We thank the anonymous referees for their very useful and detailed comments, their suggestions significantly improved the quality of the paper. Hereafter we reply to each specific comment of each referee, text in bold is copied from the reviewers' reports.

ANONYMOUS REFEREE #1:

The paper "A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the 'year without a summer' 1816" by Brugnara et al. represents an interesting data rescue effort focused on the early instrumental period. It demonstrates that climate reconstructions based on instrumental data are still far to be considered a closed work, being the unexploited data stored in the archives probably more than those already used for the early instrumental period. The paper contains no sensational scientific results: the pressure probably is not the most suitable variable to highlight the uniqueness of the event in 1816 and it would be useful to give equal importance to temperature and precipitation data too (many data are available for both these variables in Europe). However, it is a fair job of data recovery that may attract the attention of the scientific community on the still open issue of early instrumental period and that, thanks to the supplementary material, provides excellent suggestions for an extension of the data rescue activity. For these reasons I suggest the present paper for a publication on Climate of the Past.

I have few corrections to suggest to the authors before the final publication.

Page 1746 lineas 26-27: "Another difficulty arises from data quality, in particular for temperature: the homogenisation with modern data is usually not an easy task". I do not completely agree with this sentence: recent results on the application of a wide set of homogenisation tools to a benchmarking data-set (see Venema et al., 2012, published on this same Journal http://www.clim-past.net/8/89/2012/cp-8-89-2012.html) proved that almost all relative homogenisation algorithms improved the homogeneity of the temperature data. In the present case, however, the digitization of few years instead of the complete temporal series does not permit the application of the most common homogenisation procedures.

As shown by Böhm et al. (2010), the homogenisation of early instrumental temperature observations requires an additional effort with respect to those made after ca. 1850. Moreover, in our paper we deal with sub-daily data, whose homogenisation requires more advanced techniques than for monthly means (e.g., Della-Marta and Wanner, 2006; Auchmann and Brönnimmann, 2012). Even if we had complete temporal series, the homogenisation of the temperature observations for 1815-1817 with respect to modern data would be a very challenging task, nearly impossible for some records for want of metadata and reference series.

Page 1754 lines20-21: "We assumed all times to refer to local solar time, since official standardised times did not exist." Is this valid also for ship data? Please clarify this point.

We can be quite confident that it is valid for ship data as well. The reason is that the position of the ship was usually measured only once per day (using the elevation angle of the Sun for the latitude and a chronometer for the longitude): the most convenient time to do that is local noon. Most of the ship data have meteorological observations made at the same time of the coordinates observation, and the time indicated is always 12:00. This is now mentioned in the text.

Page 1756 lines 10-13: "At some observatories, however, the barometer hung in a heated room, in which case we will have an unknown error, usually with some seasonal cycle. Note that we rarely know the location of the barometer from metadata." It is not clear to me for which observatory the location is known and for which others it isnt, is it possible to specify the three possibilities (outside, inside unheated and inside heated) in table 1? For barometers located inside into a heated room the use of outside temperature probably does not produce better results than using a constant temperature value equal to the annual mean (assuming that heating maintain a constant temperature through the year).

Metadata are very limited in this sense, especially for those records which do not have the temperature of the barometer. Outside barometers are unlikely and we have only one case where metadata indicate an heated room: Brunswick (Maine). For this special case we actually assumed an arbitrary constant temperature of 18°C, similarly to what the reviewer suggested. The reviewer is right that this should be clearer from Table 1. In fact, thanks to his/her comment we realized that Table 1 wrongly indicates the use of climatology for that particular station. This was corrected introducing a new abbreviation (HR=heated room) and a sentence was added to Sect. 2.3.3. A similar mistake concerned the station of Quebec City: we wrongly indicated that climatology was used, instead the observations were corrected by the data source using outside temperature.

Page 1760 lineas 6-7: "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." Why linearly? Daily cycle should be better fitted by a trigonometric function. Is this due to the low number of sub-daily observations?

The average daily cycle of pressure is small compared to day-to-day variability (some of our pressure records barely have the resolution to see it) and the differences by using a trigonometric function would be negligible, also considering that observations usually coincide with maxima and minima of pressure (early morning and afternoon, respectively). Perhaps some small improvements in accuracy (few tenths of hPa) can be expected for the 00:00 time step (06:00 for North America), which we do not use in the analysis.

Page 1763 lines 1-3: replace "much lower variability" with "much lower spatial variability"; Figure 4 should be figure 7 (both at line 1 and 3).

Actually what we mean is the temporal variability (this is what Fig. 7 shows). It is however also true for spatial. We changed to "much lower spatial and temporal variability". Thanks for noticing the mistake in the figure number.

Page 1767 lines 7-10: this sentence should demonstrate that an average 2p.m. temperature of 19°C for summer 1816 is representative of an heatwave, but its comparison with the absolute maximum of 34°C over the 1800-1825 period does not convince.

What we mean is that 31°C is a very high value for that station if compared to the summer average of 19°C. We rephrased this sentence to make it clearer. Note that after a more detailed inspection of the data, we no longer refer to the entire period 1800-1825 because of a possible inhomogeneity around 1812.

Table 1: move "Y = available, N = not available" into a parenthesis after "Loc = exact location (within 100 m) from metadata"; move "TB = temperature of the barometer, TA = outside air temperature, CL = outside temperature climatology, CO = observa- tions already corrected for temperature into a parenthesis after "TCorr = data used for temperature correction"

Done.

In figure 4 a comparisons with other data-sets with available data for that period, such as the Berkley Earth Surface Temperature (available for Europe since mid 18th century) and the HISTALP data-set (available for the Greater Alpine region since mid 18th century), would be welcome to strengthen the conclusion of the authors.

Data in Figure 4 are from Dobrovolný et al. (2010), who used eleven homogenised temperature series for central Europe, ten from HISTALP plus the series of Prague. We are confident that this reconstruction, which was focused on Central Europe, represents the climate anomalies of that region better than large-scale focused datasets.

Ship data were presented but never used in the analysis. It would be interesting to exploit also these data, at least showing a case study that make use of them. Maybe those available around India could be

useful to validate the hypothesis that a delayed summer monsoon caused late torrential rains there.

We agree that using some ship data would be interesting. The problem is that we recovered only a few records (marine data was not our main target), moreover we cannot correct the biases in pressure the way we did for land stations in Europe. We decided to write a small section before the Conclusions (Sect. 3.4) that describes and briefly analyses SST observations from a voyage from England to the Indian Ocean through Cape of Good Hope. Robust conclusions cannot be obtained from a single record, however this particolar record has the peculiarity of providing daily means (based on 12 observations at 2-hour interval) instead of instantaneous observations and allows some speculation on the distribution of SST anomalies in the tropics (in particular of a strong negative anomaly in the Indian Ocean in July/August 1816), which could have had an impact on the monsoons.

ANONYMOUS REFEREE #2:

The study by Brugnara et al., "A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the "year without a summer" 1816", presents another important step forward in making more (sub-)daily historical data available for the scientific community. Previous studies about the climatic and social impacts caused by the Tambora eruption provided already a broad description using monthly to seasonal mean climatic data combined with some documentary evidence on extreme weather anomalies for Europe. The current study advances our knowledge by providing (sub-)daily pressure and partly temperature data to better analyse weather patterns leading to extreme events in the post eruption phase. The paper is well written and the methods and steps taken to retrieve the historical data are described in a clear way including relevant equations. The analysis of some events presented in this study is still very limited due to a lack of more relevant temperature and precipitation data. Given the importance to make such historical data available, I nevertheless suggest publication in Climate of the Past with minor revisions taking into account very few points below.

Introduction:

Page 1745, line 28f.: Please mention here also the initiative at ECMWF for ERA-20C (e.g. Poli et al., 2013) for 1901-2010.

Added: "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)".

Page 1746, line 13: Please refer here to the original source of the used data as well and not only to the secondary reference, sth. like "based on the monthly reconstruction by Casty et al. (2005, 2007). . . xy shows. . ." (e.g. Luterbacher and Pfister, 2015). In the later part of the paper: To which extent are your results comparable/different to the previous monthly reconstruction, used pressure data and analysis by Casty et al. (2005, 2007) or Luterbacher and Pfister (2015)?

It was not the aim of this study to reconstruct monthly SLP or temperature that are comparable with other datasets. Since we corrected pressure data using the gridded SLP reconstruction of Küttel et al. (2010), monthly averages of our corrected dataset for Europe mimic that reconstruction.

A reference to Casty et al. (2007) has been added, but we preferred not to change the structure of the sentence.

