Severe storms as an example of a natural hazard in the urban area – case studies of the area of Warsaw, Poland

Abstract

The main objective of this research was to determine the synoptic and thermodynamic conditions accompanying the development of two severe thunderstorms that caused significant damage in Warsaw. The storm events of 17 June and 4 September 2016 were analysed. Materials used in the research included meteorological, aerological and radar data, as well as the Fire Service interventions database. These data allowed the conditions for the formation of the storms and their spatial variations in terms of intensity to be determined. It was shown that damage in Warsaw was caused by phenomena associated with supercell storms that developed in a moderate CAPE environment and a strong shear. It was confirmed that the geometry of the city increased the wind speed and modified its direction locally. In addition, it was found that the data on the number of Fire Service interventions clearly reflected the spatial variations in storm intensity by corresponding radar signatures to the high intensity of meteorological phenomena.

Keywords

Thunderstorm • supercell • synoptic conditions • damages • urban area • Warsaw

Krzysztof Piasecki ^{1,2},
Elwira Żmudzka ³

¹Department of Climatology, Institute of Physical Geography and Environmental Formation, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University in Poznań, Poznań, Poland
²Institute of Meteorology and Water Management - National Research Institute, Warsaw, Poland
e-mail: krzysztof.piasecki@amu.edu.pl

³Department of Climatology, Faculty of Geography and Regional Studies, University of Warsaw, Warsaw, Poland
e-mail: e.zmudzka@uw.edu.pl

Received: 23 October 2020

Accepted: 10 May 2021

Introduction

One of the consequences of contemporary climate change is the growth in intensity of extreme weather phenomena that can cause widespread damages (Linnenluecke & Griffiths 2010, Brooks 2013). Storms, connected to deep convection in the atmosphere (Nirupama, Adhikari & Sheybani 2014), are especially dangerous because of the combination of many meteorological elements, the values of which are far from the normal, average climate values for a given region.

According to the European Severe Weather Database (ESWD; Dotzek et al. 2009), storms cause about 9,000 severe weather events across Europe each year (Groenemeijer & Kühne 2014) and are the main cause of death of about 100 people. Taking into account the large number of storms in Europe (Anderson & Klugmann 2014; Groenemeijer et al. 2017) and hazards connected with them (Brooks 2013), it is relevant to evaluate meteorological and synoptic conditions that favour the development of intense storms (Groenemeijer 2005; Púčik et al. 2015; Taszarek, Brooks & Czemecki 2017; Taszarek et al. 2019) and to create a rapid response warning system (Johns & Doswell 1992; Arnold 2008).

Urban climates have many individual characteristics, especially higher air temperatures, which can provoke the formation of storms (Bornstein & Johnsson 1977; Bornstein & Lin 2000). The wind pressure and wind field modified by the urbanized area create conditions for the development of thunderstorms that are different from those observed in non-urban areas. In addition, urbanized areas tend to show considerable internal variations in climatic conditions, and the high density of development and population translate to potentially extensive damage by storm events occurring in relatively small areas.

One of the phenomena accompanying thunderstorms is strong and generally gusty wind. It has been shown that the destructive effects of wind, threatening the population and infrastructure of an urbanized area, occur when gust speeds of 17 ms⁻¹ are reached (ed. Lorenc 2012). As studies show, the wind speed and direction in cities strongly depend on the geometry of the latter. The average wind speed in cities is generally lower than in the country (Jackson 1978; Kossowska-Cezak & Bareja 1998), yet the maximum speed can reach higher values. A significant increase in wind speed occurs especially in street canyons that lie in the direction of the wind as the wind penetrates a built-up area (Nakamura & Oke 1988; Richter et al. 2018). In some cases, this increase can be as high as 50% of the wind speed in an open space outside the built-up area. This is the main cause of infrastructure damage in cities. Moreover, there is strong variation in the direction of ground wind in urban areas. It depends on the street layout, the presence of squares, green areas, and so on. In addition, there is a high potential for urban flash floods (Majewski 2002; Mejia & Moglen 2010; Żmudzka et al. 2019). Therefore, the study of meteorological conditions in relation to urban areas is one of the most important issues of modern climatology.

