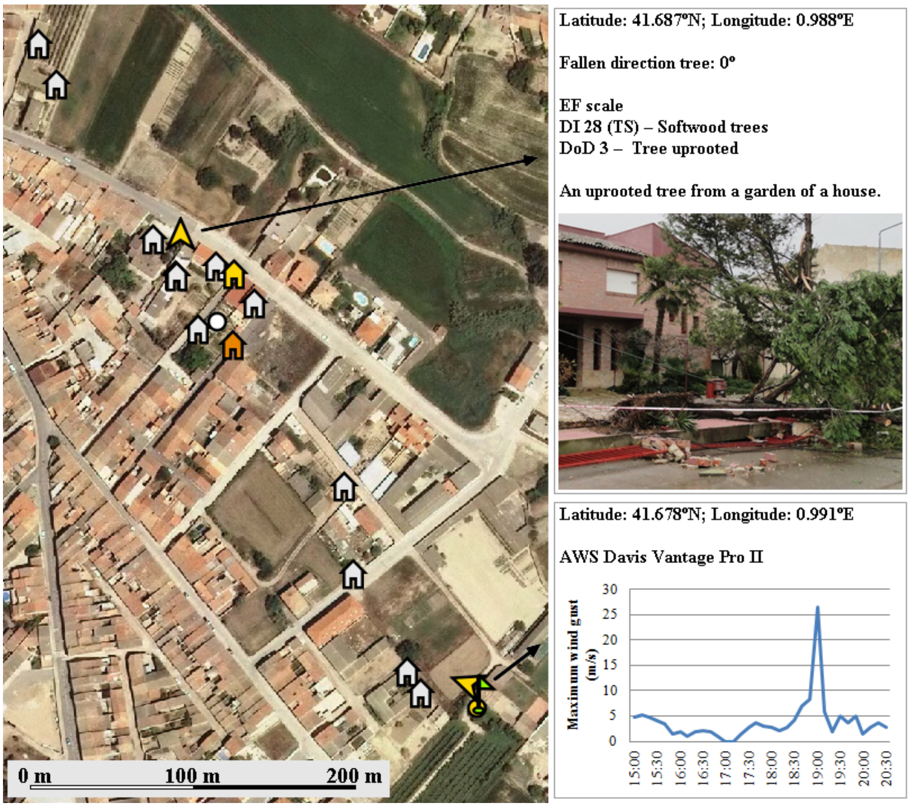

Figure 5. Data location map and two examples of recorded information from the 21 March 2012 EF1 Ivars d'Urgell (Catalonia) tornado track. Map symbols indicate locations of AWS (green flag), damage in man-made structures (house icons) and fallen tree or damaged vegetation element (arrow and circle icons if no direction is available). Icon colours indicate damage intensity using the EF-scale: EF0 (yellow), EF1 (orange), and unrated (white). The background ortophoto is from the Institut Cartogràfic i Geològic de Catalunya (ICGC), http://www.icc.cat/ (last access: September 2019), under a CC BY 4.0 license.

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Preprint. Discussion started: 17 September 2019

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Figure 6. Ciutadella de Menorca tornado hitting Punta Nati area on 1 April 2017 at 11.15 UTC. Image from a video, courtesy of Imma Pieres.

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Preprint. Discussion started: 17 September 2019