Methods:

Page 1756, line 14ff.: I don't really agree that using a temperature climatology from 20th century reanalysis starting from 1871 is a good idea. 20CR does not assimilate any land temperatures and there is also a low coverage of assimilated SSTs in the early period. The problem is not severe here as it got only applied to few stations and the statistical correction in the final step might overcome some problems. It would be fair however to mention the potentially large uncertainty of the climatology due to the above mentioned points. Independent from using 20CR, I'm in general not sure if using such a climatology is a good idea (i.e. for continental climates and/or high altitudes). See also next point.

Page 1759, Eq (8): Using a long-term climatologic mean for daily temperatures can easily lead to $> \pm$10-15 K deviations relative to the unknown daily temperature. Are you sure that simply using the standard lapse rate a in Eq. (8) might not be more accurate on daily basis for unknown temperatures? In both cases, large errors ($>$ 5 hPa) are easily possible for stations at high elevations (also the 20CR climatology based on a coarse grid will usually not capture the topography/elevation and a reasonable Ts here).

In our work the 20CR climatology is used for the temperature correction at only four stations: New Bedford, New Haven, Nuuk and Paris (1815 only). It is used at three additional stations for the reduction to sea level: Brunswick, Cambridge and Gdansk. All these stations are at elevations below 70 m. Climatology is also used to fill gaps in temperature observations, however this is a rare occurrence (ca. 0.2% of the total observations across the dataset, but none at stations above 300 m) because when temperature is missing, pressure is usually missing too.

It is true that continental climates can have large deviations from climatology on a sub-daily scale. On the other hand, it is unlikely that the barometers were exposed to extreme temperatures, therefore climatology might actually be a better solution than observed outside temperature in some cases. In either way, large errors are indeed possible on the single values. We added a sentence on this in Sect. 2.3.3, and referred to it also in Sect. 3.1 and 3.3.3.

Page 1760, line 3: That there are no to little flags for stations at high elevation is surprising given the concerns above and my own experience to calculate their P0. Table 1 indicates that with exception of Madrid the records from high altitudes were already corrected in previous studies. Nevertheless, did you evaluate them here again and if so, what were e.g. the neighbours for stations $>$ 400 m for estimating the differences with nearby stations and which standard errors are there for different seasons? Using Eq. (8), one degree difference for Ts leads already to an error of around 0.36 hPa for

Hohenpeissenberg or 0.25 hPa for Madrid etc. when estimating P0. Temperature uncertainties of e.g. 10 K would lead already to 3.6 and 2.5 hPa deviation in P0. What was the specific problem with Madrid?

Quality control was made by looking for unrealistic SLP values and by comparing the interpolated 4-daily SLP series, independently from altitude and source. Only large errors that resulted in evident spikes in difference plots were flagged (e.g., digitisation errors). In some cases, clear inhomogeneities (i.e., large jumps in the mean pressure) led to the removal of long periods.

Concerning high altitude stations, all of them had in-situ air temperature observations available, whose errors are usually < 5 K (see Böhm et al., 2010). Madrid has a large data gap between August 1815 and December 1816, and before the gap the observations have sudden jumps not compatible with sorrounding stations. Probably the barometer had some problem and there had been some attempt to recalibrate it. Moreover, pressure readings in 1814-1815 have a very coarse resolution (ca. 3 hPa); pressure readings from 1817 are given in a different unit (Castilian inches – we forgot to mention this unit in Sect. 2.3.1, this has been corrected), clearly a different barometer was used. We only used data from 1817 in the analysis.

Note that, after further evaluation, we decided to discard the series of Växjö (southern Sweden) from the case studies. This was the record with the largest number of flagged observations and with the largest statistical correction (-15 hPa in winter). A sentence was added to Sect. 3.1 to explain this choice.

Results:

Page 1762, line 12: Why not use MERRA here like in section 3.3.1 instead of 20CR?

Higher spatial and temporal resolution offered by MERRA are not really necessary here, since we are dealing with a large scale feature. In Sect. 3.3.1 we used MERRA to estimate the climatological daily cycle of pressure, which can strongly depend on local conditions and requires hourly data to be properly resolved.

Moreover, for consistency with the rest of the paper we now use the 1961-1990 climatology, which is not available from MERRA.

Page 1763, line 1+3: should be Fig. 7 in both cases.

Thanks.

Page 1763, line 5: Would remove or explain "surprisingly" here e.g. with respect to Fig. 5.

Changed to "The summer of 1817 has an higher variability in Europe than that of 1816. There are indeed indications that the summer of 1817 was also a very wet season in central Europe, although not particularly cold (see Fig. 4); in Geneva, for example, it was one of the wettest summers of the period 1799-1821, that of 1816 being the wettest (Auchmann et al., 2012)."

Page 1764, line 24f.: Add sth. like ". . .according to Eq. (8). . ." and ". . . about 2.5 hPa at low altitude and less for higher station elevations"

Now reads "according to Eq. 8, 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."

Page 1767, line 17f.: A brief qualitative comparison of your reconstruction with the maps for July 1816 shown in Luterbacher and Pfister (2015) based on the Casty et al. data would be nice here.

Most of our records are too short for such a comparison. Those long enough are the same used by Casty et al., with very few exceptions.

Page 1772, line 6: Although the focus is clearly on retrieving the historical data, I would suggest to add some concluding sentences here how your results/examples agree and advance earlier studies mentioned in the introduction/literature about the climatic features following Tambora.

New sentences have been added to the conclusions, including one that refers to a new section on the paper (SST analysis, Sect. 3.4).

Figures:

Figure 1: Although mentioned in the figure caption, a colour bar for the time would be helpful given the long time span.

A colour bar was added.

Figure 4: The anomalies relative to 1801-1830 are difficult to understand from todays perspective. It would be helpful for the reader to indicate also the deviation from more recent temperatures in addition (or mention the difference of the historical mean from the recent climatologic mean somewhere in the text).

We added the anomalies from 1961–1990 in the figure. To have more consistency in the analysis we used this period as modern climatology where possible (e.g., Fig. 5-7, 14).

Figure 5: Lon and Lat info is much too small.

Map axes in Fig. 5 have been removed because they badly affected the legibility of the maps.

Figure 6: Numbers of the colour bar are too small. Lon and lat info might be helpful for the maps. Please use an increment of 0.5

hPa for isolines in 6a to be consistent with increments in b and c.

Fig. 6-7 have been redrawn using different graphics and projection.

Figure 9+10, 12+13: The colour differences are hard to see for 5 hPa intervals. A less continuous colour bar could be useful here if possible.

We changed the colour palette as suggested. In addition we adjusted the distance power parameter used by the inverse distance interpolation algorithm so that isobars better represents actual observations in case of large gradients (e.g., in the Alpine region).

ANONYMOUS REFEREE #3:

This article by Brugnara et al. presents a valuable new set of historical subdaily pressure and temperature observations spanning the US and Europe for an early period of the 19th century. After presenting a detailed description of the data preparation, the authors focus their attention on the years following the famous Tambora volcanic eruption, using the recovered data to explore case studies of synoptic scale circulation and temperature patterns experienced from 1815 to 1817.

The authors have clearly done a lot of work in collating and preparing the early instrumental observations for analysis. The level of detail that they describe will be very helpful for future historical climatology studies. The exploration of the 1815 to 1817 extreme events are also make for fascinating reading, and provides another timely example of the value of historical data.

Overall, I enjoyed reading this paper, and believe that it is worthy of publication in Climate of the Past, subject to some minor revisions.

General comments.

1. I think that more could be said about the new data provided by this work that lies outside the 1815 to 1817 period. This could be provided by adding some explanation at the start of section 3 on why the post-Tambora period is being studied, or in the concluding remarks.

We added a couple of sentences in the conclusions to meet the reviewer's suggestion.

2. Several of the figures would be much easier to understand if they were re-created using different colour schemes.

We used a new color scale for Fig. 9–10, 12–13.

3. A lot of corrections and adjustments are made to the pressure observations. This is clearly important, but the relative size of each adjustment is not always clear. Additionally, I am unsure as to how the first round of data processing compares to the statistical corrections applied. If feasible, it might be worth creating a schematic, that outlines these steps and clarifies the average size/importance of the adjustments made, or provides an example from one source.

It is difficult to generalize, the magnitude of the different corrections depends very much from the station's characteristics and from the time of the year. Showing an average of the contributions would be somewhat misleading. The reduction to sea level is obviously dominant for inland stations (up to 127 hPa at Hohenpeissenberg in the Alps), while the temperature correction becomes particularly important (up to 6 hPa) in summer, but also in winter for continental climates (the use of outdoor temperature for the correction probably leads to large errors there, see also Fig. 3). The statistical correction affects more the stations with insufficient metadata. In general, not considering the reduction to sea level, the large majority of both physical and statistical corrections are within ±5 hPa.

Below are some specific comments, as well as some technical suggestions to help improve readability.

Specific comments

Pg 1747, final paragraph: This section seems a bit disjointed and specific, compared with the rest of the introduction. It might be better to move this information to sec- tion 2.3.3. An overview of the paper structure would be a better way to conclude the introduction.

