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A long-term chronology of summer half-year hailstorms for South Moravia, Czech Republic

Rudolf Brázdil[1,2,*], Kateřina Chromá[2], Hubert Valášek[1,3], Lukáš Dolák[1,2], Ladislava Řezníčková[1,2], Pavel Zahradníček[2,4], Petr Dobrovolný[1,2]

[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]Moravian Land Archives, Palackého nám. 1, 625 00 Brno, Czech Republic
[4]Czech Hydrometeorological Institute, Regional office Brno, Kroftova 43, 616 67 Brno, Czech Republic

ABSTRACT: Climatological analyses of hailstorms, as phenomena of local or regional occurrence with associated damage, depend strongly on the quality and density of meteorological observations. Documentary sources, both historical and modern, including insurance company records, can be used to complement existing meteorological data or extend them into the period prior to continuous meteorological observations. This paper employs such aids to compile a long-term hailstorm chronology for the summer half-year (April–September) in South Moravia (Czech Republic) based on derivations from various types of documentary evidence together with systematic meteorological records. Although the first single hailstorm record dates back to 17 August 1435, the number of hailstorms detected only increases significantly after the 18th century. Documentary sources favour reports of particularly damaging hailstorms, so frequency increases with the number of surviving documents; obviously, this can never achieve the coverage maintained in the period of organised meteorological observations. The best temporal coverage of hailstorm days during the summer half-year in South Moravia starts in 1925 and expresses an overall decreasing trend of −0.05 d per 10 yr up to 2015, more marked after 1961 (−1.4 d per 10 yr). Particularly damaging hailstorms, on 20 June 1848, 1 July 1902, 10 July 1902 and 19 July 1903, are described. Finally, uncertainties in the hailstorm chronology are discussed, and differences related to various aspects of hailstorm days detected from documentary and meteorological data in three 40 yr periods are analysed.

KEY WORDS: Hailstorms · Hailstorm days · Damaging hailstorms · Documentary data · Meteorological observations · Fluctuation · South Moravia

1. INTRODUCTION

Hailstorms are small-scale but severe weather phenomena which do considerable damage at local or regional scales ranging from a single to many square kilometres (Knight & Knight 2003). This may include totally destroyed crops, damaged roofs and windows, injuries to people, animal deaths, and more. For example, hailstones larger than golf balls fell in late July/early August 2013 in parts of Germany, chipping facades, shattering glass and even denting vehicle bodywork. Insurance losses from this storm exceeded 4 billion (bn) Euro (Münchener Rückversicherungs-Gesellschaft 2014). Faust (2016) calculated overall losses from some of the most disastrous hailstorm events, adjusted to 2015 values: hailstorms on 12 July 1984 in Germany (Munich region): US$5.4 bn (insured losses US$2.7 bn); hailstorms and severe storms on 27–28 July 2013 in Germany: US$5 bn (insured losses US$3.8 bn); severe storm Ela and hailstorms on

*Corresponding author: brazdil@sci.muni.cz

7–10 June 2014 in France, Belgium and Germany: US$3.8 bn (insured losses US$3.0 bn) and 6 fatalities; and severe storms and hailstorms on 23–24 July 2009 in Austria, the Czech Republic, Germany, Poland and Switzerland: US$2.2 bn (insured losses US$ 1.3 bn) and 11 fatalities.

Although hailstorms are not among the most frequently studied topics in climatology (for the most modern, comprehensive overview of hailstorm research in Europe, see Punge & Kunz 2016), individual disastrous events, with descriptions of corresponding meteorological patterns, synoptic causes and damaging effects, attract more frequent attention. An example may be found in the exceptionally destructive hailstorm of 12 July 1984 in southern Bavaria (Germany). In a belt of hail occurrence, some 250 km long and 5 to 15 km wide, Munich and its surroundings suffered particular damage (Heimann & Kurz 1985, Kurz 1985, 1986, Höller & Reinhardt 1986, Kaspar et al. 2009). Many similar papers describing individual hail events may also be found at national levels, such as the Czech Republic (e.g. Pavlík et al. 1988, Šálek 1998, Starostová 2000, Šálek et al. 2008, Sokol et al. 2014) and other countries (e.g. Sioutas & Flocas 2003, Farley et al. 2004a,b, Berdon 2009, Púčik et al. 2011).

The situation with respect to the climatology of hailstorms in terms of their spatiotemporal variability is more complex. This may be due in part to the quality of hail observations at meteorological stations, where weak hail may remain unnoticed or confused with sleet. Further, considering the distances between individual stations, some hailstorms of lesser areal extent may not be recorded at all. Changes in mode of observation also influence matters as, for example, in Canada, where automatic stations that do not report hail started to replace the visual observation network in 1993 (Etkin & Brun 1999). Problems with standard hail observations may be partly overcome by the use of weather radar (e.g. Skripniková & Řezáčová 2010, 2014) or the hail-pad network (e.g. Palencia et al. 2009). Although hailstorm data are primarily collected and archived at national level, the European Severe Weather Database (Dotzek et al. 2009; www.eswd.eu/) is particularly worthy of note for collecting such data at an international level.

Despite these limitations, several papers investigate hailstorm chronologies in the medium- and long-term. For example, Brázdil et al. (1998) analysed hailstorms together with thunderstorms and extreme precipitation in South Moravia (Czech Republic) for 1946–1995. Changnon & Changnon (2000) studied long-term fluctuations in hail frequency for 66 stations in the United States for 1896–1995. Vinet (2001) created a hailstorm risk map for France. Webb et al. (2001, 2009) addressed the climatology of severe hailstorms in Great Britain. Počakal (2003) compared hail characteristics for 1981–1990 and 1991–1999 in north-western Croatia (for hail in Croatia, see also Počakal et al. 2009, Počakal 2011). Chromá et al. (2005) investigated the spatiotemporal variability of hailstorms in Moravia and Silesia (Czech Republic) in 1961–2000. Simeonov et al. (2009) analysed hail in association with severe convective storms in Bulgaria for 1961–2006. Berthet et al. (2011) studied regional and annual variations in hail frequency and intensity based on 23 yr hail-pad records in south-western France. Baldi et al. (2014) worked with hail data from various sources to create a climatology of hail frequency in Italy for 1971–2009. Ćurič & Janc (2016) studied the spatiotemporal variability of hailstorms in Serbia in the 1949–2012 period.

Many authors have addressed the atmospheric characteristics that accompany hail occurrence, as well as corresponding circulation patterns. For example, Kunz et al. (2009) investigated trends in thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in south-west Germany. Eccel et al. (2012) used hail-pad networks to quantify hailstorms over Trentino in the Italian Alps for the 35 yr after 1974 and analysed linkages with atmospheric variables. Suwała (2013) employed data from 16 stations for the 1951–2010 period to examine the influence of atmospheric circulation and thermal conditions in the troposphere on hail occurrence over the North German Plain. Results from Suwała & Bednorz (2013) derived from data for 1966–2010 from stations in Germany and Poland indicate a relation between the occurrence of hailstorms and negative anomalies of sea-level pressure and 500 hPa heights. García-Ortega et al. (2014) reported upon the characteristics of atmospheric fields related to hailstorms in north-western Spain. Merino et al. (2014) analysed both the incidence and the atmospheric characterisation of hailstorms in south-western France, using data from a hail-pad network, between 2000 and 2010.

However, far less attention has been paid to the use of hailstorm data contained in various types of documentary evidence (Brázdil et al. 2005a, 2010). These may extend existing hailstorm knowledge not only into the pre-instrumental period, but may also prove a useful supplement to information derived from the period of systematic meteorological observations. For example, Prieto et al. (2001) used documentary data to investigate periodicities in annual hail intensity in the Mendoza area (Argentina) for 1887–1987. In Australia, Schuster et al. (2005) used reports of hail in the 1781–2003 period, derived from both scientific sources and the popular press, to create a hail climatology for the greater Sydney area and the state of New South Wales. Brázdil & Kirchner (2007) used documentary data and systematic meteorological observations for Moravia and Silesia to examine hailstorms from the 19th century to the present. Changnon (2009) found an increase in major hail-damage losses in the US during the 1950–2006 period. Mauelshagen (2011) described the history of hail insurance and reinsurance in Switzerland with respect to hailstorm variability in the 1880–1932 period. More recently, Brázdil et al. (2016) presented hailstorm frequency series for South Moravia (Czech Republic) derived from taxation data that dated back to the 17th century.

This study analyses the various data sources that cover hailstorms and evaluates their capacity to create a long-term chronology of hailstorms over the territory of South Moravia in the south-eastern part of the Czech Republic. A relatively small study area (ca. 15 029 km^2) was chosen for which there is relatively good data coverage in both documentary and systematic meteorological records. The analysis is limited to only the summer half-year (April–September) because hailstorms occur predominantly in this part of the year and more rarely in the winter half-year (October–March) (cf. Tolasz et al. 2007); moreover documentary evidence tends to focus on hailstorms injurious to agriculture (Brázdil et al. 2016), i.e. those occurring in the summer half-year.

2. DATA

2.1. Documentary data

The impressive local or regional nature of the damage done by hailstorms often leads to their being recorded in a variety of documentary sources (Brázdil et al. 2005a, 2010). Typically, documentary evidence refers to events in the pre-instrumental period but it also overlaps with the period of systematic meteorological observations following the establishment of national networks of meteorological stations. Hailstorm data may be extracted from various types of documentary sources, as listed below (for locations of places in South Moravia mentioned in text, see Fig. 1).

