

# Seasonal and annual variability of days with strong winds and wind damage in Krakow (Poland) during the period 2000–2007

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**Abstract** The study analyses the numbers of days with strong winds in Krakow during the period 2000–2007 using anemometric records and fire department data. Patterns are identified in the seasonal and annual variation of strong winds. Particular attention is devoted to extreme events. Based on measurements, the study finds that strong winds mostly occurred in winter. Fire department call-out data show that repair of damage caused by strong winds and gusts of wind was needed equally as frequently in summertime. Strong winds accompanying summer storms are often of a local nature and are not always recorded by weather stations. Wind damage was mapped using requests for fire department assistance.

**Keywords** Strong winds · Wind damage · Central Europe · Krakow (Poland)

## 1 Introduction

According to a report of the World Meteorological Organisation, strong winds ranked second, after floods, among weather-related causes of material damage in Europe during the last 10 years (Cornford 2002; Berz 2005). Strong winds are linked (among other factors) to deep depressions moving across Europe from west to east and accompanied by steep horizontal pressure gradients. According to some researchers, the main causes for the increase in wind speed are the extratropical cyclones, which have recently grown in frequency in the northern hemisphere (IPCC 2007). Examples of such storms include three violent storms observed in December 1999, when more than 130 people died and material

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damage exceeded 13 billion euros (Ulbricht et al. 2001; Berz 2005). The first of these storms developed on 2 December over the North Sea and moved towards Sweden. On 3 December at 18 h UTC, the air pressure at the centre located over the east coast of Jutland dropped to 953 hPa. The cyclone, named Anatol by the German Weather Service, was at 970 hPa on arrival in Lithuania the following day. Strongest wind speeds were observed to the south of the pressure system in an area stretching from Germany to the Danish coast of the North Sea and to the Polish Baltic coast. Here, a wind speed of  $43 \text{ ms}^{-1}$  ( $154.8 \text{ km h}^{-1}$ ) was recorded on the Hel peninsula on 4 December. The other two storms, named Lothar and Martin, emerged late in December, but had different tracks than Anatol (Dupont and Brunet 2006; Schindler et al. 2009). They crossed the centre of the continent, wreaking considerable damage in Poland. Since the beginning of the 21st century, there have been more than ten other cases of severe winter storms, including Erwin/Gudrun in January 2005 (Soomere et al. 2008).

In urban areas, strong winds pose an increased threat to human life and health, as well as can cause enormous material damage. Local wind conditions in urban areas are considerably affected by “urban relief”, particularly in densely built-up city centres and residential neighbourhoods, causing effects such as the slowing down (through increased roughness) and acceleration (tunnel effect) of the wind (Oke 1995). The average urban wind speed is lower than in adjacent open countryside by approximately 20–30% (Fortuniak 2003). In the Krakow city centre, just as in many other central European cities (Fortuniak 2003; Fortuniak et al. 2006), this effect is observed throughout the year (ranging from 10 to 15% at night to 25 to 30% during the day) and is greater in the warm season (Lewińska et al. 1990). Fortuniak (2003) claims that in cases of extreme wind speeds in Krakow, the urban effect can reduce such wind speed by up to 50%. According to Fortuniak (2003), quantitative information about the urban impact on the wind speed based on records from only one or even several weather stations may carry a wide error margin. For this reason, several studies on urban anemological conditions were based on laboratory research (DePaul and Sheih 1986; Nakamura and Oke 1988) or computer simulations (Macdonald 2000) taking into account such effects as the “street canyon” airflow.

Some climatologists claim that high velocity winds have increased in frequency in Europe in recent years (Knippertz et al. 2000; Ulbricht et al. 2001; Leckebusch and Ulbricht 2004; Pryor et al. 2005; Arażny et al. 2007; Makkonen et al. 2007). There are estimates putting the increase in incidence of strong winds in central Europe at 20% in the period 1990–2099 (Leckebusch and Ulbricht 2004). Wind speed is also expected to increase by up to 7–10% (Leckebusch and Ulbricht 2004). While these authors stressed that this was just a scenario, similar results on computer simulations based on real cases have already been shown in quite numerous publication concerning real cases. Indeed, there has been an increased frequency and growing of strong winds over much of Europe, including Ireland, the United Kingdom, France, Denmark, Germany and the Benelux countries (Lambert 1996; Geng and Sugi 2001; Graham and Diaz 2001; McCabe et al. 2001; Paciorek et al. 2002; Leckebusch and Ulbricht 2004; Leckebusch et al. 2008). Rockel and Worth (2007) claim that wind speeds are likely to increase, especially in January and February. Nevertheless, projections based on a regional model of climatic change for 2071–2100 only envisage small increases in extreme surface wind speed in northern Europe (Makkonen et al. 2007).

This study attempts to identify annual and seasonal patterns in the variation of strong winds in Krakow during the period 2000–2007 and to analyse the effects of such winds on the city. A particular focus is extreme events. Fire department intervention data were used to map areas with an increased risk of wind damage.

## 2 Data and methods

In climatologic research, a day with a strong or very strong wind is often defined as having at least one observed wind speed of more than  $10 \text{ ms}^{-1}$  (strong wind) or  $15 \text{ ms}^{-1}$  (very strong wind) (Adamczyk 1996). This definition of strong and very strong winds is often not very useful for studies of urban areas. This is particularly true when wind measurements are taken only a few times per day or are available for only a small number of locations. Wind speed is highly dependent on local conditions, such as surface profile and roughness, and varies greatly in time. Urban surfaces slow down wind speed considerably, while the varied “urban relief” can cause wind speed to drop or pick up depending on a specific location, such as in “wind tunnels”. The specific location of a wind meter (anemometer) to a great extent determines the measurement result, and this will not always be representative for the wind event. For a detailed analysis of wind speeds in urban areas, a large number of weather stations with measurements at different elevations above ground level done at the same point are necessary.

