The violent tornado on 24 June 2021 in Czechia: damage survey, societal impacts and lessons learned.

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Abstract

A violent tornado occurred in Czechia on 24 June 2021, killing 6 and causing at least 576 injuries. There were more indirect than direct injuries. The tornado was rated IF4 using a draft version of the International Fujita scale. This was the first violent tornado in Czechia and one of only 17 violent, i.e. (I)F4 or higher, tornadoes that occurred in Europe since 1950. The tornado reached the width of 3.5 km, the widest on record in Europe. The case presents an important opportunity to investigate the impacts of such strong tornado in the area, where they are rare, no tornado warnings are issued and where the building standards are different from the typically investigated tornadoes in the United States.

We discuss challenges in organizing the damage survey, which took 3 days and involved meteorologists from 3 countries. A wind damage survey guide to aid mitigating these was written by the European Severe Storms Laboratory and initiated the development of a wind damage surveying app.

The damage survey showed that most of the inhabited buildings built using heavy masonry and rigid ceilings did not collapse in IF2/3 winds, but only with IF4 winds. Eyewitness reports collected after the tornado show that many people were not aware of the risk associated with the tornado. Eventually, most people tried to shelter in the most secure part of the house, but it was often too late. This case highlights the need for a better communication of tornado risk to the public in Europe.
1. Introduction

Europe experiences more than 300 tornadoes annually, with approximately 200 of them occurring over land (Groenemeijer and Kühne, 2014; Antonescu et al., 2016; Groenemeijer et al., 2017; Taszarek et al., 2020). Since 2006, European tornado reports have been collected in the European Severe Weather Database (ESWD) (Dotzek et al., 2009). Prior to the establishment of the ESWD, tornado reports were collected informally at a national level: An overview of these national datasets can be found in Antonescu et al. (2016). These datasets, including the historical events, have also been added to the ESWD. Groenemeijer and Kühne (2014) state that violent tornadoes (F4 or F5) occur in Europe approximately once every 5 years. This is in line with findings of Pilguy et al. (2022), who studied the violent tornadoes in Europe and estimated their frequency at 1 to 3 per decade. While these violent tornadoes cause the highest fatality rates, strong tornadoes (F2 or F3) occur in a greater overall number and result in a greater number of fatalities in Europe. In contrast, in the United States, violent tornadoes account for over half of the total fatalities (Ashley, 2007; Anderson-Frey and Brooks, 2019). Many cases of violent and deadly tornadoes in Europe have been the topic of case studies and climatologies and published in formal scientific literature (e.g., Wesolek and Mahieu, 2011; Finch and Bikos, 2012; Taszarek and Gromadzki, 2017; Antonescu et al., 2018; Holzer et al., 2018).

The first objective of this article is to document the impacts of the violent tornado that occurred on 24th June 2021 in southeastern Czechia and to summarize the main conclusions of the damage survey and the logistics involved. The second objective is to provide useful information to increase preparedness for such events in Europe from perspective of early warning systems, risk communication, first response planning or structural engineering. The first part of the study outlines the challenges associated with the damage survey. The next part builds upon the existing damage survey report by Půčik et al. (2022) and provides additional information on the tornado's path and statistics in the various affected municipalities acquired from the GIS software. Societal impacts of the tornado, and the behavior of individuals in the tornado's path follow. The last sections of the paper detail the impact to the buildings, trees, vehicles and to the critical infrastructure.

While not explored further in this study, the event featured a largest number of large hail reports (≥ 2 cm) ever reported in the ESWD for a single day. Giant hail (≥ 10 cm in diameter)
was observed in Austria, Czechia and Poland, equalling the Austrian national hail record (12 cm) and setting a new hail record in Poland (14 cm).

1.1. Violent tornadoes in Europe

A total of 17 violent tornadoes have been reported to the European Severe Weather Database (ESWD) for the period spanning from 1950 to 2022, including the tornado discussed here. Among these tornadoes, only one was classified as F5, while the remaining 16 were rated as F4. A list of these tornadoes can be found in Table 1 along with some basic characteristics. Detailed damage surveys were conducted shortly after the tornadoes in three cases. Basic information, such as maximum path width or path length is missing for several of them. Apart from this case (24 June 2021 tornado), surveys were performed for an F4 tornado in northwestern France on 4 August 2008 (Wesolek and Mahieu, 2011) and an F4 tornado in northeastern Italy on 8 July 2015 (ESSL, 2015). Other tornadoes were rated retrospectively based on damage descriptions, photographs, or contemporary media footage. However, in many instances, it is not clearly indicated which damage indicator led to the highest damage rating on the Fujita scale. Caution should therefore be exercised when interpreting historical tornado ratings.

Table 1. A list of 17 violent tornadoes in European countries since 1950. * Only one place (village/town) affected by the tornado is given even though majority of the mentioned tornadoes affected multiple places.

<table>
<thead>
<tr>
<th>Date</th>
<th>Country</th>
<th>Place*</th>
<th>F-scale</th>
<th>Path length (km)</th>
<th>Max. path width (m)</th>
<th>Fatalities</th>
<th>Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 June 1957</td>
<td>Italy</td>
<td>Valle Scuropasso</td>
<td>4</td>
<td></td>
<td></td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>20 May 1960</td>
<td>Poland</td>
<td>Niechobrz</td>
<td>4</td>
<td>19</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 July 1965</td>
<td>Italy</td>
<td>Torricella di Sissa</td>
<td>4</td>
<td>23</td>
<td>250</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>24 June 1967</td>
<td>France</td>
<td>Palluel</td>
<td>5</td>
<td>23</td>
<td>2500</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>24 June 1967</td>
<td>France</td>
<td>Pommereuil</td>
<td>4</td>
<td>23</td>
<td>2500</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>10 July 1968</td>
<td>Germany</td>
<td>Pforzheim</td>
<td>4</td>
<td>35</td>
<td>1000</td>
<td>2</td>
<td>300</td>
</tr>
<tr>
<td>18 August 1969</td>
<td>Ukraine</td>
<td>Tynivka</td>
<td>4</td>
<td>78</td>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 September 1970</td>
<td>Italy</td>
<td>Fusina</td>
<td>4</td>
<td>60</td>
<td></td>
<td>36</td>
<td>245</td>
</tr>
<tr>
<td>25 January 1971</td>
<td>France</td>
<td>La Rochelle</td>
<td>4</td>
<td>2.9</td>
<td>50</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>26 August 1971</td>
<td>Switzerland</td>
<td>L'Abbaye</td>
<td>4</td>
<td>30</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 May 1979</td>
<td>Germany</td>
<td>Bad Liebenwerda</td>
<td>4</td>
<td>62</td>
<td>150</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2 June 1982</td>
<td>France</td>
<td>Leivier</td>
<td>4</td>
<td>3</td>
<td>350</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9 June 1984</td>
<td>Russia</td>
<td>Ivanovo</td>
<td>4</td>
<td>81.5</td>
<td>1130</td>
<td>69</td>
<td>804</td>
</tr>
<tr>
<td>3 August 2008</td>
<td>France</td>
<td>Hautmont</td>
<td>4</td>
<td>10.5</td>
<td>200</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>8 July 2015</td>
<td>Italy</td>
<td>Mira</td>
<td>4</td>
<td>11.5</td>
<td>1000</td>
<td>1</td>
<td>72</td>
</tr>
<tr>
<td>18 June 2017</td>
<td>Russia</td>
<td>Maloye Pes'yanovo</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 June 2021</td>
<td>Czechia</td>
<td>Lužice</td>
<td>4</td>
<td>27.1</td>
<td>3500</td>
<td>6</td>
<td>576</td>
</tr>
</tbody>
</table>