2.1.1. Annals, chronicles, memoirs

Hailstorms causing damage are usually reported in narrative sources together with other weather anomalies and hydrometeorological extremes. For example, Jiřík Bartošek copied an older record by Jan Kúdelka into his chronicle for Uherský Brod (Zemek 2004): '*1555 on the Wednesday after St. Martha* [31 July] *hailstones fell at Uherský Brod and did damage to vineyards*.' The parish chronicle from Nové Město na Moravě reports a hailstorm from 3 July 1668 (archival source AS6): '*On the Tuesday after Twelve Apostles* [30 June] *came* [such] *heavy weather and a hailstorm from God's own bedlam* [that] *it beat down grain in the demesnes of Nové Město* [na Moravě] *and Žd'ár* [nad Sázavou], *smashed the roofs of buildings and also broke roof timbers. May God preserve us from such punishments*.' An illustration of hailstones (Fig. 2) related to a hailstorm on 5 June 1699 in Olomouc (central Moravia) from the Franciscan 'book of memory' is unique as a pictorial hailstorm record (AS2). A relatively more recent record may be found in the chronicle of the Jalubí community for 24 June 1951 (AS5): '*A great thunderstorm with windstorm and hailstorm came on 24 June before 7 p.m. This* […] *lasted around 20 minutes and came from the north-west. Hailstones fell like snow and measured 20 to 25 millimetres. Grain was flattened in a matter of minutes. Vineyards and barley-crops were totally devastated for the greater part* […].' In general, the hailstorms that appear in narrative sources are related to larger, particularly damaging events and suffer from inhomogeneity, both temporal and territorial.

2.1.2. Visual daily weather records

Visual daily weather records are another source of documentary data. Some authors just make a short note of hail occurrence, as did the cleric Šimon Hausner from Buchlovice, who kept daily weather records for 1803–1831. Records such as '*rain with hailstones* […] *like small peas*' from 16 May 1807 and '*heavy thunderstorm with intense downpour and hailstones*' from 21 June 1815 are typical of his observations (AS4). More detailed hailstorm information, including impacts, may be found in the daily weather records kept by Lukáš Kraus, an Augustinian cleric in Brno, who kept systematic weather observations from 29 May 1826 to 21 December 1832 (Brázdil et al. 2005b). His description of a hailstorm on 15 June 1826, for example, reads: '*In the afternoon, after 6 p.m., a terrible thunderstorm with hail* [so strong]

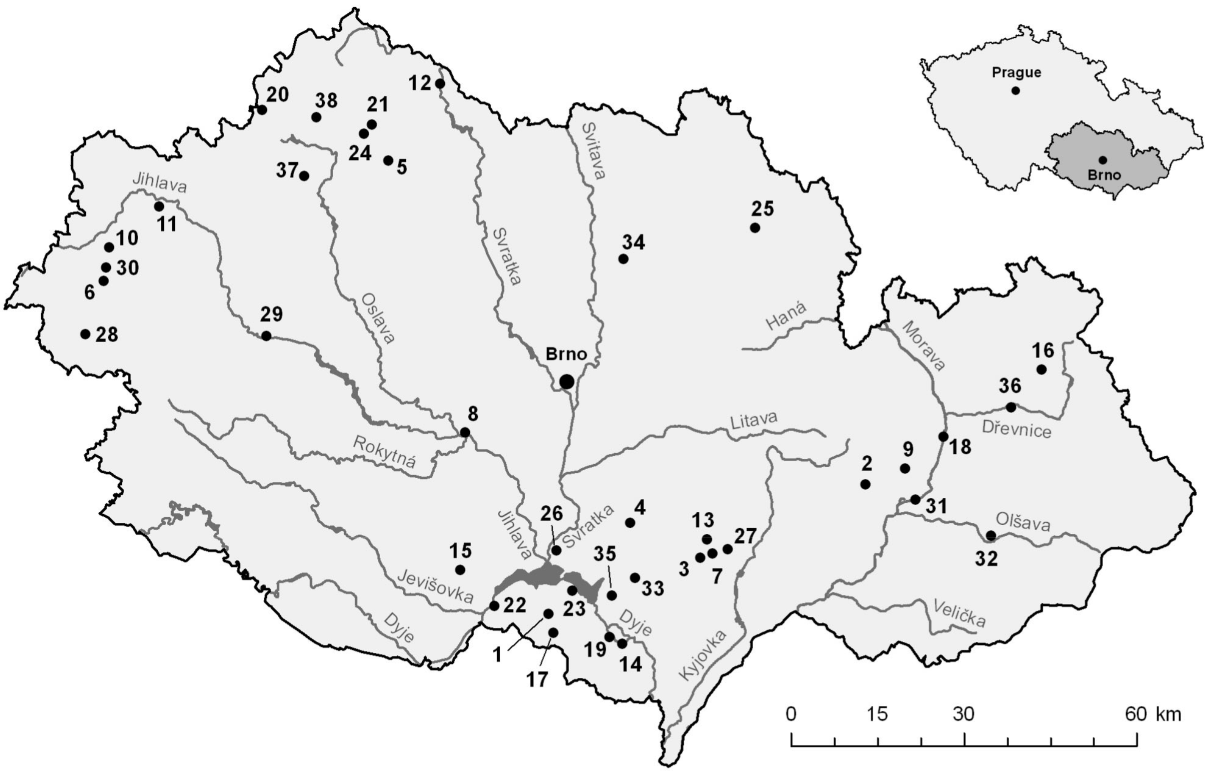

Fig. 1. Locations in South Moravia mentioned in text: 1 Bavory, 2 Buchlovice, 3 Čejč, 4 Diváky, 5 Dlouhé, 6 Hodice, 7 Hovorany, 8 Ivančice, 9 Jalubí, 10 Jezdovice, 11 Jihlava, 12 Jimramov, 13 Karlín, 14 Lednice, 15 Litobratřice, 16 Lukov, 17 Mikulov, 18 Napajedla, 19 Nejdek (now Lednice), 20 Nové Dvory, 21 Nové Město na Moravě, 22 Novosedly, 23 Pavlov, 24 Petrovice (now Nové Město na Moravě), 25 Plumlov, 26 Pouzdřany, 27 Šardice, 28 Telč, 29 Třebíč, 30 Třešť, 31 Uherské Hradiště, 32 Uherský Brod, 33 Velké Pavlovice, 34 Veselice (now Vavřinec), 35 Zaječí, 36 Zlín, 37 Znětínek, 38 Žďár nad Sázavou

that for quarter of an hour there was nothing to see in the air but rain and hail; at the same time it was so dark that it was almost impossible to read in the room. Hailstones the size of big peas could still be seen [on the ground] *around 8 p.m.'* Records of hailstorms that derive from daily visual weather records refer to their occurrence in a particular place without respect to any damage done (although this may be described too), but they are available for only a few places and for limited time spans.

2.1.3. Taxation and damage records

Taxation data provide possibly the most important documentary source for past hailstorm occurrence in South Moravia. Damage to agricultural crops resulting from hailstorm was a legitimate reason for farmers and landowners formally to request tax relief. This right was systematically codified in 1655 by the First Moravian Land Registry (Novotný 1934). The general administrative scheme required a report of damage prepared at community level (date, event and detailed description of damage) to be sent to the regional office. An independent commission assembled by this regional office then checked *in situ* damage and reported back. In turn, an application for tax relief was then made to the land office in Brno (*Gubernium*), which made a final decision and transmitted it by reverse

Fig. 2. A note from a Franciscan 'book of memory' concerning the hailstorm in Olomouc on 5 June 1699, with a drawing of some of the hailstones (archival source AS2)

procedure to the villages or farmers affected (for more details of this system, see e.g. Brázdil et al. 2012a, 2014, Dolák et al. 2013).

Many of the documents generated by the various stages of this administrative process survive in archives at estate (the basic unit of agricultural production) level and in family archives (those of the owners of estates) in the Moravian Land Archives in Brno or in some of the state district archives. Hailstorm information has been found for 73 of the 201 estates existing as units in 1848 in South Moravia (Voldán et al. 1964). Reports of hailstorms also appeared in 7 of the 61 family archives inspected. Brázdil et al. (2016) presented a number of examples of these reports as well the results of hailstorm analysis derived from taxation data for the 1650–1941 period. Taxation and damage reports, the most important historical sources of hailstorm data in South Moravia, are limited by the quantity of surviving documentation (often discarded as superfluous after a final tax decision had been reached) and by their particular concentration around the May–August period, i.e. the months most important to agriculture.

However, the hailstorm damage data held by the Imperial Royal Land Financial Directorate in Brno for the 1896–1906 period, not included in the previous study and published by Koutný (1908), constitute the most comprehensive source of taxation data available. As well as the number of hailstorms causing damage, they also include the value of the tax write-off for individual settlements, serving as a consistent proxy for both the territorial extent and intensity of hailstorms.

2.1.4. Insurance records

Companies prepared to insure against hailstorms started to appear in the Czech Lands during the 19th century. They were, however, short-lived (Fassbender 1898). The Mutual Insurance Company for Moravia and Silesia (*Vzájemná pojišťovna pro Moravu a Slezsko*), the first 'modern' insurance company in Moravia, was founded in 1829, but at the outset was prepared to insure only against fire. Hailstorm insurance, considered very hazardous, existed in 1870, but contributed to accelerated bankruptcies of insurance companies (Marvan et al. 1989). Insurance premiums were very unstable, subject to frequent changes in response to unexpected hailstorms and in the light of a dearth of long-term records of hailstorm occurrence in any given territory. Some stabilisation of fees based on more extensive knowledge of hailstorm occurrence started to appear around the end of the 19th century. The principles of modern hailstorm insurance were then formally enshrined in the 'of Hailstorm Insurance Law, no. 501', which came into force in 1919 (Schelle & Hradec 2006). The records of some estates contain insurance forms and requests for compensation for damage related to hailstorms. For example, the documents that notified damage done by a hailstorm on 5 June 1873 and a request for reimbursement for similar damage at Třešť', Hodice and Jezdovice on 30 June 1876 survive in the Třešť' estate. Wheat, barley, rye, oats and pea crops suffered, to an area of 887 *měřice* [ca. 170.3 ha], and final damage was estimated at 21 914 gulden 50 kreutzer (AS3). Despite the great potential of this type of hailstorm data, no comprehensive datasets were recognised for South Moravia (compare e.g. with Switzerland; Mauelshagen 2011).