The main purpose of this research was to determine the synoptic and thermodynamic conditions that enable the development of severe storms, causing significant damage in Warsaw. The secondary aim was to find an answer to the question of whether a city's geometry can increase the impact of a storm, for example by increasing the speed and direction of the wind. An additional goal was to assess the possibility of

Figure 1. Meteorological and sounding stations, and other places in the area of Warsaw

Source: own study

using National Fire Service intervention data to assess the spatial differentiation of the intensity of storms.

Area, data and methods

Area of study and climate of Warsaw

This study focuses on the area of Warsaw, the capital of Poland. The area of the city is 517 km², with a population density of 3,437 people per km² (Kozłowska et al. 2018). The city is located along the Vistula Valley, in the Mazovian Lowland. The average annual temperature is 8.5°C (Warsaw-Okęcie, 1981–2010). The winters are thermally varied, and the summers are generally warm. The average annual rainfall is 531 mm, with the highest precipitation in summer. Moreover, there has been a significant increase in the frequency of high temperatures in recent years (Żmudzka 2016).

An important feature of Warsaw's climate is that an urban heat island (UHI) is formed. Case studies show that the differences in air temperature between the centre of Warsaw and the surrounding non-urban area can reach 10°C and higher (Wawer 1995, 1997; Błażejczyk et al. 2014a; Żmudzka 2019). An important factor that favours the formation of UHI is wind speed (Błażejczyk et al. 2014b). Earlier studies have shown that the open-air wind speed of 2–3 ms⁻¹ favours the formation of an urban heat island of high intensity, while with a speed of 7–8 ms⁻¹ the urban heat island in Warsaw disappears. It has also been found that, in the centre, the mean wind speed can be up to 60% lower than in the suburban area (Kossowska-Cezak & Bareja 1998).

The maximum recorded wind speed in gusts in Warsaw is 40 ms⁻¹ (14 June 1979). According to the research carried out in Warsaw, the annual maximum wind speed in gusts at the height of 10 m a.s.l. with a probability of occurrence of 1% is 41.1 ms⁻¹; with 10% it is 33.1 ms⁻¹, and with 99.9% it is 18.9 ms⁻¹ (ed. Lorenc 2012). Mazovia

is therefore a region that is predisposed to the occurrence of high velocity winds. They are favoured especially by atmospheric circulation, characterized by the inflow of air from the south-west with cyclonic pressure distribution, and are associated with the occurrence of convective phenomena.

Data and methods

This research examines two storms that occurred over Warsaw in 2016. The storms were selected based on the number of interventions by the National Fire Service in Warsaw. Two of the events with the highest number of interventions were selected: 17 June 2016 (527 interventions) and 4 September 2016 (260 interventions).

Meteorological data used in this study were collected from four stations in Warsaw for days with severe storms selected above. The data contain the values of air temperature, rainfall, wind direction and speed with a 10-minute time resolution (with maximum and minimum values).

The next step – the description of the synoptic situation and conditions in the upper atmosphere – was made based on synoptic maps (00 and 12 UTC), atmospheric soundings from Legionowo station (diagrams from 00 and 12 UTC) and radar data with 10-minute time resolution, from radar located in Legionowo. In the study we used the following radar products: CMAX (maximum value of reflectivity in vertical profile); PPI 0.5° (Plan Position Indicator – map of value of reflectivity in the lowest elevation, with 0.5° slope from radar); CAPPI from a height of 1 km (Constant Altitude Plan Position Indicator – map of value of reflectivity at defined height); and VCUT (Vertical Cross Section). Moreover, due to the lack of soundings in 12-hour periods, we used the Era 5 meteorological reanalysis with 1-hour time resolution. This allowed additional soundings to be elaborated for grid point 52.25°N, 21°E (a point located in the area of Warsaw).

Figure 2. Synoptic weather charts: 17 June 2016, 00:00 UTC and 12:00 UTC
Source: National Weather Service (IMWM – NRI).

The data of the National Fire Service (time, coordinates, description of damages, number of brigades) were used to determine the spatial distribution of damage. The data were processed with ArcGIS software. In addition, photographic documentation of the effects of the storms was collected. As a result, it was possible to determine local wind conditions in different parts of the city and verify whether the city's geometry influenced the relative intensity of airflow. For this purpose, after the storm of 17 June, the damage caused by severe wind gusts in selected locations, representing green areas and various urban layouts, was inventoried. The results of the field inventory were visualized in the form of a spatial distribution of the wind directions.

