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RESEARCH ARTICLE

The longest one-man weather chronicle (1721–1786) by Gottfried Reyger for Gdańsk, Poland as a source for improved understanding of past climate variability

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In the paper we focus on the notes of botanist and meteorologist Gottfried Reyger on the weather conditions in Gdańsk, Poland. In our estimation, this chronicle, covering the period from December 1721 to June 1786 (the longest weather chronicle recorded by a single person), is a reliable source of information with the potential to contribute to the understanding of climate variability in 18th-century Gdańsk, the significant old Hanseatic city in northern Poland. The temperature and precipitation series for the period 1721–1786 were indexed against contemporary conditions using the calculated percentages of cold, normal and warm decades. The climate in the 18th century in Gdańsk was colder than nowadays; the springs were much cooler, as were the winters, while the summers were warmer. A few relatively cold periods and several warm periods were identified. The first half of the analysed period was very humid, whereas the second was quite dry. The reconstructed indexed data series were compared to annual and seasonal mean values of air temperature and precipitation derived from regular instrumental observations made in Gdańsk since 1739. The linear regression method was applied to calibrate the reconstructed index series against anomalies from the 1961–1990 average. The correlation coefficient, standard error of estimate and the root-mean-square error statistics were used to diagnose the quality of calibration and verification. The highest correlation between the temperature indices and the observational series was found for winter. The reconstructed series for precipitation has a smaller variability than in reality. The reconstructed values for the years prior to 1739 indicate cold years for 1725–1732 and a wet period in the 1730s.

KEYWORDS
18th century, climate variability, documentary data, Gdańsk, Gottfried Reyger, historical climatology, Poland

1 | INTRODUCTION

The main task of chroniclers is to describe events factually and in chronological order. These events concern the political and social life of countries, cities, organizations and other important items and are written down on an ongoing basis (typical for diaries or journals) or they are recreated on the basis of messages, descriptions, memoirs or other sources (typical for chronicles). Both diaries and chronicles often contain some additional information, such as analyses or comments of described events and phenomena, and are sometimes very personal.

Historical climatology analyses those chronicle notes which regard not only the social and economic life of a particular city or country, but also the most important weather events. The journals describe general weather conditions for particular days, months and seasons in great detail or contain descriptions of some extreme weather events. It turns out that such detailed notes may significantly contribute to reconstruction of the variability of numerous and varied climate elements.

Weather chronicles and journals belong to what are known as "documentary sources" which also include private correspondence, newspapers and journals, pictorial evidence, books or reports by official institutions, among many others. All kinds of documentary sources and their role in climatology were described in great detail by Brázdil *et al*. (2010). Alongside their undeniable advantages, weather chronicles and journals have a few limitations which are, nonetheless, crucial. First, weather conditions are perceived subjectively by a chronicler. What is more, as a chronicler ages, his or her subjectivity may deepen as, for example, older people perceive thermal discomfort differently than the young. Estimation of the intensity of a given extreme weather event may also be affected by the quality of the data obtained. Another predominant practice is to refer to only one spatially limited place, which is understandable because in the past it was difficult to gather information for large areas.

On the other hand, chroniclers who focused on a single city they were familiar with were able not only to describe local weather conditions but also to capture properly the influence which they had on the social and economic development of their particular city. Brázdil *et al*. (2010) emphasized that all the extreme weather events were precisely dated, and this is very important in the context of historical climatology research. What is more, the quality of the notes written by the same person for many years can be assessed more easily and their context may be understood better.

Despite the aforementioned disadvantages and limitations, the great importance of chronicles, journals and diaries as well as many other documentary sources in the process of climate reconstruction has been emphasized widely in the literature (Pfister *et al*., 1994; Glaser *et al*., 1999; Brázdil *et al*., 2010). Works in the field of historical climatology on documentary-based climate reconstructions involved the use of journals, chronicles, annals and calendars (e.g., Brázdil *et al*., 2008; Brázdil *et al*., 2013), information on the dates of freezing of waterways and harbours (e.g., Yoo and D'Odorico, 2002; Jevrejeva *et al*., 2004), harvest calendars (e.g., Nordli, 2001) or grape harvest dates (Chuine *et al*., 2004; Maurer *et al*., 2011). The key role of documentary sources such as weather chronicles and journals was probably most appreciated during the implementation of the EU Millennium project aimed at evaluating if the magnitude and rate of 20th-century climate change exceeded the natural variability of the European climate over the last millennium by combining existing instrumental data with documentary, biological and sedimentary archives (Brázdil *et al*., 2010; Dobrovolný *et al*., 2010). Recently, promising results of indexing precipitation from documentary sources for Czech Lands were obtained by Dobrovolný *et al*. (2015) or temperature for southwest Spain by Fernández-Fernández *et al*. (2017).

A comprehensive review of numerous Polish efforts devoted to the long-term variability of climatic conditions in Poland in relation to Europe-wide conditions was presented by Przybylak *et al*. (2010). The greater part of them analysed instrumental series (Limanówka *et al*., 2012; Graczyk *et al*., 2016; Owczarek and Filipiak, 2016, and many others). Polish experience in describing the climate of Poland based on proxy data is rather limited. The greater proportion of papers deals with documentary evidence (Sadowski, 1991; Bokwa *et al*., 2001; Nowosad *et al*., 2007; Przybylak and Marciniak, 2010). Some new approaches have been applied in the 21st century (Cedro, 2004; Przybylak *et al*., 2005; Larocque-Tobler *et al*., 2015, and others). A summary of recent developments in changes in climate and environment in the Baltic Sea Basin was presented by Niedźwiedź *et al*. (2015).

In this paper data on weather conditions derived from the 1721–1786 journals by Gottfried Reyger was used in order to reconstruct temperature and precipitation conditions in Gdańsk. Gottfried Reyger was a researcher studying Gdańsk, one of the most important Hanseatic cities on the coast of the Baltic Sea. He was a very diligent chronicler and conducted weather observations from his early youth until the end of his long life. He created what is probably the world's longest weather chronicle written by a single writer.

A short biography of Gottfried Reyger and a description of the city of Gdańsk he operated in are presented in the following section of the paper. The section 2 describes the research material and methods used to transfer the qualitative data into an indexed data series of temperature and precipitation sums. The next part of the research involved analysing the temporal variability of the obtained indices. Subsequent section describes the calibration and verification of the indexed data series using instrumental measurements. The last part of the paper includes a qualitative reconstruction of the above-mentioned weather elements, discussion and conclusions.

1.1 | Gottfried Reyger and his activity in 18th-century Gdańsk

Gottfried Reyger (1704–1788) was born in Gdańsk into a Protestant merchant family. His scientific interests regarded not only meteorological observations, but other scientific fields also—especially natural sciences, geography and astronomy. He is best known as author of the scientific studies on flora in Gdańsk and its vicinity *Tentamen florae Gedanensis methodo sexuali adcomodatae*, published in Gdańsk in the period 1764–1766 (Aleksandrowicz, 1988; Drygas, 1997).

