Clim. Past, 11, 1027–1047, 2015
www.clim-past.net/11/1027/2015/
doi:10.5194/cp-11-1027-2015

Climate
of the Past
Open Access

A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the "year without a summer" 1816

Y. Brugnara[1,2], R. Auchmann[1,2], S. Brönnimann[1,2], R. J. Allan[3], I. Auer[4], M. Barriendos[5], H. Bergström[6], J. Bhend[7], R. Brázdil[8,9], G. P. Compo[10], R. C. Cornes[11], F. Dominguez-Castro[12,13], A. F. V. van Engelen[14], J. Filipiak[15], J. Holopainen[16], S. Jourdain[17], M. Kunz[18], J. Luterbacher[19], M. Maugeri[20], L. Mercalli[21], A. Moberg[22,23], C. J. Mock[24], G. Pichard[25], L. Řezníčková[8,9], G. van der Schrier[14], V. Slonosky[26], Z. Ustrnul[27], M. A. Valente[28], A. Wypych[27], and X. Yin[29]

[1]Oeschger Centre for Climate Change Research, Bern, Switzerland
[2]Institute of Geography, University of Bern, Bern, Switzerland
[3]Hadley Centre, Met Office, Exeter, Devon, UK
[4]ZAMG (Central Institute for Meteorology and Geodynamics), Vienna, Austria
[5]Department of Modern History, University of Barcelona, Barcelona, Spain
[6]Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[7]Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland
[8]Institute of Geography, Masaryk University, Brno, Czech Republic
[9]Global Change Research Centre, Academy of Sciences of the Czech Republic, Brno, Czech Republic
[10]University of Colorado Cooperative Institute for Research in Environmental Sciences
at the Physical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA
[11]CRU (Climatic Research Unit), School of Environmental Sciences,
University of East Anglia, Norwich, UK
[12]Department of Physics, Universidad de Extremadura, Badajoz, Spain
[13]Departamento de Ingeniería Civil y Ambiental, Escuela Politécnica Nacional, Quito, Ecuador
[14]KNMI (Royal Netherlands Meteorological Institute), De Bilt, the Netherlands
[15]Institute of Geography, University of Gdańsk, Gdańsk, Poland
[16]Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland
[17]Météo-France, Direction de la Climatologie, Toulouse, France
[18]Institute for Meteorology and Climate Research (IMK), Karlsruhe Institute of Technology (KIT),
Karlsruhe, Germany
[19]Department of Geography, Climatology, Climate Dynamics and Climate Change,
Justus Liebig University of Giessen, Giessen, Germany
[20]Università degli Studi di Milano, Department of Physics, Milan, Italy
[21]SMI (Società Meteorologica Italiana), Turin, Italy
[22]Department of Physical Geography, Stockholm University, Stockholm, Sweden
[23]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
[24]Department of Geography, University of South Carolina, Columbia, SC, USA
[25]Department of History, Université Aix-Marseille, Aix-en-Provence, France
[26]McGill University, Centre for Interdisciplinary Studies on Montreal, Montreal, Canada
[27]Jagiellonian University, Department of Climatology, Cracow, Poland
[28]Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal

[29]ERT, Inc., Asheville, NC, USA

Correspondence to: Y. Brugnara (yuri.brugnara@giub.unibe.ch)

Received: 7 April 2015 – Published in Clim. Past Discuss.: 13 May 2015
Revised: 13 July 2015 – Accepted: 23 July 2015 – Published: 6 August 2015

Abstract. The eruption of Mount Tambora (Indonesia) in April 1815 is the largest documented volcanic eruption in history. It is associated with a large global cooling during the following year, felt particularly in parts of Europe and North America, where the year 1816 became known as the "year without a summer". This paper describes an effort made to collect surface meteorological observations from the early instrumental period, with a focus on the years of and immediately following the eruption (1815–1817). Although the collection aimed in particular at pressure observations, correspondent temperature observations were also recovered. Some of the series had already been described in the literature, but a large part of the data, recently digitised from original weather diaries and contemporary magazines and newspapers, is presented here for the first time. The collection puts together more than 50 sub-daily series from land observatories in Europe and North America and from ships in the tropics. The pressure observations have been corrected for temperature and gravity and reduced to mean sea level. Moreover, an additional statistical correction was applied to take into account common error sources in mercury barometers. To assess the reliability of the corrected data set, the variance in the pressure observations is compared with modern climatologies, and single observations are used for synoptic analyses of three case studies in Europe. All raw observations will be made available to the scientific community in the International Surface Pressure Databank.

1 Introduction

The measurement of atmospheric pressure has a long history, which begins with the famous experiment of Evangelista Torricelli in 1643. It was not long until, in 1657, the first European network of meteorological observatories, all equipped with a barometer, was set up by the Accademia del Cimento (Middleton, 1972). Similar short-lived attempts of organised networks would follow in the 18th century (e.g. Kington, 1974; Moberg, 1998; Brázdil et al., 2008). Eventually the barometer, as well as the thermometer, became a commercial product and an object of desire for anybody interested in the natural sciences, including not only scientists but also educated individuals from the middle and high classes, such as physicians or clergymen (Golinski, 2007). Some of these professionals used to keep meteorological diaries, in the same way that scientists in the astronomical observatories and in some universities had begun to do. This phenomenon led to the recording of millions of pressure and temperature observations, at the beginning only in Europe, but gradually also in the various ocean basins, on board intercontinental ships and finally in the colonies. The French Revolution and the Napoleonic wars caused a temporary decline in the quantity of meteorological observations in some European countries between the end of the 18th century and the beginning of the 19th century, accompanied by the dissolution of existing meteorological networks, but in the meantime the quality of the instruments continued to progress. Finally, in the 1850s a new era for meteorology began with the creation of the first national weather services (Middleton, 1964). These 2 centuries of development of the basic instruments for the atmospheric sciences are usually referred as the "early instrumental period".

Between the 1990s and the 2000s, three European Union-funded projects, ADVICE, IMPROVE and EMULATE (Jones et al., 1999; Camuffo and Jones, 2002; Ansell et al., 2006), triggered a large effort to digitise historical observations of temperature and pressure, particularly those of long and continuous series, some longer than 250 years, which were in some cases corrected and homogenised. These projects marked an important development from earlier manual efforts, which also sought to use historic barometric pressure observations to analyse changes in the atmospheric circulation but which were limited by an inability to automate the calculations (Cornes, 2014). A few years ago, most of the existing digitised pressure observations were collected and successfully assimilated into a global reanalysis that reconstructed four-dimensional meteorological fields back to 1870 (Compo et al., 2006, 2011), recently extended further back to 1850 (Cram et al., 2015). A similar enterprise was independently undertaken for the period 1900–2010 within the EU project ERA-CLIM (Poli et al., 2013; Stickler et al., 2014).

The collection described in this paper represents a first step towards a reanalysis of the first half of the 19th century. Although some of the series cover longer periods, the focus is on the years 1815–1817, the period most influenced by the eruption of Mount Tambora in Indonesia.

Located on the island of Sumbawa, about 300 km east of Bali, Tambora erupted between 10 and 11 April 1815 (Stothers, 1984; Oppenheimer, 2003). The consequences were a significant global cooling, estimated to have been between 0.5 and 1 K (e.g. Wagner and Zorita, 2005; Kandlbauer et al., 2013), as well as more delayed changes in the atmospheric circulation that deeply affected the climate of the midlatitudes in the Northern Hemisphere (e.g. Fischer et al., 2007; Wegmann et al., 2014). This culminated in the infamous "year without a summer" (Stommel and Stommel, 1979), 1816, a year characterised by strong and persistent negative temperature anomalies during the growing season in western Europe (e.g. Casty et al., 2007; Luterbacher and Pfister, 2015) as well as in eastern North America (e.g. Chenoweth, 1996; Briffa et al., 1998), with major socioeconomic impacts due to widespread crop failures (e.g. Pfister, 1999). Tambora may also have triggered an exceptional winter drought in most the Iberian Peninsula, leading to impacts comparable to those just mentioned (Trigo et al., 2009; Domínguez-Castro et al., 2012). The global crisis triggered by the 1816 climate anomaly has been described as "the last great subsistence crisis in the Western World" (Post, 1977).

Despite the many meteorological observations available for the early instrumental period, only a small fraction have been used in modern climate research (Brönnimann et al., 2006). The huge amount of documents, spread over thousands of libraries and archives, and the significant financial and human investments needed for recovery and digitisation explain why the majority of the data have never been analysed so far. Another difficulty arises from data quality, in particular for temperature: the homogenisation with modern data is usually not an easy task (e.g. Camuffo, 2002a, b; Böhm et al., 2010). Pressure is to some extent less problematic, when accompanied by detailed metadata because the barometer does not require a specific exposure (Middleton, 1964). However, observations made with mercury barometers need several corrections based on the characteristics of the barometer, on the variations in temperature and on the latitude (e.g. Moberg et al., 2002; Camuffo et al., 2006). Unfortunately, in most cases the historical observations were registered without any correction, and it is usually very difficult, if not impossible, to find any information about the barometer. The temperature of the barometer, fundamental for the correction, was also often not reported. This means that assumptions have to be made which increase the uncertainty of the original observations. Despite this, we will show that most of the data in the early instrumental period can be retained for scientific use.

This article is organised as follows. In Sect. 2 we describe the data set and the errors affecting the raw pressure observations in the early instrumental period and give a detailed account of the corrections that we applied. In Sect. 3 we analyse the data in the period 1815–1817 and introduce an additional statistical correction that allows one to produce reliable synoptic maps for case studies in Europe. Finally, we make our concluding remarks in Sect. 4.

2 Data and methods

2.1 Data set description

The collection consists of pressure observations made at 49 locations in Europe and North America, plus four ships' logbooks from voyages in the southern Atlantic, the Indian Ocean, the China Seas and the Persian Gulf (Fig. 1). More than half of the series were recently digitised at the University of Bern and considerable resources were also invested in the recovery of metadata. The digitisation usually involved the years from 1815 to 1817 only. In addition to barometer readings and the temperature of the barometer (when available), outside air temperature was also digitised, with the exception of a few stations in North America. Other series, some covering much longer periods (up to 257 years in the case of Stockholm), were provided by co-authors. Many of them have already been described in the scientific literature; their references are listed in Table S1 in the Supplement together with the sources of the new records. For two series, Milan and Stockholm, we use the homogenised version in the analysis (see the respective references for details on the homogenisation procedure). Moreover, constant corrections were applied in the years 1815–1817 to the pressure series from Bologna, London, Padua and Uppsala, following metadata.

The total amount of single pressure observations represented in the period 1815–1817 is 113 092, averaging 103 per day. Despite the considerable effort in recovering and digitising new series, the present collection still represents a minority of the existing data. According to a list that we compiled (Table S2), at least 58 additional sub-daily land series exist in that period, including at least 1 in India. The number of ships' logbooks is even larger: in Chenoweth (1996), for instance, 227 of them were collected for the summer of 1816. These numbers give an idea of the large quantity of manuscripts still to be digitised. We concentrated our resources on those series that could improve the spatial coverage of the data set. Moreover, we gave priority to instantaneous observations over daily averages or extremes. Accessibility also played a role and travels to archives or libraries took place only in exceptional cases. The number of historical documents available on the internet (Google Books and similar) has grown considerably over the last years and was an important contribution to the collection. In particular, contemporary scientific magazines have proven to be a prolific source.

Table 1 summarises the main characteristics of each land record. Almost half of the series unfortunately do not have the temperature of the barometer, nor were the pressure observations corrected for temperature. In fact, one can distinguish between two categories of observatories: the scientific observatories and the "amateurs". The former category includes astronomical observatories, universities and other scientific organisations. It offers in general a higher scientific level, since the observations were carried out by pro-

Table 1. List of land stations included in the collection, in alphabetical order. Observatories managed directly by scientific organisations are written in bold. Metadata refer to the period 1815–1817. Abbreviations: Long – longitude in degrees east; Lat – latitude in degrees north; Elev – elevation of the barometer in metres a.s.l. (rounded to the nearest full metre); Obs – typical number of pressure observations per day; Loc – exact location (within 100 m) from metadata (Y – available; N – not available); TCorr – data used for temperature correction (TB – temperature of the barometer; TA – outside air temperature; CL – outside temperature climatology; CO – observations already corrected for temperature; HR – heated room (constant temperature of 18 °C assumed)); Tot – number of pressure observations in 1815–1817; Flag – number of flagged observations after quality control. A question mark indicates estimated elevations.