Results

17 June 2016

Synoptic situation. On 17 June 2016 Poland was under the influence of an active low-pressure system. The low appeared on 16 June in the morning, as turbulence on a quasi-stationary front crossing Austria and started moving north (fig. 2a). Within the next few hours, the low moved across Poland, deepening as it did so. At 12:00 UTC, its centre was located over northern Poland and the unstable tropic air mass was observed over the eastern part of Poland (fig. 2b). Concurrently, a cold front was moving from the south to north-eastern Poland and, just a few hours later, it left Poland.

Meteorological conditions in Warsaw. On 17 June 2016 at 11:00 UTC at the Warsaw-Okęcie synoptic station the temperature dropped to 26.1°C but the dew point increased to 19.0°C. An increase in air humidity and a decrease in air temperature were observed due to the convergence zone passing before the cold front, to the convective clouds with rain showers, and a nearby thunderstorm.

Unfortunately, the sounding (from 12:00 UTC from Legionowo) was made after the passing of the convergence zone. In consequence, the real conditions before the storm could not be registered. According to that sounding, the total SBCAPE value was only 160 Jkg⁻¹ and, what is more, the intensive CIN (-140 Jkg⁻¹) was also measured. At the same time a significant increased airflow was observed, with a deep layer shear (0–6 km,

DLS, the wind speed difference between surface and layer at 6 km) equal to 30.6 ms⁻¹ and a low-level wind shear (0–1 km, LLS) up to 18.5 ms⁻¹, which is rare in this area. This was the main reason the storm was so powerful and could induce destructive wind gusts.

Concurrently, the data from Era5 showed even higher values of the thermodynamic and convective indices before the sounding time. At 10:00 UTC the SBCAPE value was 1,901 Jkg⁻¹, while CIN was about -48 Jkg⁻¹. At 11:00 UTC the values were 1,516 Jkg⁻¹ and -22 Jkg⁻¹, respectively. These CAPE values could be considered as moderately high and, with high wind shear values, they could cause severe storms. Values of Storm Relative Helicity were also high at 0–1 km: 213 m²s⁻² and 0–3 km: 299 m²s⁻². In connection with a wind shear of 0–6 km around 30 ms⁻¹ and a wind shear of 0–1 km above 18 ms⁻¹, strong supercell storms or a mesoscale convective system (MCS, system of storm cells which lasts a few hours or more and is more than 100 km in length) with squall lines could develop in this environment.

The storm trajectory and damages. The first storm cells developed at 8:00 UTC on the convergence zone. The zone was moving towards central Poland and after 10:00 UTC the next storms developed – more than an hour before moving over Warsaw. At 10:23 UTC on the PPI 0.5° product a bounded weak echo region signature (BWER) was detected (fig. 3). The updraft was strong, and features of a supercell storm were clearly visible. Several dozen minutes later, the first information about damage caused by strong wind gusts was reported. At 11:00 UTC the convergence zone passed over Warsaw and the supercell moved to south-western districts of Warsaw (fig. 4). Only four minutes later (11:04 UTC) the storm core moved to the centre of the city (the area of Warsaw Central Railway Station) and at 11:08 UTC the storm was noticed in the eastern district of the city. Most of the damage reports came from the south-western, central and eastern parts of the city. At about 11:30 UTC, storm cells formed a squall line, moving in a north-easterly direction.

Video recorded next to the Central Railway Station (fig. 1) allowed the progress of the storm to be analysed. The storm lasted only about 4.5 minutes and two zones of strong wind and heavy rainfall were observed. The first zone of strong wind was related to the forward flank downdraft and the second was caused

Figure 3. Bounded weak echo region signature, visible before tracking in Warsaw: 17 June 2016, 10:23 UTC
Source: National Weather Service (IMWM – NRI)

Figure 4. PPI 0.5° product, supercell storm core over Warsaw, bounded by other convective cells: 17 June 2016, 11:03 UTC
Source: National Weather Service (IMWM – NRI)

Figure 5. Interventions of the National Fire Service taken after several wind gusts on 17 June 2016
Source: own study based on National Fire Service data

by the rear flank downdraft, which is consistent with radar data. The wind gust recorded at the meteorological station Warszawa-Filtry was 28.0 ms^{-1} . The affected area was narrow, along the path from south-west to north-east, across the centre.

