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What's the Worst That Could Happen?

Re-examining the 24–25 June 1967 Tornado Outbreak Over Western Europe

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ABSTRACT

On 24–25 June 1967 one of the most intense European tornado outbreaks produced extensive damage (approximately 960 houses damaged or destroyed) and resulted in 232 injuries and 15 fatalities in France, Belgium, and the Netherlands. The 24–25 June 1967 tornado outbreak shows that Europe is highly vulnerable to tornadoes. To better understand the impact of European tornadoes and how this impact changed over time, the question is raised, “What would happen if an outbreak similar to the 1967 one occurred 50 years later in 2017 over France, Belgium, and the Netherlands?” Transposing the seven tornado tracks from the June 1967 outbreak over the modern landscape would potentially result in 24 990 buildings being impacted, 255–2 580 injuries, and 17–172 fatalities. To determine possible worst-case scenarios, the tornado tracks are moved in a systematic way around their observed positions and positioned over modern maps of buildings and population. The worst-case scenario estimates are 146 222 buildings impacted, 2 550–25 440 injuries, and 170–1 696 fatalities. These results indicate that the current disaster management policies and mitigation strategies for Europe need to include tornadoes, especially because exposure and tornado risk is anticipated to increase in the near future.

1. Introduction

The general public, as well as many researchers and meteorologists, do not consider tornadoes to be a large threat to Europe because of their supposed rarity and weaker intensity compared to their American counterparts. Reliable measures of the number and economic impact of European tornadoes were unavailable until recently (Groenemeijer and Kühne 2014; Grieser and Terenzi 2016; Antonescu et al. 2016, 2017). The results of these studies reveal that, not only are European tornadoes not rare events, but they can cause injuries, fatalities, and damage. According to the European Severe Weather Database (ESWD, Dotzek et al. 2009; Groenemeijer et al. 2017), 227 tornadoes and 284 waterspouts were reported on average each year between 2012–2016 (accessed on 22 May 2017). From 1950–2015, European tornadoes caused 4 462 injuries, 316 fatalities, and damage estimated at more than €1 billion (Antonescu et al. 2017).

One aspect of understanding the threat that tornadoes pose to Europe is tornado outbreaks, defined here as "multiple tornado occurrences associated with a particular synoptic-scale system" (American Meteorological Society cited 2017). Specifically, multiple tornadoes occurring in close proximity in space and time result in an increased likelihood of major damage and fatalities (e.g., Brooks 2004; Fuhrmann et al. 2014). For example, 80% of tornado-related fatalities in the United States between 1875 and 2003 were associated with tornado outbreaks (Schneider et al. 2004). Yet, despite their importance, only a few studies of European tornado outbreaks exist. Three examples show the variety of different synoptic environments in which such outbreaks occur. Apsley et al. (2016) performed an observational analysis and model simulation of the largest documented outbreak in the UK: 104 tornado reports that formed along a cold front in November 1981. Oprea and Bell (2009) analyzed a prefrontal squall line in Romania in May 2005 that produced three tornadoes in association with a bow echo. Bech et al. (2007) discussed an outbreak over Barcelona in September 2005 that occurred when waterspouts that formed along a convergence line moved onshore and caused three injuries and €9 million in damages.

To understand the characteristics of European tornado outbreaks, Tijssen and Groenemeijer (2015) examined proximity soundings from reanalysis datasets for 28 outbreaks between 1950–2014. They defined a tornado outbreak in Europe as a group of tornadoes that occurred less than 500 km and 6 h from each other and for which the sum of F-scale values for each tornado in the outbreak is greater than or equal to 7. These 28 outbreaks resulted in 1 578 injuries and 99 fatalities representing 35% of all tornado-related injuries and 31% of all tornado-related fatalities during that period (Antonescu et al. 2017). Figure 1 is a scatterplot of these tornado outbreaks plotted as a function of the number of injuries and fatalities. By this measure, the largest European outbreak was the 9 June 1984 Russian outbreak with 804 injuries and 69 fatalities (Finch and Bikos 2012, ESWD accessed on 22 May 2017), followed by the 24–25 June 1967 western Europe outbreak with 232 injuries and 15 fatalities (Bordes 1968; Wessels 1968; Delvaux). The 24–25 June 1967 outbreak is the focus of this article.

The 24–25 June 1967 tornado outbreak over western Europe provides an excellent opportunity to better understand the impact associated with a large outbreak. Furthermore, given the size and intensity of this outbreak (one F2 tornado, four F3 tornadoes, one F4 tornado, and one F5 tornado), this outbreak could serve as a representative example of a strong outbreak. Is is possible that the number of tornadoes from this outbreak was larger, for example, the ESWD contains a report of a tornado (most likely an F0 or an F1 tornado) at Jüterbog (Germany) on 24 June 1967. An important feature of this event is that detailed damage surveys were performed at the time of the event and can be used to determine footprints of damage and estimated financial losses. Similar to prior works (e.g., Rae 2000; Wurman et al. 2007; Hall and Ashley 2008; Risk Management Solutions 2009; Cannon et al. 2011; Rosencrants and Ashley 2015; Montes Berríos et al. 2016;

Ashley and Strader 2016), to understand what might be the case for a similar outbreak occurring in the same-or similar-location, we can take the tracks of these tornadoes and transpose them over different locations to see how much damage this outbreak could inflict on a modern landscape. As a result, the aim of this article is to reconstruct the outbreak using historical data in order to estimate the impact of this outbreak on a modern landscape. We thus ask the question, "What would happen if an outbreak similar to the 1967 one occurred 50 years later in 2017 over France, Belgium, and the Netherlands?"

This article is organized as follows. Section 2 presents a documentary reconstruction of the damages associated with 24–25 June 1967 tornado outbreak. Section 3 describes the research methods. The potential impact on infrastructure and population of a similar outbreak over a modern landscape is analyzed in section 4 and section 5, respectively. Section 6 discusses the results and section 7 summarizes this article.

2. Documentary reconstruction

We start by presenting evidence of the damage associated with the seven tornadoes recorded during this outbreak (Fig. 2). Three tornadoes occurred on 24 June, and four occurred on 25 June. All times are presented in UTC, which is 1 hour behind local time (UTC = LT – 1 h). The tornado tracks in Fig. 2 are reconstructed based on damage surveys and aerial photography described in Bordes (1968) for the Davenescourt, Pommereuil (Fig. 3a), Palluel (Fig. 3b), and Argoules tornadoes over France, in Delvaux for the Oostmalle tornado over Belgium, and in Wessels (1968) for the Chaam and Tricht (Fig. 3c) tornadoes over the Netherlands.

a. Davenescourt tornado: 1840 UTC 24 June

The first tornado reported in northeastern France on 24 June 1967 was first observed close to Sérévillers, 32 km north-northeast of the city of Beauvais at around 1810 UTC and moved northeastward toward Davenescourt (Fig. 4a). The tornado uprooted and severely damaged 3 000–3 500 trees and "destroyed the roofs of numerous houses and farms" (Bordes 1968) between Villers-Tournelle and Chaulnes (Fig. 4a). Close to Davenescourt, the tornado killed more than 24 cows, some of them being found 300–600 m from the farm. Between Chaulnes and Busigny, the damage reports were infrequent (Fig. 4a). Bordes (1968) indicated that the tornado path length was approximately 33 km, but the damage survey showed that the path length was at least 9 km and that damages spread over approximately 24 km were not analyzed in detail (KERAUNOS cited 2017b). The Davenescourt tornado was classified as a an F3 tornado. Note that there is a damage indicator bias present in post-event damage surveys and Fujita or Enhanched Fujita scale procedures which depends on the landscape type (i.e., developed or undeveloped). Strader et al. (2015) have studied this bias and showed that the intensity of tornadoes that occurred in rural areas (i.e., landscapes with a lower number damage indicators) tends to be underestimated, and tornadoes that occurred in more developed landscapes (i.e., landscapes with a higher number of damage indicators) are typically rated as more intense. Give that the track of the Davenescourt tornado was mainly over an undeveloped landscape, it is possible that the intensity of the tornado was underestimated.

b. Pommereuil tornado: 2000 UTC 24 June

The Pommereuil tornado was associated with a second tornado track that extended northeastward over a distance of about 23 km between the Busigny and Mormal forests (Fig. 4a). The tornado only damaged the upper part of the tall buildings between Busigny and Saint-Benin, and it caused damage at Le Cateau-Cambrésis (several houses were affected in the southeastern part of the village) and Bazuel (the northwestern part of the village being the most affected) (Bordes 1968). The tornado reached Pommereuil around 2000 UTC producing F4 damage, killing two people, and injuring another 50. Of the 240 houses in Pommereuil, 200 received varying degrees of damage (*Het Vrije Volk* 1967, p. 8) before the tornado dissipated in the Mormal forest. Because both the Davenescourt and Pommereuil tornadoes were oriented in the same direction and were close in time and space, it is probable that they were associated with the same convective storm cell (Fig. 4a).

c. Palluel tornado: 1940 UTC 24 June

The track of the Palluel tornado was parallel to and approximately 45 km west of the track of the Pommereuil tornado (Fig. 4a). According to Bordes (1968), the tornado was first reported between Ervillers and Vaulx-Vraucourt around 1940 UTC. Moving northeastward, the tornado affected eight villages and produced F5 damage at Écoust-Saint-Quentin and Palluel (Fig. 4a). Along its track, the tornado completely destroyed 17 houses and severely damaged another 135, resulting in 6 fatalities and 30 injuries (Bordes 1968; Dessens and Snow 1989). A state of emergency was declared in Nord and Pas-de-Calais counties, where damage produced by the Pommereuil and Palluel tornado was estimated at tens of millions of French francs (1 million French francs was valued at €1.7 million[1] on 15 March 2017) (*De Tijd*, 1967, p. 2).

d. Oostmalle tornado: 1515 UTC 25 June

The first tornado that occurred on 25 June 1967 was reported over northern France. The tornado was reported at Arry, Vran, and Argoules. It destroyed crops, damaged roofs to numerous houses, and uprooted 500–1000 trees (Bordes 1968). The tornado hit Argoules around 1145 UTC

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[1] Based on data from `http://fxtop.com/en/currency-converter-past.php`, accessed on 15 March 2017.

and produced F2 damage (KERAUNOS cited 2017a) (Fig. 4b). The storm system that produced the Argoules tornado moved northeastward, producing another tornado at Oostmalle in northern Belgium (Fig. 4c). The first damage associated with the Oostmalle tornado occurred at De Kempen, a furniture factory situated about 2 km southwest of Oostmalle. On its way to Oostmalle, the tornado also uprooted hundreds of trees in Renesse Castle's park. Around 1515 UTC, the tornado reached Oostmalle and produced F3 damage. The tornado completely destroyed the town hall and a sixteenth century church; around three hundred people left the church moments before the tornado hit (Delvaux). Of the 907 homes in Oostmalle, 467 were affected by the tornado, completely destroying 117 and severely damaging 105. There were no fatalities, but the tornado caused 43 serious injuries and another 67 minor injuries. The damage associated with the Oostmalle tornado was estimated at 200 million Belgian francs (€33.7 million on 5 March 2017) (Delvaux).

e. Chaam tornado: 1527 UTC 25 June

On 25 June, tornadoes were also reported in the Netherlands, affecting the villages of Chaam and Tricht (Fig. 4c) The Chaam tornado was first reported touching down east of Ulicoten, then moving northeastward and crossing the road between Chaam and Baarle-Hertog. According to eyewitnesses, the tornado lifted from the ground between Ulicoten and Chaam. At Chaam, a small number of houses were damaged by the tornado. The most affected area was a camping site—Klein Paradjjs ("Little Paradise") situated 2.2 km southeast of Chaam—where ten people were seriously injured and two were killed. After passing Chaam, the tornado reached Chaam Forest, uprooting and breaking trees over an area about 0.75 km^2 (Wessels 1968). The Chaam tornado track ended southwest of Gilze where "a lot of objects from the damage path came to [the] ground" (Wessels 1968). The total damage associated with the Chaam tornado was estimated at several million Dutch guilders (1 million Dutch guilders was valued at €2.3 million on 15 March 2017) (*Limburgs Dagblad* 1967).