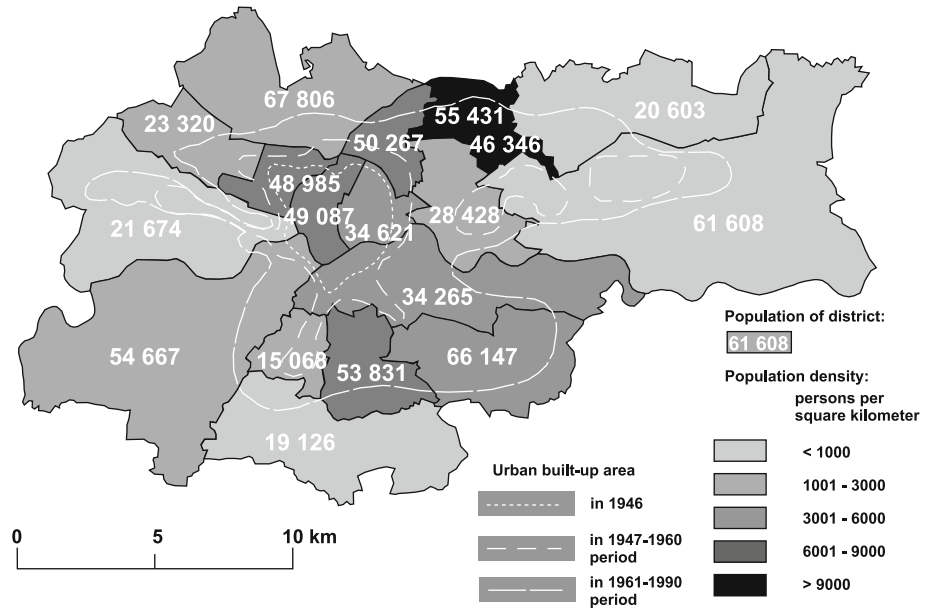
Like many other central European cities, Krakow lacks such an infrastructure. There is just one weather station within the city limits. The Jagiellonian University weather station ( $\varphi 50^{\circ}04'N$ ,  $\lambda 19^{\circ}04'E$ , h 206 m a.s.l.) was established in 1792 (the Historical Station) and expanded in 1958 (Botanical Gardens). The anemological records, however, are marred by uniformity and reliability problems caused by several changes in the location of the wind meters due to a shading effect of trees growing nearby and by data gaps following metering equipment failures. For this reason, the study is limited to the period 2000–2007, when the measurements were conducted with an automatic anemometer located on a roof at 18 m above ground. The data included measurements of average and maximum wind speed in  $\text{ms}^{-1}$  at 10-min intervals. Using this input, it was possible to calculate wind gusts defined as wind speed increases of at least  $5 \text{ ms}^{-1}$  above the average speed of the previous 10 min. A day with strong wind is defined as one with gusts of wind exceeding  $10 \text{ ms}^{-1}$  measured at the Jagiellonian University’s weather station.

Because a single weather station cannot be regarded as representative of strong winds within a city, data from a number of local fire departments in Krakow, such as details of the action responders took in relation to wind damage, are included in the analysis. This is an indirect method of analysing seasonal and annual patterns of strong winds and their related damage. In this respect, a day with strong wind was defined as one with at least five fire department interventions. This number of days corresponds to the 90th or higher percentile of all cases. With this definition, single interventions to repair damage, which may have been erroneously ascribed to wind, were excluded. The analysis also utilised details about the type and cause of the event, its exact location (geographical coordinates by GPS) and the time (day, hour, minute) of the observation the fire service. Each fire service intervention was carefully recorded, as required by law, in a computer database, including location, the reason for the intervention and the type of damage.

The synoptic environment in which strong winds in Krakow occurred was analysed using the synoptic catalogue previously defined by Niedźwiedz (2008; available at <http://klimat.wnoz.us.edu.pl>).

## 3 Description of the study area

Krakow is located in southern Poland in a temperate climate zone intermediate between maritime and continental climates. The city is representative of urban climatic conditions in central Europe. Krakow has an area of  $327 \text{ km}^2$  and extends 18 km from north to south



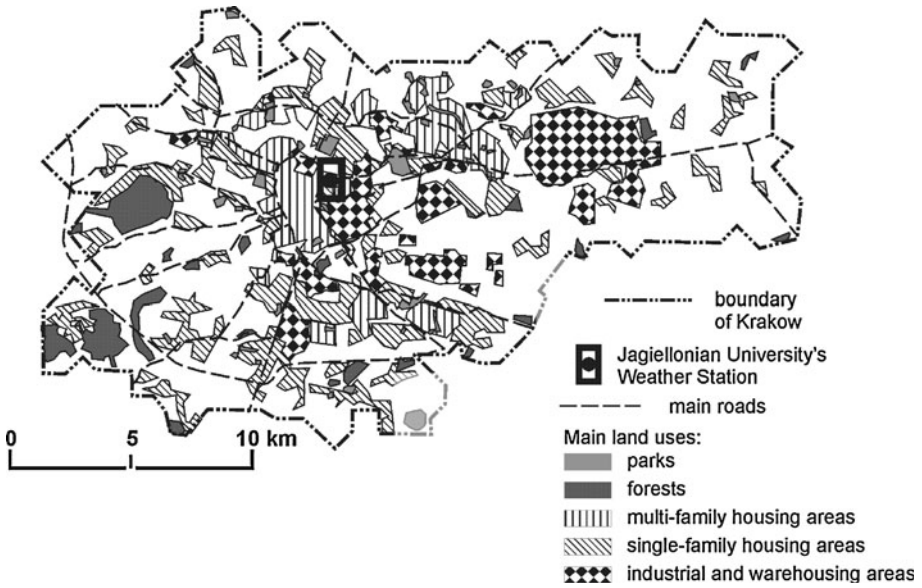
**Fig. 1** Population density in Kraków by district versus urban development zones in 2006