Most of the damage was caused by destructive wind speed due to a downburst (fig. 5). This was related to strong forward flank and rear flank downdrafts. Many trees and branches were broken and some roofs, walls of buildings and cars were damaged (fig. 6). The wind also damaged some infrastructure: traffic lights, road signs, billboards and power lines. A few hours after the storm, there was still some disruption to public transport, especially because of damaged conductor rails and the stoppage of tram traffic. The type of damage allows us to suppose that the wind speed exceeded the recorded 28 ms^{-1} (101 kmh^{-1}) locally. Possible significant causes were the shape of the urban layout and the microburst (violent downdraft reaching the ground with a high wind speed in a short time, with the diameter of the phenomena of less than 4 km) related to the supercell storm. In a few places, the damages may have been caused by wind exceeding 35 ms^{-1} (126 kmh^{-1}).

As mentioned above, the dispersion of the damage was related to buildings (fig. 7a, b, c). The most serious damage was noticed between buildings, in narrow passageways, parallel to the dominant wind direction. The buildings had an impact on the wind direction as well as on the angle of fallen trees (fig. 7a, b). The angle was different from the wind direction by about $25\text{--}45^\circ$. This confirms that the tunnel effect was accountable for the direction and maximum wind speed that day. In an area without buildings (fig. 7c), the damage dispersion was in accordance with the dominant wind direction.

4 September 2016

Synoptic situation. On 4 September 2016, the area of Poland was under a low-pressure influence. At 00:00 UTC, its centre was located over Great Britain and at 12:00 UTC, it moved over the German–Danish border (fig. 8). Concurrently, the advection of a warm air mass was observed in the south-eastern part of the low, with temperatures reaching $28\text{--}29^\circ\text{C}$. The cold front with a convergence zone was moving eastwards and it was located near the western border of Poland in the evening. The pace of the front was high and, at about 19:00 UTC, the convergence passed over Warsaw. On 5 September at 12:00 UTC the low was located over northern Ukraine and the occluded front crossed Poland.

Meteorological conditions in Warsaw. Warsaw was under the influence of a warm, polar air mass with a maximum air temperature of 28.6°C . At 14:00 UTC, a shower was reported, and this influenced air humidity. Unfortunately, it was impossible to get information about real conditions in the troposphere from soundings – the storm passed over Warsaw between the sounding times. The surface observations before the storm at Warsaw-Okęcie indicated an air temperature of 20.4°C and a dew point at 15.6°C . Both soundings – at 12:00 UTC and at 00:00 UTC – detected moderate wind shear. The deep layer shear (0–6 km, DLS) was 16.7 ms^{-1} and 15.1 ms^{-1} . At Era5 sounding the MUCAPE (the most unstable layer CAPE) was only a little above 300 Jkg^{-1} , but there were moderate and high SRH values of 0–3 km: $165 \text{ m}^2\text{s}^{-2}$, 0–1 km: $140 \text{ m}^2\text{s}^{-2}$. The second value was especially high, making it favourable for supercell storms to develop. Nevertheless, the forecasts and reanalysis did not show conditions for such an intensive event that evening in central

Figure 6. Damage in the central district of Warsaw: 17 June 2016

Photo: Krzysztof Piasecki

Figure 7. Direction of the wind based on the direction of fall of the trees; fig. 7d: map of analysed areas: 17 June 2016

Source: own study based on orthophotomap provided by geoportal.gov.pl.

Poland, despite moderate wind shear in the layer 0–6 km, the values being considered as moderate.

The storm trajectory and damages. Deep, moist convection started to develop at 14:30 UTC over south-western Poland. At 15:10 UTC first convective cells were observed over southern Greater Poland. At 17:20 UTC the storm was located about 100 km west of Warsaw and its intense development was observed up to the supercell form. At PPI 0.5° product, at 17:33 UTC, an intense, coherent storm core was visible (fig. 9), with an intense, high updraft region inside it. Before 18:00 UTC a high precipitation supercell storm structure was observed and

the storm was located over western Mazovia – a strong, locally destructive wind gust and hail were reported. At 18:50 UTC, the supercell reached Warsaw. Despite the night hours, the supercell shelf cloud was observed (fig. 10). It is very characteristic that the damage path across Warsaw was not wider than 2–4 km, with some parts not wider than 1 km. At 19:20 UTC, the storm passed over Warsaw and was still very active.