Gottfried Reyger started his meteorological observations in Gdańsk in December 1721. In the years 1720–1722 he was a student of Gdańsk Academic Gymnasium and then, according to previous findings, during the period 1722–1726 he is believed to have been a law student at Halle University

(Aleksandrowicz, 1988; Drygas, 1997). However, at the same time he was systematically observing the weather in Gdańsk. In his *Die Beschaffenheit der Witterung in Danzig* we find an explanation of that fact—Reyger claims that he spent some time out of Gdańsk, but not sooner than during the period from 1726 to 1729. That is why his weather descriptions for these particular years are less accurate—they were prepared on the basis of letters he was receiving from Gdańsk at that time. It is also probable that during the discussed period he was using the assistance of his colleague who was staying in Gdańsk at that time and taking notes for him. Although this assumption has never been confirmed, it has been proven that Reyger made a journey across Poland in 1735 and that this did not lead to any gaps in the observation data for Gdańsk. Nonetheless, it is unlikely that he used any weather descriptions for the period of 1722–1726 unknown to present scientists. In any case, the systematic observations of the weather in Gdańsk started in 1721 and were carried out until mid-1786. Gottfried Reyger used them mainly to study how climate affects the development of plants. The outcomes of his studies were published in "Die Beschaffenheit der Witterung in Danzig vom Jahr 1722 bis 1769 beobachtet nach ihren Veränderungen und Ursachen erwogen" (Reyger, 1770) and in "Die Beschaffenheit der Witterung in Danzig. Zweyter Theil vom Jahr 1770 bis 1786, nebst Zustätzen zur Danziger Flora" (Reyger, 1788).

Gdańsk has always played an important economic role in the southern Baltic region. The activity of the great harbour enabled 18th-century Gdańsk to be a rich and powerful city. It was densely inhabited by about 60,000 people, and with suburbs and surroundings this number increased to almost 80,000 people (Baszanowski, 1995). However, the population fluctuated considerably due to epidemics (e.g., the number of deaths during the Great Plague in 1709/1710 reached over 32,000) and wars (e.g., the siege of the city by Russian troops in 1734).

The strict control of city finances allowed not only the costs of social support to the poorest citizens of the city to be covered (e.g., funding for food purchases during the mentioned Great Plague), but also education and science to be considerably subsidized. Thus, sources from as early as the 16th century demonstrate a very strong interest on the part of the inhabitants of Gdańsk in the problems of observation of weather and sea conditions and their impact on economic and social life. In 1655, the first regular observations of weather were started by mathematician Friedrich Büthner, and they were conducted continuously until the end of the 17th century. However, our knowledge on their details is still fragmentary. The 18th century (the Enlightenment) brought Gdańsk a boom in interest in the problems of measurement and observation of meteorological phenomena and in their impact on various fields of economic and social life. The climax of these events, from the viewpoint of meteorology, was the beginning by Michael Christoph Hanov, outstanding mathematician and physician (Baszanowski, 1994), of regular instrumental meteorological measurements in Gdańsk on January 1, 1739, lasting to the present day, as well as the establishment of the Naturforschende Gesellschaft in Danzig (Gdańsk Nature Research Society) on November 7, 1742 (active since 1743)—an association of prominent scientific personalities of the city, including a large number of scientists interested in meteorology. Among the founders of that society was also Gottfried Reyger.

2 | DATA AND METHODS

Gottfried Reyger's descriptions published in the first volume (Reyger, 1770), covering the period from December 1721 to December 1769, usually include remarks on general weather conditions supplemented by some additional data on precipitation, air temperature, and wind direction and velocity. Reyger described the months usually in a qualitative, even aggregate, manner and very rarely in a quantitative way. His notes were very detailed and even the weather of the particular days or weeks very often was characterized. Reyger paid special attention to particularly important meteorological phenomena (heavy rain, and changes in wind direction and air temperature) and the days on which they occurred. When describing wind direction, he tried to estimate its impact on cloudiness and other weather conditions. He frequently compared adjacent months (e.g., "this month there was more sleet than last month"). There are some gaps in his observations. The descriptions for the period during which he was travelling around Europe (1726–1729) are not as detailed as the rest of his reports. However, in case of air temperature the gap is very small and is related only to a few spring months of 1728. The information on precipitation is lacking for autumns 1726–1728, spring 1728 and winter and summer 1729.

An indicative description of particular month is as follows: "… During the first four days of August 1731 there was a northern wind, cold and cloudy air. The next four days were boiling hot and rainy. From the 9th to 16th it was bright and hot and the wind was the southeasterly. Then, there were storms which made the air cooler so there were several days of moderate air temperature. But from the 23rd to the end of the month the wind changed direction to northerly and easterly and it was a bit warmer, but still there was quite a chill in the air. Generally, the whole month was very dry." (Reyger, 1770)

The more detailed information on weather conditions in Gdańsk may be found in the second part of Reyger's observations, which covers the period from the beginning of 1770 to June 1786. After Hanov's death in September 1773, Reyger, who thought of himself as a successor of Hanov's ideas and activities, started to prepare his notes much more accurately. Each season and year was widely commented and numerous comparisons with earlier years and decades were made. There were more figures, and Reyger began to quote the barometer readings systematically. Among particularly interesting information you can find precise descriptions of extreme weather phenomena, for example, heat wave in August 1781.

Reyger's notes were translated from old German very thoroughly. During the first phase of reconstruction a three-grade indexation (−1, 0, +1) of temperature and precipitation conditions in particular periods was made. Due to the detailed descriptions it was possible to prepare indexes for a 10-day-long periods (decades). It was assumed that each month was divided on three parts, two first of them lasting 10 days and the last one lasting from 8 or 9 days (in case of February) to 11 days (e.g., for January or March, etc.). The information on any extreme weather conditions (cold/dry or warm/humid) prevailing during a given decade was the basis for classifying it as thermally or precipitationally anomalous ("−1" or "+1", respectively). When there was no such data or there was a remark on relatively normal weather conditions in Reyger's notes, a given decade was classified as thermally or precipitationally normal ("0"). The indexation was made by three independent researchers (two climatologists and a historian) in relation to the current climatic conditions in Gdańsk. Then, all indexations were discussed and a final version was agreed. No more than 10% of cases were disputed.

Instead of widely used in historical climatology method of assessment of the weather conditions of particular seasons proposed by Pfister *et al*. (1994) the approach used by Fernández-Fernández *et al*. (2017) was implemented in the paper. From the decadal information the seasonal and annual percentage of cold, normal and warm decades was calculated. It was assumed that winter begins in December and finishes in February. The remainder of the seasons were determined analogically by covering three subsequent months, one after another. The years with the highest annual and seasonal percentages of cold and warm decades above the 95th percentile were indicated as the examples of the coldest and warmest years and seasons during the analysed period.

Subsequently, the series of seasonal and annual percentage of cold, normal and warm decades for particular years and seasons were then compared to annual and seasonal mean values of air temperature which had been derived from the regular instrumental observations made in Gdańsk by Michael Christian Hanov in the period of 1739–1759 and by Johann Eilhard Reinick during the years 1760–1785 (from 1760 onwards Hanov measured the elements twice a day, which influenced the quality of data). In case of precipitation the period was 1739–1772 and the entire volume of measurements came from Hanov's observations. Both series, after a tedious phase of verification and digitisation, were homogenized and are now a composite of long-term climatic series for Gdańsk, reconstructing the variability of air temperature, atmospheric pressure and precipitation in the city since 1739.

The overlapping period for both elements was divided into calibration and verification periods. It was not possible to find the same periods for temperature and precipitation as the instrumental precipitation series is shorter. For both elements the periods with the considerably strongest relationship between the variables were selected. Prior to calculations, each series was standardized by subtracting its mean and dividing by its standard deviation.

