CHANGES IN POLAND'S CLIMATE OVER THE LAST MILLENNIUM

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Abstract

This article presents the current state of knowledge on climate change in Poland over the last millennium. In so doing, it makes use of available reconstructions for the pre-instrumental period in respect of air temperature and ground-surface temperature, as well as precipitation. Available instrumental data are in turn used to address changes in climate post 1800. This dual approach to the analysis of climate-change history in Poland over the last millennium alows for the identification of 3 characteristic periods long since advocated in descriptions of the climate, i.e. the Mediaeval Warm Period (up to the mid 15th century), the Little Ice Age (from the mid 16th century to the second half of the 19th century) and the Contemporary Warm Period. The latter period's impact in Poland has entailed climatic warming of about 1°C on average, as confirmed by thermometer readings, but also visible in reconstructions using geothermal and dendrochronological methods. The present warming has not yet been asscociated with significant changes in seasonal or annual totals for precipitation.

Introduction

In recent years, the issues of climate change and variability, and their consequences for the environment (be it natural or social) have become dominant themes in research above all espoused by climatologists and meteorologists. The direct cause of this is global climatic warming observable since the second half of the 1970s, and constituting the so-called second phase to contemporary warming, the first having taken place in the years 1920–1940.

Nevertheless, as palaeoclimatic studies make clear, changes in and variability to climate on all temporal and spatial scales are a universal feature of the climate system. Indeed, they may regarded as an inherent (immanent) property of them. Why then has it only been in the last 20–30 years that such an explosion of work on climate change has taken place? The reason, as studies (like the reports from the IPCC from 1990, 1996, 2001 and 2007) make clear, is that the rate of change is far greater now than in the last several centuries, or even ten or

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more centuries. The climatic models widely applied for several decades now in simulating future climate change are almost unanimous in stating that a further rise in emissions of greenhouse gases will intensify the rate of climate change, with air temperature anticipated to have been elevated by around 3°C [IPCC 2007] in a second half of 21st-century world in which carbon dioxide concentrations are up to twice the historical levels.

While palaeoclimatic research is carried out for different geological epochs and periods, both the assessment of the causes of the contemporary climate change referred to, and the formulation of future climate scenarios (mainly for the 21st century), are most dependent on a detailed understanding of the climate over the last millennium. This reflects the need for the scope of the so-called "natural variability" of climate to be established. And this of course requires climatic information collected in the pre-industrial period (from before 1850), the influence of anthropogenic factors on the climate back then being limited enough to ignore.

A full familiarity with the climate in recent centuries is also essential if climatic models used most often in determining future climate-change scenarios are to be verified. If the model is well reconstructed in respect of the climate of past periods, there is a higher probability that these will simulate the future climate correctly.

How then to gain insights into past climates when instrument-based observations of different meteorological elements only cover the globe satisfactorily in the case of the last 100–200 years? In general, widespread use has been made of relationships between different natural phenomena (systems) (e.g. annual increments in the girth of trees, stalagmites and stalactites, as well as of coral reefs) and climate, as well as an assumption regarding stationarity over longer periods of time (via the so-called principle of geological uniformitarianism).

As sources of "indirect data", the natural systems referred to above have inscribed in them a "climatic signal" that may be more or less distinct. The aim of palaeoclimatological investigations lies in the skillful uncovering of this signal, most often by way of a process of calibration (determination of the statistical links between defined natural systems and contemporary meteorological data) and verification (checking if links established by way of calibration allow for the statistically precise reconstruction of climatic data from a period of instrumental observation other than that used in calibration). If the calibration and verification processes point to the existence of durable and statistically significant linkage between a given natural system and a defined meteorological element (e.g. air temperature), then it is possible to apply it to a period for which measurement-based observations are not available, while knowledge of the natural system back then is adequate.

More details relating to the palaeoclimatic methods that have gained application are to be found in the book by Bradley [1999], the review publication by Brázdil *et al.* [2005], and also several publications appearing at the Toruń centre [Majorowicz *et al.* 2001, 2004; Przybylak *et al.* 2004, 2005].

When it comes to possibilities for reconstructing climate over the last millennium, Europe (including Poland) is in a privileged situation compared with most other areas, due to the fact that there are written sources relating to the entire period, which are very much capable of being augmented by the climatic information obtainable from so-called "natural archives". For this reason, we now have at our disposal many reconstructions of different climatic elements (mainly air temperature, precipitation and atmospheric pressure), as well as elements of the atmospheric circulation for Europe [e.g. Luterbacher *et al.* 2002, 2004; Brázdil *et al.* 2005; Pauling *et al.* 2006; Casty *et al.* 2007; IPCC 2007; Glaser 2008; Przybylak 2008; Dobrovolný *et al.* 2009; Klimenko and Solomina 2010; Majorowicz 2010]. Progress is also clearly visible in the case of the reconstruction of the Northern Hemisphere climate, or indeed that of the world as a whole [e.g. Mann *et al.* 1999, 2008; Jones *et al.* 2001; Moberg *et al.* 2005; IPCC 2007; Juckes *et al.* 2007].