Name	Country	Long	Lat	Elev	Obs	Loc	TCorr	Years	Tot	Flag
Aarau	Switzerland	8.04	47.39	380?	2	N	CO	1815–1816	1431	1
Albany	New York, USA	−73.75	42.65	12?	3	Y	TA	1815	543	0
Althorp	England, UK	−1.00	52.28	105?	2	Y	TA	1816–1817	1400	0
Armagh	Northern Ireland, UK	−6.65	54.35	64	3	Y	TB	1796–1965	3286	0
Avignon	France	4.80	43.95	22	4	N	TB	1816	982	0
Barcelona	Spain	2.17	41.38	20?	3	Y	TA	1811–1820	3288	12
Barnton	Scotland, UK	−3.29	55.96	50?	1	N	TA	1815–1817	968	5
Bologna	Italy	11.35	44.50	74	1	Y	TA	1815–1817	1088	0
Boston	England, UK	−0.03	52.98	10?	1	N	TA	1816–1817	713	0
Brunswick	Maine, USA	−69.96	43.91	25?	3	Y	HR	1815–1817	3112	0
Cádiz	Spain	−6.30	36.53	15?	3	N	TA	1816–1820	1461	0
Cambridge	Massachusetts, USA	−71.12	42.37	9	3	N	CO	1815–1816	818	0
Coimbra	Portugal	−8.42	40.21	95?	4	Y	TB	1815–1817	3665	1
Cracow	Poland	19.96	50.06	212	3	Y	TB	1816	1098	19
Derby	England, UK	−1.48	52.93	50?	2	N	TA	1817	64	0
Düsseldorf	Germany	6.77	51.23	35?	3	N	TA	1816–1817	1187	2
Edinburgh	Scotland, UK	−3.18	55.96	110?	2	Y	CO	1817	340	0
Exeter	England, UK	−3.53	50.72	47?	3	Y	TB	1813–1817	3058	1
Gdańsk	Poland	18.65	54.35	14	3	Y	TB	1815–1817	3278	4
Geneva	Switzerland	6.15	46.23	405?	2	Y	CO	1796–1863	2129	0
Göteborg	Sweden	11.97	57.71	15?	3	N	TB	1815–1817	3288	0
Haarlem	the Netherlands	4.65	52.38	2	3	Y	TA	1801–1841	3288	6
Härnösand	Sweden	17.94	62.63	15?	3	N	TA	1815–1816	2027	0
Hohenpeissenberg	Germany	11.02	47.80	995	3	Y	CO	1781–2009	3288	3
Karlsruhe	Germany	8.40	49.01	121	3	Y	TB	1815–1817	3288	3
London	England, UK	−0.12	51.52	24	2	Y	TB	1815–1817	2192	76
Lviv	Ukraine	24.03	49.84	295?	3	Y	CO	1815–1817	2576	0
Madrid	Spain	−3.71	40.41	650?	3	N	TA	1814–1817	1488	1096
Milan	Italy	9.18	45.47	132	2	Y	CO	1778–1834	2190	3
Natchez	Mississippi, USA	−91.37	31.46	70?	3	Y	TB	1815–1817	2210	0
New Bedford	Massachusetts, USA	−70.93	41.65	30?	4	Y	CL	1815–1817	4384	0
New Haven	Connecticut, USA	−72.92	41.30	25?	3	Y	CL	1815–1817	3219	342
Nuuk	Greenland	−51.73	64.17	10?	3	N	CL	1816–1820	2102	0
Padua	Italy	11.87	45.40	31	3	Y	TB	1815–1817	2366	0
Paris (a)	France	2.34	48.84	65?	1	Y	CL	1811–1820	361	0
Paris (b)	France	2.34	48.84	65?	4	Y	CO	1816–1817	2924	0
Prague	Czech Republic	14.42	50.08	202	1	Y	CO	1815–1817	1096	0
Quebec City	Canada	−71.21	46.82	32?	2	Y	TA	1803–1819	2183	5
Rochefort	France	−0.96	45.93	25?	2	Y	TA	1815–1895	2153	7
Salem	Massachusetts, USA	−70.88	42.53	5?	2	Y	CO	1786–1820	2145	9
Stockholm	Sweden	18.05	59.35	44	3	Y	CO	1756–2012	3286	8
Turin	Italy	7.68	45.07	281	1	Y	CO	1792–2009	1096	4
Umeå	Sweden	20.27	63.82	5?	3	N	TA	1815–1817	3288	0
Uppsala	Sweden	17.64	59.86	15?	2	Y	TA	1722–1865	2194	1
Valencia	Spain	−0.38	39.47	25?	3	Y	TA	1815–1818	2697	914
Växjö	Sweden	14.80	56.88	170?	3	N	TB	1815–1817	3288	1128
Vienna	Austria	16.35	48.23	198	3	Y	CO	1815–1817	3246	6
Ylitornio	Finland	23.63	66.40	50?	3	Y	TA	1800–1825	3257	981
Žitenice	Czech Republic	14.16	50.55	223?	3	Y	TA	1800–1818	3288	5
Zwanenburg	the Netherlands	4.73	52.38	5	3	Y	TA	1801–1861	3288	15

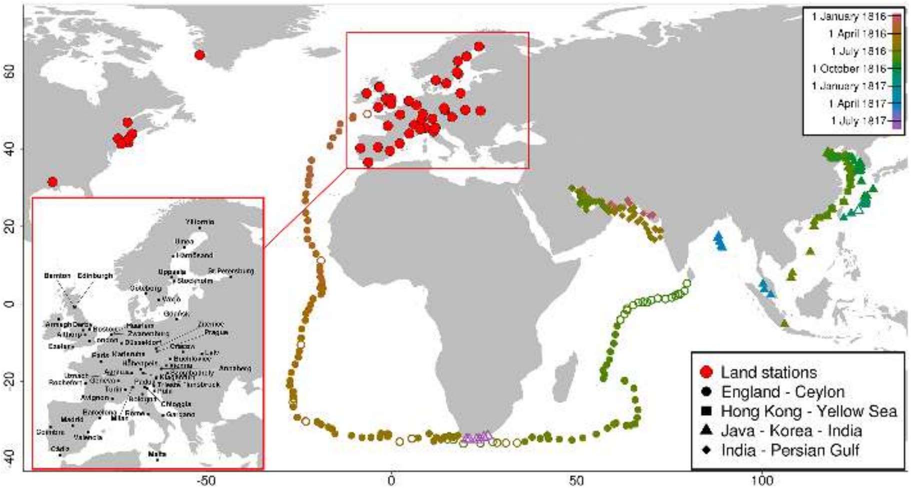

Figure 1. Position of the land observatories (red dots) and routes of the ships. For the latter, filled symbols denote locations for which pressure data are available, colours indicate time for marine data. The inset map shows the positions of the European observatories and of additional locations mentioned in Sect. 3.

Table 2. Ships' logbooks included in the collection. Abbreviations: P-Obs: number of pressure observations; TA: air temperature; SST: sea surface temperature; P: air pressure; WDir: wind direction.

Route	Ship's name	Variables	Source	P-Obs
England–Ceylon	Unknown	TA, SST, P, WDir	Davy (1817)	108
Hong Kong–Yellow Sea	H.M.S. *Alceste*	TA, P, WDir	Abel (1818)	149
Java–Korea–India	H.M.S. *Lyra*	TA, SST, P	Hall (1818)	986
India–Persian Gulf	H.M.S. *Favorite*	TA, P, WDir	Original weather journal	244

fessional scientists, usually astronomers or physicists. Moreover, metadata are more abundant and detailed. These observatories are printed in bold in Table 1. The amateurs were sometimes scientists who kept a personal weather diary, but in most cases they were learned and wealthy individuals (physicians, aristocrats, clergymen, etc.) with a strong interest in the natural sciences. Their measurements may be in general less accurate, and information about corrections or the temperature of the barometer are rarely given. Metadata are sometimes completely absent or very difficult to find. A few stations belonging to this category can actually be considered to be on the borderline, in the sense that their activity was supervised by a scientific institution, which often provided the instruments, following the model of the Societas Meteorologica Palatina in the 18th century (see Kington, 1974). This is the case for most of the observation sites in Sweden (Moberg, 1998) and for Hohenpeissenberg (Germany), where the monks of a monastery kept a meteorological register for the Bavarian Academy of Sciences (Winkler, 2006).

The series from Paris is split into two parts because we had different sources: the University of Barcelona provided one uncorrected pressure observation per day in the period 1811–1820, digitised from the original registers of the Paris astronomical observatory (Cornes et al., 2012), while four observations per day in the period 1816–1817, corrected for temperature, were digitised at the University of Bern from a contemporary scientific journal. The noon observations in the latter are the same observations as the former record; the only difference is the temperature correction. To avoid an overlap between the two series in the analysis, we removed the 1816–1817 data from the uncorrected series.

Ships' logbooks also contain pressure and air temperature observations and sometimes sea surface temperature (which was also digitised). The four records in the collection are from British vessels; they are briefly described in Table 2.

2.2 Pressure and temperature measurement in the early 19th century

In this section we give a brief summary of the instruments available in the early instrumental period and the errors affecting the observations. For a more detailed overview, we refer the reader to Middleton (1964, 1966).

At the beginning of the 19th century many different models of mercury barometers were employed for meteorological observations. They can be divided into three main categories: the fixed-cistern barometer, the Fortin barometer and

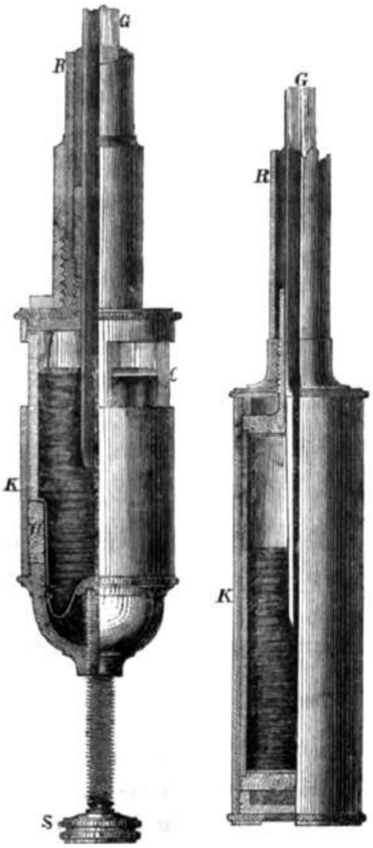

Figure 2. Drawing of the cisterns of a Fortin barometer (left) and of a fixed-cistern barometer (right). In the Fortin barometer a screw (indicated by the letter "S") allows the adjustment of the level of the mercury in the cistern. From Jelinek (1869).

the siphon barometer. A fourth category should be probably be reserved for marine barometers, which needed a special construction to be employed on moving ships.

The fixed-cistern barometer is an adaptation of the original experiment of Torricelli and was the most commonly used barometer in the early 19th century: it is composed of a cistern, where the mercury is exposed to the air pressure, and a vertical thin glass tube, closed at its upper end (where a vacuum is created) and equipped with a scale (either engraved directly on the tube or fixed externally, sometimes together with a vernier to increase the resolution) and with its open end immersed in the mercury of the cistern. The mercury is in hydrostatic equilibrium with the air, a change in the air pressure causes a change in the level of the mercury in the tube and a (smaller) change in the level in the cistern. A correction, calculated from the dimensions of the cistern and of the tube, must be applied to the readings made on the tube to take into account the change in the level of the mercury in the cistern.

The correction is unnecessary in the case of the Fortin barometer, which is provided with a variable displacement cistern, where the level of the mercury has to be set to 0 (marked by the tip of an ivory pin) through a screw before the pressure value is read on the column (Fig. 2). This kind of barometer is named after its inventor, the French instrument maker Jean Nicolas Fortin. Techniques to keep the level in the cistern constant (or to measure it) already existed in the 18th century (e.g. overflowing cisterns, leather bags, flowing gauges, etc.), but none of them had the success of Fortin's model, which was introduced at the beginning of the 19th century. At the time of the Tambora eruption, the Fortin barometer was a relatively new invention and only a very limited number of observatories had one.

Siphon barometers do not have a cistern, instead the tube is u-shaped at the bottom and the end of the shorter leg is exposed to air; the level of the mercury in both legs of the tube is needed to obtain the pressure value. The siphon barometer was often criticised by contemporary scientists, because of the additional reading required, the lack of transportability and the exposure of the mercury to dust, humidity and oxidation, which could affect the reliability of the measurements. Nevertheless, it maintained numerous advocates among scientists in Europe. In 1816 Joseph Louis Gay-Lussac eventually developed a transportable siphon barometer which temporarily increased the popularity of this kind of barometer.

Independently of the barometer's model, further corrections due to the thermal expansion of mercury and the change in gravity with latitude are necessary. In some cases, the capillarity inside the tube and the construction of the scale are also sources of significant errors and drifts (see also Camuffo et al., 2006), as are a lack of maintenance and many other factors.

From metadata we know what type of barometer was employed in 1815–1817 only in the case of 12 observatories in the collection. Seven of them (Cambridge, Haarlem, Hohenpeissenberg, London, Stockholm, Vienna and Zwanenburg) employed fixed-cistern barometers, three (Aarau, Düsseldorf and Padua) had siphon barometers, and two (Milan and Bologna) had Fortin-like barometers (provided with a floating gauge instead of the ivory pin).

Even though a recognised official standard for outside temperature measurement did not exist in the early 19th century, some common rules had been long agreed on in the scientific community, mainly inspired by the recommendations of the French physicist Réaumur (Réaumur, 1732). Thermometers were usually placed on north-facing walls or windows to minimise the effect of direct and indirect sunlight. In some cases, an iron screen was used to shield the instrument from solar radiation (e.g. Camuffo, 2002c). We do not correct temperature observations in this work and we make a limited use of them in the analysis. However, we use outside temperature to reduce pressure observations to sea level and sometimes also to correct the thermal expansion of the mercury in the barometer, when the temperature of the barometer is not available. Böhm et al. (2010) calculated that at the Kremsmünster observatory (Austria), when direct and/or scattered sunlight hits the historical thermometer location (north-east-facing window) in summer, the average overestimation in the observed temperature is about 2 K, although in the most extreme cases it can even reach 5 K. Errors of this magnitude have a negligible effect on the reduction of pressure observations to sea level at low elevation.