1.2. Wind damage surveys in Europe

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The initial damage scales introduced were the Fujita scale (Fujita, 1971) and the TORRO scale (Meaden, 1976). Edwards et al. (2013) and Edwards et al. (2021) provide a comprehensive overview of the history of damage surveys in the United States and the limitations of the used scales. In European countries, tornado damage rating began with the first attempts at establishing tornado climatologies. Retrospective tornado ratings for past cases were carried out by Dessens and Snow (1989) in France, Snitkovskii et al. (1987) in Russia, Dotzek (2001) in Germany, Holzer (2001) in Austria and Setvák et al. (2003) in Czechia.

To better align with standard building practices and engineering perspectives, the United States adopted the "Enhanced Fujita" (EF scale) (WSEC, 2006). However, worldwide application of the EF scale poses challenges as its damage categories are linked to U.S.-based construction practices (Doswell et al., 2009). As a result, adjusted versions of the EF scale have been developed in Canada (Sills et al., 2014), China (Xue et al., 2016), France (Mahieu and Wesolek, 2016), and Japan (Suzuki and Tanaka, 2017), tailored to the respective countries' building standards and codes. At a pan-European level, Feuerstein et al. (2011) expanded on Fujita's work (1992) and introduced six prototypes of buildings found in central Europe for tornado damage ratings, based on the loss ratios of individual building types.

Since 2014, the European Severe Storms Laboratory (ESSL) has been developing an International Fujita (IF scale) that incorporates a concept of Damage Indicators (DI) and Degrees of Damage (DoD), similar to the EF scale. Unlike the EF scale (WSEC, 2006), the IF scale utilizes instantaneous 3-dimensional winds at the height of the damage instead of a 3-second average horizontal wind at 10 m AGL (Groenemeijer et al., 2023). This was done for several reasons. Firstly, anemometer data (Blanchard 2013; Lombardo, 2018) show that the wind can increase and subsequently decrease strongly within 3 seconds centered around the maximum wind. Hence, a 3-second average wind speed bears little relation to the stronger wind speeds that would produce the most prominent damage. Videos of tornadoes circulating on social media confirm the short local duration of peak tornadic wind speeds and reveal that the vertical wind component of the wind speed can be very large in close vicinity to the earth’s surface, this being confirmed by anemometer measurements (Blanchard 2013). This implies that the horizontal wind component can fluctuate as much with height. The use of a 3-second-averaged horizontal reference wind speed at 10 m, although a key parameter in many wind engineering approaches based on the framework proposed by Davenport (1961)
and recommended by WMO (WMO 1987; WMO 2021), is not adequate to capture the volatile tornado characteristics. A local maximum of horizontal wind speed may occur meters above the earth’s surface (Kosiba and Wurman, 2023), not following the assumptions of the theoretical framework on boundary layer winds that motivated the choice for the 10 m measuring height standard. While there is a relative lack of research relating damage to the wind gust averaging interval the choice for the instantaneous wind is further motivated by findings such as that wind damage can be done by very short duration winds, e.g. to toe-nail connections in roofs (Morrison and Kopp 2011), and that peak forces acting on a model of a house are much higher in a 60 m/s tornado than in a straight-line wind of that intensity (Roueche et al. 2015). That said, winds should be sustained long enough to envelope the object to damage to exert differential pressure on the object. A scale analysis shows that for a $10^2$ m/s wind affecting a $10^0$–$10^1$ m object, the appropriate time scale is $10^{-2}$–$10^{-1}$ s, which for modern sonic anemometers is on the order of the maximum resolution of their measurements.

The wind speeds used in the IF scale are those of Fujita’s original wind speed scale (Fujita 1971), rather than speeds that were effectively adjusted to correct for existing biases in tornado rating practices, as was done with the EF scale (McDonald and Mehta 2006). The original Fujita scale did, however, use a speed-dependent averaging time for the wind speed “the fastest ¼ mile”, rather than the instantaneous wind. The wind speeds of the Fujita-scale themselves correspond well to the measurements of tornadic wind winds by mobile radars that span the range of up to 144 m/s, at the upper end of the (I)F5 range (Wurman et al. 2021). Further support for assuming wind speeds much higher than in the EF scale for the IF4 and IF5 classes is provided by studies pointing out that analyses of treefall patterns and analyses on mechanics consistently arrive at higher wind speed estimates than those assumed in the EF scale (Lombardo et al, 2015. Stevenson et al, 2023).

The IF scale lists one central wind speed for each step of the scale, rounded to the next multiple of 10 for the higher steps, rather than a precise range of speeds in order not to imply more accuracy than actual ratings can provide. In another way, however, the IF scale does suggest more precision than the EF and F scales, at least at lower wind speeds, namely by splitting the IF0, IF1, and IF2 categories into two, i.e., there are half steps IF0.5, IF1.5, and IF2.5. In the initial draft version used for the rating of this tornado (Groenemeijer et al. 2018), these first three whole steps were split into three, i.e., IF0 was split into IF0−, IF0, and IF0+. In the final first full version of the IF scale, this idea was abandoned and replaced by the half
steps because of the too-high implied accuracy and frequent misunderstandings of the meaning of the “-” and “+” suffixes.

The IF scale has a different approach to selecting Damage Indicators than the EF scale, which refers to a large number of structures by their function and construction practices in the United States. In contrast, the IF scale takes a more generic approach whereby each structure is assigned a sturdiness class based on the construction type, material, and quality which is not necessarily correlated to its function. Another difference is that the IF scale uses a more elaborate system to assess damage to trees. That said, many other damage indicators the IF scale borrows from the EF scale or its Canadian (Sills et al. 2014) or Japanese (JMA 2015) adaptations, typically with an approximate 20% increase in wind speed to account for the conversion to instantaneous wind speed.