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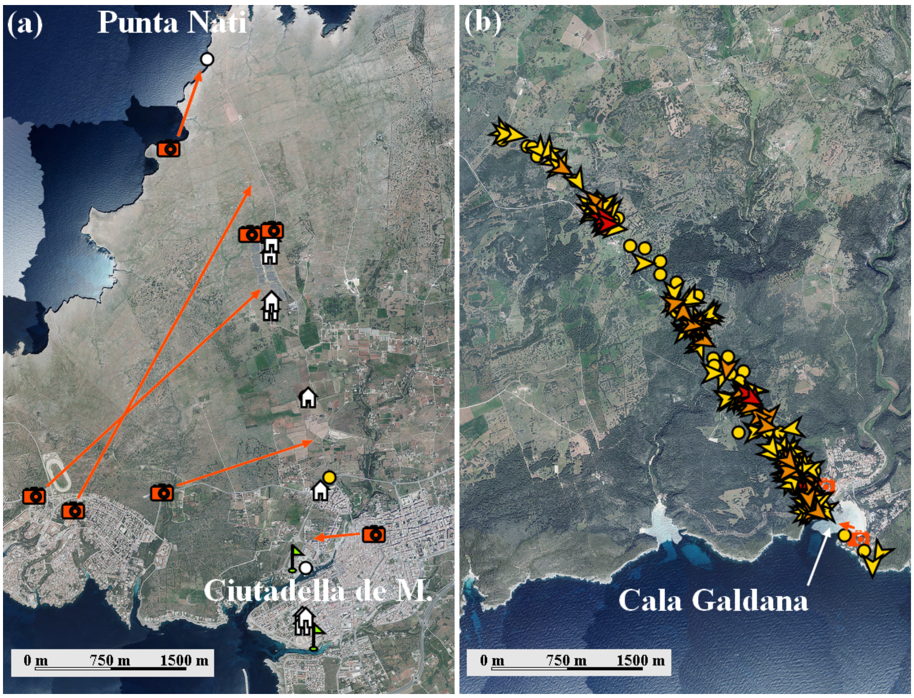

Figure 7. (a) Data location map from the fieldwork of the Ciutadella de Menorca tornado, and (b) for Ciutadella de Menorca – Ferreries (Cala Galdana) tornado. Map symbols indicate locations of pictures and orientation (camera icon and arrow pointing), AWS (green flag), damage in man-made structures (house icons) and fallen tree or damaged vegetation element (arrow and circle icons if no direction is available). Icon colours indicate damage intensity: EF0 (yellow), EF1 (orange), EF2 (red), and unrated (white). The background ortophoto is from the Instituto Geográfico Nacional (IGN), http://www.ign.es (last access: September 2019), under a CC BY 4.0 license.

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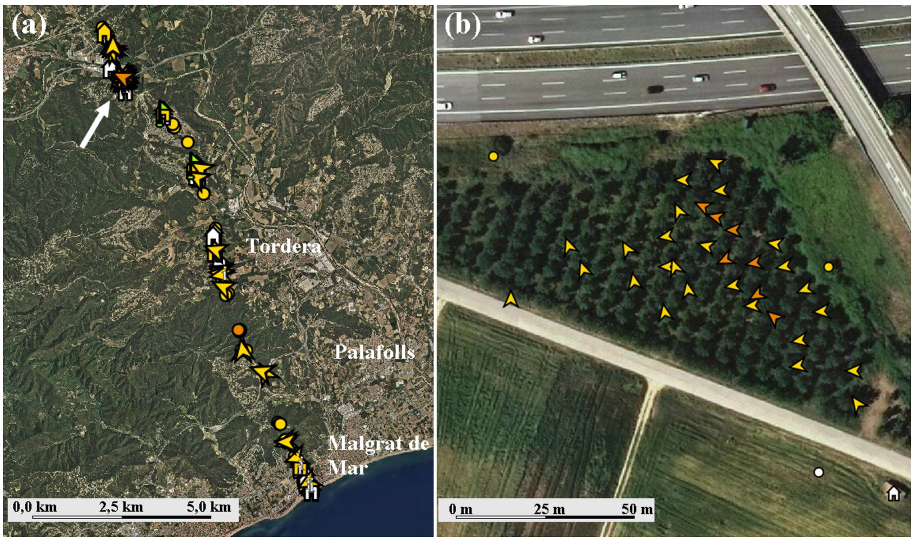

Figure 8. (a) Data location map from the fieldwork of the Malgrat de Mar – Palafolls – Tordera – Fogars de la Selva –Massanes tornado, and (b) fallen trees direction of a poplar forest (location marked in Figure 8a with a white arrow).Map symbols indicate locations of AWS (green flag), damage in man-made structures (house icons) and fallen tree or damaged vegetation element (arrow and circle icons if no direction is available). Icon colours indicate damage intensity: EF0 (yellow), EF1 (orange), and unrated (white). The background ortophoto is from the Institut Cartogràfic i Geològic de Catalunya (ICGC), http://www.icc.cat/ (last access: September 2019), under a CC BY 4.0 license.