For obvious reasons, knowledge on climate change in Poland over the last millennium is fullest in respect of the period of instrumental observations. In the last 20 years it has been possible for various workers to compile, and then engage in the homogenisation of, ten or more air temperature series for Poland [Górski and Marciniak 1992; Miętus 1996, 1998; Trepińska 1997; Głowicki 1998; Lorenc 2000; Vizi *et al.* 2000, 2000/2001; Bryś and Bryś 2010]. The most important of these are the longest series, which relate to Warsaw (from 1779 on) and Cracow (from 1792). Furthermore, high levels of correlation observed for air temperatures across the country allow for the use of these temperature series in characterising thermal conditions throughout Poland [Kożuchowski and Żmudzka 2003].

In the last several decades there has also been a marked increase in the level of knowledge on the Polish climate from the so-called pre-instrumental period. Nonetheless, this does not extend back before the start of the last millennium [*i.a.* Maruszczak 1988, 1991; Sadowski 1991; Wójcik *et al.* 2000; Bokwa *et al.* 2001; Limanówka 2001; Majorowicz *et al.* 2001, 2004; Kotarba 2004; Niedźwiedź 2004, 2010; Przybylak *et al.* 2004, 2005, 2008, 2010a; Filipiak 2007; Przybylak 2007; Filipiak and Miętus 2010; Luterbacher *et al.* 2010; Majorowicz 2010; Przybylak and Marciniak 2010; Zielski *et al.* 2010].

Indirect data generally do not allow for the reconstruction of all meteorological elements typically used in describing the climate of a given area. Overall, it is possible to regenerate with almost full continuity the main characteristics (monthly, seasonal and annual means or totals) for only (or as many as) three key elements, i.e. air temperature and ground-surface temperature and precipitation. Information on the remaining elements (e.g. on wind, cloud cover and atmospheric phenomena) are only to be found in historical sources, mostly just those with entries concerning particular days. There are unfortunately very few such sources, and they mostly concern short periods from the last millennium.

It is worth noting that the amount and quality of information concerning the aforementioned three first elements is varied, which has the effect that the reconstructions obtained on the basis of them also differ from one another. Dendrochronological and historical data may yield broad-spectrum information on air temperature, but reconstruction of precipitation data using them is much more difficult, or else simply impossible. In turn, geothermal data allow for nothing more than the reconstruction of ground-surface temperatures, and since these are correlated in a statistically significant way with air temperatures, they can be recreated by indirect means anyway. The methods of reconstruction in the case of these elements are described in detail in more recent literature [Majorowicz *et al.* 2001, 2004; Przybylak *et al.* 2001, 2004, 2005], and so are not discussed more fully here.

Readers of this article should also recall that, the further back in time we go, the lower the reliability of the presented reconstructions of climate, and the more generalised the reconstructions themselves (especially when based around historical and geothermal sources). This remark is not true of reconstructions based on dendrochronological data, however, assuming that there is stationarity in the studied relationship between climatic conditions and annual ring increments.

The main aim of this review article is thus to sum up the current state of knowledge on changes and variability in Poland's climate over the last millennium.

Air temperature and ground-surface temperature

Air temperature to 1800

In the temperate latitudes at which Poland lies, air temperature is undoubtedly the most important meteorological element conditioning the development of the biosphere. It is thus no coincidence that people since the earliest times have noted different temperature situations, but most often of all those departing markedly from the norm, and hence exerting a significant disruptive effect on life. In Poland, therefore (as in many other parts of the globe), there is most information from historical sources regarding air temperature.

Nevertheless, even in regard to temperature the amount of information is highly inadequate when set against the task of reconstructing courses over the first 500 years of the last millennium [Rojecki (ed.) 1965]. The reliability of historical sources from this period is also very limited, as was already being noted as far back as in 1922 by Semkowicz, and is confirmed by today's historians [Oliński, pers. comm.].

Equally, the dendrochronological data collected thus far extend back to 1170 in the case of northern Poland [Zielski 1997], or to 1091 in the case of the south [Szychowska-Krąpiec 2010]. In any case, these allow for nothing more than the reconstruction of mean values for air temperature, specifically for the January–April and February–March periods.

Thus in practice the number of indirect data items concerning the climate in the first two centuries of the millennium is vanishingly small, this fact necessitating attempts to reconstruct the history of changes in air temperature in Poland by reference to available data for other areas [Maruszczak 1991]. The reliability of such analogies is limited, since work relates to the UK, Greenland and California, i.e. very distant areas that differ from Poland in often showing different rhythms to changes in air temperature (see e.g. Fig. 34.2 in Bradley and Jones (eds.) 1995, in which reconstructions of air temperature for Europe and North America are presented).