The IF scale was developed by the IF scale Working Group, formed by persons who accepted an invitation to all member institutes of ESSL. It is led by ESSL and includes participants of five European weather services (Spain, Germany, Austria, Czechia, and Slovakia), civil engineers, and others with experience in rating wind damage. After several rounds of review, including a public review in Spring 2023, on 1 August 2023 it was implemented in the European Severe Weather Database, the resource of severe weather reports for Europe that ESSL maintains together with its members and partners, which include 20 European weather services (Dotzek et al. 2009) and is the de facto standard resource for scientists, authorities and commercial parties interested in such data.

In contrast to the United States, performing damage surveys for tornadoes is not a common practice among national meteorological services in Europe. Kaltenberger et al. (2020) found that in 2018, out of 32 meteorological services surveyed, only 9 sometimes performed damage surveys for tornadoes. None of the meteorological services indicated regular tornado damage survey activities. In some countries, damage surveys are carried out by other organizations, often involving amateur meteorologists. One possible reason for this is the absence of tornado warnings. Rauhala and Schultz (2009) found that of 35 meteorological services in Europe, only 8 issue tornado warnings. In a subsequent survey, Holzer et al. (2015) found a similar ratio, with 3 out of 18 national weather services claiming to issue tornado warnings. Other factors contributing to the lack of damage surveys may include limited capacity, a lack of expertise, and, more generally, the lack of preparedness resulting from the rarity of strong or violent tornadoes in individual countries.
2. Challenges associated with the damage survey of the 24 June 2021 tornado.

All but one of the surveyors of the tornado did not have previous experience with surveying damage of the violent tornado. Official training or guidelines to instruct surveyors in conducting tornado damage surveys were absent which led to numerous challenges for the surveyors to be overcome ad hoc.

2.1. Survey organization and responsibility

The survey was organized during the morning after the tornado through email communication among the employees of CHMI (Czech Hydrometeorological Institute), ESSL, and individual amateur meteorologists. The CHMI management coordinated with law enforcement to facilitate access for the surveyors to the tornado-affected area. In addition to CHMI employees, individuals from ESSL, SHMI (Slovak Hydrometeorological Institute), and ZAMG (Zentralanstalt für Meteorologie und Geodynamik, currently GeoSphere) participated in the survey. There was no explicit agreement as to who would formally lead the survey, coordinate the collection of material from the surveyors, and rate the damage. Besides the effort of the organizations, other individuals conducted independent aerial or ground surveys of specific parts of the tornado path but did not contribute to the overall survey effort. Structural engineers also expressed concerns about the lack of organization when assessing the structural integrity of damaged houses after the event (Koudelka, 2021). For example, they were not given exact information about which houses should individual engineers visit, which resulted in duplicate visits to some houses.

To prioritize the survey efforts, the surveyors decided to perform cross-sections through the damage path where it was deemed most severe. However, determining these areas was challenging on the first day due to limited information availability. Access to detailed aerial imagery, conducted by the AMS (Amateur Meteorological Society, based in the Czechia) using an ultralight aircraft on the day after the tornado, greatly aided the planning of the survey on the subsequent days. The aircraft flew three times around the tornado damage path, capturing photos and videos using a high-resolution full-frame mirrorless camera.

2.2. The scale of the event and time sensitivity of the damage
The surveyors underestimated the time required to gain access to the heavily guarded damage site, navigate through the severely damaged zones, and thoroughly investigate the most impacted buildings. Documentation of the damage to the most severely affected structures took up to 20 minutes in some cases. Aerial imagery was used to determine the edges of the tornado path.

The day following the tornado, a massive clean-up operation commenced, with hundreds of volunteers joining the efforts on the second day. As a result, access to some of the damaged buildings targeted for thorough inspection became even more challenging. In certain instances, surveyors were unable to visit certain areas prior to the clean-up process. Some severely damaged brick structures were bulldozed before the surveyors could reach them on the second day, and displaced cars were relocated from their original positions following the tornado. In such cases, the high-resolution aerial imagery played a crucial role in serving as a reference point for the initial state of the damage and to assign ratings to the structures that could not be accessed.

2.3. Physical and mental preparedness

The ground survey also posed significant physical and psychological challenges. The ongoing clean-up process and debris scattered across the ground presented physical hazards. Bricks, roof tiles, and even rafters were frequently dislodged from roofs during the clean-up efforts. It is worth noting that many surveyors were not equipped with important protective gear such as helmets and safety boots.

Encountering areas of devastation where lives were lost, or severe injuries occurred took a toll on the surveyors’ psychological well-being. Some surveyors felt bad, as their activities did not directly alleviate the suffering of survivors. Interactions with local residents generally proceeded without conflicts, as most individuals were open to sharing their stories. To establish trust during initial contact, it would be beneficial for surveyors to clearly identify themselves, such as by wearing highly visible reflective vests displaying the name of their organization. Surveyors only wore standard reflective vests without any identification.

2.4. Survey post-processing
Post-processing the results of the survey was time-consuming as it was necessary to georeference and catalogue the acquired ratings from the field survey. This would have been easier if a damage rating application that allows for geolocation on the spot, would have been available, like. Such an application is currently being developed and tested by ESSL and will be offered to all the ESSL members and cooperating voluntary observer persons/networks. The application allows to rate the tornado damage using the International Fujita scale, geolocating the rating and the photographs taken. Damaged areas not visited by the ground survey had to be rated using aerial imagery during the post-processing stage.

2.5. Survey guide

Based on the surveyors' feedback from this event, ESSL developed a damage survey guide (can be found either at https://www.essl.org/cms/wp-content/uploads/20230320-O rganizational-ESSL-guide-to-wind-damage-surveys.pdf or in the supplemental material) that addresses the various issues above. It provides recommendations on the necessary tools and equipment for a ready-to-go damage survey toolkit, strategies to be employed at the damage site, and approaches to engage with survivors, among other aspects. Furthermore, it is now part of ESSL's internal policy to actively participate in and help any damage survey effort associated with potentially violent tornado damage across Europe.

3. Tornado properties and general conclusions from the survey

According to the climatology of significant tornadoes in Czechia (Brázdil et al., 2020), the tornado on 24 June 2021 was the first violent tornado recorded in the country since at least 1811. The results of the damage survey can be found in the report by Půčík et al. (2022). The tornado was rated using draft version 0.1 of the International Fujita Scale (Groenemeijer et al., 2018). Some of the survey findings have been updated in this publication.

