Unlocking weather observations from the Societas Meteorologica Palatina (1781-1792)

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Abstract. In recent years, instrumental observations have become increasingly important in climate research, allowing past daily-to-decadal climate variability and weather extremes to be explored in greater detail. The 18th century saw the formation of several short-lived meteorological networks of which the one organised by the *Societas Meteorologica Palatina* is arguably the most well-known. This network stood out as one of those few that efficiently managed to control its members, integrating, refining and publishing measurements taken from numerous stations around Europe and beyond. Although much has been written about the network in both history, science, and individual prominent series used for climatological studies, the actual measurements have not yet been digitised and published in extenso. This paper represents an important step towards filling this perceived gap in research. Here we provide an inventory listing the availability of observed variables for the 37 stations that belonged to the Society's network and discuss their historical context. Most of these observations have been digitised and a considerable fraction has been converted and formatted. In this paper we focus on the temperature and pressure measurements, which have been corrected and homogenised. We then demonstrate their potential for climate research by analysing two cases of extreme weather. The recovered series will have wide applications and could contribute to a better understanding of the mechanisms behind climatic variations and extremes, as well as the societal reactions to adverse weather. Even the shorter series could be ingested into reanalyses and improve the quality of large scale reconstructions.

1 Introduction

For some decades now, early instrumental observations have increasingly played an important role in climate research (see Jones, 2001; Brönnimann et al., 2019). Not only have they shown enormous potential in reconstructing past changes in temperature, pressure, and precipitation, but they also allow for daily-to-decadal variability and extremes to be studied in great detail, particularly in 18th- and early 19th-century Europe (e.g. Brázdil et al., 2010; Camuffo et al., 2010; Csernus-Molnár et al., 2014; Pfister et al., 2019, 2020). The observations made by the extensive network of the *Societas Meteorologica Palatina* (henceforth referred to as SMP), or Palatine Meteorological Society, represent a major source for this research.

Though enjoying relatively great fame among historical climatologists, the abundant weather information published by the Society has yet to be understood in more depth. A lot of research has followed a historical approach, focusing on the origins of the Society and its members, as well as its contributions to the development of meteorology (Traumüller, 1885; Kington, 1974; Feldman, 1983; Cassidy, 1985; Wege and Winkler, 2004; Lüdecke, 2004, 2010; Vinther et al., 2006). Data from the Society have been used for climatological analysis, though mostly making use of single stations (Przybylak et al., 2014; Raicich et al., 2015; Camuffo et al., 2017; Häderli et al., 2020), rarely looking at more than a couple (Brázdil et al., 2010; Yiou et al., 2014). Aspaas and Hansen (2012) analysed occurrences of the aurora borealis recorded by the different stations as well as the phenological comments in the SMP's annual reports. In his book *The Weather of the 1780s over Europe*, Kington (1988) used the available station data from this decade – including several stations from the SMP – to create hand-drawn daily synoptic weather maps, showing that prevailing weather situations over Europe at the time (with regard to moving pressure systems) could be reconstructed and analysed. More recently, various data rescue projects such as IMPROVE (Camuffo and Jones, 2002), HISTALP (Auer et al., 2007), the ANR project CHEdaR (2010-2014), and CHIMES (Brugnara et al., 2020b), have incorporated larger portions of the data for reconstructing long high-quality series.

Despite these important efforts, work on SMP data has been scattered and only a small fraction of the overall measurements has been used in modern climate research; much of the data had yet to be digitised or published in extenso. There is more to be done with regard to unlocking the full potential of the data gathered by the SMP over 230 years ago. This study makes an important step toward filling this perceived gap in research by making many of the SMP's observations available for future climate research. We provide an inventory of all meteorological observations made by the stations belonging to the network to assess data availability. Most of these measurements have been digitised and are published with this paper. We also add to this new dataset converted and corrected temperature and pressure measurements from all SMP stations, which are here assessed for their quality. Finally, we explore the potential of the recovered series for climate research by analysing two historical cases of extreme weather.

Our work restates the importance of the Society and its established role in the history of meteorology with regard to its methods of measuring and compiling weather observations. Following in the steps of previous data rescue projects, this project establishes a useful new historical climatological database, though it stands out from previous efforts due to the sheer quantity of digitised observations and processed series being published. These observations will be important for studying past climatic variations and weather variability; they will also hold value for the improvement of reanalysis products that extend to the pre-industrial period. In fact, one of the main added values of this database in comparison with existing products is its subdaily resolution and as such, could contribute to research on high-resolution reconstructions and lead to increased knowledge about historical weather.

To better explore the value of the database, this paper is organised as follows. In Sect. 2 we give some historical context to the Society's network and explore the contents of its yearly publications; then we provide a detailed explanation of the data rescue procedure and the corrections applied to the temperature and pressure observations, including methods of comparison to explore their potential. In Sect. 3 we present the findings from the analysis of SMP data for consistency and availability; results from quality tests of the temperature and pressure data; and results from the analysis of two case studies. Their implications

are interpreted and discussed in Sect. 4, after which we make our concluding remarks.

2   Source and Methods

2.1   The SMP network and the *Ephemerides*

The Enlightenment movement of the 18th century saw scientists make substantial contributions to the design of precise instruments of physics. More and more members of the scientific community were calling for the improved quantification and standardisation of weather observations, as well as a more rigorous discipline in recording this information in a consistent manner that would allow for a cohesive characterisation of climate. The late 18th century witnessed a greater synthetic vision among meteorologists, marking a departure from the chaotic data gathering style that had characterised the preceding decades (Feldman, 1983). A number of short-lived national and international networks were zealously pursuing a more organised form of meteorology. In 1776, two years after publishing his influential *Treaty on Meteorology*, Père Louis Cotte began compiling data from several locations in France for the Société royale de médecine, based in Paris (Cotte, 1774). In Padua, Director of the Astronomical Observatory Giuseppe Toaldo, whose prize-winning work on the physical influence of weather on agriculture would spur the optimism of other networks (Toaldo, 1775), had been taking meteorological measurements since 1766. Additionally, Toaldo set up a network of precipitation measurements in Italy during the 1780s that functioned for nearly 30 years. Another meteorological programme was organised by the Oekonomische Gesellschaft Bern, which had distributed instruments to a number of stations in the then Republic of Bern (OeGB, 1762; Pfister, 1975). Other networks included the early Dutch meteorological society, Natuur- en Geneeskundige Correspondentie Societeit (1779–1802), led by Jan Hendrik van Swinden, and the Spanish network, Real Academia de Médica Matritense (1780–1825), based in Madrid.

The SMP is commonly regarded as the most successful and prolific among these organisations, whose work, according to Theodore S. Feldman, "was not surpassed for three-quarters of a century" (Feldman, 1990, p. 154). Founded in 1780 by the Elector Palatine of Bavaria Karl Theodor and directed by his secretary Johannes Jakob Hemmer, the SMP stood out as one of those few networks that efficiently managed to control its members, integrating, refining and publishing measurements taken from numerous stations around Europe and beyond (Kington, 1974; Cassidy, 1985). Eventually, the Society's increasing financial difficulties together with the political confusion and social turmoil caused by the French Revolution brought about the collapse of the Society in 1795 – which had already been in decline after the death of Hemmer in 1790 – and brought a swift decline to meteorology; this slump would last until the start of continuous measurements by national networks in the 1830s. Nevertheless, what the SMP and its members achieved in the late 18th century in terms of coordination and discipline of observations meant that researchers today have a wealth of more detailed and organised information about the weather of the time.

In the period 1781-92 a total of 37 stations contributed to Hemmer's project (see Table 1). The stations covered a wide area of mainland Europe, stretching from Rome in the South, La Rochelle in the West, and reaching as far North-East as St Petersburg and Moscow (Fig. 1). As such, the data of the SMP are well-placed for an extensive study to be made of Europe's climate

variability and extreme events during that decade. Notably, there was a number of stations beyond mainland Europe that was also part of the SMP, which included Cambridge, Massachusetts in North America, Godthaab in Greenland, and Pyshminsk in Siberia.

Table 1: List of stations that belonged to the SMP network, including information about height above sea level (estimations based on available information), longitude, latitude, and period for which there is data in the *Ephemerides*. This is loosely based on a list by Cassidy (1985, pp. 23-4), which does not specify the resolution of the observations.

