Climatic effects and impacts of the 1815 eruption of Mount Tambora in the Czech Lands

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Abstract. The eruption of Mount Tambora in Indonesia in 1815 was one of the most powerful of its kind in recorded history. This contribution addresses climatic responses to it, the post-eruption weather, and its impacts on human life in the Czech Lands. The climatic effects are evaluated in terms of air temperature and precipitation on the basis of long-term homogenised series from the Prague-Klementinum and Brno meteorological stations, and mean Czech series in the short term (1810–1820) and long-term (1800–2010). This analysis is complemented by other climatic and environmental data derived from rich documentary evidence. Czech documentary sources make no direct mention of the Tambora eruption, neither do they relate any particular weather phenomena to it, but they record extremely wet summer for 1815 and extremely cold summer for 1816 (the "Year Without a Summer") that contributed to bad grain harvests and widespread grain price increases in 1817. Possible reasons for the cold summers in the first decade of the 19th century reflected in the contemporary press included comets, sunspot activity, long-term cooling and finally – as late as 1817 – earthquakes with volcanic eruptions.

Key words: documentary data – climate – Tambora eruption – human impacts – Czech Lands

1 Introduction

Violent tropical volcanic eruptions, transporting large quantities of particles into the lower stratosphere, give rise to decreases in temperatures in the troposphere, which cools for two or three subsequent years in response to strongly enhanced back-scattering of incoming solar radiation (Robock and Mao, 1995; Briffa et al., 1998; Robock, 2000; Jones et al., 2004; Písek and Brázdil, 2006; Timmreck, 2012; Lacis, 2015; LeGrande and Anchukaitis, 2015). Camuffo and Enzi (1995) studied the occurrence of clouds of volcanic aerosols in Italy over the past seven centuries with particular attention to the accompanying effect of "dry fog". Volcanic cooling effects are best expressed in temperature series averaged for a large area after significant tropical volcanic eruptions (Sear et al., 1987; Bradley, 1988; Briffa et al., 1998; Sigl et al., 2015). For example, Fischer et al. (2007) analysed winter and summer temperature signals in Europe following 15 major tropical volcanic eruptions and found significant summer cooling on a continental scale and somewhat drier conditions over central Europe. The effects of large tropical volcanic eruptions on radiative balance manifest themselves not only in widespread cooling, but also contribute to large-scale changes in atmospheric circulation, leading to one or two post-volcanic mild winters in the Northern Hemisphere (Robock, 2000). Fischer et al. (2007) associated volcanic activity with a positive phase in the North Atlantic Oscillation (NAO), causing stronger westerlies in Europe and wetter patterns in Northern Europe. Literature addressing volcanic effects on precipitation is more sparse (Gillett et al., 2004). For example, Wegmann et al. (2014) analysed 14 tropical eruptions and found an increase of summer precipitation in south-central Europe and a reduction of the Asian and African summer monsoons in first post-eruption years. Weaker monsoon circulations attenuate the northern element of the Hadley Cell and influence atmospheric circulation over the Atlantic-European sector, contributing to higher precipitation totals.

A great deal of literature has been devoted to analysis of the climatological and environmental effects of the Tambora eruption. The volcanic eruption of Tambora (Lesser Sunda

Islands, Indonesia) in April 1815, is among the most powerful of its kind recorded, classified at an intensity of 7 in terms of Volcanic Explosivity Index (VEI) (a relative measure of volcanic explosiveness, VEI is an open-ended scale that ranges from 0 to 8, where 8 represents the most colossal events in history. It is based on the amount of volcanic material ejected and the altitude it reaches – see Newhall and Senf, 1982). During the Tambora eruption, around 60 Tg of SO_2 were thrown into the stratosphere, where the SO_2 oxidized to sulphate aerosols (Self et al., 2004; Kandlbauer and Sparks, 2014). The subsequent year of 1816 has been termed the "Year Without a Summer" (see e.g. Stommel and Stommel, 1983; Stothers, 1984; Harington, 1992; Vupputuri, 1992; Habegger, 1997; Oppenheimer, 2003; Bodenmann et al., 2011; Klingaman and Klingaman, 2013; Brugnara et al., 2015; Luterbacher and Pfister, 2015). Kužić (2007) investigated the effects in Croatia of an unidentified eruption in 1809 and the 1815 Tambora event. Trigo et al. (2009) studied Tambora impacts in Iberia using both documentary and instrumental data. Lee and MacKenzie (2010), referring to a farming diary from north-west England that held weather entries for 1815–1829, found significant climate anomalies for the two years following the Tambora eruption. Auchmann et al. (2012) paid particular attention to the weather and climate of the 1816 summer for Geneva (Switzerland). Cole-Dai et al. (2009) held Tambora, with a further unidentified tropical eruption in 1809, responsible for the bitter 1810–1819 period, probably the coldest decade of the last 500 years or longer. However, Guevara-Murua et al. (2014) attributed the unidentified 1809 eruption to late November/early December 1808, as the second most explosive sulphur-dioxide-rich volcanic eruption for the last two centuries. Büntgen et al. (2015) identified the 1810s as coolest summer decade for the last three centuries in central Europe, basing this conclusion on tree-rings from 565 samples of Swiss stone pine (*Pinus cembra*) from high-elevation sites in the Slovak Tatra Mountains and the Austrian Alps. Briffa and Jones (1992) classified just the summer of 1816 as extreme in that particular decade in Europe. This was also clearly demonstrated in summer temperature responses over the whole of Europe for the three post-Tambora years by Luterbacher et al. (2016; see SOM Figure S15).

There are only a few studies that address the effects of volcanic activity on the Czech Lands (central Europe). For example, Kyncl et al. (1990) analysed climatic reactions and tree-ring responses to the Katmai eruption (Alaska) in 1912, largely on a central European scale. Brůžek (1992) studied the impacts of large 19th–20th-century volcanic eruptions upon temperature series at the Prague-Klementinum station. Brázdil et al. (2003) described a number of extreme climatic anomalies following the 1783 Lakagígar eruption (Iceland) in the course of an analysis of daily weather records covering 1780–1789, kept by Karel Bernard Hein in Hodonice, south-west Moravia. Písek and Brázdil (2006) used temperature records from Prague-Klementinum, together with other central European series (Kremsmünster, Vienna-Hohe Warte and Germany), to address the temperature effects of seven large tropical eruptions and nine eruptions in Iceland and the Mediterranean, complemented by short descriptions of the Lakagígar 1783 and Tambora 1815 events based on documentary data. This paper also included the effects of three tropical eruptions on series of sums of global radiation for the Hradec Králové station (together with Potsdam in Germany and Skalnaté Pleso in Slovakia). Brázdil et al. (2010) analysed climate and floods in the first post-Lakagígar winter (1783/1784) with particular reference to central Europe. Volcanic forcing was also taken into account as part of an attribution analysis of Czech temperature and precipitation series by Mikšovský et al. (2014) and in Czech series of spring and summer droughts by Brázdil et al. (2015b).

This contribution aims to provide a comprehensive description of climatic and environmental responses to the Tambora 1815 eruption for the Czech Lands (recently the Czech Republic). Section 2 addresses temperature and precipitation instrumental series, weather-related documentary data and the socio-economic data used in this study. Section 3 presents methods used for the study of short-term and long-term responses. Section 4 gives a full description of the climatic and environmental consequences of the Tambora eruption in the Czech Lands. The broader context of the results obtained is discussed in Section 5. The final section summarises the most important findings.