The initial output of the ground survey consisted of printed maps of individual surveyed municipalities with preliminary ratings of houses or vegetation. The next step involved using aerial imagery to create preliminary swaths of the tornado's damage (Fig. 1). Aerial imagery was also utilized to rate areas not covered by the ground survey. Finally, the swaths derived from the aerial imagery were integrated into a map using ArcGIS Pro software by
georeferencing the obtained intensity ratings. Aerial imagery from the website mapy.cz (2021) captured before and after the tornado was used to identify the edges of the tornado path and assess damage to vegetation. The Web Map Service (WMS) layer created by the Czech Office for Surveying, Mapping, and Cadaster served as the base map. The Natural Neighbour method (Sukumar et al. 2001) was utilized for interpolation between neighboring damage points with an IF rating. Examples of the post-processed survey map products can be seen in Fig. 2, illustrating the map of the entire tornado path, and Fig. 3, depicting the tornado path through Mikulčice.

Fig. 1. Individual damage points identified in the aerial imagery of the tornado damage in central Mikulčice. The colours and numbers together represent the IF-ratings. Image taken by Lukáš Ronge.

Cross-sections were generated using Python program created by David Rýva that processed the CSV files containing information about the distance from the start of the cross-section, the type of damage indicator, and the corresponding rating based on the IF scale. The script can be accessed in the GitHub repository (https://github.com/DejvStorm/tornado) An example of a cross-section across Mikulčice is displayed in Fig. 4. All the maps and cross-sections can be found in the supplemental material of the paper.
Fig. 2. A map of the tornado path. Colors represent the IF rating assigned for different parts of the path. Basemap source: ČÚZK
Fig. 3. As in Fig 4., but for a detailed map of Mikulčice. A row of new houses under construction on the western edge of Mikulcice was not included in this map. Basemap source: ČÚZK

Fig 4. Cross-section through the damage swath in Mikulčice. 0 on the x-axis represents the most likely location of the tornado center and red lines represent the margins of the possible tornado center track. Colors correspond to IF scale ratings while icons represent different types of damage indicators. The position of the number on the x- and the y-axis indicates the distance from the center of the tornado and the type of damage indicator.

The tornado tracked 27.1 km over a 39-minute period and remained strong during most of its path. The continuous swath of IF2 or stronger winds had a length of 15.3 km. The tornado was extremely wide at the beginning, becoming narrower with time. The maximum path width was established at 3.5 km, the highest width ever observed in Europe according to the ESWD. The previous record was 2.5 km from an F4 tornado on 24 June 1967 in France. The average maximum path width of the F4 tornadoes in Europe was found to be 600 m (Groenemeijer and Kühne, 2014). The tornado remained very wide as it tracked through the first two villages with IF2 or stronger winds across a 1 km wide path.

The orientation of the fallen trees and power lines (no hints of a convergence) at southeastern edge of the tornado path at its beginning could suggest more “straight-line” nature of the wind (Fig. 5). This could be interpreted as a coexistence of a rear flank downdraft (RFD) along the tornado path. However, we consider the whole identified damage swath to be caused by the tornado because:
1. No wind damage was found in the area before or after the tornado. RFD surges have been known to precede the tornadogenesis (e.g. Kosiba et al. 2013, Burgess et al. 2014).

2. No divergence was found within the debris fall patterns, which would be a typical trait of the downdraft-related winds (Fujita and Wakimoto 1981, Forbes and Wakimoto 1983, Fujita 1992).

3. A certain asymmetry in the width of the damage swath on either side of the tornado vortex centerline can be expected due to the tornado movement and was documented in other tornado cases as well (Wakimoto et al., 2003, Burgess et al. 2014, Wakimoto et al. 2016). In this case, the width of the wind damage swath of the completely symmetric vortex would still take up majority of the tornado path, with width up to 2.6 km (Fig 5).

4. No secondary maxima in the wind damage intensity were found at the edge of the tornado path, the wind progressively strengthened towards the core of the vortex.

5. Non-convergent, straight-line tree fall pattern at the edges of the tornado damage path was also found by Beck and Dotzek (2010) and Karstens et al. (2013). Both publications show such pattern to the right of the tornado path, as was our case.
The maximum tornado path is extreme for Europe and high-end in the U.S. context. However, the lack of damage indicators often prevents the detection of the full tornado width in the U.S. (Wurman et al. 2021), while in Europe, few in-depth damage surveys were performed for tornadoes of higher intensity.

The tornado impacted a total area of 33.7 km². Within this area, the distribution of damage ratings was as follows: 49.6% of damage indicators were classified as IF0, 31.8% as IF1, 13.3% as IF2, 5.0% as IF3, and 0.3% as IF4. Residential areas in 5 municipalities were impacted by the tornado. By overlaying the tornado path onto the boundaries of residential areas, we determined the fraction of each municipality that was affected by a particular damage intensity (Fig. 6). The most affected municipalities were, following the tornado path, Hrušky with 69.3%, Moravská Nová Ves with 86.7%, and Mikulčice with 70.0% of the residential area affected. Mikulčice also experienced the largest proportion of its residential area affected by IF4 winds (1.7%).
To determine the number of affected buildings, the layers of individual IF-rated swaths were combined with the ZABAGED national cartographic dataset of individual postal address points. We found a total of 3,241 address points (buildings) in the tornado path. This number exceeds the count of approximately 1,200 damaged buildings reported in the media (ČTK, 2021). 76.1% were impacted by IF0 and IF1 winds, 23.3% by IF2 and IF3 winds, and 0.5% by IF4 winds. The proportion of buildings affected by violent tornadic winds (F4 or F5) was significantly lower compared to the four recent F5 or EF5-rated tornadoes discussed in Burgess et al. (2014), where F4/EF4 or F5/EF5-rated buildings constituted 17.4% to 24% of affected buildings. The concentration of IF4 damage within narrow swaths within a wide swath is similar to the Funing county EF4 tornado in China in 2016 (Meng et al., 2018). However, the Funing tornado produced EF4 damage over a longer swath, resulting in a higher number of fatalities (89).