Station	Abbr.	z (m a.s.l.)	φ (°)	λ (°)	Period covered
Andechs	AND	710	47.97	11.18	1781-92
Berlin	BRL	45	52.52	13.40	1781-88
Bologna	BOL	74	44.49	11.34	1782-84, 87-92
Brussels	BRU	60	50.85	4.35	1782-92
Budapest	BUD	168	47.50	19.04	1781-92
Cambridge (US)	CAM	9	42.37	-71.11	1782-87
Copenhagen	COP	40	55.68	12.57	1782-88
Delft	DEL	2	52.10	5.19	1784, 86
Den Haag	HAG	2	52.07	4.30	1782-83
Dijon	DIJ	250	47.32	5.04	1783-84
Düsseldorf	DUS	30	51.23	6.77	1782-84
Eidsberg	EDS	70	59.54	11.36	1787
Erfurt	ERF	202	50.98	11.03	1781-88
Geneva	GEN	380	46.20	6.14	1782-89
Godthaab (GL)	GDH	–	64.17	-51.75	1786-87
Gotthard	GOT	2093	46.55	8.57	1781-92
Göttingen	GTN	150	51.53	9.93	1783-85, 87
Hohenpeissenberg	HOH	977	47.80	11.01	1781-92
Ingolstadt	ING	369	48.75	11.43	1781-82
La Rochelle	ROC	19	46.16	-1.15	1782-90
Mannheim	MAN	112	49.49	8.47	1781-92
Marseille	MAR	44	43.30	5.36	1782-92
Middelburg	MID	15	51.49	3.61	1782-88
Moscow	MOS	130	55.76	37.62	1783-89, 91-92

Munich	MUN	525	48.13	11.58	1781-92
Padua	PAD	18	45.41	11.88	1781-92
Prague	PRA	200	50.07	14.44	1781-87, 89-91
Pyshminsk (RU)	PYS	–	56.98	60.59	1789-90
Regensburg	REG	346	49.01	12.10	1781-91
Rome	ROM	56	41.90	12.50	1782-92
Spydeberg	SPY	110	59.62	11.08	1783-86
St Petersburg	PET	15	59.93	30.36	1783-92
St Zeno	ZEN	480	47.73	12.88	1781
Stockholm	STO	44.4	59.34	18.06	1783-92
Tegernsee	TEG	740	47.72	11.77	1781-89
Würzburg	WUR	200	49.79	9.93	1781-88
Żagań	ZAG	116	51.37	15.19	1781-92

In 1780, working in Mannheim, Carlo Artaria began to manufacture the meteorological instruments that were to be distributed to the measuring sites of the network. These instruments were a mercury barometer, two mercury thermometers, a hygrometer, and for some selected sites, a magnetic declinometer (Grenon, 2010), all of which had been standardised, gauged, and calibrated to be almost identical, so that comparing measurements at a later time would be more straightforward. Other instruments, such as the pluviometer, wind vane, etc. were to be constructed locally by the observers; these instruments did not require any calibration and only needed to be placed according to Hemmer's instructions. The instruments are described in great detail in their first publication (*Ephemerides*, 1783, pp. 59-90). Using scientific Latin to overcome language differences, the SMP specified how to work with the instruments, where to place them, when to take the measurements, and in what style the observations should be written down. They were instructed to take measurements three times a day, ideally at 07:00, 14:00, and 21:00 local time, of pressure, temperature, precipitation, magnetic declination, wind direction and force, evaporation, height of rivers and lakes, clouds and state of the sky, using common units and symbology. The data was then dispatched to the headquarters in Mannheim, where it was assembled and published in the annual *Ephemerides Societatis Meteorologicae*. It is these yearly publications that form the basis for the data rescue project presented in this paper.

There are a total of twelve volumes published from 1783 to 1795, containing observations for the period 1781-92. The original volumes have already been scanned and can be found – among other places – online on the website of the Ludwig Maximilian University of Munich Library. The *Ephemerides* are structured in two parts; the main portion being the *observationes integrae* (extended observations), containing the subdaily measurements and observations, and the *appendix* or *observationes meteorologicae in compendium redactae* (synopsis), which comprises the monthly means and other summary statistics. The publications for 1781 and 1792 only contain the extended observations. For 1787-88 the format was temporarily changed to comprise a *pars prior* and a *pars posterior*, respectively containing a smaller subdaily section and an extended appendix with
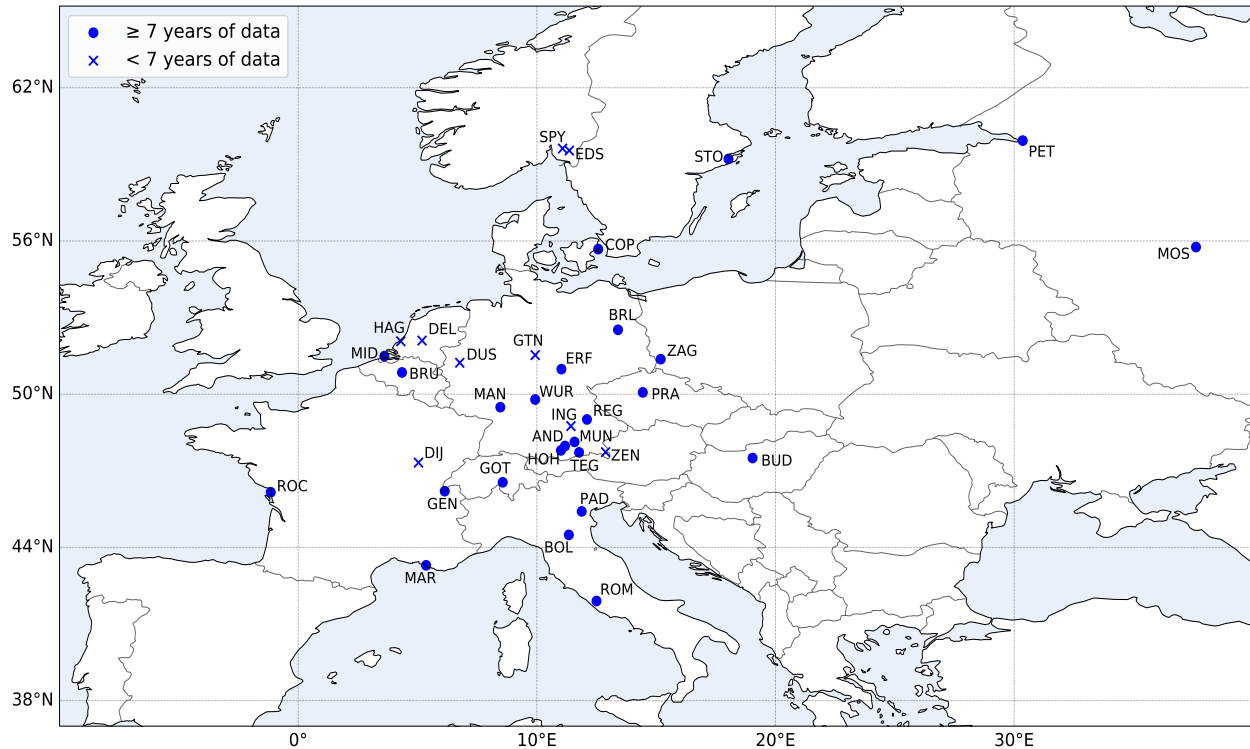
Figure 1. Network of stations that contributed to the *Ephemerides* of the *Societas Meteorologica Palatina* – see Table 1 for abbreviations. Dots represent those stations that contributed for 7 or more years of the total 12-year period 1781-92; locations with a cross are stations that sent measurements for fewer than 7 years. This distinction is made to broadly convey the varying extent of the stations' participation. Not shown on the map are the stations at Cambridge (US), Godthaab (GL), and Pyshminsk (RU).

both daily means and monthly summaries (see Sect. 3). In some volumes, there is an *additamentum* (addition) to include ob-
115 servations that had not made it to print for the previous publications.

Figure 2 shows an example for the typical arrangement of subdaily data in the publications. The table is clear and straight-
forward: above the table are written the station, the name of the observer, the observation times, and the month in question;
the table itself contains for each day measurements from the barometer (pressure), indoor thermometer (room temperature),
outdoor thermometer (air shade temperature), hygrometer (humidity), declinometer (magnetic declination), wind vane (wind
120 direction and force), rain gauge (rainfall), and an atmidometer (evaporation). Water level measurements of rivers and lakes
were also taken where possible (in the example of Budapest in Fig. 2, for the river Danube). Additionally, the SMP adopted
a common symbology to describe the phase of the moon, the state of the sky and significant weather and special phenomena,
including rain, hail, snow, frost, fog and thunderstorms. An illustration of these symbols can be found in Kington (1988, p. 24).

The protocol and instructions set out by the SMP were mostly followed, but not without the odd departure. The Russian

OBSERVATIONES BUDENSES

Autore Bruna.

Horae observationis ordinariae 7 mat. 2 pom. 9 vesp.