f. Tricht tornado: 1610 UTC 25 June

The Tricht tornado, the second tornado reported in the Netherlands on 25 June, started near an orchard at 1.5 km south of Nieuwall. The tornado damage was minimal in Nieuwall (i.e., some greenhouses were destroyed), but, after crossing the Waal river, the tornado completely destroyed a farm near Hellouw (Fig. 4c). Moving northeastward, the tornado was photographed south of Deil by passing motorists. The tornado then reached Tricht and produced extensive damage, especially in the western part of the village, resulting in five fatalities and 32 injuries (Fig. 4c). A third of the population of Tricht (approximately 500 people) became homeless after 50 houses were completely destroyed and another 91 were severely damaged. The total damage was estimated at 6 million Dutch guilders (€13.8 million or $12.0 million on 15 March 2017). An article describing the Tricht tornado published in a regional newspaper also mentions that “KNMI [i.e., The Royal Netherlands Meteorological Institute] have given a ‘unique’ warning via the radio for possible whirlwinds” on 25 June (*Dagblad van het Noorden* 2013). A more recent article, commemorating 50 years since the Chaam tornado, indicated that the Dutch weatherman Joop den Tonkelaar (1926–2001) warned on an early morning radio show about the possibility of tornadoes over the Netherlands on 25 June. His warning was based on the fact that the synoptic-scale pattern on 25 June was similar to the one associated with the tornadoes over France on the previous day. Because KNMI did not want to cause any panic, the warning was changed from ”possible tornadoes” to ”possible severe wind gusts” (*BN DeStem* 2017). Thus, the warning issued by KNMI on 25 June 1967 was probably the first verified tornado warning ever issued in Europe (Rauhala and Schultz 2009).

3. Data and methods

Previous studies that have analyzed the potential damages and fatalities associated with tornadoes have focused mainly on tornadoes striking major U.S. cities. To our knowledge, our study is the first analyzing the impact resulting from a European tornado outbreak. For example, the 3 May 1999 tornado outbreak over northern Oklahoma and Kansas (Thompson and Edwards 2000) motivated the North Central Texas Council of Governments and the National Weather Service in Fort Worth to conduct a tornado-damage risk assessment for the Dallas–Fort Worth Metroplex (Rae and Stefkovich 2000). Using Geographic Information System (GIS) technology, 53 tornado tracks from 3 May 1999 tornado outbreak were mapped and distributed across the Dallas–Fort Worth Metroplex. For the Moore F5 tornado (Marshall 2002), the most damaging tornado of the outbreak that affected Oklahoma City and surrounding areas, the actual wind and damage contours were imported from engineering surveys. Thus, the tornado outbreak was exactly the same as on 3 May 1999, but transposed from Oklahoma City to Dallas–Forth Worth. The goal was to estimate the potential impact on buildings, traffic, and people using an infrastructure and population database (e.g., land use classifications, demographic data, building locations, aerial photographs) upon which the tornado tracks were overlaid. Five scenarios were then devised by considering all the tornado tracks as a group and maintaining their length, width, and direction and then moving the focal point of the tornado outbreak (i.e., the Moore tornado) slightly north–south and east–west across the Dallas–Fort Worth Metroplex. In addition to the five scenarios, a smaller subset of tornado tracks that included the track of the Moore tornado was mapped 50 times, side by side in 2.5. miles increments across the core of the Dallas–Fort Worth Metroplex. Rae and Stefkovich (2000) showed that as many as 17 000 single family homes, 19 000 apartments, 84 000 residents, and

94 000 employees would be in the direct path of the tornadoes, and they estimated the potential damages at approximately $3 billion.

Wurman et al. (2007) argued that the methodology used by Rae and Stefkovich (2000) to estimate the effects of tornadoes crossing urban areas can underestimate the maximum damage potential. For example, the track of the 3 May 1999 Moore tornado crossed sparsely populated rural regions in Oklahoma, so the full damage potential of the tornado was likely underestimated. Transposing the track of the Moore tornado over the Dallas–Fort Worth urban area is also likely to significantly underestimate the full damage potential of the tornado. To address this issue, Wurman et al. (2007) simulated the impacts of intense tornadoes crossing urban areas with high population density using axisymmetric modeled wind fields from actual and hypothetical tornadoes crossing residential and commercial areas of major U.S. cities (e.g., Chicago, Illinois; Houston and Dallas–Fort Worth, Texas; New York, New York; Saint Louis, Missouri). U.S. census block data and satellite imagery, among other data sources, were used to estimate the number of buildings impacted and the number of fatalities. Their results indicated that a large and intense tornado crossing high-density residential areas of Chicago and Illinois could destroy up to 239 000 houses and could kill 4 500–45 000. Brooks et al. (2008) argued that the potential damage from tornadoes in urban areas described by Wurman et al. (2007) is an overestimation of the real potential due to a combination of unrealistic hight death rate associated with the destroyed homes and the area covered by the highest winds (see also the reply from Wurman et al. 2008a). Blumenfeld (2008) indicated that the mortality estimates from Wurman et al. (2007) were undermined by an oversimplified population model used in conjunction with a very detailed tornado model (see also the reply from Wurman et al. 2008b). Furthermore, Ashley et al. (2014) (their Fig. 3) and Strader et al. (2015) (their Fig. 6) noted that the tornado tracks used by Wurman et al. (2007) were 50% to 100% wider than the widest tornado on record in the United States.

Our approach in estimating the potential damages and fatalities associated with the 24–25 June 1967 tornado outbreak transposed over a modern landscape is similar to the previous approaches. As in Rae and Stefkovich (2000), the seven tracks from the 24–25 June 1967 tornado outbreak were moved at equally spaced 0.1° intervals in longitude and latitude within a 1° by 1° box centered in the original position of the track. This resulted in 121 scenarios, one in which the track is maintained in the same position as observed on 24–25 June 1967 and 120 scenarios resulting from moving the track systematically around the observed position (Fig. 4). Also as in Rae and Stefkovich (2000), only the actual tornado tracks were included in this analysis. The Davenescourt, Pommereuil, Palluel, and Argoules tornado tracks were extracted from Bordes (1968, their Fig. 1), imported as a high-resolution image into ArcMap GIS software [Environmental Systems Research Institute, Inc. (ESRI)], georeferenced, projected onto a Mercator projection, and saved in a ESRI shapefile format. The same procedure was used to extract the Oostmalle tornado track based on Delvaux (, p. 6) and the Chaam, and Trich tornado tracks based on Wessels (1968, their Figs. 9 and 11 respectively). Unlike previous studies in which the tornado impact was analyzed by moving the observed and simulated tracks to a different location (e.g., Rae and Stefkovich 2000; Wurman et al. 2007), here the orientation of the tracks is maintained and only their positions are changed in a systematic way (i.e., fixed spatial intervals) over distances up to approximately 65 km from the observed position. This approach, similar also with the approach used, for example, by Hall and Ashley (2008) and Ashley et al. (2014) in the United States, allows us not only to estimate the impact of the tornado outbreak over a modern landscape, but also to understand how the impact has changed since 1967.

No information could be retrieved from the contemporary sources about the structure of the wind swaths inside each tornado track. Thus, we were unable to provide a detailed analysis of the damages to buildings along the tornado track by relating the degree of damage to the ground-relative horizontal wind profiles as, for example, in Wurman et al. (2007). Here we assume that all the buildings intersected or inside each tornado track were impacted, without quantifying the impact on each building.

4. Impact on infrastructure

To estimate the impact on buildings, the observed tornado tracks from 24–25 June 1967 were placed over the modern landscape retrieved from OpenStreetMaps (OpenStreetMap contributors 2017). Next, for each of the 121 scenarios resulting from moving the 24–25 June 1967 tornado tracks around their observed positions, the number of buildings that were either inside or intersected by the tornado track were extracted. Figure 5 is an example showing the buildings impacted by the Davenescourt tornado track for the scenario in which the track is maintained in the same position as on 24 June 1967. In OpenStreetMaps, the buildings are created from "blocks" which can be a single detached property, a row of individual terraced houses, or an arrangement of properties. These blocks limit our approach because the analysis does not include any information about the structure of the buildings destroyed (i.e., construction material, number of stories). A visual inspection based on aerial photography showed that the majority of the buildings in the areas affected by the outbreak correspond to low-rise residential buildings.

In addition to the 121 scenarios for each tornado track, three scenarios were constructed in which the entire tornado outbreak is considered. The IDENTICAL OUTBREAK scenario results from maintaining the positions of all tornado tracks as observed on 24–25 June 1967 [i.e., center cell (0,0) in Figs. 6d and 7e]. The MAXIMUM OUTBREAK scenario is the scenario with the maximum number of buildings impacted by the outbreak (i.e., the maximum value in Figs. 6d and 7e). This scenario is obtained by adding together the scenarios associated with each tornado track (Fig. 6a–b and 7a–d), and then extracting the maximum value. For this scenario, the position of each tornado track changes relative to the observed position, but the position of tracks relative to each other is maintained. The MODIFIED OUTBREAK scenario corresponds to the case in which the number of buildings impacted is obtained by moving the tracks to their corresponding maximum (i.e., maximum values in Figs. 6a–c and 7a–d). For this scenario, the positions of tornado tracks relative to the observed positions and also relative to each other are changed.

The Davenescourt, Pommereuil, and Palluel tornado tracks over a modern landscape would result in 21 868 buildings being impacted (Table 2), being the IDENTICAL OUTBREAK. These tornado tracks resulted in 352 houses being destroyed or damaged on 24 June 1967 which is approximately 22 times lower than the minimum number of buildings (i.e., 7667 buildings) impacted considering all 121 scenarios (Fig. 6d). By moving all of the tornado tracks from 24 June 1967 approximately 39 km northwest from the observed position (MAXIMUM OUTBREAK scenario in Table 2), 131 085 buildings would be impacted, the majority (52%, 67 542 buildings) resulting from the Davenescourt tornado track crossing Amiens (France). Changing the position of tornado tracks relative to each other would result in 182 368 buildings being impacted (MODIFIED OUTBREAK scenario in Table 2), of which 114 826 (63%) would be associated with the Pommereuil and Palluel tornadoes tracks crossing Lille (France).

The impact on a modern landscape of the tornado tracks from 25 June 1967 over France, Belgium, and the Netherlands is lower compared with the impact of tornadoes from the previous day over France. Thus, the IDENTICAL OUTBREAK scenario for 25 June would result in 3 122 buildings being impacted (Table 2). Initially, the tornadoes on 25 June were associated with 608 houses being affected, which ranks 119 out the 121 scenarios (Fig. 7e). A maximum of 15 137 buildings would be impacted if all the tracks were moved 52 km northeast, the major impact resulting from the Chaam tornado crossing Rotterdam city area (Netherlands) of 11 069 buildings (MAXIMUM OUTBREAK scenario in Table 2). For the MODIFIED OUTBREAK scenario, the number of buildings impacted would increase to 34 340 buildings (Table 2) resulting from the Argoules tornado crossing Amiens (France), the Oostmalle tornado crossing Brussels (Belgium), the Chaam tornado crossing Tilburg (Netherlands), and the Tricht tornado crossing Eindhoven (Netherlands).

5. Impact on population

The major challenges for preventing tornado-related injuries and fatalities are associated with taking the appropriate actions in a prompt manner (e.g., Brown et al. 2002; Schultz et al. 2010). As such, quantifying the potential impact of tornado events by the number of injuries and fatalities provides valuable information for emergency managers to develop and improve safety recommendations, effective tornado preparedness plans, and medical response.