On the cross-section product (18:53 UTC), there was the structure of a weak echo region up to 4 km high with a massive overhang structure (fig. 11). This suggests that the updraft was really strong. Moreover, Doppler data and the right-moving path

Figure 8. Synoptic weather charts: 4 September 2016, 12:00 UTC and 5 September 2016, 00:00 UTC
Source: National Weather Service (IMWM – NRI)

Figure 9. PPI 0.5° radar product between 17:33 and 18:53 UTC (a – 17:33, b – 17:53, c – 18:13, d – 18:33, e – 18:44, f – 18:53):
4 September 2016
Source: National Weather Service (IMWM – NRI)

Figure 10. Shelf cloud in front of the forward flank downdraft (FFD) of the supercell storm approaching the central district of Warsaw: 4 September 2016, 18:55 UTC

Photo: Krzysztof Piasecki

Figure 11. PPI 0.5° and cross-section images of supercell storm before approaching Warsaw: 4 September 2016, 18:53 UTC

Source: National Weather Service (IMWM – NRI)

of the storm confirmed the rotation. That is also why the storm was so active in those conditions and why it caused severe phenomena, with strong microbursts. Along the storm path, strong wind gusts connected to downburst were reported, which was the main reason for very concentrated damage, with a path consistent with the storm core trajectory. Locally, heavy rainfall and large hailstones (with a diameter of 2.5–3.5 cm) were also observed. Most of the National Fire Service damage reports concerned broken trees or branches and interrupted power lines but there were also damaged cars and parts of roofs and some reports about flooded streets, but most of these were not dangerous.

The damage path was parallel to the movement of the supercell core (fig. 12). The first reports came from the western districts. Next, the southern part of the central district was affected (fig. 13) and the storm passed over the Vistula river. To the right of the river, the most damaged parts were those of eastern Warsaw (especially the residential areas). It was also very interesting to notice that the path of the core was really concentrated. The maximum wind gust at the Filtry meteorological station was 23.3 ms^{-1} but, locally, damages were characteristic of a wind of over 30 ms^{-1} .

Figure 12. Interventions of the National Fire Service taken after several wind gusts on 4 September 2016
Source: own study based on National Fire Service data

Figure 13. Wind damage in Warsaw on 4 September 2016 – broken trees and damaged cars
Photo: Krzysztof Piasecki

Table 1. A summary of storm detail

Date	17 June 2016	4 September 2016
Start time	11:00 UTC	18:50 UTC
Duration	5 minutes	10 minutes
Type of storm	supercell	supercell
Radar signatures	BWER	BWER, overhang
Meteorological characteristic	wind gust - 28.0 ms ⁻¹ rain - 6.4 mm	windgust - 23.3 ms ⁻¹ hail - ø 2-3 cm rain - 21.0 mm
Number of interventions	527	260

Source: own study

Summary and conclusions

The presented study documents two cases of a set of weather phenomena related to thunderstorms that hit Warsaw in 2016, resulting in an unusually high number of fire department interventions. Based on the source materials collected, these storms (Table 1) were associated with convergence zones propagating before the cold front and with the advection of warm and moist air masses. Strong airflow and significant wind upsets were associated with the presence of the low. Moderate instability values and intensified airflow influenced the development of deep convection. That such synoptic conditions are conducive to the development of severe thunderstorms is confirmed by numerous studies on storm events in other regions (John & Doswell 1992; Arnold 2008; Púčik et al. 2015).