Januarius.

Dies	Barom.	Therm. intern.	Therm. extern.	Hygr.	Declin.	Ventus	Pluvia	Evap.	Danub.	Luna	Coeli facies	Meteora

(Table of subdaily meteorological observations for 1–15 January; numeric entries for barometer, internal and external thermometer, hygrometer, declination, wind direction and force, rainfall, evaporation, Danube level, moon phase, state of the sky, and meteorological notes.)

Figure 2. Example of a typical table of subdaily measurements for the period 1-15 January 1789, in this case showing observations for Budapest, recorded by Ferenc Xavér Bruna (*Ephemerides*, 1791, p. 278).

stations and Cambridge (US) initially used their old instruments and did not receive their Réaumur thermometers until years later; in fact, delivering the instruments intact to these remote locations represented an enormous logistical hurdle. That these stations used different instruments with different scales may at first seem to go against the idea of having a robust network of comparable standardised instruments, but variation was not prohibited. The perfection and improved construction of instruments was of the utmost importance to observers. Stationed in Marseille, Guillaume de Saint-Jacques de Silvabelle was keen to warn readers that the barometer initially sent to him by the SMP did not contain enough mercury and as a result 1782-3 pressure measurements were 3 lines too high; this issue was fixed in 1784 (*Ephemerides*, 1785, p. 498). So, as long as the observers' own instruments were in very good accord with those of the SMP, they could be used. This practice is known to have been the case for Dijon and St Petersburg, which also sent data measured with their own old devices (Euler, 1782; Maret,

1783).

135   Clearly, the scientific dedication and participation of like-minded people was crucial to the project. The observers had been carefully selected by the SMP from academies, monasteries and universities across Europe to ensure that observations would be taken even after the death of initial observers (Cassidy, 1985). Indeed, it was Hemmer's decision to target organisations rather than individuals that contributed to the SMP's collaborative success. Despite the guaranteed continuity of the observations, the gathered measurements were still a product of the specific observer and therefore susceptible to heterogeneity.

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2.2   The new SMP database

2.2.1   Inventory

The *Ephemerides* entailed a lot of patchwork by Hemmer's team in Mannheim, who were clearly interested in including as much information as was reasonably possible. They included a lot of information loosely related to meteorology but not limited

145 to it, always serving the interest of economic and cultural betterment; these included reports about agriculture and medicine, as well as occasional material concerning plant and human geography. To therefore enable a more systematic understanding of the weather information these publications provide to historical climatologists, this study presents the meteorological observations in a way that is easier to visualise and analyse. We created a straightforward inventory focusing mainly on instrumental observations. The aim is to display the availability of observations for most parameters: we excluded descriptions of the state

150 of sky and form of clouds as well as any astronomical, phenological and demographic observations. It thus contains basic information about the availability of measurements for the 37 stations that participated in the SMP project.

    For each station of the network, and for each year of the 12-year period, our inventory lists for which years they reported measurements and which parameters were being measured (see Fig. 2); if data is available, then the cell was marked with an 'X'. The last four columns contain information about the resolution of the data (subdaily, daily or monthly), the observer

155 or correspondent who took/oversaw the observations, any relevant comments, and the page range from the corresponding *Ephemerides* volume where the observations in the inventory can be found. In some cases a variable will be available at a subdaily resolution and as monthly summaries; here, the highest available resolution is reported. The main patterns revealed by the inventory with regard to data coverage and consistency are presented in Sect. 3.1. This inventory can be maintained as a living document and updated by future researchers who study the *Ephemerides*; it represents an important step in the systematic

160 rescue and evaluation of the SMP's observations; it can be found as a .csv file in the supplement to this paper.

2.2.2   Data processing

In the context of this study, almost all variables from the 37 stations listed in the inventory were digitised by key entry on spreadsheets, including the observations about the state of the sky, and are available in the data supplement to this paper. Of

165 these variables, temperature and pressure underwent conversions and corrections necessary for later scientific use. The choice

to focus on these two variables is based on – besides their primary value in climate reconstruction – the advantage of being measured with carefully calibrated and standardised instruments, which ensures a more precise quantification and thus less effort to process. Converting and correcting the other digitised variables would require significantly more time, care and effort. For instance, the SMP hygrometer that measured humidity had also been standardised and supplied free of charge, but it is unclear what the exact units being used are (although Camuffo et al. (2013) offers some suggestions to convert such arbitrary units); the rain gauges that quantified precipitation were designed locally and hence come in several different units, some of which are based on specific regional subdivisions and weight units. Conversely, we know that the thermometers and barometers provided by the Palatine Society for their network reflected the standard of the time and were already rather accurate (see, e.g., the literature from the IMPROVE project - Camuffo and Jones, 2002). In fact, reliable international calibration standards were already in place by the time the Society was established (Cavendish et al., 1777), meaning that the observations require few corrections beyond the ones described in this Section. It should be noted that we did not analyse the specific surroundings of the sites of the observatories themselves, like has been done in some studies for Hohenpeissenberg (Wege and Winkler, 2004; Winkler, 2009) and Żagań (Przybylak et al., 2014), but we rely instead to a certain degree on the adherence of the stations to the recommendations given by the SMP on the positioning of the instruments.

The pressure readings were taken from a cistern barometer, filled with mercury, graduated in Paris inches and provided with a Vernier scale. The thermometers were of the mercury-in-glass type, in degrees Réaumur: one was to be mounted indoors to be affixed to the barometer to aid in the correction of the pressure readings, and the second to be mounted outside, facing north, sheltered from direct sunshine, but allowing the free passage of air. The transformation of the digitised data from raw observations to scientifically usable values begins with the unit conversion; for temperature observations the conversion from Réaumur to Celsius is straightforward:

$$T_C = T_R \times 1.25 \tag{1}$$

The SMP's Russian stations at times used thermometers in the Delisle scale, and the station in Cambridge (US) initially sent observations taken with a Fahrenheit thermometer. For these units, the conversion to Celsius is done as follows:

$$T_C = 100 - T_D \times 2/3 \tag{2}$$

$$T_C = (T_F - 32)/1.8 \tag{3}$$

In a second step, temperature values were corrected for a positive freezing-point bias due to the tendency of the freezing point of thermometers to gradually rise (Winkler, 2009). One postulated explanation for this phenomenon was the rapid cooling of the glass walls of the thermometer after the manufacturing process; this would cause a re-alignment of the glass molecules over several years as it was being slowly compressed by external air pressure (Bellani, 1808; Yelin, 1824). The rise of the 0 °C point can be corrected easily by assuming the correction used in Winkler (2009) can be applied to all stations; that is, a stepwise -0.1 °C/year extended over the first six years of observations. This correction was applied to all series with the exception of

Cambridge (US), Dijon, Middelburg, Moscow, Stockholm, and St Petersburg, which are known to have used instruments of their own, as well as the few stations that began sending data after 1785. Another known problem of the SMP thermometer is that it was only graduated until -16 °Ré, meaning that when the mercury dipped below this mark the observers estimated the value by visual extrapolation, which makes lower temperatures less accurate. The correction of any larger, non-linear errors is mainly related to the exposure of the thermometer; these strongly depend on each station's specific configuration and are beyond the scope of this paper.

For pressure measured with a mercury barometer, the full conversion requires more steps. The first is a temperature correction to take into account the thermal expansion of the mercury:

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

where γ is the thermal expansion coefficient of mercury at 0 °C ($1.82 \times 10^{-4} K^{-1}$). T is the temperature of the barometer (or room temperature) in °C, L_{mm} is the original observation in millimeters – for Paris inches the conversion factor is 27.07 mm. It should be noted that some observers at the time would reduce their observations to other temperatures, 10°R being a common standard (Brugnara et al., 2015); this is assumed to be the case for pressure values sent to Mannheim by the Russian stations. For the daily means presented in the appendices of each *Ephemerides* volume, no barometer temperatures are given. Differences with corrected pressure series of neighbouring stations show a seasonal cycle – one that reflects the cycle of the (room) temperature of the barometer – indicating that these averages in the appendices were likely not reduced to 0 °C. Thus, in order to get a good estimate of the room temperature climatology corresponding to the daily mean pressure in the tables, for each station these values were extrapolated from outdoor temperature using a linear regression based on the strong linear relationship between indoor and outdoor temperature in the available subdaily observations of other years.