2.2.1 Cistern level correction for fixed-cistern barometers

The level l read on the scale of a fixed-cistern barometer is underestimated for high values ($l > l_0$, where l_0 is the zero level, i.e. the level where no correction is needed) and overestimated for low values ($l < l_0$) due to the change in level in the cistern. Therefore, the following correction formula (Jelinek, 1869) must be applied to the raw observations:

$$L = l + \frac{d^2}{D^2 - d^2}(l - l_0), \qquad (1)$$

where L is the corrected level, d is the inside diameter of the tube and D is that of the cistern (assuming a circular section).

For the large majority of the early instrumental records, d, D and l_0 are unknown. Even if we knew them, we could not say for sure whether or not the correction was applied before recording the observations or whether the correction was necessary at all. Most commercial barometers (including those intended for scientific use) were actually sold without the indication of l_0 (Middleton, 1964). In our metadata the observer clearly stated only in one case, for Cambridge (Harvard College), that “the barometer is provided with a floating gauge and scale of correction”.

We can try to quantify the maximum error that can arise from uncorrected observations. One case where the cistern level correction could be applied in the literature is the series from Stockholm: Moberg et al. (2002) estimated a correction of 1 % to $l - l_0$. This means that even for extreme high- or low-pressure values the error is less than 0.5 hPa. Using the metadata for the observatory in London (Cornes, 2008) suggests that any correction there would be even smaller, since the cistern / tube ratio was slightly larger than in Stockholm. A similar ratio is found for the barometer in Zwanenburg (Geurts and van Engelen, 1992). We can expect smaller cisterns by some amateur observers; however, the errors introduced by the missing corrections are unlikely to be larger than 1 hPa.

2.2.2 Capillarity and drifts

In all mercury barometers, but in particular in fixed-cistern and Fortin barometers, too thin a tube can lead to underestimations in the readings due to capillarity. This error becomes larger than 1 hPa for $d < 8$ mm (Camuffo et al., 2006). The barometers in Stockholm and London had a tube with an internal diameter of only 3 and 6 mm, respectively; therefore, they were probably affected by a substantial error. Capillarity was indeed the largest source of error in barometers and could be fully bypassed only in the second half of the 19th century with the adoption of reference primary barometers (Middleton, 1964). Nevertheless, correction tables had been around since at least 1776 (Cavendish, 1776), although their use is never mentioned in the metadata in our possession. The error introduced by capillarity can be assumed to be constant over a period of a few years, with the exception of siphon barometers, in which the tube is exposed to air (and thus to humidity and dust).

The scale was often prone to physical changes, such as mechanical drifts or irregular changes due to thermal expansion or to the humidity’s effect on the wood of the support. The latter was estimated in Moberg et al. (2002) as negligible; however, it depends on the individual instrument. Other significant errors and drifts can arise from the quality of the mercury or from bubbles of air that enter the tube. In general, most barometers probably had a drift of some kind and were less reliable after a few decades of use.

2.3 Data processing

In this section we describe the procedure that was necessary to transform the raw data to a common consistent format that we could use for the analysis. After the conversion of all variables to metric units and of the observation times to the standard UTC, we corrected the pressure observations for temperature and local gravity, and we reduced them to mean sea level. We followed, when appropriate, the directives of the World Meteorological Organization (WMO, 2008). At the end of the procedure, we interpolated the observations to regular 6-hourly time steps in order to have simultaneous values.

2.3.1 Unit conversion

In 1815 only France had officially adopted the metric system; elsewhere, metric units were rarely used. The English inch (= 25.40 mm) was the standard length unit in the English-speaking world. In the rest of the world, the most common unit for barometer scales was the Paris inch (= 27.07 mm). We encountered four other non-metric units, which were used only in specific countries: the Swedish inch (= 29.69 mm) in Sweden, the Vienna inch (= 26.34 mm) in Austria, the Rijnland inch (= 26.15 mm) in the Netherlands and the Castilian inch (= 23.22 mm) in Spain. The English and the Swedish inch had decimal subunits (the resolution was usually 1/100 of an inch); the others were divided into 12 “lines”, which were in turn divided into 4 to 16 “points”.

The temperature was measured using either the Fahrenheit or the Réaumur scale. The only exceptions were in France and in Sweden, where the Celsius scale had already been adopted. We converted all temperature observations to °C.

2.3.2 Observation times

Observation times are available in various formats in the original records. Usually the observations were fixed at specific hours, but for some series they were indicated only qualitatively (e.g. "morning"), and in some others one of the observations was made at sunrise or sunset, whose time varies during the year. In 1815 all the countries of the observatories in the collection had already adopted the Gregorian calendar.

We assumed all times to refer to local solar time, since official standardised times did not exist. This also includes observations from ships, which were usually made at local noon together with the calculation of the geographical coordinates. For qualitative observation times, we applied the following fixed conversions when we did not have any information from the available metadata: morning – 08:00 LT; noon — 12:00 LT; afternoon – 16:00 LT; evening – 20:00 LT. However, when quantitative observation times are indicated only at the beginning of a manuscript (e.g. only on the first page of a meteorological register), we assume that they hold for the whole manuscript or the whole series of manuscripts (e.g. if there is one volume per year and quantitative observation times are indicated only for the first year).

In cases for which observation times are noted as "sunrise" and "sunset", the local sunrise and sunset is computed based on the date and latitude of the station using the following equation:

$$H_{\mathrm{sun}} = \arccos(-\tan\phi \cdot \tan\delta) \cdot \frac{24}{2\pi}, \tag{2}$$

where H_{sun} is the half-day length in hours, ϕ the latitude of the station and δ the declination of the sun, computed applying the algorithms described in Meeus (1999). The local sunrise (sunset) time is $0.5H_{\mathrm{sun}}$ before (after) local noon.

If observation times for single observations are missing but observations were taken at regular intervals, we replaced the missing observation times with the most frequent observation time for this interval (e.g. 21:00 LT for evening observations if 21:00 LT is the most frequent known time for evening observations at one specific observatory).

We finally translated local observation dates and times to UTC. For this we used a simple equation based on the longitude of the station:

$$t_{\mathrm{UTC}} = t_{\mathrm{loc}} - \lambda \cdot \frac{24}{360}, \tag{3}$$

where λ is the longitude of the station in degrees east, t_{loc} is the local time and t_{UTC} is the UTC time.

2.3.3 Reduction to 0 °C

About half of the observatories in our data set recorded the temperature of the barometer. It was in fact common to have a mercury thermometer fixed on the same support as the barometer. Since the mercury expands and shrinks depending on the temperature, observations made with a mercury barometer must be corrected accordingly:

$$L_0 = (1 - \gamma T) L_{\mathrm{mm}}, \tag{4}$$

where γ is the thermal expansion coefficient of mercury at 0 °C ($1.82 \times 10^{-4}\,\mathrm{K}^{-1}$), T is the temperature of the barometer in °C, L_{mm} is the original observation in millimetres of mercury and L_0 is the observation reduced to 0 °C. Today, the "neutral" temperature of 0 °C is dictated by international standards; this was partially the case already in the early 19th century. Note that some observers used to reduce their observations to other temperatures (10 °R being the most common).

When the temperature of the barometer was not available, we used outside air temperature for the reduction. In many cases this is a good approximation because often the barometer was located in an unheated room or in a meteorological window and was fairly close to the "outside" thermometer. At some observatories, however, the barometer hung in a heated room, in which case we have an unknown error, usually with some seasonal cycle. Note that we rarely know the location of the barometer from metadata. When outside temperature observations were also missing, we used the closest (in space and time) 30-year climatology of 2 m air temperature from the Twentieth Century Reanalysis (Compo et al., 2011) at 3-hourly resolution. This reanalysis has a spatial resolution of 2 ° for both latitude and longitude. As the base period for the climatologies, we chose 1871–1900 to minimise the difference with early 19th century temperatures. To reduce variability, we applied an 11-day moving mean per time step, so that the climatology for temperature on 6 January, 12:00 UTC, is the average of temperature on 1–11 January, 12:00 UTC, in the years 1871–1900. The use of climatologies was necessary for four stations only – one in Europe (Paris in 1815) and three in North America (see Table 1) – and for occasional gaps in the other series. In one case (Brunswick), metadata indicate that the barometer was in a heated room; therefore, we preferred to use an arbitrary constant temperature of 18 °C for the correction.

To evaluate the errors introduced by the use of outside temperatures or climatologies, we made use of the stations where the temperature of the barometer was measured by correcting their pressure observations using either outside temperature or climatology and analysing the differences with the "right" correction.

The errors in the mean (Fig. 3a and b) have, as expected, a seasonal cycle. In summer, differences between inside and outside temperatures are on average very small for all stations, but in winter the barometers located in heated rooms are 5 to 17 °C warmer than the outside air (corresponding to average errors of 1 to 3 hPa when using outside temperature for the pressure reduction). We obtained similar results using observations from a certain part of the day (e.g. only morning or afternoon observations); in particular, the average errors in summer always remain within ±1 hPa (not shown). Climatologies from the reanalysis introduce errors similar to

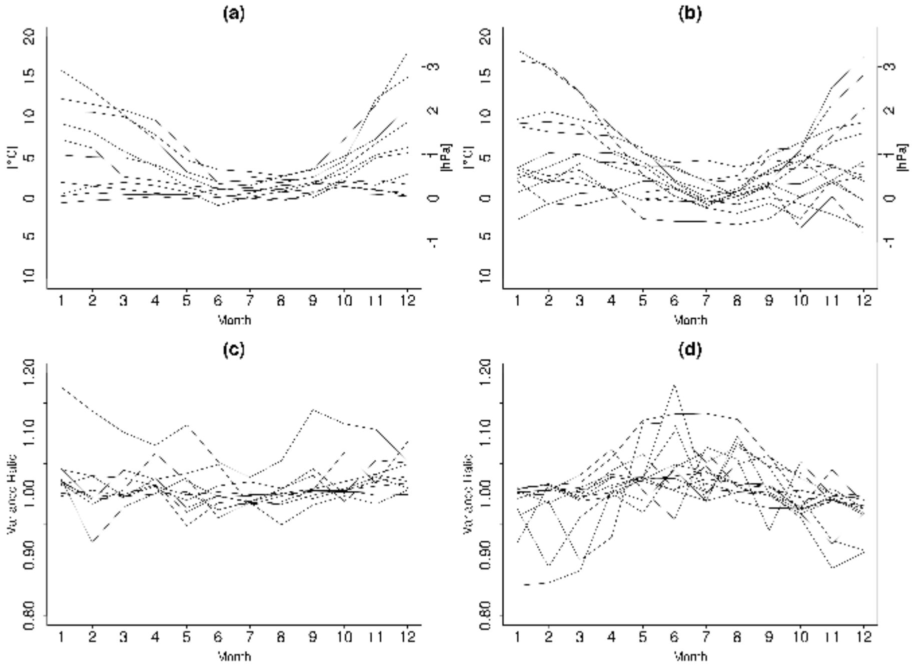

Figure 3. Panel **(a)**: monthly averages of the differences between temperature of the barometer and outside temperature for the stations where both are available. Panel **(b)**: monthly averages of the differences between temperature of the barometer and temperature climatologies from the Twentieth Century Reanalysis for the stations where the temperature of the barometer is available. In both panels the corresponding error in the pressure reduction to 0 °C is shown on the right axis, calculated considering an uncorrected barometer reading of 760 mm. Panel **(c)**: monthly ratios between the variance of pressure observations corrected using outside temperature and the same observations corrected using the temperature of the barometer, for the same stations as in **(a)**. Panel **(d)**: monthly ratios between the variance in pressure observations corrected using climatologies and the same observations corrected using the temperature of the barometer, for the same stations as in **(b)**. All plots are based on the period 1815–1817; climatologies are calculated for the period 1871–1900.

those introduced by outside temperatures; these are slightly larger when the barometer is not in a heated room.

In Sect. 3.3 we try to correct these errors using a statistical method. However, much larger errors (> 5 hPa) are possible for single sub-daily values in continental climates, specifically in New England and Fennoscandia, when large deviations from climatology occur.

Temperature has, in general, a vertical gradient along the barometer, meaning that the observed temperature of the barometer is actually the temperature of only one part of it (depending on where the thermometer is attached). Therefore, the correction can introduce errors of the order of some tenths of hPa even when the temperature of the barometer is available.

Compared to the mean, the variance is more strongly affected when using climatologies (Fig. 3c and d). Using outside temperature introduces a random error in the variance that does not depend on the season and is usually smaller than 5 % for all stations but one: in Natchez (Mississippi) there is a systematic overestimation of the variance of about 10 %, which could be due to the subtropical climate of this station (i.e. a smaller pressure variance than any other station in the collection) or simply on the quality of the temperature observations (e.g. unshielded thermometer). Climatologies introduce a seasonal cycle in the variance error for some stations, with an underestimation (overestimation) of the variance in winter (summer).

We did not apply corrections for the thermal expansion of other parts of the barometer (cistern, tube, scale), which are usually 1 order of magnitude smaller than the correction for mercury and depend on the material used to build the barometer.

We also used Eq. (4) to rebase to 0 °C pressure observations that had been reduced to some other temperature at the time of the readings. This results in a small inconsistency because the correction tables in use at the time were purely empirical, γ not being known with sufficient precision. Therefore, the original corrections do not correspond exactly to those resulting from Eq. (4).