We moved the paragraph to the end of Sect. 2.2 (temperature is now mentioned in this section's title) and replaced it with a description of the paper structure, as suggested.

Pg 1749, final paragraph: I understand why you removed the 18161817 Paris data from the University of Barcelona, but how did these removed observations correlate with the data digitised by the University of Bern? Even giving a correlation coefficient would give future data users more confidence in the full 1811-1820 series.

They are exactly the same observations, but those from the University of Barcelona are not corrected for temperature. Thus the correlation is nearly 1, to be precise 0.99. We rephrased the paragraph to make this clearer.

Section 2.2. Please provide a couple of references to support your comments about the history of barometers. Alternatively, expand the sentence referring the reader to Middleton (1964) to indicate that you obtained all of this information from his work.

We added a sentence at the beginning of the section.

Pg 1752 Eq 1: Where did this equation come from?

We added a reference to the text.

Pg 1755 L13: Why did you choose 2pm for the assumed local observation time?

We removed the sentence because such situation actually applied only to the early stages of the data rescue. Eventually, with a more careful analysis of metadata, it was always possible to assign at least a qualitative time to each observation.

Section 2.3.4: Can you estimate the average difference that the correction to local gravity made on the pressure readings?

We added a sentence on this.

Similarly, can you provide some basic statistics on the impact that the interpolation step had on the data? It would be good to know the range of adjustments made during this stage. Also, how did you linearly interpolate data for stations that only had one observation per day?

We added a sentence on the statistics for each of the four time steps. As expected, the mean differences from the observed values has a maximum at 0 UTC and a minimum at 12 UTC.

When only one observation per day is available, we just interpolate between two consecutive days. For example, if 1000 hPa are measured at 09:00 UTC on day x and 995 hPa at 09:00 UTC on day $x+1$, the interpolated values at 12:00 UTC on day x will be $1000 + (995 - 1000) \cdot 3/24 = 999.4$ hPa (note that values at 18:00 and 00:00 are considered missing in this case).

Section 3.3.1. Did you re-interpolate the statistically corrected data back to the synoptic hours mentioned in section 2.3.7, or apply the adjustments to the already interpolated values? This is not clear.

The latter. We added a sentence to clarify this. Note that since the interpolation is linear, the two approaches lead to identical results for nearly all values. The only exceptions (max 8 per year) are those values at the transition between seasons.

Pg 1764 L12: What is the resolution of the 20CR?

Added in Sect. 2.3.3.

Section 3.3.3: The tenses are a bit confusing in this section.

Changed present to past in a few sentences.

Section 4, second last paragraph: I think it is a good idea to remind the reader of the supplementary section here. Most of the analysis is only on 1815–1817, but you are actually providing a lot more data to the ISPD.

See the general comments.

Figure 1: If you can, it would be helpful to add an inset map showing some of the places mentioned in the text (Exeter, Paris, Ylitornio, St Petersburg etc), for non-European readers. The colours of the ship routes are also very confusing. Maybe try a graded scale instead (from light to dark).

We added an inset map of Europe showing all places mentioned in the text (many of them are probably not so familiar even for European readers), and a legend for time.

Figure 6: Define SD in the caption, as well as the text.
It was an editorial choice to replace "standard deviation" with an abbreviation.

Figure 8: Could you specify the stations that have the largest corrections? It might also be interesting to explain these differences in the text.
In the revised version we printed on the plot the names of the stations with mean absolute corrections larger than 5 hPa, and also added a few comments in the last paragraph Sect. 3.3.1 (although metadata is usually insufficient to explain the source of the errors for the single stations).

Figures 9-10, 12-13: The colours used are very difficult to distinguish. Have a look at http://colorbrewer2.org/ and see if you can use a diverging scale that can be more easily understood.
This was indeed a much needed improvement. We also improved the interpolation employed to draw the isobars.

Technical comments

Pg 1744, L23: 'the first', rather than 'a first'

Pg 1745, L4: 'Some of these professionals', instead of 'Some of them'

Pg 1745, L6: 'universities', not 'university'. It would also be good to see a reference here, for those interested in reading more on the role of meteorological observations and the role of the upper class. Maybe Golinski (2007)?

Pg 1745, L6: 'begun' not 'began'

Pg 1745 L8: 'on board', not 'on board of'

Pg 1745 L9: 'French Revolution' is capitalised

Pg 1745 L14: A reference here would also be nice.

Pg 1745 L28: Add reference to Cram et al. (2015).

Pg 1746 L29: Perhaps say 'does not require such specific exposure', instead of 'does not have to be outside'. Also provide a reference for this.

Pg 1747 L4: add 'historical' before 'observations' just to clarify.

Pg 1747 L8: Similarly, I would add 'in the early instrumental period' after 'most of the data'.

Pg 1748 L6: add 'and' after the University of Bern

Pg 1748 L9-10: 'with the exception of a few stations'

Pg 1748 L24: 'give an idea of', not 'give an idea on'

Pg 1751 L8: 'among', rather than 'inside'

Pg 1751 L9: 'exposure' rather than 'exposition'

Pg 1753 L12: 'of a few year', rather than 'of few years'

Pg 1756 L27: Add a comma between 'summer' and 'differences'

Pg 1762 L1: Do you have a more recent reference for storm track analysis? Maybe Matulla et al. (2008)?

Pg 1763 L7: 'suspicion' rather than 'suspect'

Pg 1763 L11: I suggest rewriting to read '...among the variability of most of the series, the lack of metadata...' or something similar. The current sentence is hard to understand.

Pg 1764 L2: 'the data are', rather than 'the data is'

Pg 1764 L20: 'relative', not 'relatively'

All these very appreciated technical comments have been applied in the revised version.

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Relevant changes in the manuscript:

- New section (Sect. 3.4) that analyses SST observations in 1816.
- Figures 6-7 have a new graphics with different projection and the reference period is now 1961-1990.
- The series of Växjö (Sweden) has been withdrawn from the case studies because of bad quality.

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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, 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, Krakow, Poland
[28]Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, Portugal
[29]ERT, Inc., Asheville, NC, USA

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

Abstract

The eruption of Mount Tambora (Indonesia) in April 1815 is the largest documented volcanic eruption in history. It ~~caused~~ 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 fifty 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 dataset, the variance of 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, ~~a~~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 organized 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, ~~like~~ such as physicians or clergymen (Golinski, 2007). Some of ~~them~~ these professionals used to keep meteorological diaries, in the same way ~~the~~ that scientists in the astronomical observatories and in some ~~university had began~~ 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 ~~of~~ intercontinental ships, and finally in the colonies. The French ~~revolution~~ 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 two 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.~~ 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 Sunbawa, 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 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 mid-latitudes in the Northern Hemisphere (e.g., Fischer et al., 2007; Wegmann et al., 2014). The highlight of this period is 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 Central and Western Europe (e.g., Luterbacher and Pfister, 2015, and references therein) (e.g., Casty et al., 2007; Luterbache well as in eastern North America (e.g., Chenoweth, 1996; Briffa et al., 1998)during the growing season, with major socio-economical impacts due to widespread crop failures (e.g., Pfister, 1999). Comparable impacts might also have been triggered by Tambora through an exceptional winter drought in most of the Iberian Peninsula (Trigo et al., 2009; Domínguez-Castro et al., 2012). The global crisis caused triggered by the 1816 climate anomaly has been described as "the last great subsistence crisis in the Western World" (Post, 1977).

Despite the large amount of many meteorological observations available for the early instrumental period, only a small part has been exploited 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 have to be outdoors. Observations require a specific exposure (Middleton, 1964). However, observations made with mercury barometers need however several corrections based on the characteristics of the barometer, on the variations of 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.

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 inside the scientific community, mainly inspired by the recommendations of French physicist Réaumur (Réaumur, 1732). Thermometers were usually placed on north-facing walls or windows to minimize 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 the sunlight hits the historical thermometer location (northeast-facing window) in summer, the average overestimation in the observed temperature is of about 2 , although in the most extreme cases it can reach even 5 .Errors of this magnitude have a negligible effect on the reduction of pressure observations to sea level at low elevationThis article is organised as follows. In Sect. 2 we describe the dataset 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 draw our concluding remarks in Sect. 4.

2 Data and methods

2.1 Dataset description

The collection consists of pressure observations made at 49 locations in Europe and North America, plus four ships' log-books 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 temperature of the barometer (when available), also outside air temperature was 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 of 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 one in India. Even larger is the number of ships' log-books: in Chenoweth (1996), for instance, 227 of them were collected for the summer of 1816. These numbers give an idea ~~on~~ 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. Historical documents available on the internet (Google Books and similar) have grown considerably over the last years and gave 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 organizations. It offers in general a higher scientific level, since the observations were carried out by professional 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 at 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 of Paris is split into two parts because we had different sources: 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 ~~the Annales de chimie et de physique, where the corrected~~ a contemporary scientific journal. The noon observations in the latter are the same observations of the ~~astronomical observatory were published starting in 1816. There is no~~ 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 ~~in the first series)~~from the uncorrected series.

