Theor Appl Climatol
DOI 10.1007/s00704-017-2146-1

ORIGINAL PAPER

The second most disastrous windstorm of the nineteenth century in the Czech Lands, 26-27 October 1870

Rudolf Brázdil[1,2] · Peter Stucki[3,4] · Péter Szabó[5] · Petr Dobrovolný[1,2] · Ladislava Řezníčková[1,2] · Oldřich Kotyza[6] · Hubert Valášek[1] · Lukáš Dolák[1,2] · Pavel Zahradníček[2,7] · Silvie Suchánková[5]

Received: 13 December 2016 / Accepted: 1 May 2017

Abstract One of the most disastrous windstorms to take place over the Czech Lands occurred on the night of 26/27 October 1870. It is here analysed through the use of documentary data (narrative sources, newspapers, forestry journals, printed documents) and systematic meteorological observations (wind force and direction). Combining this evidence with information derived from an atmospheric reanalysis dataset allows the severity of the windstorm to be attributed to the passage of a cold front, a frontal system associated with a secondary low in a typically storm-prone synoptic environment. Its social impacts were characterised by great material damage, particularly to buildings and other structures, trees and forests. These are recorded not only for 174 places around the countryside and lesser settlements of the Czech Lands, but also for 28 city quarters in Prague, the capital city. The windstorm occurred in the night hours, so only a few people were killed or injured. However, the 1870 windstorm totally devastated many forested areas of the Šumava Mts. in south-west Bohemia. Damage to forests in other parts of the Czech Lands was also severe, but difficult to quantify exactly for lack of high-resolution spatial data. Because this windstorm followed only shortly upon a previous similarly disastrous wind event on 7 December 1868, the enormous quantity of windthrown wood in forests, which simply could not be fast-processed, contributed significantly to a subsequent bark-beetle infestation calamity in the 1870s. In certain forest stands, imprints of these aggregate effects appear to this day. The central-European scale of 1870 windstorm is also well documented by meteorological and documentary data from Germany, Austria and Slovakia.

✉ Rudolf Brázdil
brazdil@sci.muni.cz

1 Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

2 Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic

3 Oeschger Centre for Climate Change Research, Falkenplatz 16, CH-3012 Bern, Switzerland

4 Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland

5 Department of Vegetation Ecology, Institute of Botany, Czech Academy of Sciences, Lidická 25/27, 602 00 Brno, Czech Republic

6 Regional Museum, Mírové nám. 171, 412 31 Litoměřice, Czech Republic

7 Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 43, 616 67 Brno, Czech Republic

1 Introduction

Severe windstorms in Europe may have disastrous impacts on human society, reflected particularly in loss of human life and huge material damage, thus generating considerable research attention. Much of this analysis tends to focus on various aspects of their occurrence, frequency, seasonality, intensity, meteorological and synoptic causes and human impacts (e.g. Barredo 2010; Donat et al. 2010; Ulbrich et al. 2013; Karremann et al. 2014; Roberts et al. 2014; Stucki et al. 2014; Welker et al. 2016; Kašpar et al. 2017). This information is also frequently utilised by the insurance industry (e.g. Della-Marta et al. 2010; Deutsche Rück 2015; Swiss Re 2015; Zimmerli and Renggli 2015).

In comparatively recent years, during which systematic meteorological measurements have been commonplace, a large number of contributions have addressed disastrous windstorms. In the main, these tend to concentrate on windstorm intensity and synoptic analysis of meteorological

Published online: 24 May 2017

patterns. In particular, they include well-known events, such as a series of severe storms in 1990 (Munich Re 1990; Schüepp et al. 1994; Goyette et al. 2001), 1999 (Pearce et al. 2001; Ulbrich et al. 2001; Bründl and Rickli 2002; Kurz 2002; Wernli et al. 2002) and 2007 (Hostýnek et al. 2008; Fink et al. 2009). Several other severe windstorms in Europe have been analysed on a national basis, also with respect to their impacts (Gregor 1955; Setvák and Strachota 1986; Kaňák et al. 2007; Minár et al. 2009; Liberato et al. 2011; Simon et al. 2011; Freitas and Dias 2013; Liberato 2014; Stucki et al. 2015).

The number of analyses of individual severe windstorms occurring in the pre-instrumental or early instrumental periods is considerably smaller. These are largely based on documentary evidence, usually focussing more tightly on societal impacts, and they often employ analogical approaches to reconstruct associated meteorological patterns (Kington 1998; Munzar 2002, 2006; Wheeler 2003; Vaquero et al. 2008; Pfister et al. 2010; Pfeifer 2014, 2015; Brázdil et al. 2016).

Windstorms are among the most significant types of disturbance event affecting woodlands in many parts of the world (Webb 1999; Lugo 2008; Mitchell 2013). Because of this special threat, they are often analysed with respect to their effects on forests (Brázdil 1998; Nekovář and Valter 1998; Schelhaas et al. 2003; Nilsson et al. 2004; Falťan et al. 2009; Gardiner et al. 2010; Usbeck et al. 2010; Brůna et al. 2013; Usbeck 2014).

This study combines information from documentary data, meteorological observations, and a numerical reanalysis to examine the severity of the 26–27 October 1870 windstorm. The aim is to provide a comprehensive analysis of the windstorm over the territory of the Czech Lands with respect to its meteorological causes, course, societal impacts and its central European context. Section 2 presents basic meteorological observations, an atmospheric reanalysis dataset and the documentary data used in the study. After methodological considerations (Section 3), the windstorm is described with respect to its course and meteorological situation, territorial extent and societal impacts, with particular respect to forest damage (Section 4). Section 5 discusses the windstorm in terms of the central European context and the previous extraordinary windstorm of 7 December 1868. Concluding remarks are presented in the final section.

2 Data

2.1 Meteorological data

The two-hourly values of basic meteorological variables taken at the Prague-Klementinum meteorological station (for locations of stations and other places within the territory of the Czech Lands reported herein, see Fig. 1) were published in the "magnetic and meteorological observations yearbook" (Hornstein 1871). For the other 13 meteorological stations within the territory of the Czech Lands, only the thrice-daily readings (0600, 1400 and 2200 hours local mean time (LMT) or alternatively 0700, 1400 and 2100 hours LMT) are available, from the archives of the Czech Hydrometeorological Institute (CHMI). Observers recorded wind in 16 basic directions and its force on an 11-degree scale from 0 (calm or very light air) to 10 (hurricane); specific wind speeds were also allocated to every degree (Jelinek 1876). Certain stations also added extra windstorm information. For example, Hermann Schindler complemented his records at the Dačice meteorological station with: "*To the hurricane, starting with a thunderstorm from 23 h 45 min* [26 October] *to the morning* [27 October]. [...] *I add that, during the rain, flashes of lightning were seen and thunderclaps were heard*. [...] *The windstorm from 27th* [October] *generated terrible devastation in forests*." Additional data were also retrieved from the meteorological yearbook of the Central Institute for Meteorology and Earth Magnetism in Vienna for 1870 (Jelinek and Fritsch 1873), since the Czech Lands were part of the Austro-Hungarian empire at that time and recorded as such.

2.2 Atmospheric reanalysis

The Twentieth Century Reanalysis version 2c (20CR; Compo et al. 2011) is a dataset describing the global atmosphere at a horizontal grid of 2° × 2°, which corresponds to about 200 km east-west and 300 km south-north over the Czech Lands. In the vertical, 24 pressure levels are implemented. The 20CR version 2c covers the period from 1 January 1851 0000 hours UTC to 31 December 2014 1800 hours UTC in time-steps of 6 h. Its dataset is independent of ground observations except for air pressure levels, the only data assimilated into the reanalysis. Given its coarse temporal and spatial resolution, the meteorological variables in 20CR may be used to provide only a synoptic view of weather dynamics. Time series information from a single grid point is used to track the temporal evolution of a given windstorm. Input data (surface pressure observations; Cram et al. 2015) become sparser in the nineteenth century compared to more recent periods, which leads to less well-defined pressure gradients and other meteorological fields; thus, wind speeds are arguably under-represented in the reanalysis. This may hold particularly true for the ensemble mean, which is used here. For the time period under review, 20CR may still be considered the best available numerical estimate of the atmospheric circulation at large temporal and spatial scales. In fact, 20CR has already been used successfully to analyse synoptic-scale weather systems over Europe in the second half of the nineteenth century (e.g. Brönnimann et al. 2012; Stucki et al. 2012; Brázdil et al. 2017).

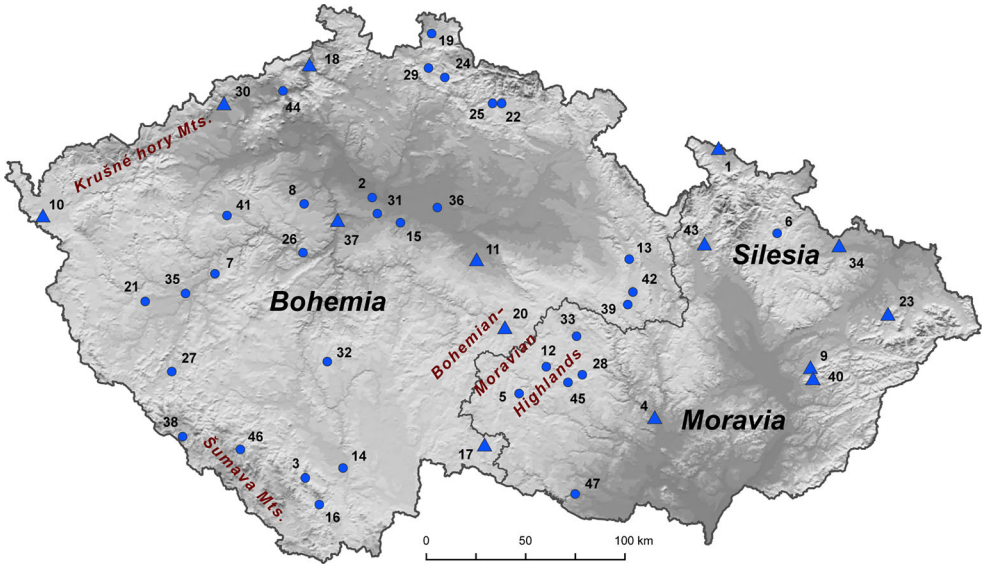

Fig. 1 Locations of meteorological stations (*triangles*) and other places (*circles*) in the Czech Lands mentioned in the paper: Bernartice (*1*), Brandýs nad Labem (*2*), Brloh (*3*), Brno (*4*), Brtnice (*5*), Bruntál (*6*), Břasy (*7*), Buštěhrad (*8*), Bystřice pod Hostýnem (*9*), Cheb (*10*), Čáslav (*11*), Černá (*12*), Česká Třebová (*13*), České Budějovice (*14*), Český Brod (*15*), Český Krumlov (*16*), Dačice (*17*), Děčín-Podmokly (*18*), Frýdlant (*19*), Havlíčkův Brod (*20*), Heřmanova Huť (*21*), Horní Branná (*22*), Hukvaldy (*23*), Jablonec nad Nisou (*24*), Jilemnice (*25*), Karlštejn (*26*), Klatovy (*27*), Křižanov (*28*), Liberec (*29*), Litvínov (*30*), Horní Litvínov, Malé Jirny (*31*), Milevsko (*32*), Nové Město na Moravě (*33*), Opava (*34*), Plzeň (*35*), Poděbrady (*36*), Prague-Klementinum (*37*), Prášily (*38*), Radiměř (*39*), Rusava (*40*), Senomaty (*41*), Svitavy (*42*), Šumperk (*43*), Ústí nad Labem (*44*), Velké Meziříčí (*45*), Vimperk (*46*) and Znojmo (*47*)