The series from Milan, Salem, Stockholm and Turin had already been reduced to 0 °C in previous works by data contributors (see the respective references for more details). In Exeter, the observer started to register the temperature at the barometer only in 1817; outside air temperature was used before that year (absolute differences between temperature at the barometer and outside temperature were on average smaller than 2.5 K during 1817).

2.3.4 Conversion to pressure units and correction for local gravity

The conversion of pressure readings from millimetres to hectopascal follows from the hydrostatic equation:

$$P_n = \rho g_{\varphi,h} L_0 \times 10^{-5}, \tag{5}$$

where P_n is the absolute pressure in hectopascal reduced to normal gravity, $\rho = 1.35951 \times 10^4\,\mathrm{kg\,m^{-3}}$ is the density of mercury at 0 °C, $g_{\varphi,h}$ is the local gravity (see below) and L_0 is the barometric reading in millimetres (corrected for temperature). This is equivalent to the usual procedure of first converting pressure readings from millimetres to hectopascal by using normal gravity acceleration in Eq. (5) and then correcting for local gravity by using

$$P_n = \frac{g_{\varphi,h}}{g_n} P_0, \tag{6}$$

where P_0 is the absolute pressure not reduced to normal gravity and $g_n = 9.80665\,\mathrm{m\,s^{-2}}$ is the normal gravity acceleration.

We estimated the local gravity $g_{\varphi,h}$ from the latitude φ and elevation h (in m a.s.l.), assuming flat terrain around the station (see WMO, 2008):

$$g_{\varphi,h} = \Big[9.80620 \cdot \big(1 - 0.0026442 \cdot \cos 2\varphi - 0.0000058 \cdot \cos^2 2\varphi\big) - 0.000003086 \cdot h\Big]\,\mathrm{m\,s^{-2}}. \tag{7}$$

Since all land stations in the data set are in the midlatitudes and at relatively low elevations, the gravity correction is on average small (ca. 0.5 hPa; positive for high latitudes and negative for low latitudes).

2.3.5 Reduction to mean sea level

To use the pressure observations for synoptic analysis, we reduced P to sea level:

$$P_0 = P \cdot \exp\left(\frac{\frac{g_{\varphi,h}}{R} \cdot h}{T_\mathrm{S} + a \cdot \frac{h}{2}}\right), \tag{8}$$

where $R = 287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the gas constant for dry air, $a = 6.5 \times 10^{-3}\,\mathrm{K\,m^{-1}}$ is the standard lapse rate of the fictitious air column below the station and T_S is the outside temperature at the station in K.

We did not apply further corrections described in WMO (2008), since the uncertainty in our data set is much higher than that required for modern barometers (i.e. ±0.1 hPa).

Similarly to the reduction in pressure readings to 0 °C (Sect. 2.3.3), we used in situ air temperature observations where available and resorted to climatological temperatures from the Twentieth Century Reanalysis (1871–1900) otherwise. We did not use the temperature of the barometer to reduce pressure readings to sea level.

The series from Stockholm and Turin had already been reduced to sea level by the respective data contributors.

2.3.6 Quality control

We inspected visually each sea level pressure (SLP) series (and differences with nearby stations) to flag erroneous outliers and clear inhomogeneities in the period 1815–1817. Nearly all outliers derive from mistakes in the digitisation or in the transcriptions by the observer. When possible (i.e. when the original sources were readily available) we corrected them; otherwise, we flagged them as erroneous and excluded them from the analysis.

The total number of pressure observations flagged after the quality control is 4657, corresponding to 4.1 % of the 1815–1817 data set. Most of the flagged observations correspond to long periods in a few series where we detected large inhomogeneities: Madrid (whole year 1815 flagged), New Haven (most of autumn and winter of 1815/16), Valencia (all summer observations), Växjö (whole 1817) and Ylitornio (11 months in 1817). The number of flagged observations for each series is indicated in Table 1.

2.3.7 Interpolation on regular time steps

Another requirement for a synoptic analysis is that observations must be simultaneous. To achieve this, we linearly interpolated all pressure observations to four daily, equally spaced time steps: 00:00, 06:00, 12:00 and 18:00 UTC. If no observations of a certain station were available within ±6 h from a certain time step, then we did not interpolate and considered the station to have no data for that specific time step. In Europe (on which our analysis will focus), most observations were made very close to 06:00, 12:00 and 18:00 UTC; interpolated values for 00:00 UTC are in general less reliable and will not be analysed. Across all stations, the mean absolute differences between the interpolated values and the closest observations are 0.9 hPa for 00:00 UTC, 0.5 hPa for 06:00 UTC, 0.4 hPa for 12:00 UTC and 0.8 hPa for 18:00 UTC. By using a linear interpolation, we did not account for the daily cycle of pressure; this choice does not significantly affect the results because the amplitude of the daily cycle is much smaller than the day-to-day variability that we want to study.

We did not interpolate outside temperature observations because of their larger daily cycle and its strong dependance on other meteorological variables such as cloud cover and wind.

3 Analysis

3.1 The post-Tambora period in monthly data sets

We start the analysis with a brief overview of the circulation and temperature anomalies that characterized the period from 1815 to 1817 in Europe. For this, we exploit seasonal gridded SLP fields statistically reconstructed by Küttel et al. (2010) using station pressure series and ships' logbook information from the northern North Atlantic. We also use the monthly

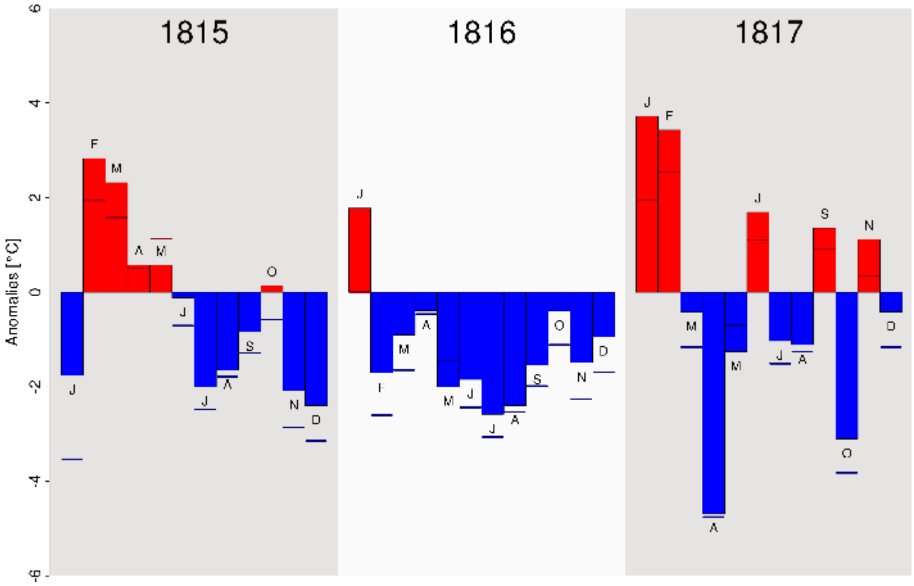

Figure 4. Monthly temperature anomalies in Central Europe (Southern Germany, Bohemia, Austria, and Switzerland) in the period 1815–1817 with respect to 1801–1830 (bars) and 1961–1990 (segments). Data are from Dobrovolný et al. (2010).

temperature series for central Europe from Dobrovolný et al. (2010), based on 11 homogeneous temperature series of stations located in southern Germany, Bohemia, Austria and Switzerland in 1760–2007 and on documentary index series in 1500–1759.

Figure 4 shows the monthly temperature anomalies in central Europe with respect to a contemporary and a modern climatology. From June 1815 to December 1816, almost all months had negative anomalies. However, the largest negative anomaly was registered in April 1817, the coldest April of the entire series (i.e. in more than 500 years). The summer (June to August) of 1816 was the coldest in the instrumental part of the series and the second-coldest since 1500.

Winters following large tropical volcanic eruptions are often stormier and warmer than the average over northern Europe and drier over the Iberian Peninsula (Dawson et al., 1997; Fischer et al., 2007). This is caused by the increased meridional temperature gradient in the stratosphere produced by volcanic aerosols, which supports a more positive North Atlantic Oscillation (NAO) in the troposphere (e.g. Kirchner et al., 1999). The winter of 1815/16 did not follow this rule and was colder than usual in central and northern Europe, despite a mild period in January (Fig. 4; see also Trigo et al., 2009). SLP anomalies (Fig. 5) in fact resemble a weak negative NAO and are very similar to those reconstructed for the other seasons of 1816. By contrast, the winter of 1816/17 had a strong positive NAO and brought substantial warm anomalies in Europe (Fig. 4).

The spring of 1817 was again much colder than the climatology, but the SLP pattern was different than that of 1816. In Sect. 3.3 we describe this pattern and its effects on central and southern Europe in more detail.

3.2 Storminess

One of the advantages of daily pressure observations with respect to monthly data is the possibility to study variability on the timescales of the typical large-scale weather phenomena. In particular, the variance in bandpass-filtered daily pressure observations (hereafter "storminess") is related to the frequency of stormy weather caused by extratropical cyclones and is commonly used for storm track analysis (e.g. Blackmon et al., 1977; Chang et al., 2002). In this section, we apply a 2–6-day bandpass Lanczos filter (Duchon, 1979) with a 31-day convolution vector to analyse winter and summer storminess in 1815–1817 in Europe and north-eastern North America.

We use only interpolated SLP observations at 12:00 UTC because this is the only time step available for every series. Furthermore, we require at least 90 % of the 12:00 UTC values to be available in a certain season to calculate the variance for that season. To analyse winters we apply the filter to the 120-day period from 15 November to 14 March (13 March in leap years) and for summers to the period from 18 May to 14 September.

The storminess for the winters of 1815/16, 1816/17 and 1817/18 is shown as SD in the last three panels of Fig. 6, where instead of absolute values we plotted the anomalies from the 1961–1990 climatology of the closest grid point in the Twentieth Century Reanalysis (contours in Fig. 6). This analysis also constitutes a useful tool to verify the quality of the data. It is particularly evident from the map of 1816/17 that one station in Spain (Valencia) is not reliable, having too high a variability, and likewise one in North America (New Haven), which seems to have too low a variability when com-

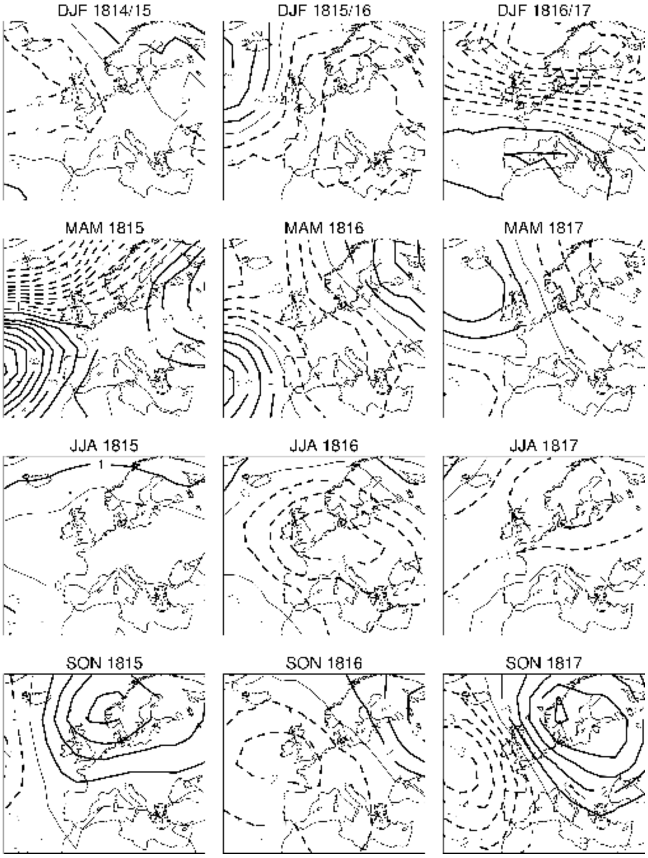

Figure 5. Seasonal SLP anomalies (in hPa) in Europe for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) for the years 1815–1817 (reference period 1961–1990), reconstructed by Küttel et al. (2010).