Ships' log-books 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 the siphon barometer. Probably a fourth category should be reserved to 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 on 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), while its open end is immersed in the mercury of the cistern. The mercury is in hydrostatic equilibrium with the air, a change of the air pressure causes a change of the level of the mercury in the tube and a (smaller) change of the level in the cistern. A correction, calculated from the dimensions of the cistern and of the tube, must be applied on the readings made on the tube to take into account the change of the level of the mercury in the cistern.

The correction is avoided 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 the zero (marked by the tip of an ivory pin) through a screw before the pressure value is read on the column (Fig. 2). ~~The Fortin~~ 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 ~~at the time inside the scientific community~~by some contemporary scientists, because of the additional reading required, the lack of transportability~~and the exposition~~ , 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 Central Europe~~(Middleton, 1964)~~. In 1816 Joseph Louis Gay-Lussac eventually developed a transportable siphon barometer which temporarily increased the popularity of this kind of barometer~~in the following years~~.

Independently from the barometer's model, further corrections due to the thermal expansion of mercury and the change of 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 ~~(e.g., Camuffo et al., 2006)~~(see also Camuffo et al., 2006), as is a lack of maintenance and many other factors. ~~The reader is referred to Middleton (1964) for a detailed overview on errors affecting observations made with mercury barometers.~~

From metadata we know what type of barometer was employed in 1815–1817 for only twelve 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, 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 inside the scientific community, mainly inspired by the recommendations of French physicist Réaumur (Réaumur, 1732). Thermometers were usually placed on north-facing walls or windows to minimize 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 (northeast-facing window) in summer, the average overestimation in the observed temperature is of about 2 K, although in the most extreme cases it can reach even 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's 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 of level in the cistern. Therefore the following correction formula (Jelinek, 1869) must be applied to the raw observations:

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

where L is the corrected level, d is the inside diameter of the tube and D 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 cannot 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 the ones those intended for scientific use) were actually sold without the indication of l_0 (Middleton, 1964). In our metadata only in one case, for Cambridge (Harvard College), the observer clearly stated 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's level correction could be applied in the literature is for the series of 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 lower less than 0.5 hPa. We can have another example using Using the metadata for the observatory in London (Cornes, 2008) : for the barometer in use there at the time the correction suggests that any correction there would be even lowersmaller, 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, a too thin 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 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, like mechanical drifts or ~~periodical~~ 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 airs that ~~enters~~ enter the tube. In general most barometers ~~had probably~~ 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 three 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 Austriaand , 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 one hundredth of an inch), the others were divided in 12 "lines", which were in turn divided in 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 = 8 a.m.; noon = 12 p.m.; afternoon = 4 p.m.; evening = 8 p.m. 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 in 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:

$$H_{\text{sun}} = \arccos(-\tan\phi \cdot \tan\delta) \cdot \frac{24}{2\pi} \quad (2)$$

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 $0.5H_{\text{sun}}$ before (after) local noon.

If observation times for single observations are missing, but observations have been taken at regular intervals, we replaced the missing observation times with the most frequent observation time for this interval (e.g., 9 p.m. for evening observations if 9 p.m. is the most frequent known time for evening observations at one specific observatory). If the observation schedule was not regular, we assumed a local observation time of 2

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

$$t_{\text{UTC}} = t_{\text{loc}} - \lambda \cdot \frac{24}{360} \quad (3)$$

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 used to record recorded the temperature of the barometer. It was in fact common to have a mercury thermometer fixed on the same support of the barometer. Since the mercury expands and shrinks depending on the temperature, observations made with a mercury barometer must be corrected accordingly:

$$L_0 = (1 - \gamma T)L_{\text{mm}} \quad (4)$$

where γ is the thermal expansion coefficient of mercury at 0 °C ($1.82 \times 10^{-4}\,\text{K}^{-1}$), T is the temperature of the barometer in °C, L_{mm} is the original observation in mm of mercury and L_0 is the observation reduced to 0 °C. The "neutral" temperature of 0 °C is dictated by international standards nowadays and it partially was already in the early 19th century. Some observers however Note that some observersF 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 a 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 will 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 missing tooalso missing, we used the closest (in space and time) 30 year climatology of 2 m air temperature from the 20th Century Reanalysis (Compo et al., 2011) at 3 hourly resolution. As This reanalysis has a spatial resolution of 2 degrees for both latitude and longitude. As the base period for the climatologies, we chose 1871–1900, to minimize the difference with early 19th century temperatures. To reduce variability, we applied aan 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 six four stations only, one in Europe (Paris in 1815) and five 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 took advantage 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 those introduced by outside temperatures, 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.

~~The~~ 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 depend on the sub-tropical 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 one 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, ~~being~~ γ not being known with sufficient precision. Therefore the original corrections do not correspond exactly to those resulting from Eq. (4).

The series of Milan, Salem, Stockholm, and Turin had already been reduced to 0 °C in ~~precedent~~ 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 mm to hPa 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 hPa 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 mm (corrected for temperature). This is equivalent to the usual procedure of first converting pressure readings from mm to hPa 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):

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

Since all land stations in the dataset are in the mid-latitudes 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 dataset is much higher than that required for modern barometers (i.e., ± 0.1 hPa).

Similarly to the reduction of 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 20th Century Reanalysis (1871–1900) otherwise. We did not use temperature of the barometer to reduce pressure readings to sea level.

The series of 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 dataset. 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/winter 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 (where 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 ~~strong daily cycle~~ larger daily cycle and its strong dependance from other meteorological variables such as cloud cover and wind.

3 Analysis

3.1 The post-Tambora period in monthly datasets

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' log-book information from the northern North Atlantic. We also use the monthly 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 AD 1760–2007 and on documentary index series in AD 1500–1759.

Figure 4 shows the monthly temperature anomalies in Central Europe with respect to ~~the period 1801–1830~~a contemporary and a modern climatology. From June 1815 to December 1816, ~~17 months out of 19~~ 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 ~~AD~~ 1500.

~~Figure 5shows the maps of seasonal SLP anomalies in Europe, calculated from the reconstruction using the same reference period (1801–1830).~~

Winters following large tropical volcanic eruptions are often stormier and warmer than the average over Northern Europe, as well as 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) resemble in fact a weak negative NAO and are very similar to those reconstructed for the other seasons of 1816. On the contrary, the winter of 1816/17 had a strong positive NAO and brought substantial warm anomalies in Central Europe (Fig. 4).

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

3.2 Storminess

One of the advantages of daily pressure observations with respect to monthly data is the possibility to study variability on the time scales of the typical large-scale weather phenomena. In particular, the variance of bandpass filtered daily pressure observations (hereafter "storminess") is related to the frequency of stormy weather caused by extra-tropical cyclones and is commonly used for storm track analysis ~~(e.g., Blackmon et al., 1977)~~(e.g., Blackmon et al., 1977; Chang et al., 2002). In this section, we apply a 2–6 days bandpass Lanczos filter (Duchon, 1979) with a 31 day convolution vector, to analyse winter and summer storminess in 1815–1817 in Europe and northeastern 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), 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 ~~1981–2010~~ 1961–1990 climatology of the closest grid point in the Twentieth Century Reanalysis (contours in Fig. 6~~, top panel~~). 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 a too high variability, and probably also one in North America (New Haven), which seems to have a too low variability when compared to the neighbouring stations. The observations in these two stations were corrected for temperature using, respectively, ~~in-situ~~ in situ outside temperature and climatologies from the reanalysis~~, but it is unlikely, as demonstrated by Fig. 3, that the correction is the main~~

~~responsible for errors of this magnitude.~~ . For Valencia, ~~however, a~~ 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 suspicious low variability also affects the series of 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 ~~Scandinavia~~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. ~~4~~7~~, top panel~~) 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. ~~4~~7) show a quite similar pattern of variability in Europe, in particular a reduced storminess in Northern Europe. ~~Perhaps surprisingly, the summer with the highest~~ The summer of 1817 has an higher variability in Europe ~~is that of 1817.~~ than that of 1816. There are indeed indications that the summer of 1817 was also a very wet season in Central Europe, although not particularly cold (see Fig. 4); in Geneva, for example, it was 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. ~~Besides~~Additionally, the maps ~~confirm the suspect of a~~ further support the suspicion of too low variability in the series of New Haven.