The next step is a unit conversion of the mercury column from millimetres to hectopascal (hPa) and the application of a gravity correction that takes into account the latitudinal and height-dependent variation of gravity acceleration:

$$P_0 = \rho g_{\varphi,h} L_0 \times 10^{-5} \tag{5}$$

where P_0 is the absolute pressure in hPa, ρ is the density of mercury at 0 °C ($1.35951 \times 10^4 kg\, m^{-3}$), $g_{\varphi,h}$ is the local gravity acceleration (estimated from latitude φ and altitude h, see Brugnara et al. (2015)), and L_0 is the temperature-corrected barometric reading in mm calculated in Eq. 4. Finally, a reduction of the measurements to mean sea level is performed for use in the synoptic analysis:

$$P_{SLP} = P_0 \times exp\left(\frac{\frac{g_{\varphi,h}}{R} \times h}{T_{ext} + a \times \frac{h}{2}} \right) \tag{6}$$

where R is the gas constant for dry air, a is the standard lapse rate of the fictitious air column below the station, and T_{ext} is the outside temperature of the station in question.

Following the unit conversion, we performed quality control tests to detect any errors present in the series. Many outliers are typically due to mistypes that occurred during the digitisation, though several could be due to transcription errors made by the

original observer, or even during the printing process. When possible and deemed reasonable, after careful inspection of the original source, the values were corrected, otherwise they were flagged as suspicious. To aid in their detection, the C3S Quality Control (QC) software provides R functions that identify climatic outliers (values outside the interquantile range), occurrences of equal consecutive values, and records where the observations exceed the WMO suggested tolerances for temperature and pressure time consistencies, among other quality tests (Brugnara et al., 2020a). Visual plots were also used to inspect the data as an alternative test for erroneous values.

Homogenisation is a final step typically performed to identify and remove systematic biases – i.e. non-climatic influences – that may have arisen in the climate time series. This can be due to a change in the local environment, the instrument, the observer, or perhaps even a change in observational procedures. Temperature and pressure series of 7 years and longer were thus tested for homogeneity visually by applying the Craddock test (Craddock, 1979). This involves testing each series against other series based on their monthly cumulative differences according to the following equation:

$$c(t_i) = c(t_{i-1}) + \bar{x}_c - \bar{x}_r + x_r(t_i) - x_c(t_i) \tag{7}$$

with $c(t_0)$ equal to zero and where the candidate series to be tested is $x_c(t_1...t_n)$ and the reference series is $x_r(t_1...t_n)$. If either series is inhomogeneous – i.e. their mean has a sudden change – c will exhibit a sharp change in slope. It is useful to plot c several times against mutiple well-correlated reference series in order to better detect the inhomogeneity (or breakpoint) and to avoid making bad corrections (see Fessehaye et al., 2019). According to Venema et al. (2012), compared to other breakpoint detection tests the Craddock test allows for good accuracy, though the manual effort involved is higher, meaning it is better suited to smaller datasets such as the one in this study. Furthermore, there is some subjectivity in the selection of breakpoints: the choice to homogenise or not is linked to the specific approach of the researcher (Brunetti et al., 2006).

Series with inhomogeneities were adjusted with a constant correction. These corrections were computed by calculating the mean difference between the candidate series with the reference series before and after the breakpoint. For instance, if the difference of a given pressure series with respect to the reference is on average 3 hPa before the breakpoint and 7 hPa after, the correction is to be 4 hPa. The more reference series are available to calculate this mean difference, the more accurate the estimated correction will be. Where possible, corrections were applied at the subdaily level and QC tests were performed again to ensure no further errors were being introduced. The results from the homogeneity tests, as well as those from the quality control, are presented in Sect. 3.2.

The corrected temperature and pressure series in our database are not only presented in their original resolution: daily mean values were computed from the subdailies and concatenated to daily means published by the SMP. For temperature, the calculation of daily means from subdaily measurements was weighted taking into account the known observation times to represent the true means with respect to the UTC day. The SMP daily means of 1787/8 were also adjusted using the known observation times from the closest year for which these are available. This adjustment was done using monthly mean diurnal cycles of 2-metre temperature at the nearest grid point in the ERA5-Land reanalysis (Muñoz-Sabater, 2019; Hersbach et al., 2020), calculated over the period 2001-2018. The choice of the type and length of the reference diurnal cycle can have different

effects on the adjustment of daily means. Thus, for comparative purposes, a corrected version of the Żagań temperature series from Przybylak et al. (2014) is available in the data supplement, which used hourly temperature data from Wrocław for the period 1999-2003. The conversion from local time to UTC was done assuming mean solar local time (i.e., the UTC offset is linearly proportional to longitude). We discard the seasonal fluctuations related to the apparent local solar time (as measured by a sundial), as these have a negligible effect on the daily means (see Camuffo et al., 2021). For pressure, the average of the available observations for a given day was calculated, with no correction for the diurnal cycle. Values that were flagged by the QC tests are ignored in the computation.

From the daily series, monthly averages were calculated and concatenated to the monthly data in the *Ephemerides*. Months with more than 5 missing days were excluded. The monthly 'means' in the *Ephemerides* are arithmetic means of all subdaily measurements until around 1784, after which mid-range values between maxima and minima were used. It would seem that editors in Mannheim could not keep up with the vast quantity of observations. Thus, published monthly data after 1784 were not included in the final monthly series.

All the data are stored in the so-called Station Exchange Format (SEF), a novel output for the transcription of climate data and metadata developed by the Copernicus Climate Change Service (C3S) (Brönnimann et al., 2018). SEF files have a .tsv (tab-separated values) extension and follow a straightforward structure, listing basic metadata regarding the station and the series in a header. Each line of the data table represents one observation time for which are specified: year, month, day, hour, minute, period (time period of observations), value, and meta. This last column contains any metadata that is of interest to the specific value, including flags that specify if the value has failed any QC test. The common format is designed to allow people rescuing instrumental measurements to present them for widespread use in an uncomplicated format and recognisable by software. The final aim is for such SEF files to be easily ingested into global repositories (Brunet et al., 2020). The historical series presented in this study will be eventually submitted to the Global Land and Marine Observations Database (GLAMOD).

2.2.3 Exploring potential

Following the analysis of data availability and quality, we explored the potential of the corrected SMP temperature and pressure series on behalf of two historical cases of extreme weather – namely two devastating storms around the new year 1783/4 and the anomalously cold March 1785. The SMP data were used in combination with additional synoptic information from existing studies of pre-industrial weather and climate. We used the CAP7 weather type reconstructions by Schwander et al. (2017), which extend MeteoSwiss' CAP9 classifications back to the year 1763 (Weusthoff, 2011), a catalogue of recurrent dynamical weather patterns over Central Europe (overall 7 types) that can provide important information on the state of the atmosphere during these years. Additionally, we used John Kington's hand-drawn synoptic maps (Kington, 1988) a unique source that allow insight into the daily progression and distribution of surface pressure features over Europe during these extreme events. Monthly reanalyses such as the EKF400v2 (Franke et al., 2017; Valler et al., 2021) can also contextualise anomalies on broader time scales than those of the SMP observations, which on average only cover the best part of a decade. Finally, documentary sources are a vital archive of weather information that provide important environmental and socio-economic dimensions to natural disasters (Pfister et al., 2002). Taking all these materials together, these case studies serve to demonstrate the value of

the SMP data for weather and climate reconstruction.

3 Results

3.1 Data coverage

The inventory reveals important information regarding the availability of meteorological observations in the *Ephemerides*. The coverage and consistency of the SMP observations are more variegated than at first meets the eye; some of these aspects are summarised in Figure 3. Station participation in the network fluctuated significantly over the years (Fig. 3a). The years with most participants are 1783 and 1784, which is fortunate for climate research as these years coincide with the Laki eruptions in Iceland, whereas the final years are those with the fewest participating stations. Indeed, 1788 marks the last year when a number of stations sent data to the Society, including dedicated stations that had provided observations for many years up until then, such as Berlin, Copenhagen, Erfurt, Middelburg, and Würzburg (see Table 1). A year later in 1789, Geneva and Tegernsee also stopped sending data. The last *Ephemerides* volume, for 1792, appeared in 1795, and it contained data recorded at 14 persevering stations. Overall, more than half of the 37 stations in the network sent data to Mannheim for longer than 7 years; 12 of these, mostly stationed in Central Europe, had their data published in almost every *Ephemerides* issue. 11 stations provided observations for 4 years or less (Fig. 3b).
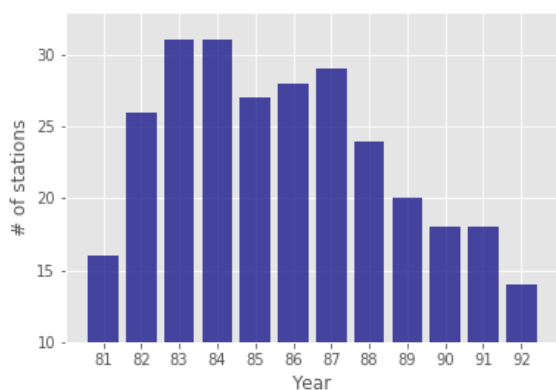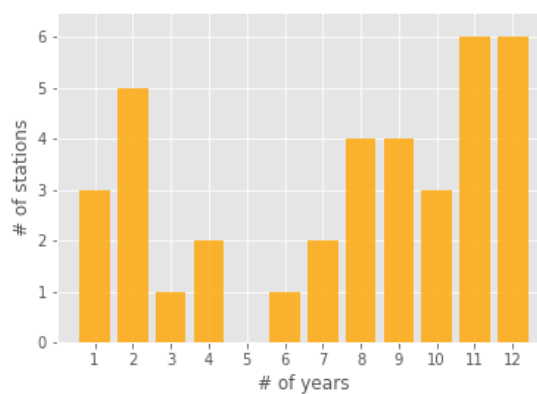
Figure 3. Bar charts showing (a) the number of stations for each year in the period 1781-92 and (b) the number of stations based on the length of available records.