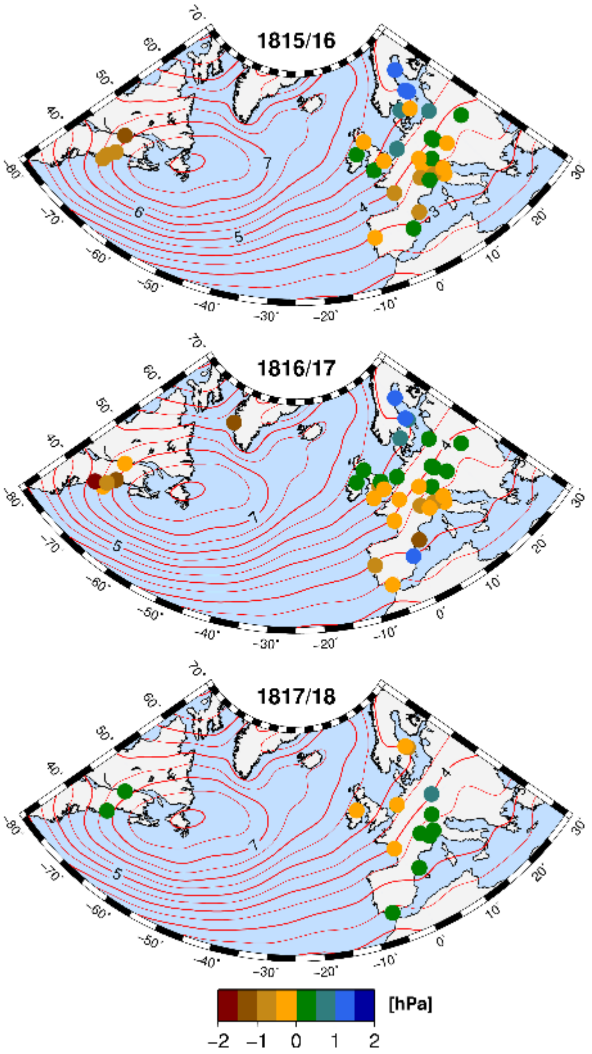

Figure 6. SD of daily (12:00 UTC) bandpass-filtered SLP (in hPa) in winter (120-day period starting on 15 November). Contours show the 1961–1990 climatology in the Twentieth Century Reanalysis. Points represent observations for 1815/16, 1816/17 and 1817/18 in terms of anomalies from the nearest grid point in the reanalysis.

pared to the neighbouring stations. The observations in these two stations were corrected for temperature using, respectively, in situ outside temperature and climatologies from the reanalysis. For Valencia, a systematic error similar to that described in Sect. 2.3.3 for Natchez is a possible contributor to the overestimation of the variance, while the continental climate of New Haven introduces large uncertainties in the absence of detailed metadata. A suspiciously low variability also affects the series from Växjö (southern Sweden) in the winter of 1815/16. For this station the temperature of the barometer was available; therefore, the problem originates from the raw observations.

The difference between the winters of 1815/16 and 1816/17, which is very clear when looking at mean SLP fields (Fig. 5), disappears for the variance. The storminess anomalies suggest an eastward shift of the storm track in both winters, since the variance in all stations in North America is reduced by about 20 %, while it is increased by approximately the same amount in north-eastern Europe. The few stations available in 1817/18 are enough to see a very different situation in terms of storminess, with a reduction in northern Europe and positive anomalies in southern Europe and New England.

SLP has climatologically a much lower spatial and temporal variability in summer (contours in Fig. 7), and it is difficult to interpret the results in terms of storm track, since baroclinic instability is much reduced. The summers of 1815 and 1816 (Fig. 7) show quite a similar pattern of variability in Europe, in particular a reduced storminess in northern Europe. The summer of 1817 has a higher variability in Europe than that of 1816. There are indeed indications that the summer of 1817 was also a very wet season in Europe, although not particularly cold (see Fig. 4); in Geneva, for example, 1817 had one of the wettest summers of the period 1799–1821, that of 1816 being the wettest (Auchmann et al., 2012). In New England, the storminess of 1816 is similar to that of 1817. Additionally, the maps further support the idea that the variability in the series from New Haven is too low.

3.3 Synoptic analysis for three case studies in Europe

3.3.1 Statistical correction

Even though the results of the previous section demonstrate a good consistency among the variability in most of the series, the lack of metadata for many of them causes large systematic errors in the mean values. A statistical approach is the only viable option to obtain absolute SLP values accurate enough for a synoptic analysis; thus, we use the reconstruction by Küttel et al. (2010) as a reference to correct the land series in Europe.

It is important to mention that the reconstruction is not independent; in fact, the monthly means of 16 series in our collection were used as input for the reconstruction. However they were all homogenised by Küttel et al. (2010); therefore, we are confident that the reconstruction offers the best possible estimation of mean SLP and that the application of the corrections guarantees a better reliability of synoptic weather maps.

Using the original SLP observations, we calculated seasonal means for each series in the period 1815–1817 and then applied a constant offset necessary to match the 1815–1817 seasonal means of the nearest grid point in the reconstruction. This was possible only if enough data were available: we calculated the offset using only the years with at least 90 % of the days in the target season having at least one observation available. When a series does not have enough data in any year for a certain season, we used the average of the offsets from the available seasons. The seasonal offsets were then applied directly to the interpolated SLP values described in Sect. 2.3.7.

If the data are insufficient in every season, the series is not used in this section. This was the case for Derby, which has only 1 month of data. Moreover, we excluded the series from Valencia and Växjö, which showed low reliability in the previous section. We did not correct the already homogenised series from Milan and Stockholm.

Since the reconstruction is based on monthly means, in turn calculated from daily means, we must apply a further correction to the offsets to take into account that our data are instantaneous observations rather than daily means. For this, we estimated the mean daily cycle of SLP for each season from the 1981–2010 climatology of the closest grid point of the MERRA (Modern-Era Retrospective analysis for Research and Applications) reanalysis (Rienecker et al., 2011). MERRA offers the advantage of an hourly resolution and a higher spatial resolution (1/2° latitude × 2/3° longitude) than the Twentieth Century Reanalysis. For stations with variable observation times, we used for the calculation the observation times (rounded to the hour) adopted most frequently at the target station in the target season. The resulting corrections are very small for all series and smaller than 1 hPa even for stations with only one observation per day.

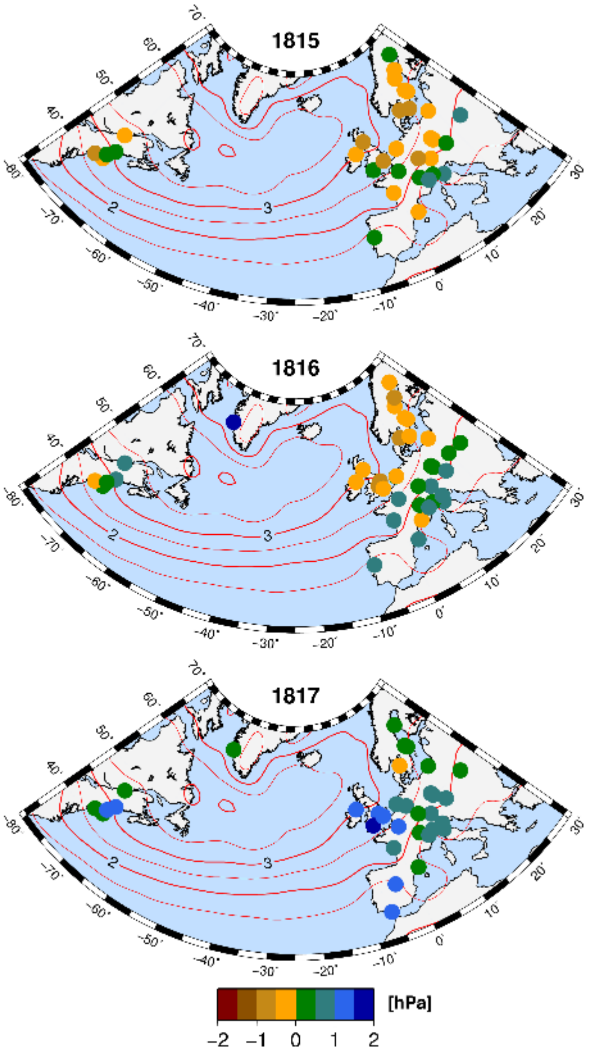

Figure 7. Similar to Fig. 6 but for summer (120-day period starting on 18 May).

On the other hand, the total statistical corrections are in some cases larger than 10 hPa (Fig. 8), while their root mean square is 4.4 hPa. The average correction (thick line in Fig. 8) has a seasonal cycle with a peak-to-peak amplitude of 1.9 hPa, indicating overestimated values in winter relative to summer. This is nothing more than what we expected because of incorrect temperature corrections for barometers in heated rooms (Fig. 3a and b).

The largest corrections are usually related to amateur observatories with scarce metadata and with the temperature of the barometer missing, but in some cases (e.g. Prague) they are also related to official observatories with high scientific standards. An important source of systematic errors is the uncertainty of the barometer elevation: according to Eq. (8),

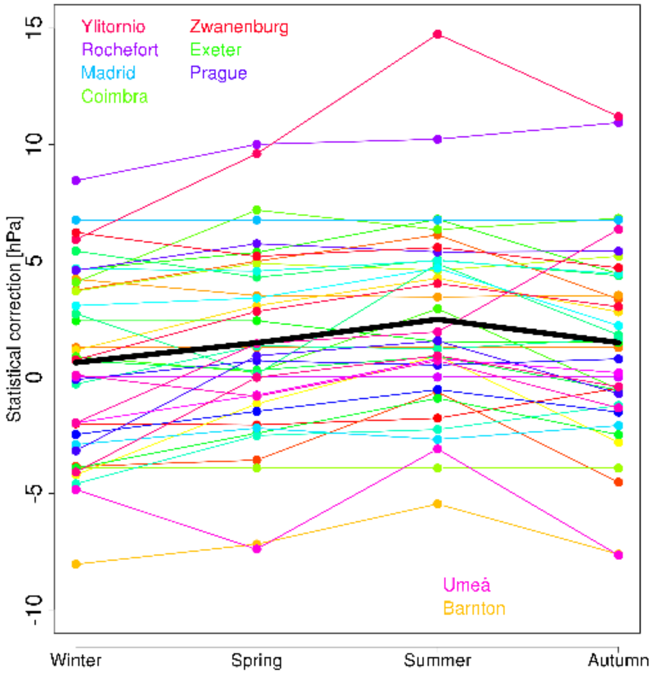

Figure 8. Seasonal corrections applied for the case studies. Each colour represents a different station in Europe; the thick black line is the average of all corrections. The names of the stations with mean absolute corrections larger than 5 hPa are also printed.

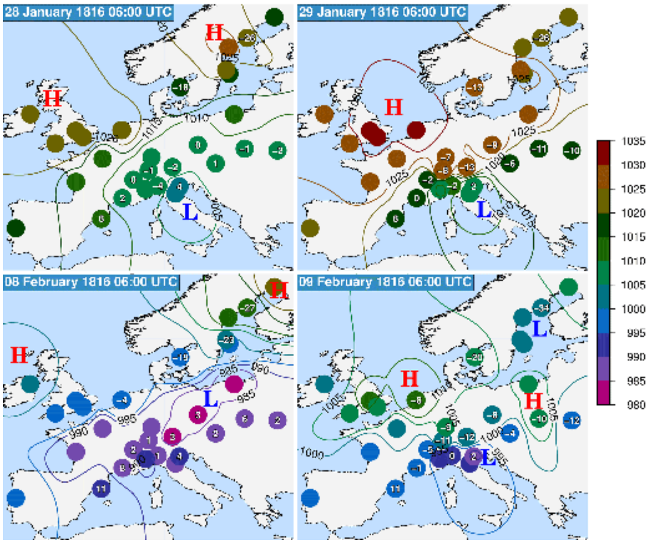

Figure 9. Synoptic maps for the two main cold spells in Europe during winter 1815/16. Coloured points represent SLP observations (in hPa). To facilitate interpretation, isobars at intervals of 5 hPa are drawn using inverse distance weights, and the approximate position of pressure minima and maxima are indicated by the letters L and H, respectively. White numbers represent temperatures (in °C) observed within ±1 h.

considering a standard atmosphere, an uncertainty of 20 m (which applies to most stations) results in an uncertainty in SLP of about 2.5 hPa near the sea level or less for higher elevations. Moreover, the statistical correction can also take into account capillarity (see Sect. 2.2.2), which is probably the reason why the majority (about two thirds) of the applied offsets are positive (capillarity always causes an underestimation in mercury barometers) and represent the main contributor to the large corrections needed in some of the official observatories.

3.3.2 Cold spells in winter 1815/16

As already mentioned, the winter of 1815/16 was not a typical post-volcanic winter in terms of temperatures, being colder than usual in most of Europe. From our temperature data we detected two severe cold spells that hit in quick succession between the end of January and the first half of February, which significantly contributed to the cold anomaly. We use these two cold spells as a case study to evaluate the quality of the corrected SLP data set.

Figure 9 shows four SLP synoptic maps corresponding to the initial phase of the two cold spells. We plotted the 06:00 UTC time step because more temperature observations (also shown in the maps) are available near that time.

A common SLP pattern is evident for the two cold spells, although the one in February, the most severe, is characterised by much lower pressure values. In both cases there is a low-pressure system over southern Europe and a high pressure area over northern Europe (note that the position of the centre of cyclones and anticyclones drawn by the isobars in the maps is often an artefact due to the lack of observations near the borders, in particular in the Mediterranean). This pattern represents a typical blocking situation and drives a westward flow of cold continental air towards western Europe (e.g. Rex, 1950), consistent with a severe cold outbreak.

A curious anecdote is related to the cold spell of February 1816. Samuel Parkes, a contemporary British chemist, exploited the unusual cold for an experiment on the freezing point of wine. His results were published as a short article in the first issue of *The Quarterly Journal of Science, Literature and the Arts*, where he reported that the temperature on the morning of 9 February (probably near his house in London) was "22° below the freezing point", which, assuming a Fahrenheit scale, corresponds to −12 °C. On the following night another London chemist, Luke Howard, made several observations with different thermometers in Tottenham (*Annals of Philosophy*, vol. 7). On 10 February at 07:30 LT he measured a temperature of −19 °C, ca. 2 m (8 feet) above the ground. According to Howard, this was the lowest value measured in London since 1797.