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 of most of the seriesfor what concerns variability, 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; namely, we use the reconstruction by Küttel et al. (2010) as 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 sixteen 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(not the interpolated values), 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 applied 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 is are insufficient in every season, the series is not used in this section. This was the case for Derby, which has only one month of data. Moreover, we excluded the series of Valencia and Växjö, which showed low reliability in the previous section. We did not correct the already homogenised series of 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 reanalysis (Rienecker et al., 2011). MERRA offers the advantage of an hourly resolution, as well as a higher spatial resolution ($\frac{1}{2}^\circ$ latitude $\times \frac{2}{3}^\circ$ 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, smaller than 1 hPa even for stations with only one observation per day.

On the other hand, the total statistical corrections are in some cases larger than 10 hPa (Fig. 8), while their root mean square is ~~4.9~~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 ~~relatively~~ relative to summer, nothing more than what we expected because of wrong temperature corrections for barometers in heated rooms (Fig. 3a and b).

~~Another~~ The largest corrections are usually related to amateur observatories with scarce metadata and missing temperature of the barometer, but in some cases (e.g., Prague) also to official observatories with high scientific standards. An important source of systematic errors is the uncertainty of the barometer elevation: ~~considering a standard atmospherenear the sea level~~according to Eq. 8, 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), as well as 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 Central and Northern Europe. From our temperature data we detected two severe cold spells that hit Central and Northern Europe 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 ~~first~~ a case study to evaluate the quality of the corrected SLP dataset.

Figure 9 shows four SLP synoptic maps corresponding to the initial phase of the two cold spells in Central Europe. 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 ~~an~~ 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 Central Europe (e.g., Rex, 1950), ~~consistently~~ 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 first issue of The Quarterly Journal of Science, Literature and the Arts, where he reported that the temperature on the morning of the 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 Londoner chemist, Luke Howard, made several observations with different thermometers in Tottenham (Annals of Philosophy, vol. 7). On the 10th at 7:30 a.m. 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 dataset, 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 homogenised series of Stockholm allows a comparison with modern data: in the ~~period 1981–2010 there has been only one cold spell (in January 1987) that was~~ reference period 1961–1990 there have been three cold spells that were more severe than that of February 1816. However, cold spells of this magnitude were probably not so 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, altough 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 can be (not shown) are obtained by analysing the temperature series of 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 summer 1816 in Central Europe (e.g., about 7 °C colder than usual in Geneva, see Auchmann et al., 2012). Abundant rainfall fell in the Alps where, in the night between the 3th and the 4th, 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, 7/1816).

A shallow low-pressure system crosses crossed the Alps between 1 and 2 July (Fig. 10), which is consistent with cold and rainy weather, and then probably moves moved to south-eastern Europe on the 3rd, when easterly winds are were observed in the stations in eastern 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 the 19 July, always accompanied by westerly winds except for one day.

An area of high pressure is present over Scandinavia was present over north-eastern Europe during the whole period shown in Fig. 10, suggesting fair weather there (confirmed by temperatures). In particular, on the north-eastern corner the maps show the temperature registered in Ylitornio at 2 p.m. LT, which are remarkably high for that latitude (the maximum temperature is reached on the 5 July at 31 °C, not shown). The quality of the measurements is questionable (see Klingbjer and Moberg, 2003), however it is interesting to point out that the average 2 p.m. temperature measured in Ylitornio in summer the first week of July 1816 was 19is 9 °C and that the absolute maximum in the entire series (1800–1825) is 34higher than the average 2 . p.m. temperature of the whole summer 1816. Therefore our data suggest the occurrence of an a heatwave in north-eastern Europe in conjunction with the cold period in Central Europe. Again, the daily temperature series of St. Petersburg supports our conclusion, indicating 13 consecutive days (6–18 July) with mean daily temperature $> 20\,^{\circ}$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 (e.g., Luterbacher and Pfister, 2015)(Luterbacher and Pfister, 2015), showing how even relatively long-lasting events can be overlooked by monthly means. 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 big final 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 did some research in examined contemporary newspapers and other historical sources. The most badly 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, the snow fell in 18 days out of 30 (Fliri, 1998), while over two metres of snow were reported in Annaberg (976 m), near Vienna, after 16 consecutive days with snowfall (Lemberger Zeitung, 9 May 1817). At Buchlovice (234 m, southeast Moravia) a priest, Šimon Hausner, recorded snowfall on 11–14, 19–26 and 28 April, i.e. in 13 days (with other two days with sleets). Permanent frosts were also typical in this month. Hausner concluded “that such bad was not any previous April” (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 drew the attention of newspapers. In 1817 the Austrian foreign minister, the influential Prince von Metternich, had organised an ambitious scientific 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, 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 damages. The *Austria* was able to dock in Pula (today's Croatia) and could resume the journey after only one week. The *Augusta* was shorter on luck, losing all its masts, sails and boats, and reached under great difficulties the port of Chioggia, near Venice, four days after the storm hit. The reparation of the ship took about seven weeks.

Many renowned scientists and intellectuals were on board one of the two frigates; among them, 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 dataset are located. The observatories of Padua and Bologna, which are close to the Adriatic coast, reported on that day thunderstorms, very strong wind from the north-east and snow flakes. 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 the 11th 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 ~~Scandinavia~~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 most common 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 stationed 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 the 22th, they could see the promontory of the Gargano, which reaches a maximum elevation of 1065 m, "covered with snow very low down". They also repeatedly reported of stormy weather in the following days, culminating on the 27th in another violent storm 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. We think anyhow 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 Central and Southern Europe. This time the snow fell abundant even in the Po valley. In Bologna, the register of the astronomical observatory reported about 15 cm ("half shoe") of snow, again accompanied by a strong north-easterly wind. The wind was also responsible for the propagation of a fire which destroyed the Hungarian town of Szombathely, near the Austrian border, where 250 houses were reportedly burned down to the ground in the night between the 26th and the 27th (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 the 11th, but the temperatures registered were in some places even lower, despite the advancing of the season, and stayed low for days. On the 29th, −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 log-book

A quite unique record among the ships' log-books 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 two hours, day and night, for most of the journey.

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 dataset (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 expected from uninsulated bucket measurements (e.g., Folland et al., 1984). On the other hand, SST reconstructions from proxies support extreme 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 four 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). Other two areas of large negative anomalies (not shown) were crossed by Davy in the mid-latitudes 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 Mt. Tambora in 1815, which had an impact on global climate and ~~caused~~ probably contributed to important changes in the atmospheric circulation ~~, especially in~~ 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 a 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 Central and Southern Europe and in New England, when compared to modern climatology, suggesting an increased baroclinic instability in those regions. The variability of the summer 1817 was even higher, particularly in Western Europe. One of the case studies that we described showed an example of an extratropical cyclone affecting Central Europe 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 become 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 dataset are limited by its low spatial coverage. For instance, in Europe the lack of data in key regions like the North Atlantic and the Mediterranean prevents a complete analysis of synoptic patterns, although we ~~could still give several interesting insights on some of the most important large-scale meteorological events of 1815–1817. We also~~ showed that documentary sources can give valuable assistance.

On the other hand the data can be a ~~useful boundary condition~~ useful resource for numerical weather model simulations in order to produce complete four-dimensional re-analysis. In this view the dataset will be made available in its raw ~~(uncorrected) format~~ format (uncorrected original observations) in the International Surface Pressure Databank (Yin et al., 2008) and will be assimilated in a reanalysis using the ~~model~~ scheme of the Twentieth Century Reanalysis (Compo et al., 2011).

This paper ~~gives also~~ also gives a picture of the quantity of meteorological observations available ~~in~~ for the early instrumental period ~~,~~ (the majority of which ~~has~~ 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 give an important contribution to our understanding of the climatic changes occurred in Europe during the 18th and the 19th century.