2 Data

2.1 Instrumental data

The climatological analysis herein is based on the following monthly, seasonal and annual temperature and precipitation series for the Czech Lands (Fig. 1):

(i) Prague-Klementinum (central Bohemia): homogenised series of temperatures (1775–2010) and precipitation (1804–2010), starting in a block of buildings that were once the Jesuit college of St. Clement, and located on the same site until quite recently (for data see Brázdil et al., 2012a)

(ii) Brno (south-eastern Moravia): homogenised series of temperatures (1800–2010) and precipitation (1803–2010) compiled from a number of places in the Brno area and homogenised to the recent Brno airport station (for data see Brázdil et al., 2012a)

(iii) Czech Lands: series of mean areal temperatures (1800–2010) and mean areal precipitation (1804–2010) calculated from ten homogenised temperature series and 14 homogenised precipitation series over the Czech Lands (for data and details of calculation, see Brázdil et al., 2012a, 2012b)

(iv) Žitenice (north-western Bohemia): homogenised series of temperatures (1801–1829) measured by parish priest František Jindřich Jakub Kreybich at Žitenice (measurements started in 1787 but incomplete before 1801), worked up by Brázdil et al. (2007)

(v) Central Europe: reconstructed temperature series (AD 1500–2007), consisting of temperatures derived from documentary-based temperature indices for Germany, Switzerland and the Czech Lands up to 1759 and homogenised temperature series of 11 secular meteorological stations located in these three countries and Austria from 1760 onwards (Dobrovolný et al., 2010).

2.2 Documentary data

The pre-instrumental and early-instrumental period of meteorological observations in the Czech Lands is well covered by documentary evidence that contains information about weather and related phenomena. It occurs in a number of data sources (e.g. annals, chronicles, memoirs, diaries, newspapers, financial records, songs, letters, epigraphic records, and others), which provide the basis for research in historical climatology (Brázdil et al., 2005b, 2010b). As well as a wealth of chronicles and personal histories reporting various climatic and weather anomalies, their impacts and consequences (for those used in this study see Section 4.2), the following sources have proved particularly valuable:

(i) Annual summaries of the weather and the general economic situation that accompany the daily weather observations kept by František Jindřich Jakub Kreybich in Žitenice for the years 1815, 1816 and 1817 (S1–S3)

(ii) Qualitative daily weather observations and their monthly and annual summaries kept by Reverend Šimon Hausner of Buchlovice (south-eastern Moravia), spanning the 1803–1831 period (S4)

(iii) The detailed weather records kept by Anton Lehmann, a teacher in Noviny pod Ralskem, over the 1756–1818 period, which were copied into the local "book of memory" by Joseph Meissner in 1842 (S6)

(iv) Notes extracted from meteorological observations kept by Antonín Strnad and Alois David, the third and fourth directors of the Prague-Klementinum observatory (Poznámky, 1977).

Moreover, the editions of newspapers published in Prague (*Prager Zeitung*), Brno (*Brünner Zeitung*) and Vienna (*Wiener Zeitung*) covering the post-Tambora years were also systematically scrutinised for 1815–1817. Although weather information appears relatively rarely in their pages with respect to descriptions of events in the Czech Lands or Austria, related stories from other parts of Europe or North America clearly prevail there.

3 Methods

In this paper, descriptions of weather and related phenomena in the Czech Lands post-Tambora, i.e. May 1815–December 1817 are derived from documentary data. All such the data extracted were critically evaluated, including analysis of source credibility, place and time attribution of records, content analysis, interpretation of records with respect to recent meteorological terminology and cross-checking of records against various different places in the Czech Lands. The creation of a database was the next step, in which information about place, time and event, characterised by key-words, full reports and data sources, has been recorded to provide a basis for further use (see Section 4.2). Kreybich's records from Žitenice (S1–S3) and Hausner's observations from Buchlovice (S4) were then further employed for calculation of monthly numbers of precipitation days in 1815–1817 (see Fig. 6).

The climatic effects of the volcanic eruption based on instrumental observations are expressed in the short-term and long-term contexts. In the short-term, the approach followed is that taken by several other papers addressing the effects of eruptions on temperature series (e.g. Sear et al., 1987; Robock and Mao, 1995; Kelly et al., 1996; Písek and Brázdil, 2006; Fischer et al., 2007). Temperature patterns related to the eruption are described over a ten-year period to avoid the possible influence of a strong trend. The month of the eruption is taken as month zero. The mean temperature for each month was calculated using temperature data from five years prior to the eruption. Each monthly mean temperature for five years before and after the eruption was then expressed as a departure from the calculated mean value. The same approach was applied to series of precipitation totals. For the long-term context, the eruption year and two subsequent years were characterised by their order and magnitude in the whole series shown in increasing (temperatures) or decreasing (precipitation) order.

4 Results

This section describes climate, weather and related phenomena in the Czech Lands during the time after the Tambora eruption. Because the character of the data differs quite sharply, a division is maintained between information obtained from quantitative meteorological measurements and more qualitative data arising out of documentary evidence.

4.1 The Tambora eruption in the context of meteorological observations

Fig. 2 shows seasonal temperature anomalies for the Prague-Klementinum, Žitenice and Brno stations and for mean series for the Czech Lands and central Europe. These are expressed with respect to the 5-year period pre-eruption. Cooling, as indicated by negative anomalies, is already evident in the summer and autumn of 1815 and, after the slightly positive winter of 1815/1816 temperature anomaly it continued for the rest of 1816. After a very mild winter of 1816/1817 (the mildest in the 1811–1820 period in four series; only winter in Brno 1814/1815 was slightly warmer), negative anomalies occurred, especially in spring with the strongest negative anomaly (stronger than in summer 1816). Autumn 1817 also exhibited a negative anomaly. However, it also follows from Fig. 2 that a cooler period was already in process from spring 1812 to autumn 1814, interrupted by slightly positive anomalies in spring 1813 at two Bohemian stations (Prague-Klementinum, Žitenice), while warm patterns prevailed in 1811. Among monthly temperature anomalies, April 1817 is worthy of mention, fluctuating between –4.2°C and –4.8°C for the five series studied (Fig. 3a). Other very cold months included October 1817, December and July 1815. On the other hand, very high positive anomalies occurred in January 1816 and in January–February 1817.

A considerable drop in differences between mean winter and summer temperatures in 1815 was followed by a clear reduction of seasonality after the Tambora eruption for all five series (Fig. 4). This is related to the fact that tropical eruptions induce a positive phase in NAO circulation over Europe in the first and second years post-eruption, leading to winter warming on the one hand and summer radiative cooling due to volcanic aerosols on the other (Fischer et al., 2007).

Seasonal precipitation anomalies in the Prague-Klementinum, Brno and Czech Lands series (Fig. 5) exhibited positive anomalies in both summer 1815 (particularly June and partly August) and 1816 (mainly June), with the first-mentioned particularly rainy. Another clear but negative anomaly occurred in autumn 1817, while the remainder of the 1815–1817 seasons showed somewhat smaller, or even opposite, anomalies. For monthly precipitation (Fig. 3b), the highest positive anomalies, in relative terms, were achieved in February 1817, June 1815 and in May 1817 (the latter only for Prague-Klementinum). These may be attributed either to natural spatial differences in precipitation totals between two stations distant from one another, or to weaknesses in the homogenisation of precipitation series (lower spatial correlations and lack of stations for calculation of reference series for the past) (Brázdil et al., 2012a).

