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TEMPERATURE CHANGES IN POLAND FROM THE 16TH TO THE 20TH CENTURIES

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ABSTRACT

A standardized tree-ring width chronology of the Scots pine (*Pinus sylvestris* L.) along with different types of documentary evidence (e.g. annals, chronicles, diaries, private correspondence, records of public administration, early newspapers) have been used to reconstruct air temperature in Poland. The ground surface temperature (GST) history has been reconstructed based on the continuous temperature logs from 13 wells, using a new method developed recently by Harris and Chapman (1998; *Journal of Geophysical Research* **103**: 7371–7383) which is compared with the functional space inversion (FSI) method applied to all available Polish temperature–depth profiles analysed before.

Response function calculations conducted for trees growing in Poland (except in mountainous regions) reveal a statistically significant correlation between the annual ring widths of the Scots pine and the monthly mean air temperatures, particularly from February and March, but also from January and April. Therefore, it was only possible to reconstruct the mean January–April air temperature.

The following periods featured a warm late winter/early spring: 1530–90, 1656–70 (the warmest period), 1820–50, 1910–40, and after 1985. On the other hand, a cold January–April occurred in the following periods: 1600–50, 1760–75, 1800–15, 1880–1900, and 1950–80.

Reconstructions of thermal conditions using documentary evidence were carried out for winter (December–February) and summer (June–August) from 1501 to 1840 and, therefore, their results cannot be directly compared with reconstructions based on tree-ring widths. Winter temperatures in this period were colder than air temperature in the 20th century. On the other hand, 'historical' summers were generally warmer than those occurring in the 20th century. Such situations dominated in the 16th and 17th centuries, as well as at the turn of the 18th and 19th centuries. Throughout almost the entire period from 1501 to 1840, the thermal continentality of the climate in Poland was greater than in the 20th century.

GST reconstructions show that its average pre-instrumental level (1500–1778) is about 0.9–1.5 °C lower than the mean air temperature for the period 1951–81. Lower amplitude of GST warming (0.9 ± 0.1 °C) results from the individual and simultaneous inversions of well temperature data using the FSI method. A very good correspondence of the results has been found between series of annual mean GSTs from the FSI method and mean seasonal air temperatures reconstructed using documentary evidence. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Poland; temperature variability; proxy data; temperature reconstructions

1. INTRODUCTION

Our present knowledge concerning temperature changes in Poland for the last 500 years is somewhat piecemeal in character. It is obvious that it is best for the instrumental period. In the last decade of the

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20th century great efforts were made to obtain long-term homogeneous air temperature series. As a result, at least 10 such series are available for Poland (Górski and Marciniak, 1992; Miętus, 1996, 1998; Głowicki, 1997; Trepińska, 1997; Lorenc, 2000; Vizi *et al.*, 2000–01). The most important are those that have the longest series of data, i.e. from Warsaw (since 1779) and from Cracow (since 1792). Owing to significant spatial correlation of air temperature over the area of Poland (Kożuchowski and Żmudzka, 2003), either of these series may be used to describe air temperature changes for the country as a whole.

Knowledge about temperature changes in Poland for the pre-instrumental period is rather limited. Up to 1999 there were two basic sources of proxy data available: documentary evidence and dendrochronological data. The former are generally abundant (e.g. Sadowski, 1991; Limanówka, 2001; Przybylak *et al.*, 2004), although they are not so numerous as for countries such as China, the Czech Republic or Switzerland. However, to date the documentary evidence has very rarely been used for the reconstruction of weather and climate in Poland. In most of the extant research (e.g. Semkowicz, 1922; Polaczkówna, 1925; Maruszczak, 1991; Sadowski, 1991; Bokwa *et al.*, 2001) climatic conditions are described in a general way, most often using the frequency of occurrence of seasons (winter and summer) which were characterized by extreme weather (cold, warm, dry, wet). Recently, Michalczewski (1981) and Limanówka (2000, 2001) have carried out quantitative reconstructions of temperature changes (Warsaw, July 1760–March 1763) and climatic changes (Cracow, 1502–40) respectively, though these were spatially and temporally limited. Here, based on all available documentary evidence, we present the reconstruction of the mean 10 year winter (December–February) and summer (June–August) temperatures averaged for the whole of Poland from 1501 to 1840.

The latter (dendrochronological) source of data for the reconstruction of climate in Poland has been used more broadly in the 1990s, when a large number of regional dendrochronologies were constructed. For example, in the case of the Scots pine (*Pinus sylvestris* L.) as many as 136 such dendrochronologies are now available, covering almost the whole area of Poland (see Zielski *et al.* (2001)). These authors have also distinguished nine dendroclimatological regions in Poland (Wilczyński *et al.*, 2001: Figure 11).

To date, however, these dendrochronological data have also seldom been used for the reconstruction of climate in Poland. Only Bednarz (1996) has carried out such a reconstruction, and only for the area of Babia Góra National Park (Beskidy Mountains, southern Poland). Other studies in this area of research provide only general remarks about the climate of different parts of Poland based on correlation analysis between tree-ring growth indices and some climatic variables (e.g. Bednarz, 1984; Zielski, 1997; Krawczyk and Krąpiec, 1999; Wilczyński, 1999; Wójcik *et al.*, 1999, 2000).

More recently (since 1999), reconstructions of the ground surface temperature (GST) history for Poland using geothermal data have been undertaken. So far, three such reconstructions have been carried out: (1) for southwestern Poland (Wójcik *et al.*, 1999); (2) for northern Poland (Wójcik *et al.*, 2000); (3) for the whole area of Poland, excluding the mountains (Majorowicz *et al.*, 2001, 2004).

The main aim of this paper is to present a synthesis of the most important results of our research project concerning the reconstruction of temperature of Poland during the last 500 years based on multi-proxy (documentary, dendrochronological, and geothermal) data.

2. DATA AND METHODS

2.1. Climatological

Long-term homogeneous air temperature series from Warsaw (after Lorenc (2000)), Bydgoszcz (after Vizi *et al.* (2000–01)) and Gdańsk (after Miętus (1998)) have been taken to characterize temperature changes in Poland (Figure 1). For purposes of calibration and comparison with temperature reconstructions based on the dendrochronological data, January–April areally averaged air temperatures for Warsaw, Bydgoszcz, and Gdańsk have been calculated.

2.2. Historical

Within our research project, more than 200 historical documents of different types (e.g. annals, chronicles, diaries, private correspondence, records of public administration, early newspapers, etc.) have been used for