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Table 1. List of land stations included in the collection, in alphabetical order. Observatories managed directly by scientific organizations are written in bold. Metadata refer to the period 1815–1817. Legend of abbreviations: Lon = longitude in degrees East, Lat = latitude in degrees North, Elev = elevation of the barometer in m a.s.l. (rounded to the unit), Obs = typical number of pressure observations per day, Loc = exact location (within 100 m) from metadata , TCorr = data used for temperature correction, Tot = number of pressure observations in 1815–1817, Flag = number of flagged observations after quality control, (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	Lon	Lat	Elev	Obs	Loc	TCorr	Years	Tot	Flag
Aarau	8.04	47.39	380?	2	N	CO	1815–1816	1431	1
Albany	−73.75	42.65	12?	3	Y	TA	1815	543	0
Althorp	−1.00	52.28	105?	2	Y	TA	1816–1817	1400	0
Armagh	−6.65	54.35	64	3	Y	TB	1796–1965	3286	0
Avignon	4.80	43.95	22	4	N	TB	1816	982	0
Barcelona	2.17	41.38	20?	3	Y	TA	1811–1820	3288	12
Barnton	−3.29	55.96	50?	1	N	TA	1815–1817	968	5
Bologna	11.35	44.50	74	1	Y	TA	1815–1817	1088	0
Boston	−0.03	52.98	10?	1	N	TA	1816–1817	713	0
Brunswick	−69.96	43.91	25?	3	Y	~~CL~~ HR	1815–1817	3112	0
~~Cadíz~~ Cádiz	−6.30	36.53	15?	3	N	TA	1816–1820	1461	0
Cambridge	−71.12	42.37	9	3	N	CO	1815–1816	818	0
Coimbra	−8.42	40.21	95?	4	Y	TB	1815–1817	3665	1
Cracow	19.96	50.06	212	3	Y	TB	1816	1098	19
Derby	−1.48	52.93	50?	2	N	TA	1817	64	0
Düsseldorf	6.77	51.23	35?	3	N	TA	1816–1817	1187	2
Edinburgh	−3.18	55.96	110?	2	Y	CO	1817	340	0
Exeter	−3.53	50.72	47?	3	Y	TB	1813–1817	3058	1
Gdańsk	18.65	54.35	14	3	Y	TB	1815–1817	3278	4
Geneva	6.15	46.23	405?	2	Y	CO	1796–1863	2129	0
Göteborg	11.97	57.71	15?	3	N	TB	1815–1817	3288	0
Haarlem	4.65	52.38	2	3	Y	TA	1801–1841	3288	6
Härnösand	17.94	62.63	15?	3	N	TA	1815–1816	2027	0
Hohenpeissenberg	11.02	47.80	995	3	Y	CO	1781–2009	3288	3
Karlsruhe	8.40	49.01	121	3	Y	TB	1815–1817	3288	3
London	−0.12	51.52	24	2	Y	TB	1815–1817	2192	76
Lviv	24.03	49.84	295?	3	Y	CO	1815–1817	2576	0
Madrid	−3.71	40.41	650?	3	N	TA	1814–1817	1488	1096

Table 1. Continued.

Name	Lon	Lat	Elev	Obs	Loc	TCorr	Years	Tot	Flag
Milan	9.18	45.47	132	2	Y	CO	1778–1834	2190	3
Natchez	−91.37	31.46	70?	3	Y	TB	1815–1817	2210	0
New Bedford	−70.93	41.65	30?	4	Y	CL	1815–1817	4384	0
New Haven	−72.92	41.30	25?	3	Y	CL	1815–1817	3219	342
Nuuk	−51.73	64.17	10?	3	N	CL	1816–1820	2102	0
Padua	11.87	45.40	31	3	Y	TB	1815–1817	2366	0
Paris (a)	2.34	48.84	65?	1	Y	CL	1811–1820	361	0
Paris (b)	2.34	48.84	65?	4	Y	CO	1816–1817	2924	0
Prague	14.42	50.08	202	1	Y	CO	1815–1817	1096	0
Quebec City	−71.21	46.82	32?	2	Y	~~CL~~ TA	1803–1819	2183	5
Rochefort	−0.96	45.93	25?	2	Y	TA	1815–1895	2153	7
Salem	−70.88	42.53	5?	2	Y	CO	1786–1820	2145	9
Stockholm	18.05	59.35	44	3	Y	CO	1756–2012	3286	8
Turin	7.68	45.07	281	1	Y	CO	1792–2009	1096	4
Umeå	20.27	63.82	5?	3	N	TA	1815–1817	3288	0
Uppsala	17.64	59.86	15?	2	Y	TA	1722–1865	2194	1
Valencia	−0.38	39.47	25?	3	Y	TA	1815–1818	2697	914
Växjö	14.80	56.88	170?	3	N	TB	1815–1817	3288	1128
Vienna	16.35	48.23	198	3	Y	CO	1815–1817	3246	6
Ylitornio	23.63	66.40	50?	3	Y	TA	1800–1825	3257	981
Žitenice	14.16	50.55	223?	3	Y	TA	1800–1818	3288	5
Zwanenburg	4.73	52.38	5	3	Y	TA	1801–1861	3288	15

Table 2. Ships' log-books included in the collection. Legend of 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

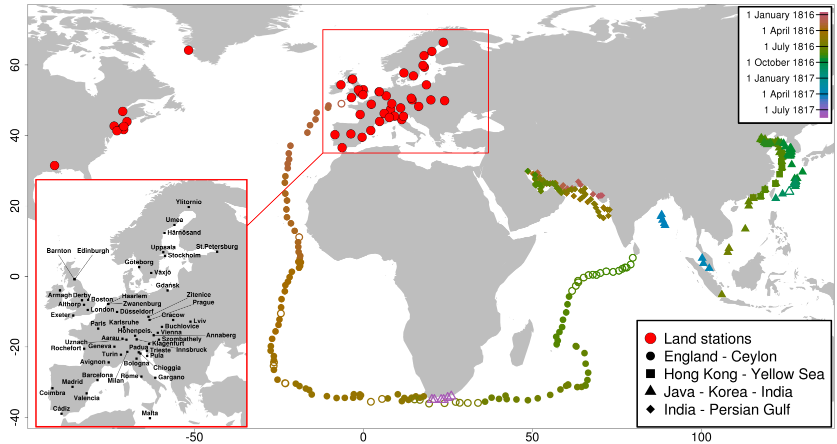

Figure 1. Position of the land observatories (red dots) and routes of the ships. For the latter, filled symbols denote locations for which pressure data are available, colours indicate time ~~from December 1815 (magenta) to March 1817 (blue)~~for marine data. The inset map shows the positions of the European observatories and of additional locations mentioned in Sect. 3.

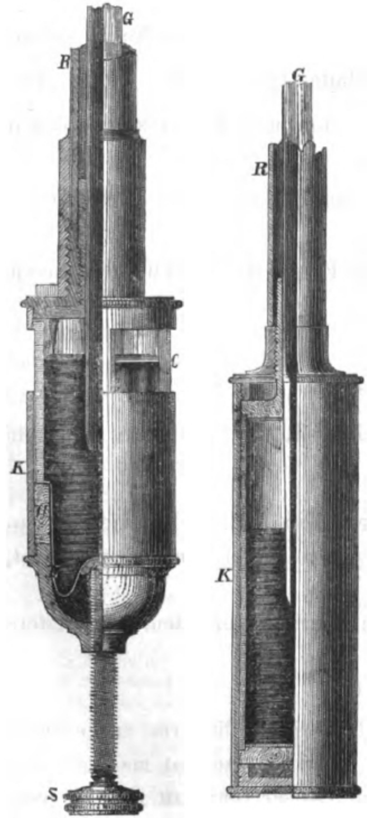

Figure 2. Drawing of the cisterns of a Fortin barometer (left) and of a fixed-cistern barometer (right). In the Fortin barometer a screw (indicated by the letter "S") allows to adjust the level of the mercury in the cistern. From Jelinek (1869).

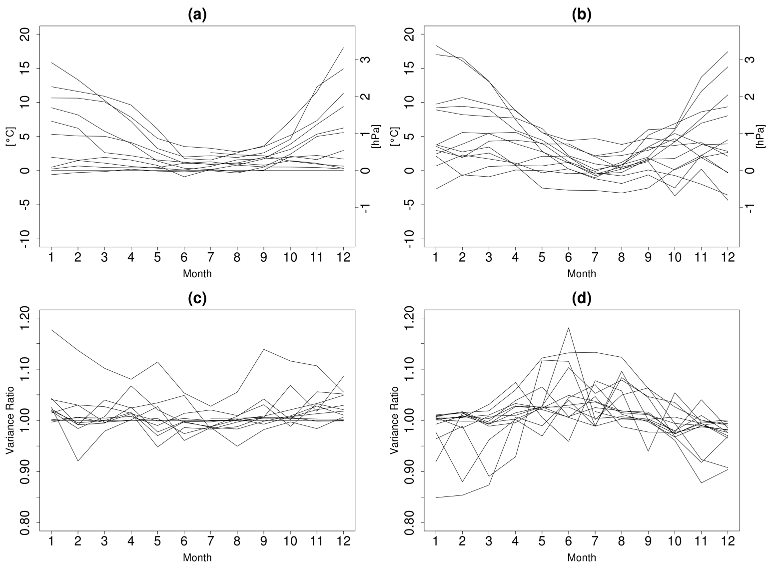

Figure 3. (a) Monthly averages of the differences between temperature of the barometer and outside temperature for the stations where both are available. **(b)** Monthly averages of the differences between temperature of the barometer and temperature climatologies from the Twentieth Century Reanalysis 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. **(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)**. **(d)** Monthly ratios between the variance of 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 from the period 1871–1900.