4.2 Post-Tambora eruption times, based on documentary data

The year 1815

Šimon Hausner, a reverend, kept daily weather records for Buchlovice. He mentions a rather cold May 1815 with more frequent rain and frosts on 29–30 May. Further, he characterises June, after some early fine days, as a windy and rainy month. July weather was variable, with frequent rain, strong winds, and cold mornings and evenings; the whole month was somewhat cooler than usual. August was rainy, with the exception of a few days, often with "torrents of water" [*Wassergüsse*]. Haymaking and the grain harvest (particularly wheat) took place in rainy weather. If two days were fine, it then rained again for the following two days. The wine vintage of 1815 was bad for the third year, after 1813 and 1814 (S4). František Jindřich Jakub Kreybich, a parish priest in Žitenice, speaks of the leaves on fruit trees entirely eaten away by caterpillars in May. Moreover, at the beginning of the following month, the wheat and some of the rye were infested with rust. Periods of rain in July–August complicated the harvest at higher altitudes in particular, where all the hay rotted (S1). A message from Litoměřice dated 9 August reports a flood lasting eight days on the River Elbe after five weeks of rainy periods. The water rose to a level of two feet [*c*. 65 cm] under the bridge, so the structure survived, but grain, vegetable and other field crops were damaged (Katzerowsky, 1895). The water level reported would correspond to a *c*. 20-year return period if this were compared with systematically measured water levels at Litoměřice between 1851 and 1969 (Brázdil et al., 2005a). In a similar vein, Kreybich in his records at Žitenice reports a flood on the Elbe for 10–14 August with extensive damage to agricultural crops (S1). A flood on the River Vltava, reported for 9–10 August for Prague, inundated fields and damaged crops (Brázdil et al., 2005a). Flood damage to fields tied to the aristocracy was reported around the Bečva River at Troubky (Brázdil and Kirchner, 2007).

The wet, cold summer gave way at the end of August to a very dry, cold autumn in 1815, confirmed by sources from Bohemia (S1) and Moravia (S4), and clearly documented by negative precipitation anomaly (Fig. 5) and lower monthly numbers of precipitation days (Fig. 6). The grape harvest was below average in terms of both quality and quantity (Katzerowsky, 1895), there was no fruit and the potato yield was bad (Bachmann, 1911). Frosts set in from 7 December at Buchlovice (S4), but on 1 January 1816 the ice-floes had dispersed from the River Elbe at Roudnice nad Labem and Litoměřice (S1).

The year 1816

Hausner describes the two winter months of 1816 in Buchlovice as: January – relatively cold weather to mid-January, mild with rain afterwards; February – variable with deep frosts on the one hand and periods of thaw on the other (S4). Kreybich records for Žitenice characterise January as mild and February as much colder with the Elbe and Ohře rivers frozen from 8 to 20 February. The ice was definitely gone by 8–9 March (S2). Lehmann reports a 3/4-ell [*c*. 58-cm]-thick crust of ice on some fields in Noviny pod Ralskem (S6). Frosty weather prevailed in March with blizzards from 26 to 31 March. April was cold and dry, with no heavy rain (S4). Other Czech documentary sources report 1816 as particularly cold and wet, with bad harvests and rising prices of all products. Around Nové Město na Moravě in the Bohemian-Moravian Highlands, lingering snow cover hampered the spring sowing, which started as late as 15 May (Trnka, 1912). Václav Jan Mašek of Řenče, who kept records, writes: "[...] *started to rain on St. Medard's day* [8 June] *and* [continued to do so] *for eight weeks, such that for this entire time one day in the week without rain was rare; around St. John's* [24 June], *when the hay was harvested, God granted a few fine days* [...] *All the grain was saturated, it was too wet to dig the potatoes and from this* [situation] *it followed that the yield was* *bad, prices rose terribly high and hunger* [appeared]" (Urban, 1999). Šimon Hausner's monthly summary for Buchlovice describes the summer as: June – rainy, very windy, cold, little warmth; July – little warmth, mostly rain and strong winds, people driven by poverty to start harvesting early; August – except for a few days, cold and wet weather, harvest continued long time (S4). Kreybich reports cold and rainy weather from May onwards, for the whole summer up to September. For the summer months, he makes particular mention of a number of unusually dense fogs and damaging thunderstorms. It rained for 191 days of the year at Žitenice (S2); the mean for 1806–1818 is 166 days (Brázdil et al., 2007). Records kept by Martin and František Novák in Dřínov report a bad grain harvest (frost damage in May, especially to the rye), almost no fruit, wetness and rainy periods. The wheat was harvested very late, around 21 September. Barley was added to bread mixes, but it was not long before nearly every possible substitute came into use – oats, vetch, peas, potato, and acorns are mentioned. Many farmers fell into debt (Robek, 1974). The "Book of Memory" for the school in Chrást even mentions that "*in many small villages, people prepare grass scalded in hot milk for food, and* [also] *eat bran*" (Anonymous, 1919).

The subsequent wet autumn of 1816 saw delays to the bean harvest and autumn sowing; winter wheat was sown late, even delayed to 5 November around Boskovice (S5). Reports from Olešnice indicate that low rye yields meant that some farmers had to use anything available for new sowing (Paměti starých písmáků moravských, 1916). No wine was available in Litoměřice (Katzerowsky, 1895). In Opava, unusual cold periods from June 1815 continued up to December 1816. A shortage of grain resulted in a decree banning the distillation of spirits, issued on 13 November (Kreuzinger, 1862). Anton Lehmann reports imports of grain (with the exception of oats, which had a good yield) from Silesia, transported there from Russia where the yield, together with that of Poland, had been good (S6). This is also confirmed by *Prager Zeitung* (6 October 1816, p. 1113) reporting transport of Russian grain to Trieste in Italy. However, a terse note from Hausner in his annual summary for 1816 reads: "*Hunger is inevitable*." (S4).

The year 1817

According to Šimon Hausner, severe frosts occurred in Buchlovice between 8 and 16 January 1817; they followed on from a thaw and were replaced by variable weather. Changeable weather with fewer frosts prevailed in February as well, when roads were muddy (S4). A flood on the River Vltava in Prague is reported for 7 March (Brázdil et al., 2005a). March is described by Hausner as an unpleasant month with daily frosts, snow and rain making roads muddy. April 1817 was especially remarkable, described as a month with few fine days, continuous frosts, cold winds, incessant snowfall, very muddy roads and such awful weather that "*almost no previous April* [since 1803] *has been as bad*". After sleet on 7 April, Hausner reports 13 days upon which snow fell and a further three of precipitation – one with drizzle, one with rain and one with sleet, between 11th and 28th April (S4). Reports from Vienna are similar. Cold weather set in on 11 April and snow fell almost daily between 17th and 28th April (*Wiener Zeitung*, 8 May 1817, p. 421). Kreybich, the Žitenice cleric, reports four landslides in spring, the result of extremely wet conditions in north-western Bohemia: the first on Křížová hora Mt. north of Žitenice, the second on Trojhora Hill between Chudoslavice and Třebušín, the third at Vitín near Malé Březno (community now defunct) and the fourth east of Jílové (S3). A fifth landslide is reported at Bohyně (east of Jílové) at the end of November, in addition to Kreybich (S3), by the *Prager Zeitung* from 22 December 1817 (p. 1403). The five landslides in 1817 in north-western Bohemia, which are not included in the historical catalogue of landslides by Špůrek (1972), are among the three most important landsliding events to appear in documentary evidence before 1900. Other recorded landslides documented in this area took place only in 1770 (14 landslides), as a result of the very wet and rainy year of 1769, and in winter 1769/1770 (see e.g. Raška et al., 2016) and in 1897–1900 (50 landslides altogether), due to persistent wet and rainy patterns (Rybář and Suchý, 2000). Apart from these three events, only 13 landslides in the remaining nine years during the 1770–1900 period are documented; this distribution also reflects the number of documentary sources available for extraction (Raška, 2016). May was recorded as too wet to work on the fields in Noviny pod Ralskem (S6).