To estimate the impact on population of a modern tornado outbreak similar with the 24–25 June 1967 outbreak, the same approach to the one described in section 3 was used, in which the building dataset from OpenStreetMaps was replaced with the Gridded Population of the World, Version 4 (GPWv4, Doxsey-Whitfield et al. 2015). The GPWv4 consists of estimates of human population based on national censuses, adjusted to match the 2015 Revision of the United Nations World Population Prospects country totals for 2000, 2005, 2010, 2015, and 2020. The gridded population dataset was created by distributing the population estimates to a 30 arc-second (approximately 1-km) grid using an areal-weighting method. Only the grid containing the 2015 population estimates was used here. Figure 5b shows an example of how the number of inhabitants was extracted for the scenario in which the Davenescourt tornado track is maintained in the same position as on 24 June 1967. In extracting the number of inhabitants we employed the “intersecting” method (Hall and Ashley 2008) in which the total number of inhabitants is obtained by summing all the population grid cells that are within or intersected by the tornado track. This can lead to an overestimation of the of the number of inhabitants, because, for example, grid cells with very small portions inside the track are considered in their entirety (e.g., Ashley et al. 2014). To provide more accurate estimation, Strader and Ashley (2016) used an areal weight method in which, for example, the number of inhabitants is adjusted based on the fraction of the grid cells intersected by the tornado track. Here we are using the intersecting method given that we are constructing a worst-case scenario, and also given the uncertainties in constructing tornado tracks for historical events.

Figures 8 and 9 show the number of impacted inhabitants from the 121 possible scenarios resulting from moving the tornado tracks from 24–25 June 1967 around their observed position. Based on the median values, 25 597 inhabitants will be impacted by a tornado outbreak similar with 1967 outbreak (Table 3). If all the tornado tracks from 24 June are maintained in the same position as observed, then 14 488 inhabitants will be impacted (IDENTICAL OUTBREAK scenario in Table 3). A maximum number of 145 971 inhabitants will be impacted if all the tornado tracks will be moved approximately 57 km northeast from their initial position (MAXIMUM OUTBREAK scenario in Table 3). This maximum is associated mainly with the track of the Palluel tornado intersecting Lille (Fig. 8c), the fourth largest urban area in France after Paris, Lyon, and Marseille. For 25 June, the IDENTICAL OUTBREAK scenario will result in 2 675 impacted inhabitants. The MAXIMUM OUTBREAK scenario results from moving all the tracks approximately 59 km northwest from the initial position and impacts 23 673 inhabitants (Table 3). For the MAXIMUM OUTBREAK scenario, 57% of the impacted inhabitants will result from the Tricht tornado track intersecting Eindhoven city area.

So far, we have estimated the number of inhabitants impacted, but we can also estimate, based on the previous studies of tornado-related fatalities, the number of fatalities associated with an outbreak similar with the 24–25 June 1967 outbreak. For example, Wurman et al. (2007), in their study of violent tornadoes (i.e., those rated F4 and F5 on the Fujita scale) in urban areas of the

United States, assumed that 10% of the inhabitants in the tornado path would be killed. Brooks et al. (2008) argued that this assumption is inconsistent with the previous studies of tornado-related fatalities. They indicated that the fatality rate (defined as the number of fatalities divide by the total number of inhabitants along the tornado track) ranges from 0.1%, based on a survey of the inhabitants of the damaged and destroyed houses, regardless of the F-scale rating, along the track of the 3 May 1999 Oklahoma city F5 tornado (Daley et al. 2005) to 1.0%, based on a survey of destroyed housed along the track of 8 April 1998 Birmingham F4 tornado (Legates and Biddle 1999). We need to note here that there are differences in the building construction standards between Europe and the United States. Doswell et al. (2009) argued that that the building construction standards in western Europe are more homogeneous and in general higher than in the central United States. For example, most of the houses in Moore (Oklahoma) damaged by the 3 May 1999 tornado were one-story and two-story, wooden-framed houses constructed on concrete slab foundations (Marshall 2002). A simple analysis using street view images from Google Maps along the tornado tracks from 24-25 June 1967 showed that the old and new buildings over northwestern France, Belgium, and the Netherlands appears to be constructed of concrete masonry of bricks of likely greater than one course in thickness and with Spanish tile roofs. Thus, when results associated with building construction standards in the United States (e.g., fatality rate) are applied to Europe, it is likely that they will result in an overestimation (e.g., number of fatalities).

Fatality rates proposed by Brooks et al. (2008) were applied to the number of inhabitants along the tornado tracks resulting from the scenarios summarized in Tables 2 and 3. For comparison, the 1967 tornado outbreak resulted in 15 fatalities and would result over a modern landscape in 17 to 172 fatalities (IDENTICAL OUTBREAK scenario in Table 3) based on the 0.1% and 1% fatality rates. For 24 June, the minimum number of fatalities, based on the 121 scenarios in Fig. 8 and using the 0.1% fatality rate, is 10 compared with 8 fatalities reported in 1967. For 25 June, the minimum number of fatalities is 2 compared with 7 fatalities reported in 1967, which ranks 63 out of the 121 scenarios (Fig. 9). For MAXIMUM OUTBREAK and MODIFIED OUTBREAK scenarios, the number of fatalities resulting from the 0.1% and 1% fatality rates is between 170 fatalities and 3 564 fatalities. This high number of fatalities is an unrealistic estimate when compared with other deadly European tornadoes. The European tornado history contains three tornadoes for which the death toll was greater than 50 fatalities: the F5 Montville (France) tornado on 19 August 1845 associated with at least 70 fatalities (Dessens and Snow 1989), the F5 Ivanovo (Russia) tornado on 9 June 1884 associated with at least 69 fatalities (Finch and Bikos 2012), and the F4 Oria (Italy) tornado on 21 September 1897 associated with 55 fatalities[2] (Gianfreda et al. 2005). A more plausible estimate of the death toll from an outbreak similar to the 24–25 June 1967 tornado outbreak is 26–256 fatalities, based on the median values in Tables 2 and 3 and the 0.1% and 1% fatality rates, respectively. This number of fatalities is still large by modern standards (e.g., according to the European Severe Weather Database, of the 117 European tornadoes associated with fatalities between 1950–2016, only 12 were associated with more than 5 fatalities), but these estimates of the number of fatalities are for an outbreak with seven tornadoes occurring over two days.

In addition to the estimates of the number of fatalities associated with a tornado outbreak over western Europe, estimates of the number of injuries, and in particular those requiring hospital admission, is also important for emergency managers and disaster-response teams. Brown et al. (2002) documented the magnitude of fatal and nonfatal injuries associated with the 3 May 1999 tornadoes in Oklahoma and showed that there were about 15 people treated at a hospital for

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[2] The highest number of tornado-related fatalities in Europe after 1800 was reported for a tornado that occurred in Sicily (Italy) in December 1851 (*Illustrated London News* 1851) where more than 500 people were killed, but this event is documented from secondary sources which could be an overestimate of the actual number of fatalities.

tornado-related injuries for each tornado-related fatality. Similar values for the ratio between the number of tornado fatalities and tornado injuries were reported by Eidson et al. (1990) for the 28 March 1984 tornadoes in the North and South Carolina (i.e, approximately 16 injuries for each fatality), and by Corfidi et al. (2010) for the Super Outbreak of 3–4 April 1974 (i.e, approximately 17 injuries for each fatality). Lower rates were reported by Kuligowski et al. (2014) for the Joplin tornado on 22 May 2011 (i.e., approximately 6 injuries for each fatality) and by Wang et al. (2017) for the Funing (China) tornado on 23 June 2016 (i.e., approximately 7 injuries for each fatality).

The number of injuries and fatalities associated 24–25 June 1967 tornado outbreak indicated that there were approximately 15 injuries for each tornado-related fatality. If we consider this estimate for the number of injuries, then an outbreak similar to that of 24–25 June 1967 over a modern landscape will result in 255–2 580 injuries (based on the IDENTICAL OUTBREAK scenario) and in 2 550–25 455 injuries (based on the MAXIMUM OUTBREAK scenario). For example, the Pommereuil and Palluel tornadoes over a modern landscape will result in 150–1 440 injuries (based on the IDENTICAL OUTBREAK scenario) and, assuming in the worst case scenario that all of the injured people will need hospital admission, 0.6%–5.7% of all available hospital beds in the Nord and Pas-de-Calais departments would be required (25 176 beds in 2014 based on data from Eurostat 2017). Our approach here does not take into account the indirect tornado-related injuries (and even fatalities) associated with the rescue and recovery activities, which will further increase the number of hospital admissions (Brown et al. 2002). Furthermore, estimation for number of fatalities and injuries associated with the 24–25 June 1967 tornado outbreak over a modern landscape assume that the vulnerability and resilience have not changed. Even though the warnings system for European tornadoes have not changed much (e.g., Antonescu et al. 2017), many aspects of vulnerability (e.g., population over 65 years of age, population bellow poverty level, population with physical or sensory disability, Dixon and Moore 2102) and resilience (e.g., social capital, physical infrastructure and interdependent of the community, cultural patterns, collective action, Houston et al. 2017) have changed.

6. Discussion

This re-examination of the 24–25 June 1967 tornado outbreak over western Europe allows us to understand and to quantify the impact (e.g., number of buildings impacted, number of fatalities) of European tornadoes and also to understand how this impact has changed in time. The scenarios devised here that result from transposing the tornado tracks from this historical tornado outbreak over a modern landscape indicate that the impact has increased significantly over the last 50 years (see Table 1 compared with Tables 2 and 3). This increase is driven by an increase in the number of inhabitants and implicitly by an increase in the number of buildings. For example, according to United Nations (2017b), the population of France increased from 48.9 million inhabitants in 1965 to 64.4 million inhabitants in 2015 and is projected to reach 71.5 million inhabitants by 2065 (an increase by 46.2% since 1965). Similar increases in the number of inhabitants are projected for Belgium (by 33.89% since 1965 reaching 12.6 million inhabitants in 2065) and the Netherlands (by 40.0% since 1965 reaching 17.1 million inhabitants in 2065). Ashley et al. (2014) argued that is not just the number of inhabitants that is important when analyzing the impact of tornadoes, but also how the population and the built environment are distributed across the landscape. The cities are expanding the exposure, and vulnerability is increasing (the expanding bullseye effect proposed by Ashley et al. 2014, and further discussed by Ashley and Strader 2016, Strader et al. 2017a, and Strader et al. 2017b). United Nations (2017a) estimated that 54.4% of the world's population lived in urban settlements in 2016, which will increase to 60% by 2030, with one in three people living in a city with at least 0.5 million inhabitants. Thus, the impact of tornadoes in Europe not only has increased since 1967, but will continue to increase in the near future. Assuming that the average annual number of tornadoes (i.e., 227 tornadoes per year between 2012–2016) is not going to change in a future warmer climate, the impact of European tornadoes will increase due to an increase in societal exposure associated with an increasing population and an increasing growth of cities through urbanization and urban sprawl.

Future climate projections summarized by Brooks (2013) and Tippett et al. (2015) have suggested an increase in the frequency of the environments supportive of severe convective storms and their associated hazards (e.g., tornadoes) over the United States and Europe. For example, Diffenbaugh et al. (2013) showed that an increase is expected in the occurrence of severe thunderstorm environments over the eastern United States in response to global warming by 2100, and the number of days supportive of tornadic storms might increase. Púčik et al. (2017) suggested than an increase in the frequency of the environments supportive of severe convective storms is projected over Europe in the 21st century, especially south-central, central, and eastern Europe. Thus, assuming that there is no change in the societal exposure during the 21st century, an increase in the frequency of environments supportive of severe convective storms implies an increasing impact of European tornadoes if global warming continues (e.g., Strader et al. 2017b).

Because both the exposure (i.e., population increase, city growth) and risk (i.e., frequency of environments associated with severe convective storms) will increase during the 21st century, the impact of severe convective storms in general, and tornadoes in particular will increase. On the other hand, Schultz and Janković (2014) and Janković and Schultz (2017) have argued that the exposure will surpass the effects of climate change. Even if current tornado research and tornado mitigation strategies are not a priority for European meteorological services, researchers, and emergency managers, these topics will become important in the near future. Thus, any mitigation strategies that aim to make communities more resilient will need to include tornadoes.