The linear regression method was applied to calibrate the reconstructed temperature and precipitation index series against the anomalies from the 1961–1990 average. Instrumental series were used as the predictand, while reconstructed index data were used as the predictor. The correlation coefficient (r), standard error (SE) of estimate and the root-mean-square error (RMSE) statistics were used to diagnose the quality of calibration and verification. In order to analyse the climatic conditions in Gdańsk during the above-mentioned period, the standard climatological methods were used. Statistical significance was verified using the t-Student test at a significance level of $1-\alpha = 0.95$.

3 | RESULTS

3.1 | Air temperature

The typical year in the 18th century was slightly colder than those occurring during the reference current climatic period (Figure 1). The average percentage of cold decades during the year reached almost 35%, whereas in the case of warm weeks it was only 27%. Among the years with the highest number of cold decades were 1740, 1771, 1777, 1726 and 1785 (Table 1). In the case of 1740 almost 64% of decades were classified as cold periods. The remaining indicated years were also much harsher than usually, the percentage of cold decades exceeded the 95th percentile. Several longer cold periods can be distinguished: 1729–1732, 1739–1742, 1750–1751, 1762–1765, 1774–1777 and the first half of the 1780s when analysing the course of the annual percentages of cold decades. Conversely, it seems that 1759, 1735, 1757 and 1779 were among the warmest years of the analysed period. In 1759 more than 50% of decades were classified as the warm ones. Almost 70% of decades in 1752 did not differ considerably from the climatological norm 1961–1990. Such a high percentage of normal decades was associated with a particularly low number of cold ones.

The situation for individual seasons was differentiated. The seasonal percentages of cold, normal and warm decades for winter were almost the same as for the year (Figure 2). Thus, we can assume that winters in the 18th century in Gdańsk were slightly colder than in present times. The winter of 1729 was particularly cold, none of the decades was classified as a warm or even normal period. After a relatively

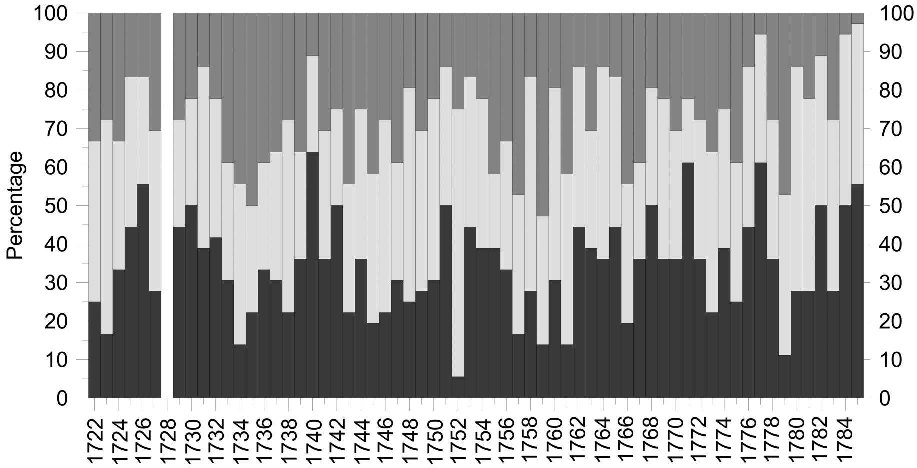

FIGURE 1 The annual percentage of cold (dark grey bars), normal (light grey bars) and warm (medium grey bars) decades in Gdańsk in the period 1722–1785

cold period between 1726 (very cold winter) and 1731, the temperature stabilized until the next cold weather event in 1740. In 1734 the highest percentage of warm decades during winter was recorded, none of cold decades was then registered. Then, in the 1740s and early 1750s the temperature started to grow. In 1750, 1756 and 1761 warm decades considerably prevailed (Table 1). In 1768 a very cold winter occurred again and after a few years in the late 1770s and early 1780s there were cold winters recorded again. The last winter during which the only warm decades were registered occurred in 1779.

More than 45% of the decades during spring were estimated as cold. Thus, spring was considerably colder than in present times, except for the period of 1732–1738 (Figure 2). Springs of the periods 1739–1749 and 1760–1772 and of the first half of the 1780s were especially cold. In 1729, 1740 and 1785 all decades were classified as cold ones (Table 1). The highest percentage of warm decades occurred in 1735. Summers were a bit warmer in the past as warm decades prevailed (Figure 2). The warm decades constituted 34% while in the case of cold periods it was 25%. Some symptoms of cooling were recorded in the period 1753–1755 and then from 1762 the cooling was quite intense until 1772. In 1753 the whole summer was very cold, the high percentage of cold decades was also noted in 1726 and 1732 (Table 1). The summer of 1759 was classified as a season with the highest percentage of warm decades (100%), such periods were also very frequent in the summers of 1745 and 1757. As for the autumn, the percentage of cold and warm decades is almost equal (32% of cold decades to 30% of warm ones). After a relatively cold beginning of the 1730s and a very cold autumn of 1751, there were two decades of relatively warm autumns and then in the 1770 this season started to be cold again (Figure 2). In 1774 the highest percentage of cold decades occurred (Table 1). Conversely, the autumns of 1729 and 1767 were identified among those with the most frequent warm decades (almost 80% of decades were warm). Additionally, during seven autumns no cold decades occurred.

The analysis of temperature conditions in particular months (Table 2) has shown that all spring months, in particular April, were considerably colder than today. The percentage of colder temperature conditions was at least twice higher than the frequency of warmer temperatures at that time. In March there was only 12% of warm decades whereas the percentages of cold and normal decades were equal about 44%. Besides the above-mentioned spring months, the months from October to January were also a bit colder than in present times. July, August and September were slightly warmer than nowadays. In February and June the percentages of warm and cold decades was almost equal, in February it was even the same as in the normal cases. In July the total number of thermally normal cases almost equalled the total number of thermally abnormal ones, so it

TABLE 1 Years and seasons with the highest percentages of cold, normal and warm decades (values above the 95th percentile) in Gdańsk in the period 1721–1786

Season	The years with the greatest percentage of		
	Cold decades	Normal decades	Warm decades
Year	1740, 1771, 1777	1752, 1780	1759, 1735, 1757, 1779
DJF	1729, 1726, 1740, 1768	1752, 1753, 1766	1734
MAM	1729, 1740, 1785		1735
JJA	1753, 1726, 1732	1738, 1760, 1729	1759, 1745, 1757
SON	1774, 1751	1746	1729, 1767