and 31 km from east to west. The local population is 756.3 thousand, and the urban agglomeration has 1.3 million inhabitants (2006). The average population density is 2,314 persons per square kilometre, but varies between areas (Figs. 1 and 2). The most densely populated areas include the city centre, districts with multi-family and single-family residential areas. The spatial structure of the city is heavily dominated by the densely populated central districts. The city's spatial and functional structure is highly cohesive, and there are several functional districts with a high concentration of technical development (residential, transport, industrial and warehousing) that differ in terms of the nature of development, including: the fully built-up city centre (with a domination of administrative and commerce-and-services functions); housing estates (dense development with buildings up to more than 10 floors high); single-family housing neighbourhoods (with relatively few and small multi-family residential buildings); and industrial and warehousing areas with medium intensity development and buildings lower than 10 floors (Fig. 2).

Areas with trees account for nearly 8% of the overall area of the city, including 4.4% of forests and 1.2% of parks (there are in total 41 individual forests and parks), while 'street and square greenery' accounts for 2.3% of the total area. Large parks surround the city centre; forests are found in peripheral districts and the remaining 'tall greenery' is distributed irregularly throughout the city (Fig. 2). The tree stands mainly comprise deciduous trees (predominantly beech, oak and birch), with a proportion of coniferous (pine) trees of less than 20% and with very widely varying ages.

#### 4 Days with wind gusts above $10 \text{ ms}^{-1}$

During the study period, wind speed averaged approximately  $2 \text{ ms}^{-1}$  and peaked at  $18.3 \text{ ms}^{-1}$  (on 28 October 2002). Weak and very weak winds dominated ( $1\text{--}4 \text{ ms}^{-1}$ ), just

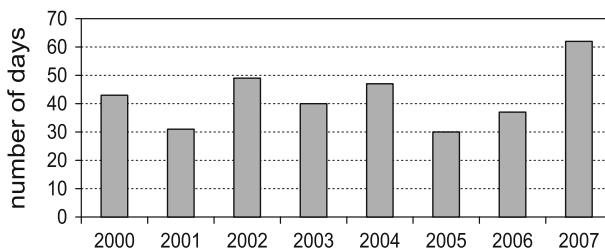


**Fig. 2** Predominant land uses in Kraków in 2000

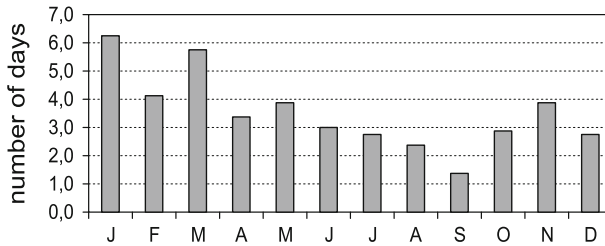
as this was the case in other Polish and central European cities (Fortuniak 2003; Fortuniak et al. 2006; Lewińska et al. 1990). The probability of occurrence of such winds was ca. 88% (Kowanetz 2007). The highest wind speeds were recorded in March ( $2.5 \text{ ms}^{-1}$ ) and the lowest in September ( $1.4 \text{ ms}^{-1}$ ) (Kowanetz 2007). The probability of moderately strong winds in Krakow ( $7\text{--}10 \text{ ms}^{-1}$ ) stood at 1.6%, but dropped to just 0.1% with regard accounted for much of the study period (to speeds greater than  $10 \text{ ms}^{-1}$  (Kowanetz 2007). Calm conditions are accounted on average ca. 25% per annum.

The greatest number of days with strong winds in Krakow during the period 2000–2007, 62, was recorded in 2007, while the lowest number of days, 30, was recorded in 2005 (Fig. 3). An annual analysis revealed that strong winds were most common in winter and spring, especially in January (6.3 days), while they were seldom recorded in summer and autumn, especially in September (only 1.4 days) (Fig. 4).

In terms of synoptic situations, as many as 69.1% of the days with strong winds were observed during depressions, especially when southern Poland (including Krakow) was



**Fig. 3** Number of days with strong wind in Krakow during the period 2000–2007



**Fig. 4** Annual number of days with strong wind in Krakow during the period 2000–2007

under the influence of westerly or north-westerly (W + NWc) airflow, which accounted for 41.9% of the total number of days with strong winds (Table 1). A high proportion of these events owe their existence to strong depressions with very low pressures in the centre and steep horizontal pressure gradients. Such systems mostly occur during the cool half of the year (November–March) and typically in winter (December–February). No strong depressions were recorded in summer during the period 1901–2004 (Bąkowski and Piotrowicz 2007). Besides the low pressure areas, the strong winds observed in Krakow also occurred during thunderstorms, especially thunderstorms associated with cold fronts.

## 5 Frequency of fire department interventions related to wind damage

Data from the Krakow Fire Department show that there were 5,925 requests to repair damage caused just by strong winds during the study period. The largest number was in 2007 when the fire department was called out 2,335 times (Fig. 5a). The number would have been half this figure if it had not been for the effects of two strong wind events in January and August, which are discussed in detail in below.