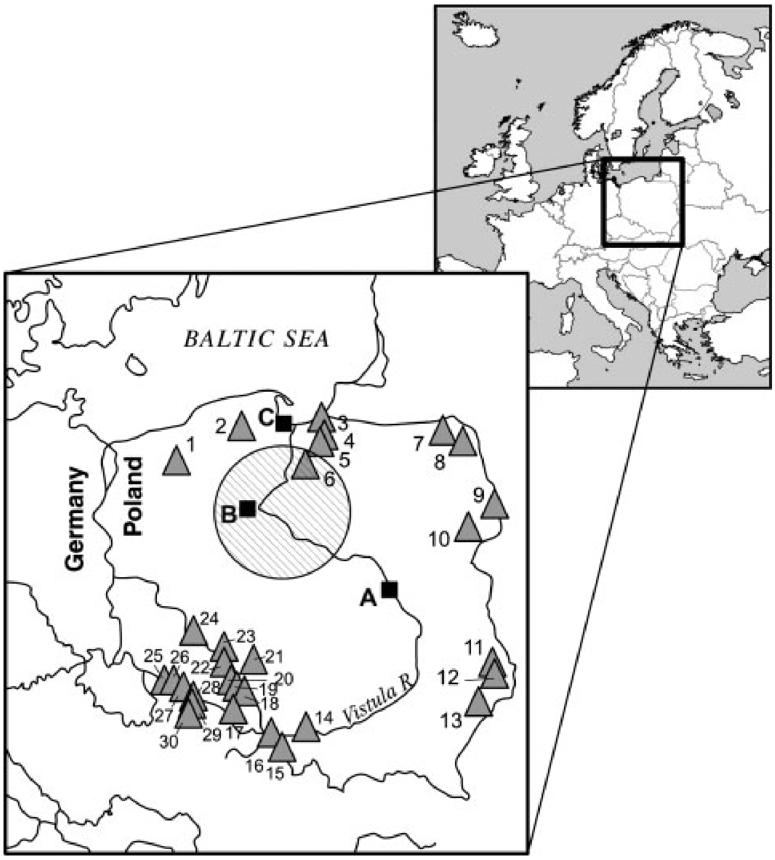


Figure 1. Location of source data used in the present paper. Triangles: boreholes with temperature logs; squares: long-term series of air temperature; (A) Warsaw; (B) Bydgoszcz; (C) Gdańsk; dashed area: area for which tree-ring widths regional chronology of the Scots pine was constructed Wells with continuous and precise point temperature logs in Poland suitable for climatic history analysis are numbered 1, 3, 5, 9, 10, 11, 12, 13, 15, 16, 25, 26, and 28. These are the 13 deep wells with continuous temperature logs picked for the reconstruction presented in Figure 7. Wells numbered 2, 4, 6, 7, 8, and 14 were analysed using the FSI inversion technique in Wójcik *et al*. (2000). Wells numbered 17–24 and 29–30, which have lower depth precise point temperature logs, were analysed using individual and simultaneous FSI inversions by Majorowicz *et al*. (2001, 2004). All wells were used for the reconstructions presented in Figure 6

the reconstruction of mean winter (December–February) and summer (June–August) air temperatures for Poland from 1501 to 1840. Their reliability and usefulness for that purpose were checked using historical methods. Two main categories of information in these documents can be distinguished. The first contains information describing single, short-term events, specific to small areas. The second category of information is that which provides data on the general characteristics of weather conditions over a larger area and for a longer period (months, seasons, years). Such information, characterized by its synthetic nature, is particularly valuable when there is very little other data that can be used.

For the area of Poland about 13 000 excerpts (notes) have been collected. For the present analysis, only documentary evidence for winter (3466 excerpts) and summer (3402 excerpts) has been used. The data cover the period from 1501 to 1840, excluding a few decades in the 18th century (Table I). The density of historical records was estimated using the index of record density (H_z) proposed by Pejml (1968):

$$H_z = 84.1p_1/365 + 12.0p_2/52 + 2.8p_3/12 + 0.9p_4/4 + 0.2p_5$$

where p_i is the number of records ($i = 1$, daily; $i = 2$, weekly; $i = 3$, monthly; $i = 4$, seasonally; $i = 5$, annually). After Brázdil (1996) we must say that the index 'does not say anything about the quality of the

Table I. Number of excerpts, the years they cover, and the mean 10-year values of the record density index (H_z, after Pejml (1968)) for Poland, 1501–1840

Decade	Number of excerpts		Number of years covered by excerpts	H_z (%)
	DJF	JJA		
1501–10	9	26	8	1.6
1511–20	25	36	9	2.1
1521–30	13	36	10	2.6
1531–40	30	38	9	2.8
1541–50	19	17	8	1.5
1551–60	13	21	9	1.3
1561–70	17	61	10	2.8
1571–80	5	8	6	0.5
1581–90	13	5	8	0.9
1591–1600	9	7	6	0.6
1601–10	12	9	6	0.6
1611–20	13	7	7	0.8
1621–30	13	9	6	0.8
1631–40	25	29	8	2.3
1641–50	33	33	9	2.2
1651–60	462	422	10	41.9
1661–70	762	821	10	73.4
1671–80	858	898	10	81.1
1681–90	385	395	10	36.8
1691–1700	22	42	6	2.8
1701–10	5	6	5	0.4
1711–20	2	12	5	0.6
1721–30	38	24	10	2.0
1731–40	66	50	10	3.9
1741–50	232	137	10	15.6
1751–60	13	5	9	0.5
1761–70	270	184	3	23.1
1771–80	1	—	—	—
1781–90	—	—	—	—
1791–1800	20	11	9	1.4
1801–10	40	25	10	2.8
1811–20	21	10	9	1.1
1821–30	11	12	8	0.9
1831–40	9	6	7	0.5

records and their usability for the interpretation. The increase in the H_z values thus need not necessarily mean an increase in climatically interpretable information'. The record density in most cases is low and does not exceed 5% (Table I). Only in decades for which daily records are available (e.g. Chrapowicki diary, 1656–85) are the mean 10 year values of H_z significantly higher (up to 81.1% in the 1670s). Comparison of the H_z values calculated for Poland (Table I) and the Czech Lands (Brázdil, 1996: Figure 1) shows similar results for the common period of analysis (16th century).

Based on the analysis of all available excerpts, the thermal conditions for each winter and summer were classified jointly by a team of historians and climatologists using the seven-degree index scale recently proposed by Pfister *et al.* (1994). In that study, the indices are treated as integer values between +3 and −3, where values of +3 and −3 are applied to anomalies that are unmistakably 'extreme' by 20th century standards, i.e. beyond 2.0 standard deviations (SD) from the mean of the reference period 1901–60. Values of indices +2/−2 and of +1/−1 are applied to less extreme deviations that are 1.41–2.00SD and 0.7–1.4SD from the mean of the reference period respectively. The value 0 ($<\pm 0.7$SD) is applied to cases that correspond to the average climate of the reference period or to missing data.

Our investigation showed that the above criteria used by Pfister *et al*. (1994) are not particularly well suited to the climate conditions in Poland. Therefore, we have modified them slightly, based on Sadowski's (1991) results of the calibration of documentary evidence with air temperature data from Warsaw for the period 1789–1850. He limited his investigation to winters and summers that can be described as severe and hot respectively. Sadowski (1991) found that to separate these kinds of seasons, the mean temperatures of all the winter months, and of July and August of the summer months, should be less than or equal to/more than or equal to by 1.5SD/1.0SD from the 1789–1850 mean respectively. Przybylak *et al*. (2004) found that Sadowski's 'hot summers' include all summers that we have described using indices both +2 (very warm) and +3 (extremely warm). Thus, for summers described using index +3 the threshold of 1.5SD is proposed, as was done for the winter. In order to extend the proposition given by Sadowski (1991) to our estimate of thermal conditions in seasons based on a seven-degree scale, an additional threshold of 0.5SD has also been introduced. Thus, in this paper, seasons described by indices from +3 to −3 fulfil the following criteria:

$$+3 \geqslant m + 1.5\text{SD}$$
$$m + 1.0\text{SD} \leqslant +2 < m + 1.5\text{SD}$$
$$m + 0.5\text{SD} \leqslant +1 < m + 1.0\text{SD}$$
$$m - 0.5\text{SD} < 0 < m + 0.5\text{SD}$$
$$m - 1.0\text{SD} < -1 \leqslant m - 0.5\text{SD}$$
$$m - 1.5\text{SD} < -2 \leqslant m - 1.0\text{SD}$$
$$-3 \leqslant m - 1.5\text{SD}$$

where m is the long-term mean (for calibration period 1789–1850) air temperature from the Warsaw series and SD is the standard deviation of that series. Having these criteria it is possible to determine the ranges of air temperatures related to particular indices (for winter $m = -3.3\,^\circ$C, SD $= 2.60\,^\circ$C, and for summer $m = 17.9\,^\circ$C, SD $= 1.18\,^\circ$C (Table II)).

Next, using the Warsaw temperature series from 1779 to 1999, every winter and summer was allocated to one of the above air temperature ranges, according to mean values. Sample sizes of the winters and summers which were grouped in this way were not lower than eight for the extreme intervals, whereas for the other intervals they were higher than 20. By averaging mean winter (summer) temperatures within each group, mean air temperatures related to particular indices have been obtained (Table III). Similar calculations conducted for the early instrumental part (1789–1850) of that series give almost the same results.