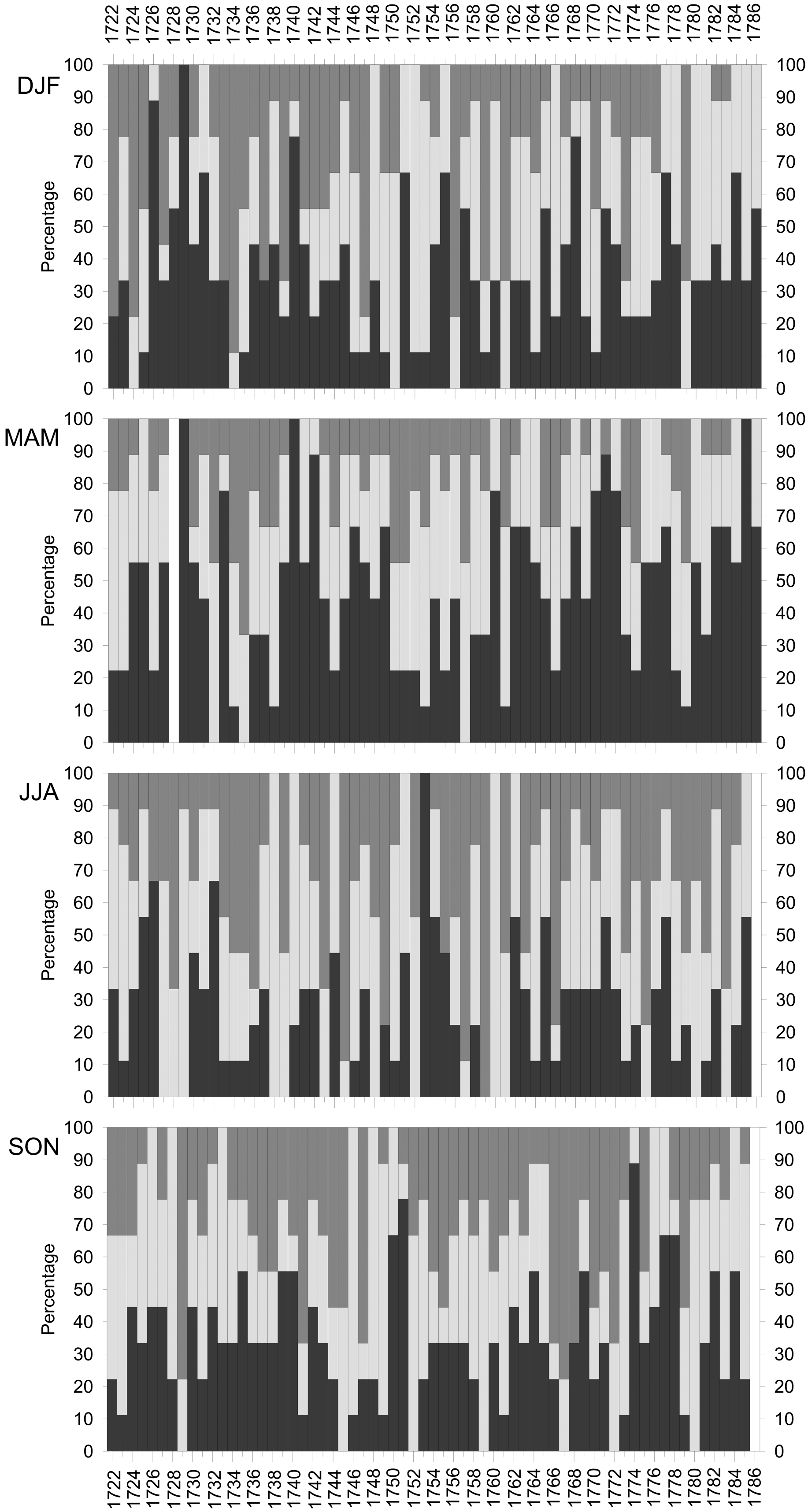

FIGURE 2 The seasonal percentages of cold (dark grey bars), normal (light grey bars) and warm (medium grey bars) decades (DJF, winter; MAM, spring; JJA, summer; SON, autumn) in Gdańsk in the period 1722–1785 (1786 for DJF and MAM)

TABLE 2 The average monthly percentages of cold, normal and warm decades in Gdańsk in the period 1721–1786

Weeks	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cold	39.9	33.2	44.5	47.9	46.6	31.3	18.2	26.0	26.7	35.1	34.9	32.0
Normal	36.3	32.6	43.5	31.3	35.1	36.4	46.9	38.5	40.3	35.1	40.6	44.3
Warm	23.8	34.2	12.0	20.8	18.3	32.3	34.9	35.4	33.0	29.8	24.5	23.7

can be stated that this month was thermally stable. A high percentage of normal decades, significantly exceeding 40%, occurred also in December and March.

3.2 | Precipitation

During the early years of the analysed period (Figure 3) a slight increase in the percentage of dry decades was observed. Then, in the 1730s and the first half of 1740s with much frequent humid decades than the present norm of precipitation prevailed. During this period there were a few very humid years (1732–1733, 1738–1740 and 1744–1745) (Table 3). The year 1732 was particularly humid as almost 70% of decades throughout this particular year were humid. In the 1730s there was also a high percentage of normal decades. A short period since 1746 had relatively stable precipitation conditions, similar to those observed today. However, 1748 was very dry. The second half of the 1750s and the 1760s were clearly drier than the modern norm with the frequent dry years (1761–1762 and 1765–1766). The 1770 was very humid and then the year-to-year variability of precipitation considerably increased. After humid years, dry ones occurred, for example, 1771–1773 and during the subsequent 1774 more than 50% of decades were classified as humid ones. The next humid year, 1778, was followed by a dry 1779 and a humid 1780. Again, the first half of the 1780s was quite humid. The average annual percentage of humid, normal and dry decades was equal 38, 30 and 32%, respectively, which indicates that the 18th century was slightly more humid than present years.

Winters were wetter than nowadays. Seasons in the period of 1722–1741 were humid (Figure 4). In the mid-1730s a few seasons with particularly frequent precipitationally normal decades occurred. The 1740s were a dry decade, with the exception of the winter of 1747 (Table 3) when there was no dry season. During the next 10 years precipitation amount was strongly differentiated—after an extremely dry winter in 1751, there were very humid and humid ones as well as very dry and dry winter seasons. In the 1760s precipitation conditions became more stable and then, after 1770, humid winters started to prevail.

In turn, springs were only slightly drier in the historical period, with a percentage of dry decades only 1% greater than in the case of humid decades (the rate 35–34%). Springs were dry during the 1720s and then, from 1729, there were almost 20 years of high spring precipitation (Figure 4). However, at that time, there was also one dry season—two thirds of decades in 1736 were estimated as dry. The highest seasonal precipitation sums were recorded in 1745—during this year nearly 80% of decades were classified as humid (Table 3). Starting from the late 1740s and early 1750s the precipitation tendency began to change. As a result, there were mainly dry seasons recorded until the end of the 1760s with the greatest percentage of dry periods in 1766. The last decade of the analysed period was exceptionally stable, with only one very humid spring of 1780.

Similarly to winters, summers and autumns were wetter than today. The 1720s were a decade when humid summers (particularly 1725 with almost 90% of wet decades) alternated with very dry ones (1724 and 1728). During the period of 1730–1745 there were many humid summer seasons

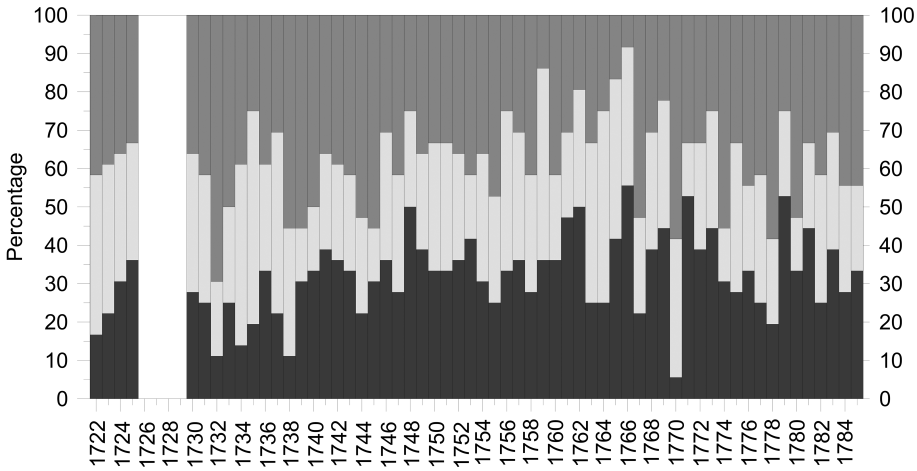

FIGURE 3 The annual percentage of dry (dark grey bars), normal (light grey bars) and humid (medium grey bars) decades in Gdańsk in the period 1722–1785