Also long known is the phenomenon of the simultaneous occurrence of "positive and negative" anomalies of air temperature (i.e. departures from norms) across Europe (including Poland) and over Greenland [Kosiba 1949], especially in winter. Contemporary climatology explains such phenomena by reference to a differential influence on thermal conditions in Europe and Greenland due to atmospheric circulation – as described with the aid of the index for the North Atlantic Oscillation (NAO) – [Hurrell 1995, 1996].

Bearing in mind the reservations referred to above, but not having other reconstructions at our disposal, we cite here the results of the work by Maruszczak [1991]. According to him, the 11th century was probably warmer than the norm determined for the period he studied, while the 12th century (especially the second half) was the warmest of the entire millennium. The reconstructed mean temperature for the months from January to April was one of the higher ones in the case of the years 1170–1200, albeit not the highest (Fig. 1). In southern Poland, the temperature in February and March was high at the beginning and end of the 12th century. In contrast, it was very low in mid-century [Szychowska-Krąpiec 2010].

For the period 1201–1500 we now have slightly more information, thanks to the availability of the work by Sadowski [1991], albeit a study drawing on limited and low-reliability historical sources. It was within the framework of a research project under the Ministry of Science and Higher Education (N306 018 32/1027) that a new reconstruction of air temperature for the 15th century (Fig. 2) [Przybylak *et al.* 2010c] came into being, if still with many gaps.

Thus, according to Maruszczak [1991], mean annual values for air temperature were above the norm in the 13th century and first half of the 14th, only to give way to around 100 years of cooling. A warmer climate returned in the second half of the 15th century. According to the research by Sadowski [1991], the 13th century was a time of both the least severe winters and the least hot summers to a greater extent than at any other time throughout the nearly 800-year period under study. That would mean in turn that the period was one of the greatest oceanicity of climate (see Fig. 6 in Sadowski 1991). As Fig. 1 shows, mean January–April values of air temperature were relatively high, and varied only little in the 13th century, with only slightly lowered values in the first half. A similar course was characteristic for the 14th century. Research by Sadowski [1991] also gives no indication of greater changes in air temperature during that century. There is thus no confirmation of the occurrence of the cooling of climate in the second half of the 14th century that Maruszczak [1991] wrote about.

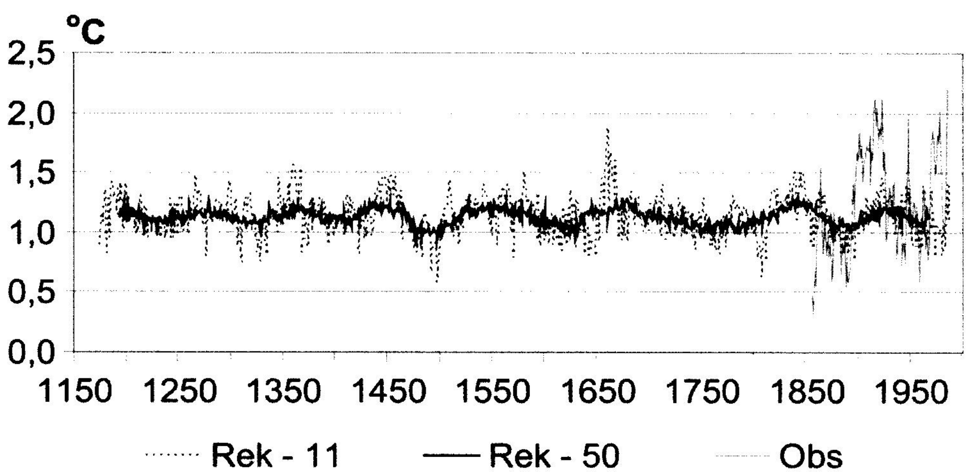


Fig. 1. A reconstruction of mean January–April air temperature in Poland for the period 1170–1994 using a standardised chronology of tree-ring widths for Scots pine (*Pinus sylvestris* L.) (after Przybylak *et al.* 2001, modified). Key: Rek-11, Rek-50 – 11- and 50-year running means; reconstruction using areally-averaged air temperatures from Warsaw, Bydgoszcz and Gdańsk for calibration, Obs – mean January–April areally-averaged air temperature from Warsaw, Bydgoszcz and Gdańsk.

Ryc. 1. Rekonstrukcja średniej temperatury powietrza w okresie od stycznia do kwietnia w Polsce w latach 1170–1994 na podstawie standaryzowanej chronologii szerokości pierścieni drzew sosny zwyczajnej (*Pinus sylvestris* L.) (Przybylak i in. 2001, zmienione). Objaśnienia: Rek-11, Rek-50 – odpowiednio średnie ruchome 11- i 50-letnie; rekonstrukcja oparta na kalibracji wykonanej na podstawie serii temperatury obszarowej obliczonej z danych z Warszawy, Bydgoszczy i Gdańska, Obs – średnia temperatura obszarowa od stycznia do kwietnia obliczona z danych z Warszawy, Bydgoszczy i Gdańska.