The BWER signature identified on the radar image allowed us to extend our knowledge and confirm that these were supercell storms with intense downward currents. This signature also appeared for other supercells studied in Poland (Popławska 2014; Pilorz 2014; Pilgus et al. 2019; Poręba & Ustrnul 2020). There was also a clear overhang signature in the radar images during the 4 September 2016 storm, indicating that the updraft was strong and completely separate from the downdraft. The moderate values of CAPE were the enabling factor for the development of storm cells, while their organization into a supercell form occurred due to the significant values of wind uplift. For the 17 June 2016 storm, the 0–6 km layer wind shear (DLS) was 30.6 ms⁻¹. In the light of the Taszarek et al. (2017) study results, wind shear values in the 0–6 km layer (DLS) that favour strong wind gusts during thunderstorms (above 33 ms⁻¹) are generally between 13 ms⁻¹ and 32 ms⁻¹, with the most common value occurring at circa 18 ms⁻¹. Moderate CAPE values reduce the risk of supercell evolution into a storm system form, even of derecho scale (Taszarek et al. 2019). Such conditions occurred in the cases analysed in this study. The consequence was an isolated mode of convection. At the same time, in both cases the supercells developed in a typical synoptic situation, as described for example by Poręba and Ustrnul (2020), associated with the advection of warm and humid air in the warm sector of the low. In addition, the large role of the wind convergence zone before the cold front was confirmed, which was the main factor supporting convection.

For the meteorological events analysed, wind gusts with high maximum speeds were considered the main threat to infrastructure and residents. However, no threat of flooding or flash floods was identified. The precipitation that accompanied the storms, even though significant, was short-lasting. The research therefore points to another important element of weather – that wind, which, in addition to heavy rainfall accompanying storms and generating urban flooding (e.g. Majewski 2002; Nirupama & Simonovic 2007; Żmudzka et al. 2019), can cause a variety of damage in different parts of the city, covering larger area compared with flood damage. In addition, wind is difficult to forecast, especially when accompanying deep convection.

The conducted field research confirmed that the distribution and character of buildings and the presence of green areas, especially those covered with tall vegetation, have a significant impact on wind speed and direction. Based on the inventoried damage, it was estimated, according to the classification proposed by Popławska (2016), that wind speeds in gusts could exceed 35 ms⁻¹ in some locations (broken street lamps, devastated trees). Locally, the wind speed was therefore higher than the maximum gust measured at meteorological stations by up to 30%. It is worth noting that this is a wind speed above the maximum wind speed in gusts with a probability of occurrence of 5% (ed. Lorenc 2012). The distribution of damage suggesting particularly high wind speeds confirms the regularities identified by other authors (e.g. Nakamura & Oke 1988; Rotach & Calanca 2003; Richter et al. 2018). There was an increase in wind speed, among other things, in streets parallel to the direction of the wind and in constrictions between buildings. What should be noted also is the convergent distribution of damage on the leeward side of the buildings and the divergent distribution directly behind the space constrictions between buildings (where a significant tunnel effect was also observed).

It was also shown that data on the number of interventions by the National Fire Service can be used to assess spatial variation of storm intensity. The areas where a large number of interventions occurred corresponded to radar signatures indicating high intensity of meteorological phenomena. This method has been used before in studies on urban climate (Żmudzka et al. 2019). However, the concentration of damage (and interventions) is not always related solely to the severity of the adverse events accompanying the storm. It is also an illustration of the presence of vulnerable areas.

Atmospheric soundings are performed only twice a day, which significantly limits the ability to accurately forecast meteorological hazards. In the analysed cases, the thunderstorms developed before they moved over an urban area, which provided an opportunity to warn the residents. Unfortunately, there was no such warning system in Warsaw at that time. The lack of such information made it impossible to prepare for the imminent threat.