TABLE 3 Years and seasons with the highest percentages of dry, normal and humid decades (values above the 95th percentile) in Gdańsk in the period 1721–1786

	The years with the greatest percentage of		
Season	**Dry decades**	**Normal decades**	**Humid decades**
Year	1766, 1771, 1779	1735, 1759, 1764	1732, 1778
DJF	1751, 1748, 1757, 1779	1735, 1752, 1765, 1766	1774, 1747, 1776
MAM	1766, 1760, 1769, 1774	1727, 1735, 1750, 1778	1780, 1740, 1745
JJA	1728, 1762, 1757, 1761	1766, 1734, 1770, 1775	1744, 1725, 1732
SON	1766, 1742, 1773, 1780	1764, 1735	1767, 1774, 1778

(Figure 4). In 1732 there was again almost 90% of humid decades during this year's summer, in 1744 it was even more—all summer decades were classified as humid ones (Table 3). After this wetter period, from 1746 to 1762 summers were mostly dry and in the mid- and end of 1760s precipitation sums were relatively stable. The percentage of dry decades during the summers of 1757, 1761 and 1762 exceeded 70%, in case of 1762 it was even nearly 90%. Then number of anomalous decades started to increase considerably thus the pluvial conditions of summer seasons were differentiated, sometimes year by year.

The average percentage of humid decades for autumn is slightly greater than in case of other seasons, we can observe the more frequent occurrence of humid periods exceeding 40% whereas in case of dry decades it is only 30%. After the relatively stable 1720s (including the gap of 1726–1728), the next 10 years were rich in humid seasons (Figure 4). Autumns were very humid in periods 1732–1733 and 1738–1739. The 1740s were generally dry and then from 1748 a wetter period occurred which lasted until the beginning of 1760s. During the next 25 years, autumns were strongly contrasted in terms of precipitation levels. For instance, after an extremely dry autumn of 1766 (100% decades were classified as dry ones) (Table 3) there was a very humid one next year (percentage of humid decades reached almost 90%). The similar situation occurred in 1773 and 1774 when, after a dry autumn, there was a humid one. The subsequent two autumns after humid 1778 were very dry. A humid autumn occurred also in 1785.

The average percentage of decades with abnormally low precipitation (in comparison to the modern norm) was recorded only in January and during the period from March to June (Table 4). The values for June and May indicate that these months were much drier than nowadays, we can observe the percentages at the level of 44 and 42%, respectively. February, months from July to September, as well as November and December were abnormally humid. Particularly in November humid decades were very frequent, the percentage was very close to 50%, whereas in the case of dry decades it was only 21%. October was the most stable month in terms of precipitation with the ratio between the normal and anomalous events at its greatest, while August was the month with the highest number of abnormal cases (the average percentage of normal decades less than 26%).

3.3 | Calibration and verification of air temperature and precipitation series

Comparison of the temperature conditions reconstructed from Reyger's weather observations with the observational series indicates that the highest statistically significant correlation between the seasonal/annual temperature observational and reconstructed series for the whole overlapping period 1739–1785 (1876) was for winter (correlation coefficient of 0.90). For summer and spring the coefficient is 0.73 and 0.69, respectively, and for autumn is 0.74; for the annual series it is 0.75. The relationship is considerably higher in the case of the calibration period (Table 5). The reconstructed series for winter properly reflects the course of seasons with temperatures that were extremely high (1756, 1759 and 1779) or extremely low (1740, 1751 and 1755). As for spring, the reconstructed series is less correlated with the observational series in the period 1747–1757. Summer temperatures of the latter decades of the analysed period are well reproduced by the reconstruction, however overestimated. For autumn, the period after 1765 is well represented. However, the reconstruction underestimates the seasons of the end of the 1740s and 1750s.

The reconstructed precipitation conditions in Gdańsk during the period of 1739–1772 are comparable to the annual and seasonal precipitation sums measured by Hanov. The correlation coefficient for the annual values is 0.70, and for the warm months, when the share of precipitation of convective origin is even higher, reaching 0.79 (summer) and 0.78 (autumn) (Table 6). For spring the coefficient is 0.68 and, finally, for winter the relationship is considerably lower (0.56). The methodology applied by Hanov is difficult to reconstruct and that is why assessing the real precipitation sums for this season is very problematic (Filipiak, 2007). The analysed correlations are statistically significant.

The statistics obtained for the calibration and verification periods indicate that the linear regression model has potential for use in reconstruction. The nature of long-term variability in observational and reconstructed series is similar. However, there are some disadvantages of the performed reconstruction. As can be seen from Tables 5 and 6, the reconstructed series can in some selected periods explain only part of the temperature and precipitation variability. In the case of temperature the annual values are overestimated in the period between the mid-1740s and mid-1750s, and in