All the Czech documentary sources speak of shortages of food and rising prices in 1817. The high prices continued until the harvest of 1817, with shortages of food so severe that people milled rotting oats for flour (Trnka, 1912). A chronicle from Velká Bystřice reports that even when grain was available, there was insufficient money to buy it. It also records a far higher number of beggars than had been seen for many years (Roubic, 1987). The situation was significantly ameliorated by a good harvest (a very high potato yield, for example, was reported for Boskovice – S5). However, Litoměřice had a below-mean grape vintage, in terms of both quality and quantity (Katzerowsky, 1895).

The qualitatively-described increase in prices may be confirmed by actual records of mean prices for the basic grain crops. Data from Prague in Bohemia and for Moravia, indicate bad harvests in 1815 and 1816 driving prices up from 1813 onwards, culminating in 1817 (Fig. 7). While in Moravia grain prices rose threefold (doubling for oats), the figures for Prague were *c*. 4.5-fold for rye and barley and tripled for wheat. A higher increase in prices in Bohemia compared with Moravia has been confirmed for many other places in the province by Tlapák (1977), but with prices available only up to 1817; for example, the figures for Litoměřice were fivefold for rye and barley and tripled for wheat and oats. Again the better harvest of 1817 drove prices down sharply, to the level of 1813 or below. While prices for wheat, rye and barley exhibited similar steep increases and decreases, fluctuations in those for oats were more stable, also due to a good yield in 1816 (S6).

5 Discussion

5.1 Post-Tambora climate anomalies in the long-term context

The post-Tambora climate anomalies may also be compared from the long-term viewpoint by ordering the mean seasonal temperatures in increasing series of seasonal values over the 1775–2007 period (Table 1). Based on Prague-Klementinum temperatures, among the seasons following the Tambora eruption, only summer 1816 stands out, as the fifth coldest (summer 1815 was the 11th coldest, tied with three other years). Central European temperature series averaging data over a broader area discloses summer 1816, post-Tambora, as absolutely the coldest in the 1775–2007 period. Furthermore, the general central European view significantly enhances the position of the cold spring of 1817 as the eighth–ninth coldest compared with Prague (16th–18th coldest). This reveals that spatial averaging of data and moving the territorial area of interest south-west of Prague (where the majority of the stations used for calculation of the central European series are located) may strengthen the summer signal of volcanic eruptions, including large tropical eruptions.

In terms of individual months, those following the Tambora eruption appear among the ten coldest years four times. The coldest month to appear in both complete series was April 1817. Among the ten coldest years were also July 1815 (Prague-Klementinum only), July 1816 (central Europe only – the third coldest), August 1816 and October 1817 (both series).

Precipitation totals expressed for the Prague-Klementinum and Brno stations (1804–1810), did not achieve extremes of temperature. However, summer 1815 was the wettest for Prague-Klementinum and the third wettest for Brno (Table 1). Spring 1817 was also the third wettest at Prague-Klementinum. In terms of individual months, June 1815 was the third wettest for both stations. August 1815, June 1816 and May 1817 also appeared among the ten wettest months at Prague-Klementinum.

In Büntgen et al. (2015), the summers of the 1810s constitute the coolest decade in central Europe in the past three centuries, based on the analysis of tree-rings in Swiss stone pine. Cole-Dai et al. (2009) refer to this time as probably the coldest decade in the last 500 years or more in the Northern Hemisphere and the tropics. However, these findings are not confirmed by the temperature series used in this study. In central European temperature series based on documentary and instrumental records (Dobrovolný et al., 2010), the 1810s summers were third-coldest after the 1690s and 1910s (in the 1500–2007 period). In the Czech Lands, the series from Brno was fourth-coldest (1800–2010) and those from Prague-Klementinum and mean Czech areal series the fifth-coldest (1780–2010 and 1800–2010 respectively). In the light of papers by Cole-Dai et al. (2009)

and Guevara-Murua et al. (2014), the cold summers early in the second decade of the 19th century may also have been influenced by an unknown volcanic eruption in 1808/1809. In this context, Brönnimann (2015) demonstrated cool April–September 2010 patterns compared to mean surface air temperatures in 1801–1830 and argued that this eruption could have set the stage for sustained ocean cooling (compare Stenchikov et al., 2009). However, 1811 was already warmer in the Czech Lands from spring to autumn, and lower temperatures started in 1812 (see Fig. 2).

5.2 Explanations of post-volcanic weather and climatic effects

Czech documentary sources recorded no remarkable weather phenomena directly attributable to the Tambora eruption. However, the series of cold summers from 1812 onwards, and particularly that of 1816, led to speculation about possible causes. The newspaper *Wiener Zeitung* of 9 July 1816 (p. 755) and the *Brünner Zeitung* of 12 July 1816 (pp. 759–760) reprinted an article from a certain Böckmann from *Badischen Staatszeitung*, responding to the series of consecutive cold summers after the warm summer of 1811. First he mentioned Flaugergues' comet (Fig. 8a) observed in the autumn of 1811: "*… the large, remarkable comet of 1811 had a particular influence on our solar system, and* […] *stimulated physical processes in the Earth's atmosphere, hitherto unknown, through which unusual warmth was generated, concurrently perhaps leaving* [certain] *substances or removing others, which otherwise in usual circumstances, particularly in summer weather, might not have had such a visible influence*." His article also discusses the possibility that the cool summers may have resulted from the number of sunspots (Fig. 8b): "*Therefore certain natural scientists believed an explanation of the cold years* [might be found in that] *during them the Sun produced less* [sun]*light and in warm* [years] *more than usual.* [...] *These views themselves are, however, not yet proven; we have had hot summers with many sunspots and cold winters with few*." A slow cooling of the Earth is mentioned as a third possible trigger: "*From another side, an explanation for the unusual cold weather has been sought for many years in the fact that Earth was once very hot and should now be getting cooler. Were such cooling alone real, so our mean annual warmth would be reduced by only one degree for every 10,000 years that have passed, and thereby our climate would be similar* [in the same steps], *over such a large time interval, to the climate which is* [now] *in the area situated about 70 hours to the north.*"

However, remarks made by the I. R. Astronomical Observatory [*k. k. Sternwarte*] in Vienna concerning the extremely cold and snowy second half of April 1817, published in *Wiener Zeitung* on 8 May 1817 (p. 421), turn attention to earthquakes and volcanic eruptions rather than to comets or sunspots: "*But earthquakes and volcanic eruptions could well give rise to the origin of the recent* [snow and heavy thunderstorms in places], *as a public newspaper has already mentioned. That ongoing chemical processes in the Earth interior and on its surface as well, due to changes in the atmosphere, give rise to various phenomenon that may be based on them, might be something more than mere surmise, and more probable than that comets, at distances of millions of miles, having in any event no case significant mass, as well as more or fewer sunspots, could have the ascribed effect on the weather patterns that are appearing on our Earth*." Finally, some contemporary scientists attributed the cold summer of 1816 in western Europe to huge masses of ice drifting in the North Atlantic (Bodenmann et al., 2011).