The typical number of requests for assistance received by the fire department is between 300 and 400, including those to remove broken trees and branches, damaged or displaced roofs, billboards and TV antennae. Typically, the busiest months for calls for assistance are May to September (Fig. 5b), which represent the warm part of the year when strong winds often accompany thunderstorms, including both frontal and air-mass events. Fire department interventions were much larger in 2002, 2004 and 2007, compared with other year in the study period due to strong winds in January, March and October 2002, in November 2004 and in January 2007. In addition, a thunderstorm that affected Krakow in August 2007 also caused severe damage.

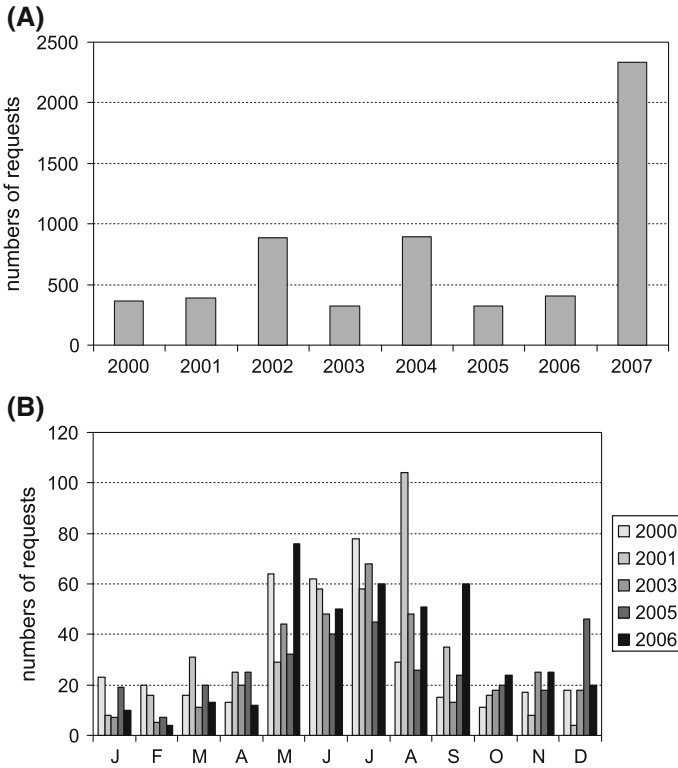
The main cause of fire department action related to wind was damage caused by wind gusts associated with thunderstorms. Indeed, during the cool half of the year when Poland is affected by deep low pressure systems, the frequency with which the fire department is asked for assistance was much lower and did not exceed 20–30 cases per month.

Using the provided definition for a day of strong winds as one with at least five fire department interventions linked to wind damage, the greatest number of such days occurred in the summer months (June–August) (Table 2). In June and July, there were days with strong wind in each year of the study period, while they were much less frequent in the remaining months.

**Table 1** Frequency of days with strong wind in different types of atmospheric circulation during the period 2000–2007 (according to the classification by Niedźwiedz 2008; <http://klimat.wnoz.us.edu.pl/>)

Year	Ca + Ka	Cc + Bc	E + SEa	E + SEc	N + NEa	N + NEc	S + SWc	W + NWa	W + NWc	x	Sum
2001	–	21.7	–	–	4.3	4.3	8.7	13.0	47.8	–	100.0
2002	–	6.1	18.4	6.1	–	4.1	4.1	24.5	36.7	–	100.0
2003	2.5	17.5	12.5	–	2.5	12.5	5.0	12.5	35.0	–	100.0
2004	4.3	12.8	6.4	4.3	2.1	–	4.3	14.9	51.1	–	100.0
2005	–	13.3	3.3	6.7	3.3	–	3.3	20.0	50.0	–	100.0
2006	2.7	5.4	24.3	–	2.7	–	5.4	21.6	35.1	2.7	100.0
2007	1.6	17.7	6.5	4.8	–	1.6	6.5	9.7	51.6	–	100.0
Sum	1.7	13.2	10.8	3.5	1.7	3.1	5.2	16.3	44.1	0.3	100.0

Explanation—Anticyclonic situations: *Na* North (direction of air masses advection, geostrophic wind), *NEa* North-East, *Ea* East, *SEa* South-East, *Sa* South, *SWa* South-West, *Wa* West, *NW* North-West, *Ca* central anticyclone situation (high centre), *Ka* anticyclonic wedge or ridge of high pressure; Cyclonic situations: *Nc* North, *NEc* North-East, *Ec* East, *SEc* South-East, *Sc* South, *SWc* South-West, *Wc* West, *NWc* North-West, *Cc* central cyclonic, centre of low, *Bc* trough of low pressure (different directions of airflow and frontal system in the axis of trough); *x* unclassified situations or pressure col



**Fig. 5** Number of calls to the Fire Department related to damage caused by strong winds in Krakow during the period 2000–2007; **a** per year and **b** per month

**Table 2** Number of days per month with more than five Fire Department call-outs related to damage caused by strong winds in Krakow during the period 2000–2007

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Sum
2000	2	–	–	–	2	3	3	1	–	–	–	–	11
2001	–	1	2	–	2	2	4	6	1	–	–	–	18
2002	3	1	3	–	–	3	5	7	–	4	–	1	27
2003	–	–	–	1	2	3	3	1	–	1	–	1	12
2004	–	1	2	–	–	1	4	1	1	–	10	–	20
2005	–	–	–	–	1	2	2	–	–	–	–	2	7
2006	–	–	–	–	2	3	2	1	2	1	–	–	11
2007	11	1	2	–	7	8	8	11	12	–	–	–	60
Sum	16	4	9	1	16	25	31	28	16	6	10	4	166