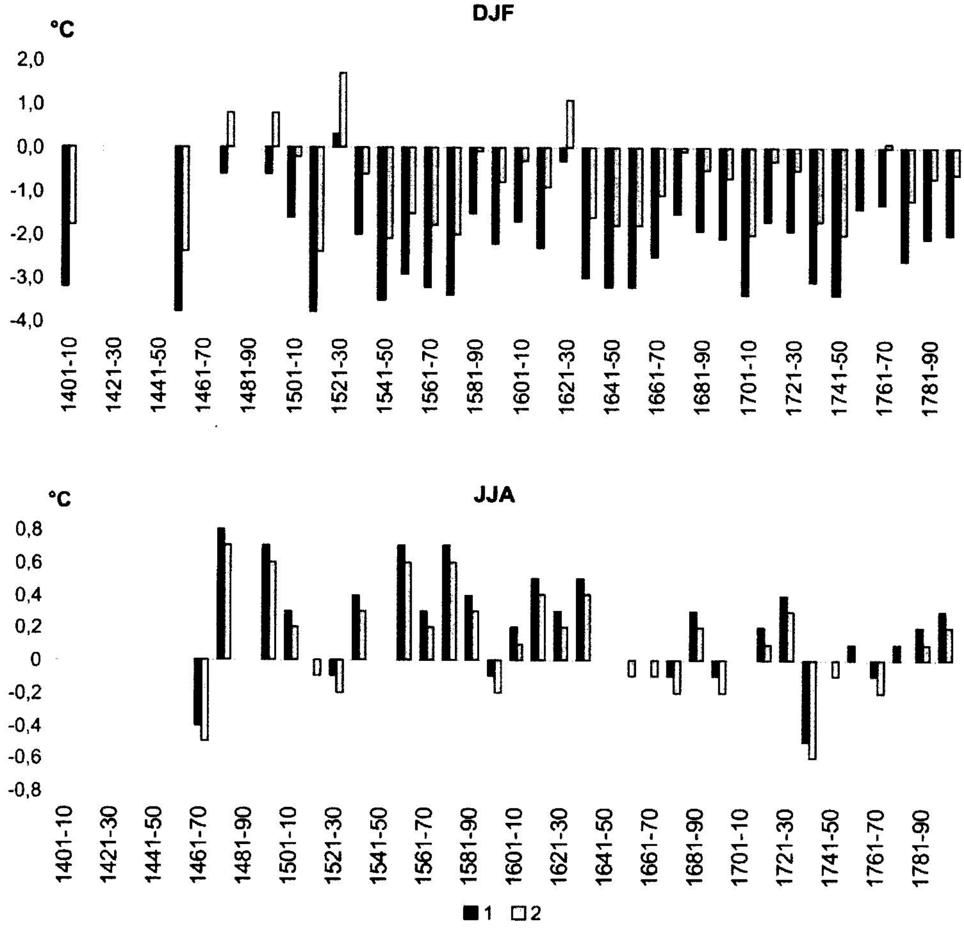


Fig. 2. Reconstructions of mean 10-year air temperatures (°C) in Poland from 1401 to 1800: a) winter (DJF) and b) summer (JJA). 1 and 2 – anomalies with respect to 1901–1960 and 1789–1850 means, respectively [after Przybylak *et al.* 2010c].

Ryc. 2. Rekonstrukcje średnich sezonowych (DJF – zima, JJA – lato) dekadowych wartości temperatury powietrza w Polsce w okresie 1401–1800. 1 i 2 – anomalie w stosunku do odpowiednich średnich z okresów 1901–1960 i 1789–1850 [za Przybylak i in. 2010c].

In turn, the newest reconstructions of mean temperature in late winter and early spring (the February–March period) show clearly how the whole 13th century and beginning of the 14th century were cool, while a marked warming kicked in from the 3rd decade onwards [Koprowski *et al.* 2010; Szychowska-Krąpiec 2010]. According to Sadowski, the 15th century was characterised by the greatest degree of climatic continentality at any time in the years 1201–1980. At this time, there was an abrupt increase in the number of severe winters to as many as 6 in the decade 1451–1460. The same result was also obtained by Przybylak *et al.* [2010c]. Sadowski [1991] also reported the occurrence of a large number of hot summers

(2–5 per decade) in the period from 1470. In line with the results obtained from historical sources [Maruszczak 1991; Sadowski 1991; Przybylak *et al.* 2010c], the last 30 years of the 15th century were apparently either within – or rather warmer than – the norm, most especially in summer. On the other hand, reconstructed mean values for air temperature for the January–April period, as based on the width of tree rings, point to the occurrence of a period of cooling at this time (Fig. 1). More in line with the results of the reconstruction based on historical sources are the newest reconstructions of mean temperatures in February and March obtained on the basis of dendrochronological data from northern Poland [Koprowski *et al.* 2010], as well as southern Poland [Szychowska-Krąpiec 2010].