7. Conclusions

The 24–25 June 1967 tornado outbreak over France, Belgium, and the Netherlands is illustrative of the impact associated with European tornadoes. This impact, as argued by Antonescu et al. (2017), is currently underestimated, with tornadoes being treated as a curiosity by the general public, meteorological services, and emergency managers, rather than as damaging weather phenomena. The results presented here indicate that the 24–25 June 1967 tornado outbreak transposed over a modern landscape could result in 24 990 buildings being impacted, 255–2 580 injuries, and 17–172 fatalities. A worst case scenario was also constructed by considering the maximum values for the number of buildings and inhabitants impacted resulting from moving the tornado tracks around their observed positions in a systematic way. In this scenario, 146 222 buildings will be impacted, 2 550–25 440 inhabitants will be potentially injured, and 170–1 696 will potentially be killed.

More scenarios can be constructed that can result in a larger number of buildings impacted and larger death tolls. For example, transplanting a single tornado track over a high populated urban area can produce a weather-related disaster, as some of the scenarios devised here based on tornado tracks for the June 1967 outbreak have suggested. Here, we have not considered such extreme scenarios (e.g., the Palluel tornado track crossing Paris, the Tricht tornado track crossing Amsterdam). Instead, we focused on scenarios in which tornadoes are occurring in the same region as in June 1967, which allowed us to understand how the impact of the June 1967 tornado outbreak has changed over the last 50 years. Thus, in terms of buildings impacted, the impact of the June 1967 outbreak (960 buildings) is approximately 13 times lower than the lowest ranked scenario (12 924 buildings) out of the 121 scenarios resulting from moving the tracks around their observed position. The 1967 outbreak would rank 99th in injuries out of the 121 scenarios (232 injuries) and 121st in fatalities (15 fatalities).

The potential number of injuries and fatalities that result from some of the scenarios based on the June 1967 tornado outbreak over a modern landscape is high even when compared with high-impact U.S. tornadoes [e.g., the ”Tri-State Tornado” on 17 March 1925 killed 695 people and injured 2,027 in Missouri, Illinois and Indiana (Johns et al. 2013)]. Such a high number of injuries and fatalities is conceivable for Europe given the lack of tornado awareness and preparedness programs and tornado warnings in the majority of European countries. But, given the differences in the construction practices between western Europe and Central United States, it also likely that the number of fatalities and injuries is overestimated. Since 1967, when KNMI issued the first tornado warning for Europe, tornado warnings have been issued for eight other countries (Rauhala and Schultz 2009). Currently, KNMI is the only meteorological service in Europe that is currently issuing tornado warning (Holzer et al. 2015).

Given the potential increase in exposure (i.e., population increase, city growth) and tornado risk (i.e., increase in the frequency of environments associate with severe convective storms), the results from this study highlights the importance of changing the current disaster management policies and mitigation strategies to include tornadoes. These changes will reduce the impact of tornadoes in Europe in the current and the future environment. Furthermore, the methodology developed here can be used to analyze the impact of tornadoes in other regions of Europe (e.g., the impact of the 9 June 1984 tornado outbreak over the Ivanovo and Yaroslavl regions north of Moscow, Russia). Understanding how the impact is changing in time and how it varies across Europe is essential for developing pan-European mitigation strategies that aim to make communities more resilient to tornado damages and to reduce the number of tornado-related injuries and fatalities.

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References

American Meteorological Society, cited 2017: Tornado outbreak. Glossary of Meteorology. [Available online at http://glossary.ametsoc.org/wiki/Tornado_outbreak].

Antonescu, B., D. M. Schultz, A. Holzer, and P. Groenemeijer, 2017: Tornadoes in Europe: An underestimated threat. *Bull. Amer. Meteor. Soc.*, **98**, 713–728.

Antonescu, B., D. M. Schultz, F. Lomas, and T. Kühne, 2016: Tornadoes in Europe: A synthesis of the observational datasets. *Mon. Wea. Rev.*, **144**, 2445–2480.

Apsley, M. L., K. J. Mulder, and D. M. Schultz, 2016: Reexamining the United Kingdom's greatest tornado outbreak: Forecasting the limited extent of tornadoes along a cold front. *Wea. Forecasting*, **31**, 853–875.

Ashley, W. S., S. Strader, T. Rosencrants, and A. J. Krmenec, 2014: Spatiotemporal changes in tornado hazard exposure: The case of the expanding bull's eye effect in Chicago, IL. *Wea. Climate Soc.*, **6**, 175–192.

Ashley, W. S., and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc.*, **97**, 767–786.

Bech, J., R. Pascual, T. Rigo, N. Pineda, J. M. López, J. Arús, and M. Gayá, 2007: An observational study of the 7 September 2005 Barcelona tornado outbreak. *Natural Hazards and Earth System Sciences*, **7(1)**, 129–139.

Blumenfeld, K. A., 2008: Comment on "low-level winds in tornadoes and potential catastrophic tornado impacts in urban areas". *Bull. Amer. Meteor. Soc.*, **89**, 1578–1579.

BN DeStem, 2017: 50 jaar na de windhoos in Chaam: Het was een mooie zomerse dag... (50 years after the whirlwind in Chaam: It was a beautiful summer day...). 25 June, [Available online at https://www.bndestem.nl/breda/50-jaar-na-de-windhoos-in-chaam-het-was-een-mooie-zomerse-dag a85361d0/.

Bordes, A., 1968: Trombes et phénomènes exceptionnels des 23, 24 et 25 Juin 1967 sur le nord de la France (Tornadoes and exceptional phenomena on 23, 24 and 25 June 1967 over northern France). *La Meteorologie*, **V(7)**, 373–398.

Brooks, H. E., 2004: On the relationship of tornado path length and width to intensity. *Wea. Forecasting*, **19**, 310–319.

Brooks, H. E., 2013: Severe thunderstorm and climate change. *Atmos. Res.*, **123**, 129–138.

Brooks, H. E., C. A. Doswell, and D. Sutter, 2008: Comment on “low-level winds in tornadoes and potential catastrophic tornado impacts in urban areas”. *Bull. Amer. Meteor. Soc.*, **89**, 87–90.

Brown, S., P. Archer, E. Kruger, and S. Mallonee, 2002: Tornado-related deaths and injuries in Oklahoma due to the 3 May 1999 tornadoes. *Wea. Forecasting*, **17**, 343–353.

Cannon, A. R., K. Klockow, R. Peppler, and H. E. Brooks, 2011: Deriving Population Exposure Fatality Rate Estimates for Tornado Outbreaks Using Geographic Information Systems (GIS). Center for Analysis and Prediction of Storms Research Experiences for Undergraduates, University of Oklahoma, 9 pp. URL http://www.caps.ou.edu/reu/reu11/papers/Cannon.pdf.

Corfidi, S. F., S. J. Weiss, J. S. Kain, S. J. Corfidi, R. M. Rabin, and J. J. Levit, 2010: Revisiting the 3–4 April 1974 Super Outbreak of Tornadoes. *Wea. Forecasting*, **25**, 465–510.

Dagblad van het Noorden, 2013: Tricht herdenkt dodelijke windhoos (Tricht commemorates the tornado victims). 21 June, 8. [Available online at http://www.dekrantvantoen.nl/vw/page.do?code=DVHN&id=DVHNDO-01-005-20070621&aid=DVHN-20070621-DO01005003].

Daley, W. R., S. Brown, P. Archer, E. Kruger, F. Jordan, D. Batts, and S. Mallonee, 2005: Risk of tornado-related death and injury in Oklahoma, May 3, 1999. *Amer. J. Epidemiol*, **161**, 1144–1150.

Delvaux, C., ????: *Toen vering de wereld in Oostmalle! Tornado 25 Juni 1967 (When the world ended in Oostmalle! The tornado from 25 June 1967.*

Dessens, J., and J. T. Snow, 1989: Tornadoes in France. *Wea. Forecasting*, **4**, 110–132.

De Tijd, 1967: Belgisch doopfeest vindt triest einde (Belgian baptismal party ends bad). 26 June, 2. [Available online at http://www.delpher.nl/nl/kranten/view?query=Belgisch+doopfeest+

vindt+triest+einde&coll=ddd&identifier=ddd%3A011238554%3Ampeg21%3Aa0031&resultsidentifier=ddd%3A011238554%3Ampeg21%3Aa0031].

Diffenbaugh, N. S., M. Scherer, and R. J. Trapp, 2013: Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proceedings of the National Academy of Sciences of the United States of America*, **110(41)**, 16 361–16 366.

Dixon, R., and T. Moore, 2102: Tornado vulnerability in Texas. *Wea. Climate Soc.*, **4**, 59–68.

Doswell, C. A., H. E. Brooks, and N. Dotzek, 2009: On the implementation of the enhanced Fujita scale in the USA. *Atmos. Res.*, **93**, 554–563.

Dotzek, N., P. Groenemeijer, B. Feuerstein, and A. M. Holzer, 2009: Overview of ESSLs severe convective storms research using the European Severe Weather Database (ESWD). *Atmos. Res.*, **93**, 575–586.

Doxsey-Whitfield, E., K. MacManus, S. B. Adamo, L. Pistolesi, J. Squires, O. Borkovska, and S. R. Baptista, 2015: Taking advantage of the improved availability of census data: A first look at the Gridded Population of the World, Version 4. *Papers in Applied Geography*, **1(3)**, 226–234.

Eidson, M., J. A. Lybarger, J. E. Parsons, J. N. MacCormack, and J. I. Freeman, 1990: Risk factors for tornado injuries. *Int J Epidemiol.*, **19**, 1051–1056.

Eurostat, 2017: Hospital days of in-patients by NUTS2 regions. [Available online at http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hlth_rs_bdsrg&lang=en, accessed on 27 June 2017].

Finch, J. D., and D. Bikos, 2012: Russian tornado outbreak of 9 June 1984. *Electron. J. Severe Storms Meteor.*, **7(4)**.

Fuhrmann, C., C. Konrad, M. Kovach, J. McLeod, W. Schmitz, and P. Dixon, 2014: Ranking of tornado outbreaks across the United States and their climatological characteristics. *Wea. Forecasting*, **29**, 684–701.

Gianfreda, F., M. M. Miglietta, and P. Sansò, 2005: Tornadoes in Southern Apulia (Italy). *Natural Hazards*, **34**, 71–89.

Grieser, J., and F. Terenzi, 2016: Modeling financial losses resulting from tornadoes in European countries. *Wea. Climate Soc.*, **8**, 313–326.

Groenemeijer, P., and T. Kühne, 2014: A climatology of tornadoes in Europe: Results from the European Severe Weather Database. *Mon. Wea. Rev.*, **142**, 4775–4790.

Groenemeijer, P., T. Púçik, A. M. Holzer, B. Antonescu, K. Riemann-Campe, D. M. Schultz, T. Kühne, B. Feuerstein, C. A. D. H. E. Brooks, H. Koppert, and R. Sausen, 2017: Severe convective storms in Europe: Ten years of research at the European Severe Storms Laboratory. *Bulletin of the American Meteorological Society*, in press.

Hall, S. G., and W. S. Ashley, 2008: The effects of urban sprawl on the vulnerability to a significant tornado impact in northeastern Illinois. *Nat. Hazards Review*, **9**, 209–219.

Het Vrije Volk, 1967: Tornado over frankrijk: Ramp voltrok zich in vier minuten (Tornado over France: Disaster in four minutes). 26 June, 5. [Available online at http://www.delpher.nl/nl/kranten/view?query=Ramp+voltrok+zich+in+vier+minuten&coll=ddd&identifier=ddd%3A010956346%3Ampeg21%3Aa0177&resultsidentifier=ddd%3A010956346%3Ampeg21%3Aa0177].