2.3 Documentary data

The various kinds of documentary data sources applied in historical climatology (Brázdil et al. 2005, 2010) may be used for description of the course and impacts of the 26–27 October 1870 windstorm, as below:

1. Annals, chronicles, "books of memory"

Such narrative sources provide valuable background to the 1870 windstorm with respect to its occurrence, the places affected and the damage done. For example, the "book of memory" for the Bohemian town of Plzeň gives a graphic description (Koráb 1883, p. 1119): "[...] a horrible hurricane raged. The damage [it did to] this town was great. There was scarcely a house that did not suffer considerable damage. At St. Bartholomew's Church, the gale tore down part of the gable, which fell and broke the vault of the Sternberg Memorial Chapel. The southern part of the military bakery on Klatovská Street was practically levelled to the ground. Roofs were carried away from many houses [...] The roofs of houses and barns in the suburbs were almost demolished, the tower of the water tank was considerably damaged, the chimney-stack at the Škoda factory was pushed so out of true that the street had to be shut off [...] The raging hurricane uprooted and broke many trees in the communal forests, doing great damage there as well."

2. Newspapers

Many newspapers reported the 1870 windstorm in terms of its course, material damage, human fatalities and casualties in the Czech Lands and in other parts of central Europe. Almost identical or very similar reports appeared repeatedly in several newspapers, either immediately after the windstorm or after a delay of some days. For example, the newspaper *Bohemia* (20 Oct. 1870, p. 3894) reported on the situation in České Budějovice in southern Bohemia: "Yesterday [26 October] at 10 o'clock in the evening, a windstorm came up from the south-west, which became a rapid hurricane around midnight [26/27 October], and blew through the whole area with horrible fury until three in the morning. In the morning, it was not possible [anywhere] in our town to see a street that was not covered in broken glass from windows and [dislodged] tiles. Cornices, chimney-stacks, window shutters and downspouts were knocked down by the ravaging winds; many roofs were partly broken through or lifted up, garden walls demolished, trees uprooted or broken […]".

3. Forestry journals

Two forestry associations existed in the Czech Lands in the nineteenth century (Nožička 1957). The Bohemian Association was established in 1848 and the Moravian-Silesian Association a year later. The latter was originally a part of the local agricultural society (*k. k. Mährisch-Schlesische Gesellschaft für*

Ackerbau, Natur- und Landeskunde). Both organisations published their own journals: *Vereinschrift für Forst-, Jagd- und Naturkunde herausgeben von böhmischen Forstvereine* and *Verhandlugen der Forstsektion der k. k. Ackerbaugesellschaft für Mähren und Schlesien* (renamed in 1870 to *Verhandlungen der Forstwirthe von Mähren und Schlesien*). These recounted various aspects of the activities of the associations as well as providing transcriptions of the discussions held at the annual meetings of foresters. Many contributions to them mentioned the 1870 windstorm, often in connection with the 1868 windstorm as well (Brázdil et al. 2017). For example, Issue 3 of *Verhandlungen der Forstwirthe von Mähren und Schlesien* for 1871 ran the following report from the Křižanov estate in western Moravia: "The [wind]storm of 26–27 October [1870] again ravaged our forest stands and downed 6600 trunks with c. 3500 klafter of wood [9947 m^3 – for calculation see Section 3] [...] The damage in the local forests is more extensive this time than that on 7 December 1868, because while [in the previous windstorm] the majority of trunks were only uprooted, this time most of the damage consisted of breakage, leaving the timber good for only firewood."

4. Other publications

Information about the October 1870 windstorm also appears in a number of other papers, some published close to the event, others later. For example, immediately after the storm, *Zeitschrift der österreichischen Gesellschaft für Meteorologie* ran several short news stories, one of them reading, for Horní Litvínov (now Litvínov) in north-west Bohemia (Stainhaussen 1870): "At half past eleven on the evening of the 26th [October] lightning [flashed] in the west, and in only slightly-moving air a thunderstorm with strong thunderclaps passed swiftly through the zenith to the east; then suddenly, at 12 o'clock [midnight 26/27 October] a hurricane W^{10} [the Figure. 10 identifies hurricane wind force moving from the west] occurred, which threatened to destroy everything, to break windows, to strip roofs, [and] to uproot trees; it continued until four in the morning [27 October] and the mountains [the Krušné hory Mts.] were covered in snow. […]" This windstorm was also frequently reported in papers specialising in forestry matters. For example, Nožička (1956, p. 102), in an account of the history of the forests of Silesia, noted: "Although the consequences of the 1868 hurricane [7 December] had not yet been alleviated everywhere, the forests around Bruntál were affected by a new windstorm in the night of 26/27 October 1870, which led to 12,000 fathoms [34,104 m^3] of windthrow."

3 Methods

Documentary data provided the place and time of the windstorm, its course and various kinds of impacts to buildings, other structures and objects, trees and forests, together with qualitative or quantitative estimates of the damage caused. Before further use, these data were first critically evaluated with respect to place and time assignment and their content carefully analysed. All the places reported were allocated accurately to recent equivalent settlements in the territory of the Czech Republic (many towns bore German names at the time that have fallen out of use, while some smaller settlements have come, gone or moved over time). Information repeated in a number of sources (e.g. different newspapers) allowed cross-checking of data to avoid certain inaccuracies. Such carefully interpreted data were entered into a database that was employed for further analyses. A similar critical approach was taken to work with meteorological observations of wind force and wind directions, as well as to observer's remarks, which were directly taken from the original written climatological records for individual stations or verified against them.

Some of the documentary data interprets estimated damage financially, using gulden, the currency of the time. For purposes of orientation and comparison, it is worth noting the value of employment around 1870. The per-diem wage of a simple labourer was around a quarter of a gulden; artisans such as bricklayers or carpenters earned a gulden a day. Annual incomes were around: farm-worker 20 gulden and clothing, textile worker in northern Bohemia 250 gulden, miner 360–400 gulden, chartered accountant 600 gulden, office worker 800 gulden (the latter two with additional material benefits) and a teacher at a secondary school 700 gulden (Machačová and Matějček 2002; Brzobohatý 2003).

Quantitative damage to forests related to the 1870 windstorm was usually expressed in terms of the amount of windthrown trees, expressed in *Klafter* (in Czech *sáh*, a fathom) of timber (1 *Klafter* equals 2.842 m^3 of stacked wood or 1.8954 m^3 of solid wood, i.e. without the air between the logs and the bark); for the purposes of this contribution, the cubic meter unit refers to stacked wood unless otherwise indicated. The overall sizes of the forests in which the damage occurred were expressed in *Joch* (in Czech *jitro*; 1 *Joch* = 0.5754 ha). Some reports contain names of individual "forest districts" (*Forstbezirke*) with details of corresponding forest damage. These districts were named after their central settlements and appear in the localisation of places with windstorm damage over the territory of the Czech Lands in Fig. 5.

For comparisons with meteorological observations and documentary information, the 20CR dataset provides a range of weather variables that are suitable for the description of the synoptic features and dynamics of the 1870 windstorm. Among these are the fields of mean sea-level pressure (MSLP), indicating surface cyclones, and wind fields at pressure levels throughout the troposphere. Wind speeds at the 850 hPa level are used to represent the general flow in the lower troposphere (at approximately 1500 m asl) and wind

speeds at 250 hPa to represent the jet stream in the upper troposphere. In addition, temperature differences of more than 6–8 °C per km in the vertical indicate layers of increased instability; the temperature difference between 1000 and the 500 hPa levels is employed to identify areas where strong turbulence from the mid- to lower troposphere may be mixed down to the surface. In addition, a totals index that calculates instability up to the mid-troposphere, based on the temperature lapse rate from 850 to 500 hPa and including the dew-point temperature at 850 hPa (Stull 2015), has been employed. Equivalent potential temperature (θe) at the 850 hPa pressure level is also taken into consideration. Areas of strong θe gradient typically mark the transition between subtropical and polar air masses associated with mid-latitude cyclones (e.g. Ulbrich et al. 2001; Pinto et al. 2008; Liberato 2014).

4 Results

4.1 Course of the windstorm and the meteorological situation

Records of wind direction and force ("wind pressure") at the Prague-Klementinum station were provided by the *Windautograf von Kreil*, a measuring instrument constructed by Karl Kreil, a former director of this observatory. Measurements of the wind force last only until midnight 26/27 October 1870 (Fig. 2) because the hurricane broke the wind vane of the recorder (Hornstein 1871); the wind pressure at that time was 47 decagrams per 100 square Paris inches (i.e. ~733 cm^2). The observer added observations of lightning at midnight and a hurricane between midnight and 0200 hours on 27 October (Hornstein 1871). Slightly different times appear in newspaper reports: *Národní listy* (28 October 1870, p. 2) reports lightning at 2300 hours (26 October), while the actual windstorm started at midnight, achieved a maximum around 0100 hours and continued at high intensity to 0300 hours (27 October). Matters calmed towards later morning. Surface air pressure had decreased steadily from the morning of 26 October (982.6 hPa at 0800 hours LMT) and reached a minimum of 964.6 hPa at midnight. With the arrival of colder air, it then increased sharply and reached 981.4 hPa at 1200 hours LMT on 27 October. The two hourly temperature measurements show a relatively sharp increase at midnight and clear cooling thereafter. Concurrently, the wind direction changed from sector south-south-west to sector west in the morning hours (at 0600 and 1000 hours LMT; other daily readings are unavailable). It follows from the characteristic variations in these weather variables that the severe winds were related to the passage of a cold front across Prague in the early hours of 27 October.