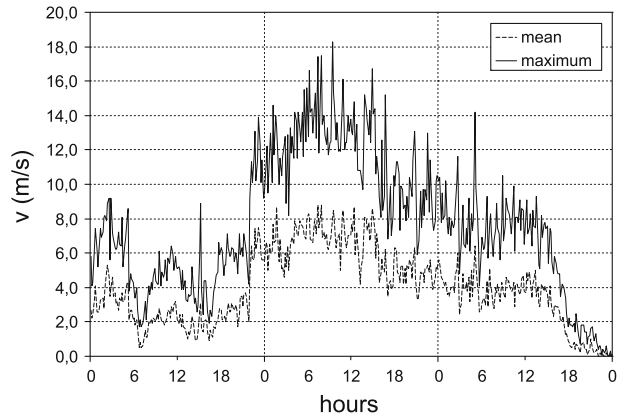
## 6 Case studies of strong winds in Krakow

### 6.1 28 October 2002

On 28 October 2002, a low pressure system involving a cold front and centred over the Baltic Sea was moving across Poland. Arctic air flowed from the north-east. During the

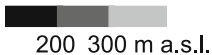
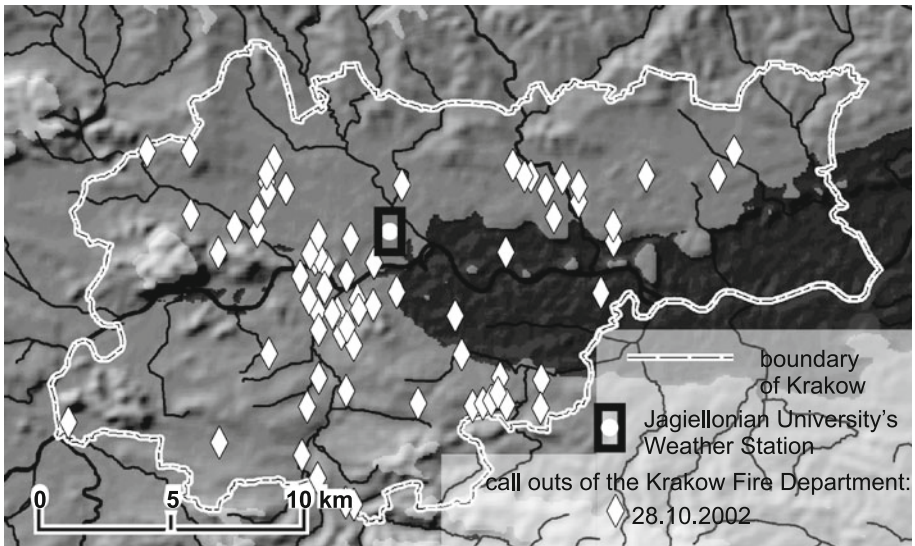


**Fig. 6** Average and maximum wind speed in Krakow during 27–29 October 2002



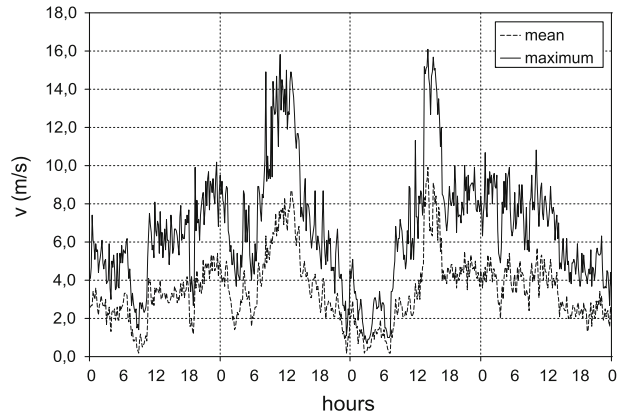
night of 27/28th October, the wind speed gradually increased to a maximum in the morning (Fig. 6). Piotrowicz et al. (2004–2005) used records from 16 weather stations located in southern Poland and calculated that the associated wind energy reached record levels. At eight of the stations, all located in cities, the energy levels of wind gusts were the highest of the entire 5-year period analysed by the authors (2000–2004).

On that day, the Fire Department in Krakow received 114 requests for intervention to repair wind damage. The first requests came at just 30 min past midnight, and they increased as the wind speed grew. The city centre, where the wind broke tree branches, felled entire trees and damaged roofs, suffered the most (Fig. 7).



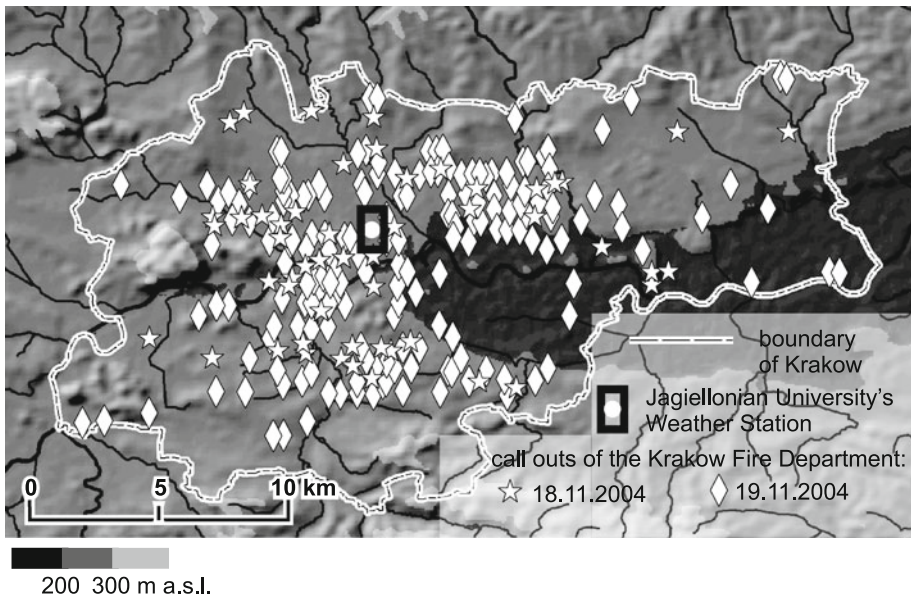
**Fig. 7** Call-outs of the Krakow Fire Department on 28 October 2002