Holzer, A. M., K. Nissen, N. Becker, U. Ulbrich, D. Paprotny, P. H. A. J. M. van Gelder, O. N. Morales, A. Vajda, I. Juga, P. Nurmi, H. Gregow, A. Venäläinen, P. Groenemeijer, and T. Púčik, 2015: Present state of risk monitoring and warning systems in Europe: RAIN project report. Tech. rep., 132 pp. [Available online at http://rain-project.eu/wp-content/uploads/2015/11/D2.3-Warning-Systems.pdf, accessed on 20 October 2016].

Houston, J., M. L. Spialek, J. First, J. Stevens, and N. L. First, 2017: Individual perceptions of community resilience following the 2011 Joplin tornado. *J Contingencies and Crisis Management*, **25**, 354–363.

Illustrated London News, 1851: Five hundred persons destroyed by a waterspout. 20 December, 731 pp.

Janković, V., and D. M. Schultz, 2017: Atmosfear: Communicating the effects of climate change on extreme weather. *Wea. Climate Soc.*, **9**, 27–27.

Johns, R. H., D. W. Burgess, C. A. Doswell III, M. S. Gilmore, J. A. Hart, and S. F. Piltz, 2013: The 1925 Tri-State tornado damage path and associated storm system. *Electron. J. Severe Storms Meteor.*, **8(2)**.

KERAUNOS, cited 2017a: Tornado EF2 áa Argoules (Somme) le 25 juin 1967. [Available online from KERAUNOS/Observatoire Français des Tornades et des Orages Violents (French Observatory of Tornadoes and Severe Storms,www.keraunos.org) at http://www.keraunos.org/actualites/faits-marquants/1950-1969/tornade-argoules-25-juin-1967-somme-picardie-outbreak.html].

KERAUNOS, cited 2017b: Tornado EF3 áa Davenescourt (Somme) le 24 juin 1967. [Available online from KERAUNOS/Observatoire Français des Tornades et des Orages Violents (French Observatory of Tornadoes and Severe Storms,www.keraunos.org) at http://www.keraunos.org/actualites/faits-marquants/1950-1969/tornade-davenescourt-24-juin-1967-somme-picardie-outbreak-tornades].

Kuligowski, E. D., F. T. Lombardo, L. T. Phan, M. L. Levitan, and D. P. Jorgensen, 2014: Final report, national institute of standards and technology (nist) technical investigation of the may 22, 2011, tornado in joplin, missouri. National Construction Safety Team Act Reports (NIST NCSTAR), National Construction Safety Team Act Reports (NIST NCSTAR), 428 pp. URL http://nvlpubs.nist.gov/nistpubs/NCSTAR/NIST.NCSTAR.3.pdf.

Legates, D. R., and M. D. Biddle, 1999: Warning response and risk behavior in the Oak Grove-Birmingham, Alabama, tornado of 08 April 1998. Natural Hazards Center Quick Response Rep. 116. [Available online at www.colorado.edu/hazards/research/qr/qr116/qr116.html.].

Limburgs Dagblad, 1967: Windhozen richten ramp aan (Tornado leads to disaster). 26 June, 1. [Available online at http://www.delpher.nl/nl/kranten/view?coll=ddd&identifier=ddd%3A010538746%3Ampeg21%3Ap003&pres%5Bmaxperpage%5D=36].

Marshall, T., 2002: Tornado Damage Survey at Moore, Oklahoma. *Wea. Forecasting*, **17**, 582–598.

Montes Berríos, K. M., A. R. Cook, A. C. Davis, M. Shafer, and S. Erickson, 2016: The impact of a violent tornado in Norman, OK. Center for Analysis and Prediction of Storms Research Experiences for Undergraduates, University of Oklahoma, 7 pp. URL http://www.caps.ou.edu/reu/reu16/finalpapers/MontesBerrios_FinalDraft.pdf.

OpenStreetMap contributors, 2017: Planet dump retrieved from https://planet.osm.org. accessed from https://www.openstreetmap.org.

Oprea, I. C., and A. Bell, 2009: Meteorological environment of a tornado outbreak in southern Romania. *Natural Hazards and Earth System Sciences*, **9(2)**, 609–622.

Púčik, T., P. Groenemeijer, A. T. Rädler, L. Tijssen, G. Nikulin, A. F. Prein, E. van Meijgaard, R. Fealy, D. Jacob, and C. Teichmann, 2017: Future changes in European severe convection environments in a regional climate model ensemble. *J. Clim.*, **30**, 6771–6794.

Rae, S., 2000: Tornado Damage Risk Assessment Dallas-Fort Worth Metroplex. Study Summary and Methodology, North Central Texas Council of Governments/National Weather Service Fort Worth, 45 pp. URL http://www.nctcog.org/weather/study/.

Rae, S., and J. Stefkovich, 2000: The tornado damage risk assessment predicting the impact of a big outbreak in dallas-fort worth, texas. *Preprints, 20th Conf. on Severe Local Storms*, Orlando, FL, Amer. Meteor. Soc., 295–296.

Rauhala, J., and D. M. Schultz, 2009: Severe thunderstorm and tornado warnings in Europe. *Atmos. Res.*, **93**, 369–380.

Risk Management Solutions, 2009: The 1999 Oklahoma Tornado Outbreak: 10-year Retrospective. RMS Special Report, 13 pp. URL http://forms2.rms.com/rs/729-DJX-565/images/scs_1999_oklahoma_tornado_outbreak.pdf.

Rosencrants, T., and W. S. Ashley, 2015: Spatiotemporal analysis of tornado exposure in five U.S. metropolitan areas. *Nat. Hazards*, **78**, 121–140.

Schneider, R. S., H. E. Brooks, and J. T. Schaefer, 2004: Tornado outbreak days: An updated and expanded climatology (1875–2003). *Preprints, 22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., P5.1.

Schultz, D. M., E. C. Gruntfest, M. H. Hayden, C. C. Benight, S. Drobot, and L. R. Barnes, 2010: Decision making by Austin, Texas, residents in hypothetical tornado scenarios. *Wea. Climate Soc.*, **2**, 249–254.

Schultz, D. M., and V. Janković, 2014: Climate change and resilience to weather events. *Wea. Climate Soc.*, **6**, 157–159.

Strader, S., W. S. Ashley, A. Irizarry, , and S. Hall, 2015: A climatology of tornado intensity assessments. *Meteorol. Appl.*, **22**, 513–524.

Strader, S. M., W. S. Ashley, T. J. Pingel, and A. J. Krmenec, 2017a: Observed and projected changes in United States tornado exposure. *Wea. Climate Soc.*, **9**, 109–123.

Strader, S. M., W. S. Ashley, T. J. Pingel, and A. J. Krmenec, 2017b: Projected 21st century changes in tornado exposure, risk, and disaster potential. *Climatic Change*, **141**, 301–313.

Strader, T. J. P., S. M., and W. S. Ashley, 2016: A Monte Carlo model for estimating tornado impacts. *Meteorol. Appl.*, **23**, 269–281.

Thompson, R., and R. Edwards, 2000: An overview of environmental conditions and forecast implications of the 3 May 1999 tornado outbreak. *Wea. Forecasting*, **15**, 682–699.

Tijssen, L., and P. Groenemeijer, 2015: Tornado outbreaks in Europe. *8th European Conference on Severe Storms 14–18 September 2015*, Wiener Neustadt, Austria.

Tippett, M. K., J. T. Allen, V. A. Gensini, and H. E. Brooks, 2015: Climate and hazardous convective weather. *Current Climate Change Reports*, **1**, 60–73.

United Nations, 2017a: The World's Cities in 2016. http://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2016_data_booklet.pdf, accessed on 12 July 2017.

United Nations, 2017b: World Population Prospects: The 2017 Revision. Custom data acquired via website from https://esa.un.org/unpd/wpp/DataQuery/, accessed on 12 July 2017.

Wang, K., S. Zhong, X. Wang, Z. Wang, L. Yang, Q. Wang, S. Wang, R. Sheng, R. Ma, S. Lin, W. Liu, R. Zu, and C. Huang, 2017: Assessment of the Public Health Risks and Impact of a Tornado in Funing, China, 23 June 2016: A Retrospective Analysis. *Int. J. Environ. Res. Public Health*, **14**, 1201.

Wessels, H. R. A., 1968: De zware windhozen van 25 Juni 1967 (The intense tornadoes from 25 June 1967). *Hemel en Dampkring*, **66**, 155–177.

Wurman, J., P. Robinson, C. Alexander, and Y. Richardson, 2007: Low-level winds in tornadoes and potential catastrophic tornado impacts in urban areas. *Bull. Amer. Meteor. Soc.*, **88**, 31–46.

Wurman, J., P. Robinson, C. Alexander, and Y. Richardson, 2008a: Reply. *Bull. Amer. Meteor. Soc.*, **89**, 90–94.

Wurman, J., P. Robinson, C. Alexander, and Y. Richardson, 2008b: Reply. *Bull. Amer. Meteor. Soc.*, **89**, 1580–1581.

LIST OF TABLES

TABLE 1. Summary of the tornado reports for the 24–25 June 1967 tornado outbreak.

Tornado track	Country	Date	Time (UTC) (start–end)	F scale	Path length (km)	Path width (m)	Fatalities	Injuries	Houses (damaged or destroyed)
Davenescourt	France	24 Jun	1810	F3	33(9)	400	no data	no data	no data
Pommereuil	France	24 Jun	2000	F4	23	500	2	50	200
Palluel	France	24 Jun	1940	F5	25	250	6	30	152
Argoules	France	25 Jun	1245	F2	10	150	no data	no data	no data
Oostmalle	Belgium	25 Jun	1515	F3	6	300	no data	110	467
Chaam	Netherlands	25 Jun	1527–1540	F3	11	300	2	10	no data
Tricht	Netherlands	25 Jun	1610–1624	F3	15	200	5	32	141

TABLE 2. Impact of the 24–25 June 1967 tornado outbreak showing minimum, median, and mean number of buildings impacted by each tornado track (Figs. 6a–c and 7a–d). The IDENTICAL OUTBREAK scenario indicates the number of impacted buildings if all tornado tracks are maintained in the same position as observed (center cell in Figs. 6d and 7e). The MAXIMUM OUTBREAK scenario indicates the maximum number of impacted buildings if the positions of tornado tracks relative to each other are maintained (maximum in Figs. 6d and 7e). The MODIFIED OUTBREAK scenario shows the maximum number of impacted building if each track is moved to its maximum (maximum in Figs. 6a–c and 7a–d). For the MODIFIED OUTBREAK scenario, the position of the tornado tracks relative to each other is altered.

Tornado track	minimum	median	mean	IDENTICAL OUTBREAK scenario	MAXIMUM OUTBREAK scenario	MODIFIED OUTBREAK scenario
Davenescourt	3 242	9 091	11 384	10 107	67 542	67 542
Pommereuil	126	5 368	8 793	6 829	37 442	61 719
Palluel	403	4 440	8 151	4 932	26 101	53 107
Total 24 June				21 868	131 085	182 368
Argoules	0	959	1 352	1 185	0	7 272
Oostmalle	3	246	547	729	11	5 134
Chaam	8	1 091	2 020	321	11 069	11 981
Tricht	33	769	1 457	887	4 057	9 953
Total 25 June				3 122	15 137	34 340

TABLE 3. Same as in Table 2, but for the number of inhabitants impacted.