The effect of the Tambora eruption on air temperature was mentioned marginally by Humphreys (1913) in a discussion of the role of volcanic dust and other factors in climatic changes. First he attributed the cold years of 1783–1785 to the explosion of the Japanese volcano Asama in 1783 (see e.g. Aramaki, 1956, 1957; Zielinski et al., 1994) and then mentioned that "*the "year without a summer," that was cold the world over, followed the eruption of Tomboro, which was so violent that 56,000 people were killed and "for three days there was darkness at a distance of 300 miles*".

5.3 Social impacts of the Tambora eruption

The ways in which the Tambora eruption impacted on society must be addressed in the light of the contemporary socio-political situation. Emperor Franz I, deeply conservative, was ruler of the

Austrian Empire, to which the Czech Lands belonged, during the 1810s. He expanded royal power to penetrate every corner of society, creating what was essentially a police state, with rampant bureaucracy, censorship and resistance to reform (Taylor, 1998). The Czech Lands were the first part of the Austrian Empire to participate in the industrial revolution. Craftsmanship and manufacturing gathered pace, and agriculture took to the rotation of crops. The Napoleonic wars marred the first five years of the 1810s, accompanied by stagnation of population growth, rising prices, poverty, hunger, increasing numbers of beggars and higher incidence of unrest in the countryside. Constant warfare led to state bankruptcy in 1811 (Bělina et al., 2013). However, change was not far off. Demand for grain and foodstuffs rose and with it prices, leading to higher incomes for farmers, characteristic of the period. The internal situation calmed down after 1815, demand for foodstuffs increased still further, agriculture developed and population growth revived. There was an agricultural boom in the Czech Lands that lasted until 1817 (Lněničková, 1999). Albert (1964), investigating an agricultural crisis after 1817 in Moravia, explains the increase in grain prices after the Napoleonic wars in terms of agriculture intensification. He posits that expanding potato cultivation started to compete with grain, and livestock numbers were low, insufficient to absorb any corn-growing surplus. He did not associate the less productive years with the Tambora eruption. A drop in grain prices after 1817 in Moravia was related to good harvests in 1818–1821. Farmers' incomes fell in response to decreasing prices and they found themselves unable to meet taxation demands.

On the other hand, Post (1970) attributed the growth in grain prices that followed the Napoleonic wars in Europe to, apart from inflation and overproduction, the barren years of 1816–1817 resulting from low temperatures and abundant precipitation related to volcanic eruptions, particularly of Tambora. The subsequent drop in prices led to a series of bankruptcies, poverty and vagrancy; this situation was reflected in population decline and increased mortality.

6 Conclusions

The literature addressing the climatological and environmental consequences of large volcanic eruptions at various spatial and temporal scales is extensive. The eruption of Tambora in April 1815, the strongest, at VEI-7, has attracted the most attention and widespread interest in its impacts, particularly in 1816, the "Year Without a Summer". In addition to those of summer 1816, cooler patterns in post-Tambora seasons were also expressed in summer 1815 and spring 1817. The analyses and documentation cited in this paper demonstrate relatively weaker effects at regional or local scales for central Europe (e.g. Briffa and Jones, 1992; Písek and Brázdil, 2006). This has also been confirmed by Mikšovský et al. (2014), who revealed the prominent and statistically significant imprint of major volcanic events on the global temperature signal while changes in mean Czech temperature series remained negligible (1866–2010 period).

The consequences of the climatic effects of the Tambora eruption were hard on society. A bad grain harvest contributed to rising prices, which were in turn reflected in a lack of bread, hunger and high vagrancy. This situation even peaked in famine in some central European countries, such as Germany (Bayer, 1966) and Switzerland (Krämer, 2015). Post (1977) even spoke of this time as "the last great subsistence crisis in the Western world". However, the impacts on life in the Czech Lands in the post-Tambora years were not comparable with the "Hungry Years" of 1770–1772 (Brázdil et al., 2001; Pfister and Brázdil, 2006) or with other known, massive famines before AD 1500 (in the 1280s, 1310s and 1430s – see Brázdil et al., 2015a).

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(S2) Archiv Akademie věd České republiky, Praha, fond Státní hvězdárna, inv. č. 783 (VI C 8, č. 18): Meteorologische Beobachtungen mit oekonomischen Bemerkungen vom Jahre 1816 beobachtet in Schüttenitz 1/2 Stunde Nordöstlich von der K. Kreisstadt Leitmeritz enfernt von Franz Jacob Heinrich Kreybich.
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(S6) Státní okresní archiv Česká Lípa, fond Sbírka rukopisů, sign. 13/3: Witterungs-Geschichte. Auszug aus den Titl: Lesenwürdige Sammlungen der hinterlegten Jahrgängen. Von Anton Lehmann Lehrer in Neuland. Abgeschrieben durch Joseph Meißner.

Table 1. The order of mean seasonal temperatures and precipitation for 1815–1818, the years after the Tambora eruption: a) temperature in order of increasing values (from lowest to highest), Prague-Klementinum and central Europe; b) precipitation in order of decreasing values (from highest to lowest totals), Prague-Klementinum and Brno

a) Temperature

Year	Prague-Klementinum (1775–2007)				Central Europe (1775–2007)			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
1815	-	187–193	11–14	36–45	-	198–201	9–12	36–40
1816	90–91	92–98	5	21–26	60–63	46–58	1	29–32
1817	181–184	16–18	93–107	71–79	183–190	8–9	73–84	89–97
1818	146–150	172–175	66–73	125–127	142–148	149–156	73–84	107–116

b) Precipitation

Year	Prague-Klementinum (1804–2010)				Brno (1804–2010)			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
1815	-	190–192	1	196	-	135–136	3	206
1816	114–116	129–130	25–26	111–113	80–81	80–81	38–40	54–58
1817	117–126	3	76–79	123–124	100–105	165–167	89–90	177–181
1818	171–172	80–81	129–130	93	189–192	64–65	159	111–112

List of Figures:

Figure 1. The Czech Republic, showing places from which meteorological observations (circles) and documentary weather reports (triangles) were obtained for the purposes of this study. Locations of other places reported in the text (crosses). Key: 1 – Bohyně, 2 – Chudoslavice, 3 – Jílové, 4 – Litoměřice, 5 – Třebušín, 6 – Vitín, 7 – Žitenice.

Figure 2. Seasonal temperature anomalies at Prague-Klementinum (1), Žitenice (2), Brno (3), in the Czech Lands (4) and central Europe (5) series around the time of Tambora eruption in 1815 (Wi – Winter, Su – Summer). Anomalies are expressed with respect to the 5-year period pre-eruption: month zero – April 1815.