2.1.5. Newspapers

Newspapers have always been interested in stories of unusual weather or hydrometeorological extremes, especially any disastrous impacts. For example, *Moravské noviny* (13 July 1865, No. 83, p. 331) reported windstorm and hailstorm in Diváky on 10 July, 1865: '*A tremendous gale tore through on Monday 10 July at 4 p.m.*, [...] *immediately followed by an awful hailstorm* [so fierce] *that all the field crops are now* [so] *squashed into the ground* [that] *it is difficult to imagine that a single straw might be salvaged. The hailstones resembled large nuts with spikes; the trees that remain are crushed and stripped to the wood, and will dry out for the greater part. Many hares, as well as partridges and other birds, were found beaten to death in the fields.*' Newspaper reports often express the extent of hailstorms, describing damage for a number of places, as in the case of torrential rain and hailstorm on 29 June 1890, reported in *Brünner Zeitung* (1 July 1890, No. 149, p. 3): '*At Uherské Hradiště* [...] *Grain was beaten down by hailstones the size of pigeons' eggs, trees were stripped of leaves and north-facing window-panes were broken*. *Large hailstones* [also] *fell in Ivančice. There are similar reports from Mikulov. There is a lot of damage to the vineyards. According to reports from Zaječí, hailstones the size of walnuts covered the ground in places in a layer 10 centimetres deep. In 12 minutes of drumming hail, prospects for harvests from fields and gardens were devastated, windows shattered and poultry and small animals killed*. *Further Čejč, Pavlov,* [Velké] *Pavlo-*

vice, Šardice and Hovorany were heavily affected by bad weather. The loss [of harvest] *brought grief to every conversation* [...]' Newspapers also published requests for financial support from various bodies for the people affected, or reported, as in the above hailstorm of 29 June 1890 (*Brünner Zeitung*, 2 August 1890, No. 176, p. 2): '*The following donations have been made to the Gubernium for the Moravian inhabitants afflicted by hailstorm: from the Třebíč Credit Union 10 gulden* [and] *from the following communities of the Mikulov district: Litobratřice 20 gulden 98 kreutzer; Pouzdřany 30 gulden 83 kreutzer; Nejdek 9 gulden 34 kreutzer; Bavory 5 gulden; Novosedly 8 gulden 39 kreutzer; and Lednice 9 gulden 80 kreutzer.*' Newspapers constitute important sources of information relating to damaging hailstorms, particularly with respect to their extent, the damage done by them and any help extended to affected communities. However, the density of such reports decreases in times of war or pressing socio-political matters.

2.1.6. Early instrumental meteorological observations

The earliest Moravian instrumental meteorological observations, made by the physician František Alois Mag of Magg from Telč, covering the period from 7 May 1771 to 9 March 1775, describe, inter alia, hailstorms. For example, hail during a thunderstorm in Telč and its surroundings, when hailstones the size of walnuts did damage in some villages, is reported in his entry for 20 June 1774 (Brázdil et al. 2002). However, only the monthly frequencies of hailstorms are available for some early instrumental datasets, when original observations are missing and deductions have to be made from summaries presented in later work. The observations made in the 1816–1840 period by Magistrate Councillor Andreas Sterly from Jihlava serve as an example, with observed phenomena at daily resolution until 1826 and then only his published monthly frequencies thereafter (Brázdil et al. 2007). Early meteorological observations include information about all the hailstorms occurring in a given place, but the number of such observations is very low.

It follows from the various documentary sources above (Sections 2.1.1 to 2.1.6) that taking each type separately may be limited by the selection of hailstorms described, the number of sources and their spatial and temporal heterogeneity. However, gathering information from all sources allows the number of reported events to be increased, providing information on their spatiotemporal density; further, events may be cross-checked. Although documentary data are very effective when used in concert, it must be borne in mind that they depend on a variable number of surviving documentary sources.

2.2. Meteorological data

Quite accurate meteorological data concerning hailstorm occurrence exists in systematic meteorological observations made at meteorological (i.e. climatological and rain-gauge) stations. One set of hailstorm data was collated by systematic excerption from the original records kept by meteorological stations in the 1859–1962 period, archived by the Czech Hydrometeorological Institute (CHMI) in Brno for the region of South Moravia. The number of stations inspected fluctuated from just one (Rusava) at the very beginning of the series to 69 in 1934. A second set of hailstorm data was collated from observations taken at 90 meteorological stations (Fig. 3), checked and corrected with respect to their accuracy, for the 1961–2015 period; one station represents a mean area of 167 km^2. A total of 47 stations covers the entire 55 yr period, while data for a further 5 stations were compiled from hail observations from 2 nearby sites. Short interruptions in observations exist for the remaining 38 stations, but only on the order of a few months at most (again, data for one 'station' was compiled from 2 nearby sites). Despite somewhat weak spatial coverage in the western part of South Moravia, this network is dense enough for the study of hailstorm frequency in the South Moravian area.

3. METHODS

A hailstorm database was created from the various types of documentary data. Individual hailstorm events, dates of occurrence, accompanying convective phenomena, settlements affected, type of damage (crops and their area, damage intensity, tax adjustment) and source of data made up the basic information included and employed for further analysis. The database was then employed to create series of hailstorm days for the summer half-year (April–September), using only the most carefully-checked documentary data (see Fig. 4): firstly based on meteorological observations from the archived observations from individual CHMI stations (see Fig. 5) and secondly on those from the stations that