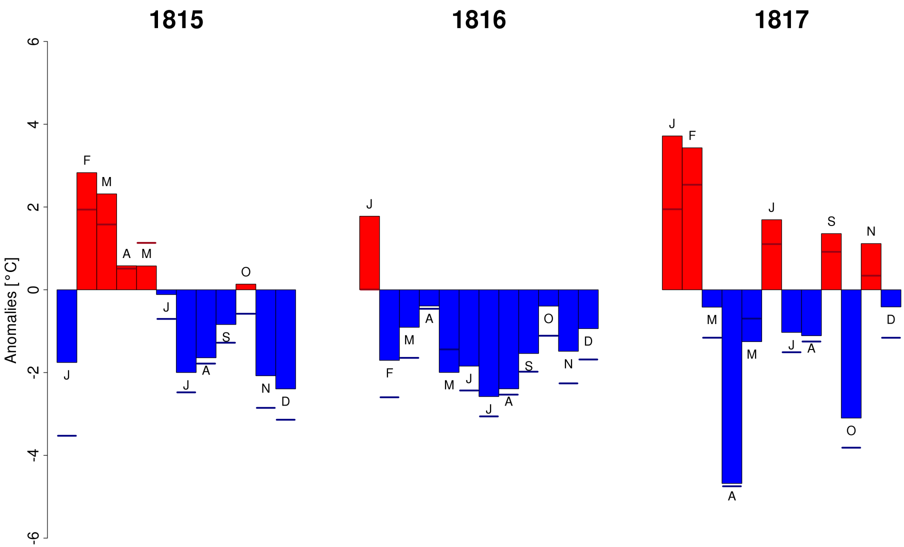

Figure 4. Monthly temperature anomalies in Central Europe (Southern Germany, Bohemia, Austria, and Switzerland) in the period 1815–1817 with respect to 1801–1830 ~~(Dobrovolný et al., 2010)~~(bars) and 1961–1990 (segments). Data are from Dobrovolný et al. (2010).

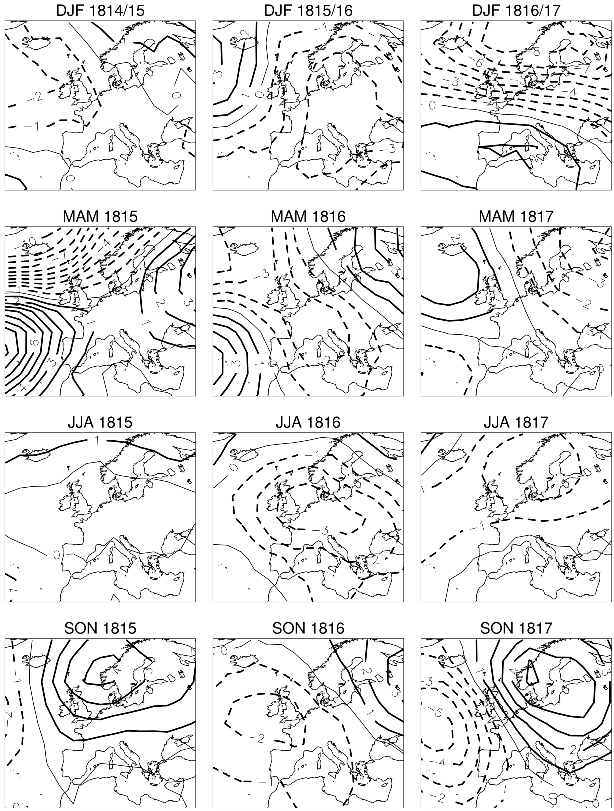

Figure 5. Seasonal SLP anomalies (in hPa) in Europe for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) for the years 1815–1817 (reference period ~~1801–1830~~1961–1990), reconstructed by Küttel et al. (2010).

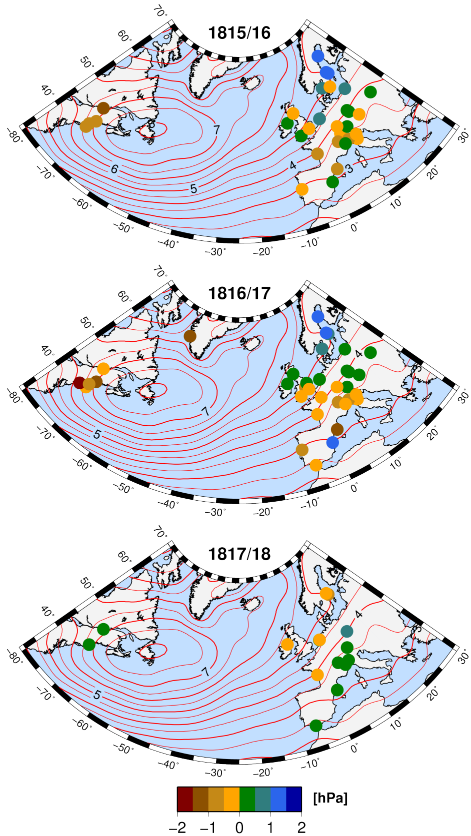

Figure 6. SD of daily (12:00 UTC) bandpass filtered SLP (in hPa) in winter (~~as defined in~~ 120 day period starting on the ~~text~~15th of November). ~~The top panel shows~~ Contours show the ~~1981–2010~~ 1961–1990 climatology in the Twentieth Century Reanalysis. ~~The other panels show land~~ Points represent observations for 1815/16, 1816/17 and 1817/18 ~~,~~ in terms of anomalies from the ~~top panel~~nearest grid point in the reanalysis.~~Empty squares indicate stations with insufficient data (see text).~~

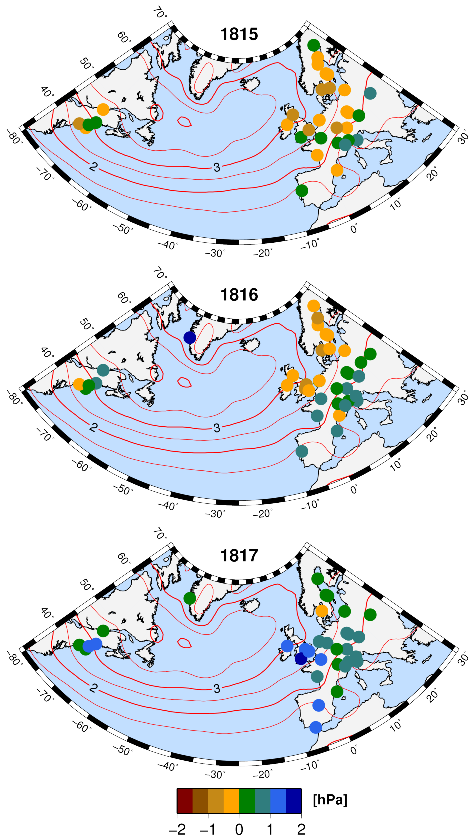

Figure 7. Similar to Fig. 6, but for summer (~~as defined in~~ 120 day period starting on the ~~text~~18th of May).

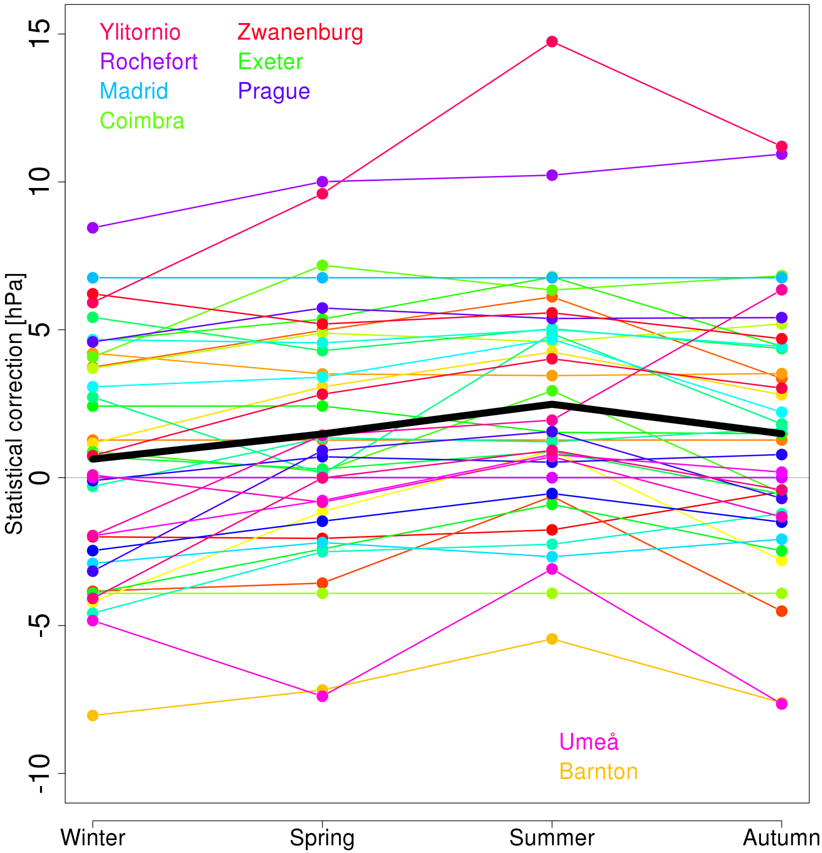

Figure 8. Seasonal corrections applied for the case studies. Each color represents a different station in Europe, the thick black line is the average of all corrections. The names of the stations with mean absolute corrections larger than 5 hPa are also printed.