Figure 3. Monthly temperature (a) and precipitation (b) anomalies in Prague-Klementinum (1) and Brno (2) series after the Tambora eruption (May 1815–December 1817). Anomalies are expressed with respect to the 5-year pre-eruption period

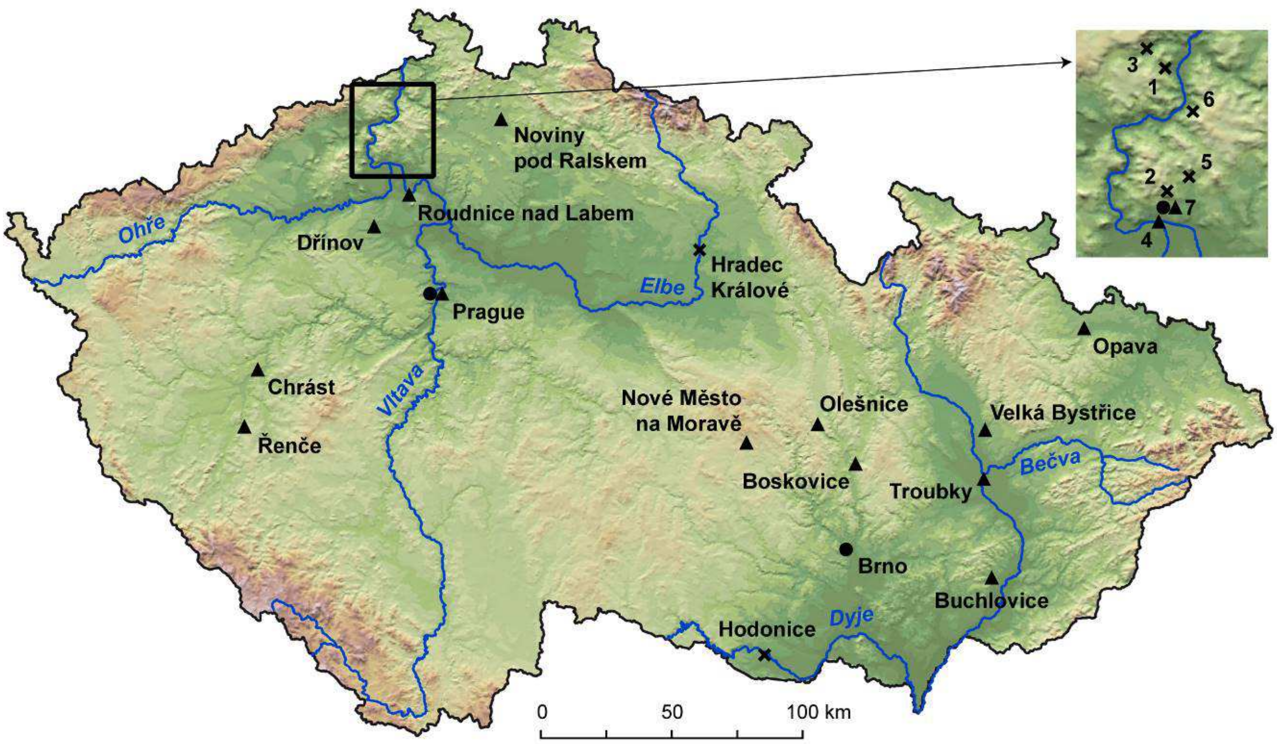
Figure 4. Differences between mean summer and winter temperatures in Prague-Klementinum (1), Žitenice (2), Brno (3), Czech Lands (4) and central Europe (5; C.E.) series, demonstrating reduction of seasonality after the Tambora eruption in 1815. Central European differences are calculated from temperature anomalies with respect to the 1961–1990 reference period (right axis).

Figure 5. Seasonal precipitation anomalies in Prague-Klementinum (1), Brno (2) and Czech Lands (3) series around the time of Tambora eruption in 1815. Anomalies are expressed with respect to the 5-year period pre-eruption: month zero – April 1815.

Figure 6. Fluctuations in the monthly numbers of precipitation days in 1815–1817: 1 – Prague-Klementinum (Meteorologická pozorování, 1976), 2 – Žitenice (S1–S3), 3 – Buchlovice (S4).

Figure 7. Fluctuations in prices of staple cereals (wheat, rye, barley, oats) in Prague (gulden/61.49 l) and in Moravia (gulden/hl) in the 1811–1820 period. Data: Prague – Schebek (1873), Moravia – Albert (1964).

Figure 8. a) Flaugergues' comet observed in September 1811 was, according to many people, responsible for the dry weather and a portent of its continuation. The illustration shows the position of the comet on 11 September at 10 p.m. in projection to the constellation of Ursa Major, recorded in Brno (attachment to *Hesperus*, 1812, no. 25); b) Sunspots observed by Cassian Hallaschka in Brno from 9 April to 3 May 1814 (supplement to Hallaschka, 1814).



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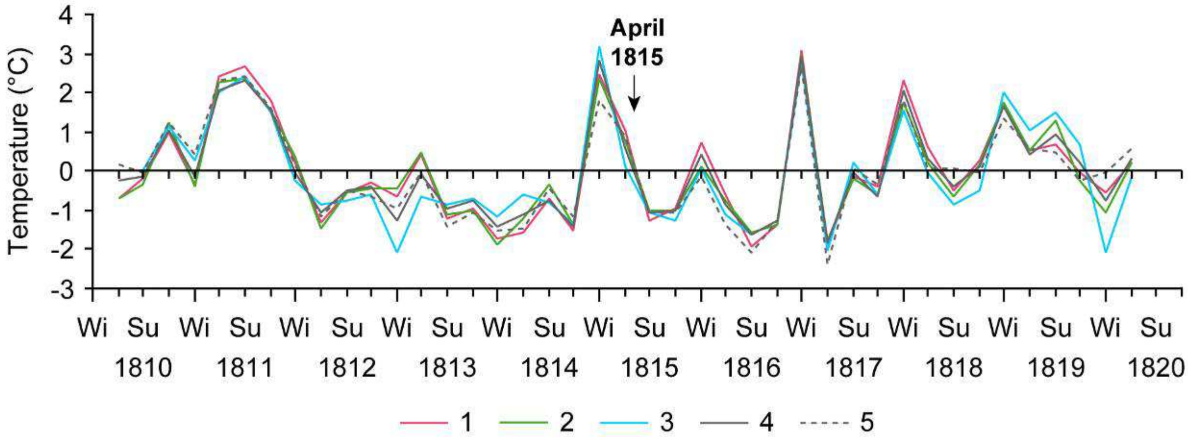