The utility of satellite data in identifying tornado tracks in inaccessible areas has been highlighted in studies by Molthan et al. (2014) and Shikhov and Chernokulsky (2018). In our investigation, satellite imagery was primarily used to confirm that the event represented a single tornado in areas where damage to fields was not visually apparent. By calculating the differences in bands 3, 4, 5, 11, and 12 from the Sentinel 2 satellite, we detected changes in vegetation condition between two scans: the first taken on 19 June before the tornado and the second on 29 June 2021 after the tornado (Fig. 7). The DN (digital number) values were acquired from each of the bands. First, we added the values of DN from each scene. After that, we subtracted the sums of the DNs of the selected bands before and after the tornado. Extreme negative or positive values (exceeding 40 000) were related to the clouds and after the verification of the visual imagery were masked using grey polygons. The imagery illustrates the drying of vegetation along the tornado path and a distinct reduction in the tornado width between Hrušky and Mikulčice. The most pronounced damage to fields was observed in the area between Hrušky and Moravská Nová Ves, where the ground survey showed the removal of crops and grass by the tornado. Drying was also evident within residential areas. Here, the signal can be due to the damage by the tornado, debris pile up in some places, or the disturbance of grass by heavy machinery during the cleanup process.
Fig. 7. Composite imagery showing the difference in Sentinel 2 bands 3, 4, 5, 11, and 12 between 19 June and 29 July 2021. Significant negative change implies drying of the vegetation. The tornado path is plotted using a thick black line. Hatched areas outlined with thin black lines represent the residential areas of municipalities. Grey areas represent masked-out clouds.

4. Societal impacts from the tornado

According to media reports (Deník.cz, 2021) the tornado killed six people. Three fatalities occurred inside houses with two individuals crushed by a collapsed roof, and one person was struck by a roof tile near a window. One fatality occurred outside with person being crushed by an unknown object on the porch, another in a vehicle, and one in a collapsed outbuilding. The locations of five of the six fatalities were within the IF2 to IF3 damage swaths, while the exact location of another fatality remains unknown. No fatality has occurred from persons being lifted by the tornado, which was found to be the second most common cause of death in the review of the polish deadly tornadoes by Taszarek and Gromadzki (2017).
Regarding injuries, information had to be gathered from various sources. We combined the reports of the emergency services of the South Morava (Gáfriková, 2021) with the annual reports of the hospitals in Hodonín (Raiskubová, 2021), Břeclav (Hospital Břeclav, 2022) and the information on the several persons transported to the Brno and Vienna hospitals. The reports contain dedicated chapters on the injuries related to the tornado and the procedures that hospitals underwent as the event unfolded. The tornado resulted in a minimum of 259 direct injuries (injuries inflicted directly by the tornadic wind) and at least 576 injuries in total. At least 24 individuals were severely injured, with injuries such as pneumothorax and severe skull fractures. Light to moderate injuries included open or closed fractures, abdominal injuries, and lacerations. Over the following days, even more injuries, compared to the evening and night of the tornado, were treated, largely related to the clean-up process. This implies that indirect injuries accounted for over 50% of the total number. According to an eyewitness report (Bránik, personal communication), individuals who survived the tornado often engaged in hazardous behavior during the cleanup process.

The tornado also had a severe psychological impact on survivors, leading to over 4,000 psychosocial interventions conducted by psychologists from the integrated rescue service of Czechia between June 25 and July 9 (Hoskovcová et al. 2021). This number surpassed the average annual count of such interventions performed throughout the entire country.

The direct injury to fatality ratio in this tornado was 43.2, higher than in some of the European and U.S violent tornadoes and tornado outbreaks mentioned by Antonescu et al. (2017) or by Tijssen and Groenemeijer (2015). Antonescu et al. (2017) mentions a ratio of 6 to 17 for the U.S tornado outbreaks and 15.5 for the 24-25 June 1967 tornado outbreak in France, Belgium and Netherlands. The F4 tornado that struck Wiener Neustadt in 1916 caused 34 fatalities and 328 injuries (Holzer et al., 2018), a ratio of 9.6. The difference with the U.S. could be attributed to different building standards, while the difference to the previous European tornadoes might be due to underreporting of injuries as the exact data on injuries are often difficult to obtain. Considering an average occupancy rate of 2.8 inhabitants per house (Moravec, 2020), it is estimated that around 9,000 people were exposed to the tornado. Using this estimation and considering only direct injuries and deaths, 2.88% of affected people were injured and 0.07% killed. This indicates a higher injury rate and lower fatality rate per capita compared to the average U.S. casualty producing tornado (2.1 and 0.15% respectively, Fricker, 2020). Several eyewitnesses mentioned the presence of very...
large hail before the tornado which may have contributed to lower the fatality rate, as most people sheltered indoors because of the hail as the tornado approached. The hail size varied between 4 and 9 cm in the path of the tornado based on the ESWD reports.

5. The behavior of people during the tornado

Videos shared on social media (see Appendix) and the eyewitness accounts gathered by Bartoník (2022) or by the surveyors show how locals reacted to the tornado. The reactions of the local people to the tornado need to be understood in the context of the available warnings. CHMI does not issue tornado warnings. On the day of the tornado, the area was under an "orange" thunderstorm warning, which was issued seven hours before the tornado occurred. The warning mentioned isolated occurrence of severe wind gusts exceeding 24 ms⁻¹ and large hail exceeding 2 cm in diameter (CHMI, 2023). CHMI's warning text was accompanied by a standardized set of actions that do not cover precautions specific to tornadoes, but which include the following recommendations: secure the windows, doors and garden furniture, don’t stay near larger trees, if possible, stay indoors and slow down if driving (CHMI, 2023).

Based on the interviews and videos, some individuals recognized the tornado, while others did not, despite observing the funnel cloud and debris cloud approach. One man described seeing a strange "yellow cloud," and a woman mentioned a "black cloud" approaching her location. Even if people recognized the tornado, some did not fully comprehend the associated threat. For example, a man who recorded the tornado on video stated that he was unaware of the risk despite seeing airborne debris including roof material. The director of a local hospital observed the tornado from his balcony but was surprised about the number of injured people transported to the hospital.

Eventually, most people recognized the danger and attempted to seek shelter shortly before the tornado arrived at their respective location, but in many cases it was too late to avoid serious impacts. For instance, a man who observed rotating debris in the air initially considered hiding in the cellar but then decided to secure the ducks in the barn first. A common reaction was to close windows because of the increasing wind and to look outside from the window to check what was happening, which put them at risk. One man described going to the kitchen to close a window when a neighbor's roof flew over his head, narrowly missing him. Another man remembered hearing knocking sounds on the window. As he
approached the window, it broke, resulting in cuts. He then sought shelter in the stairway. A woman tried to close her windows but found it impossible, grabbed her children and hid in the bathroom as the windows broke and survived without injuries. One fatality occurred when a man, looking out of a window, was struck in the head by a flying shingle (Bránik, personal communication). A similar fatality occurred during a tornado in Kursk, Russia, on September 18, 2022, when a student filming the tornado was hit in the abdomen by a flying piece of roof.