Table II. Ranges of winter and summer temperatures (°C) in Poland relative to thermal index scale and their descriptive characteristics

	Winter		Summer	
Index	Temperature ranges (°C)	Descriptive characteristic	Temperature ranges (°C)	Descriptive characteristic
+3	⩾0.6	Extremely warm	⩾19.7	Extremely warm
+2	−0.7 to 0.5	Very warm	19.1–19.6	Very warm
+1	−2.0 to −0.8	Warm	18.5–19.0	Warm
0	−4.5 to −2.1	Normal	17.4–18.4	Normal
−1	−5.8 to −4.6	Cold	16.8–17.3	Cold
−2	−7.1 to −5.9	Severe	16.2–16.7	Very cold
−3	⩽−7.2	Very severe	⩽16.1	Extremely cold

Table III. Mean seasonal temperatures relative to thermal index scale and frequency of occurrence of mean seasonal temperatures within the temperature ranges estimated for each index based on temperature series from Warsaw, 1779–1999

Index	Winter (DJF) Mean temp. (°C)	Winter (DJF) Freq. of occurrence (%)	Summer (JJA) Mean temp. (°C)	Summer (JJA) Freq. of occurrence (%)
+3	1.3	7.3	20.3	4.5
+2	−0.1	14.5	19.3	8.6
+1	−1.3	25.0	18.7	13.6
0	−3.1	32.8	17.9	43.0
−1	−5.2	10.9	17.1	15.4
−2	−6.4	4.5	16.5	11.3
−3	−8.1	5.0	15.8	3.6

The above results show that average thermal conditions (index 0) occurred in Warsaw in winter and summer with frequencies of 32.8% and 43.0% respectively. Owing to the fact that there were no significant changes in mean temperatures (seasonal and annual) in Poland (Majorowicz *et al*., 2004), Europe (Luterbacher *et al*., 2004), and in the Northern Hemisphere as a whole (Mann *et al*., 1999) from the 16th to the 19th centuries, and also that changes in the total number of extreme seasons in Poland were small (see Table IV), it can be assumed that any changes in temperature variance that occurred were insignificant. Thus, changes in normal distribution of temperature were small and, therefore, we can assume that frequencies of occurrence of index 0 (Table III) in the early instrumental period (1789–1850) and in the pre-instrumental period (1501–1778) in Poland were similar. That is why we decided to supplement index 0 with the maximum to 3 years (for winter) and 4 years (for summer) for each decade of the study period when documentary evidence did not permit estimation of the thermal conditions of a given season or when there was no information available. The last assumption was also made, for example, by Pfister *et al*. (1994), Brázdil (1996, 2002) and Xoplaki *et al*. (2001), and is based on the fact that 'normal' (in contrast to extreme) weather situations were very rarely noted in historical times.

Subsequently, using mean temperatures calculated for particular indices (Table III) and frequencies of their occurrence in each decade of the period in question, mean *m* winter and summer temperatures for each

Table IV. Frequency of occurrence of exceptionally warm and cold winters (DJF) and summers (JJA) in Poland from 1501 to 1840[a]

Period	DJF 2 and 3	DJF −2 and −3	JJA 2 and 3	JJA −2 and −3	Extreme seasons Total	Extreme seasons %
1501–50	**7**	12	2	0	21	15.9
1551–1600	1	**14**	7	0	22	16.7
1601–50	0	11	**10**	0	21	15.9
1651–1700	4	11	3	1	19	14.4
1701–50	2	12	1	**3**	18	13.6
1751–1800	1	10	2	0	13	9.9
1801–40	0	9	7	2	18	13.6
1501–1840	15	79	32	6	132	
%	11.4	59.8	24.3	4.5		100.0

[a] Explanations of the indices (+3, +2, −2, and −3) are given in the text. The highest frequencies of occurrence of the exceptionally warm and cold seasons in 50-year periods are shown in bold.

decade have been calculated. For this purpose, formulae for a weighted mean was utilized:

$$m = (m_1n_1 + m_2n_2 + m_3n_3 + m_4n_4 + m_5n_5 + m_6n_6 + m_7n_7)/10$$

where m_1, m_2, ..., m_7 are the mean (winter or summer) temperature related to indices +3, +2, ..., −3 respectively, and n_1, n_2, ..., n_3 are the number of years within a decade whose thermal (winter or summer) conditions were described by indices +3, +2, ..., −3.

Calculations were made only for those decades for which information on thermal conditions was available at least for 6 years.

2.3. *Dendrochronological*

For the purposes of temperature reconstruction in Poland, an absolute regional chronology of Scots pine tree-ring width from the Lower Vistula region (Figure 1) for the period from 1500 to 1994 has been used (Zielski, 1997). The compilation included measurements of tree-ring widths in living trees (since 1767) and in historical timber (wooden roof constructions and wooden frames from old churches and residential buildings). First, local dendrochronologies were established: 16 based on living trees and 26 for historical timber. Each local dendrochronology was constructed using samples from 2 to 18 living trees (bores were taken using a Pressler drill at the so-called 'breast-height diameter', i.e. about 130 cm above the ground) or historical timber. The correctness of the construction of those chronologies was checked using the COFECHA program (Holmes, 1994). In the next step, these tree-ring width chronologies were transformed using CRONOL computer code (Dendrochronology Program Library — DPL, routine CRN; Holmes, 1994). The detrending procedure was applied to each of the series. Computing of the chronologies was then carried out with the aim of obtaining a maximum common signal and a minimum amount of noise. Application of the autoregressive procedure (modelling) to the detrended tree-ring series produced a residual version of the chronologies.

All 42 local dendrochronologies prepared in this way formed the basis for the construction of the regional dendrochronology used in the present study. Zielski (1997) found that this dendrochronology can represent the whole of Poland (except mountains and coastal areas), and even the areas of Lithuania and Gotland Island (Sweden).

The relationship between the residual regional chronology of tree-ring widths from Poland and the mean monthly temperatures from Bydgoszcz was investigated using the response function model (see Fritts (1976)) for the period 1861–1991 (Zielski, 1997). This model takes into account both data from the present year and data for the last few months from the previous vegetation period. Response functions were calculated using the RESPO program from the DPL software package (Holmes, 1994). Zielski (1997) reveals statistically significant correlations between annual tree-ring widths and the monthly mean air temperatures, particularly from February and March, but also from January and April. Their values were equal to 0.47, 0.55, 0.26 and 0.18 respectively. This means that in Poland the low temperature occurring at the end of winter and at the beginning of spring has a strong negative influence on the width of the tree-rings. Similar relationships between temperature and Scots pine tree-ring widths were also obtained for the northern-central European Lowland (e.g. see Linderson (1992) or von Lührte (1992)). For these reasons the temperature reconstruction presented here only concerns averaged air temperature for the period from January to April.

Calibration and verification procedures have been conducted using the above-mentioned regional dendrochronology of the Scots pine and the temperature data from the instrumental period. Two 50 year series of air temperature and tree-ring width data were used, one for calibration (1921–70) and the second for verification (1871–1920). The calculations were also repeated with the periods reversed, but the results were similar and, therefore, are not shown. Reconstructions of air temperature in Poland have been conducted using transfer functions (multiple regression) obtained and verified according to series of temperature data from Bydgoszcz (not shown) and series of areally averaged temperature from Warsaw, Bydgoszcz, and Gdańsk. Because thermal conditions in Poland in a given year influence tree-ring growth significantly both in the same year and in the next year, this fact has also been used to reconstruct temperature.

2.4. *Geothermal*

The thermal 'memory' of the Earth under its surface permits the reconstruction of a long-term GST. Data come from temperature profiles measured in industrial fluid-filled wells. In recent decades it is the functional space inversion (FSI) technique that has mainly been used (see Shen and Beck (1991; Shen *et al*., 1995) for the method's description) for this purpose in a variety of regional, continental and global studies (e.g. Lachenbruch and Marshall, 1986; Majorowicz and Šafanda, 1998, 2001; Skinner and Majorowicz, 1999; Pollack and Huang, 2000; Wójcik *et al*., 1999, 2000; Majorowicz *et al*., 2001).