The spatio-temporal development of the 1870 windstorm was not only documented for Prague; it is also confirmed from a number of locations in the Czech Lands. Reports agree about the thunderstorm occurrence in some places or observed distant thunderstorm or lightning at others. They give windstorm durations of several hours with a clear shift in the time of duration and maximum intensity from the west to the east of the Czech territory. For example, a thunderstorm was reported for 2330 hours (26 October) at the Horní Litvínov meteorological station. Around midnight, a windstorm of hurricane force (degree 10) came from the west. It raged up to 0400 hours on 27 October (Stainhaussen 1870). At České Budějovice in southern Bohemia, a stormy south-west wind was reported after 2200 hours (26 October). It reached hurricane force around midnight, was accompanied by thunderstorms and continued up to 0300 hours on 27 October (*Bohemia*, 29 Oct. 1870, p. 3894). At the city of Brno in southern Moravia, a severe windstorm started at 0200 hours, achieved a maximum around 0400 hours, then weakened, but after 0600 hours intensified once more (*Moravská orlice*, 28 October 1870, p. 3). At the Bernartice meteorological station in Silesia, the observer reported a decline in the air pressure from the afternoon of 26 October, and the onset of strong wind gusts from the south-west at 2200 hours. The strong windstorm became severe while changing to sector west during the night.

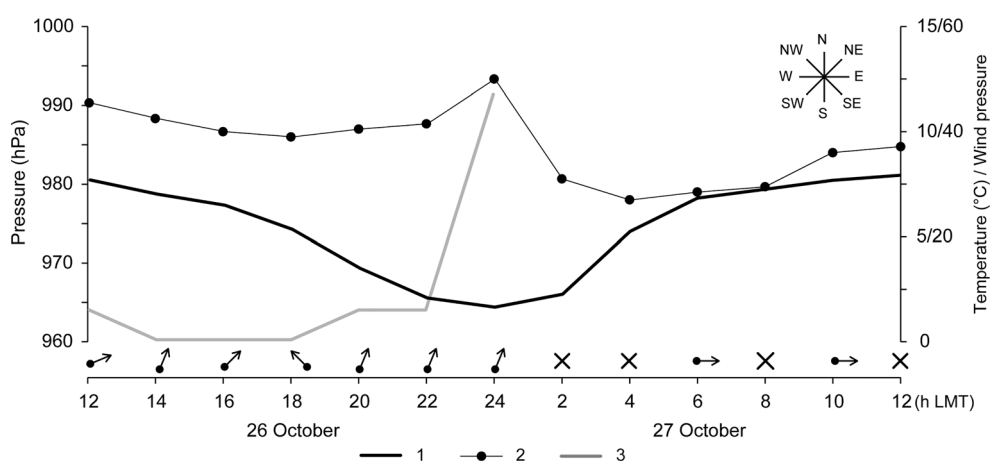

Fig. 2 Sub-daily variations in air pressure (*1*), temperature (*2*), wind pressure (decagrams per 100 square Paris inches) (*3*) and wind direction (*arrows*) on 26–27 October 1870 at the Prague-Klementinum station (data after Hornstein 1871; wind directions also given for hours with wind pressure of zero; *x* no data)

Some lightning appeared around 0200 hours on 27 October. The windstorm calmed towards noon, concurrently with a rapid increase in air pressure.

As the records from the 13 meteorological stations in Table 1 show, the standard thrice-daily readings fail to express clearly the passing of a cold front together with windstorm over the territory of the Czech Lands during the night of 26/27 October, particularly in terms of observed wind force values. Apart from the standard 16 wind directions, observers expressed wind force on an 11-degree scale from 0 (calm) to 10 (hurricane – *Orkan*) (Jelinek 1876). The evening reading on 26 October, taken at 21 or 2200 hours LMT, recorded highest wind at force 8 (stormy wind) for the Čáslav station and at force 7 (very strong wind) for the Bystřice pod Hostýnem station, with particular southerly and south-westerly components, respectively. On the mornings at 0600 or 0700 hours LMT on 27 October, higher winds were already being recorded in the eastern part of the country (Bernartice, Dačice: degree 10 – hurricane, Brno, Šumperk: degree 8 – stormy wind). The wind continued to weaken at all stations during the 27th. At 1400 hours LMT, the wind force of degree 7 (very strong wind) was recorded at only the Bernartice, Čáslav and Dačice stations. Airflow with a strong westerly or north-westerly component prevailed at both the latter observation times.

For comparisons with the observed temporal evolution, time series of temperature, wind and surface pressure have been calculated from 20CR at the grid point 14° E/50° N. This is situated approximately 20 km from the Prague-Klementinum meteorological station. Figure 3 shows a rapid pressure drop with a minimum on 26 October 1870 1800 hours UTC (1900 hours LMT) and a subsequent rise. This marks the passage of the cold front, associated with increasing temperature before the passage and decreasing temperature after it. However, the strongest winds in 20CR occur much later, around noon on 27 October 1870.

Analysis of the 20CR data also highlights the characteristics of the windstorm at a synoptic scale (Fig. 4). On 26 October 1870 1800 hours UTC (1900 hours LMT), a predominantly zonal jet stream extended from the mid-North Atlantic across central Europe, associated with a strong gradient of mid-tropospheric geopotential (Fig. 4a). A region of divergence marked the left exit zone of the jet stream (label X). This region aloft was co-located with a secondary surface low (Fig. 4b), a situation known to support the intensification of surface low-pressure systems, decreases in atmospheric stability and favouring near-surface wind acceleration and turbulence by downward mixing of momentum (e.g. Markowski and Richardson 2010; Stull 2015). Consistent with this, a band of strong near-surface wind was located south(-west) of the secondary surface low in an area of strong pressure gradients reaching east into the European continent.

At 0000 hours UTC (0100 hours LMT) on 27 October 1870, a steering cold low persisted north of the British Isles (Fig. 4c). At the same time, a secondary surface low had propagated into the region just north of the Czech Lands and was located at the tip of a distinct air mass gradient, adjacent to an area of high θe and increased temperature differences in the lower troposphere (i.e. 1000 to 500 hPa; Fig. 4c). This situation indicates increased baroclinicity and potential latent heat release, which typically contributes to the intensification of severe windstorms and may support thunder and lightning (e.g. Wernli et al. 2002; Liberato 2014). As a consequence, a band of strong, low-level winds associated with this frontal zone reached the Czech Lands. During the night, the totals

Table 1 Wind direction (WD) and wind force (WF) on an 11-degree scale (Jelinek 1876; 0 – calm, 10 – hurricane) in thrice-daily readings (T – 0600 or 0700, 1400, 2100 or 2200 hours LMT) at selected meteorological stations in the territory of the Czech Lands (data: CHMI archives; Cheb after Stainhaussen 1870)

Station	26 October			27 October					
	T	WD	WF	T	WD	WF	T	WD	WF
Bernartice	22	SW	6	06	W	10	14	W	7
Brno	22	SSW	0	06	WNW	8	14	NW	5
Bystřice pod Hostýnem	22	S	7	06	W	4	14	WNW	2
Cheb	22	SW	4–5	06	WSW	2	–	–	–
Čáslav	22	S	8	06	SW	7	14	SW	7
Dačice	22	SE	4	06	WNW	10	14	WNW	7
Děčín-Podmokly	22	–	–	06	W	4	14	W	4
Havlíčkův Brod	22	WSW	5	06	WSW	6	14	WSW	4
Hukvaldy	22	SW	–	06	SW	–	14	W	–
Litvínov, Horní Litvínov	22	E	1	07	W	5	14	NW	4
Opava	22	–	–	06	S	7	14	SW	4
Rusava	22	W	3	06	W	3	14	W	3
Šumperk	21	–	6	07	W	8	14	W	4

See Fig. 1 for station locations

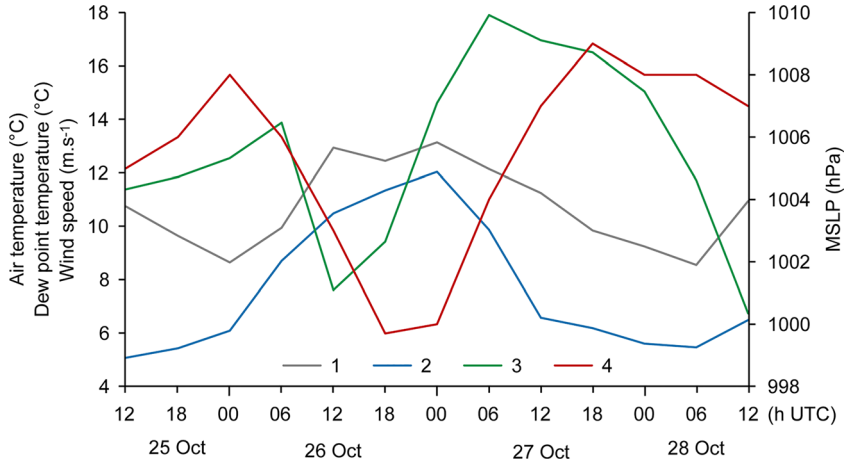

Fig. 3 Sub-daily variations in wind speed at 850 hPa (*1*), 2-m air temperature (*2*), 2-m dew-point temperature (*3*) and MSLP (*4*) from 25 October 1870 1200 hours UTC to 28 October 1870 1200 hours UTC, calculated from 20CR at grid point 14° E/50° N