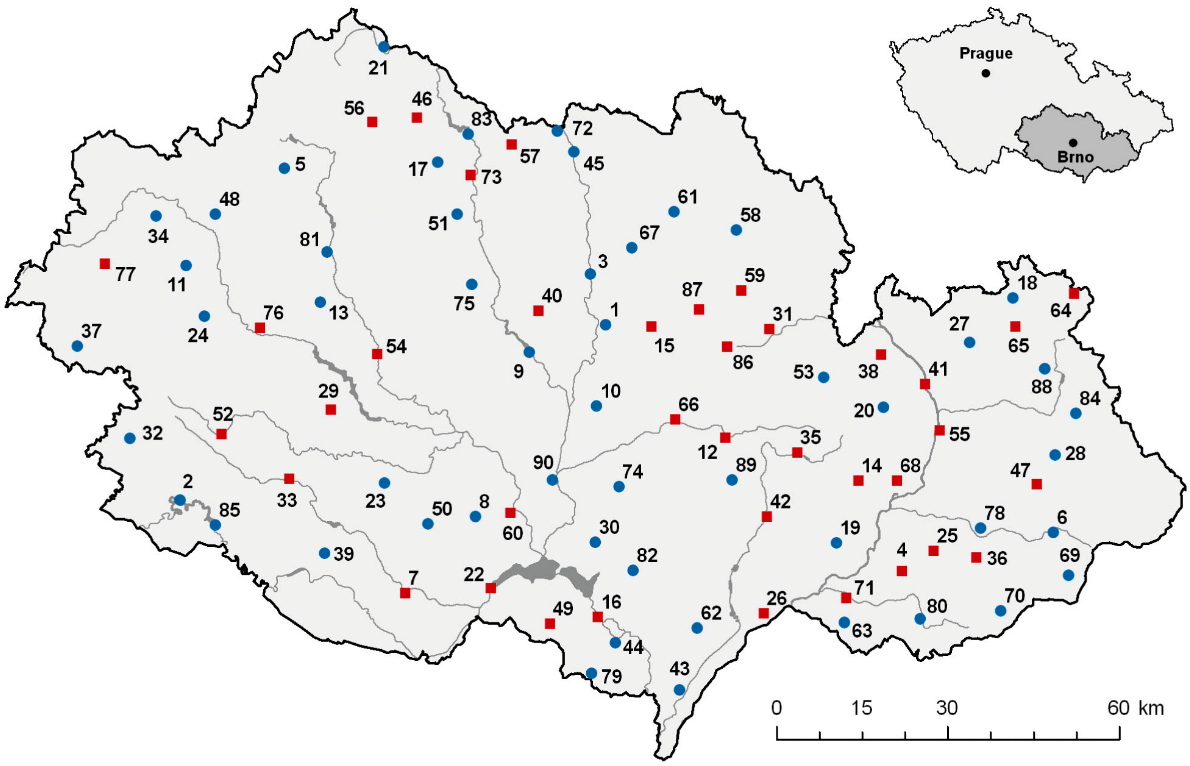

Fig. 3. Meteorological stations in South Moravia with available hailstorm data in the 1961–2015 period: (●) stations with complete 55-yr series (■) stations with incomplete series. 1 Babice nad Svitavou, 2 Bítov, 3 Blansko-Dlouhá Lhota/Blansko, 4 Blatnice pod sv. Antonínkem, 5 Bohdalov, 6 Bojkovice, 7 Božice, 8 Branišovice, 9 Brno-Kníničky/Brno-Žabovřesky, 10 Brno-Tuřany, 11 Brtnice, 12 Bučovice, 13 Budišov, 14 Buchlovice, 15 Bukovinka, 16 Bulhary/Dolní Věstonice, 17 Bystřice nad Pernštejnem, 18 Bystřice pod Hostýnem, 19 Bzenec, 20 Chřibsko-Kostelany, 21 České Milovy/Moravské Křižánky, 22 Drnholec, 23 Džbánice/Morašice, 24 Heraltice/Štěměchy, 25 Hluk, 26 Hodonín, 27 Holešov, 28 Horní Lhota, 29 Hrotovice, 30 Hustopeče, 31 Ivanovice na Hané, 32 Jemnice, 33 Jevišovice/Střelice, 34 Jihlava/Hubenov, 35 Koryčany/Lískovec, 36 Korytná/Nivnice, 37 Kostelní Myslová, 38 Kroměříž, 39 Kuchařovice, 40 Kuřim, 41 Kvasice, 42 Kyjov, 43 Lanžhot, 44 Lednice, 45 Letovice, 46 Lísek/Vojtěchov, 47 Luhačovice/Luhačovice, Kladná-Žilín, 48 Luka nad Jihlavou-Vysoké Studnice, 49 Mikulov, 50 Miroslav, 51 Moravecké Pavlovice/Sejřek, 52 Moravské Budějovice, 53 Morkovice-Slížany, 54 Náměšť nad Oslavou, 55 Napajedla, 56 Nové Město na Moravě, 57 Olešnice, 58 Plumlov/Žárovice, 59 Podivice na Moravě, 60 Pohořelice, 61 Protivanov, 62 Prušánky, 63 Radějov, 64 Rajnochovice, 65 Rusava, 66 Slavkov u Brna, 67 Sloup/Šošůvka, 68 Staré Město, 69 Starý Hrozenkov, 70 Strání, 71 Strážnice, 72 Stvolová-Vlkov, 73 Štěpánov nad Svratkou, 74 Těšany, 75 Tišnov/Úsuší-Čížky/Tišnov, Hájek, 76 Třebíč, 77 Třešť, 78 Uherský Brod, 79 Valtice, 80 Velká nad Veličkou, 81 Velké Meziříčí, 82 Velké Pavlovice, 83 Vír, 84 Vizovice, 85 Vranov nad Dyjí, 86 Vyškov, 87 Vyškov-Rychtářov, 88 Zlín-Velíková, 89 Ždánice, 90 Židlochovice

have been continuously present within the CHMI database since 1961 (see Fig. 6). A final series of summer half-year numbers of hailstorm days for South Moravia was compiled from hailstorms derived separately from documentary data, meteorological observations, and their overlap (see Fig. 7). The individual and final series were further analysed and smoothed by Gaussian filter for 5 and 10 items to show interdecadal variability. However, some of the hailstorms were not exactly dated. They have been included with summer half-year numbers if only a single hailstorm was reported in the given year, in order to exclude possible overlap with an already-detected event. If not, they are excluded or expressed in separate figures.

Linear trends in series of hailstorm day numbers were calculated only for the periods with the best data coverage. The suitability of the linear regression model was evaluated using analysis of the variance *F*-ratio test, while the significance of any increasing (decreasing) trend was estimated by means of *t*-test (both at significance level $p = 0.05$). From all the hailstorms in the database, 17 outstandingly damaging hailstorms, with >50 affected communities per event, were selected (see Table 1) and 4 of them, with the highest numbers of such communities, were described in more detail (see Fig. 8). To demonstrate the influence of documentary sources and meteorological observations on the number and fluctuations of hailstorm days, three 40 yr periods, corresponding

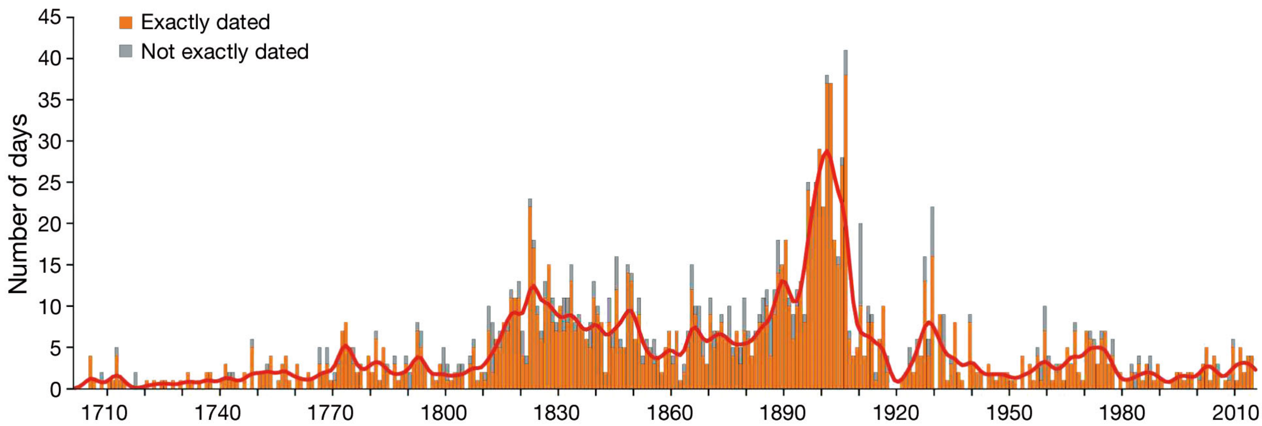

Fig. 4. Fluctuations in summer half-year numbers of hailstorm days derived from documentary evidence in South Moravia for the 18th to early 21st centuries. Red line: data smoothed by Gaussian filter for 10 items

to 3 local maxima in the final compiled series, were selected to generate data on the numbers of sources providing information about hailstorms, number of hailstorm days and finally the mean number of locations (including meteorological stations) attributed to one hailstorm day.

4. RESULTS

4.1. Hailstorm days from documentary data

Hailstorms derived from documentary evidence clearly reflect the availability of documentary evidence. The earliest record of a hailstorm in South Moravia appears in the chronicle of the Flesar family for Nové Dvory on 17 August 1435 (Flesar 2013): '*In the summer on 17 August, large pieces of ice fell from the sky; they did great damage to everyone in the area.* [In both] *smallholders' and lords' fields only beaten-down crops remained. Loud lament is to be heard throughout the land and there is a wringing of hands for people will have nothing to put in their mouths.*' Further hailstorm events are reported there for 9 July 1484 ('*Pieces of ice are falling and doing immense damage.*'); August 1500 ('*Crops destroyed in places, but it* [the storm] *missed our village.*'); 22 August 1513 ('*On 22 August a heavy thunderstorm with hail came. It did great evil everywhere …*'), 19 August 1520 ('*A heavy thunderstorm came on 19 August and destroyed all our crops …*') and 11 August 1532 ('*Pieces of ice the size of hens' eggs size fell. Havoc in the fields, only stubs remaining of cereals, beans, beet, cabbage and other crops.*'). Not long after this, the first further hailstorm recorded in the chronicle for Jihlava kept by Martin Leupold von Löwenthal, appears for 7 July 1543 (d'Elvert 1861). In the summer half-years of the entire 16th century, all documentary sources describe a total of only 36 hailstorm days for South Moravia. The number of hailstorm days detected almost doubles during the 17th century to 84 events, but once again a lack of documentary evidence is apparent.

The numbers of summer-half-hailstorm days increase slightly in the figures for the 18th century (total 195 d) and the first maximum appears between the early 1810s and the early 1850s (Fig. 4). This maximum may be attributed to the preservation of archival documents related to damaging hailstorms intrinsic to the taxation process (see Brázdil et al. 2016). The second maximum appears in 2 last decades of the 19th century and the first decade of the 20th century, particularly in 1896–1902 and 1905–1906, largely as a consequence of including data of damaging hailstorms provided by Koutný (1908). The number of documentary-based hailstorm days in the subsequent years of the 20th century (with a few exceptions, such as 1910, 1927 and 1929) decreases to under 10 d, and in the majority of half-years even below 5 d. The highest numbers of hailstorm days detected from documentary data were 41 in 1906, 38 in 1901 and 37 in 1902 (from the 1896–1906 period covered by Koutný 1908). Maxima from earlier and later historical periods were lower, i.e. only 23 d in 1822 and 22 d in 1929.

4.2. Hailstorm days from meteorological data

The numbers of hailstorm days derived from systematic meteorological observations are represented by 2 datasets. The first was obtained by extraction of

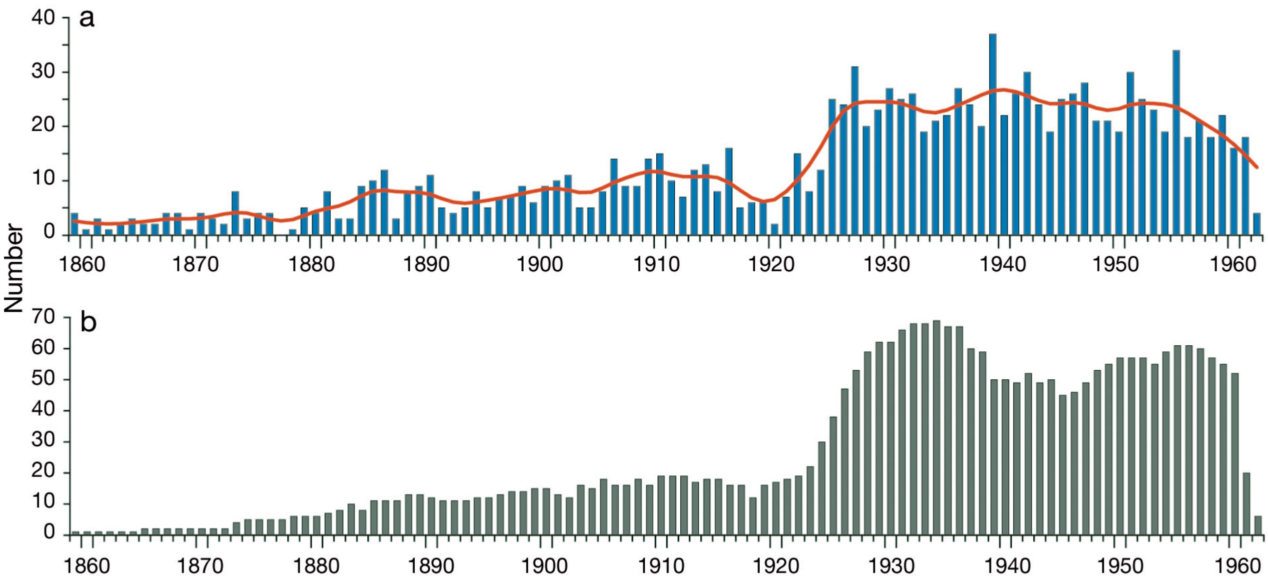

Fig. 5. Fluctuations in (a) the summer half-year number of hailstorm days derived from systematic meteorological observations (red line shows data smoothed by Gaussian filter for 10 items) and (b) the number of meteorological stations used in South Moravia during the 1859–1962 period

hailstorm information from the original monthly records kept by meteorological stations and held in the CHMI Brno archive (Fig. 5). An increasing number of hailstorm days parallels the growing number of meteorological stations excerpted (i.e. does not reflect climatological trends), with a significantly higher number of stations in the latter half of the 1920s (the number of stations varies from only one in 1859–1864 [Rusava] to a maximum of 60 or more in 1929–1937). The number of hailstorm days fluctuated around 20 per summer half-year from the 1930s until the beginning of the 1960s.