Reconstructions of GST histories using the geothermal method generally have a low time resolution, which gradually gets smaller as more and more old periods are analysed. Such behaviour is a result of the diffusive character of the temperature signal decay with depth. As a result, the reconstructed GST, using FSI techniques (Shen and Beck, 1991; Shen *et al*., 1995), is averaged for longer and longer periods the further back we go. For this reason, Harris and Chapman (1998) have proposed a modification of the method. According to them, the most realistic application of the geothermal method is its use in determining average GST prior to the period of instrumental observation. They called their method 'pre-observational mean temperature' (POM). In the accepted model it is assumed that the GST in the period of instrumental observation is the same as air temperature measured in a standard meteorological station. On the other hand, different methods are used for the pre-instrumental period to find such values of mean GST, which best fit anomalies of rock temperature with depth, calculated using measured borehole temperatures. The anomalies of the rock temperatures at different depths obtained using this model are compared iteratively (i.e. using a method of subsequent approaches for obtaining the fewest differences between modelled and observed temperature profiles) with their anomalies calculated from measured temperatures in the wells. In this paper, we present the results of our first attempt to describe the GST history from 1500 to just before the start of air temperature measurement (1779) at the Warsaw station.

For the present study we calculate average temperature–depth anomalies based on 13 continuous temperature profiles deeper than 500 m, which have been chosen out of the set of Polish wells analysed for the individual FSI climatic reconstructions (see Figure 1 for locations). The above series of data were obtained from the archives of the State Geological Institute in Warsaw. The choice of these wells was determined by the archival data available, using the following criteria: (1) the fixed level of thermal equilibrium in the whole part of the study well; (2) the lack of hydrogeological disturbances in the well and in its surroundings; (3) a good quality of measured temperature.

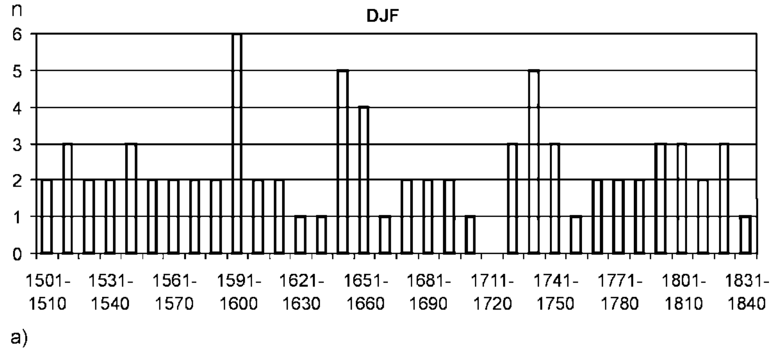
Temperature anomalies have been calculated for each of the above profiles. Anomalies were obtained as differences between measured temperature in a well and the temperature (which is only a result of deep heat flux) on which climatic changes in the last few centuries had only a very small (near-zero) influence. Calculations show that below a depth of 250 m the changes in temperature are so small that they lie within the margin of measurement error.

3. RESULTS AND DISCUSSION

3.1. *Reconstruction of air temperature using documentary evidence*

Documentary evidence for Poland, similar to the majority of other European countries, provides markedly more information about thermal conditions than about precipitation. In the present paper, the variation of air temperature in the period 1501–1840 is investigated using: (1) frequency of occurrence of seasons (winter and summer) described as anomalous in 10- and 50-year periods, and (2) reconstruction of mean 10-year air temperatures.

The frequency of occurrence of all extreme events (Table IV) was greatest in the first 150 years of the study period. Later they were noted more rarely, especially in the first half of the 18th century. Very severe and severe winters (indices −3 and −2 respectively) in the 10-year periods were most frequent in the last decade of the 16th century (six winters) and in the decades 1641–50 and 1731–40 (five winters in both cases) (Figure 2(a)). The fewest such winters occurred in the decades 1621–30, 1631–40, 1751–60, 1831–40, and



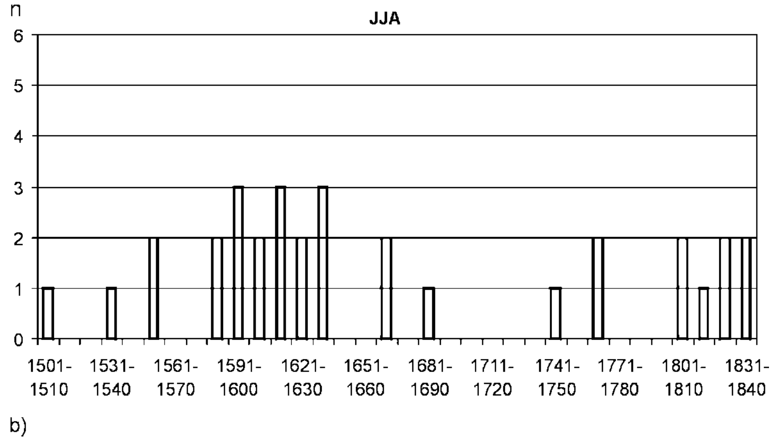


Figure 2. Absolute frequencies of occurrence n in decades: (a) of extremely cold and very cold winters (indices −3 and −2) and (b) of extremely warm and very warm summers (indices 3 and 2) in Poland, 1501–1840

probably in the period 1701–20. From the 50-year periods, the second half of the 16th century was the richest in very severe and severe winters (14). A large number of such winters (12) also occurred in the first halves of the 16th and 18th centuries. Sadowski (1991) also obtained quite similar results.

There are significantly fewer historical sources that describe extremely warm and very warm winters (indices +3 and +2 respectively) in comparison with severe winters. However, the results presented in Table IV show that their maximum frequency was in the first half of the 16th century (seven) and in the second half of the 17th century (four).

Only a third as many notes have been found for summer thermal conditions in comparison with those for winter (Table IV). Significantly more excerpts (32) describe the hot (extremely warm) and very warm (indices +3 and +2 respectively) summers than extremely cold and very cold summers (indices −3 and −2 respectively). The first group of summers occurred with the greatest frequency in the period 1580–1640 and at the beginning of the 19th century (Figure 2(b)). Information about the second group of summers has only been found after 1650, with the highest frequency in the first half of the 18th century (Table IV).

Reconstructed mean 10-year air temperatures for winter and summer presented in the form of anomalies with respect to contemporary conditions (1901–60 mean) and to the early instrumental period (1789–1850 mean) are shown in Figure 3. It can be seen that all mean 10-year winter air temperatures in Poland in the period from 1501 to 1840 were lower than the air temperatures occurring in the 20th century. The coldest winters, on average, occurred in the decade 1741–50 (anomaly −3.7 °C). Large negative anomalies (near −3.0 °C) were observed in the following decades: 1541–50, 1571–80, 1591–1600, 1641–50, 1651–60 and 1771–80. On the other hand, warm winters, on average, occurred in the first and third decades of the 16th century, and in the 17th century, except the periods from 1630 to 1660 and from 1680 to 1700. However, the warmest winters occurred in the 1760s.