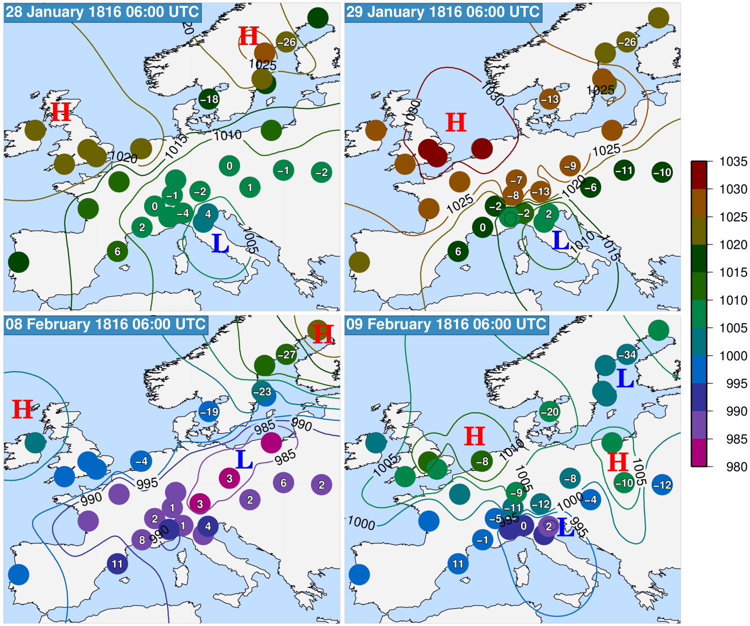

Figure 9. Synoptic maps for the two main cold spells in Central Europe during winter 1815/16. Coloured points represent SLP observations (in hPa). To facilitate interpretation, isobars at intervals of 5 hPa are drawn using inverse distance weights and the approximate position of pressure minima and maxima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

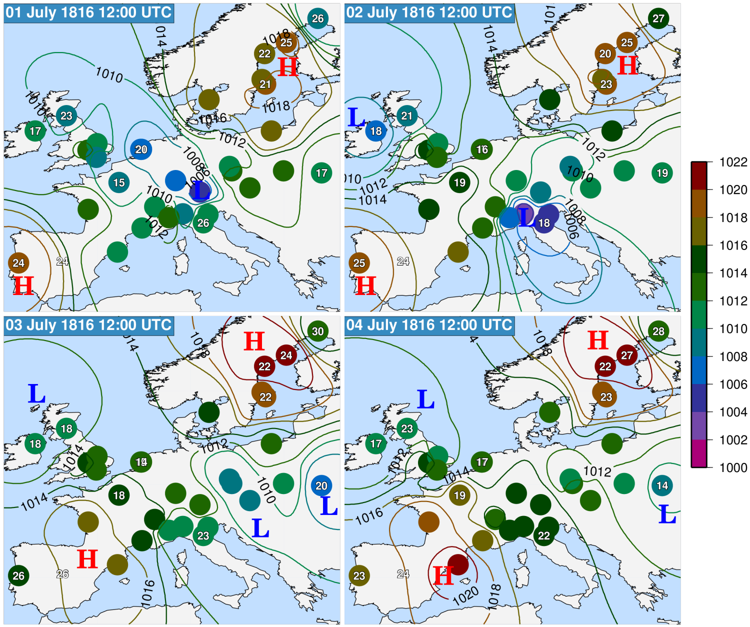

Figure 10. Similar to Fig. 9, but showing maps for the first four days of July 1816 at 12:00 UTC. Note that the colour scale has changed and isobars are drawn at intervals of 2 hPa.

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.

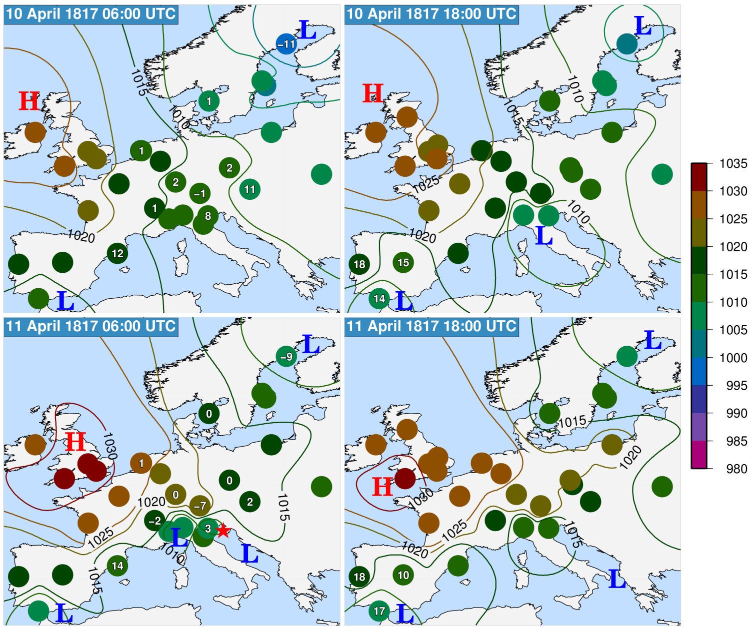

Figure 12. Similar to Fig. 9, but showing maps for 10–11 April 1817 at 12 h interval. A star marks the position of the frigates *Austria* and *Augusta* in the morning of the 11th.

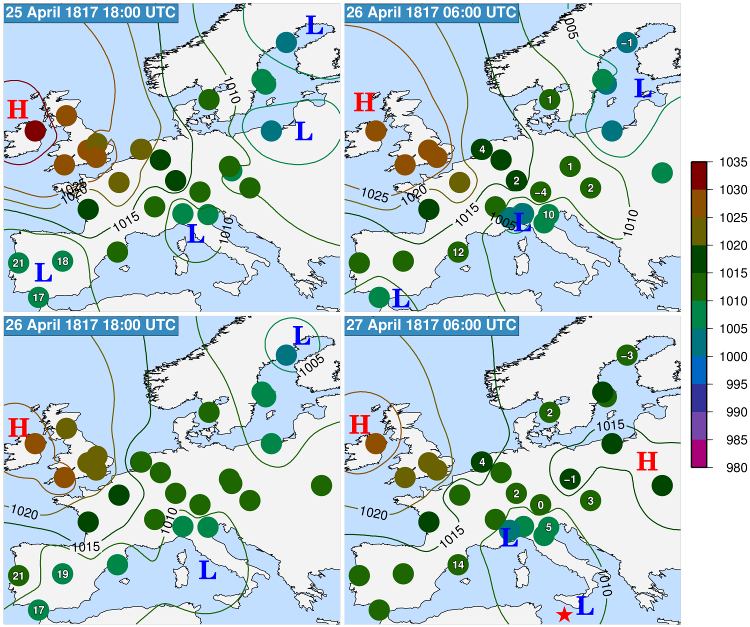

Figure 13. Similar to Fig. 9, but showing maps for 25–27 April 1817 at 12 h interval. A star marks the position of the frigate *Austria* in the morning of the 27th.

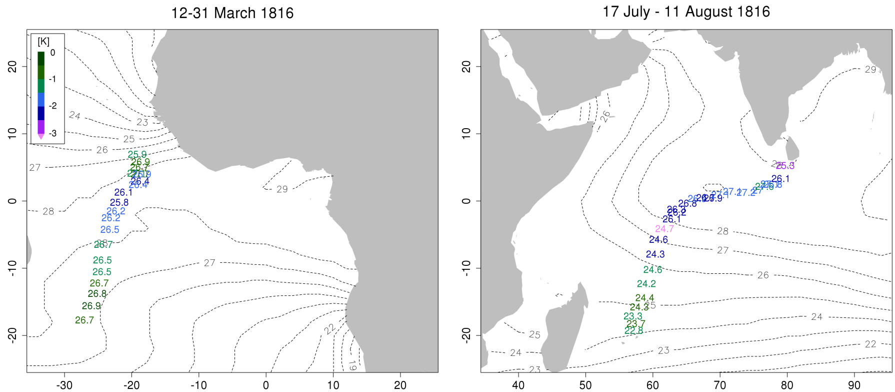

Figure 14. Daily averages of SST observations made by John Davy during his voyage to Ceylon in 1816. Contours represent 1961–1990 climatologies in ERSSTv3b for March (left) and July (right). Colours indicate the difference of the daily averages from monthly climatologies (nearest grid point). Units are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