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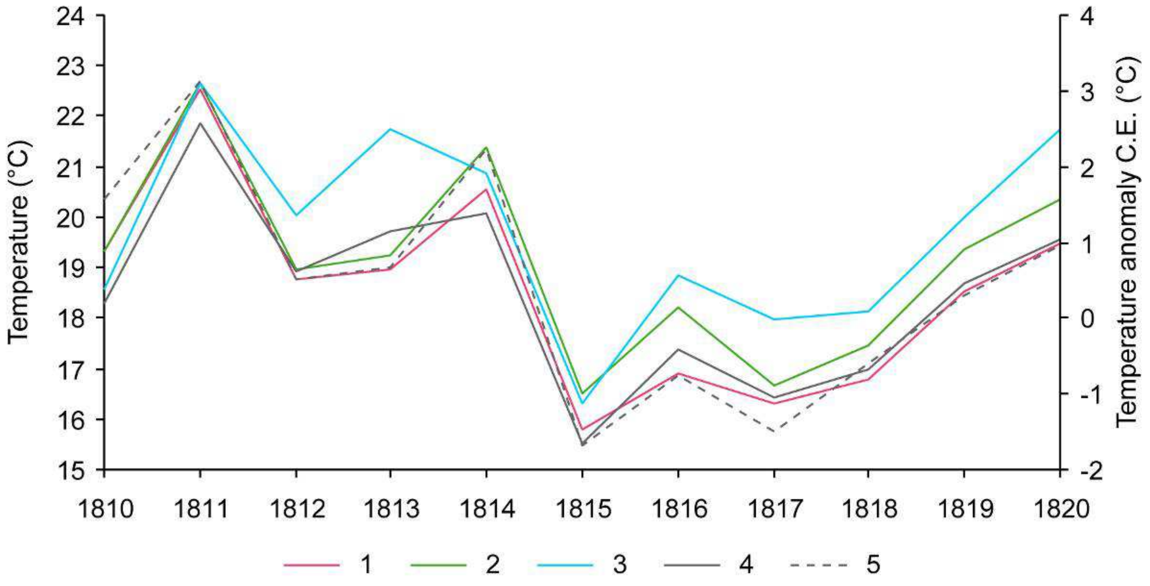

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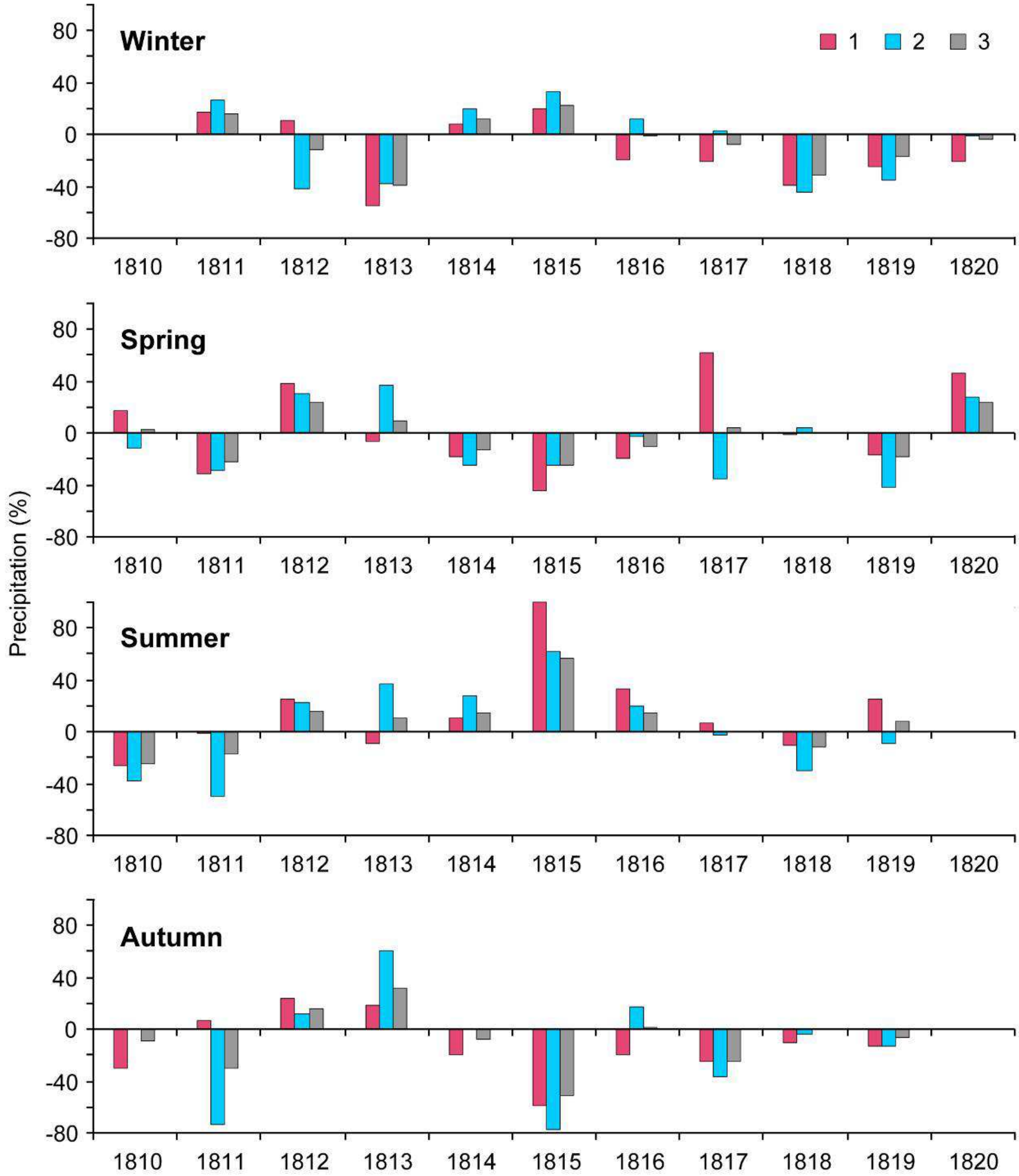

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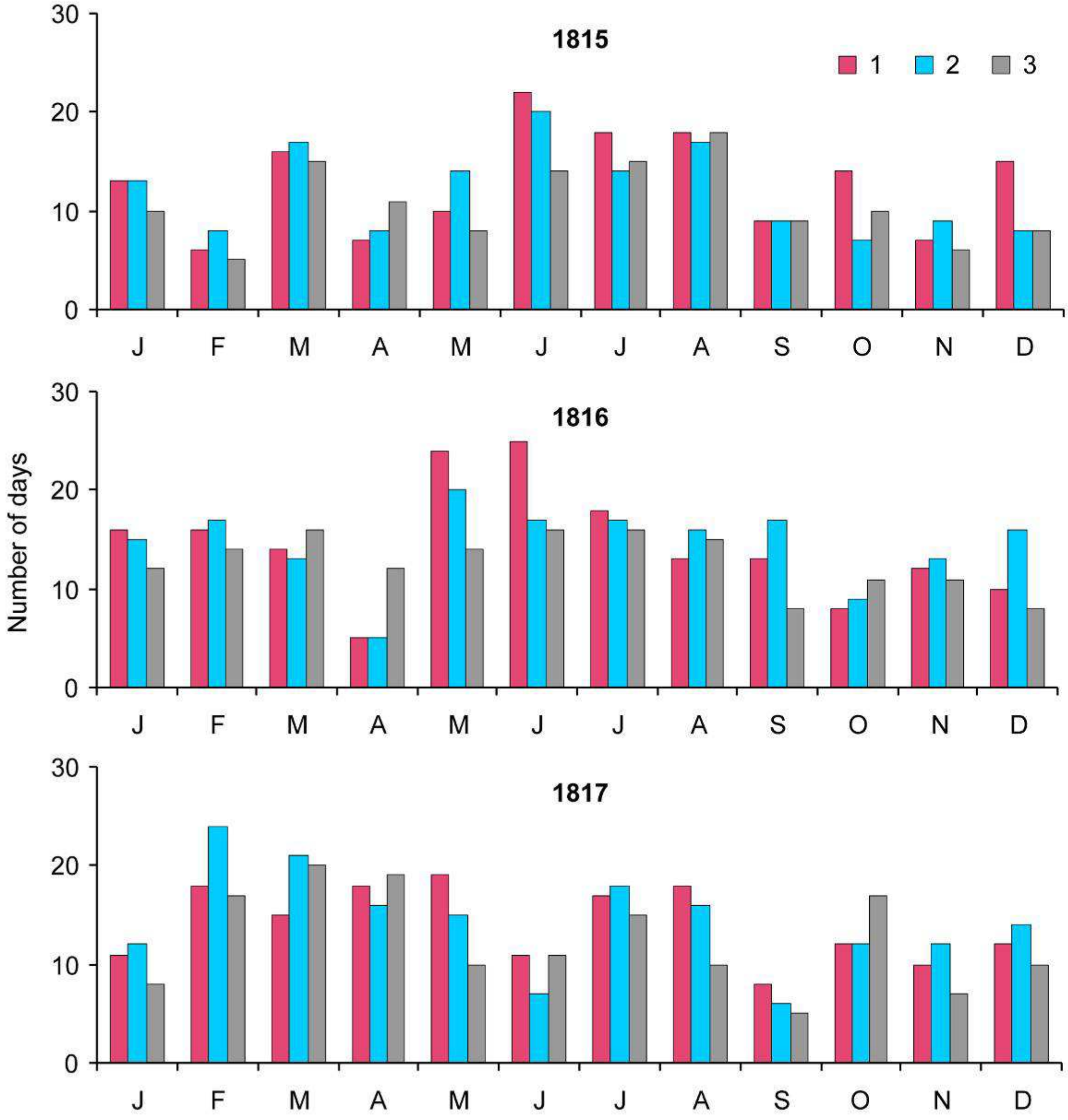