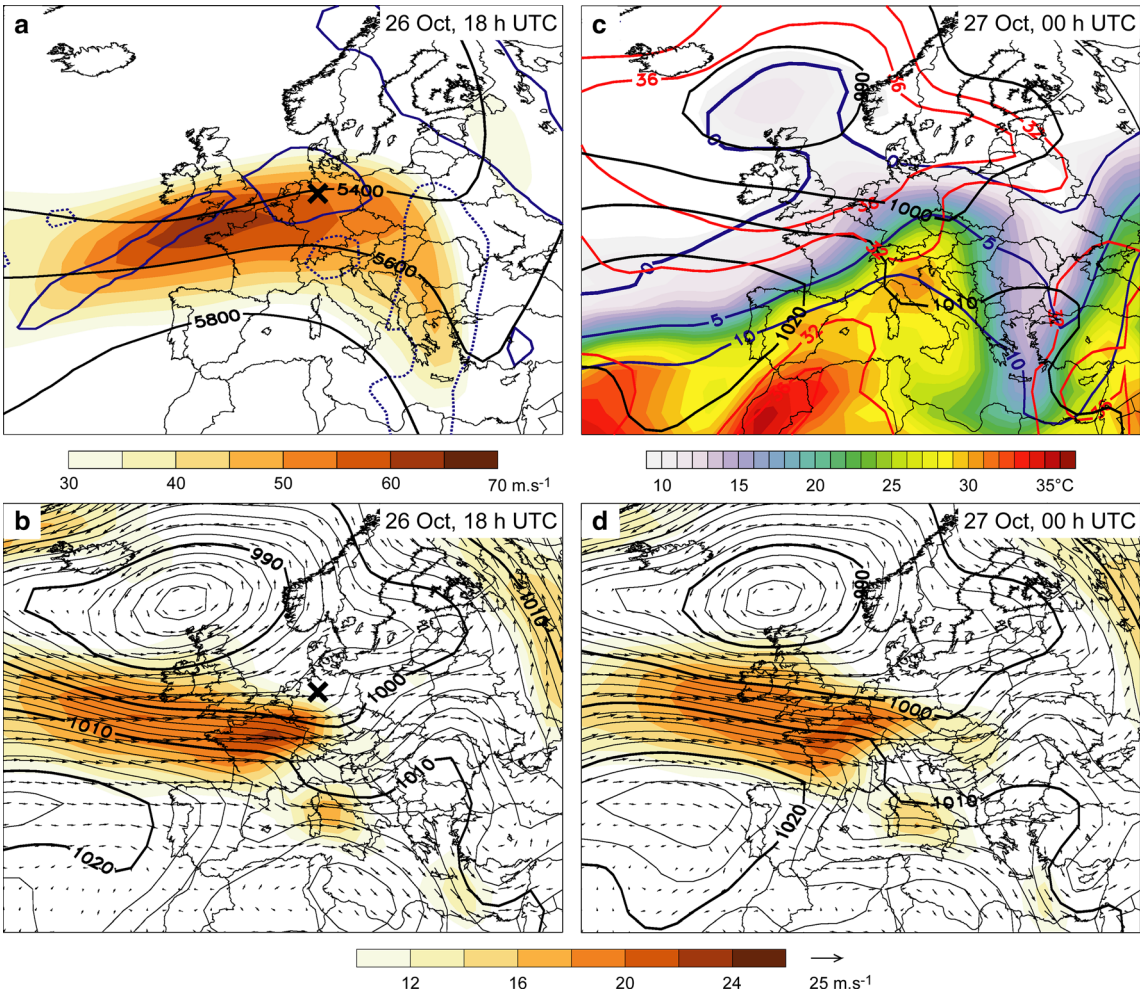

Fig. 4 Meteorological variables calculated from 20CR over the eastern Atlantic-European area on **a** 26 October, 1800 hours UTC (1900 hours CET): wind speed (*coloured*, m s^{-1}), horizontal divergence (*solid blue line*, unit 1×10^{-6} s^{-1}), and convergence (*broken line*, unit -1×10^{-6} s^{-1}) at 250 hPa height and 500 hPa heights (gpm – isolines in *black*), **b** as in **a**, but with MSLP (hPa – isobars in *black*) and wind characteristics (speed, direction as *arrows*, speeds also coloured, in m s^{-1}) at 850 hPa height, **c** 27 October, 0000 hours UTC (0100 hours CET): equivalent potential temperature (*θe*, °C, *coloured*), MSLP (hPa – isobars in *black*), surface air temperature (2 m height, °C – isotherms in *blue*), and 1000–500 hPa temperature difference (°C – isolines in *red*), **d** as in **b** for 27 October, 0000 hours UTC (0100 hours CET)

index (a severe-weather index – see Section 3; Stull 2015) increased to values of ≥52 °C on 27 October 1870 0600 hours UTC (0700 hours CET), a value that indicates potentially severe thunderstorms (not shown). In the course of the day, the front propagated further to the east along the northern border of the Czech Lands and then weakened (not shown).

It is evident from these analyses that intensities in absolute terms cannot be reflected in the 20CR dataset, and the exact timing of the frontal passage may be missing in parts. This can be explained by the large grid size (2° × 2° in 20CR) and the 6-h steps, in which lesser features such as small but nonetheless powerful secondary surface lows are not fully captured. Moreover, a much lower number of data are assimilated for the 1870 windstorm compared with more recent periods, and there are potential smoothing effects from selecting the ensemble mean. As a consequence, the most intense phase of the windstorm during the night of 26/27 October may be missed at grid point 14° E/50° N. At synoptic scales, however, the 20CR data have the capacity to describe a number of spatial patterns, interdependences and temporal dynamics that are typically associated with severe European windstorms (e.g. Ulbrich et al. 2001; Wernli et al. 2002; Pinto et al. 2008; Liberato 2014). In sum, 20CR gives strong support to the analyses based on the meteorological observations and documentary information otherwise collected.

4.2 Territorial extent and societal impacts

Instrumental and documentary data both indicate that the windstorm of the night of 26/27 October affected the entire territory of the Czech Lands. In particular, narrative sources and newspapers have facilitated the creation of a map of locations with respect to various kinds of damage (Fig. 5). General damage is reported for a total of 174 places. Specified harm to buildings and other structures is documented for 80 places, to forest stands for 91 places, and without detailed specification for 30 places. Spatial distribution of the windstorm's affects shows a higher concentration in a belt extending from western Bohemia over its central part to the broader area of the Bohemian-Moravian Highlands. The Šumava Mts. region, southern and northern Bohemia also suffered. A lower concentration of places affected is generally evident in Moravia. However, this aspect of the distribution could be partly related to different spatial densities of documentary sources available for extraction. For example, among the newspapers used was the *Reichenberger Zeitung*, published in Liberec and naturally reporting its relatively local situation in northern Bohemia, while several newspapers published in Prague concentrated on matters of interest to their readers in terms of damage reports from Prague and central Bohemia. Finally, the complicated terrain of the territory of the Czech Lands may also have had a role to play in intensifying or diminishing the actual impacts of the windstorm.

Since the most detailed descriptions of damage during the 1870 windstorm appear for the capital Prague in the majority of newspapers, Fig. 6 provides details of harm to 28 city quarters recently included in the Prague City zone. They generally complement the picture of the spatial extent of damage over the Czech Lands shown in Fig. 5. As the newspaper *Posel z Prahy* (28 Oct. 1870, p. 3) reported, "there is scarcely a house that has not suffered damage to the roofs, windows, gutters and pipes, shop signs, etc. In the morning, the streets were scattered with bricks, roofing tiles, various windows, torn-down signs, gutters, etc. The storm was of such strength that everything inside houses shook; glasses on tables, pictures on walls, etc." Detailed damage descriptions tended to focus on buildings and other structures in the Nové Město, Staré Město and Hradčany quarters. The parish church of St. Stephan in Nové Město (Fig. 7a), the Schwarzenberg palace in Hradčany (Fig. 7b) and various houses on many Prague streets (Fig. 7c) come in for particular mention (e.g. *Politik – Abendblatt*, 27 Oct. 1870, p. 2; *Politik*, 28 Oct. 1870, p. 4;

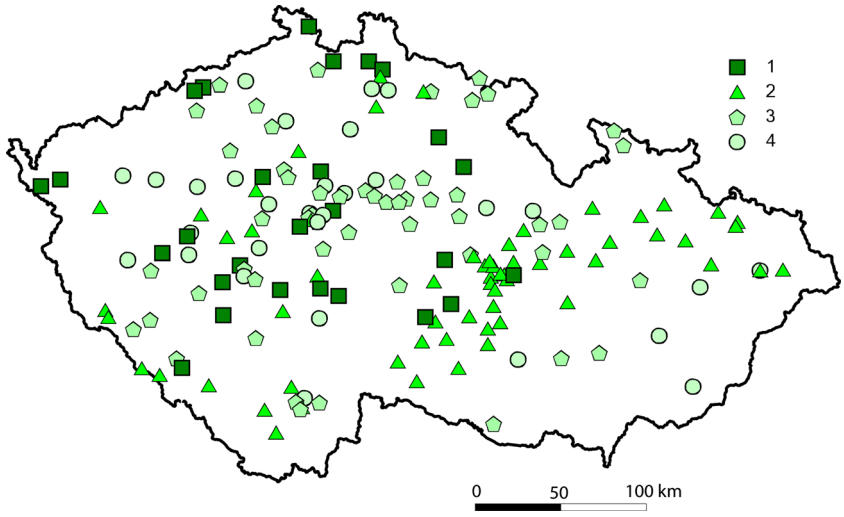

Fig. 5 Locations in the Czech Lands identifying the windstorm on 26–27 October 1870, based on documentary data with damage to forests and buildings (27 places) (*1*), forests (64) (*2*), buildings (53) (*3*) and other types of damage (30) (*4*)

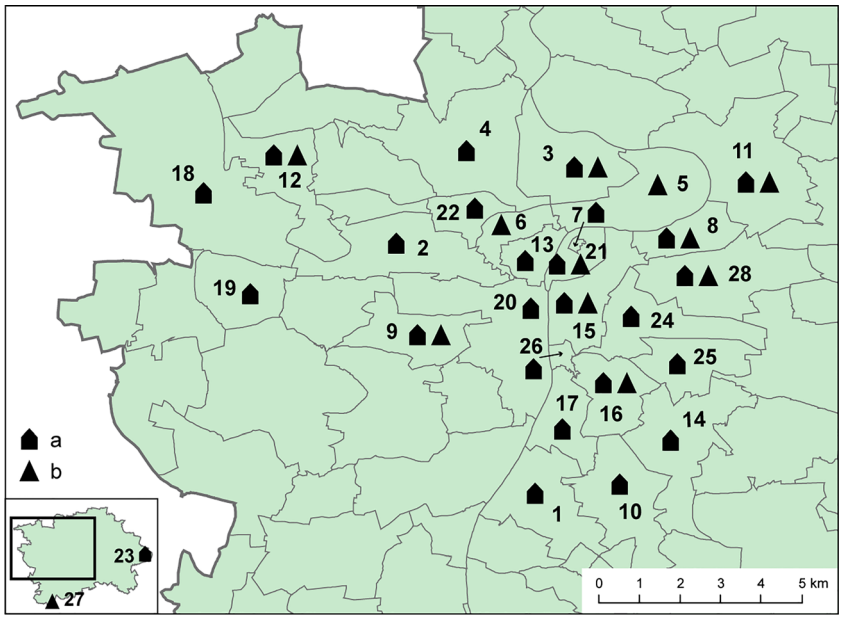

Fig. 6 Quarters of the city of Prague for which damage related to the 1870 windstorm was reported in contemporaneous newspapers (**a** buildings and other structures; **b** trees): Bráník (*1*), Břevnov (*2*), Bubeneč (*3*), Dejvice (*4*), Holešovice (*5*), Hradčany (*6*), Josefov (*7*), Karlín (*8*), Košíře (*9*), Krč (*10*), Libeň (*11*), Liboc (*12*), Malá Strana (*13*), Michle (*14*), Nové Město (*15*), Nusle (*16*), Podolí (*17*), Ruzyně (*18*), Řepy (*19*), Smíchov (*20*), Staré Město (*21*), Střešovice (*22*), Újezd nad Lesy (*23*), Vinohrady (*24*), Vršovice (*25*), Vyšehrad (*26*), Zbraslav (*27*) and Žižkov (*28*)

Politik – Abendblatt, 28 Oct. 1870, p. 2; *Politik*, 29 Oct. 1870, p. 4; *Pražský denník*, 28 Oct. 1870, pp. 2–3). The destruction at the Church of St. Stephan attracted a great deal of attention: On 27 October, it was visited by the municipality commission, Cardinal Bedřich Josef Schwarzenberg and Governor of Bohemia Alexander I. Duke Dietrichstein, Count Mensdorff-Pouilly (*Pražský denník*, 28 Oct. 1870, p. 3; ibid., 30 Oct. 1870, p. 2). As well as the harm done to various significant buildings and churches, sheds were also destroyed, crosses cast down in the cemetery, street illumination damaged, trees uprooted and other consequences also reported. Several commercial timber rafts on the River Vltava ("Na Františku") were torn away and "at that moment, the view offered by the Vltava was horrible. Troubled waves around an ell high [c. 59 cm] rocked [the river]. Torn-away rafts were forced [downstream] to the pool at the third bridge and beaten

Fig. 7 Damage to buildings caused by the 1870 windstorm in Prague as featured in drawings by F. Chalupa, published in *Světozor* (11 Nov. 1870, pp. 361, 364): **a** the Parish Church of St. Stephan, **b** Schwarzenberg palace at Hradčany and **c** house no. 549 on Ječná Street

to pieces there. Individual logs stuck vertically, but could not resist the raging torrent and fell back to the water, then turned on their ends again. Some [logs] were thrown by the mighty waves [right] over the weir." (ibid., 28 Oct. 1870, p. 3). In financial terms, the damage in Prague was estimated at considerably more than 100,000 gulden (*Národní listy*, 1 Nov. 1870, p. 3).