ORCID

Krzysztof Piasecki <https://orcid.org/0000-0002-4471-5468>

Elwira Żmudzka <https://orcid.org/0000-0003-3497-7904>

References

- Anderson, G & Klugmann, D 2014, 'A European lightning density analysis using 5 years of ATDnet data', *Natural Hazards and Earth System Sciences*, vol. 14, no. 4, pp. 815–829.
- Arnold, DL 2008, 'Severe deep moist convective storms: Forecasting and mitigation', *Geography Compass*, no. 2/1, pp. 30–66.
- Błażejczyk, K, Kuchcik, M, Błażejczyk, A, Milewski, P & Szmyd, J 2014a, 'Assessment of urban thermal stress by UTCI – experimental and modelling studies: an example from Poland', *Die Erde*, vol. 145, no. 1–2, pp. 16–33.
- Błażejczyk, K, Kuchcik, M, Milewski, P, Dudek, W, Kręcisz, B, Błażejczyk, A, Szmyd, J, Degórska, B & Pałczyński, C 2014b, *Miejska wyspa ciepła w Warszawie: uwarunkowania klimatyczne i urbanistyczne* [Urban Heat Island in Warsaw: climate and urban characteristics], Wydawnictwo Akademickie SEDNO, Warsaw.
- Bornstein, RD & Johnson, DS 1977, 'Urban-rural wind velocity differences', *Atmospheric Environment*, vol. 11, no. 7, pp. 597–604.
- Bornstein, RD & Lin, Q 2000, 'Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies', *Atmospheric Environment*, vol. 34, no. 3, pp. 507–516.
- Brooks, HE 2013, 'Severe thunderstorms and climate change', *Atmospheric Research*, vol. 123, pp. 129–138.
- Dotzek, N, Groenemeijer, P, Feuerstein, B & Holzere, AM 2009, 'Overview of ESSl's severe convective storms research using the European Severe Weather Database ESWD', *Atmospheric Research*, vol. 93, no. 1–3, pp. 575–586.
- Groenemeijer, P 2005, *Sounding-derived parameters associated with severe convective storms in the Netherlands*, Institute of Marine and Atmospheric Research Utrecht (IMAU), Utrecht.
- Groenemeijer, P & Kühne, T 2014, 'A climatology of tornadoes in Europe: Results from the European Severe Weather Database', *Monthly Weather Review*, vol. 142, pp. 4775–4790.
- Groenemeijer, P, Púčik, T, Holzer, AM, Antonescu, B, Riemann-Campe, K, Schultz, DM, Kühne, T, Feuerstein, B, Brooks, HE, Doswell, CA, Koppert, H & Sausen, R 2017, 'Severe convective storms in Europe: Ten years of research and education at the European Severe Storms Laboratory', *Bulletin of the American Meteorological Society*, vol. 98, pp. 2641–2651.
- Jackson, PS 1978, 'Wind structure near a city center', *Boundary-Layer Meteorology*, vol. 15, no. 3, pp. 323–340.
- Johns, RH & Doswell, CA III 1992, 'Severe local storms forecasting', *Weather and Forecasting*, vol. 7, no. 4, pp. 588–612.
- Kossowska-Cezak, U & Bareja, P 1998, 'Wpływ zabudowy miejskiej Warszawy na kierunek i prędkość wiatru' [Influence of Warsaw built area on wind direction and speed], *Acta Universitatis Lodzensis, Folia Geographica Physica*, vol. 3, pp. 463–465.
- Linnenluecke, M & Griffiths, A 2010, 'Beyond adaptation: Resilience for business in light of climate change and weather extremes', *Business & Society*, vol. 49, no. 3, pp. 477–511.
- Lorenc, H (ed.) 2012, *Klęski żywiołowe a bezpieczeństwo wewnętrzne kraju* [Impact of natural disasters on the country's internal security], Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, Warsaw.
- Majewski, W 2002, 'Powódź w Gdańsku w lipcu 2001' [The flood in Gdańsk in July 2001], *Gospodarka Wodna*, vol. 62, no. 1, pp. 21–23.
- Mazovian Centre for Regional Research 2019, *Ze statystyką przez Warszawę 2019*, [With statistics through Warsaw 2019], Statistical Office in Warsaw. Available from: <<http://warszawa.stat.gov.pl/>>. [31 August 2020].
- Mejia, JM & Moglen, GE 2010, 'Impact of the spatial distribution of imperviousness on the hydrologic response of an urbanizing basin', *Hydrological Processes*, vol. 24, no. 23, pp. 3359–3373.
- Nakamura, Y & Oke, TR 1988, 'Wind, temperature and stability conditions in an east-west oriented urban canyon', *Atmospheric Environment*, vol. 22, no. 12, pp. 2691–2700.
- National Weather Service (IMWM – NRI) 2016, *Radar & meteorological stations data*. Available from: <<https://danepubliczne.imgw.pl/>>. [10.10.2019].
- National Fire Service 2016, *Severe weather events data*. Available from: <<https://www.gov.pl/web/kgpsp/miejscowe-zagrozenia-polska/>>. [17.10.2019].
- Nirupama, N & Simonovic, SP 2007, 'Increase of flood risk due to urbanization: a Canadian example', *Natural Hazards*, vol. 40, pp. 25–41.
- Nirupama, N, Adhikari, I & Sheybani, A 2014, 'Natural hazards in Ontario, Canada: an analysis for resilience building', *Procedia Economics and Finance*, vol. 18, pp. 55–61.
- Pilgaj, N, Taszarek, M, Pajurek, Ł & Kryza, M 2019, 'High-resolution simulation of an isolated tornadic supercell in Poland on 20 June, 2016', *Atmospheric Research*, vol. 218, pp. 145–159.
- Pilorz, W 2014, 'Radarowa detekcja superkomórek burzowych w Polsce', *Teledetekcja Środowiska*, vol. 51, pp. 93–105.
- Popławska, J 2014, 'Tornado superkomórkowe w Polsce – studium przypadku z 15 sierpnia 2008', *Prace i Studia Geograficzne*, vol. 56, pp. 205–229.
- Popławska, J 2016, *Zastosowanie wybranych metod detekcji tornad i trąb powietrznych na obszarze Polski – studia przypadków* [Application of selected methods of detection tornadoes and spouts in Poland – case studies], Ph. D thesis, Faculty of Geography and Regional Studies University of Warsaw, Warsaw.
- Poręba, S & Ustrnul, Z 2019, 'Forecasting experiences associated with supercells over South-Western Poland on July 7, 2017', *Atmospheric Research*, vol. 232, no. 104681.
- Púčik, T, Groenemeijer, P, Ryba, D & Kolář, M 2015, 'Proximity soundings of severe and nonsevere thunderstorms in central Europe', *Monthly Weather Review*, vol. 143, no. 12, pp. 4805–4821.
- Richter, A, Ruck, B, Mohr, A & Kunz, M 2018, 'Interaction of severe convective gusts with a street canyon', *Urban Climate*, vol. 23, pp. 71–90.
- Rotach, MW & Calanca, P 2003, 'Microclimate' in Encyclopedia of Atmospheric Sciences, eds JR Holton, JA Curry & JA Pyle, Academic Press, Amsterdam, pp. 1301–1307.
- Taszarek, M, Brooks, HE & Czernecki, B 2017, 'Sounding-derived parameters associated with convective hazards in Europe', *Monthly Weather Review*, vol. 145, pp. 1511–1528.
- Taszarek, M, Piguj, N, Orlikowski, J, Surowiecki, A, Walczakiewicz, S, Pilorz, W, Piasecki, K, Pajurek, Ł, Półrolniczak, M 2019, 'Derecho Evolving from a Mesocyclone—A Study of 11 August 2017 Severe Weather Outbreak in Poland: Event Analysis and High-Resolution Simulation', *Monthly Weather Review*, vol. 147, pp. 2283–2306.
- Wawer, J 1995, 'Wpływ warunków pogodowych na intensywność miejskiej wyspy ciepła w Warszawie' [Influence of weather