According to our data set, temperatures were particularly low in Sweden, reaching −38.5 °C in Umeå and −37 °C in Härnösand, while the absolute minimum was measured in Ylitornio (Finland) with −40 °C (not shown). The ho-

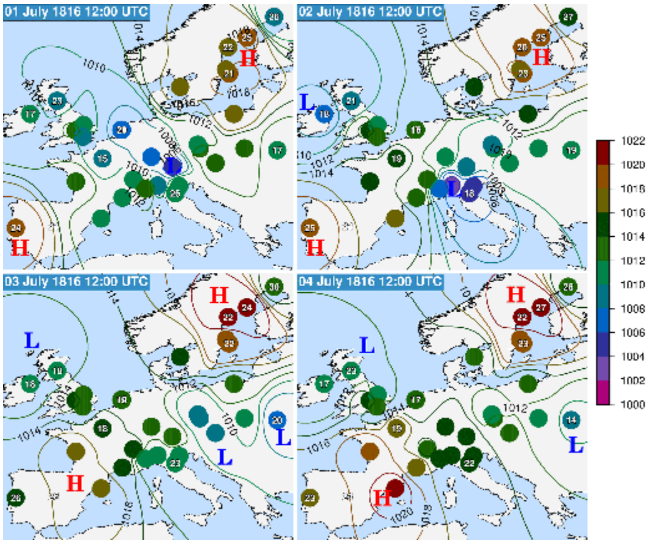

Figure 10. Similar to Fig. 9, but showing maps for the first 4 days of July 1816 at 12:00 UTC. Note that the colour scale has changed and isobars are drawn at intervals of 2 hPa.

mogenised series from Stockholm allows a comparison with modern data: in the reference period 1961–1990 there were three cold spells that were more severe than that of February 1816. However, cold spells of this magnitude were probably not as rare in the early instrumental period. In fact, Moberg et al. (2002) and Bergström and Moberg (2002) found a particularly high frequency of very cold winter days in Stockholm and Uppsala in the late 18th and early 19th century, although they warned that the data might still be affected by inhomogeneities. Daily temperatures lower than those of February 1816 were registered, for example, in January 1814 and again in December 1817. Similar results (not shown) are obtained by analysing the temperature series from St. Petersburg, in north-western Russia (Jones and Lister, 2002).

3.3.3 Summer 1816

We analyse here one case at the beginning of July, one of the coldest periods of the summer of 1816 in central Europe (i.e. about 7 °C colder than usual in Geneva; see Auchmann et al., 2012). There was abundant rainfall in the Alps, where, in the night between 3 and 4 July, a huge landslide, about 300 m wide, killed at least 14 people near the town of Uznach in eastern Switzerland (Erdrutsch in der Au (Goldingertal): Situationsplan, State Archives St. Gallen, Ref. KPG 1/65.1, 7/16).

A shallow low-pressure system crossed the Alps between 1 and 2 July (Fig. 10), which is consistent with cold and rainy weather, and then probably moved to south-eastern Europe on 3 July, when easterly winds were observed at the stations in eastern Europe (not shown). Afterwards, the Alps remained under the influence of unstable air coming from the Atlantic for several days. The weather diary kept for Aarau, in northern Switzerland, reports precipitation every day until 19 July, always accompanied by westerly winds except on 1 day.

An area of high pressure was present over north-eastern Europe during the whole period shown in Fig. 10, suggesting fair weather there (confirmed by temperatures). In particular, in the north-eastern corner the maps show temperatures registered in Ylitornio at 14:00 LT which are remarkably high for that latitude (the maximum temperature is reached on 5 July at 31 °C, not shown). The quality of the measurements is questionable (see Klingbjer and Moberg, 2003); however, it is interesting to note that the average 14:00 LT temperature measured in Ylitornio in the first week of July 1816 is 9 °C higher than the average 14:00 LT temperature of the whole summer 1816. Therefore, our data suggest the occurrence of a heatwave in north-eastern Europe in conjunction with the cold period in western Europe. Again, the daily temperature series from St. Petersburg supports our conclusion, indicating 13 consecutive days (6–18 July) with a mean daily temperature of > 20 °C, the longest such series in the years 1815–1817. The month of July as a whole had, nevertheless, slightly negative temperature anomalies in that region (Luterbacher and Pfister, 2015), showing how even relatively long-lasting events can be overlooked when considering monthly means only. Note also that the SLP values in Ylitornio are clearly underestimated in the analysed period, and in general they are not very reliable because of the continental climate of the region (see Sect. 2.3.3).

3.3.4 April 1817

After a relatively mild winter, the spring of 1817 struck a serious blow to Europe. In particular, as already mentioned, the month of April was extremely cold (see Fig. 4).

To gather more information on the most important weather events that distinguished this month, we examined contemporary newspapers and other historical sources. The worst affected area was probably the northern slope of the Alps. Exceptional snowfalls and avalanches were often reported in that month, especially in Austria: in Innsbruck (574 m a.s.l.), for instance, snow fell on 18 out of 30 days (Fliri, 1998), while over 2 m of snow were reported in Annaberg (976 m), near Vienna, after 16 consecutive days of snowfall (Lemberger Zeitung, 9 May 1817). At Buchlovice (234 m, south-east Moravia), a priest, Šimon Hausner, recorded snowfall on 11–14, 19–26 and 28 April, i.e. on 13 days (with another 2 days with sleet). Permanent frosts were also typical in this month. Hausner concluded that "no previous April has been this bad" (Tägliche Witterungs-Beobachtungen des Buchlowitzer Pfarrer Simon Hausner von Jahren 1803 bis 1831 excl., Moravský zemský archiv Brno, fond G 138 Rodinný archiv Berchtoldů (1202) 1494–1945, inv. č. 851).

One episode in particular attracted the attention of newspapers. In 1817 the Austrian foreign minister, the influential Prince von Metternich, had organised an ambitious scientific

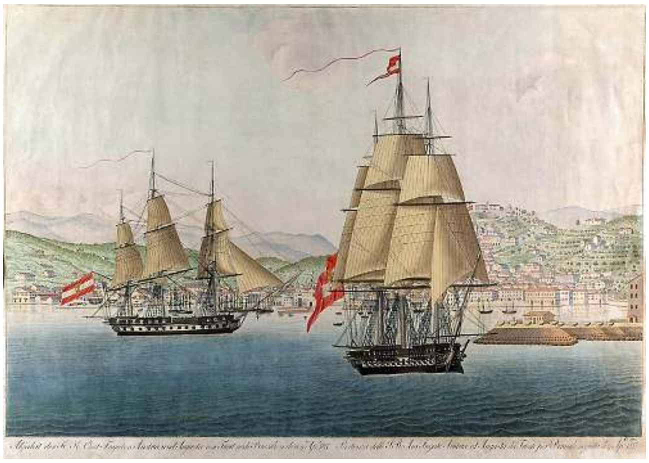

Figure 11. The frigates *Austria* and *Augusta* in the port of Trieste on 9 April 1817 in a coloured engraving by G. Passi. Source: Österreichische Nationalbibliothek (Bildarchiv und Grafiksammlung, PK 286), Vienna, Austria.

expedition to Brazil, the first major overseas mission ever undertaken by the Austrian navy. On 10 April two frigates, the *Austria* and the *Augusta* (Fig. 11), weighed anchor from the port of Trieste, in today's north-eastern Italy, and headed to Rio de Janeiro. On the morning of the second day of navigation, near the coast of Istria, the ships were surprised by a violent storm and suffered heavy damage. The *Austria* was able to dock in Pula (today's Croatia) and could resume the journey after only 1 week. The *Augusta* was shorter on luck, losing all its masts, sails and boats, and reached the port of Chioggia, near Venice, with great difficulties, 4 days after the storm hit. The repair of the ship took about 7 weeks.

Many renowned scientists and intellectuals were on board the two frigates. Among them were two members of the Bavarian Academy of Sciences: Johannes Baptist von Spix (biologist) and Carl Friedrich Philipp von Martius (botanist), who were on the *Austria*. Their detailed account of the expedition (Spix and Martius, 1824) gives us a description of the storm:

> "The night passed over quietly; but in the morning we were all awakened from our sleep by an uncommonly violent motion of the ship. Those whom sea-sickness had not rendered insensible, readily perceived [...] that we were in a great storm.
>
> The Bora, a cold, very violent north-east wind, which, especially in spring, frequently blows from the Istrian mountains, and prevails in the northern part of the Adriatic sea, had suddenly assailed the two ships. A black cloud, hanging very low, was the only indication that the officer on duty had of the approach of the gale; so that there was scarcely time to take in the sails. In a few minutes we lost sight of the Augusta, which hitherto had kept at a small distance from us. A thick fog enveloped our ship; a cold rain, mixed with hailstones, which the storm furiously drove before it, covered the deck with pieces of ice of considerable size, and almost froze the crew. The ship was tossed violently; the yards and tackle were torn and broken: the waves rushed through the window into the forecastle, partly filled the hold with water; and at last, when the storm was at its height, the bowsprit broke short off. The hurricane raged with the utmost fury till noon, when the sea grew calmer, and the bleak Bora being succeeded by a mild east wind, we cast anchor in the middle of the sea, about three miles to the west of Rovigno."

As suggested by the two German scientists, who demonstrate a remarkable knowledge of climatology, the storm was related to a severe bora wind event (Yoshino, 1976). The event was also felt in most of the Po Valley (northern Italy), where four of the stations in our data set are located. The observatories of Padua and Bologna, which are close to the Adriatic coast, reported thunderstorms, very strong wind from the north-east and snow flakes on that day. Newspapers reported heavy snowfall in the eastern Alps during the same event; in particular, about 50 cm of snow were measured in northern Slovenia and 10 cm in the city of Klagenfurt (Gazzetta di Milano, 8 May 1817).

In Fig. 12 we show the synoptic maps for 10 and 11 April. The position of the Austrian frigates in the morning of 11 April is marked by a star in the third map. Again, we are dealing with a blocking pattern, characterized by high pressure over north-western Europe and low pressure over Fennoscandia. This configuration represents the negative phase of the so-called Scandinavian pattern (e.g. Rogers, 1990), which is normally completed by a third pole (in this case, an area of high pressure) over central Siberia. This pattern stayed in place for most of the month of April 1817, continuously pumping Arctic cold air towards central and southern Europe. Enzi et al. (2014) singled out this configuration as the feature most commonly responsible for widespread exceptional snowfall in Italy.

A cold air outbreak is the condition necessary for a severe Adriatic bora storm, and the synoptic pattern of 11 April (third panel in Fig. 12) is in fact a typical pattern for severe bora events (Jurčec, 1989). The maps show clearly the build-up of a pressure gradient between the northern and the southern slope of the Alps caused by the interaction of the cold air with the orographic barrier. It is likely that an orographically induced cyclone formed in the Mediterranean as a typical "cut-off" and that it remained there for several days (e.g. Tibaldi and Buzzi, 1983). Spix and Martius (1824) wrote that when the *Austria* was near the coast of southern Italy on 22 April, they could see the Gargano promontory, which reaches a maximum elevation of 1065 m, "covered with snow very low down". They also repeatedly reported stormy weather in

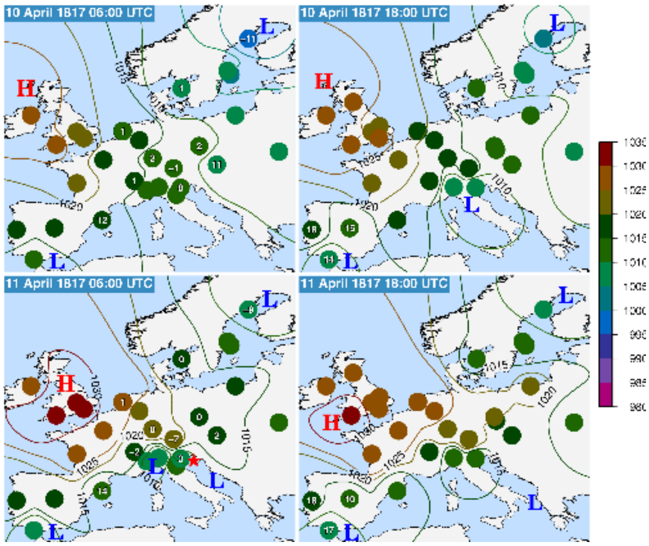
10 April 1817 06:00 UTC
10 April 1817 18:00 UTC
11 April 1817 06:00 UTC
11 April 1817 18:00 UTC

Figure 12. Similar to Fig. 9 but showing maps for 10–11 April 1817 at 12 h interval. A star marks the position of the frigates *Austria* and *Augusta* on the morning of 11 April.

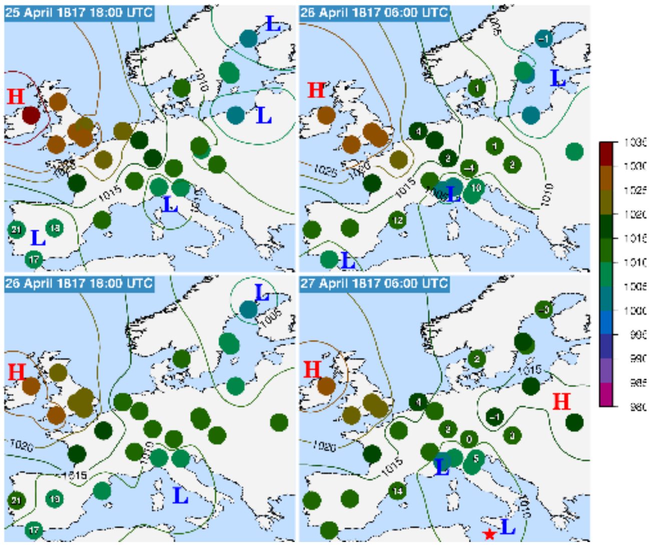
25 April 1817 18:00 UTC
26 April 1817 06:00 UTC
26 April 1817 18:00 UTC
27 April 1817 06:00 UTC

Figure 13. Similar to Fig. 9 but showing maps for 25–27 April 1817 at 12 h interval. A star marks the position of the frigate *Austria* on the morning of 27 April.

the following days, culminating in another violent storm on 27 April that forced the frigate to seek shelter in Malta. They wrote

> "On the following morning we were already forty-two leagues to the west of Malta, when the wind suddenly settled in the N.N.W. It soon increased, and the waves ran so high, that it was impossible to keep the course to the south-west. The frigate rolled so violently, that in a short time the tackling was materially damaged; every thing movable was thrown backwards and forwards; and it seemed dangerous longer to expose the ship to the fury of the waves."