Numerous videos from social media depict people attempting to seek shelter only once their windows start breaking. Such reactions are not uncommon during strong European tornadoes. A man who survived the tornado along with his wife and 2 friends within an IF4-rated structure impacted by a bus, vividly described the event: Just before the tornado, they attempted to hide car under the roof as fist-sized hail started falling. The tornado suddenly arrived, and they took cover inside. One wall collapsed when the bus hit the house. The man was struck by flying debris and the woman was buried under an iron grid. He also recalled that power lines from the nearby railroad were lashing the house and an explosion occurred before the power went out. The injured woman then tried to assist the injured passengers from the bus. According to an eyewitness on the bus (Počtová, 2022), who was severely injured, the bus driver did not react to the tornado and continued driving even as the windows shattered.

The behaviour of people in the path of the tornado and under the tornado warning has been described in detail for example in the context of the 2011 U.S. violent tornado cases with multiple fatalities (Hayes 2011, Wagenmaker et al. 2011, NOAA 2011, Sherman-Morris and Brown 2012, Ripberger et al. 2015). Across the U.S., one concern is people seeking secondary confirmation of the tornado threat after the warning has been issued. This stems from some inevitable false alarms associated with tornado warnings. Another concern is associated with no proper shelters available in poorer communities (Strader et al. 2021). Such studies are lacking in Europe so far and are needed as the landscape of sheltering option is quite different than the U.S. given the difference in housing types, rural community structures and cultural attributes.

In Europe, the primary concern is the lack of a dedicated warning system for tornadoes (Rauhala and Schultz 2009 and Antonescu et al. 2017), even in the areas that encounter
strong tornadoes regularly, such as the Italian coastlines (Miglietta and Rotunno 2016) and even that there is a possibility of a high-end tornado outbreak event involving more than 100 fatalities (Antonescu et al. 2018). The standard set of precautions mentioned with the severe convective wind gusts in Europe (such as staying away from trees, slowing down the car or going indoors) may not be enough to protect people from tornado harm. Pilorz et al. (2023) showed that 44% of tornado-related fatalities happened indoors while this percentage dropped to 7% for non-tornadic fatalities. This shows that the risk of harm is more substantial for tornadoes and additional set of actions must be formulated for the public.

The secondary concern is the lack of education about the tornado risk among the public. This was clear also in this case when people saw the tornado but didn’t act accordingly. Better education concerning tornado risk and a proper warning may have prevented some injuries or fatalities (Demuth et al., 2022). Had people sought shelter immediately upon seeing the tornado, the majority of the houses in the tornado's path would have offered safety in some spots given their relatively sturdy construction. Many people did successfully identify which parts of the house would be the safest for hiding. Still, it was often too late given the lack of warning or their perception of the danger from the approaching tornado.

6. Damage to buildings

The most common type of building in the path of the tornado was a one or two-story terraced house made of masonry with a gable roof. These houses were of heavy construction. The masonry used in these houses involved traditional or hollow bricks, both burnt and unburnt. Newer constructions also used autoclaved aerated concrete blocks or ceramic blocks. The upper floors of these houses typically had wooden beam ceilings with backfill, and newer houses featured Hurdis (ceramic elements) ceiling slabs with stiffening ring beams. The roofs were typically constructed using a wooden or steel truss system, with ceramic tiles as the roof covering.

The most typical damage observed in the houses along the tornado's path was the removal of the roof covering, accompanied by damage to the gable walls. The trusses and lower floor masonry remained mostly undamaged (Fig. 8A). The damage to the gable walls was primarily attributed to their poor attachment to the roof trusses. This was also noted as a problem in the U.S. houses (Minor et al. 1977) The quality of post anchoring, roof truss...
fixing, and the horizontal and lateral fixing of supporting walls under the posts played a crucial role in the resistance of the roof against the tornado winds.

Due to the different age of buildings within the tornado track, the load-bearing structures of buildings constructed in tornado-affected areas were designed according to the standards valid at the time of construction. Prior to 1951, modified regulations derived from the Austrian Building Code of 1886 were valid. In 1951, Czechoslovakian standards began to be implemented. The standards worked the maximum wind load on the building based on the different wind regions. Recently, the European standards, the so-called Eurocodes have been implemented, which work with the average (10 minute) wind speed. In the area affected by a tornado, the value of the wind speed to which buildings must be designed is 25 m/s.

While older houses typically did not have ring beams, the roof trusses were adequately anchored into the masonry according to the construction codes. The removal of roof trusses strongly attached to the masonry resulted in its damage, affecting the upper parts of the walls (Fig. 8C). In cases where the roof trusses were weakly anchored (anchoring weaker than the other components of the roof), the structure underneath the roof remained intact, but the roof easily detached and was blown away. Many houses with standing load-bearing walls were subsequently demolished due to the structural instability caused by the roof removal. In the southern part of Hrušky, for example, 58 houses with IF2–IF3 damage ratings were demolished.
Fig. 8. Examples of damage to inhabited masonry buildings. A) most elements (light roof tiles) are removed while roof trusses remain. DI: T-, DoD: 2, Rating: IF1. B) roof blown away including the ceiling. House has a sturdiness rating of E. DI: BRE, DoD: 2, Rating: IF2+. C) roof blown away, leading to partial destruction of walls under the roof. Wall had a sturdiness rating of D. DI: BD, DoD: 1, Rating: IF3. D) Partial destruction (not more than ⅔) of the walls with a sturdiness rating of E. DI: BE, DoD: 1, Rating: IF4. Photos taken by Tomáš Púčík.

To rate buildings using the IF scale, they are assigned a sturdiness class. Each observed type of damage to a building of a given sturdiness class gives a rating on the IF scale that represents the wind speed responsible for the damage. For more detail we refer to Groenemeijer et al. (2018). In the tornado's path, 14 buildings were given an IF4 damage rating based on consultation with structural engineers. Among these buildings, 8 had a sturdiness class of D and experienced near complete destruction, with more than ⅔ of the walls being destroyed. The remaining 6 buildings had a sturdiness class of E and suffered partial destruction, with less than ⅔ of the walls being destroyed (Fig. 8D). Of the IF4-rated buildings, 12 were located in Mikulčice and 2 in Lužice.
A concrete steel-reinforced wall 15 cm in width, collapsed along with a ceiling within a cattle pen west of Moravská Nová Ves, leading to the death of 70 bulls. The concrete walls of the cattle pen building were connected via concrete beams. The wall's sturdiness class was lowered from borderline E to D due to environmental damage caused by constant saturation with dirt water, weakening its integrity. The partial destruction of the concrete walls resulted in an IF3 rating for the pen.