Tornado track	minimum	median	mean	IDENTICAL OUTBREAK scenario	MAXIMUM OUTBREAK scenario	MODIFIED OUTBREAK scenario
Davenescourt	3 509	8 116	12 791	4 861	7 619	76 729
Pommereuil	1 063	7 300	13 378	7 112	13 492	103 048
Palluel	1 432	4 723	12 299	2 515	124 860	124 860
Total 24 June				14 488	145 971	304 637
Argoules	0	912	1 575	620	0	16 925
Oostmalle	89	625	954	453	664	6 255
Chaam	171	2 393	3 475	663	9 452	15 032
Tricht	322	1 528	2 366	939	13 557	13 557
Total 25 June				2 675	23 673	51 769

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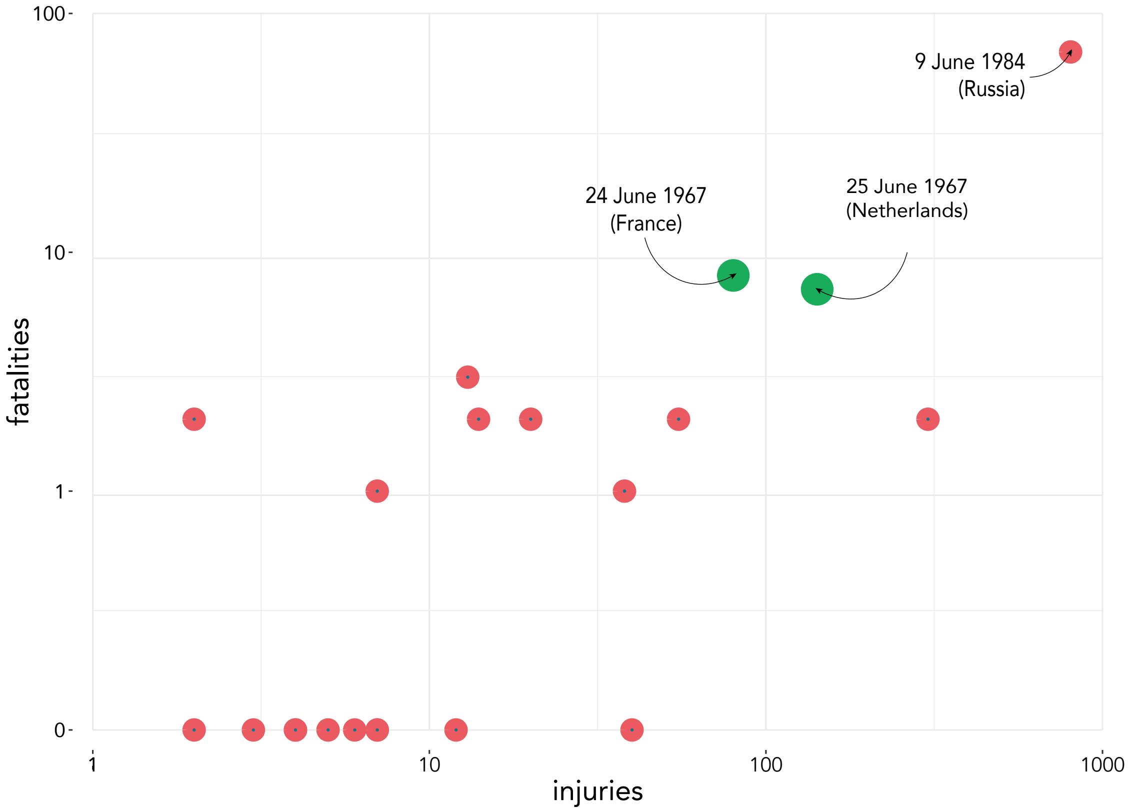


FIG. 1. Tornado outbreaks in Europe between 1950–2014 identified by Tijssen and Groenemeijer (2015) and associated with at least one injury or fatality (red dots). The number of injuries and fatalities associated with the 24–25 June 1967 tornado outbreak are indicated by the green dots.

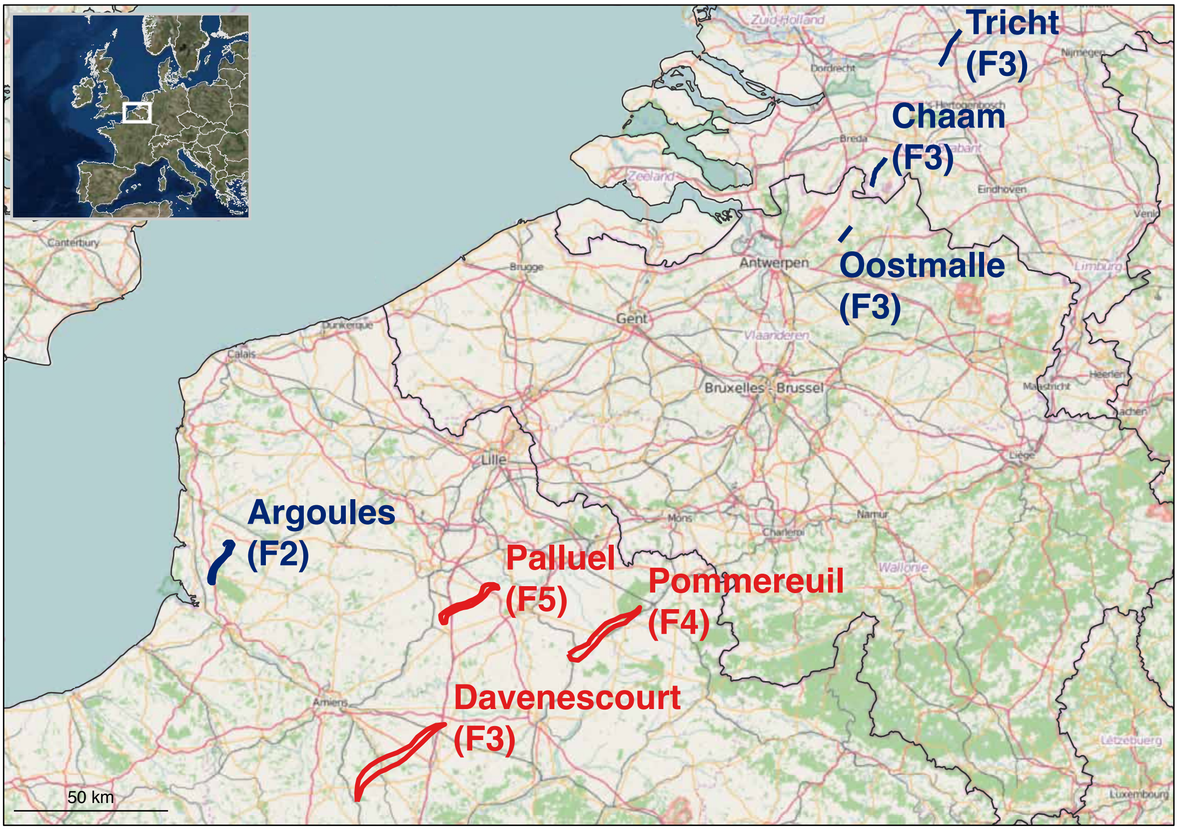


FIG. 2. Tornado tracks during the 24–25 June 1967 tornado outbreak. The tornado tracks from 24 June are shown in red and those from 25 June in blue.

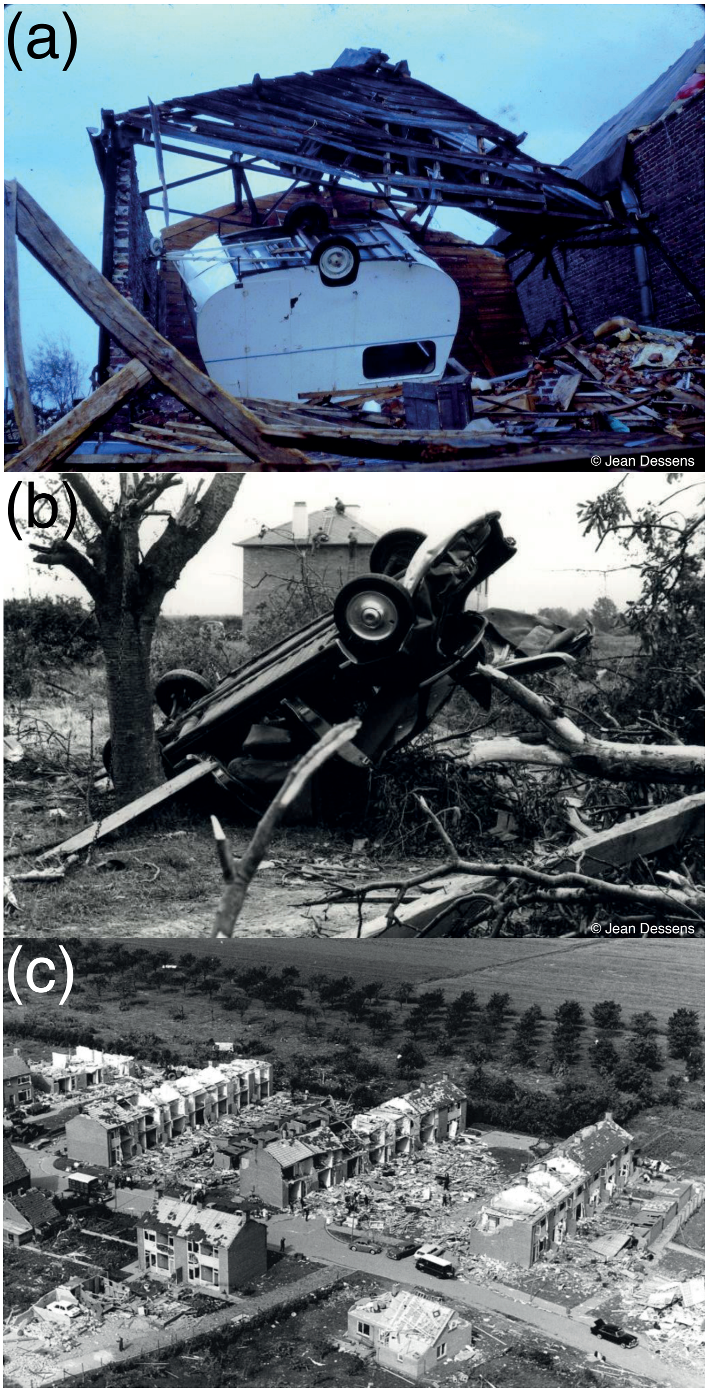


FIG. 3. Tornado damages associated with the (a) Pommereuil, (b) Palluel tornadoes from 24 June 1967 over France (courtesy of Jean Dessens), and (c) Tricht tornado (Netherlands) from 25 June 1967 (courtesy of ANP Historisch Archief).