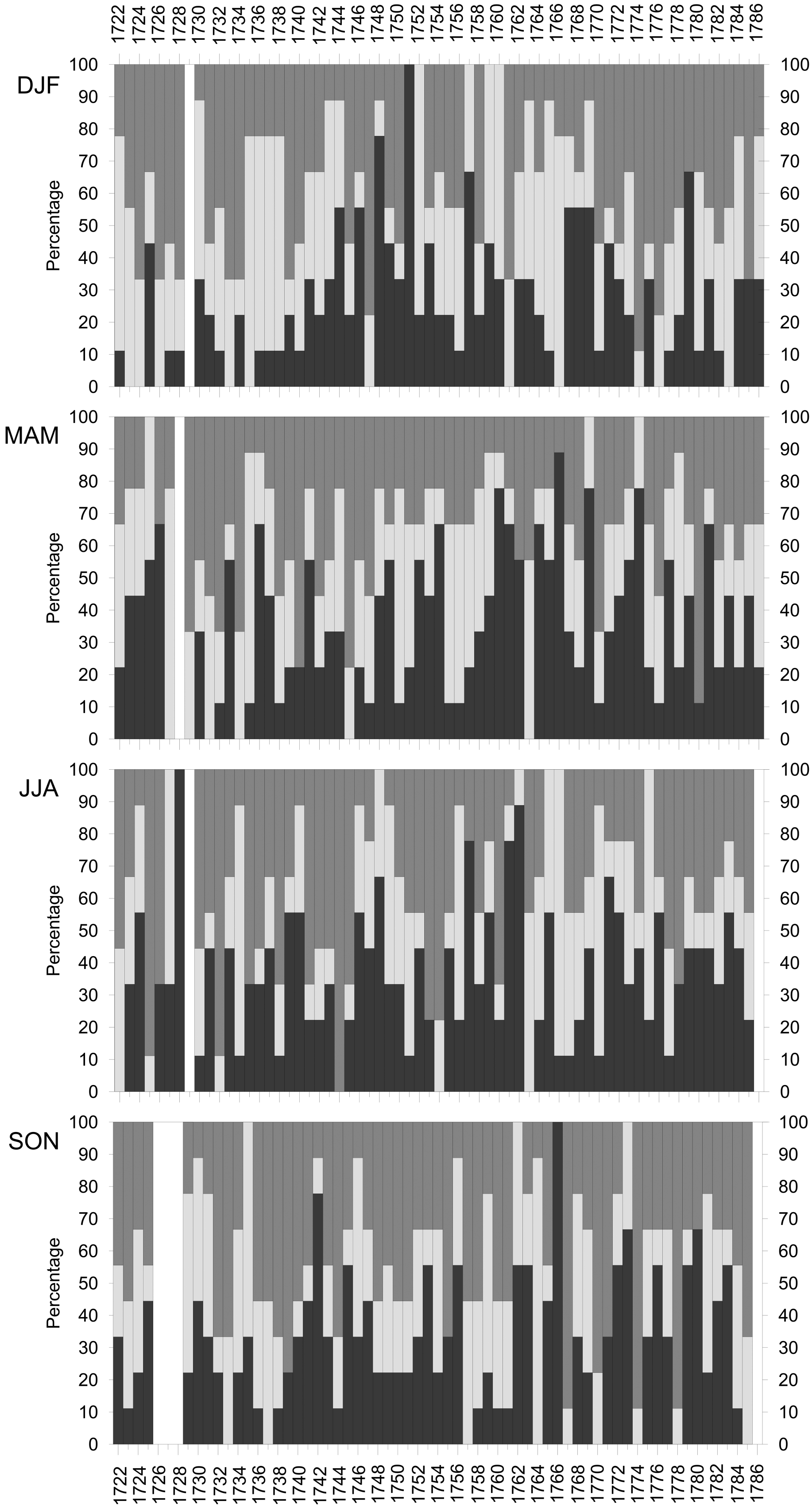

FIGURE 4 The seasonal percentages of dry (dark grey bars), normal (light grey bars) and humid (medium grey bars) decades (DJF, winter; MAM, spring; JJA, summer; SON, autumn) in Gdańsk in the period 1721–1785 (1786 for DJF and MAM)

TABLE 4 The average monthly percentages of dry, normal and humid decades in Gdańsk in the period 1721–1786

Weeks	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry	33.3	24.1	27.1	38.2	41.7	43.5	32.4	30.3	33.7	35.5	21.3	21.9
Normal	37.5	31.4	29.3	30.9	29.7	28.8	27.1	25.5	27.7	28.4	29.5	36.4
Wet	29.2	44.5	43.6	30.9	28.6	27.7	40.4	44.1	38.6	36.1	49.2	41.7

TABLE 5 Statistics of calibration and verification periods for temperature (standardized series)

	Calibration period		Verification period	
Season	***r***	**SE (°C)**	***r***	**RMSE (°C)**
DJF	0.97	0.24	0.89	0.77
MAM	0.88	0.34	0.61	1.39
JJA	0.85	0.39	0.67	0.92
SON	0.83	0.35	0.73	0.83
Year	0.91	0.09	0.67	0.65

r = the correlation coefficient; RMSE = root-mean-square error; SE = standard error of estimate.

TABLE 6 Statistics of calibration and verification periods for precipitation (standardized series)

	Calibration period		Verification period	
Season	***r***	**SE (mm)**	***r***	**RMSE (mm)**
DJF	0.74	11.5	0.12	42.7
MAM	0.76	10.4	0.61	20.4
JJA	0.86	12.7	0.72	31.0
SON	0.89	6.5	0.73	39.6
Year	0.74	49.4	0.59	57.0

r = correlation coefficient; RMSE = root-mean-square error; SE = standard error of estimate.

the mid-1760s (Figure 5). Among the seasons, the most considerable inconsistencies in both series occurred generally in spring (in the 1950s and 1960s of the 18th century) and autumn (in the period from the mid-1740s to the 1760s). The best fit of the reconstructed series to the measurement series occurs in winter (Figure 6).

One characteristic feature of the precipitation series reconstructed on the basis of the model is also a slightly smaller variability than in reality (Figures 7 and 8). Winter shows a poor fit—the reconstructed series visibly overestimated the values measured. The variance reproduced in the reconstructed series is highest in autumn and summer.

4 | DISCUSSION

The analysis of temperature reconstruction for the period of 1721–1786 based on the indexation of the Reyger's chronicles shows that thermal conditions in Gdańsk slightly differ when compared to the rest of Poland, where, winters were clearly colder in the period of 1721–1750 (Przybylak *et al.*, 2005), as well as in the remaining years of the analysed period Przybylak (2011). However, the data for Gdańsk indicate that the city's thermal conditions were similar to those in the western part of the Baltic Sea where, according to the sea ice index, ice conditions were the mildest in the discussed period; in fact this period had the mildest ice conditions of the entire three hundred years of the 16th–18th centuries (Koslowski and Glaser, 1999). This means that winters must have been warm, too. There are also

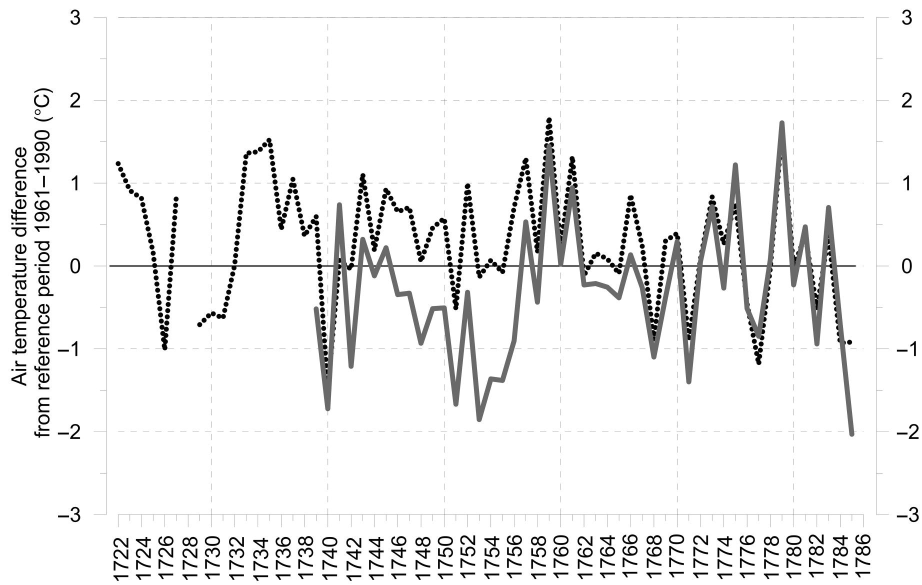

FIGURE 5 Annual air temperature reconstruction for Gdańsk for the period 1722–1785 presented in the context of observational series, 1739–1785. Both series are expressed as anomalies from reference period 1961–1990. Solid line shows observational data; dotted line shows reconstructed series