Lists such as the one in Table 1 or the one provided in Cassidy's article (1985) give a rough idea of which location participated in which year, however, they do not distinguish between the type, resolution, or quantity of data recorded for each location.

A station that in a specific year contributed only subdaily wind force observations, and in another year submitted subdaily measurements for every parameter, have a different value to a researcher. While the station did participate in both years, the weight of the contribution is different. Table 2 shows an extract from the inventory to illustrate this point.

Table 2. Extract from the inventory for the station in Budapest for the years 1786 to 1788, showing how distinguishing between which parameter observations are available is both useful and informative.

Budapest	1786	1787	1788
Barometer	X		X
Thermometer (indoor)	X		
Thermometer (outdoor)	X		X
Hygrometer	X		X
Declinometer	X		X
Wind direction & force	X	X	X
Rainfall	X		X
Evaporation			
River height	X		X
Resolution	subdaily	subdaily	daily (wind: subdaily; rainfall & river h.: monthly)

320   Although there is a clear overarching framework that guided the collection of observations for the SMP, there is a number of lacunae and inconsistencies. Sometimes measurements were not taken as instructed by the SMP. For example, in the case of Żagań, measurements were not taken at regular intervals. In the case of St Petersburg, temperature and pressure were even observed at different times. Furthermore, not all observers used the instruments provided by the Society; for instance, the station in Cambridge, Massachusetts, used a Fahrenheit thermometer until 1784. In fact, the Russian stations seemed to follow a

325 protocol of their own: Moscow and St Petersburg only provided pressure (likely already reduced to a standard temperature), outdoor temperature, and wind observations. Moreover, there is clear evidence that they switched instruments throughout the 12-year period. Moscow used a Delisle scale thermometer until 1787, then began reporting in Réaumur units; it also used a barometer in English inches, and eventually started reporting observations in Paris inches, though it is unclear whether a SMP barometer was used. St Petersburg switched back and forth between Réaumur and Delisle thermometers. All these cases show

330 why inconsistencies could arise.

     As the inventory shows, it is also often the case that observations are only available for portions of the year, or that measurements of some parameters are interrupted or missing. In some cases, measurements are printed in the next edition of the *Ephemerides* as an *additamentum*, most likely due to the data not arriving in Mannheim in time to be organised, collated,

and printed. For instance, Stockholm's subdaily tables from 1788 to 1791 are published together in the *additamentum* of the *Ephemerides* published in 1793 (covering 1791 data).

One particular pattern that emerges in the inventory is a 'thinning out' of measurements available for 1787 and 1788. The data received from each location for these two years was not printed *in extenso*, as they had been in the other *Ephemerides*. Wind direction and force observations are subdaily, but the rest of the data appear in the appendices as daily or monthly means – one need only glance at Mannheim or Rome in the inventory to see this. Figure 4 illustrates this pattern very clearly. After these diluted editions in the late 1780s, the old extensive publication style resumes until the last volume, containing data for 1792, although by this time the size of the network is notably smaller.
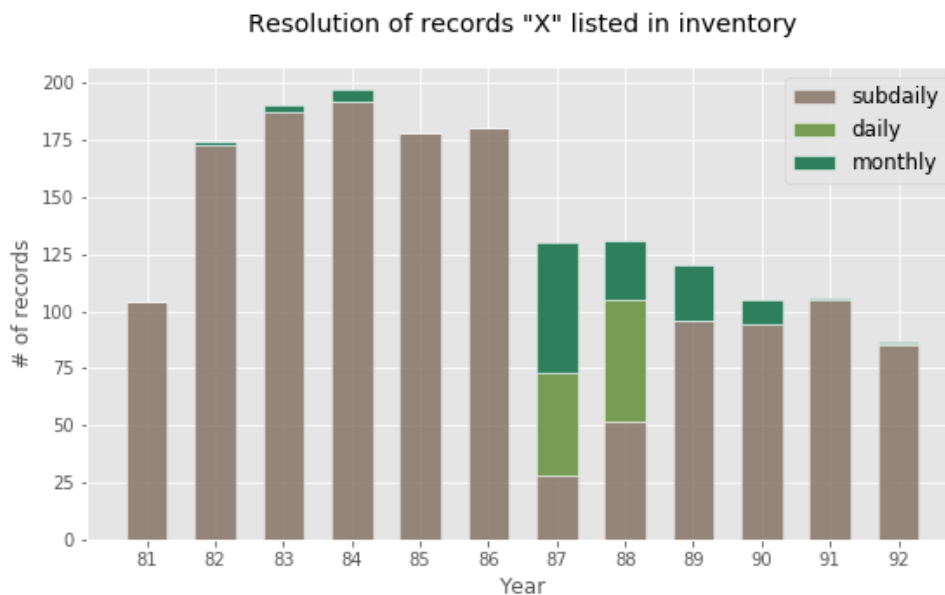
Figure 4. Bar chart showing the resolution for each data series marked by an 'X' in the inventory. The different formatting of the years 1787 and 1788 meant many records were printed as daily means and monthly summaries instead of the usual subdaily tables.

3.2 Data quality

The most common type of error reported for subdaily values by the QC software was the *wmo_time_consistency*, which flags observations that exceed the WMO-suggested tolerances for the temperatures and pressure tendency as a function of time. The Munich subdaily temperature series, covering the years 1781-86, 88, 90-92, had as many as 82 of its observations flagged with this error, most of them in the last three years of observation. This hints to the possibility that for some periods at a time the thermometer was partially exposed to sunlight and did not actually measure air shade temperature. This lead to several afternoon observations being overestimated, thereby creating unrealistic jumps in the measured temperature diurnal cycle.

On the whole, however, the *wmo_time_consistency* flags in a given series are relatively few. Some of these errors may have

Figure 5. Barometer readings at Żagań for 1-17 July 1781 (*Ephemerides*, 1783, pp. 373-4). The columns represent the days, observations times, and Parish inches and lines. The highlighted values are likely printing errors and flagged in the SEF file as *wmo_time_consistency* errors.

350 been due to misprints in the publications, or they were probably misread by compilers in Mannheim. Figure 5 illustrates this example with Żagań pressure readings. The highlighted barometer lines are erroneous and not in line with the expected pressure tendency for a 6- or 7.5-hour time interval. One could hypothesise that the first value '0.2' was meant as '10.2', but the real measured value cannot be known and so should ideally be left as a flagged value. That said, the correction of a suspected printing error is at the discretion of the researcher and, whenever applied, a note should be made in the digitised table.

355 A number of winter values in the temperature series were flagged as *subdaily_out_of_range* for exceeding the default threshold (-30 °C) of the QC function. These were mostly ignored as they seemed reasonable given the internal variability of temperature during the 1780s. Indeed, for extreme meteorological conditions, it could be that values are flagged as suspect, though being correct (WMO, 1993).

A closer look at the Brussels temperature series revealed suspicious values in December 1788. It would seem that daily
360 hygrometer observations for this month were mistakenly copied into the temperature column (*Ephemerides*, 1790, *pars posterior*, pp. 38-9). The error became apparent when comparing temperature values with those of Middelburg, located just over 100 km from Brussels. The QC software did not recognise this inconsistency due to the hygrometer measurements resembling a plausible range of temperature values.