In addition to that in the 28 quarters in Prague, material damage to buildings and other structures (e.g. mills, barns and other farm buildings and equipment) was reported for 80 places over the territory of the Czech Lands (Fig. 5). The example of the description of damage in Plzeň (Section 2.3, part a) may be complemented by the situation in Klatovy, where the windstorm knocked down *Černá věž* (the Black Tower) in the square, "the nicest adornment of the town". Together with damage to other objects, the total value of damage in Klatovy was estimated at 50,000 gulden (*Pražský denník*, 29 Oct. 1870, p. 2). Many newspapers also reported damage to Karlštejn, one of the most famous castles in central Bohemia (e.g. *Politik*, 1 Nov. 1870, p. 4). In Brno, the largest town in Moravia, the windstorm destroyed, among other things, five pillars of a newly repaired wall of the Augustinian monastery garden, knocked down only a few days previously by a tornado on 13 October, as described by the famous geneticist Gregor Johann Mendel, who worked there (Mendel 1871). Damage to the roof of the Church of St. Nicholas and heavy damage to other buildings was reported from Znojmo, also in southern Moravia (*Znaimer Wochenblatt*, 29 Oct. 1870, p. 468).

The windstorm also brought down the poles and wires of telegraphic lines, severing connections between towns. This created particular problems for railway transport. For example, just between the stations of Poděbrady and Český Brod (*c*. 44 km), 115 telegraph poles were put out of action (*Politik – Abendblatt*, 29 Oct. 1870, p. 2). Buildings associated with some railway stations (e.g. Buštěhrad, Česká Třebová, Děčín-Podmokly, Svitavy) also suffered, while the smaller signalling/security stations around railway lines were left in ruins. Quite apart from delays to train services, total damage to the northern track of the state railways was estimated at 6000 gulden (*Národní listy*, 1 Nov. 1870, p. 3). The total damage was also exacerbated by several fires: For example, at Senomaty, a strong wind reignited a fire that had been quenched, and the eventual damage totalled 80,000 gulden (*Prager Abendblatt*, 31 Oct. 1870, p. 3).

Because the windstorm occurred during the night of 26/27 October, there was less loss of human life and fewer casualties reported than would have been the case if a windstorm had blown up during the day. One watchman was found dead in a collapsed cottage in a field in Horní Branná (*Reichenberger Zeitung*, 4 Nov. 1870, p. 3). Falling roofing tiles killed a young worker at Heřmanova Huť (*Prager Abendblatt*, 31 Oct. 1870, p. 3). The death of a housewife was reported in Malé Jirny; she had tried to close a door in loft that had been smashed in the windstorm (*Posel z Prahy*, 1 Nov. 1870, p. 3). A young boatman was drowned in the River Elbe at Ústí nad Labem, thrown from his craft into the river when two vessels collided in the storm (*Pražský denník*, 30 Oct. 1870, p. 2). A farmer was killed at Brloh when he went to the forest to examine the extent of damage and an uprooted tree fell on him (*Národní listy*, 9 Nov. 1870, p. 1). Two workers were injured by a falling tree on the road from Jablonec nad Nisou to Frýdlant (*Bohemia*, 2 Nov. 1870, p. 3965). Two tilers were injured in Prague while attempting to repair roofs (*Politik*, 2 Nov. 1870, p. 3) and one person while clearing planks (*Pražský denník*, 28 Oct. 1870, p. 3).

4.3 Damage to trees and forests

Quite apart from the destruction brought upon buildings and other structures, the 1870 windstorms uprooted and smashed trees, a factor important to a country in which forests and orchards have always played an important part in the economy. The damage was especially acute to the many fruit trees in gardens and other trees in parks, avenues and along roads on the one hand (e.g. "A nice avenue of poplar on the road to the Nusle palace [Prague] is almost totally destroyed." – *Bohemia*, 28 Oct. 1870, p. 3880), while extensive commercial forest stands suffered as well (e.g. "On the estates of the Strahov monastery at Milevsko the damage done in forests amounts to 15,000–20,000 guldens." – *Posel z Prahy*, 4 Nov. 1870, p. 3). A total of 91 places/forest districts with damage to forest stands are identified in Fig. 5. According to the newspaper *Politik* (7 Nov. 1870, p. 4), the Schwarzenberg forests in the Prášily Domain of the Šumava Mts. region were heavily affected, with the quantity of damaged timber possibly reaching *c*. 48,000 fathoms (136,416 m^3) in a forested area of 19,000 *Joch* (10,933 ha). A total of 12,000 fathoms of damaged timber (34,104 m^3) was reported for the Harrach forests in the Jilemnice Region (*Reichenberger Zeitung*, 4 Nov. 1870, p. 3).

The existing literature supplies various quantitative data describing harm to trees and the amount of timber damaged. For example, according to Saitz (1898), in just the surroundings of Český Krumlov alone, 2.29 million m^3 of timber were destroyed over an area of 3800 ha, i.e. 602.6 m^3 of timber per hectare (this figure was later cited by Chadt-Ševětínský 1913 and Frič 1934). Záloha (1970) reported for just the Vimperk area, 264,235 fathoms of timber (i.e. 750,956 m^3) lost over an area of nearly 1000 ha; foresters' reports mentioned total destruction of trees, not only of individual trunks and branches but also of whole belts of forest. For eight forestry districts around Vimperk, Jelínek (1988), using a report from the forestry office dating to 25 November 1870, mentions a total of 548,999 m^3 of solid wood (96.7% of it conifers) in a windthrow area of 902.9 ha, i.e. 607.8 m^3 of solid wood per hectare. Older forest stands proved especially vulnerable, with

losses of a mean amount of 600 m^3 of solid wood per hectare. Chief Forester Josef John was so shocked by the disaster that he requested the owner of the Vimperk domain to allow him to retire. Hošek (1981) reported forest damage of 4 million m^3 of solid timber in the Czech Lands for the 1870 windstorm, when the area of the Šumava Mts. was particularly heavily affected. According to Vicena et al. (1979), the quantity of damaged timber reached 6 million m^3, but this figure includes the Czech Lands together with Slovakia.

It is difficult to verify the above figures quantifying the totals of damaged timber because the data coverage is incomplete. The only contemporary attempt to gather data systematically at high spatial resolution was made by the Moravian-Silesian forestry association. It requested that all managers of forest districts (*Forstbezirke*, of which there were approximately 200 in Moravia and Silesia) to report back damage data in the same way that they had done after the 1868 windstorm (cf. Brázdil et al. 2017). However, only 24 forest districts responded to the call. They reported total damage of 375,968 m^3 of timber. The highest quantity of timber (56,940 m^3) was reported for the Brtnice District in the Bohemian-Moravian Highlands, where the forested area occupied 4767 ha, i.e. 11.95 m^3 of damaged timber per hectare.

5 Discussion

5.1 The 1870 windstorm in European context

Although the 26–27 October 1870 windstorm does not appear either in the exhaustive list of historic windstorms of the North Sea, British Isles and Northwest Europe by Lamb and Frydendahl (1991) nor among the disastrous windstorms described for Switzerland by Stucki et al. (2014), its importance in the central European area is documented not only by data from the Czech Lands but also from the area of what now constitutes Germany, Austria and Slovakia, as shown in Fig. 8. In Germany, a thunderstorm with subsequent windstorm appeared in the evening of 26 October. References in the press cite several examples: Karlsruhe—windstorm raged between 1800 and 2100 hours, at its highest intensity at 1930–2030 hours (*Freiburger Zeitung*, 30 Oct. 1870, p. 1); Munich—highly intense windstorm between 2200 and 2300 hours (*Bohemia*, 29 Oct. 1870, p. 3892); and Nuremberg—windstorm occurred between 2100 hours and midnight (*Bohemia*, 28 Oct. 1870, p. 3888). Windstorm impacts in Germany were reported in newspapers for a total of 26 places, particularly in the southern half of the country. As well as extensive damage to buildings and other structures (e.g. in Mannheim, Nuremberg, Regensburg and Stuttgart), roads and avenues rendered impassable by uprooted or broken trees, there were also serious consequences for forestry. For example, Vicena et al. (1979) mentioned a total of 11 million m^3 of windthrown wood for Germany arising out of the October 1870 windstorm.

A total of 17 places (four of them now parts of Vienna) were reported in Austrian connection with the windstorm. At Bregenz, a storm of hurricane force from the south-west started at 2030 hours on 26 October and a *foehn* blew until nearly the morning of the next day (Schiedermayer 1870). At Kremsmünster, a distant thunderstorm was observed between 2200 and 2300 hours and then a windstorm raged until 0400 hours of 27 October (ibid.). In Vienna, a hurricane started at midnight and continued to 0600 hours (beginning corresponds to Hollabrunn—windstorm from the south-west starting at 0015 hours and a thunderstorm with rain at 0030 hours; Stainhaussen 1870). In addition to extensive material damage to buildings and other structures (e.g. the roofs of the Hofburg and the Paulaner churches), there was also one fatality—a workman—and two other casualties (*Die Presse*, 27 Oct. 1870, p. 4).

In Slovakia, *Städtische Pressburger Zeitung* (28 Oct. 1870, p. 3), published in Bratislava, reported damage to roofs, windows, gardens, vineyards and water-mills. A further report from Turčiansky Svätý Martin mentioned a thunderstorm on the night of 26/27 October with a high wind and downpour afterwards; during the day, it became cold and snow appeared in the mountains (*Národné noviny*, 30 Oct. 1870, p. 2).