As can be seen from this brief summary, the state of knowledge concerning changes in air temperature in the period 1001–1500 is very limited indeed, existing reconstructions being very uncertain. In some periods there are even cases in which opposing trends for the course of air temperature are presented.

Knowledge concerning climate change in Poland is much fuller from the 16th century onwards, hence the several successful attempts at the reconstruction of air temperatures in this period carried out on the basis of historical sources brought together [Maruszczak 1991; Sadowski 1991; Przybylak *et al.* 2004, 2005, 2010c], or else dendrochronological data [e.g. Bednarz 1996; Wójcik *et al.* 1999, 2000; Przybylak *et al.* 2001, 2005; Kaczka 2004; Niedźwiedź 2004; Koprowski *et al.* 2010; Szychowska-Krąpiec 2010].

Certain reconstructions of air temperature on the basis of historical sources that are characterised by a higher (daily) level of detail have also been generated, though obviously these deal with shorter overall periods of just a couple of decades [e.g. Bokwa *et al.* 2001; Limanówka 2001; Nowosad *et al.* 2007; Niedźwiedź 2010; Pospieszyńska and Przybylak 2010; Przybylak and Marciniak 2010; Przybylak *et al.* 2010b; Przybylak and Pospieszyńska 2010].

In relation to the 18th, and additionally also the 15th, centuries, the widening of the historical databases in the context of the study project referred to above has markedly increased the level of completeness and reliability to reconstructions of air temperature in Poland. This can be discerned when old reconstructions of air temperature [after Przybylak *et al.* 2004, 2005] are compared with the new ones presented in Fig. 2. The analysis of these reveals that the coldest winters in the period 1501–1800 (as judged in terms of departures from the 1901–1960 mean in the range –3.5 to –3.4°C) occurred in the decades 1511–1520, 1541–1550, 1571–1580, 1701–1710 and 1741–1750. Other than in the decade 1521–1530, all of these runs of winters were cooler than in the period 1901–1960 (black bars). On average, the coldest winters were those of the 16th century (an anomaly then of –2.4°C), while the warmest characterised the 17th century (anomaly –2.2°C). The differences between the secular means are thus very small.

Within the period under study, winters worthy of the description extremely cold (being 2 standard deviations below the long-term mean for the period 1901–1960) occurred most often in the 16th century (32 cases) and the 17th (21) (Fig. 3). There were fewest of these (18) in the 18th century. It was in the decade 1641–1650 that the greatest number of very severe winters (6) was recorded (these having indices of –2 and –3). There were also a number of examples of this category of winter (i.e. 5) in both the 1511–1520 and 1731–1740 periods.