During the survey, it was observed that older multi-story masonry buildings with rigid ceilings and properly anchored gable walls to the roof trusses withstood the wind much better than lightweight new buildings with wooden trusses and non-rigid ceilings. The weakness in the connection between the walls and roofs in these new structures contributed to their vulnerability.

Outbuildings, often single-story masonry buildings, sustained more serious damage compared to the permanently inhabited manufactured homes, leading to complete destruction even in IF2 or IF3 winds. The masonry in these outbuildings consisted of various types or shapes of bricks, (Fig. 9A) sometimes using leftover materials from other construction projects and not necessarily meeting building code standards for inhabited buildings. Many outbuildings in garden colonies, built for recreational purposes, had walls made of plywood or wood with a poor connection to the foundation (Fig. 9B). Dozens of such structures were completely destroyed by the tornado, with damage ratings of IF2 or IF3. Two of the six fatalities occurred in these garden colonies. The structural integrity of these outbuildings in garden colonies was comparable to the inhabited houses in less wealthy regions of the United States, which have been found to have high fatality rates in tornadoes (Strader et al., 2021).
Fig. 9. Examples of ratings of destroyed outbuildings. A) Outbuilding used as a “wine cellar” with several brick walls destroyed, but not more than ⅔ of the whole structure. DI: BD, DoD: 1, Rating: IF3. B) Detail of a connection of the wooden frame outbuilding to an elevated concrete foundation. The outbuilding was swept away from the foundation. DI: BB, DoD: 2, Rating: IF2. Photos taken by Tomáš Púčik.

In addition to residential buildings and outbuildings, numerous industrial buildings were also damaged or destroyed by the tornado (Fig. 10). One case occurred in the industrial park at the beginning of Lužice, where a large metal building suffered significant damage (Fig 10A). The outside panels of the building were blown out, leaving only the steel frames remaining. Some of the vertical frame members were bent in the direction of the wind, and the ceiling crane construction collapsed. The impact of numerous vehicles being thrown from the parking lot into the building could have contributed to additional damage beyond the effect of the wind. Similarly, in the agricultural complex near Moravská Nová Ves, several large buildings with steel frames were also destroyed by the tornado (Fig 10B).

Fig. 10. Examples of damage to the large steel frame buildings in the tornado path in A) Lužice and B) agricultural complex near Moravská Nová Ves. Damage to other buildings nearby was rated as IF3. Photos taken by Tomáš Púčik.

7. Damage to vegetation and its comparison to building damage

The evaluation of vegetation damage was a challenge since trees within settlements had been removed to facilitate emergency vehicle access. The scale of vegetation damage became more apparent when comparing photos taken before and after the tornado in certain locations. In
areas away from the main roads and villages, damaged vegetation was not immediately cleared in the days or weeks following the tornado. In some instances, it was possible to compare the damage ratings of buildings with the damage observed in the surrounding vegetation, although the direct comparison is complicated by the large horizontal gradient of wind speed within the tornado.

Complete debranching of trees was typically associated with IF3 to IF4 damage to buildings. Strong debranching (Fig. 11 A and B), where more than 60% of the crown volume was ripped off, frequently occurred in areas with IF2 to IF3 damage to nearby structures. In rare cases, debranching also occurred next to buildings that sustained only IF1 damage. Accurately assessing the magnitude of debranching often requires consulting photos taken before the tornado, which can be time-consuming.

Extensive debarking of trees (Fig. 11. C and D), with more than 60% of the tree trunk surface affected, was observed in areas with IF4 or IF3 damage to nearby buildings. In Mikulčice, debarked trees were found within a range of 10 to 30 meters upwind and 20 to 100 meters downwind of the IF4-rated buildings, following the tornado path. In Lužice, a debarked tree was found 120 meters downwind of the IF4-rated buildings. Extensive debarking was not observed in areas where the damage to nearby buildings was rated IF2 or lower. Another instance of debarking was observed between Hrušky and Moravská Nová Ves, although no nearby buildings were present in that location.

Topsoil removal (Fig. 12) was observed in four locations, coinciding with IF3 or IF4 damage ratings for nearby buildings and vegetation.
Fig. 11. Significant damage to the vegetation caused by A) and B) strong debranching (DoD 5), rated as IF3 damage given average tree strength and C) and D) extensive debarking (DoD 6), rated as IF4. Photos taken by Tomáš Púčik.

Fig. 12A) Topsoil removal exposing onions within the IF4 damage swath in Mikulčice. B) Accumulation of grass and topsoil against the damaged tree alley within the IF3 damage swath between Hrušky and Moravská Nová Ves. Photos taken by Tomáš Púčik.

Most coniferous trees with shallow root systems were uprooted before the most intense winds of the tornado arrived, so debranching or debarking was typically only observed on deciduous trees. In some instances, trees were transported over more than 5 meters (Fig. 13). Such damage was most common within the swaths of IF3 or stronger damage.
Fig. 13A) Part of a tree ripped off from the ground and transported by the tornado between Mikulčice and Lužice. The original location of the tree is unknown. The tree flew to the location, leaving no drag marks. Photo taken by Tomáš Púčik. B) Tree dragged by the tornado along the ground for 80 m between Hodonín and Pánov (path marked by yellow arrow). Aerial photo taken by Lukáš Ronge.

Near buildings that suffered IF4 damage, almost complete removal of leaves from both standing trees and fallen trees/bushes was noted. In areas with IF2+ to IF3 damage, more leaves remained on small bushes or fallen trees, while leaves were usually completely removed from standing trees. The combination of debarking and/or complete debranching along with the complete removal of leaves indicated the presence of intense winds, typically IF3 or stronger. Tree uprooting and snapping were the most common types of damage observed with IF2 winds or weaker.

8. Damage to vehicles

The tornado caused significant damage to vehicles, with many being lifted, overturned, or thrown considerable distances. However, determining the original locations of the vehicles before and after the tornado was often challenging since vehicles had often been removed to clear the streets quickly. In Hrušky, a caravan weighing 7 tonnes that was lifted and carried for 20 meters. It flew over a garage and ultimately landed in the garden of a house. In the agricultural complex of Moravská Nová Ves, tractors and heavy trailers were either overturned or lifted and thrown by the tornado (Fig. 14). A bus was thrown over a railroad embankment and rotated. The bus landed on its side against a two-story house. This incident resulted in injuries to the driver and the only two passengers that were onboard. The bus was
not airborne for the entire duration of the event, as surveyors found impact marks on both sides of the embankment.

Fig. 14A) and B) Tractor trailers thrown by the tornado in the agricultural complex west of Moravská Nová Ves. Photos taken by Tomáš Púčik.