5.2 Comparison with the 7 December 1868 windstorm

The 26/27 October 1870 windstorm occurred nearly 2 years after another extraordinarily disastrous windstorm, on 7 December 1868 (Brázdil et al. 2017). Bearing this in mind, certain reports attempted comparisons. For example, a report from Brandýs nad Labem maintained that the degree of damage done by the 1868 windstorm was already severe, but "this time it was higher by far" (*Politik*, 3 Nov. 1870, p. 5). According to Záloha (1970), in the Šumava region the 1870 windstorm far exceeded that of 1868 (cf. Jelínek 1988).

As was the case with the 1868 windstorm, the high winds were related to the passage of a cold front over the territory of the Czech Lands, but in 1868, they did so in the morning and afternoon hours. Although the extent of its damage to buildings and other structures in the earlier storm was similar, there were 27 fatalities and 38 people seriously injured, a considerably higher figure (against five fatalities and five injured in 1870), because of the 1868 occurrence during the day. Contemporary newspapers and other documentary sources indicated a windstorm with damage for 237 places compared with 174 places in the current paper. Moreover, the 1868 windstorm extended farther into Europe; its imprints were recorded from the British Isles to the Netherlands, Belgium, Germany, Poland and Austria, while the 1870 windstorm is documented for only Germany, Austria and Slovakia beyond the Czech Lands.

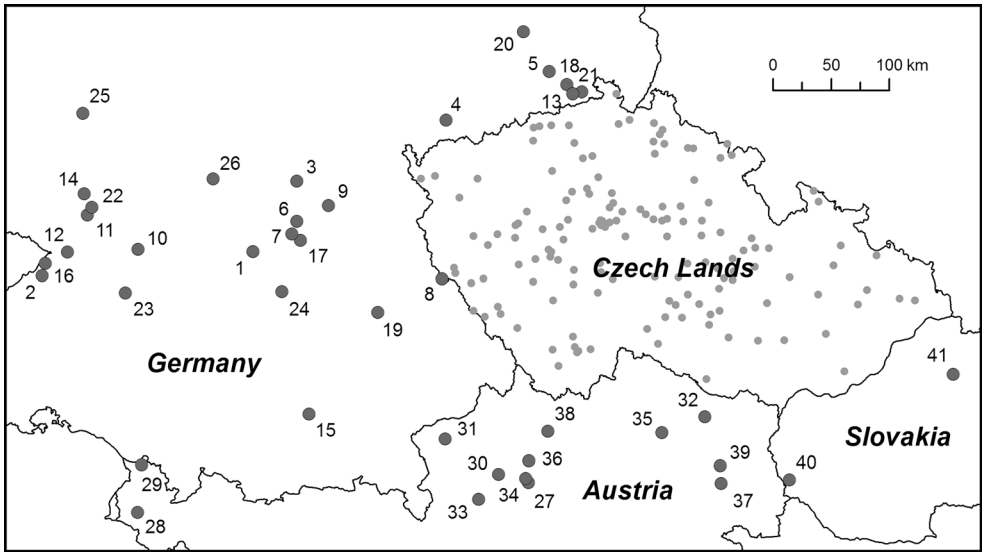

Fig. 8 Places appearing in reports of damage related to the windstorm of 26–27 October 1870 in central Europe, as extracted from newspapers (for locations in the Czech Lands see Fig. 5): Germany: Ansbach (*1*), Baden–Baden (*2*), Bamberg (*3*), Bärenwalde (*4*), Dresden (*5*), Erlangen (*6*), Fürth (*7*), Furth im Wald (*8*), Gössweinstein (*9*), Heilbronn (*10*), Hockenheim (*11*), Karlsruhe (*12*), Königstein (*13*), Mannheim (*14*), Munich (*15*), Murgthal (*16*), Nuremberk (*17*), Pirna (*18*), Regensburg (*19*), Röderau (*20*), Schandau (*21*), Schwetzingen (*22*), Stuttgart (*23*), Wiesbaden (*24*), Weissenburg in Bayern (*25*), Würzburg (*26*); Austria: Alpernstein (*27*), Bludenz (*28*), Bregenz (*29*), Gmunden (*30*), Hausruck (*31*), Hollabrunn (*32*), Ischl (*33*), Kirchdorf (*34*), Krems an der Donau (*35*), Kremsmünster (*36*), Laxenburg (*37*), Linz (*38*), Vienna (*39*); Slovakia: Bratislava (*40*) and Turčiansky Svätý Martin (*41*)

The 1868 and 1870 windstorms have often been compared in terms of forestry losses. For example, damage in 1870, reported in a letter from Břasy, was described as equal to, or higher than, that in 1868 (*Politik*, 1 Nov. 1870, p. 4). Similar claims were made for Křižanov and Nové Město na Moravě (*Verhandlungen* 1871/3, pp. 103–105). However, in those Moravian and Silesian forest districts for which data exist for both windstorms, damage in 1870 was considerably less than in 1868. On average, the 1870 windstorm damaged *c.* 9000 m^3 less timber per forest district than the 1868 one. This may have been associated with the fact that many of the trees susceptible to windthrow had already succumbed in 1868. This trend was perhaps exacerbated by the same general westerly direction of the windstorm in both cases, as observed for example in Radiměř (*Verhandlungen* 1871/3, pp. 108–109). Foresters in Brtnice also noted that fortunately, conditions (quite unlike those before the 1868 windstorm) preceding the 1870 windstorm included a prolonged dry period, which kept the ground firm (*Verhandlungen* 1871/3, p. 105). On the other hand, several forest districts (such as Křižanov, Černá or Velké Meziříčí) reported that financial damage was more severe in 1870 because many trees were broken (rather than uprooted, as in 1868), which rendered them useless as commercial timber and they could only be sold as firewood (*Verhandlungen* 1871/3, pp. 103,108).

Based on data by Saitz (1898), Záloha (1970), Hošek (1981) and Jelínek (1988), the forest damage done by the 1870 windstorm in the Šumava Mts. was particularly extensive. It even found a reflection in literature. The novella *Ze světa lesních samot* ("From the World of Lonely Forest Dwellings") by Karel Klostermann, a writer who set many of his stories in the middle Bohemian forests, the Šumava region, describes the fate of two men who spend a dramatic night of windstorm in the forest, and the sadness of foresters at the extensive damage they find after the disaster (Klostermann 1894).

The processing of damaged timber required access, in the form of roads and tracks negotiable by people and animal-drawn carts. It is a sobering measure of the loss of timber that, from only the accessible parts of the Vimperk area, 33,000 trunks were processed during November 1870 (Záloha 1970). To deal with the timber, an additional seven water sawmills were created and 850 workers from Bohemia and Bavaria were hired, of whom 670 worked throughout the summer of 1871. The "tidying-up" was finished by 1877, but afforestation continued further (Záloha 1970).

A more indirect consequence of the aggregated effect of the 1868 and 1870 windstorms, and probably the greatest burden on the forest economy of all, resulted from a major outbreak of the European spruce bark beetle (*Ips typographus*) in the 1870s. Bark beetles use fallen trees as bases in which they propagate prodigiously and then invade healthy individuals. The connections between windstorms and bark-beetle outbreaks seem evident both generally (Mitchell 2013) and locally (Zatloukal 1998; Bláha and Kotěcký 2015). On the German side of the border, the 1870 windstorm did more than 620,000 m^3 of timber damage, and together with the 1868 windstorm and the subsequent bark-beetle outbreak devastated 12.3% of all the forests there (Elling et al. 1987). On the

Czech side, salvage logging between 1868 and 1882 removed as much as 3.5 million m^3 of solid wood (Jelínek 2005). The most extensive study of the effects of the two windstorms and the bark beetle outbreak in spatial terms in the region of the Šumava Mts. and Bayerischer Wald, by Brůna et al. (2013), maintains that *c*. 40% of the 43,247 ha for which exact data are available were at least partly disturbed (7725 ha totally, 4647 ha by half). The effects of the two windstorms and the beetle outbreak are still visible in many, but not all, stands in the Šumava Mts. (Svoboda et al. 2012). These traces may take two forms: Either a characteristic wider "release" ring may be observed for a number of years after the windstorm among the growth-rings of living trees (testifying to the fact that those trees that survived the windstorm had more light available for growth), or waves of tree regeneration may also indicate the occurrence of windstorms in the past. In the Šumava area, release rings have been observed for the 1870s (Čada et al. 2013), and strong recruitment waves from the 1870s until *c*. 1900 (Janda et al. 2010; Svoboda et al. 2010).

With all these data in mind, it is hard to explain the relative lack of interest on the part of professional foresters in the consequences of the 1870 windstorm as a whole. While reaction was overwhelming after the 1868 windstorm, and data were sent back to the central forest associations from all parts of the country (Brázdil et al. 2017), after the 1870 disaster, requests by the Moravian-Silesian and the Bohemian forestry associations for similar data (*Vereinschrift* 1871/1, pp. 93–94) met with lukewarm responses. It appears that while the 1868 windstorm struck the Czech Lands after three and half decades of hurricane-free conditions (the immediately preceding disastrous windstorm, of 18–19 December 1833, damaged an estimated 3.7 million m^3 of solid timber in Bohemia and 0.5 million m^3 in Moravia and Silesia—see e.g. Hošek 1981; Brázdil et al. 2004) and therefore evoked particular shock, the 1870 windstorm seems to have failed to stimulate a similar reaction because it followed too soon upon a previous event.

6 Conclusions

The catastrophic windstorm of 26/27 October 1870, resulting in extensive material damage to buildings and other structures, windthrow in forests, some fatalities and other casualties, may be considered the second most disastrous windstorm of the nineteenth century over the Czech Lands (cf. Brázdil et al. 2004). It is runner-up to only the catastrophic event of 7 December 1868 (Brázdil et al. 2017). Combining meteorological analyses from 20CR, systematic meteorological observations, and documentary data, the high winds were related to a large horizontal pressure gradient over western and central Europe with the passage of a cold front over the territory of the Czech Lands.

Although there is a lack of high-resolution spatial data exactly to quantify the damage to forests in the Czech Lands, it is demonstrated that the 1870 windstorm totally devastated many forested areas of the Šumava Mts. It may safely be assumed that damage to forest stands in other parts of the Czech Lands was also probably severe. Subsequent to the 1868 windstorm, this second disastrous event after only 2 years, with enormous amounts of damaged trees, quickly led to the eruption of a major bark beetle calamity, starting in 1872 and continuing into 1878. The aggregate effect of these events may still be observed in many forest stands in the Czech Republic.

Despite limited documentary evidence beyond the Czech Lands, the 1870 windstorm seriously affected at least a considerable area of central Europe and was fully comparable with other severe windstorms known from more recent times. Hopefully, this study may help motivate similar research based on systematic meteorological observations and documentary data in neighbouring countries, with the aim of revealing the extraordinary character of this event in the past and the recent history of meteorological extremes and their societal impacts in central Europe.