On the lower end of the quality 'spectrum' of the recovered series is the Moscow pressure series (Fig. 6). The availability of

365   data is patchy to begin with: observations started being taken in 1783 until 1792, except for 1790; 1783-84 and 1787 are available in the form of monthly summaries; the rest are in subdaily form. About 13% of the total available subdaily values were flagged as *subdaily_repetition*s, i.e. occurrences of equal consecutive values. This hints at the poor quality of the barometer that was being used. For the Moscow station, 1785 marks both a change in observer, from Engel to Stritter, and a change from noting observations in English to Paris inches. It is unclear whether there was a change in instrument: it may not have been a

370   SMP barometer, as lines were still being reported in 1/100 instead of 1/12; on the other hand, it could be that readings from the old English barometer were simply being converted to Paris inches in the editing process. Furthermore, as can be seen in the time series, the pressure series likely needs to be homogenised, a task which could not be carried out, given the paucity of nearby reference series.
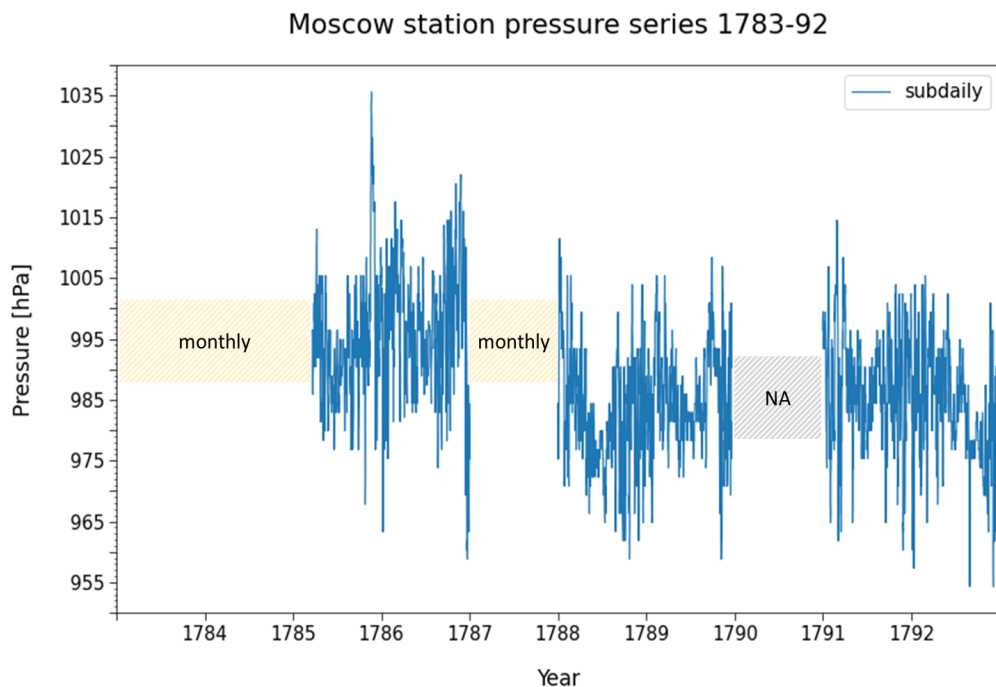
Figure 6. Station pressure series of Moscow in the period 1783-92. Shown are subdaily values in hPa (blue) and shadings that represent the availability of monthly data (yellow) or no available data (gray).

375   Overall, the correlations in the Craddock test showed good agreement for both variables between stations in Central Europe, meaning that for most candidate series there was a sufficient number of reference series. The SMP temperature series did not manifest any significant breakpoints, though the Craddock test allowed for the detection of other systematic quality problems: series such as Rome and Regensburg showed evidence of an annual cycle in the test, indicating that the thermometers may have been measuring indoor or at least in conditions of poor exposure; additionally, the Andechs series seems to overestimate

380 temperature after spring 1791. A number of breakpoints were detected in the pressure series, though as a criteria only those with a mean difference between before and after the breakpoint(s) greater than 1 hPa were adjusted. Constant corrections were applied to the following SMP pressure series: Andechs, Bologna, Brussels, Erfurt, Gotthard, Hohenpeissenberg, Prague and Rome (see Table 3).

Table 3. Station pressure series for which breakpoints were detected, showing the location in the series where the breakpoint is, the extent of the correction, and where in the series this was applied.

Series	Breakpoint(s)	Correction [hPa]	Application
Andechs	Jun 1782	- 1.2	1 Jan 1781 - 30 Jun 1782
	Mar 1787	+ 2.4	1 Jul 1786 - 31 Mar 1787
Bologna	Aug 1783	+ 8.6	14 Jan 1782 - 23 Aug 1783
	Dec 1784	+ 3.9	16 Jan 1784 - 31 Dec 1784
Brussels	Jul 1782	+ 3	1 Jan 1782 - 31 Jul 1782
	Dec 1783	- 2.5	1 Dec 1783 - 31 Dec 1785
Erfurt	Dec 1782	+ 3.2	1 Jan 1781 - 31 Dec 1782
	Jan 1788	+ 2.4	1 Jan 1788 - 31 Dec 1788
Gotthard	Mar 1782	+ 5.9	1 Jun 1781 - 31 Mar 1782
Hohenpeissenberg	Dec 1788	+ 2.7	1 Jan 1788 - 31 Dec 1788
Prague	Jul 1784	+ 4.3	1 Aug 1781 - 31 Jul 1784
Rome	Dec 1783	+ 6	1 Jan 1782 - 31 Dec 1783
	Oct 1788	+ 3.8	1 Oct 1788 - 31 Dec 1792

3.3 Case studies

3.3.1 Storms during the winter 1783/84

Around 24-26 December and the first days of January 1784 two violent storms hit Europe from the Northwest (see Lamb, 2005, pp. 87-8). While the greatest impacts from the storms – in terms of destructive winds – occurred in the British Isles, the severe flooding that ensued in parts of mainland Europe during this season have been well-documented (Demarée, 2006; 390 Brázdil et al., 2010). There was considerable material damage in wide regions north of the Alps that exacerbated the already harsh socio-economic conditions caused by the severe winter.

The storms occurred following a long spell of extreme weather. Europe had been experiencing bitter cold temperatures, the result of persistent high pressure systems (type 5) that had lingered over Central Europe from 26 November to 16 December, which were then followed by successive northerly and easterly winds (types 1,4,6). All this was acting to prevent milder tem-395 peratures from the Atlantic Ocean moving eastwards over the continent. With the storm around Christmas and again in the first

days of the new year came an upswing in temperatures: the daily mean temperature in Brussels, for instance, changed from -12.5 °C on 31 December to 4.6 and 2.1 °C in the following two days. With these milder temperatures came heavy rainfall and snowmelt, which caused the first floods. This was the case for the Dijle and Demer catchments of the Scheldt basin in Belgium. The Gete River also flooded at Orp-le-Grand on 2 January and at Tienen on 4 January 1784 (Demarée, 2006). In Mannheim, Hemmer noted how the rivers "swelled greatly"; the thick ice that had constrained the Neckar tributary of the Rhine rose and broke; around 6 in the evening the river flooded at Feudenheim, inondating the bridge and breaking parts of it off, which flowed all the way downtown towards the station (*Ephemerides*, 1786, p. 53).

Not surprisingly, the SMP data fit very well with Kington's daily SLP fields. Figure 7 shows SMP pressure data reduced to sea level (using Eq. 6) plotted onto Kington's maps. By 24 December a depression had arrived from the Northwest and soon developed an intense centre that within days had moved over the English Channel. As the low expanded all sites recorded a drop in pressure with Middelburg and Mannheim respectively at 984 and 986.2 hPa. On 2-3 January another frontal system arrived in from the Atlantic, pushing against a large high pressure system centred over Scandinavia, creating a strong pressure gradient over the North Sea that blew gusts of Arctic air over Denmark, Germany and the Low Countries. According to SMP
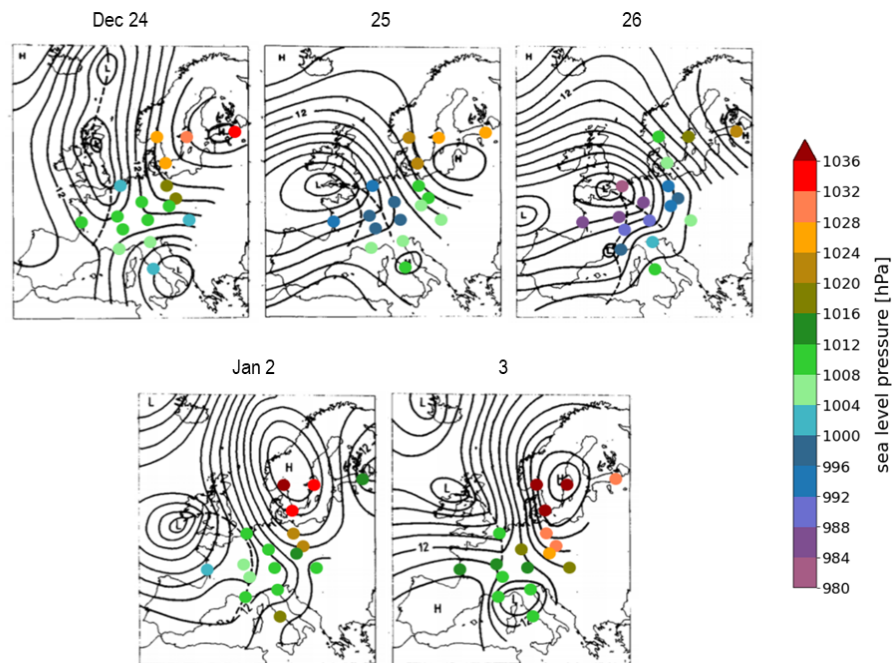
Figure 7. Kington's hand-drawn synoptic maps showing the storms as they moved over Europe covering the days 23-26 December 1783 and 2-3 January 1784. Isobars are drawn at 4 hPa intervals, and '12' denotes the 1012 hPa isobar; dashed lines indicate fronts. Coloured points represent SMP pressure observations in hPa reduced to sea level from 17 selected stations. Adapted from Kington (1988, pp. 99-100), reproduced with permission of Cambridge University Press through PLSclear.