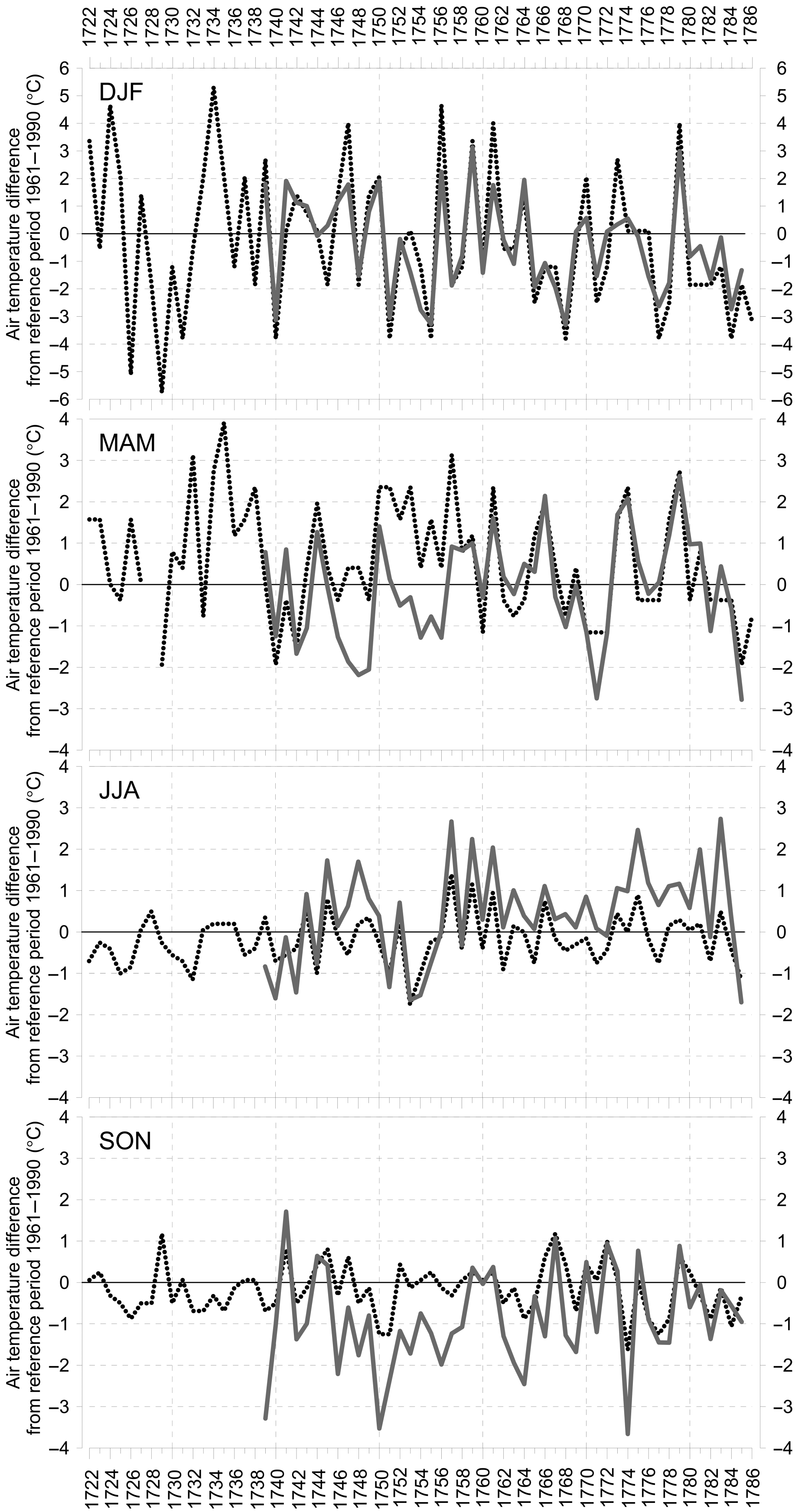

FIGURE 6 Seasonal air temperature reconstructions (DJF, winter; MAM, spring; JJA, summer; SON, autumn) for Gdańsk for the period 1722–1785 (1786 for DJF and MAM) presented in the context of observational series, 1739–1785. Both series are expressed as anomalies from reference period 1961–1990. Solid lines show observational data; dotted lines show reconstructed series. Note the different *Y*-axis scale for winter

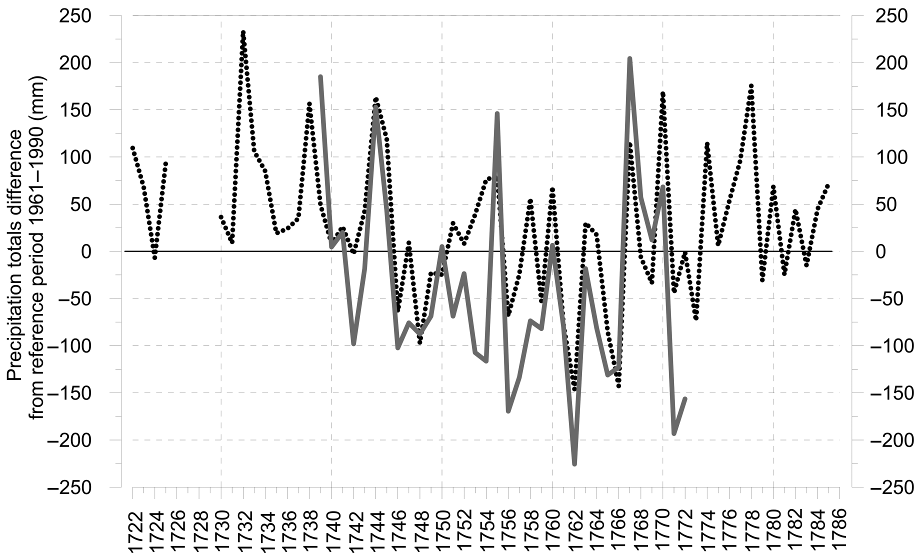

FIGURE 7 Annual precipitation reconstruction for Gdańsk for the period 1722–1785 presented in the context of observational series, 1739–1772. Both series are expressed as anomalies from reference period 1961–1990. Solid line shows observational data; dotted line shows reconstructed series

similarities between reconstructions of summer thermal conditions for Gdańsk (Figure 6), the Polish lowlands (Przybylak *et al.*, 2005) and the Tatra Mountains (Niedźwiedź, 2004), although in the mountains the temperature was slightly higher than the today's norm.

It is worth mentioning that during the period from 1501 to 1840 analysed by Przybylak *et al.* (2005) summer seasons were colder only from 1731 to 1750 and, according to the newer and more complete reconstruction, also in the period of 1761–1770 (Przybylak, 2011). Some authors (Wallen, 1953; Bergström and Moberg, 2002) who analysed instrumental data obtained in southern Sweden (Uppsala and Stockholm) claim that the southern part of the Baltic Sea basin was relatively warmer in summer in the 18th century and at the beginning of the 19th century.

However, the warming described by aforementioned authors was not confirmed by any indirect sources (proxy) dated back to the first half of the 18th century (sowing calendars of Scandinavian farmers, Nordli, 2001). The fact that there were colder years in Fennoscandia in the 18th century was also confirmed by some dendrochronological analysis (Gouirand *et al.*, 2008). It was partly confirmed by Holopainen (2006), who calculated mean temperature anomalies for a 30-year period for southwest Finland. The period 1751–1780 was characterized by cold winters (anomaly of −0.76 °C with respect to 1961–1990), springs (−0.53°) and autumns (−0.23 °C), as well as cold years (anomaly of −0.24°). Summer seasons were warmer than in the period 1961–1990 (anomaly of +0.43 °C). Only the 60s were particularly warm in southwest Finland. The same author reconstructing spring temperatures (February–June) through multiproxy data and instrumentally observed temperatures for southwest Finland from 1750 revealed the occurrence of very cold springs in the period 1750–1790, with particularly cold seasons in the 80s of the 18th century. Przybylak *et al.* (2014), when analysing air temperature changes in the city of Żagań, SW Poland, identified that the mean annual air temperature in the 80s and the beginning of the 90s of the 18th century was about 0.8 °C lower than for the period 1981–2010. It was particularly cold in Żagań in the subperiod 1784–1788, probably as a result of the eruption of the Laki volcano in Iceland in 1783/1784. In Gdańsk we can also observe the occurrence of a very cold winter and spring in 1784. In both locations 1785 was very cold, which was most probably influenced by the Laki eruption in Iceland (however, D'Arrigo *et al.*, 2011 suggested the cooling was a result of combined activity of teleconnection patterns North Atlantic Oscillation [NAO] and El Niño–Southern Oscillation [ENSO]).