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Preprint. Discussion started: 17 September 2019

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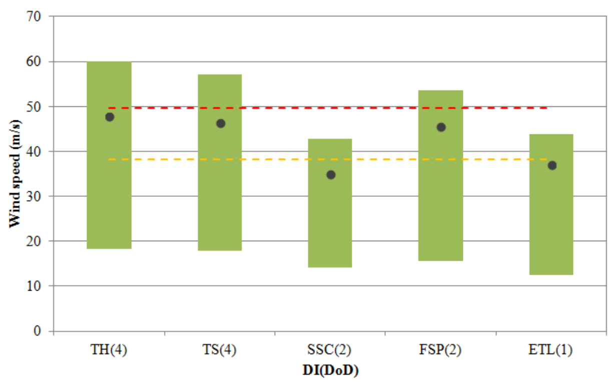

Figure 9. Damage Indicators (DI) found in Malgrat de Mar fieldwork with its maximum Degree of Damage (DoD). DI are: TH(4), snapped trunk of hardwood tree; TS(4) snapped trunk of softwood tree; SSC(2), fascia material blown from service station canopy; FSP(2), bent flag pole (in this case), and ETL(1), threshold of visible damage of an electrical transmission line. Green boxes extend from the lower bound to the upper bound wind velocity values for each DoD, grey points are the expected value of wind speed for each DoD, yellow discontinuous line is the lower bound of EF1 intensity and red discontinuous line is the lower bound of EF2 intensity.

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Table 1. Witness enquiry questions.

Question reference	Question
Q1	At what time did the phenomenon occur?
Q2	Where did you were in the moment of the phenomenon?
Q3	How long did the strongest winds last? (Some seconds, around one minute, several minutes...).
Q4	During the phenomenon, did you hear any special or rare noise?
Q5	How was the weather like before, during and after the phenomenon? (Light rain, heavy rain, small hail, large hail, snow, no precipitation).
Q6	Have you noticed other areas with damage?
Q7	Do you remember any similar phenomenon in this area before?

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Preprint. Discussion started: 17 September 2019

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Table 2. Information location type.

Location reference	Description
L1	Damage in trees with fall direction
L2	Damage in trees without fall direction
L3	Damage in man-made structures
L4	AWS location (latitude, longitude and data)
L5	Witness location at the moment of the meteorological event (latitude and longitude)
L6	Wind-borne debris (latitude, longitude, distance and direction of the displacement, size and weight if measured)

https://doi.org/10.5194/nhess-2019-294
Preprint. Discussion started: 17 September 2019

Table 3. Date, hour, affected municipalities, maximum intensity (EF-scale) and damage swath length and maximum width from the analyzed events.

Date	Hour (UTC)	Affected municipalities (Region)	EF-scale	Length (km)	Maximum width (m)
1 April 2017	11.15	Ciutadella de Menorca (Balearic Islands)	0	5.9	50
1 April 2017	11.30	Ciutadella de Menorca and Ferreries (Balearic Islands)	2	5.9	280
15 October 2018	01.40	Malgrat de Mar, Palafolls, Tordera, Fogars de la Selva and Massanes (Catalonia)	1	14.7	150

https://doi.org/10.5194/nhess-2019-294
Preprint. Discussion started: 17 September 2019

Table A1. Location and links of 1 April 2017 Menorca tornadoes.

Latitude (deg.)	Longitude (deg.)	Link
40.039	3.817	https://www.youtube.com/watch?v=1jGEkRMV1OY
40.008	3.816	https://www.youtube.com/watch?v=jIYjG4bqHNA
40.006	3.805	https://www.youtube.com/watch?v=mAFTk0but4A
40.008	3.801	https://www.youtube.com/watch?v=Flh5llkE53s
40.004	3.840	https://www.youtube.com/watch?v=J7kFucKKqoc
39.940	3.956	https://www.youtube.com/watch?v=HtK7HiOtpbo
39.935	3.960	https://www.menorca.info/menorca/videos/video-cap-fiblo-5.html