measurements, the tight gradient ranged on 2 January from 1000.2 hPa in La Rochelle to 1037.2 hPa in Spydeberg.

410

3.3.2   1785: the coldest March

In Central Europe, March 1785 may well have been the coldest March in over 300 years. According to the EKF400v2 reanalysis (Franke et al., 2017; Valler et al., 2021), this was the coldest March since 1701 for the regions surrounding Mannheim and Padua, the second coldest for the region in and around Żagań, and for Budapest it remains in the top ten coldest. Table 4 shows

415   the extent of these anomalies: for Żagań, March 1785 was over 6 °C colder than the average during the period of the SMP's activity, and around 5 °C colder for both Mannheim and Padua. There is reasonable agreement between the SMP monthly temperature anomalies and those of the EKF400v2, with a difference <0.7 °C for all stations, except for Budapest where the anomaly is 2 °C colder for the observations than in the reanalysis. These differences are partly due to the spatially coarser resolution of the reanalysis compared to the local measurements of the SMP station data.

420   In Switzerland, the Vierwaldstätter Lake had frozen over in Lucerne's bay and similarly the Geneva Lake at the Geneva-end (Pfister, 1999, p. 121). The SMP observer stationed in Geneva, Jean Senebier, had been observing subzero temperatures for days and described how by 2 March the lake had frozen over by the mouth of the Rhône (*Ephemerides*, 1787, p. 215). The future 2nd President of the USA, John Adams, working as 1st Minister to the Netherlands and living near Paris at the time, wrote about his conversation with a local abbot, recording "that neither he nor his brother, (and they are both turned of seventy)

425   remember ever to have experienced so cold weather in the beginning of March" (Adams, 1785/1981).

Table 4. Monthly anomalies of March 1785 at four stations in Central Europe: Mannheim, Padua, Budapest, and Żagań. The first column is calculated with respect to monthly climatologies from the SMP instrumental measurements, whereas the other three columns are calculated with respect to the climatologies of the EKF400v2 reanalysis gridboxes closest to the location of the four stations. (*) anomalies computed excluding 1781 and 1787.

	anomalies [°C]			
Stations	**1781-92** **SMP**	**1781-92** **EKF400v2**	**1751-1800** **EKF400v2**	**1951-2000** **EKF400v2**
Mannheim	-4.8	-5.3	-6	-6.5
Padua	-5.1	-4.4	-5.2	-4.7
Budapest	-5.6*	-3.6*	-3.6	-4.1
Żagań	-6.7	-6	-6.5	-6.8

Figure 8. Daily mean temperature from February to April 1785 at 6 SMP locations: Mannheim, Padua, Budapest, Żagań, Prague, and Regensburg. The bottom bar indicates the CAP7 weather type classifications by Schwander et al. (2017)

.

SMP data allow us to track the daily development of temperature throughout these weeks. Shown in Figure 8 are mean daily temperature series for selected locations, along with the highest probability daily weather types. We present only 6 series for visual clarity and the chosen stations are meant to be representative of a central area in Europe. The series have very good agreement, displaying mutual correlations between 0.78 and 0.91. Two features are immediately apparent. The first is the severe cold snap from 27 February to 2 March, with Żagań and Prague reaching temperatures below -20 °C. This was likely due to the strong Northeast winds – type 1 weather type according to Schwander et al. (2017) – bringing freezing continental air into Central Europe and was soon reversed by milder West-Southwest winds (type 2). The second feature is the cold March itself, manifesting for many locations as persistent below zero conditions for almost the entire month. Looking at the weather types, the main cause seems to have been successive days of type 4 (East, indifferent), type 1 (Northeast, indifferent), type 5 (High pressure) and type 6 (North), hinting to the constant flow of cold air into the region.

Both the Palatina series and the weather types nicely complement Kington's daily synoptic maps. The maps show blocking over Northwest Europe until 7 March with a centre over the North Sea and Scotland (see Fig. 9); this is interrupted by a large cold front moving into France on 8 March, which coincides with a slight warming in the SMP series and a weather type 2; over

440 the next weeks blocking resumes, this time mainly between Great Britain and Iceland (occasionally over Ireland), providing a constant flow of northerly Arctic air into Central Europe.
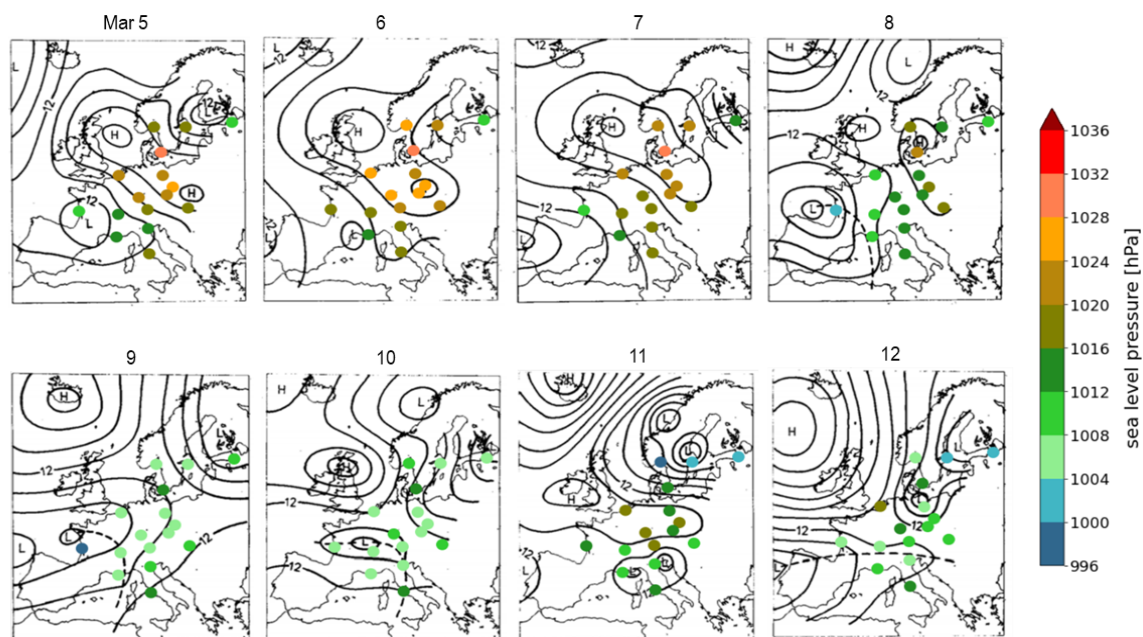
Figure 9. Kington's hand-drawn synoptic maps showing main SLP patterns over Europe covering the days 8-12 March 1785. H and L denote respectively centres of high and low pressure. Isobars are drawn at 4 hPa intervals, and '12' denotes the 1012 hPa isobar; dashed lines indicate fronts. Adapted from Kington (1988, p. 128), reproduced with permission of Cambridge University Press through PLSclear.

4   Discussion

The inventory makes clear that not every station belonging to the network made measurements for the whole period, nor did

445 they always record the observations in a consistent manner at a subdaily resolution, at the specific hours instructed by the SMP. Exploring the sources and existing literature on SMP stations can shed light on some of the reasons for this heterogeneity.