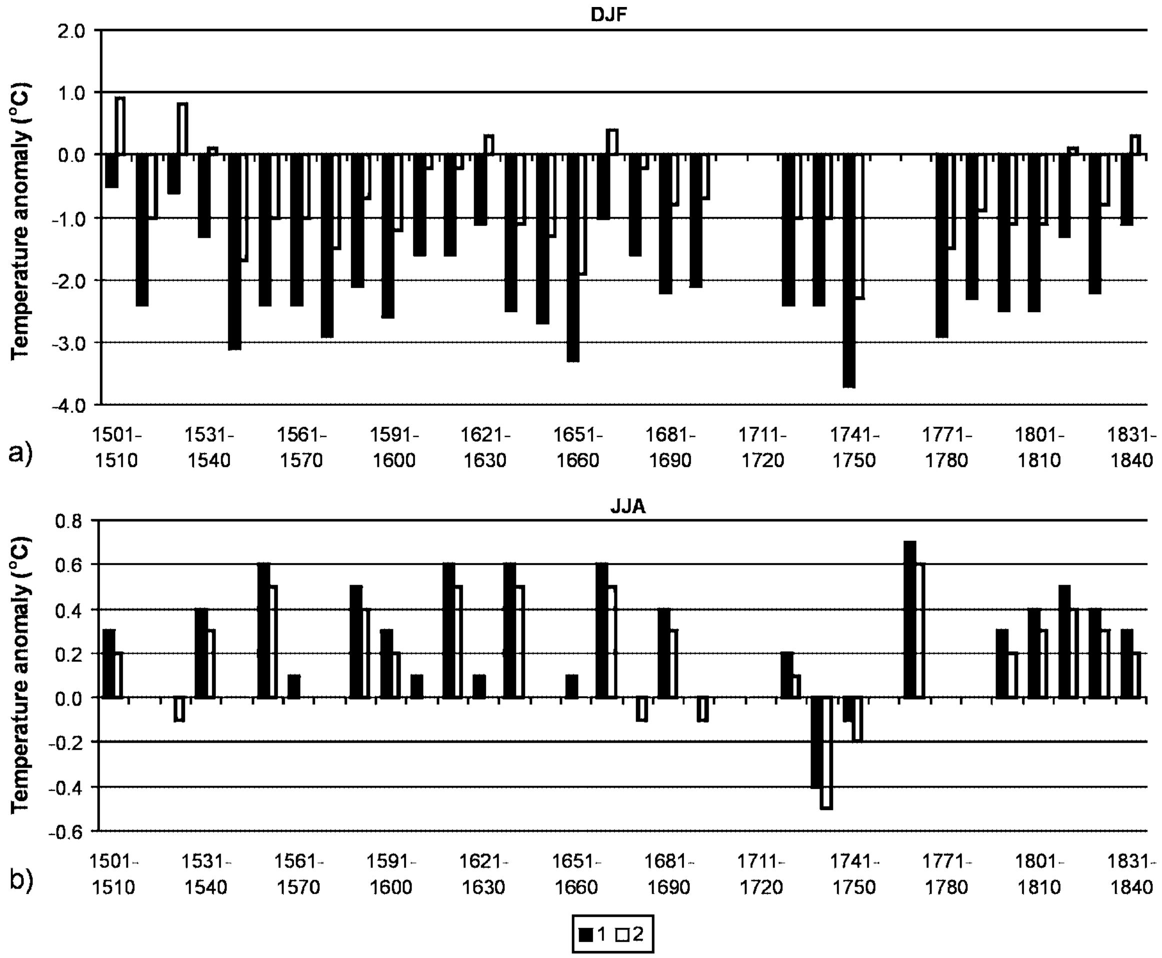


Figure 3. Reconstructions of mean 10-year air temperatures (°C) in Poland from 1501 to 1840: (a) winter (DJF) and (b) summer (JJA). 1 and 2: anomalies with respect to 1901–60 and 1789–1850 means respectively

More limited documentary evidence describing thermal conditions in summer permits the reconstruction of the mean temperatures of these summers for a smaller number of decades (compare Figure 3(a) and (b)). The results obtained show that anomalies which are positive or equal to 0.0 dominated almost throughout the entire first 200 years of the study period. The second maximum of warm summers occurred at the turn of the 18th and 19th centuries. The warm summers around this time were also noted in southern Sweden and central Europe (see Moberg *et al.* (2003: Figure 4). On average, summers were coldest mainly in the first half of the 18th century, and especially between 1731 and 1750. Comparison of summer and winter air temperature changes shows that, with the exception of the first half of the 18th century, winters that were colder than those of the present day were accompanied simultaneously by warmer summers. Thus, in the study period the climate of Poland has a greater degree of thermal continentality in comparison with the present climate. Similar results for the Czech Lands have been reported by Brázdil (1994), and for southern Sweden by Moberg and Bergström (1997).

These results correlate quite well with the reconstructions of winter and summer thermal conditions presented for other parts of central Europe, and especially the Czech Republic, e.g. see Brázdil (1994: Figure 2), Pfister (1995: Figure 6.4), Brázdil and Kotyza (2000: Figure 36) or Brázdil (2002: Figures 4 or 6).

For winter, the correlation between mean 10-year temperature reconstructions from Poland and the Czech Republic is strong ($r = 0.83$) for the 16th century. In the following 170 years (the time period covered by

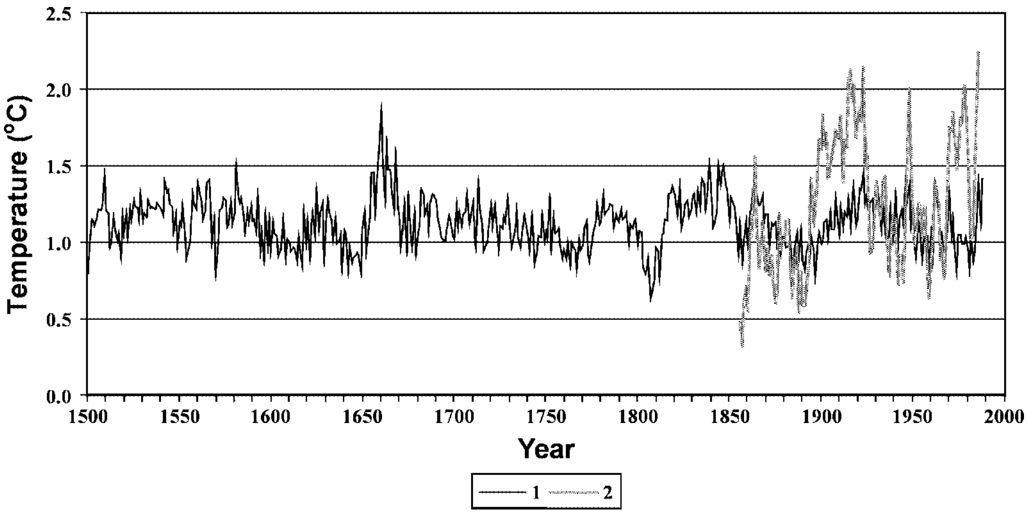


Figure 4. A reconstruction of mean January–April air temperature (°C) in Poland for the period 1500–1994 using a standardized chronology of Scots pine tree-ring widths (*P. sylvestris* L.). (1) Reconstruction of mean January–April temperature using for calibration areally averaged air temperatures from Warsaw, Bydgoszcz and Gdańsk. (2) Mean January–April areally averaged air temperature from Warsaw, Bydgoszcz and Gdańsk

the reconstruction for the Czech Republic) this good correlation was lost, although in both areas for each decade a consistency of the signs of the anomalies calculated in relation to the period 1851–1950 was found (see Przybylak *et al*. (2004)). The largest discrepancy between the two reconstructions exists for the decade 1741–50, which in Poland was coldest in the period from 1500 to 1840 (Figure 3(a)), whereas in the Czech Republic the winters were, on average, only slightly colder than normal (see Brázdil (1996, 2002)). The reconstructed mean January–April temperature based on dendrochronological data (Figures 4 and 5) also shows that this decade was very cold (although not the coldest in the study period). Analysis of the very well known instrumental series of winter temperature from central England (e.g. see Jones and Briffa (2000: Figure 2) shows (similar to Poland) significant negative anomalies in comparison with the present conditions. On the other hand, the mean 10-year winter European temperature shows near-normal values (Luterbacher *et al*., 2004). Large discrepancies between the reconstructions of winter temperature in Poland and the Czech Republic were also found in the period 1641–60. Winters in Poland were significantly colder; the accuracy of this finding for the decade 1641–50 is also confirmed by the reconstruction of the mean January–April temperature based on dendrochronological data (see Figures 4 and 5). In turn, the results presented by Pfister (1999) for the northern parts of the Alps for this period suggest that winters in the first decade (1641–50) were slightly colder than normal (as in the Czech Republic), whereas in the second decade (1651–60) their negative anomalies reach, on average, almost 1.0 °C and were three times greater than in the Czech Republic. These regional differences are probably the result of (1) the spatially inhomogeneous influence of atmospheric circulation (expressed e.g. by the North Atlantic oscillation (NAO)), in particular in northern and southern Europe (Hurrell, 1995, 1996) or (2) weaknesses in reconstructions. It is worth adding that the spatial differences of the temperature anomalies in central Europe are significantly smaller for warm winters.