**Fig. 8** Average and maximum wind speed in Krakow during 17–20 November 2004



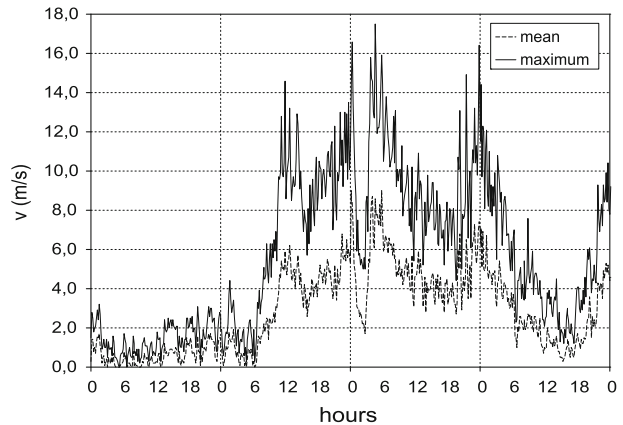
6.2 18–19 November 2004

Strong winds on 18–19 November 2004 had catastrophic effects in much of central Europe. The wind was generated by strong depressions that had emerged in the middle of the Atlantic Ocean, west of the British Isles (Bąkowski and Piotrowicz 2007) and moved rapidly eastward through northern France, Germany and Poland (Unton-Pyziółek 2005). Such was the wind force that it claimed seven lives, and seven people were injured in Poland alone. In the Slovak Tatra Mountains, 12 thousand hectares of forest were felled and the event has been dubbed in literature as the “Vel’ka Vetrova Kalamita”, or the Great Wind Calamity (Widawski and Łakomiak 2008). In the Krakow city centre, gusts of wind were recorded with speeds of up to  $16 \text{ ms}^{-1}$  (Fig. 8) and of up to  $18 \text{ ms}^{-1}$  at the airport



**Fig. 9** Call-outs of the Krakow Fire Department on 18–19 November 2004

**Fig. 10** Average and maximum wind speed in Krakow during 17–20 January 2007



weather station of Krakow-Balice (Bąkowski and Piotrowicz 2007). Many trees and tram power lines were damaged, and traffic in the city centre came to a complete stop for more than two and a half hours. The greatest damage was observed in the centre and the north of the city (Fig. 9). On the main outbound thoroughfares, wind pushed cars off the road.

The fire department received its first request for wind-related assistance at 9:00 am on 18 November. By 6:40 pm, when the wind speed had decreased considerably, there had been 51 interventions, mostly to remove trees from the roads, restore tram power lines and retrieve a trailer blown into a ditch. On the following day, wind gusts were much more dangerous. Even though the average 10-min wind speed was less than  $2 \text{ ms}^{-1}$  greater and wind gusts were of a similar speed as the day before (Fig. 8), the fire department had 346 interventions and 37 requests were attended to on the following day. These involved damaged roofs, power line cables and posts and fences damaged by falling trees and branches.

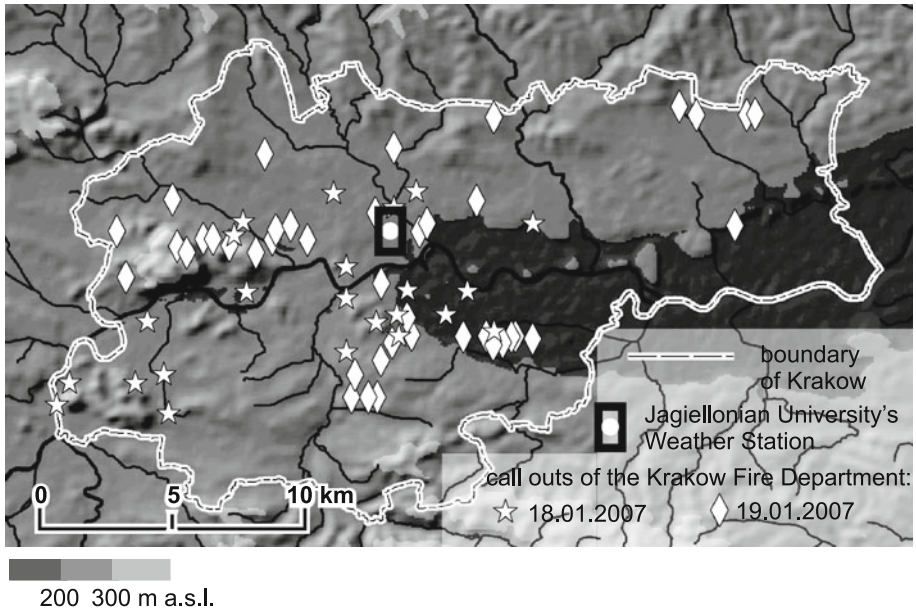
### 6.3 18–19 January 2007

A strong wind event in January 2007 observed across much of Poland and central Europe was caused by a strong depression with its centre moving from the North Sea to the Baltic Sea. It is known in literature as Kyrill or Cyril (Kaseja 2007; Holub et al. 2008; Friederichs et al. 2009). Storms are developed along a related cold front (Fig. 10). Damage caused by these winds in Krakow was greatest along an east-west axis (Fig. 11). There were 94 fire department interventions on 18 January and 342 interventions on 19 January.