The personalities and interests of SMP observers would have had an effect on the quality of the series. Taking observations in Bologna, for instance, Abbot Petronio Matteucci was far more interested in astronomy than meteorology and was therefore not too diligent in organising the meteorological observations for the SMP (Camuffo et al., 2017). He prepared subdaily obser-

450 vations for 1782-4, 1791-2, daily means for 1788, and substituted subdaily readings for monthly averages in 1789 and 1790; 1785 and 1786 were skipped alltogether. The observations include at times significant gaps, also the pressure series needed homogenising. Almost in stark contrast to this example, reporting from Padua, were Giuseppe Toaldo and his nephew Vin-

cenzo Chiminello. Both were good and accurate scientists – especially Chiminello, whose handwriting was neat and ordered (Camuffo et al., 2020). This commitment is reflected to some extent in the inventory: Padua followed (with few departures) the protocol set out by Hemmer and became one of the few stations that reported measurements for every year of the 12-year period. Indeed, unlike for Bologna, the recovered temperature and pressure series for Padua are in very good condition and required no adjustments.

Decisions by the SMP itself in Mannheim were also a factor affecting the year-to-year changes in the *Ephemerides*: the edition published in 1790 – containing the observations for 1788 – marks not only the absence of a number of stations that had hitherto been reporting measurements, but was also the year with the highest proportion of lower resolution observations. There is not much information in the *Ephemerides* as to why the volumes containing data for 1787 and 1788 were not published in extenso. The preface to the 1787 *Ephemerides*, published in 1789, mentions that the SMP is glad to finally be able to publish the volume after having overcome various "obstacles" posed by editing (*Ephemerides*, 1789, p. v). It would seem that there were delays due to observations from various stations arriving late and at different quality/resolution, which may have caused the decision to adopt this abridged format. The preface for the 1788 volume, published in 1790, complains about the strains of editing and compiling getting "higher every year" (*Ephemerides*, 1790, p. v-vi); this also may explain the choice to simplify the format then. Nevertheless, it was decided to revert to the old unabridged format after "many" expressed their "dissatisfaction" (*Ephemerides*, 1790, p. v). To today's climate scientists wishing to use these data for research, these diluted editions should not become an issue, as pressure, temperature, moisture and other data are usually still available as tables of daily means, or monthly maxima and minima. That said, monthly data that has been calculated from quality-controlled subdaily observations would lead to a higher quality monthly product than that obtained from the mid-range values of the monthly tables in the *Ephemerides*.

There is another issue for researchers who wish to use this data to reconstruct meaningful synoptic weather maps. That bigger issue is the gradual loss of synoptic coverage over Europe after 1787-9, as stations stopped sending observations to the SMP. This is made more problematic by the fact that most of the station observations in 1787 are in the form of monthly maxima, minima, and mid-range values. However, even this shortcoming can be overcome by supplementing the analysis with data from independent neighbouring stations that were recording observations at the time. That thus ensures better geographic distribution – though this may be harder to achieve in Eastern Europe.

Retrospectively, the declining participation among stations is no surprise. Jakob Hemmer died unexpectedly in 1790 without designating a successor (Cassidy, 1985, p. 19): the impetus of the SMP's project had thus died with its leading organiser. Furthermore, what had been difficult obstacles to overcome up until then, such as the shipment of fragile instruments, personal rivalries, and poor communication, became compounded by the rapidly changing political situation in Europe. Hemmer himself had complained about the extreme difficulty in delivering instruments to the stations, which sometimes arrived vitiated and in pieces due in part to the negligence of custom officials, especially in France (*Ephemerides*, 1983, p. 45). It is no wonder that most of the stations that delivered data for the entire twelve years were in Palatinate-Bavaria. In 1792, France declared war against Austria and started its eastward expansion, occupying Mannheim on its way and putting an abrupt end to the Society's activities. One publication even mentions that on 8 November 1792 the observer for the Brussels station, the Abbot Théodore

Augustin Mann, had been forced to escape Belgium because of the French invasion (*Ephemerides*, 1795, p. 112). The French Revolution undoubtedly weakened the SMP's otherwise efficient integration of the network.

490   Our inventory revealed that the availability of records is heterogeneous and depends on the station and variable under consideration. Yet, despite the few inhomogeneities highlighted above, it remains a fact that the SMP managed to integrate and coordinate the collection of meteorological data on a very large scale. Amazingly, they did it rather efficiently at a time when this sort of scientific communication was very difficult, compounded also by personal and political differences. It is only due to the relatively tight control of its members, long-term central coordination, and perseverance of the SMP's founder, Hemmer,

495 that this project lasted as long as it did. Thanks to the efforts of the Society's member stations, today we have access to unique climate data for the late 18th century.

     Indeed, keeping in mind the usual degree of uncertainty associated with early instrumental measurements, the temperature and pressure SMP data restored in this study are in usable condition. Their overall quality is good, likely due to the SMP's insistence on the use and free dispatch of standardised, comparable instruments. Nevertheless, the series are not free of errors

500 (some more than others). A number of SMP temperature series occasionally showed evidence of the instrument being badly exposed, either indoors or in the sunlight. Some of the pressure series needed to be homogenised, and this could not be done for the Russian data. Nevertheless, the level of consistency among the SMP pressure records is remarkable if compared to similar pan-European datasets for the early instrumental period. In Brugnara et al. (2015), for instance, additional correction of up to 10 hPa were necessary before synoptic maps for the 1810s could be drawn. Suspicious values were flagged with the C3S QC

505 software, thereby providing an indication of the kind of problem at hand. The SEF files in the database furnish the necessary metadata pertaining to each measurement so that future users of this database can take into account the specific uncertainties of a given series when evaluating any results.

     Finally, the two examples of extreme weather illustrated the usefulness of the instrumental data recovered in this study. When paired with narrative sources and atmospheric dynamical information, the SMP data can provide in situ, quantitative

510 knowledge about the weather during these extreme events. The daily time scale of these measurements series is particularly important as they allow a detailed understanding of the progression and development of the event. This is especially useful for climate research because the data happen to overlap with a period in Europe's history of high climatic variability, which include a high number of outstanding weather extremes (White et al., 2018). The figures showing the maps of Kington and SMP values demonstrate another advantage of the data: they show the relative ease of producing and visualising the data spatially,

515 as opposed to the laborious hand-drawn charts of Kington.

5   Conclusions

The precise correction of pre-industrial meteorological data remains a challenge for climate research; they typically suffer from a lack of uniform procedures and protocols for their recording, meaning that the effort involved to recover, correct, and

520 study them is much greater. These reasons make the data collected by the *Societas Meteorologica Palatina* even more valuable:

their insistence on precise standardised instruments and emphasis on coordinating observations to a common plan mean that historical climatologists and data rescuers can use the database presented in this study with more confidence.

We presented a dataset that aims to uncover the historical weather data from the SMP, thereby filling a perceived gap in the research on the rescue of early instrumental observations. An assessment of the data availability in the *Ephemerides* revealed that the coverage and resolution vary significantly depending on the year, station, and parameter in question. Our inventory could be enriched and improved by focusing on specific stations or other variables, such as air moisture and rainfall. Additionally, 37 temperature and pressure records were digitised, converted, quality-controlled, homogenised where needed, and formatted into an accessible and standard ASCII format. Their quality is generally quite good in comparison to other early instrumental datasets, though specific uncertainties associated with some of the measurements generate a need for locating and exploring further details regarding the individual stations. Two case studies highlighted the usefulness of the data when compared to existing research and historical documentary sources. These records have a number of different possible applications for climate research, including their assimilation in reanalysis datasets for use in regional dynamical downscaling studies and their use in the statistical reconstruction of daily fields over Europe with the analog method. Their usefulness may depend on the specific goals of the study being undertaken, including which focus area and variables are of interest.

The potential here is large not only for climate science but for historians as well. The generated time series are of sufficient quality to allow historians to inspect the impact of specific periods of extreme weather on historical events. The weather information uncovered here could be used to study social developments that might have depended on day-to-day weather, or indeed on health and agriculture. More specifically, one could trace the daily impact of weather during this period on political and economic affairs, military operations, or any travels and expeditions. Databases of the type presented in our study will certainly benefit from the deep collaboration between historians and scientists.

Code and data availability. The inventory, data and relevant code related to this article are available as supplement.

Author contributions. DP created the inventory, processed the data, performed the analysis, created the figures, and drafted the manuscript. YB oversaw the digitisation and collection of measurements, as well as verified the data rescue process. SJ, AP, and RP contributed a number of digitised series and, together with CR, they provided critical feedback to improve the final version of the manuscript. SB helped shape the research and supervised the project.

Competing interests. The authors declare that they have no conflict of interest.

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