Unfortunately, there is a shortage of sources which can be used to assess precipitation conditions in Gdańsk in the analysed period in relation to the regional scale. The number of precipitation series for Europe starting in the first decade of the 18th century is very small (Jones, 2001). In the Baltic Sea region precipitation was measured only in Lund, and the measurement started in the late 1740s. The data obtained in Lund indicate that in the 1750s and 1760s there were more relatively dry summers (Jones, 2001). The analysis presented herein confirms that claim. However, in Gdańsk the 1760s were drier than the modern norm while in Lund it was the 1750s which were drier.

A detailed analysis of drought occurrence in southeastern Sweden in the period of 1650–2002 was made by Seftigen *et al.* (2013) using dendrochronological methods. The author applied the commonly used standardized precipitation index (SPI) in order to estimate total precipitation for June and July. One of the most significant findings resulting from this reconstruction was that a 50-year very humid period

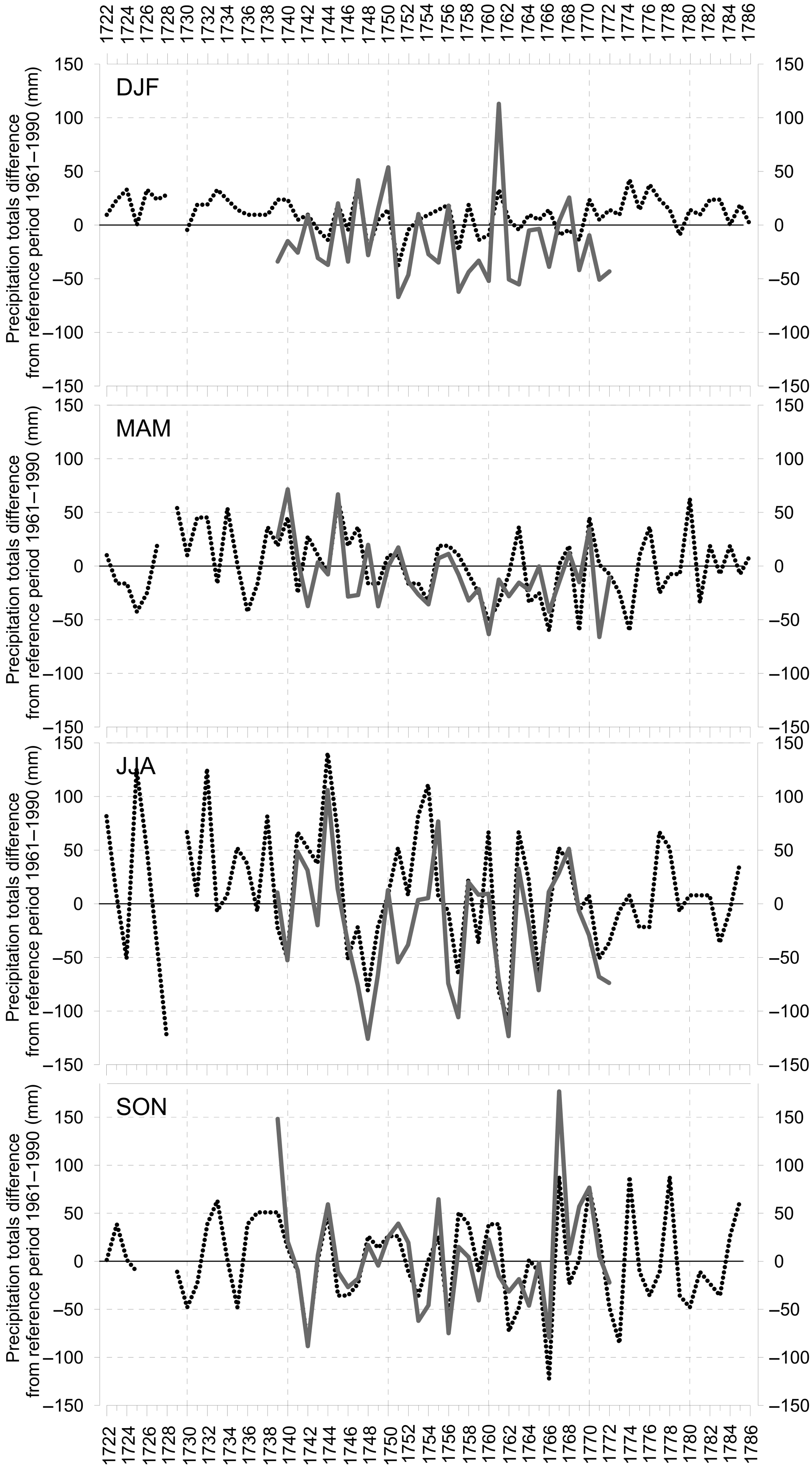

FIGURE 8 Seasonal precipitation reconstructions (DJF, winter; MAM, spring; JJA, summer; SON, autumn) for Gdańsk for the period 1722–1785 (1786 for DJF and MAM) presented in the context of observational series, 1739–1772. Both series are expressed as anomalies from reference period 1961–1990. Solid lines show observational data; dotted lines show reconstructed series

(beginning in the second half of the 1720s) was identified. Comparison of the accumulated June and July precipitation indices for Gdańsk with the results presented by Seftigen has indicated that precipitation conditions in these two places were similar, with only few exceptions. For instance, the period of heavy rainfall in Gdańsk was limited to the early years of the 1750s, while in southeastern Sweden such a period lasted until 1761 and during the period of 1750–1761 there were seven very humid seasons. Moreover, some selected humid seasons indicated by Seftigen (1753, 1769 and 1779), have also not been confirmed. In these years in Gdańsk, June was dry. However, the year 1725 was humid in both Gdańsk and in the area analysed by the Swedish researcher. Since drought occurrence in southeastern Sweden is clearly correlated with similar phenomena occurring in other parts of Scandinavia and on the southern coast of the Baltic Sea, it seems that there is a strong connection between summer rainfall in the Baltic Sea region and the regional circulation patterns over the North Atlantic.

5 | CONCLUSIONS

Our paper addressed the potential of an historical source, the chronicle of botanist Gottfried Reyger, to describe weather conditions in the 18th century in Gdańsk, Poland. As we were in possession of notes covering an extraordinarily long period (1721–1786) authored by one man, we used the indexed data not only to compare them to the regular instrumental observations made in Gdańsk since 1739. Applying the linear regression method we calibrated the indexed series against the anomalies from the 1961–1990 average and then reconstructed annual and seasonal mean values of air temperature and precipitation also for the period not covered by the instrumental data. The highest correlation between the temperature indices and the observational series was found for winter. For precipitation, the reconstructed series displays a smaller variability than in reality.

We can assume now that 18th-century Gdańsk was colder than nowadays. Particularly springs were much cooler. Winters were only slightly colder than in present times, however a few relatively cold and several warm periods were identified. Conversely, summers were a bit warmer in the past. The first decades of the analysed period were very humid, whereas the latter ones quite dry.

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