### 6.4 24 August 2007

A wind event recorded on 24 August was of an entirely different origin. It was caused by a thunderstorm on the night of 23/24 August. Wind gusts exceeded  $16 \text{ ms}^{-1}$ , but they only lasted for approximately 10 min (Fig. 12).

The thunderstorm that crossed through Krakow from south-west to north-east destroyed trees and blew down power poles and damaged cars and buildings (Fig. 13). The fire department was first involved at 1:10 am, and by the end of the day, it had attended to 570 incidents. This was the largest number of incidents involving wind-related damage on one day since 2000. A total of 103 requests were not attended to until the following day.



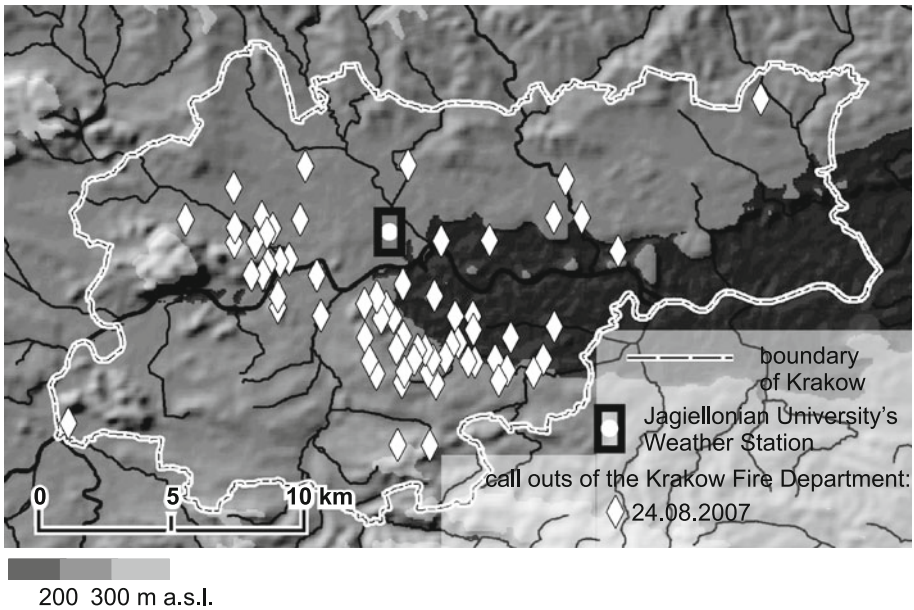
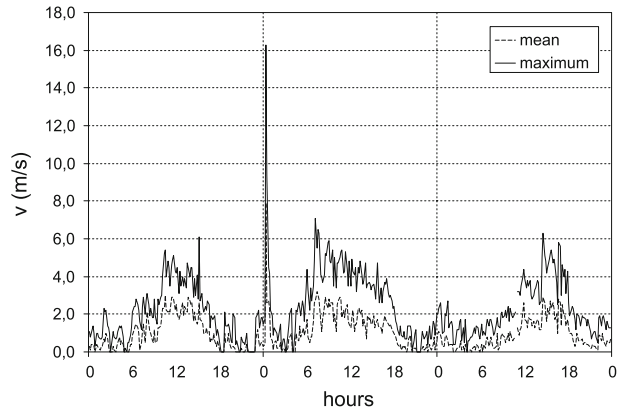
**Fig. 11** Call-outs of the Krakow Fire Department on 18–19 January 2007

## 7 Areas particularly exposed to damage due to strong winds in Krakow

A map of areas with an increased risk of damage due to strong winds (Fig. 14) was drawn based on the data obtained from the fire service (exact GPS-based geographical coordinates of the site) and on the analysis of the city's geographical environment, including its land relief, land use (e.g. greenery; Fig. 2) and population density (Fig. 1). Maps of wind-damage risk can also be made for specific seasons and months of the year or for different synoptic circulation types, for which Figs. 7, 9, 11 and 13 would be useful. Such maps, however, would stand to gain in credibility if they were based on records of fire department call-out data longer than just 8 years. The risk map made for the purpose of this paper (Fig. 14) combines map layers of individual analysis elements (land use, population density and land relief) and the map of fire service interventions on days with strong winds during the period 2000–2007. The final visualisation was made using a land relief map.

The highest risks were identified in a central zone covering the Vistula valley (with varied types of buildings) and the lower portions of the northern slopes of higher ground in the southern part of the city, which are all characterised by the highest intensity of urban development. Facilities recorded to have been damaged there included: buildings (roofing, TV antennae and mobile telephony masts, chimneys and cornices), a power line (including street light posts), a communications line, advertising including billboards and trees. Low-intensity residential areas on higher hills, both in the northern and in the southern part of the city, suffered a moderate degree of damage. This damage was predominantly due to falling trees or branches. The least risk was noted in the eastern (within the Vistula valley) and south-western peripheries of the city (in more elevated areas with a greater proportion of forest), which generally were characterised by a lower population density and a relatively low proportion of developed land and technical infrastructure.