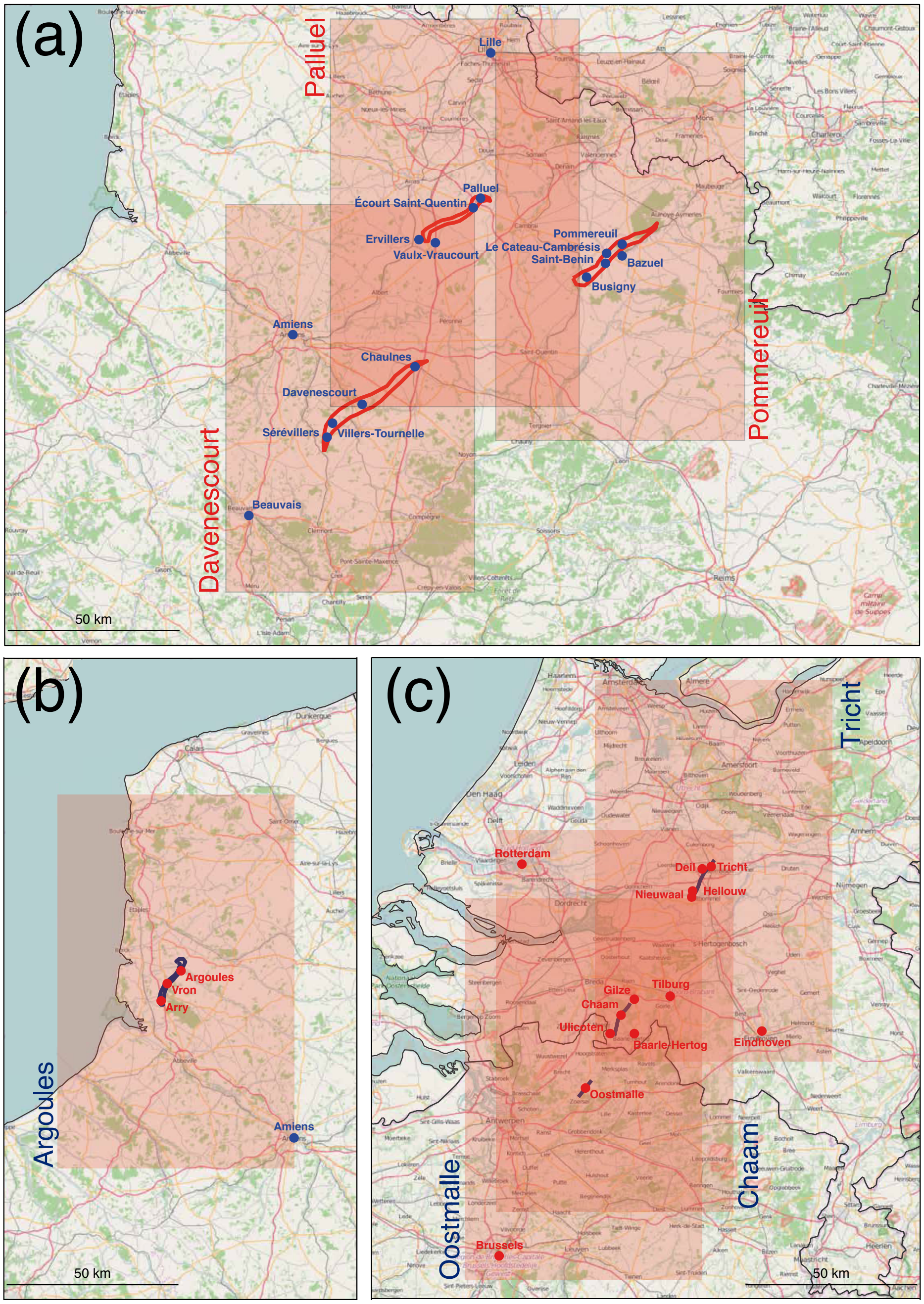


FIG. 4. The extent of the areas (1° by 1°, red rectangles) in which the tornado tracks were then moved at equally spaced 0.1° intervals in longitude and latitude for the (a) Davenescourt, Pommereuil, and Palluel tornadoes, (b) Argoules tornado, and (c) Oostmalle, Chaam, and Tricht tornadoes.

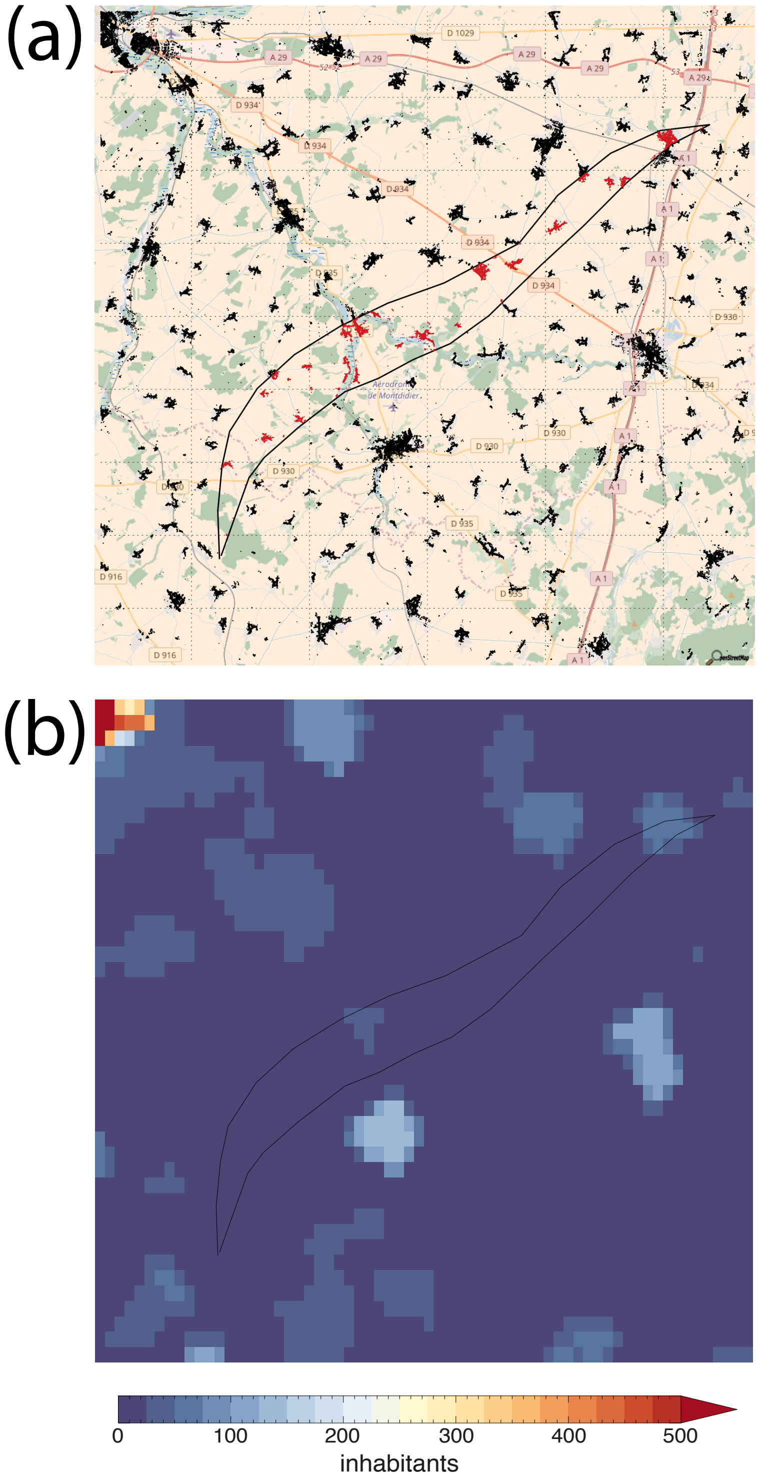
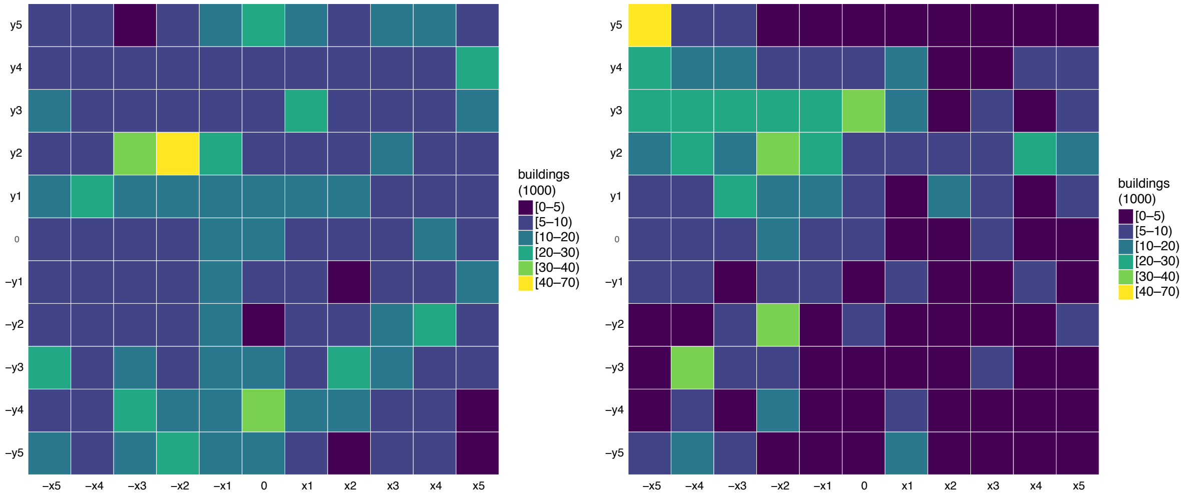
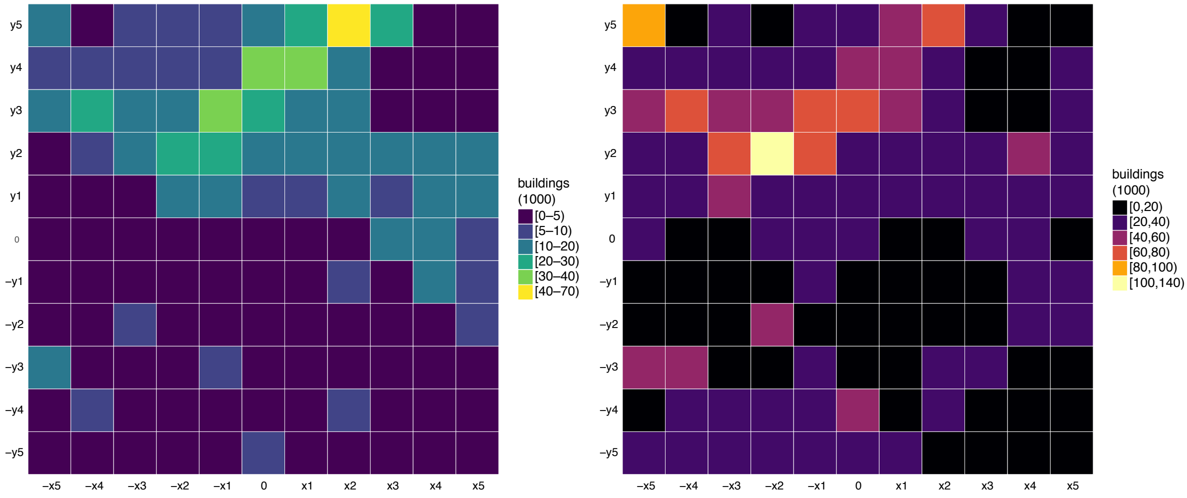


FIG. 5. An example showing how (a) the number of buildings (in red areas inside of the tornado track) and (b) the number of inhabitants have been extracted for the original position of the Davenescourt tornado track. Black areas in (a) represent buildings.



(a) Damages from Davescourt tornado track

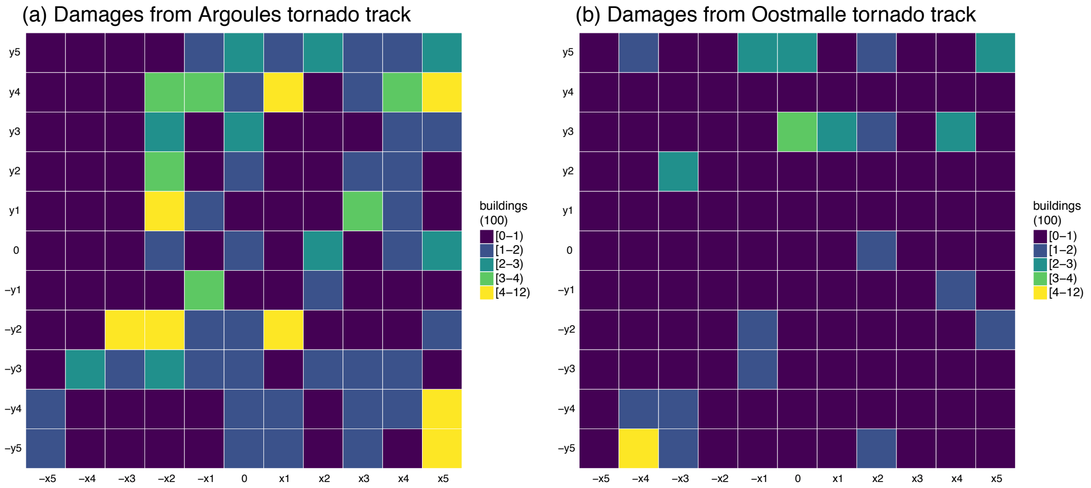
(b) Damages from Pommereuil tornado track