Acknowledgements RB, PSz, PD, HV, LŘ, SS and LD were supported by project of the Czech Science Foundation ref. no. 15-11805S. RB, PD, LŘ and LD also received funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. PSz and SS were also supported by long-term research development project ref. no. RVO 67985939. PSt was supported by the Dr. Alfred Bretscher Fonds, University of Bern, Bern, Switzerland. Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and the Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. Our sincere thanks are extended to Lenka Hájková (CHMI Ústí nad Labem), Lucie Kašičková (CHMI Hradec Králové), Pavel Lipina and Miroslav Řepka (CHMI Ostrava) for the wind data from the stations cited in Table 1. Tony Long (Svinošice) helped work up the English.

References

Barredo JI (2010) No upward trend in normalised windstorm losses in Europe: 1970–2008. Nat Hazards Earth Syst Sci 10:97–104. doi:10.5194/nhess-10-97-2010

Bláha J, Kotěcký V (2015) Spruce bark beetle in Sumava NP: a precedent case of EU Wilderness Protection, the role of NGOs and the public in wilderness protection. In: Watson A, Carver S, Krenova Z, McBride B (eds) Science and stewardship to protect and sustain wilderness values: Tenth World Wilderness Congress symposium; 2013, 4–10 October; Salamanca, Spain. Proceedings RMRS-P-74. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, pp 42–54

Brázdil R (1998) Meteorological extremes and their impacts on forests in the Czech Republic. In: Beniston M, Innes JL (eds) The impacts of climate variability on forests. Springer-Verlag, Berlin, pp 20–47

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2010) European climate of the past 500 years: new challenges for historical climatology. Clim Change 101:7–40. doi: 10.1007/s10584-009-9783-z

Brázdil R, Dobrovolný P, Štekl J, Kotyza O, Valášek H, Jež J (2004) History of weather and climate in the Czech Lands VI: Strong winds. Masaryk University, Brno, p 378

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe—the state of the art. Clim Change 70:363–430. doi: 10.1007/s10584-005-5924-1

Brázdil R, Szabó P, Dobrovolný P, Řezníčková L, Kotyza O, Suchánková S, Valášek H (2016) Windstorm of the eighteenth century in the Czech Lands: course, extent, impacts. Theor Appl Climatol. doi: 10.1007/s00704-016-1806-x

Brázdil R, Szabó P, Stucki P, Dobrovolný P, Řezníčková L, Kotyza O, Valášek H, Melo M, Suchánková S, Dolák L, Chromá K (2017) The extraordinary windstorm of 7 December 1868 in the Czech Lands and its central European context. Int J Climatol. doi: 10.1002/joc.4973

Brönnimann S, Martius O, von Waldow H, Welker C, Luterbacher J, Compo GP, Sardesmukh PD, Usbeck T (2012) Extreme winds at northern mid-latitudes since 1871. Meteorol Z 21:13–27. doi:10.1127/0941-2948/2012/0337

Brůna J, Wild J, Svoboda M, Heurich M, Müllerová J (2013) Impacts and underlaying factors of landscape-scale, historical disturbance of mountain forest identified using archival documents. For Ecol Manag 305:294–306. doi:10.1016/j.foreco.2013.06.017

Bründl M, Rickli C (2002) The storm Lothar 1999 in Switzerland—an incident analysis. Forest Snow and Landscape Research 77:207–216

Brzobohatý D (2003) Ceny a mzdy v zemědělství (Prices and salaries in agriculture). Městské muzeum Slavičín, Slavičín, p 29

Chadt-Ševětínský JE (1913) Živelní pohromy (Natural disasters). Rozmara, Písek, p 19

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ (2011) The Twentieth century reanalysis project. Q J R Meteorol Soc 137:1–28. doi:10.1002/qj.776

Cram TA, Compo GP, Yin X, Allan RJ, McColl C, Vose RS, Whitaker JS, Matsui N, Ashcroft L, Auchmann R, Bessemoulin P, Brandsma T, Brohan P, Brunet M, Comeaux J, Crouthamel R, Gleason BE, Groisman PY, Hersbach H, Jones PD, Jónsson T, Jourdain S, Kelly G, Knapp KR, Kruger A, Kubota H, Lentini G, Lorrey A, Lott N, Lubker SJ, Luterbacher J, Marshall GJ, Maugeri M, Mock CJ, Mok HY, Nordli Ø, Rodwell MJ, Ross TF, Schuster D, Srnec L, Valente MA, Vizi Z, Wang XL, Westcott N, Woollen JS, Worley SJ (2015) The international surface pressure databank version 2. Geosci Data J 2:31–46. doi:10.1002/gdj3.25

Čada V, Svoboda M, Janda P (2013) Dendrochronological reconstruction of the disturbance history and past development of the mountain Norway spruce in the Bohemian Forest, central Europe. Forest Ecol Manag 295:59–68. doi:10.1016/j.foreco.2012.12.037

Della-Marta PM, Liniger MA, Appenzeller C, Bresch DN, Köllner-Heck P, Muccione V (2010) Improved estimates of the European winter windstorm climate and the risk of reinsurance loss using climate model data. J Appl Meteorol Climatol 49:2092–2120. doi:10.1175/2010JAMC2133.1

Deutsche Rück (2015) Sturmdokumentation 2015 Deutschland. Deutsche Rückversicherung, Düsseldorf, p 62

Donat MG, Leckebusch GC, Pinto JG, Ulbrich U (2010) Examination of wind storms over Central Europe with respect to circulation weather types and NAO phases. Int J Climatol 30:1289–1300. doi:10.1002/joc.1982

Elling W, Bauer E, Klemm G, Koch H (1987) Klima und Boden. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten, München, p 255

Falťan V, Katina S, Bánovský M, Pazúrová Z (2009) The influence of site conditions on the impact of windstorms on forests: the case of the High Tatras foothills (Slovakia) in 2004. Morav Geogr Rep 17:10–18

Fink AH, Brücher T, Ermert V, Krüger A, Pinto JG (2009) The European storm Kyrill in January 2007: synoptic evolution, meteorological impacts and some considerations with respect to climate change. Nat Hazards Earth Syst Sci 9:405–423. doi:10.5194/nhess-9-405-2009

Freitas JG, Dias JA (2013) 1941 windstorm effects on the Portuguese Coast. What lessons for the future? In: Conley DC, Masselink G, Russell PE, O'Hare TJ (eds) Proceedings 12th International Coastal Symposium (Plymouth, England). J Coastal Res Special Issue 65: 714–719. doi: 10.2112/SI65-121

Frič J (1934) Lesy v historické minulosti (Forests in the historical past). Československý háj 11:331–338

Gardiner B, Blennow K, Carnus JM, Fleischer P, Ingemarson F, Landmann G, Lindner M, Marzano M, Nicoll B, Orazio C, Peyron JL, Schelhaas MJ, Schuck A, Spielmann M, Usbeck T (2010) Destructive storms in European forests?: past and forthcoming impacts. Available from: http://www.efiatlantic.efi.int/portal/research/storm_european_study/

Goyette S, Beniston M, Caya D, Laprise R, Jungo P (2001) Numerical investigation of an extreme storm with the Canadian Regional Climate Model: the case study of windstorm VIVIAN, Switzerland, February 27, 1990. Clim Dyn 18:145–168. doi:10.1007/s003820100166

Gregor Z (1955) Rozbor povětrnostní situace, provázené orkánem na území ČSR, ze dne 17. ledna 1955 (Analysis of the weather situation accompanied by hurricane over the CSR territory from 17 January 1955). Meteorol Zpr 8:80–82

Hornstein C (1871) Magnetische und meteorologische Beobachtungen auf der k. k. Sternwarte zu Prag im Jahre 1870. K. k. Hofbuchdruckerei von Gottlieb Haase Söhne, Prag, p 200

Hostýnek J, Novák M, Žák M (2008) Kyrill a Emma v Česku – meteorologické příčiny, průběh bouří s hodnocením větrných extrémů (The Kyrill and Emma storms in Czechia – meteorological causes and course of the storms, with an evaluation of extremes of wind). Meteorol Zpr 61:65–71

Hošek E (1981) Studie o výskytu kalamit na území ČSR od roku 1990 (A study of calamity occurrence over the territory of ČSR since 1990). Lesprojekt, Brandýs nad Labem, p 110

Janda P, Bače R, Svoboda M, Starý M (2010) Věková a prostorová struktura horského smrkového lesa v I. zoně "Trojmezná" v NP Šumava (Temporal and spatial structure of the mountain Norway spruce forest in the core zone of "Trojmezná" in the Šumava NP). Silva Gabreta 16:43–59

Jelinek C (1876) Kurzgefasste Anleitung für meteorologische Stationen dritter Ordnung, d. h. solche Stationen, welche blos mit einem einfachen Thermometer und einem Regenmesser ausgerüstet sind. Druck der kaiserlich-königlichen Hof- und Staatsdruckerei, Wien

Jelinek C, Fritsch C (1873) Jahrbücher der k. k. Central-Anstalt für Meteorologie und Erdmagnetismus. Neue Folge, VII. Band, Jahrgang 1870. Wilhelm Braumüller, Wien, p 272

Jelínek J (1988) Větrná a kůrovcová kalamita na Šumavě z let 1868 až 1878 (The wind and bark-beetle disaster in Šumava from 1868 to 1878). Lesprojekt, Brandýs nad Labem, p 46

Jelínek J (2005) Od jihočeských pralesů k hospodářským lesům Šumavy (From the south Bohemian primeval forests to the commercial forests of Šumava). MZE ČR, Úsek lesního hospodářství, UHUL Brandýs nad Labem, p 124 (+ 29 supplements)

Kaňák J, Benko M, Simon A, Sokol A (2007) Case study of the 9 May 2003 windstorm in southwestern Slovakia. Atmos Res 83: 162–175. doi: 10.1016/j.atmosres.2005.09.012

Karremann MK, Pinto JG, von Bomhard PJ, Klawa M (2014) On the clustering of winter storm loss events over Germany. Nat Hazards Earth Syst Sci 14:2041–2052. doi:10.5194/nhess-14-2041-2014

Kašpar M, Müller M, Crhová L, Holtanová E, Polášek JF, Pop L, Valeriánová A (2017) Relationship between Czech windstorms and air temperature. Int J Climatol 37:11–24. doi: 10.1002/joc.4682

Kington J (1998) The great storm of 1–2 October 1697. Weather 53:424–428. doi:10.1002/j.1477-8696.1998.tb06361.x

Klostermann K (1894) Ze světa lesních samot (From the world of lonely forest dwellings). Jos. R. Vilímek, Praha, p 158

Koráb J (1883) Kniha pamětní král. krajského města Plzně od roku 775 až 1870. Založena a sestavena od Martina Hrušky, městského archiváře (Memorial book of the royal district town of Plzeň from 755 to 1870. Established and compiled from the work of Martin Hruška, town archivist). Nákladem dědiců Hruškových, Plzeň, p 1125

Kurz M (2002) Die Dezemberstürme 1999. Berichte des Deutschen Wetterdienstes 220, Offenbach am Main, p 75