The second dataset is based on the constant total of 90 CHMI meteorological stations during the 1961–2015 period. Although the number of hailstorm days fluctuates over a broad range (between 40 d in 1961 and 12 d in 1977 and 2015), a statistically significant linear negative trend ($\alpha = 0.05$) emerges, i.e. a decrease of −1.2 d per 10 yr (Fig. 6). The F-ratio test indicates a suitable linear regression model ($F = 5.439$, $p < 0.023$).

4.3. Chronology of hailstorm days

Fig. 7 shows fluctuations in the summer half-year numbers of hailstorm days in South Moravia during the 18th to early 21st centuries, compiled from docu-

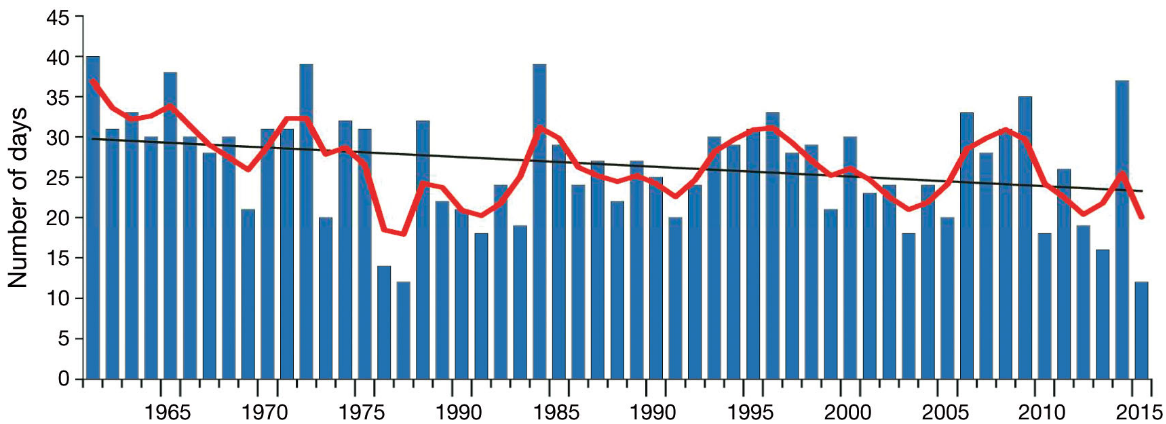

Fig. 6. Fluctuations and linear trend in the number of hailstorm days in the summer half-year derived from systematic observations taken at 90 meteorological stations in South Moravia during the 1961–2015 period. Red line shows data smoothed by Gaussian filter for 5 items; black line: the linear trend

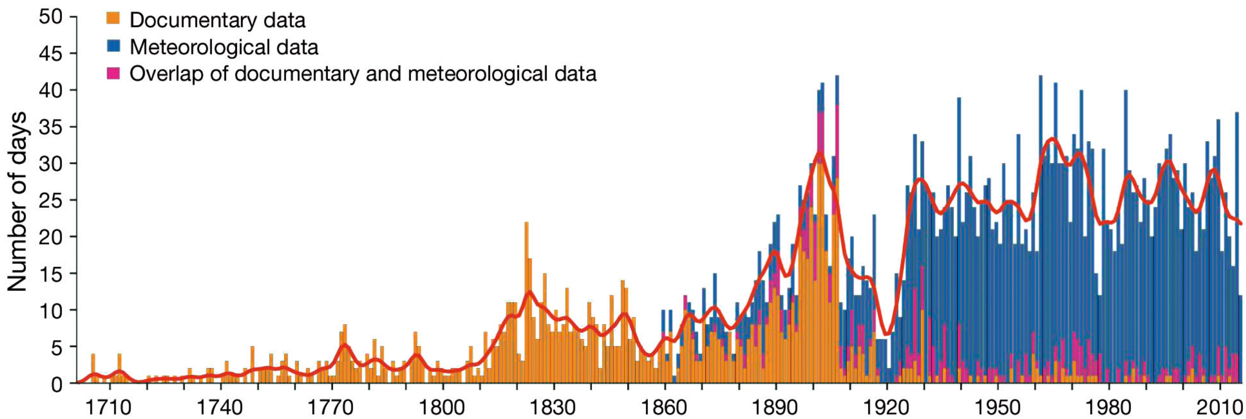

Fig. 7. Fluctuations in the numbers of hailstorm days in the summer half-year compiled from documentary evidence and systematic meteorological observations in South Moravia during the 18th to 21st centuries. Red line shows data smoothed by Gaussian filter for 10 items

mentary evidence and systematic meteorological observations. Quite comparable fluctuations appear between 1925 and 2015, showing a linear trend of −0.048 hailstorm days per 10 yr, which is, however, statistically insignificant. But the linear regression model in this case is not appropriate as the *F*-ratio test is insignificant ($F = 0.030$, $p < 0.862$). This period is only comparable to data for the period between 1896 and 1906, mainly in the light of the detailed evidence of damaging hailstorms provided by Koutný (1908). Smoothed numbers of hailstorm days show the most consistently high values appearing in the 1960s and early 1970s, with 3 smaller peaks afterwards. Although there is some overlap of events derived from documentary and meteorological records, 1906 saw the absolute maximum within the entire chronology, 42 hailstorm days (40 or 41 d were recorded in 6 other summer half-years). The lowest numbers of hailstorm days occurred in 1917–1921 (only between 2 and 7 d per summer half-year), coinciding with the end of the First World War and the beginning of meteorological network in the newly-created state of Czechoslovakia. Only 3 summer half-years had 20 hailstorm days or more before 1896 (1822, 1889 and 1890).

4.4. Outstandingly damaging hailstorms

The long-term series of hailstorms created for South Moravia facilitates selection of certain exceptional hailstorms. From the meteorological point of view, the descriptive term might relate to the size of hail particles, their density and their duration. From a practical point of view, the focus would be on damage calculations, where totals of material losses and details of insurance payouts figures prominently. The selection criterion chosen herein is the number of communities affected, i.e. the territorial extent of damaging hail (see e.g. Brázdil et al. 2016).

From records of hailstorms that affected >50 communities, a total of 17 were selected (Table 1). Of these, 10 are from Koutný (1908), who gave a detailed list of places requesting tax relief after hail damage. Damage to agricultural crops frames much of the disastrous nature of hailstorms, which is in turn reflected in their timing: 6 in June and 6 in July, with the remainder in August (3), May and September. The spatial distribution of places affected by the 4 most severe events is shown in Fig. 8; further details are provided below.

20 June 1848. A total of 44 documentary reports identify damage to 107 communities, although exact

Table 1. Hailstorms in South Moravia that affected more than 50 communities

Order	Date	No. of communities
1	1 Jul 1902	112
2	10 Jul 1902	110
3	20 Jun 1848	107
4	19 Jul 1903	104
5	6 Sep 1902	100
6	22 Jul 1939	96
7	6 Jun 1932	93
8	29 May 1896	80
9	23 Jun 1898	76
10	29 Jun 1890	71
11	25 Jun 1844	70
12	4 Jun 1899	63
13	28 Jul 1902	62
14	12 Jul 1984	55
15	7 Aug 1902	54
16	20 Aug 1890	53
17	1 Aug 1901	51