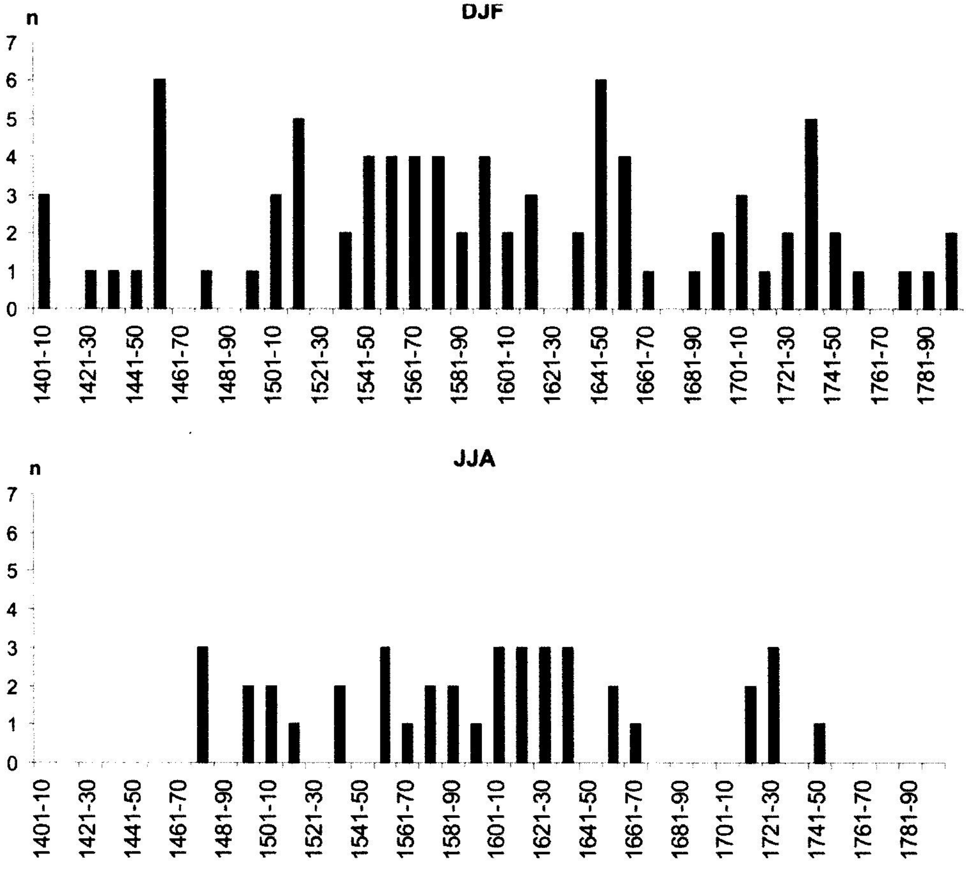


Fig. 3. Decadal frequencies of occurrence: a) of extreme cold and very cold winters (DJF, indices –3 and –2) and b) of extreme warm and very warm summers (JJA, indices 3 and 2) [after Przybylak *et al.* 2010c]. Key: indices –3 and +3 denote that temperature in winter and summer, respectively is lower (higher) than 2σ from reference period 1901–1960 mean. Indices –2 and +2 denote smaller deviations varying between 1.41 and 2.0σ.

Ryc. 3. Częstość występowania (n – liczba przypadków na 10 lat) skrajnie chłodnych i bardzo chłodnych zim (DJF, indeksy –3 i –2) i skrajnie ciepłych i bardzo ciepłych sezonów letnich (JJA, indeksy +3 i +2) [za Przybylak i in. 2010c]. Objaśnienia: indeksy –3 i +3 oznaczają, iż temperatura odpowiednio w zimie i w lecie jest niższa (wyższa) niż 2σ od średniej wieloletniej z okresu 1901–1960. Indeksy –2 i +2 są zastosowane do mniejszych odchyleń wahających się w przedziale 1,41–2,0σ.

Very warm winters were also noted most often (8 times) in the 16th century, while they were not noted at all in the 18th. The reliability of this assessment is much lower, however, on account of the fact that those keeping notes always paid greater attention to severe winters than to mild ones or very warm ones that were less burdensome.

Comparison of the reconstruction for temperatures in winter (Fig. 2) with that involving temperature in the Jan–Apr period (Fig. 1) indicates rather good concordance in the 18th century, as well as disparities in the 16th and 17th. According to Przybylak *et al.* [2004], the probable reason for the lack of accord in the results obtained may be: not fully-comparable data (mean temperature for different periods of the year overlapping only partly), as well as imperfections in the reconstructed air temperature values.

Fig. 1.3 in the work by Luterbacher *et al.* [2010] reveals the existence of a strong correlation for the period of the last 500 years between averaged temperature in winter from the area of Poland and the temperatures in almost all regions of Europe. At the same time, the coefficient for the correlation between reconstructed values for air temperature in winter in the Czech Republic [Przybylak *et al.* 2004, 2005] and in Poland (Fig. 2) in the 1501–1800 study period has a value of zero. Particular subperiods do in fact display weak or moderate correlations, but these change sign. In the 16th century, a strong positive correlation (r = 0.58) was obtained, while in the 17th and 18th centuries, the correlations were inverse (respective r values of –0.27 and –0.43). It is this radical change in the nature of the link (which most probably arose in the late 16th and early 17th centuries) that is responsible for the lack of correlation in the period as a whole.

For the above reason, the correlations calculated for particular centuries would seem to be more reliable, even if they are not statistically significant. Certain disparities between the studied reconstructions of winter temperatures for the Czech Republic and Poland may also result from different methods applied in the reconstruction. These include:

1. availability of historical source materials, greater for the Czech Republic, and allowing for a thermal (indexing) assessment of different months, as opposed to seasons only in the case of Poland;

2. rather different selections of years included within decades (e.g. Czech Republic 1500–1509, Poland 1501–1510).

The greater concordance and stability to the courses for the two air temperature series in the summer months probably result from the far lesser variability from day to day and year to year than is to be found for winter temperatures. This should favour the making of fewer errors in the course of the reconstruction of air temperatures for summer as opposed to winter, even where the number of indirect data is much smaller.

Comparisons between reconstructed thermal conditions for Poland in the winter period and analogous ones for Latvia [Jevrejeva 2001] and Estonia [Tarand and Nordli 2001] point to weaker connections than in the case of the Czech lands. However, it should be recalled that recreations of air temperature in the Baltic States have made use of long-term observations of the ice cover at the ports of Riga and Tallinn, this giving good insight into the severity of winters, but obviously offering lesser comparability.