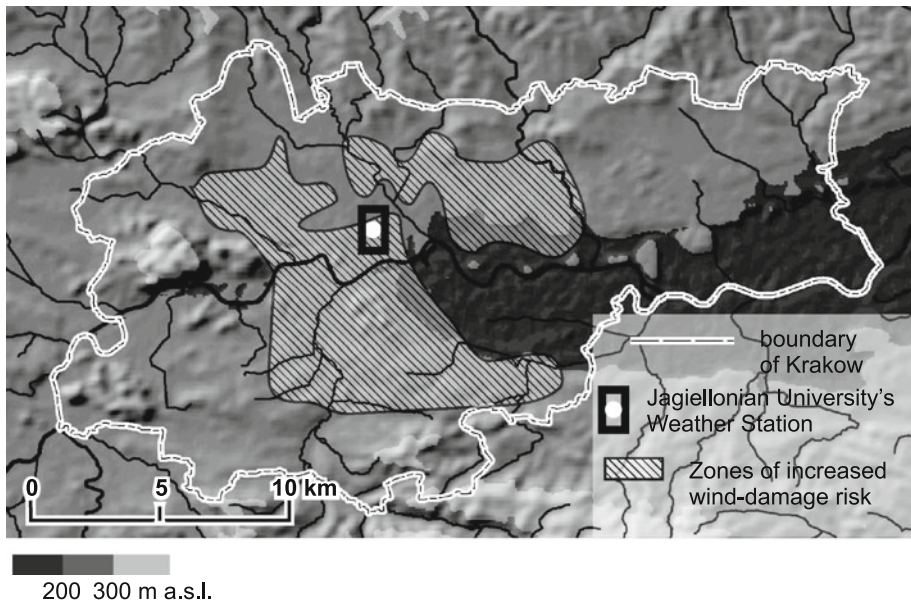
**Fig. 12** Average and maximum wind speed in Krakow during 23–24 August 2007



**Fig. 13** Call-outs of the Krakow Fire Department on 24 August 2007

**8 Discussion and conclusions**

Most European studies of strong winds and wind gusts focused on their occurrence during winter storms (Ágústsson and Ólafsson 2009; Pinto et al. 2009). Examples of damage caused by strong winds were mostly of forests (Schindler et al. 2009; Blennow et al. 2010; Peltola et al. 2010; Usbeck et al. 2010a, b). An analysis of these events can help in-depth understanding of tree damage caused by strong winds. Indeed, as trees in cities range from single-tree to forest stands, so the wind-caused threats also differ. When analysing urban woodlands or big parks, findings from research on open-area forests can be very useful. In central Europe, the greatest damage to forests is caused by northern hemispheric mid-latitude cyclones (Usbeck et al. 2010a). Wind gusts pose a greater threat to compact wood



**Fig. 14** Zones of increased wind-damage risk in Kraków

stands than winds with a high mean speed. Large trees (more than 18 m tall) with dense canopies are the most vulnerable due to their large surface area. A study by Johnson et al. (Pokorny 1992) demonstrated that 84% of the trees damaged during high wind storm events had pre-existing defects. This could be avoided through proper tree planting and pruning practices and could have been detected and corrected if the trees had been inspected for the presence of hazardous defects (Pokorny 1992). The few studies that analyse these aspects in urban areas, especially at a local scale (topoclimate), come from the USA (Martin 2007; Changnon 2009) where wind-related damage in coastal zone cities is caused mainly by tropical cyclones unknown in this part of Europe. Lopes et al. (2009) looked at tree damage due to wind in urban environments in Europe and specifically in Lisbon (Portugal). The study claims that more than 60% of tree and branch falls in the city occur during the autumn and winter. This is caused by strong winds accompanying deep depressions that travel across Europe during these seasons. An urban environment is generally unfavourable to tree growth due to air and soil pollution and to a depressed ground water table. Trees planted in paved areas (street trees) are more exposed to environmental stress than trees growing in urban parks (park trees) or in small urban forests (urban woodlands) (Lopes et al. 2009). For this reason, the relationship between observed tree damage and the measured wind speed is not sufficient to evaluate wind damage to trees.

This study proposed an alternative analysis of strong winds in urban areas using a combination of wind measurements and indirect observations. Anemometric measurements from the Jagiellonian University Weather Station in Krakow city centre were supplemented by Krakow's Fire Department call-out data. A considerably different understanding of the temporal characteristics of damaging winds was obtained from the two data sets. The wind speed measurements from the Jagiellonian weather station point to strong winds as most frequent in winter when they are typically related to low pressure systems,

including, in particular, deep cyclones moving over central Europe. This is compatible with other research, including Usbeck et al. (2010b). On the other hand, the call-out data from the Krakow Fire Department suggested more frequent damaging winds during summer when the high winds and gusts are linked to thunderstorms.

Another advantage of the fire department reports is that the location of the incidents is provided, allowing for an assessment of spatial variations in wind hazard. In Krakow, areas most affected by wind damage include the city centre and other districts with intensive urban development. The more frequent reports of damage in summer, especially in the city centre, are likely in part because the predominantly deciduous stands of mixed age tend to be much more exposed to wind damage at this time of year when leaf surface area is much greater than in other seasons. Risk maps such as those provided here can be used in urban strong-wind hazard zoning. For this purpose, however, ongoing monitoring would be recommendable covering the condition of the tree stands and land-use change (type, development type, technical infrastructure intensity). For example, Duntemann (2006) has proposed three spatial zones with tree condition assessment performed annually in the highest-hazard zone, every 3 years in the medium-hazard zone and only after storms or thunderstorms in the low-hazard zone.

These expanded findings highlight the benefits of proxy data in evaluating urban wind climatologies and impacts and support previous studies that also utilised proxy data, including damage reports in the MRNat Cat archive of the Munich Re reinsurance company (Porcu and Carrassi 2009) or Fire Brigade and Rescue Services reports (Lopes et al. 2009), to evaluate wind damage in urban areas. If future projections of increased wind speeds prove true (Leckebusch and Ulbrich 2004; Leckebusch et al. 2008; Usbeck et al. 2010a, b), wind speed will have to be considered in spatial planning, the design of buildings and other infrastructure and in educational curricula, especially in large urban areas such as Krakow.

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