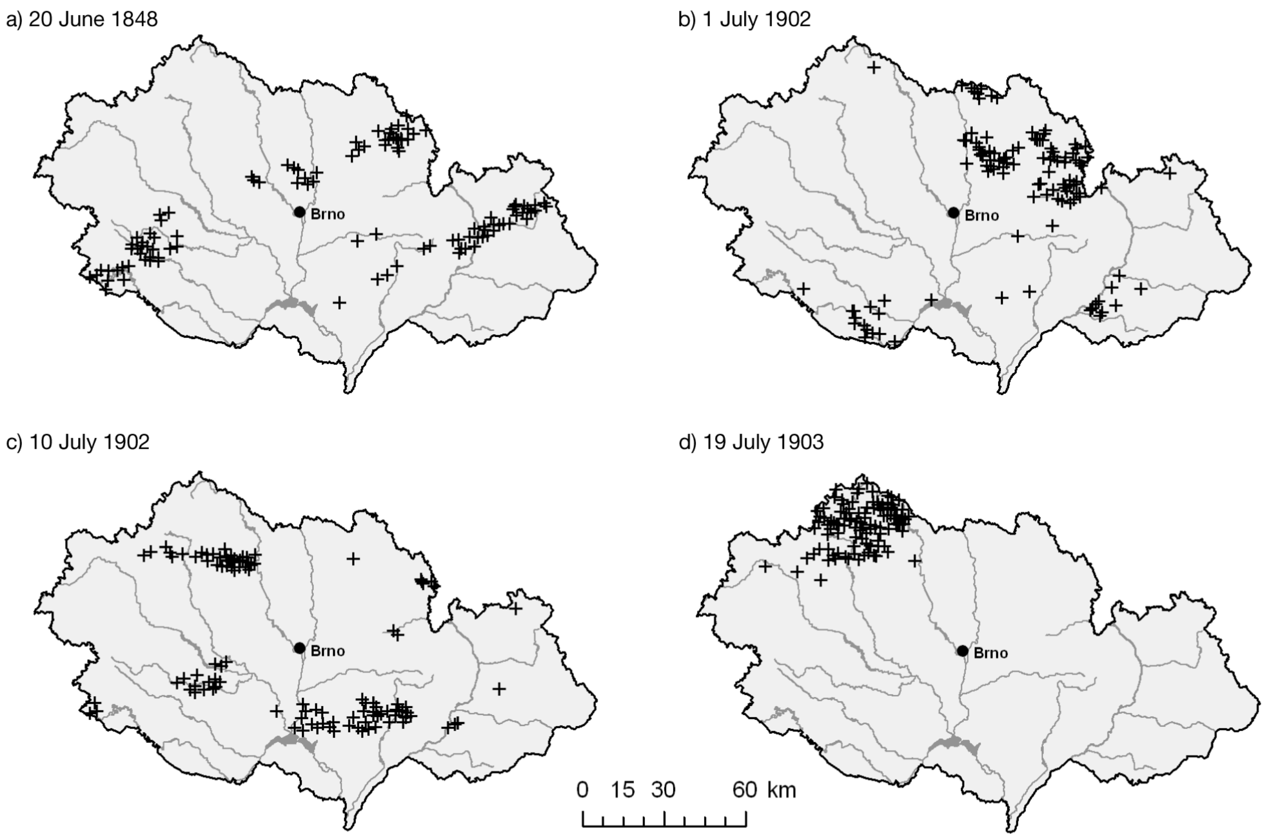

Fig. 8. Locations of places affected by 4 outstandingly damaging hailstorms in South Moravia

specification of which communities were damaged is absent from the Jimramov estate records. These locations are concentrated in 2 belts, extending from south-west to north-east over South Moravia, testimony to the movement of thunderstorm cells in this direction (Fig. 8a). Hail damage was combined in some of the places with other storm impacts, flooding or flash floods. In particular, the reports mention heavy damage to crops and vineyards, but also describe damaged and battered fruit trees, smashed windows and damaged buildings. There were even animal fatalities in the Zlín region, and people injured (Nekuda 1995). There was particularly significant damage to crops, followed by announcements of public collections of aid for disaster victims (e.g. on the Napajedla, Plumlov and Lukov estates). The hailstorm of 20 June was also reported by other documentary sources (e.g. for Velká Bystřice, near Olomouc; see Roubic 1988) and as far away as the Nový Jičín area in northern Moravia (Prasek 1882).

1 July 1902. Based on 190 records (particularly 97 damage reports from Koutný 1908, which overlap considerably with 87 reports in the *Gubernium* records [AS1]), hailstorms affected 112 communities on this date. They concentrated particularly around the north-east and north of the city of Brno and, to a lesser extent in south-west Moravia and around the River Morava to the east (Fig. 8b). Written documents report a heavy thunderstorm accompanied by hail compared in size variously to walnuts, pigeons' eggs, or even hens' eggs, which destroyed crops and ruined fruit trees as well as damaging roofs and smashing windows, even killing poultry. For example, a report from Veselice (AS1) reads : '*On the same day* [1 July] *after noon, black clouds rushed over our area; with continuous lightning and thunder they poured down hailstones, pieces of ice the size of small hens' eggs. The hail devastated everything: crops, trees and dwellings. Windows are knocked out in places, roofs covered in 'paper' here and there look as if they have been riddled by gunfire, trees are battered, and the unripe fruit under them can be raked up* [with hand-rakes]. *But the fury of the hail was at its worst in the fields. The rye is two-thirds destroyed in some places, in others totally. The same is so with the wheat and barley.*

Potatoes and other crops are also damaged.' In some places, all this was exacerbated by downpours that washed fertile topsoil from the fields and hay from the meadows.

10 July 1902. A total of 151 written reports (107 from Koutný 1908, and 40 from *Gubernium* records [AS1]), record hailstorm damage to 110 communities, of which 6 had already suffered from hail on 1 July. These places are concentrated into 3 regions lying west-to-east (Fig. 8c). In addition to significant harm to crops, damage to vineyards appears. For example, a report from Karlín (AS1) states: '*All the cereals were fully ripening when* [on 10 July] *a hailstorm came upon our lands. That we are terribly damaged is witnessed by the estimate of the inspector from the agrarian insurance company who granted up to 65% compensation to people insured, unfortunately only a few, and* [those] *only partially. According to the estimate, total damage is up to 25,000 crowns.* [...] *Vast damage was also done to vineyards and fruit trees,* [so bad] *that vineyards will remember this day for many years.*' Hailstorm damage to vineyards had already been cited as the second most negative weather impact of that year, after the severe frost on 28 April at Pouzdřany (Policky 1936).

19 July 1903. This hailstorm appears in 215 pieces of documentation (76 from Koutný 1908, but 133 from *Gubernium* records [AS1]). A total of 104 affected communities were concentrated in the Bohemian-Moravian Highlands in the north-western part of South Moravia (Fig. 8d). The event was part of a storm belt extending from south-west Bohemia, which was also heavily affected (Pollak 1911). Great damage to crops was exacerbated by the fact that the hail occurred close to harvest time. Besides damage to field crops, broken windows and damaged roofs are also reported. Some communities had also been affected by hailstorm in the previous year (e.g. Petrovice and Znětínek, which were affected a total of 3 times). Topsoil washed from the fields and meadows flooded by downpours are also reported. A request for support addressed to the *Gubernium* on 10 August 1903 from the Dlouhé community (AS1) reads: '[...] *all the windows that faced the storm were completely smashed, while many birds and game animals perished* [...]. *The total damage amounts to eighty thousand crowns. Because our inhabitants have, in the past year, already suffered great damage from natural disaster, debt and poverty* [in] *our community have risen to the point that one can expect nothing other than the highest degree of distress and poverty* [...] *the recent crops, nearly all of them ruined by natural disaster, are only fit for animal bedding.*'

5. DISCUSSION

5.1 Uncertainties in documentary and meteorological data

It follows from Fig. 4 that the numbers of hailstorm days constitute a non-homogeneous dataset, strongly reflecting the availability and number of documentary sources accessible to analysis. Increasing numbers of meteorological stations used for hailstorm extraction contribute to higher figures for hailstorm days. It seems that this relationship becomes insignificant after 30 or more meteorological stations per year are employed, as follows from comparable numbers of hailstorm days and their fluctuations in relation to the 1961–2015 period (Fig. 7), best covered by meteorological stations (cf. Fig. 6). Despite quite a rich hailstorm database for South Moravia, the compilation of a valuable, long-term, areal hailstorm chronology, combining documentary data with systematic meteorological observations, is a difficult task. This is mainly due to a basic difference between hailstorm descriptions derived from documentary data and those observed at meteorological stations. Identification of hailstorms in documentary evidence is usually associated with unusual dimensions of hailstones or the damage done, appearing in records at various levels of detail. The immediate consequence of this is that only heavier and damaging hailstorms are often the only ones recorded, while the spatiotemporal density of such data may be highly variable.

Neither are observations of hail at meteorological stations entirely consistent; they depend upon the instructions given to observers, which have changed to various degrees since the beginning of instrumental observations. Fluctuations in numbers of hailstorm days may be very variable if the data from individual meteorological stations are employed, as Fig. 9 illustrates. Four selected CHMI stations with high-quality observations taken by professionals (nos. 10, 27, 37 and 39 in Fig. 3) reveal that none of them records a statistically significant linear trend in 1961–2015 (moreover, the negative trend for Kostelní Myslová contrasts with the positive trends at the 3 other stations). Neither are the local maxima and minima of smoothed frequencies well comparable. For example, while the Brno-Tuřany station demonstrates a clear decrease in hailstorm frequency after 2000, Holešov shows the opposite tendency. From comparison of Fig. 9 with the fluctuations expressed in Fig. 6 for the whole of South Moravia, it follows that areal hailstorm series with lower local bias give