Comparison of winter temperature changes in Poland with reconstructed winter temperatures for Latvia (Jevrejeva, 2001) and Estonia (Tarand and Nordli, 2001) do not show such close relationships as those with the Czech Republic.

Comparison of mean 10-year summer temperatures in Poland and in central Europe is more difficult than for winter because of the lack of data for some decades. In general, on analysing the signs of anomalies in Poland (Figure 3(b)) and in the Czech Republic (see Brázdil (1996, 2002)), it can be seen that majority of them are the same, though in some decades (e.g. 1621–30, 1721–30) large differences occurred, including the signs. Summers in the latter decade in the Czech Republic (Brázdil, 1996, 2002), the northern part of the Alps (Pfister, 1999) and northern Fennoscandia (Briffa and Schweingruber, 1992) were warmer, whereas

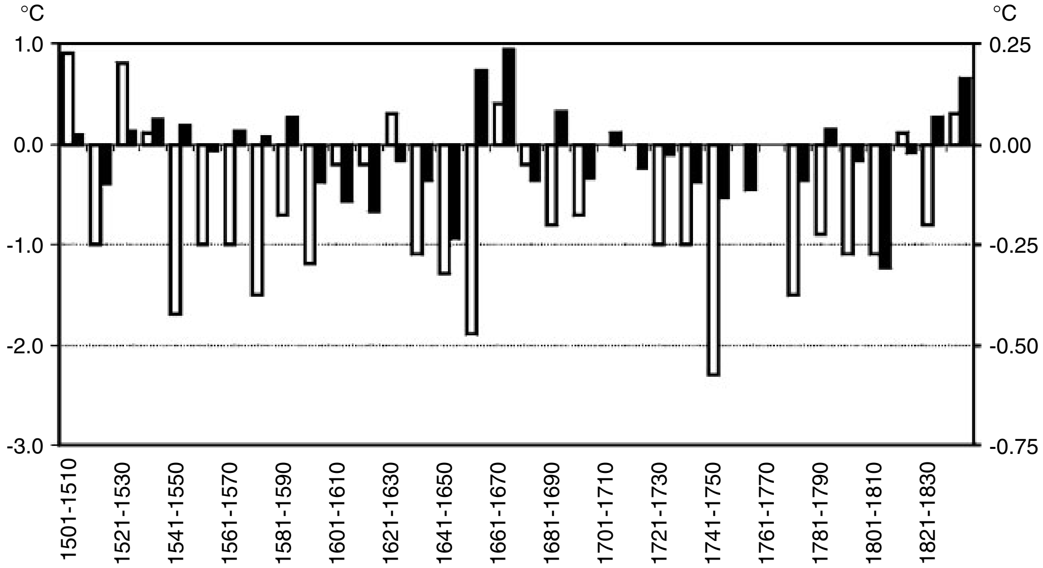


Figure 5. Comparison of mean 10-year winter (December–February, white bars, left axis) temperature reconstructed using documentary sources and mean 10-year January–April (black bars, right axis) temperature reconstructed based on dendrochronological data. Anomalies (°C) are calculated with reference to their 1789–1850 means

in Poland and in Europe as a whole (Luterbacher *et al.*, 2004) they were colder than in the 20th century. Again, in the decade 1621–30, the signs of the anomalies were the same (but positive) in Poland and in Europe, as well as in northern Fennoscandia. They were also the same both in the Czech Republic and in the northern part of the Alps, though negative. A lack of data for some decades (mainly for Poland) prevents the calculation of a correlation coefficient between mean 10-year summer temperatures in Poland and the Czech Republic for the whole common period (1501–1770). It was possible, however, for the period 1581–1700, for which the correlation coefficient was equal to 0.64.

As can be seen from Figure 3, the anomalies in summer are significantly lower than in winter; this is also a result of a year-to-year variability of mean summer temperatures, which is smaller than that of mean winter temperatures. For this reason, spatial differences of summer temperatures in central Europe are also smaller than those of winter temperatures.

3.2. Reconstruction of air temperature based on dendrochronological data

Statistical analysis conducted for the calibration period (1921–70) showed that there is a close correlation between annual tree-ring widths and areally averaged mean January–April air temperature series in Poland. Air temperature explains more than 40% of tree-ring width variability in a given year t and in the year $t+1$. This explained variance is about 20% greater than that obtained by Bednarz (1996). The transfer function is described by the following multiple regression equation:

$$X_t = -1.875 + 7.611D_t - 4.608D_{t+1}$$

where X_t is the mean areally averaged January–April air temperature in a year t, D_t is the index of annual tree-ring width in a year t, and D_{t+1} is the index of annual tree-ring width in a year $t+1$. Using the above equation, mean areally averaged January–April temperatures were calculated for the verification period (1871–1920). Comparison of predicted and observed temperatures reveals a statistically significant correlation coefficient equal to 0.57. Thus, the results of the verification test show that 32.5% of the independent temperature variance is recovered in the estimated data. This calculation procedure was then repeated with the calibration and verification periods reversed, and similar results were obtained. The level of explained variance is sufficient to state that the temperature reconstructions presented in Figures 4 and 5 are reliable.

Visual inspection of the reconstructed series that was obtained allows us to distinguish five main periods with above-normal January–April air temperatures: 1530–90, 1656–70 (the warmest), 1820–50, 1910–40 and from 1985 onwards. On the other hand, lower than normal air temperatures occurred in the following periods: 1600–50, 1760–75, 1800–15, 1880–1900 and 1950–80. The third and fourth periods were especially cold. In both cases coolness came suddenly and lasted briefly (Figures 4 and 5).

It is worth noting that in Poland, similar to the high northern latitudes (Briffa *et al.*, 1998) and some regions in Europe (e.g. the Brandenburg region, Lithuania, Gotland Island), a reduced sensitivity of tree-growth to temperature after 1970 is noted (Wójcik *et al.*, 2000). As a result, the discrepancy between reconstructed and observed temperatures is very clear (Figure 4). The reasons for the recent decrease in the tree-ring widths are not known, but are probably caused by combined simultaneous action of several factors. Briffa *et al.* (1998) have made some suggestions about what these factors are.

Comparison of mean 10-year winter (December–February) and mean 10-year January–April temperatures (Figure 5), reconstructed from documentary evidence and dendrochronological data respectively, shows quite a good coincidence. Except for a few decades, the anomalies of both series have the same signs. Divergences are especially clearly seen for the second half of the 16th century. However, the greatest disagreement was found for the decade 1651–60. The correlation coefficient r calculated between both series for the period 1501–1840 is equal to 0.28 and is not statistically significant. However, when we do not include in calculations the data for the aforementioned decade, the correlation coefficient increases (0.39) and is statistically significant at the 0.05 level. The strongest ($r = 0.58$) statistically significant correlation was found for the period 1720–1840. There was also a high correlation ($r = 0.50$) in the 17th century. Although the periods of the year are not the same (December–February and January–April), the comparison presented is valid because there is a strong correlation coefficient between mean temperatures for both periods mentioned calculated using the Warsaw series for the period 1779–1999 ($r = 0.83$).