Lamb HH, Frydendahl K (1991) Historic storms of the North Sea. British Isles and Northwest Europe. Cambridge University Press, Cambridge, p 204

Liberato MLR (2014) The 19 January 2013 windstorm over the North Atlantic: large-scale dynamics and impacts on Iberia. Wea Clim Extremes 5–6:16–28. doi:10.1016/j.wace.2014.06.002

Liberato MLR, Pinto JG, Trigo IF, Trigo RM (2011) Klaus—an exceptional winter storm over northern Iberia and southern France. Weather 66:330–334. doi:10.1002/wea.755

Lugo AE (2008) Visible and invisible effects of hurricanes on forest ecosystems: an international review. Austral Ecology 33:368–398. doi:10.1111/j.1442-9993.2008.01894.x

Machačová J, Matějček J (2002) Nástin sociálního vývoje českých zemí 1780–1914 (Outline of social development in the Czech Lands, 1780–1914). Slezské zemské muzeum, Opava, p 498

Markowski P, Richardson YP (2010) Mesoscale Meteorology in Midlatitudes. Wiley-Blackwell, Chichester, p 414

Mendel G (1871) Die Windhose vom 13. October 1870. Verhandlungen des naturforschenden Vereines in Brünn, Abhandlungen 9:229–246

Minár J, Falťan V, Bánovský M, Damankošová Z, Kožuch M (2009) Influence of site conditions on the windstorm impact: a case study of the High Tatras foothills in 2004. Landform Analysis 10:95–101

Mitchell SJ (2013) Wind as a natural disturbance agent in forests: a synthesis. Forestry 86:147–157. doi:10.1093/forestry/cps058

Munich Re (1990) Windstorm—new loss dimensions of a natural hazard. Münchener Rück, München, p 114

Munzar J (2002) Vichřice ve střední Evropě 29./30. ledna 1801, její škody a ohlasy (A windstorm in Central Europe on 29/30 January 1801, damage done and responses). Meteorol Zpr 55:82–86

Munzar J (2006) Josef Stepling a vichřice ve střední Evropě v únoru 1756 (Josef Stepling and windstorms in Central Europe in February 1756). Meteorol Zpr 59:86–90

Nekovář J, Valter J (1998) Vybrané kalamitní polomy a jejich meteorologické vyhodnocení (Selected catastrophic examples of wind-damage to trees and their meteorological evaluation). Meteorol Zpr 51:106–112

Nilsson C, Stjernquist I, Bärring L, Schlyter P, Jönsson AM, Samuelsson H (2004) Recorded storm damage in Swedish forest 1901–2000. Forest Ecol Manag 199:165–173. doi:10.1016/j.foreco.2004.07.031

Nožička J (1956) Z minulosti slezských lesů. Nástin jejich vývoje od nejstarších časů do r. 1914 (From the past of the Silesian forests. An outline of their development from the oldest times to 1914). Slezský studijní ústav, Opava, p 129

Nožička J (1957) Přehled vývoje našich lesů (An overview of the development of our forests). Státní zemědělské nakladatelství, Praha, p 463

Pearce R, Lloyd D, McConnell D (2001) The post-Christmas 'French' storms of 1999. Weather 56:81–91. doi:10.1002/j.1477-8696.2001.tb06541.x

Pfeifer K (2014) Stürme über Europa. Eine Auswahl aus den Niederlanden und Österreich in der Frühen Neuzeit. Eine Kulturgeschichte. LIT Verlag, Berlin, Münster, Wien, Zürich, London, p 359

Pfeifer K (2015) On the representation of an early modern Dutch storm in two poems. Culture Unbound 7:433–454

Pfister C, Garnier E, Alcoforado MJ, Wheeler D, Luterbacher J, Nunes MF, Taborda JP (2010) The meteorological framework and the cultural memory of three severe winter-storms in early eighteenth-century Europe. Clim Change 101:281–310. doi: 10.1007/s10584-009-9784-y

Pinto JG, Zacharias S, Fink AH, Leckebusch GC, Ulbrich U (2008) Factors contributing to the development of extreme North Atlantic cyclones and their relationship with the NAO. Clim Dyn 32:711–737. doi:10.1007/s00382-008-0396-4

Roberts JF, Champion AJ, Dawkins LC, Hodges KI, Shaffrey LC, Stephenson DB, Stringer MA, Thornton HE, Youngman BD (2014) The XWS open access catalogue of extreme European windstorms from 1979 to 2012. Nat Hazards Earth Syst Sci 14:2487–2501. doi:10.5194/nhess-14-2487-2014

Saitz A (1898) Beschreibung der Fürst Adolf Josef zu Schwarzenberg'schen Domaine Krumau mit besonderer Rücksicht auf deren Forste: nebst Beschreibung der Excursionstour des Böhmischen Forstvereines in obgennante Forste im Jahre 1898. Verlag d. Böhm. Forstvereines, Prag, p 120

Schelhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. Glob Change Biol 9:1620–1633. doi:10.1046/j.1365-2486.2003.00684.x

Schiedermayer C (1870) Der Sturm vom 26. und 27. Oktober. Zeitschrift der österreichischen Gesellschaft für Meteorologie 5:609–610

Schüepp M, Schiesser HH, Huntrieser H, Scherrer HU, Schmidtke H (1994) The windstorm "Vivian" of 27 February 1990: about the meteorological development, wind forces and damage situation in forests of Switzerland. Theor Appl Climatol 49:183–200. doi:10.1007/BF00865533

Setvák M, Strachota J (1986) Vichřice dne 23. 11. 1984 z pohledu distančních metod měření (The windstorm of 23 November 1984 from the point of view of remote sensing). Meteorol Zpr 39:1–9

Simon A, Kaňák J, Sokol A, Putsay M, Uhrínová L, Csirmaz K, Okon Ľ, Habrovský R (2011) Case study of a severe windstorm over Slovakia and Hungary on 25 June 2008. Atmos Res 100:705–739. doi:10.1016/j.atmosres.2010.12.012

Stainhaussen O von (1870) Der Sturm vom 26. und 27. Oktober. Zeitschrift der österreichischen Gesellschaft für Meteorologie 5:610

Stucki P, Brönnimann S, Martius O, Welker C, Imhof M, von Wattenwyl N, Philipp N (2014) A catalog of high-impact windstorms in Switzerland since 1859. Nat Hazards Earth Syst Sci 14:2867–2882. doi:10.5194/nhess-14-2867-2014

Stucki P, Brönnimann S, Martius O, Welker C, Rickli R, Dierer S, Bresch DN, Compo GP, Sardeshmukh PD (2015) Dynamical downscaling and loss modeling for the reconstruction of historical weather extremes and their impacts. A severe foehn storm in 1925. Bull Amer Met Soc 96:1233–1241. doi:10.1175/BAMS-D-14-00041.1

Stucki P, Rickli R, Brönnimann S, Martius O, Wanner H, Grebner D, Luterbacher J (2012) Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868. Meteorol Z 21:531–550. doi:10.1127/0941-2948/2012/368

Stull RB (2015) Practical meteorology: an algebra-based survey of atmospheric Science. University of British Columbia, Vancouver, p 938 (http://www.eos.ubc.ca/books/Practical_Meteorology/)

Svoboda M, Janda P, Nagel TA, Fraver S, Rejzek J, Bače R (2012) Disturbance history of an old-growth sub-alpine *Picea abies* stand

in the Bohemian Forest, Czech Republic. J Veg Sci 23:86–97. doi:10.1111/j.1654-1103.2011.01329.x

Svoboda M, Fraver S, Janda P, Bače R, Zenáhlíková J (2010) Natural development and regeneration of a central European montane spruce forest. Forest Ecol Manag 260:707–714. doi:10.1016/j.foreco.2010.05.027

Swiss Re (2015) Natural catastrophes and man-made disasters in 2014: convective and winter storms generate most losses. Sigma report no. 2/2015

Ulbrich U, Fink AH, Klawa M, Pinto JG (2001) Three extreme storms over Europe in December 1999. Weather 56:70–80. doi:10.1002/j.1477-8696.2001.tb06540.x

Ulbrich U, Leckebusch GC, Donat MG (2013) Windstorms, the most costly natural hazard in Europe. In: Boulter S, Palutikof J, Karoly DJ, Guitart D (eds) Natural disasters and adaptation to climate change. Cambridge University Press, Cambridge, pp 109–120

Usbeck T (2014) Wintersturmschäden im Schweizer Wald von 1865 bis 2014. Schweiz Z Forstwes 166:184–190

Usbeck T, Wohlgemuth T, Dobbertin M, Pfister C, Bürgi A, Rebetez M (2010) Increasing storm damage to forests in Switzerland from 1858 to 2007. Agric For Meteorol 150:47–55

Vaquero JM, García-Herrera R, Wheeler D, Chenoweth M, Mock CJ (2008) A historical analog of 2005 hurricane Vince. Bull Amer Meteorol Soc 89:191–201. doi:10.1175/BAMS-89-2-191

Vereinschrift (1871) Vereinschrift für Forst-, Jagd- und Naturkunde. Böhmischen Forstvereine. Prag

Verhandlungen (1871) Verhandlungen der Forstwirthe von Mähren und Schlesien. K. k. Ackerbaugesellschaft für Mähren und Schlesien, Brünn

Webb SL (1999) Disturbance by wind in temperate-zone forests. In: Walker LR (ed) Ecosystems of disturbed ground. Elsevier Science Press, New York, pp 187–263

Welker C, Martius O, Stucki P, Bresch D, Dierer S, Brönnimann S (2016) Modelling economic losses of historic and present-day high-impact winter windstorms in Switzerland. Tellus A 68:29546. doi:10.3402/tellusa.v68.29546

Wernli H, Dirren S, Liniger MA, Zillig M (2002) Dynamical aspects of the life cycle of the winter storm "Lothar" (24–26 December 1999). Q J R Meteorol Soc 128:405–429. doi:10.1256/003590002321042036

Wheeler D (2003) The great storm of November 1703: a new look at the seamen's records. Weather 58:419–427. doi:10.1256/wea.83.03

Vicena I, Pařez J, Konôpka J (1979) Ochrana lesa proti polomům (Protection of forests against windthrow). Ministerstvo lesního a vodního hospodářství ČR ve Státním zemědělském nakladatelství, Praha, p 244

Záloha J (1970) Sto let od šumavské lesní katastrofy (100 years on from the Šumava forest catastrophe). Výběr z prací členů Historického kroužku Jihočeského muzea v Českých Budějovicích 7:9–13

Zatloukal V (1998) Historické a současné příčiny kůrovcové calamity v Národním parku Šumava (Historical and current factors of the bark beetle calamity in the Šumava national park). Silva Gabreta 2:327–357

Zimmerli P, Renggli D (2015) Winter storms in Europe: messages from forgotten catastrophes. Swiss Re, Zurich, p 22