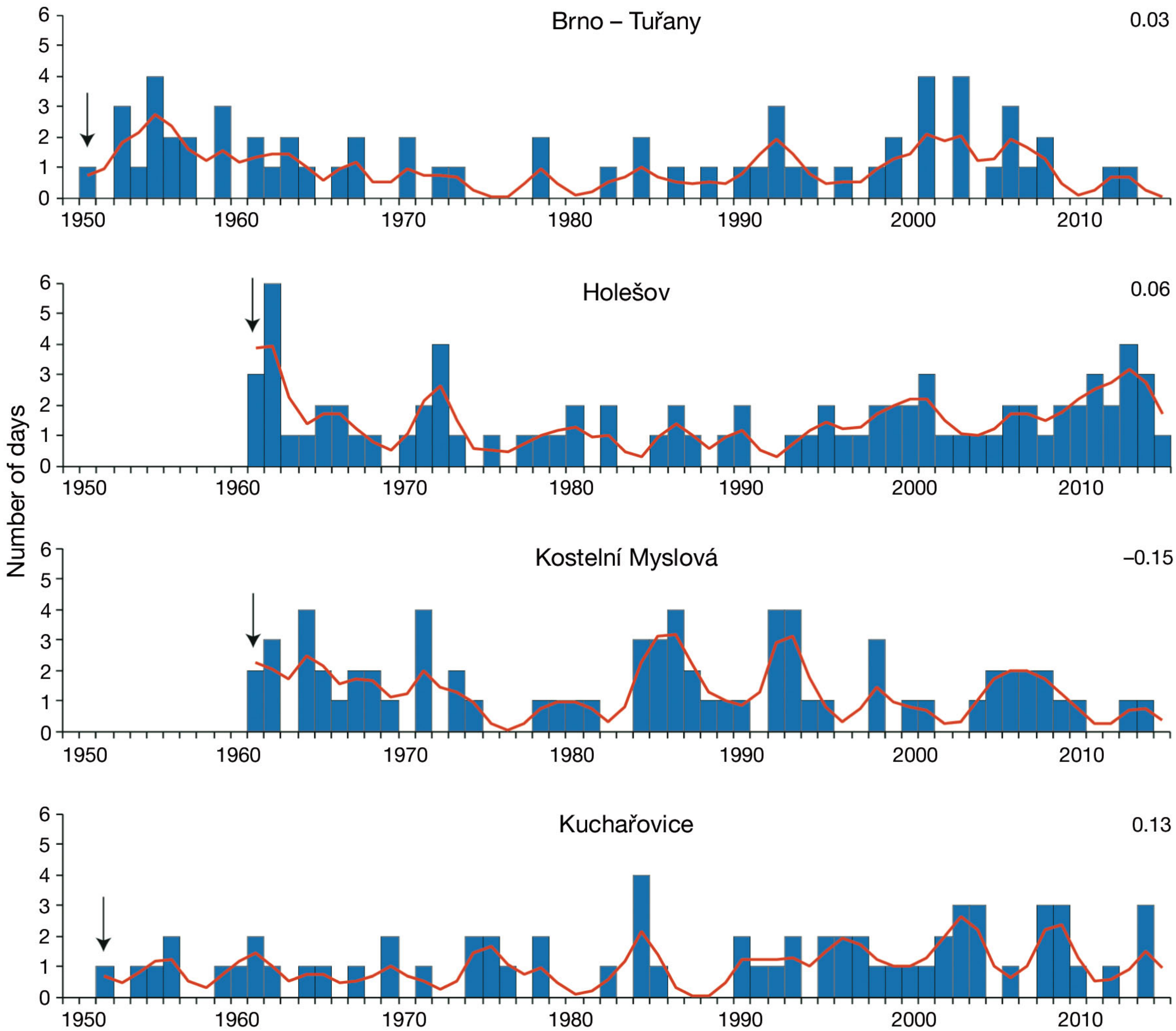

Fig. 9. Fluctuations in summer half-year numbers of hailstorm days at 4 selected meteorological stations in South Moravia. Red line shows data smoothed by 5-yr Gaussian filter. Arrows indicate observation starting points. Values of insignificant linear trends (α = 0.05) for the 1961–2015 period, expressed as number of days per 10 yr are shown at the top right of each graph

a clear climatic signal showing a decreasing trend in the number of hailstorm days over several recent decades.

The decrease in the number of summer half-year hailstorm days in South Moravia accords with negative trends found in European and other countries. For example, Svabik (2004) reported a negative trend in hail events in Austrian Styria in the 1982–2001 period. A decreasing tendency in days with hail was also detected for Lower Austria in 1981–2000 (Svabik 2005). Chromá et al. (2005) found a statistically significant trend of −2.3 hailstorm days per 10 yr based on data from 135 stations in the eastern Czech Republic (Moravia and Silesia) during 1961–2000. Schuster et al. (2005) reported a statistically significant decrease in hailstorm frequency during 1990–2003 compared with the preceding 1953–1989 period for Sydney in Australia. For Trentino in the Italian Alps, Eccel et al. (2012) also found a slight, non-significant, decreasing trend in the number of hail events and in surfaces struck during the 35 yr after 1974. In Serbia, Ćurič & Janc (2016) reported a decreasing trend in hail frequency, in both complex and flat terrain, for April–September in the 1949–2012 period. Further negative trends in hail frequency have also been reported in a number of papers for Poland, Hungary and Romania (see Punge & Kunz 2016 for more details) and Bulgaria (Simeonov et al. 2009). In Turkey, Kahraman et al. (2016) found a decrease in cases of severe hail (ice particles ≥1.5 cm) from the 1960s to the early 2000s, with an increase afterwards. On the other hand, Kunz et al. (2009) found a significant increase in hail days and hail damage in the 1974–2003 period in Baden-Württemberg in Germany. However, this is also in agreement with data from South Moravia, which show a corresponding (insignificant) linear trend in the same period, i.e. an increase of 0.8 d per 10 yr. But the linear regression model appears inappropriate according to the F-ratio test ($F = 0.374$, $p < 0.546$). This shows, in the light of great inter-annual hailstorm variability, the importance of the duration and localisation of the period studied.

In the context of the recent decreasing trend for hailstorm days in the Czech Lands, it is interesting to note that modelling has predicted a downward trend in the total number of damaging hailstorms during the 21st century for the UK, statistically significant for hailstones with diameters between 21 and 50 mm (Sanderson et al. 2015).

The general trends in fluctuations of hailstorm days in South Moravia may also be considered in the context of long-term climate variability there, as represented by the homogenised April–September temperature and precipitation series from the Brno meteorological station in the 19th century. While Fig. 10 (based on data reported in Brázdil et al. 2012b, extended to 2015) shows a clear, statistically significant upward trend for temperature, particularly from the early 1980s onwards, precipitation totals show no significant long-term trends. For the periods with the most credible hailstorm records, the negative trends they exhibit contrast with statistically significant positive trends in temperatures (0.20°C and 0.43°C per 10 yr in 1925–2015 and 1961–2015, respectively), and with statistically insignificant positive trends in precipitation totals (2.2 and 6.3 mm per 10 yr in 1925–2015 and 1961–2015 respectively).

5.2. A comparison of 3 periods of high hailstorm activity

Despite the prevailing uncertainties in the chronology of hailstorm days for South Moravia that appears in Fig. 7, data from 3 periods with the highest number of exactly-dated hailstorm days, corresponding to local maxima (i.e. 1813–1852, 1879–1918 and 1961–2000) were considered to be sufficiently comprehensive to merit further analyses. The total of 342 hailstorm days detected in the 1813–1852 period is based exclusively upon documentary sources. Documentary-based hailstorm days also predominate in the 1879–1918 period: of 720 detected days, 393 d (54.6%) originated from documentary data, 213 d (29.6%) from meteorological data and 114 d (15.8%) from both sources. In the final 1961–2000 period, of a total of 1117 hailstorm days, 1024 d (91.7%) were recorded at meteorological stations, while only 22 d (2.0%) were derived exclusively from documentary data and 71 d (6.3%) identified by both sources. The overlap of hailstorms derived from documentary sources and meteorological observations is related exclusively to damaging hailstorms. These figures do not include hailstorms that are not exactly dated, which occurred on 52 d, 61 d (60 from documentary and 1 from meteorological data) and 19 d (17 from documentary and 2 from meteorological data) in 1813–1852, 1879–1918 and 1961–2000, respectively.

The total number of hailstorm records increases considerably from 857 in 1813–1852 to 3766 in 1879–1918; it then decreases to 3299 in 1961–2000. The range of available hailstorm records fluctuates between broad limits: between 70 (1848) and 3 (1842) in the first period, between 779 (1902) and 6 (1918) in the second period, and finally between 154 (1961) and 32 (1980) in the most recent (Fig. 11a). Extreme values for the number of hailstorm days appear in Fig. 11b: 23 d in 1822 (1 event not dated) and 2 in 1842 in the period 1813–1852; 45 in 1906 (3 events not dated) and 6 in 1918 in the period 1879–1918; and 42 in 1961 as well as 13 (1 event not dated) in 1977 in the period 1961–2000. The mean numbers of places/stations attributed to 1 hailstorm day (Fig. 11c) fluctuate within narrow limits for the instrumental period, i.e. between 4.3 stations in 1977 and 1.5 in 1980. Minimum mean numbers of places/stations with 1 hailstorm day are similar for the 2 earlier periods (1.7 places in 1821 and in 1852, and only 1.0 place/station in 1918). However, corresponding maximum values are as high as 16.4 places in 1844 and 13.8 places in 1847 during the period 1813–1852, and 14.6 places in 1902 during the period 1879–1918. Comparing the mean number of places with 1 hailstorm day, this decreases from 4.8 in the first period to 4.5 in the second and to 3.0 in the third. This is related to the nature of the documentary and meteorological evidence: for example, the observation of a given hailstorm may be attributed to a particular meteorological station but its damaging impacts may have been recorded in several other places in its surroundings.