conditions on the intensity of urban heat island in Warsaw'] in *Klimat i bioklimat miast*, ['Climate and bioclimate of cities'], ed. K. Kłysik, Wydawnictwo Uniwersytetu Łódzkiego, Łódź, pp. 71–78.

Wawer, J 1997, 'Miejska wyspa ciepła w Warszawie' ['Urban heat Island in Warsaw'], *Prace i Studia Geograficzne*, vol. 20, pp. 145–197.

Żmudzka, E 2016, 'Zmienność czasowa i zróżnicowanie przestrzenne wybranych elementów klimatu na terenie Warszawy' ['Temporal variability and spatial diversity of selected climate elements in Warsaw'], Zakład Klimatologii Wydziału Geografii i Studiów Regionalnych, University of Warsaw, Warsaw.

Żmudzka, E, Kulesza, K, Lenartowicz, M, Leziak, K, Magnuszewski, A 2019, 'Assessment of modern hydro-meteorological hazards in a big city – identification for Warsaw', *Meteorological Applications*, vol. 26, pp. 500–510.

Żmudzka, E 2019 'Badania klimatu Warszawy prowadzone w Zakładzie Klimatologii Wydziału Geografii i Studiów Regionalnych Uniwersytetu Warszawskiego (1951-2018)' ['Studies on Warsaw's climate carried out at the Department of Climatology, Faculty of Geography and Regional Studies, University of Warsaw (1951-2018)'], *Acta Geographica Lodziensia*, vol. 108, pp. 127-139.