Przybylak *et al.* (2003) investigated the influence of the NAO and the Arctic oscillation (AO) on thermal conditions in Poland from the 16th to the 20th centuries (represented by, for example, reconstructed mean January–April air temperature). For this purpose, the monthly (1659–1990) and seasonal (1500–1658) NAO and AO indices reconstructed by Luterbacher *et al.* (1999, 2002) have been used. The correlation coefficients between these series (1500–1990) were not high (*ca* 0.2 for both winter indices NAO and AO), but they were, nevertheless, statistically significant. The explained variances are low and oscillate from 2.2% for the first 300 years to 8.4% for the last 190 years. The weaker relationships in the first 300 years are probably connected with the lower reliability of the NAO and AO reconstructions prior to 1800 AD. For purposes of comparison, it is worth adding that changes in atmospheric circulation (both NAO and AO) explain about 25% of winter (December–February) air temperature variation in Warsaw in the period from 1779 AD to 1990 AD (Przybylak *et al.*, 2003).

For the extreme NAO and AO years the relationships with the winter temperature in Poland are significantly greater. The influence of atmospheric circulation was about twice as strong during negative phases of the NAO and AO indices in comparison with their positive phases. It has also been found that two-thirds of the cases with the annual extreme high/low tree-ring widths of the Scots pine were noted during the occurrence of the positive/negative NAO and AO indices respectively (Przybylak *et al.*, 2003).

3.3. GST reconstruction using geothermal data

In our first paper on the topic (Wójcik *et al.*, 1999), the reconstructions of GST histories were carried out using 10 temperature profiles from wells located in southwestern Poland, which have a fixed state of thermal equilibrium. For the last 100 years, GST warming has oscillated from 0.7 to 0.95 °C and was in a good correlation with the rise of annual air temperature both areally averaged (0.5 °C; Berlin, Warsaw, Leizpig, Wrocław, and Prague) and taken from individual stations located in the study area (0.7–0.9 °C). In our next study (Wójcik *et al.*, 2000) we presented a comparison of the GST history reconstruction for northern Poland (increase of temperature *ca* 1.5 °C from 1500 to 1980) with: (1) a similar reconstruction from western Belarus

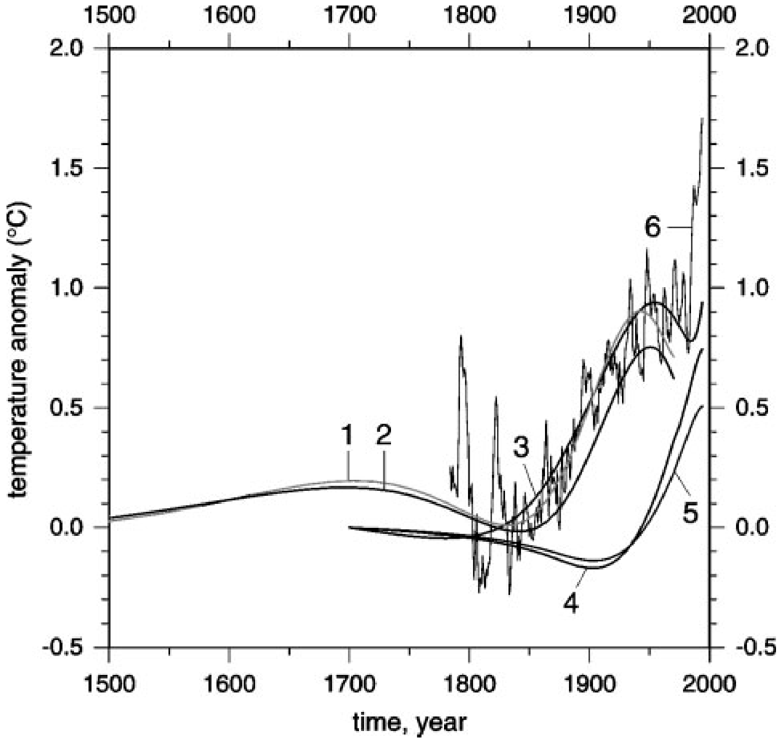


Figure 6. Reconstruction of ground surface temperature (°C) history. Curve 1: reconstruction from the continuous temperature logs (from wells deeper than 450 m) which indicate large ground surface temperature warming (wells marked on the map: 5, 9, 10, 25, 28); curve 2: average based on all deep wells shown as 1, 3, 5, 9, 10, 11, 12, 13, 15, 16, 25, 26, 28; curve 3: reconstruction based on the entire depth of temperature profile in well Grodziec (19 on the location map); curves 4 and 5: reconstructions based on the upper portions of precision temperature profiles above the region of abrupt thermal gradient changes for the high and low assumed error of the *a priori* conductivity model for wells 17–24 and 29–30; curve 6: homogeneous air temperature series from Warsaw (11-year running average) (Lorenc 2000)

(change *ca* 1.0 °C) (Zui, 1999); (2) the annual air temperature from Berlin, Stockholm, Warsaw, Riga, and Vilnius; (3) dendrochronological data from Lithuania, the Lower Vistula region (Poland), the Brandenburg region (Germany) and Gotland Island (Sweden). The significant divergences that were observed between individual GST reconstructions based on the FSI technique used for each of the five borehole temperatures in northern Poland indicate that the selection of geothermal data must be more rigorous, both in terms of accuracy and considering the occurrence of hydrodynamic disturbances in the vicinity of the wells. Majorowicz *et al.* (2001, 2004) extended the analysis to the whole of Poland using additional borehole temperatures from other parts of the country, including 13 deep continuous temperature profiles obtained by means of geophysical surveying. Again, the FSI technique was used, permitting the reconstruction of the GST for the last 500 years (Majorowicz *et al.*, 2004). Comparison of the GST with the recently homogenized annual air temperature series from Warsaw (Lorenc, 2000) showed that the courses of both series during the last 200 years were very similar (Figure 6). The amplitude of GST warming (0.9 ± 0.1 °C) results from the individual and simultaneous inversions of well temperature data using the FSI method (Figure 6). The simultaneous inversions of the deep 13 continuous logs (Figure 6) and of the deep precise point temperature depth profile (Figure 6, curve 3) shows excellent agreement with the homogenized Warsaw temperature time series (Figure 6, curve 6). However, when shallow-depth precise temperature logs from the upper 150 m are inverted, the minimum GST shifts towards the beginning of the 20th century (Figure 6, curves 4 and 5) in comparison with GST histories from the deep logs (curves 1–3) and the Warsaw temperature time series (curve 6). The spurious minimum of the GST history is created artificially by the inversion procedure due to a lack of a deeper part of the temperature gradient in these shallow logs.