The reconstruction of air temperature for the summer season on the basis of historical data is mardkedly less complete than that for winter (Fig. 2). This is linked to the fact that less information is accessible, but it does not prevent general outlines from looking quite legible. The summers in the studied period of several centuries extending from 1501 to 1800 were primarily warmer than in the reference period (Fig. 2). However, the positive departures are markedly smaller than the negative ones characterising winter. The greatest mean decadal values for these, not exceeding 1°C, were mainly reported in the second half of the 16th century. The coolest summers (0.5°C down on the mean for 1901–1960, on average) were noted in the decade 1731–1740. Moreover, in periods of study involving five different decades (1521–1530, 1591–1600, 1671–1680, 1691–

–1700 and 1761–1770), they were slightly (on average 0.1°C) cooler than contemporary ones. The centuries' mean departures noted for temperature were always somewhat positive, ranging from 0.1°C in the 18th century to 0.3°C in the 16th.

During the summers, in turn, it was far more usual for hot (often also very dry) summers to be noted, than cool and wet ones. Very hot or extremely hot summers were most often noted in the 17th century (15 cases) and the 16th (14 cases) (Fig. 3). In turn, there were far fewer of them in the 18th century. Very cool or extremely cool summers were not noted more than 3 times in any century.

The above reconstruction of mean temperatures in the summer season is in essence concerned with lowland Poland. However, Niedźwiedź [2004] recently reconstructed mean summer-season temperatures for the Tatra Mountains in the post-1550 period (Fig. 4), identifying two warm phases (1550–1575 and 1676–1792), two cool phases (1576–1675 and 1793–1895), as well as a (more) contemporary period extending from 1896 to 2004 and characterised pre-1990 by a decided prevalence of negative anomalies.

Under the latter reconstruction, the warmest summer seasons are seen to have arisen in the period 1676–1688, with a culmination in 1687 (2.1°C above the long-term norm from 1927–2004). It was only warmer than that in 1992, when the anomaly was of +2.4°C. In contrast, the coolest summer seasons in the Tatra Mountains were those occurring in the periods 1580–1595, 1830–1850, 1910–1925 and 1970–1985. The coolest summer of all came in 1913, when the mean temperature was 2.5°C below the long-term norm.

When comparing the reconstruction for summer-season air temperatures in the Tatra Mountains (Fig. 4) with those presented previously for lowland Poland (Fig. 2) and the Czech Republic [Przybylak *et al.* 2004], it is necessary to note (perhaps not surprisingly) the greater concordance with the Czech series. The coefficient of correlation (r) for the reconstructed values for summer-season temperature in the Czech lands (1500–1799) as opposed to lowland Poland (1501–1800, new reconstruction) assumes a value of 0.29. The lowest value is that for 17th-century data (r = 0.27), and the highest for the 18th century (r = 0.66). Nevertheless, in no period are the links between the series analysed statistically sgnificant.

In summarising, it needs to be noted how our knowledge of Poland's climate over the 300-year period analysed has increased greatly in the last few years, albeit still being very limited, especially when it comes to summer. However, the quality is sufficient to support the contention that the period 1501–1800 saw Poland's climate subject to greater thermal continentality than is noted these days. The result of that was far colder winters and rather warmer summers than could be noted in the years 1901–1960.

Post-1800 air temperatures

Recently, Przybylak [2010] offered a synthetic presentation of existing knowledge on changes in Poland's air temperature in the period over which observations using instruments have been possible, and carried out. For this reason, the present sub-chapter deals only with the key results concerning mean annual and seasonal values for air temperature. The mean annual temperatures in Warsaw and in Cracow rose between 1801 to almost the end of the 20th century – by more than 1°C (Fig. 5). The trends to changes in air temperature are upward at a rate in excess of 0.5°C per 100 years, and are statistically sgnificant [Trepińska and Kowanetz 1997; Lorenc 2000]. Such significant increases also characterise the