The direction of the wind suggests that a cyclone was centred close to eastern Sicily. Note that the position reported in the official translation is probably affected by a mistake in the unit conversion: the original German version reports "vierzig Seemeilen", literally 40 nautical miles (74 km). The word Seemeile was, however, commonly used also to indicate the "league" (i.e. 3 nautical miles), although it is not clear why the translator converted it to 42 leagues instead of 40. In any case, we think that the literal translation gives a more realistic position for the ship, which would have been only a few kilometres from the coast of Africa otherwise.

In fact, between 26 and 27 April another cold outbreak affected southern Europe. This time the snow fell abundantly even in the Po Valley. In Bologna, about 15 cm ("half shoe") of snow were reported (Osservazioni meteorologiche 1817, Historical Archives of the Astronomical Department, University of Bologna), again accompanied by a strong north-easterly wind. The wind was also responsible for the spread of a fire which destroyed the Hungarian town of Szombathely, near the Austrian border, where 250 houses were reportedly burned to the ground in the night between 26 and 27 April (Corriere di Milano, 17 May 1817). Snow was observed even in Rome, but the exact date is unknown (Mangianti and Beltrano, 1993); in any case it would be the latest snowfall ever recorded in Rome.

The synoptic pattern underlying this event is shown in Fig. 13. Again, a star marks the position of the frigate *Austria* when it was hit by the second storm. The large-scale SLP pattern had not changed from 11 April, but the temperatures registered were even lower in some places, despite the season being advanced, and stayed low for days. On 29 April, −4 °C were measured in Geneva, the lowest temperature of the whole spring there. At the beginning of May, in the Austrian Alps at 600 m a.s.l., the snow was still "higher than fences" (Fliri, 1998). When temperatures finally returned to more usual levels, the enormous amount of snow in the mountains melted rapidly (including the snow that had not melted in the previous summer), causing widespread floods in the Alps and surrounding regions (e.g. Fliri, 1998; Pfister, 1999; Wetter et al., 2011).

3.4 John Davy's logbook

A unique record among the ships' logbooks in the collection describes a voyage from England to Ceylon (today's Sri Lanka) of John Davy, a doctor and chemist from Cornwall. With the help of two fellow travellers, Davy was able to measure air and sea surface temperature (SST) every 2 hours, day and night, for most of the journey.

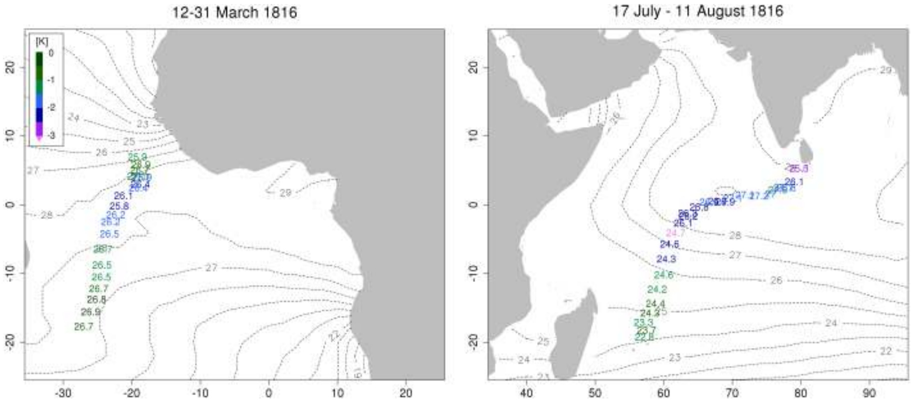

Figure 14. Daily averages of SST observations made by John Davy during his voyage to Ceylon in 1816. Contours represent 1961–1990 climatologies in ERSSTv3b for March (left) and July (right). Colours indicate the difference between the daily averages and monthly climatologies (nearest grid point). Units are °C.

Unlike marine air temperature (e.g. Brohan et al., 2012), early instrumental SST observations have not received much attention in the literature, probably because of the much smaller amount of available records. For this reason, it can be interesting to compare Davy's observations with modern SST climatologies.

Davy described the measurement procedure in a letter to his brother (Davy, 1817):

> "The water used was taken from the surface of the ocean, in a large clean bucket. [. . .] For ascertaining the temperature of the air and of the water of the ocean, I used delicate pocket-thermometers, the bulbs of which projected about an inch from the ivory scale. In the experiments on the temperature of the ocean, the water was tried the instant it was drawn, before it was affected by the air."

Figure 14 shows a comparison of daily means measured by Davy in the tropical Atlantic (March 1816) and Indian (July–August 1816) oceans with the respective 1961–1990 monthly SST climatologies from the ERSSTv3b (Extended Reconstructed Sea Surface Temperature, version 3b) data set (Smith et al., 2008). For the Indian Ocean, we used July climatologies (differences between July and August climatologies are negligible near the Equator). The magnitude of the anomalies (up to -3 K) suggests a cold bias in Davy's observations with respect to modern data, which is to be expected from uninsulated bucket measurements (e.g. Folland et al., 1984). On the other hand, SST reconstructions from proxies support extremely cold anomalies in the Indian Ocean in 1816: recently Tierney et al. (2015), using available coral archives, ranked 1816 as the third-coldest year of the last 4 centuries in the tropical Indian Ocean.

Assuming a constant bias in Davy's observations, we can at least speculate on the spatial distribution of the anomalies. The largest negative anomalies are near the Equator in both oceans; in the Indian Ocean, they cover the region where SSTs correlate best with proxies (Tierney et al., 2015). The other two areas of large negative anomalies (not shown) were crossed by Davy in the midlatitudes of the Southern Hemisphere (between 30 and 35° S), around the longitudes 0°(April 1816) and 60° E (June 1816).

4 Conclusions

We described a collection of hundreds of thousands of surface pressure and temperature observations covering the early instrumental period and in particular the years following the eruption of Mount Tambora in 1815, which had an impact on global climate and probably contributed to important changes in the atmospheric circulation of the Northern Hemisphere. An anomalous circulation pattern affected in particular Europe, where most of the data are centred, during the summer of 1816, causing widespread famine and social unrest.

We applied standard physical corrections (for temperature and gravity) to the pressure readings and reduced them to mean sea level. An additional statistical correction was necessary to produce reliable absolute sea level pressure values because metadata are usually insufficient for this purpose. An analysis of the data in the period 1815–1817 revealed realistic and spatially consistent behaviour of the corrected pressure observations, both concerning their variability and their absolute values. We found only a small fraction of the 49 land series to have evident problems in terms of data quality in at least part of the period, usually related to a lack of metadata.

Pressure variability during the wet and cold summer of 1816 was high in southern Europe and in New England when compared to modern climatology, suggesting an increased baroclinic instability in those regions. The variability of the summer of 1817 was even higher, particularly in western Europe.

One of the case studies that we described showed an example of an extratropical cyclone affecting the Alps in July 1816. The other case studies gave some insights into a series of cold outbreaks that affected Europe in the winter of 1815/16 and in the spring of 1817, the latter resulting in the coldest April ever observed in the Alpine region. The recovered data allow similar analyses for specific events in the period 1801–1820, while the quantity of digitised observations becomes increasingly smaller before and after that period.

We also analysed a record of SST observations made in the tropical Atlantic and Indian oceans in 1816. Even though more data would be necessary to increase the robustness of the results, we showed indications of large cold anomalies near the Equator, which would be consistent with reconstructions from coral archives (Tierney et al., 2015).

Direct applications of this data set are limited by its low spatial coverage. For instance, in Europe the lack of data in key regions such as the North Atlantic and the Mediterranean prevents a complete analysis of synoptic patterns, although we showed that documentary sources can give valuable assistance. On the other hand, the data can be a useful resource for numerical weather model simulations in order to produce a complete four-dimensional reanalysis. With this in mind, the data set will be made available in its raw format (uncorrected original observations) in the International Surface Pressure Databank (Yin et al., 2008) and will be assimilated into a reanalysis using the scheme of the Twentieth Century Reanalysis (Compo et al., 2011).

This paper also gives a picture of the quantity of meteorological observations available for the early instrumental period (the majority of which have not been digitised yet) and of their potential for climate research. In particular, future initiatives aimed at the recovery of historical records in the North Atlantic and the Mediterranean would make an important contribution to our understanding of the climatic changes that occurred in Europe during the 18th and the 19th centuries.

The Supplement related to this article is available online at doi:10.5194/cp-11-1027-2015-supplement.

Acknowledgements. This work was supported by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (www.met-acre.org), the Swiss National Science Foundation (SNF) Sinergia project FUPSOL-II (Grant CRSII2-147659) and the EU Horizon 2020 EUSTACE project (Grant Agreement no. 640171). Renate Auchmann was supported by the SNF project TWIST (200021_146599/1), Rob Allan by the EU FP7 ERA-CLIM2 (European Reanalysis of Global Climate Observations 2) project and the Met Office Hadley Centre Climate Program (HCCP), Rudolf Brázdil by the Grant Agency of the Czech Republic for the project no. P209/11/0956, Ladislava Řezníčková by the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I, grant no. L01415), Janusz Filipiak by the Polish National Science Centre (grant no. 2012/07/B/ST10/04214) and Fernando Domínguez-Castro by the Prometeo Project, Secretariat of Higher Learning, Science, Technology and Innovation. Support for the Twentieth Century Reanalysis Project data set is provided by the US Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. We are grateful to the many people who helped in the collection of manuscripts and metadata, including the personnel of the archives and libraries that we visited or contacted. The contributions and suggestions of James P. Bowen, William Brown, Michele Brunetti, Dario Camuffo, Martín Jacques-Coper, A. José Leonardo, Raphael Neukom, Matthias Röthlisberger, Arturo Sanchez-Lorenzo, Alexander Stickler and Clive Wilkinson, in particular, were much appreciated. We also thank the three anonymous reviewers for their useful feedback. Twentieth Century Reanalysis data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. MERRA data were provided by the NASA Global Modeling and Assimilation Office (GMAO) and the NASA GES DISC.

Edited by: E. Zorita

References

Abel, C.: Narrative of a Journey in the Interior of China, Longman and Co., London, 1818.

Ansell, T. J., Jones, P. D., Allan, R. J., Lister, D., Parker, D. E., Brunet, M., Moberg, A., Jacobeit, J., Brohan, P., Rayner, N. A., Aguilar, E., Alexandersson, H., Barriendos, M., Brandsma, T., Cox, N. J., Della-Marta, P. M., Drebs, A., Founda, D., Gerstengarbe, F., Hickey, K., Jónsson, T., Luterbacher, J., Nordli, O., Oesterle, H., Petrakis, M., Philipp, A., Rodwell, M. J., Saladie, O., Sigro, J., Slonosky, V., Srnec, L., Swail, V García-Suárez, A. M., Tuomenvirta, H., Wang, X., Wanner, H., Werner, P., Wheeler, D., and Xoplaki, E.: Daily mean sea level pressure reconstructions for the European-North Atlantic region for the period 1850–2003, J. Climate, 19, 2717–2742, 2006.

Auchmann, R., Brönnimann, S., Breda, L., Bühler, M., Spadin, R., and Stickler, A.: Extreme climate, not extreme weather: the summer of 1816 in Geneva, Switzerland, Clim. Past, 8, 325–335, doi:10.5194/cp-8-325-2012, 2012.

Bergström, H. and Moberg, A.: Daily air temperature and pressure series for Uppsala (1722–1998), Climatic Change, 53, 213–252, 2002.

Blackmon, M. L., Wallace, J. M., Lau, N.-C., and Mullen, S. L.: An observational study of the Northern Hemisphere wintertime circulation, J. Atmos. Sci., 34, 1040–1053, 1977.

Böhm, R., Jones, P. D., Hiebl, J., Frank, D., Brunetti, M., and Maugeri, M.: The early instrumental warm-bias: a solution for long central European temperature series 1760–2007, Climatic Change, 101, 41–67, 2010.

Brázdil, R., Kiss, A., Luterbacher, J., and Valášek, H.: Weather patterns in eastern Slovakia 1717–1730, based on records from the Breslau meteorological network, Int. J. Climatol., 28, 1639–1651, 2008.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., and Osborn, T. J.: Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years, Nature, 393, 450–455, 1998.

Brohan, P., Allan, R., Freeman, E., Wheeler, D., Wilkinson, C., and Williamson, F.: Constraining the temperature history of the past millennium using early instrumental observations, Clim. Past, 8, 1551–1563, doi:10.5194/cp-8-1551-2012, 2012.