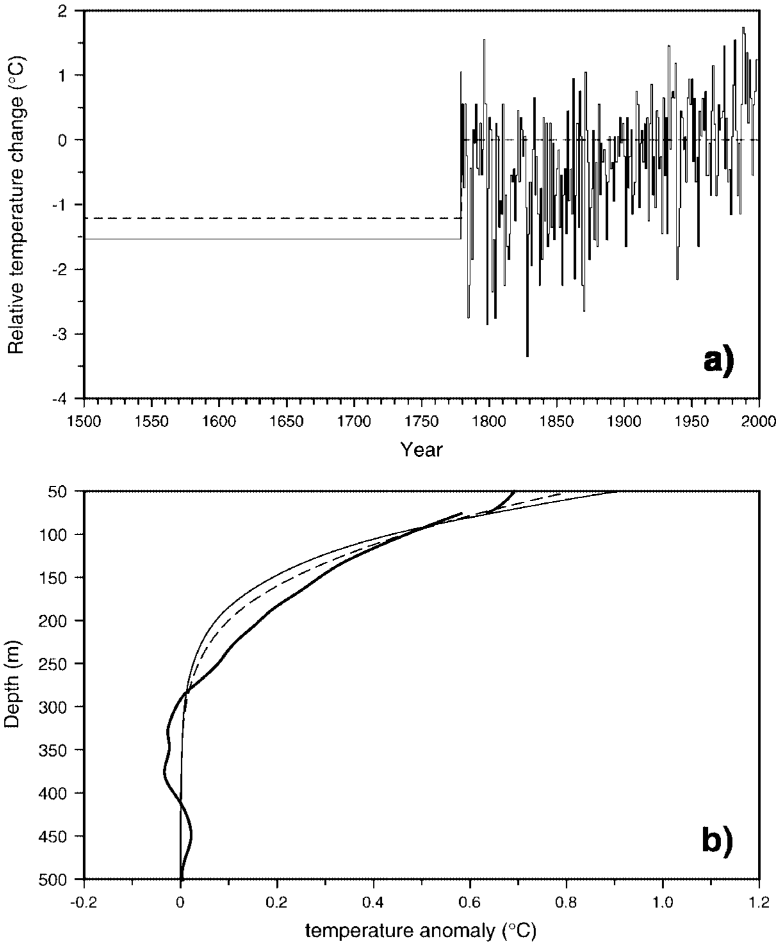


Figure 7. A reconstruction of ground surface temperature (°C) changes relative to 1951–81 mean annual temperature (a) for the period 1500–2000 obtained on the basis of adjustments to curves representing mean temperature anomalies with depth (b, thick curve) calculated using 13 temperature profiles (1, 3, 5, 9–13, 15, 16, 25, 26 and 28). The adjustment has been carried out using two models: (1) a simple model of abrupt temperature increase in ground surface temperature (dashed line); (2) a binary model with curve presenting ground surface temperature changes during a period of instrumental observations from 1779 to 2000 (based on the assumption that the values are the same as those for air temperature in Warsaw), along with a reconstruction of the mean level of ground surface temperature for the period 1500–1778 (thin continuous line). For other explanations see text

The vertical distribution of mean anomalies of rock temperatures was calculated using 13 temperature profiles from wells selected for the present paper (Figure 7(b), thick solid line). Positive anomalies of averaged temperature in the upper part of the temperature profile indicate the occurrence of the modern warming. Our previous studies (Wójcik *et al.*, 1999, 2000; Majorowicz *et al.*, 2001, 2004) focused on reconstructing the GST history using the FSI method; here, we present for the first time (Figure 7(a)) this reconstruction for the time span prior to 1779 (the year in which meteorological observations began in Warsaw) based on the Harris and Chapman (1998) method. In Figure 7(a) we show the course of annual air temperature in Warsaw and the most probable 'level' of the pre-observational GST history, i.e. that which best fits the observable anomalies with the depth (solid line). This model produces temperature changes with depth (Figure 7(b), thin solid line) approaching observed temperature anomalies with depth (differences less than 0.07 °C and, thus, lower than measurement errors) (Figure 7(b), thick solid line). The difference calculated between the mean temperature for the period 1951–81 and the mean temperature for the pre-observational period (prior to 1779) is equal to 1.53 °C. For purposes of comparison, a simple model of abrupt temperature increase in 1779 (dashed line), which also quite closely approaches changes in temperature anomalies with depth, is shown in Figure 7(a).

The modelling studies presented above indicate that the contemporary 'level' of mean annual air temperature in Poland is significantly higher (>1.5 °C) than the mean 'level' of the GST from 1500 to 1778. This difference is about two times greater than its analogous value calculated from borehole temperatures located in the Northern Hemisphere (0.7 °C; Harris and Chapman, 2001). It is also greater than the GST increase for southwest Poland calculated using the FSI technique (0.9–1.0 °C; Majorowicz *et al*., 2001, 2004) and about 1.0 °C for the most northeasterly corner of Poland (Šafanda *et al*., 2004). It seems that one reason for this divergence of the results obtained for Poland might be the differences in the assumptions that are inherent in both methods. Harris and Chapman's method is based on the assumption that the range of GST change in the instrumental period of observation is the same as in the case of air temperature measured at meteorological stations. In the FSI technique, reconstruction of the GST history has been obtained using measurement of rock temperature in industrial wells from the surface to 300–500 m depth. Comparison of the mean GST obtained in this way for the last 200 years with the air temperature changes in Warsaw showed that an increase in the GST during this time was, on average, lower by 0.3 °C. Yet, this explains only part of the difference between reconstructed GST obtained using Harris and Chapman's method (1.5 °C) and the FSI technique (0.9–1.0 °C). The average 'level' of the GST prior to the instrumental period is significantly lower when Harris and Chapman's method is used. The assumption in Harris and Chapman's method (that changes in air temperature are similar to changes in the GST) is appropriate for the area of Poland for the range of observed time series (compare curve 6 (time series, Figure 6) with FSI reconstructed temperature variations from precise well logs (curves 1–3, Figure 6)). The suspected reason for the difference 1.5 versus 1.0 °C (Harris and Chapman's method versus FSI approach) is the lack of the upper 50 m of temperature logs in the case of the continuous logs from deep wells. It is shown in Figure 7(b) that the observed temperature anomaly decreases towards the surface and the theoretical curves (thin line and dashed line) based on the assumed models (shown in Figure 7(a)) deviate by some 0.20 °C at 50 m and by close to 0.5 °C when extrapolated to the surface. This discrepancy between observations and simple model can explain the observed difference. Therefore, we assume that the change of 1 °C derived from the FSI method is better documented by the data.

4. CONCLUDING REMARKS

Temperature history for Poland, in comparison with other areas of central Europe, was investigated less until almost the end of the 20th century and, as a result, less was known about it. More recently, however, significant progress has been made. This paper, in providing a set of quantitative reconstructions of temperature for Poland for the last 500 years, should further extend our knowledge.

Three different kinds of proxy data (derived from both natural and man-made sources) have been used separately to reconstruct the temperature of Poland from the 16th century onwards. However, owing to the relationships that exist between natural phenomena (tree growth, subsurface diffusion of heat) and temperature on the one hand and, on the other hand, the density of documentary evidence, all the reconstructions that have been presented relate to different parts of the year. This means that, although the reconstructions that have been obtained are not fully comparable, together they provide comprehensive and reliable information about temperature patterns in the study area.

A very good correspondence of the results has been found between series of annual mean GSTs (Figures 6 and 7) and mean seasonal air temperatures reconstructed using documentary evidence (Figure 3). The mean annual GST for the period 1500–1778 was 1.53 °C colder than the mean temperature for the period 1951–1981. All mean winter 10-year air temperatures in the period 1501–1840 were colder than in the 20th century. Anomalies of the majority of mean decadal temperatures oscillated between −2 and −3 °C in comparison with the 1901–60 mean. On the other hand, summers were generally slightly warmer than in the 20th century. Thus, the fact that colder winters and warmer summers dominated in the first 300 years of the study period means that the climate had a more continental character. These results from Poland are in good correspondence with results obtained for other parts of central Europe, and especially the Czech Republic (e.g.

Brázdil, 1994, 1996, 2002; Pfister, 1995, 1999; Šafanda *et al.*, 1997; Brázdil and Kotyza, 2000). The existing differences, aside from those differences resulting from different climatic regimes in Poland and other areas of central Europe, can probably be ascribed (1) (for the reconstruction based on documentary evidence) to a different density and quality of historical data, as well as to the interpretation or quantification of historical data (Brázdil, 1996) and (2) (for the reconstruction based on geothermal data) to the quality of the data.

Reconstructions of climate based on dendrochronological data (due to the detrending of the source data) allow us to distinguish periods in which air temperatures were greater or lower than the means from the entire period of study. Comparison of mean January–April air temperature (Figures 4 and 5) and winter (December–February) air temperature (Figure 3) shows quite a good correspondence of the results for the period from the 17th century to the 19th century, whereas for the 16th century (and especially for its second half) it is mostly divergences that exist.

For the reconstructions presented here, all the available data for Poland have been used. In spite of this, it is still possible that they may be improved, especially in the case of the reconstruction based on documentary evidence. Here, the possibility lies firstly in the broadening of the database. On the other hand, the improvement of the two other reconstructions (due to the non-existence of other data) can only be conducted in the near future through the modification of the methods used, or by applying other different methods.

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