The tornado caused extensive damage to vehicles in the industrial complex in Lužice (Fig. 15 A and B). At least 35 cars were lifted and thrown from the parking lots, landing 20 to 50 meters away. Many of these cars ended up piled up against nearby buildings. In addition, a vehicle was discovered in a tree alley on the northern side of the tornado track between Mikulčice and Lužice. This car was located 100 meters away from the nearest road, and its engine and tire were found approximately 200 meters away from the car, against the direction of the tornado movement (Fig. 15C, D, and E). The exact spot, where the car originated could not be determined.
Fig. 15A) and B) Examples of damaged cars in the industrial complex in western Lužice. The cars were towed back to the parking lot. C) A heavily damaged car that was thrown by the tornado and its D) tire and E) engine. Photos taken by Tomáš Púčik.

9. Damage to critical infrastructure

The tornado had significant impacts on transportation infrastructure, including both the D2 highway and the main railway corridor in Czechia. The D2 highway, which connects Brno, Czechia, and Bratislava, Slovakia, was completely closed for one day. However, the impact on the railway corridor was even more severe and long-lasting. The tornado tracked parallel to the main railway corridor from Austria to Poland and crossed it three times. The railway was completely closed for weeks and only fully reopened in the autumn of 2021.

The damage to the railway infrastructure included the destruction of the catenary (overhead wires) and sound-cancelling barriers. The most serious damage occurred within Mikulčice, where an IF4-section of the tornado impacted the railway, resulting in the destruction of multiple pylons (Fig. 16) and railway signals. The estimated cost of the damage to the railway infrastructure was approximately € 13.5 million (Přinesdomová, 2021). Additionally, the tornado destroyed 15.6 km of low-voltage, 10.5 km of high-voltage (22 kV), and 4.5 km
of very high-voltage (110 kV or more) power lines. Thirteen power transmission towers were also destroyed in the process (EG.D, 2021).

Fig. 16A) and B) Collapsed traction power pylons. Photos taken by Tomáš Púčik. Their location is shown on the aerial imagery in C). Yellow arrows denote the orientation of fallen trees, showing that the tornado center crossed the railway in this spot. Aerial image taken by Lukáš Ronge.

10. Summary

An outbreak of severe thunderstorms occurred over northern Austria, eastern Czechia and Poland on 24 June 2021, including a violent tornado. The tornado's maximum intensity was determined to be IF4 using the draft version of the International Fujita scale, based on a damage survey that lasted 3 days and involved surveyors from 3 countries. Its path length was 27.1 km and its maximum width reached 3.5 km, which is an extreme value from the perspective of European tornado climatology. The IF4 rating was given to the (partial) destruction of load-bearing brick walls and extensive debarking of trees. The area of IF4 damage comprised only 0.2% of the total path area. The tornado caused 6 fatalities and at least 576 injuries. Based on the hospital data, there were more indirect injuries during the...
clean-up process than direct injuries from the tornado itself. We estimate that more than 3200 structures were affected by the tornado and 180 of them had to be demolished (CTK, 2021).

Detailed documentation of this case is important because violent tornadoes in Europe are rather rare. This case presents a rare example for national weather services and emergency services in Europe to learn how to respond effectively in the aftermath of such an event. It also provides insight into how the tornado risk is perceived among the general public which is relevant for improving weather warnings. Furthermore, the case demonstrated how typical central European buildings behave in the winds of a violent tornado, making the case an important reference from an engineering perspective.

The survey of widespread wind damage requires careful preparation with a high level of organization, including coordination of damage survey teams and communication with the emergency services. As a reaction to this event, ESSL has created a wind damage survey guide to help national weather services to be more prepared for tornado damage surveys. One of the recommendations involves performing an aerial survey covering the whole tornado track, which proved indispensable in this case. The survey could have been carried out more efficiently if data would have been geolocated in the field using a damage rating application for mobile devices (Molthan et al. 2020). Some of the areas that were not reached by the ground survey could have been mapped by a drone making detailed photos of the structural integrity of roofs and walls from above to help assess the sturdiness classes of the houses.

Eyewitness reports showed that many people were unaware of the danger associated with the approaching tornado. Numerous injuries and at least one fatality were caused by people approaching the windows to check on the weather situation. Two other fatalities happened with people being outdoors (one on the porch, one in the vehicle). Weather services in Europe should issue special warnings in extreme situations like these and improve the communication of the tornado risk to the public. Emergency services should practice for such scenarios, especially in the most tornado prone regions of Europe, such as northeastern Italy. Such exercise was performed by the emergency services and the city management of Wiener Neustadt with the deadly 1916 tornado in mind (https://www.essl.org/cms/essl-supports-civil-defense-exercise/). There is also need to better educate public about the tornado risk and the actions that need to be taken, such as do not waste time with closing the windows and go hide in windowless and sturdy room. The authors would also like to advocate for better spotter
programs that could help with early tornado reporting and enhancing the chances of successful tornado warnings.

Due to the high intensity of the tornado and the large area affected (33.7 km²), the case offered the possibility to apply a wide range of damage indicators and degrees of damage from version 0.1 of the IF scale. The feedback from the surveyors has been used to improve the IF scale. Future steps will include a close investigation of the meteorology of the event, concentrating on the evolution of the mesoscale environment and storm interactions prior to the tornadogenesis.

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Appendix

List of youtube videos demonstrating the behavior of people in the tornado:
https://youtube.com/shorts/5tqeuof9KAQ?feature=share
https://youtu.be/uDc0nFhOc8w
https://youtube.com/shorts/cY2On7F_GdI?feature=share
https://youtu.be/YKdNAuF9vUo

Availability Statement

Maps created for this publication are based on the data produced by the Czech Office for Surveying, Mapping and Cadastre, which are publicly available here:
Data concerning individual address points used to calculate the number of affected buildings in the tornado can be found here:

Maps and cross-sections from the damage survey can be found here:
https://www.dropbox.com/sh/gclmw514kjj5d63/AABc5egSasEwi-b3PCAXghipa?dl=0

The photos from aerial survey of Lukáš Ronge can be found here:
https://www.dropbox.com/sh/zmkwrcj8bp73avt/AAC91jNjZ-z62myU_t6Q_amRa?dl=0

The photos from ground surveys from multiple individuals on different days can be found here:
https://www.dropbox.com/sh/3xgb985enpqnatz/AADpiMWzgzX1QmdwvDFAY26ma?dl=0

Additional aerial imagery used to delineate the edges of the tornado path can be found here:

SENTINEL 2 data that were used are publicly available here:
https://scihub.copernicus.eu/dhus/#/home
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