Brönnimann, S., Annis, J., Dann, W., Ewen, T., Grant, A. N., Griesser, T., Krähenmann, S., Mohr, C., Scherer, M., and Vogler, C.: A guide for digitising manuscript climate data, Clim. Past, 2, 137–144, doi:10.5194/cp-2-137-2006, 2006.

Camuffo, D.: Calibration and instrumental errors in early measurements of air temperature, Climatic Change, 53, 297–329, 2002a.

Camuffo, D.: Errors in early temperature series arising from changes in style of measuring time, sampling schedule and number of observations, Climatic Change, 53, 331–352, 2002b.

Camuffo, D.: History of the long series of daily air temperature in Padova (1725–1998), Climatic Change, 53, 7–75, 2002c.

Camuffo, D. and Jones, P. (Eds.): Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources, Springer, Dordrecht, 2002.

Camuffo, D., Cocheo, C., and Sturaro, G.: Corrections of systematic errors, data homogenisation and climatic analysis of the Padova pressure series (1725–1999), Climatic Change, 78, 493–514, 2006.

Casty, C., Raible, C. C., Stocker, T. F., Wanner, H., and Luterbacher, J.: A European pattern climatology 1766–2000, Clim. Dynam., 29, 791–805, 2007.

Cavendish, H.: An account of the meteorological instruments used at the Royal Society's House, Phil. Trans., 66, 375–401, 1776.

Chang, E. K. M., Lee, S., and Swanson, K. L.: Storm track dynamics, J. Climate, 15, 2163–2183, 2002.

Chenoweth, M.: Ships' logbooks and "The Year Without a Summer", B. Am. Meteorol. Soc., 77, 2077–2094, 1996.

Compo, G. P., Whitaker, J. S., and Sardeshmukh, P. D.: Feasibility of a 100-year reanalysis using only surface pressure data, B. Am. Meteorol. Soc., 87, 175–190, 2006.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J.: The twentieth century reanalysis project, Q. J. Roy. Meteor. Soc., 137, 1–28, 2011.

Cornes, R.: The barometer measurements of the Royal Society of London: 1774–1842, Weather, 63, 230–235, 2008.

Cornes, R.: Historic storms of the northeast Atlantic since circa 1700: a brief review of recent research, Weather, 69, 121–125, 2014.

Cornes, R. C., Jones, P. D., Briffa, K. R., and Osborn, T. J.: A daily series of mean sea-level pressure for Paris, 1670–2007, Int. J. Climatol., 32, 1135–1150, 2012.

Cram, T. A., Compo, G. P., Yin, X., Allan, R. J., McColl, C., Vose, R. S., Whitaker, J. S., Matsui, N., Ashcroft, L., Auchmann, R., Bessemoulin, P., Brandsma, T., Brohan, P., Brunet, M., Comeaux, J., Crouthamel, R., Gleason Jr., B. E., Groisman, P. Y., Hersbach, H., Jones, P. D., Jónsson, T., Jourdain, S., Kelly, G., Knapp, K. R., Kruger, A., Kubota, H., Lentini, G., Lorrey, A., Lott, N., Lubker, S. J., Luterbacher, J., Marshall, G. J., Maugeri, M., Mock, C. J., Mok, H. Y., Nordli, Ø., Rodwell, M., Ross, T. F., Schuster, D., Srnec, L., Valente, M. A., Vizi, Z., Wang, X. L., Westcott, N., Woollen, J. S., and Worley, S. J.: The International Surface Pressure Databank version 2, Geoscience Data Journal, 2, 31–46, 2015.

Davy, J.: Observations on the temperature of the ocean and atmosphere, and on the density of sea-water, made during a voyage to Ceylon, Philos. T. R. Soc. Lond., 107, 275–292, 1817.

Dawson, A. G., Hickey, K., McKenna, J., and Foster, D.: A 200-year record of gale frequency, Edinburgh, Scotland: possible link with high-magnitude volcanic eruptions, Holocene, 7, 337–341, 1997.

Dobrovolný, P., Moberg, A., Brázdil, R., Pfister, C., Glaser, R., Wilson, R., van Engelen, A., Limanówka, D., Kiss, A., Halíčková, M., Macková, J., Riemann, D., Luterbacher, J., and Böhm, R.: Monthly, seasonal and annual temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500, Climatic Change, 101, 69–107, 2010.

Domínguez-Castro, F., Ribera, P., García-Herrera, R., Vaquero, J. M., Barriendos, M., Cuadrat, J. M., and Moreno, J. M.: Assessing extreme droughts in Spain during 1750–1850 from rogation ceremonies, Clim. Past, 8, 705–722, doi:10.5194/cp-8-705-2012, 2012.

Duchon, C. E.: Lanczos filtering in one and two dimensions, J. Appl. Meteorol., 18, 1016–1022, 1979.

Enzi, S., Bertolin, C., and Diodato, N.: Snowfall time-series reconstruction in Italy over the last 300 years, Holocene, 24, 346–356, 2014.

Fischer, E., Luterbacher, J., Zorita, E., Tett, S., Casty, C., and Wanner, H.: European climate response to tropical volcanic eruptions over the last half millennium, Geophys. Res. Lett., 34, L05707, doi:10.1029/2006GL027992, 2007.

Fliri, F.: Naturchronik von Tirol, Wagner, Innsbruck, 1998.

Folland, C. K., Parker, D. E., and Kates, F. E.: Worldwide marine temperature fluctuations 1856–1981, Nature, 310, 670–673, 1984.

Geurts, H. A. M. and van Engelen, A. F. V.: Beschrijving antieke meetreeksen, Koninklijk Nederlands Meteorologisch Instituut 165-V, KNMI, De Bilt, 1992.

Golinski, J.: British weather and the climate of the Enlightenment, The University of Chicago Press, Chicago, 2007.

Hall, B.: Account of a voyage of discovery to the west coast of Corea, and the great Loo-Choo island, Murray, London, 1818.

Jelinek, C.: Anleitung zur Anstellung meteorologischer Beobachtungen und Sammlung von Hilfstafeln, K.k. Hof- und Staatsdruckerei, Vienna, 1869.

Jones, P. and Lister, D.: The daily temperature record for St. Petersburg (1743–1996), Climatic Change, 53, 253–267, 2002.

Jones, P. D., Davies, T. D., Lister, D. H., Slonosky, V., Jónsson, T., Bärring, L., Jönsson, P., Maheras, P., Kolyva-Machera, F., Barriendos, M., Martin-Vide, J., Rodriguez, R., Alcoforado, M. J., Wanner, H., Pfister, C., Luterbacher, J., Rickli, R., Schuepbach, E., Kaas, E., Schmith, T., Jacobeit, J., and Beck, C.: Monthly mean pressure reconstructions for Europe for the 1780–1995 period, Int. J. Climatol., 19, 347–364, 1999.

Jurčec, V.: Severe Adriatic bora storms in relation to synoptic developments, Hrvatski meteorološki časopis, 24, 11–20, 1989.

Kandlbauer, J., Hopcroft, P. O., Valdes, P., and Sparks, R.: Climate and carbon cycle response to the 1815 Tambora volcanic eruption, J. Geophys. Res., 118, 12–497, 2013.

Kington, J.: The Societas Meteorologica Palatina: an eighteenth-century meteorological society, Weather, 29, 416–426, 1974.

Kirchner, I., Stenchikov, G. L., Graf, H.-F., Robock, A., and Antuña, J. C.: Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption, J. Geophys. Res., 104, 19039–19055, 1999.

Klingbjer, P. and Moberg, A.: A composite monthly temperature record from Tornedalen in northern Sweden, 1802–2002, Int. J. Climatol., 23, 1465–1494, 2003.

Küttel, M., Xoplaki, E., Gallego, D., Luterbacher, J., Garcia-Herrera, R., Allan, R., Barriendos, M., Jones, P., Wheeler, D., and Wanner, H.: The importance of ship log data: reconstructing North Atlantic, European and Mediterranean sea level pressure fields back to 1750, Clim. Dynam., 34, 1115–1128, 2010.

Luterbacher, J. and Pfister, C.: The year without a summer, Nat. Geosci., 8, 246–248, 2015.

Mangianti, F. and Beltrano, M. C.: La neve a Roma dal 1741 al 1991, MIPAAF-UCEA, Rome, 1993.

Meeus, J. H.: Astronomical Algorithms, 2nd edn., Willmann-Bell, Richmond, VA, 1999.

Middleton, W. E. K.: The History of the Barometer, Johns Hopkins, Baltimore, MD, 1964.

Middleton, W. E. K.: A History of the Thermometer and its Use in Meteorology, Johns Hopkins, Baltimore, MD, 1966.

Middleton, W. E. K.: The Experimenters: A Study of the Accademia del Cimento, Johns Hopkins, Baltimore, MD, 1972.

Moberg, A.: Meteorological observations in Sweden made before AD 1860, Paläoklimaforschung/PalaeoClim. Res., 23, 99–119, 1998.

Moberg, A., Bergström, H., Krigsman, J. R., and Svanered, O.: Daily air temperature and pressure series for Stockholm (1756–1998), Climatic Change, 53, 171–212, 2002.

Oppenheimer, C.: Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815, Prog. Phys. Geog., 27, 230–259, 2003.

Pfister, C.: Wetternachhersage, Haupt, Bern, 1999.

Poli, P., Hersbach, H., Tan, D., Dee, D., Thépaut, J.-N., Simmons, A., Peubey, C., Laloyaux, P., Komori, T., Berrisford, P., Dragani, R., Trémolet, Y., Hólm, E., Bonavita, M., Isaksen, L., and Fisher, M.: The data assimilation system and initial performance evaluation of the ECMWF pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C), Tech. rep., ECMWF, ERA report series No. 14, available at: http://old.ecmwf.int/publications/library/ecpublications/_pdf/era/era_report_series/RS_14.pdf (last access: 9 June 2015), 2013.

Post, J. D.: The Last Great Subsistence Crisis in the Western World, Johns Hopkins University Press, Baltimore, MD, 1977.

Réaumur, R. A. F.: Régles pour construire des thermomètres dont les degrés sont comparables, in: Mémoires de l'Academie Royale Des Sciences pour 1730, 452–507, Durand, Paris, 1732.

Rex, D. F.: Blocking action in the middle troposphere and its effect upon regional climate, Tellus, 2, 275–301, 1950.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, Siegfried D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M., and Woollen, J.: MERRA: NASA's modern-era retrospective analysis for research and applications, J. Climate, 24, 3624–3648, 2011.

Rogers, J. C.: Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies, J. Climate, 3, 1364–1379, 1990.

Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J.: Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006), J. Climate, 21, 2283–2296, 2008.

Spix, J. B. and Martius, C. F. P.: Travels in Brazil, in the Years 1817–1820, Vol. 1, Longman and Co., London, 1824.

Stickler, A., Brönnimann, S.,Valente, M. A., Bethke, J., Sterin, A., Jourdain, S., Roucaute, E., Vasquez, M. V., Reyes, D. A., Allan, R., and Dee, D.: ERA-CLIM: historical surface and upper-air data for future reanalyses, B. Am. Meteorol. Soc., 95, 1419–1430, 2014.

Stommel, H. and Stommel, E.: The year without a summer, Sci. Am., 240, 176–186, 1979.

Stothers, R. B.: The great Tambora eruption in 1815 and its aftermath, Science, 224, 1191–1198, 1984.

Tibaldi, S. and Buzzi, A.: Effects of orography on Mediterranean lee cyclogenesis and its relationship to European blocking, Tellus A, 35, 269–286, 1983.

Tierney, J. E., Abram, N. J., Anchukaitis, K. J.,Evans, M. N., Giry, C., Kilbourne, K. H., Saenger, C. P., Wu, H. C., and Zinke, J.: Tropical sea surface temperatures for the past four centuries reconstructed from coral archives, Paleoceanography, 30, 226–252, 2015.

Trigo, R. M., Vaquero, J. M., Alcoforado, M.-J., Barriendos, M., Taborda, J., García-Herrera, R., and Luterbacher, J.: Iberia in 1816, the year without a summer, Int. J. Climatol., 29, 99–115, 2009.

Wagner, S. and Zorita, E.: The influence of volcanic, solar and CO_2 forcing on the temperatures in the Dalton Minimum (1790–1830): a model study, Clim. Dynam., 25, 205–218, 2005.

Wegmann, M., Brönnimann, S., Bhend, J., Franke, J., Folini, D., Wild, M., and Luterbacher, J.: Volcanic influence on European summer precipitation through monsoons: possible cause for "Years without Summer", J. Climate, 27, 3683–3691, 2014.

Wetter, O., Pfister, C., Weingartner, R., Luterbacher, J., Reist, T., and Trösch, J.: The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence, Hydrolog. Sci. J., 56, 733–758, 2011.

Winkler, P.: Hohenpeißenberg 1781–2006 – das älteste Bergobservatorium der Welt, Deutscher Wetterdienst, Offenbach am Main, 2006.

WMO: Guide to meteorological instruments and methods of observation, WMO-No. 8, World Meteorological Organization, Geneva, 2008.

Yin, X., Gleason, B., Compo, G., Matsui, N., and Vose, R.: The International Surface Pressure Databank (ISPD) land component version 2.2, Tech. rep., National Climatic Data Center, Asheville, NC, available at: ftp://ftp.ncdc.noaa.gov/pub/data/ispd/doc/ISPD2_2.pdf (last access: 11 May 2015), 2008.

Yoshino, M.: Local Wind Bora, University of Tokyo Press, Tokyo, 1976.