(c) Damages from Palluel tornado track

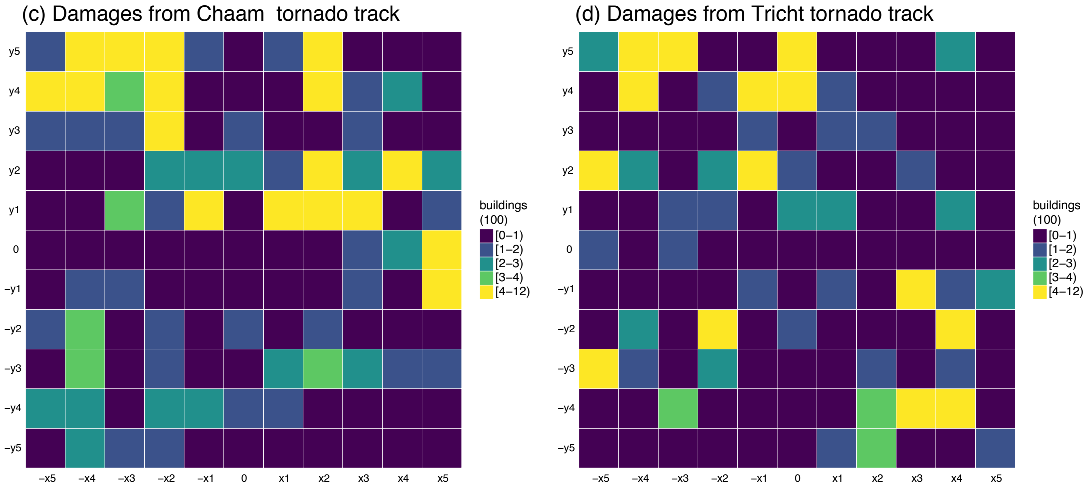
(d) Damages from all tornado tracks on 24 June

FIG. 6. The number of buildings (based on OpenStreetMaps) impacted (shaded according to the scale) as a result of systematically moving (a) Davenescourt, (b) Pommereuil, and (c) Palluel tornado tracks from 24 June 1967 over a modern landscape (Fig. 4). The impact of all tornadoes from 24 June 1967 is shown in (d) as a sum of impacts from each of the three tornado tracks.



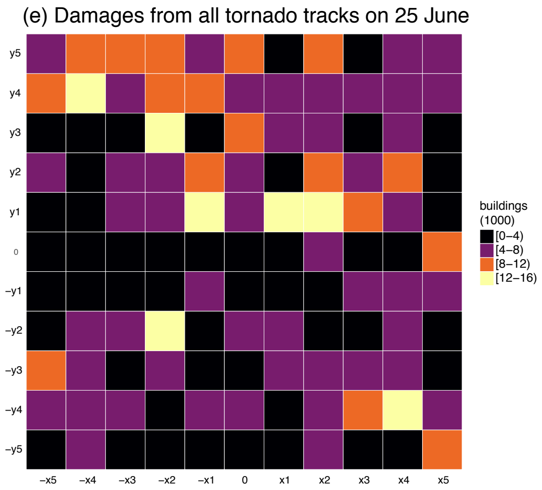
(a) Damages from Argoules tornado track

(b) Damages from Oostmalle tornado track



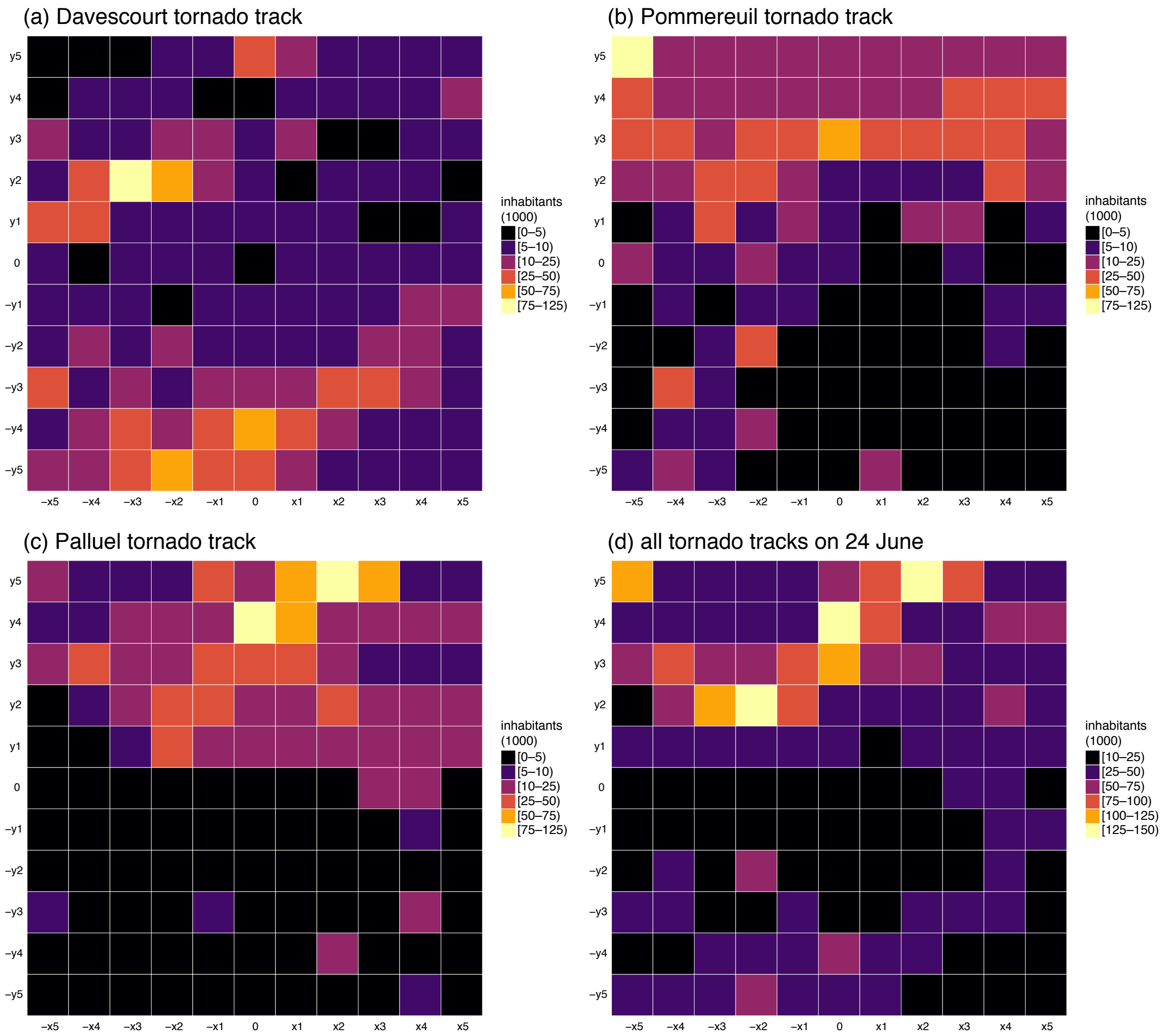
(c) Damages from Chaam tornado track

(d) Damages from Tricht tornado track



(e) Damages from all tornado tracks on 25 June

FIG. 7. As in Fig. 6, but for 25 June 1967.



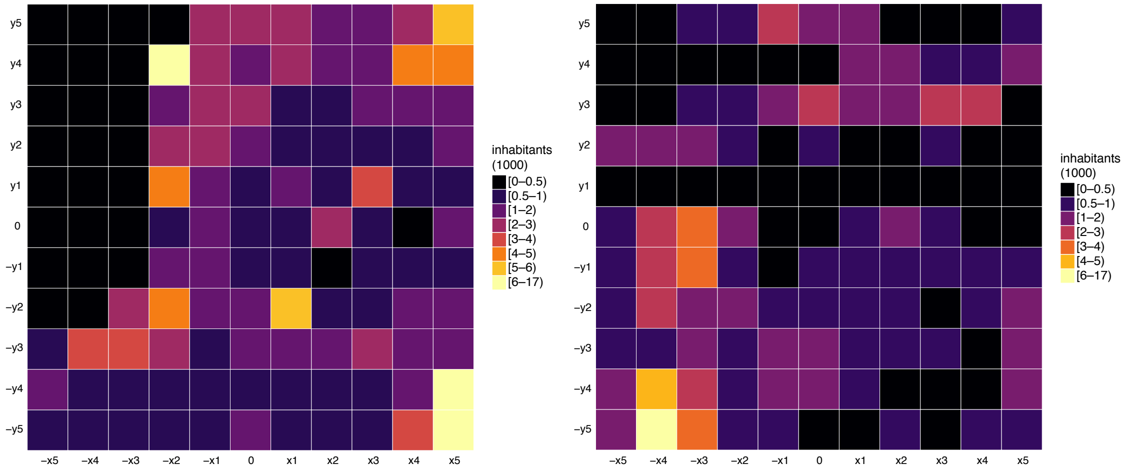
(a) Davescourt tornado track

(b) Pommereuil tornado track

(c) Palluel tornado track

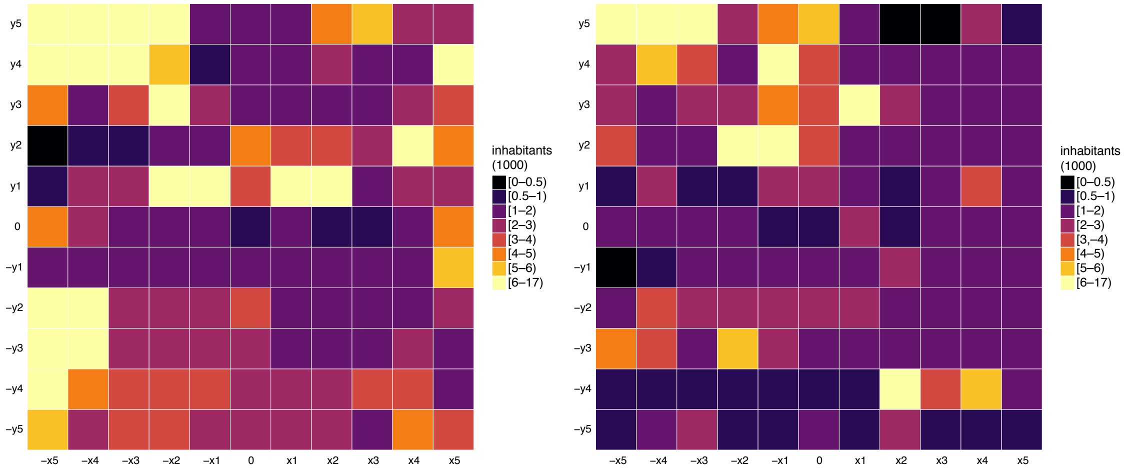
(d) all tornado tracks on 24 June

FIG. 8. The number of impacted inhabitants (shaded according to the scale) as a result of systematically moving (a) Davenescourt, (b) Pommereuil, and (c) Palluel tornado tracks from 24 June 1967 over a modern landscape (based on OpenStreetMaps). The impact of the outbreak form 24 June 1967 is shown in (d) as a sum of impacts from each of the three tornado tracks.



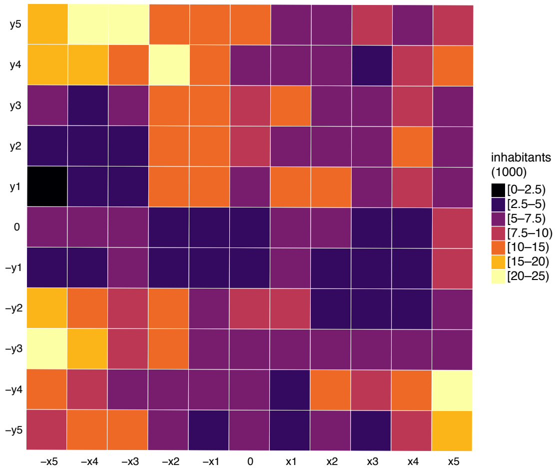
(a) Argoules tornado track

(b) Oostmalle tornado track



(c) Chaam tornado track

(d) Tricht tornado track



(e) all tornado tracks on 25 June

FIG. 9. As in Fig. 8, but for 25 June 1967.