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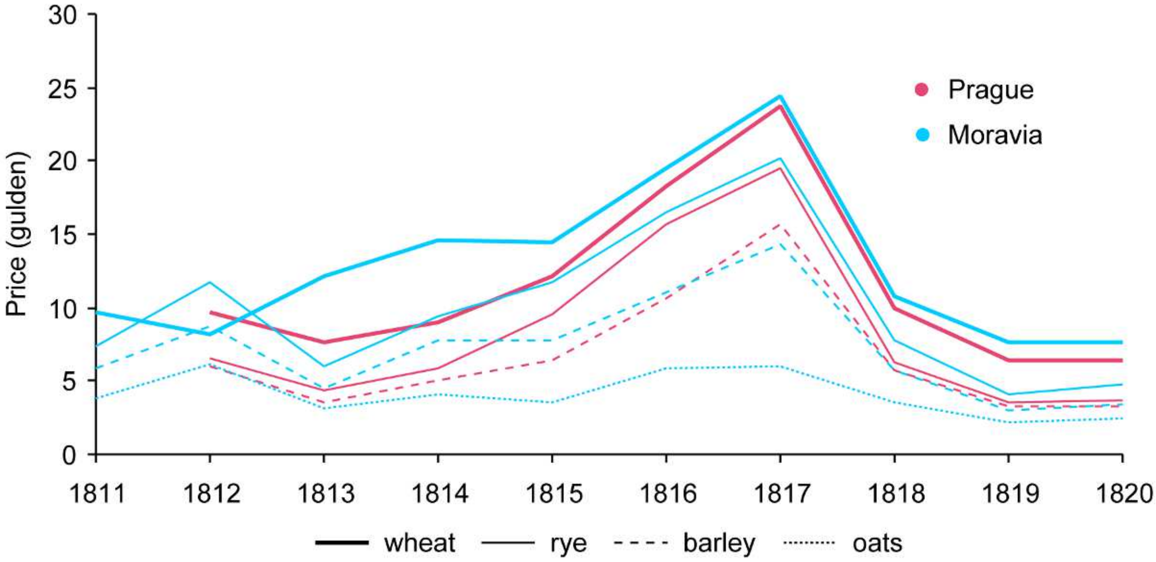

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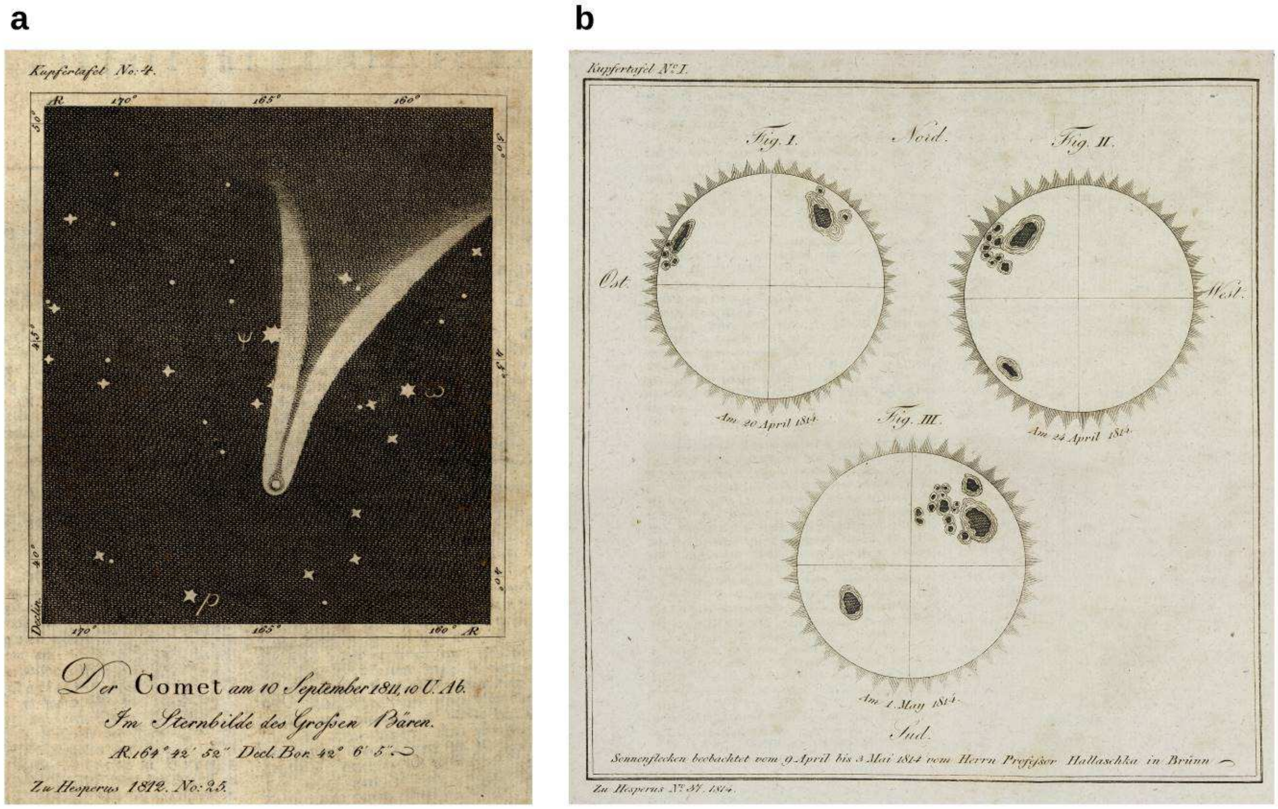

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