The 3 periods studied also exhibit certain differences in the monthly distribution of hailstorm days (Fig. 12). While May is the month of maxima (25.2%)

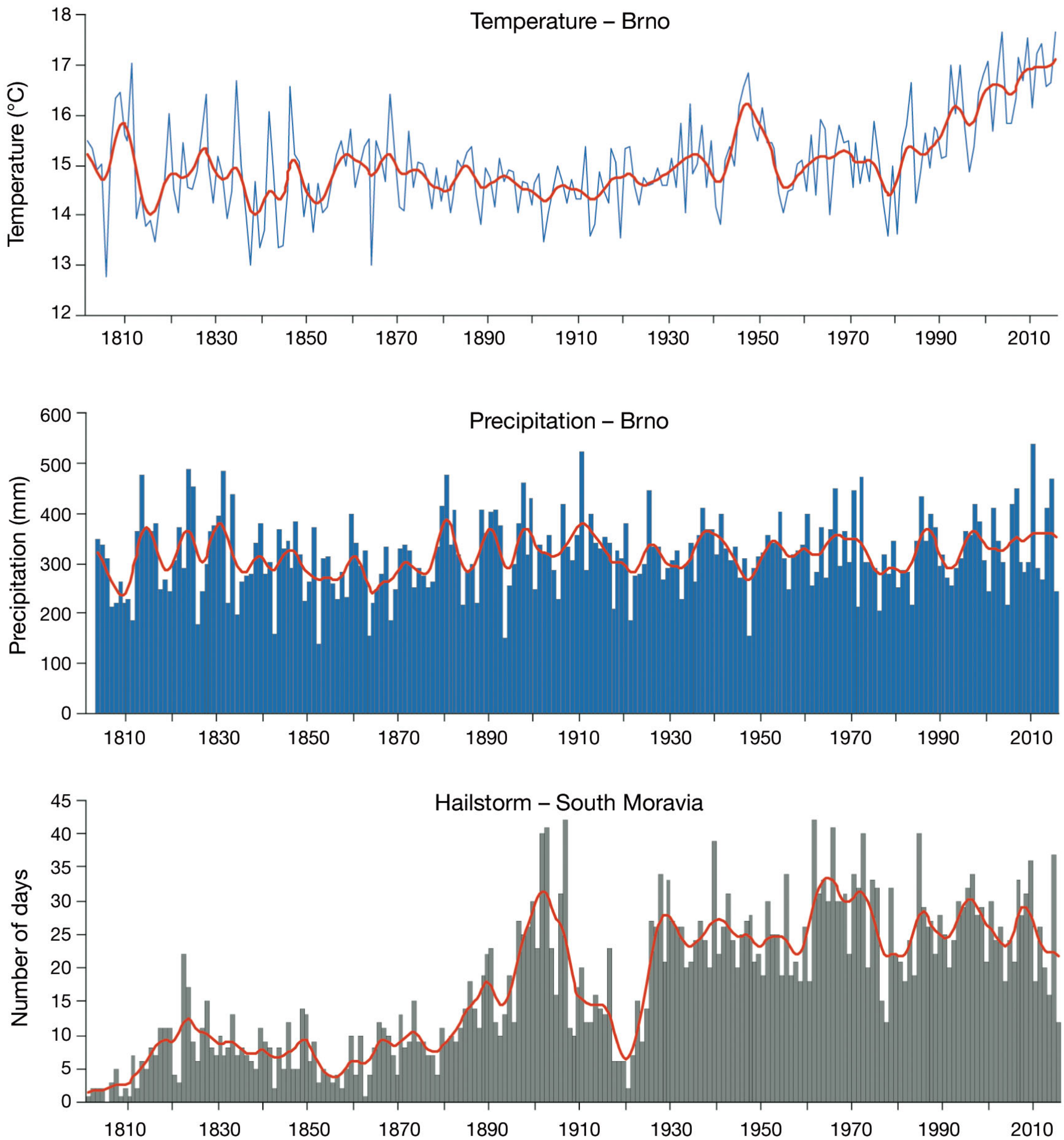

Fig. 10. Fluctuations in summer half-year mean temperatures (1801–2015) and precipitation totals (1803–2015) at the Brno meteorological station, and numbers of hailstorm days in South Moravia (1801–2015). Red lines show data smoothed by Gaussian filter for 10 items

in the instrumental 1961–2000 period, the maximum frequency of hailstorms occurs in June in the 2 other periods (24.4 and 25.8%, respectively) and July frequencies are also higher than those in May. The earlier period also exhibits relatively high frequencies of hailstorms lacking exact dates, reaching 13.2% in 1813–1852 and 7.9% in 1879–1918, compared to 1.7% in 1961–2000.

6. CONCLUSIONS

Using South Moravia as an example, this study demonstrates the potential of documentary data and systematic meteorological observations in the compilation of a reliable long-term hailstorm chronology. Series of areal numbers of hailstorm days are more suited to the investigation of hailstorm trends than

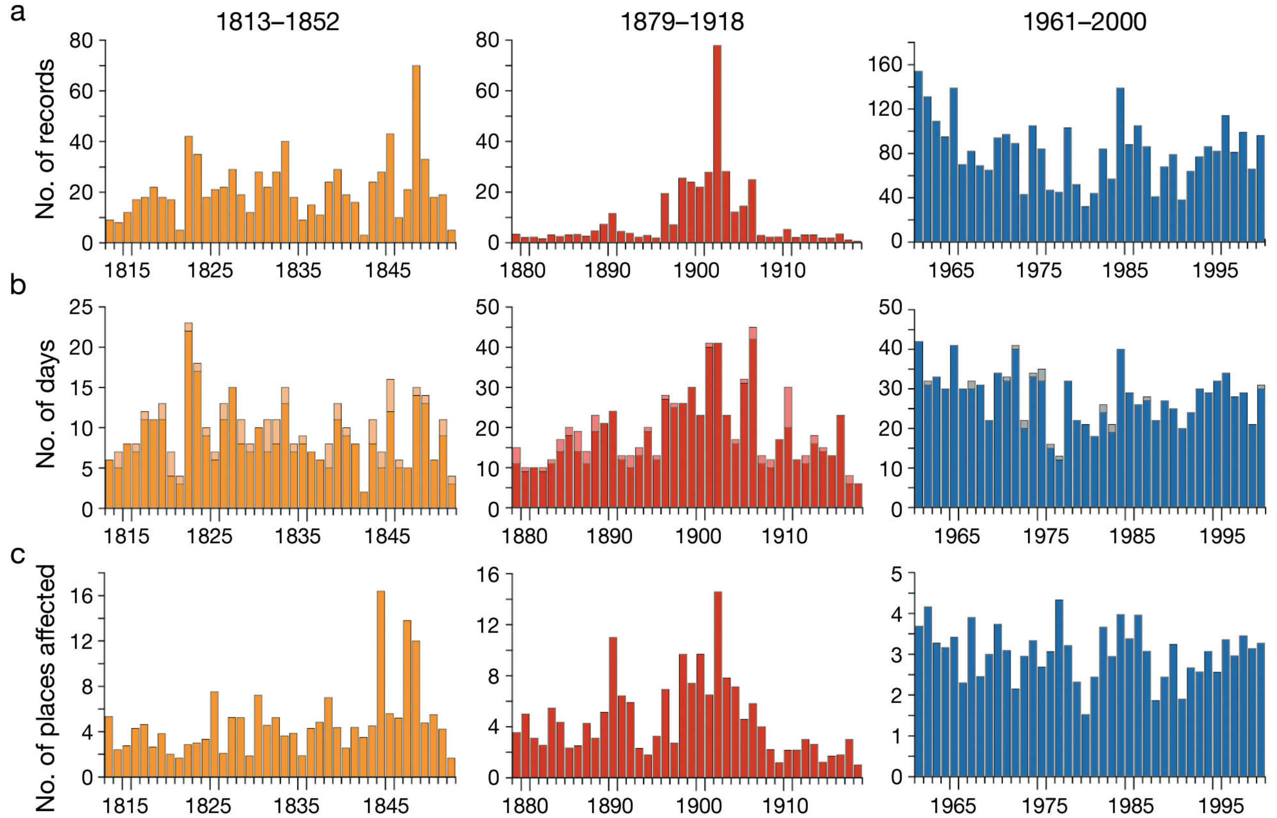

Fig. 11. Comparison of summer half-year hailstorm characteristics in South Moravia in the periods 1813–1852 (documentary data), 1879–1918 (mainly documentary and some meteorological data) and 1961–2000 (mainly meteorological and some documentary data): (a) number of hailstorm records, (b) number of hailstorm days (dark hues: exactly dated; light hues: not exactly dated), and (c) mean number of places with 1 hailstorm day

the data from individual stations, which provide only site-specific evidence. However, because any change in the number of meteorological stations used may be a source of bias which is difficult to quantify, trend analysis has to be based on nearly the same set of stations as were employed for the 1961–2015 period. Any decrease in the number of stations used may be accompanied by a concomitant fall in the numbers of hailstorms recorded. Documentary data, particularly in the pre-instrumental period, gives significantly lower hailstorm frequencies than those recorded in the instrumental period. This is due to the fact that such records usually relate to heavy hailstorms that do damage, corresponding to approximately a quarter of all events observed (cf. Changnon 1997, Brázdil et al. 1998, 2016). Thus documentary data may help to identify periods with higher or lower hailstorm damage and pinpoint extremely heavy events, highlighting therefore the intervals between them, but cannot be used for identification of long-term trends. In this context, the decreasing trend detected in the number of hailstorms days of the summer-half year in

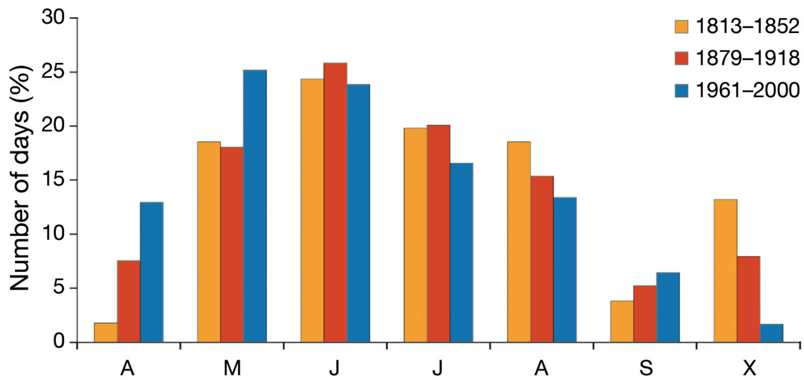

Fig. 12. Comparison of relative summer half-year temporal distribution (%) of hailstorm days in South Moravia, from April (A) to September (S) in the 1813–1852, 1879–1918 and 1961–2000 periods. X: not exactly dated hailstorm days

South Moravia based on meteorological data is interesting, particularly with respect to significantly rising temperatures in recent years (Brázdil et al. 2012b).

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