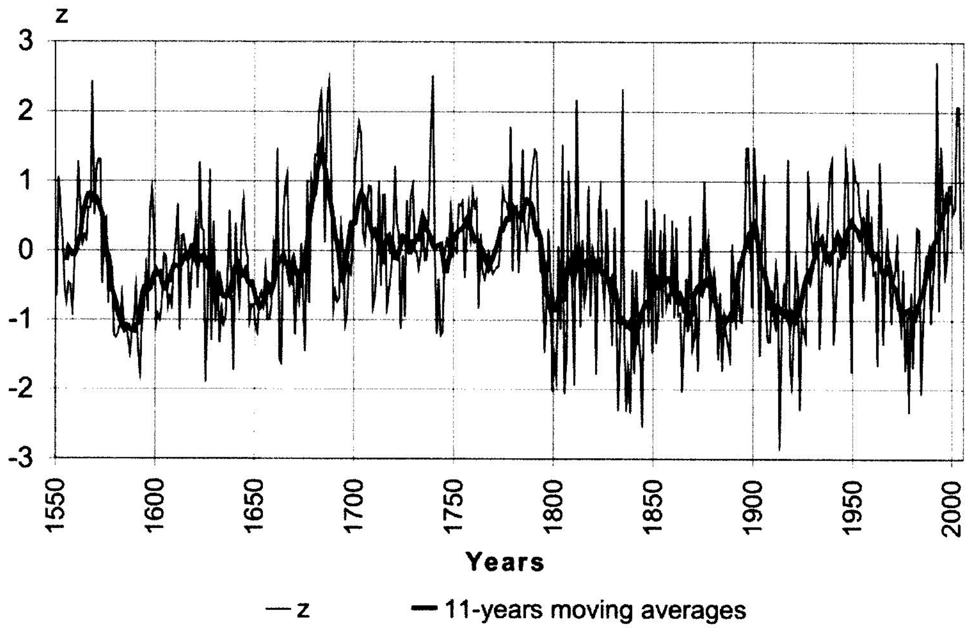


Fig. 4. Mean summer (Jun–Aug) temperature variations in the Tatra Mountains (Hala Gąsienicowa, 1520 m a.s.l.) from 1550 to 2004 (after Niedźwiedź 2004). Key: z – standardised values, average = 0.0, standard deviation = 1.0; solid line – year-on-year course, heavy line – 11-year running means.

Ryc. 4. Zmienność temperatury powietrza w sezonie letnim (VI–VIII) w Tatrach (Hala Gąsienicowa 1520 m n.p.m.) w latach 1550–2004 (wartości standaryzowane „z": średnia = 0,0; odchylenie standardowe = 1,0) (Niedźwiedź 2004).

series for the Baltic coast involving the period 1836–1990 [Miętus 1996], as well as that for Poland as a whole extending between 1901 and 2000 [Kożuchowski and Żmudzka 2003] (Fig. 5).

It has emerged that the areally averaged temperature for Poland as a whole is exceptionally strongly correlated with temperatures noted for Cracow and Warsaw, with the effect that the thermal series of the two stations may indeed be used to characterise this element of the country's climate in relation to the whole of Poland, of course leaving aside the distinctive mountain areas of the far south.

In line with expectations, the greatest increases in air temperature are those reported for winter, which exceed 2 °C in relation to Cracow, Warsaw and the Baltic coast [Fig. 5.6 in Przybylak 2010]. Indeed, all four studied seasons of the year feature a distinct increase in air temperature over the last 200 years. Furthermore, most of the trends for air temperature are statistically signficiant – other than those for the summer in Kraków, Warsaw and the Bałtic coast, as well as winter temperatures for Poland as a whole.

Ground-surface temperature

Climatic studies first turned to the reconstruction of mean annual temperatures of the ground surface in the work of Čermak [1971], and later Lachenbruch and Marshall [1986]. Elsewhere in the

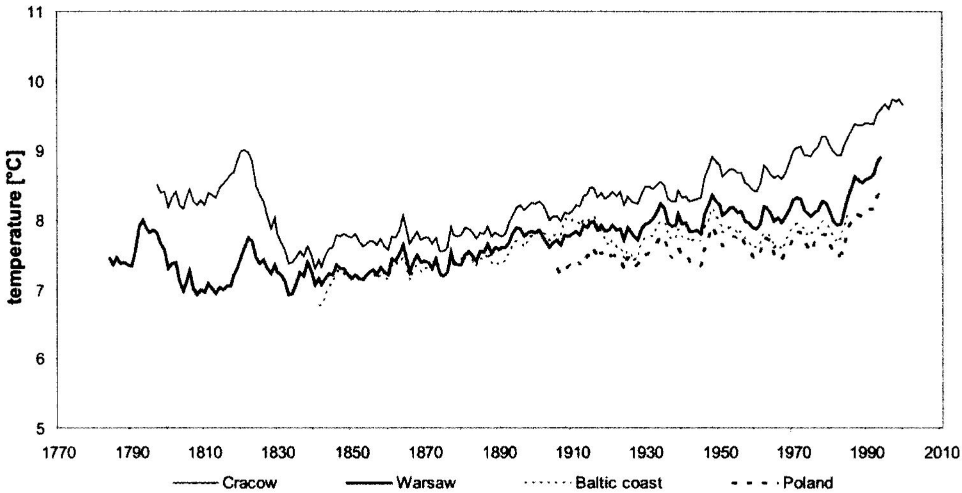


Fig. 5. Long-term courses of 11-year running mean annual air temperatures in Poland during the period of instrument-based observation [after Przybylak 2010, modified]. Key: Data for Cracow after Trepińska [1971] and Matuszko [2007, ed.], for Warsaw after Lorenc [2000], for the Baltic coast after Miętus [1996], and for Poland as a whole after Żmudzka [2008].

Ryc. 5. Wieloletni przebieg 11-letnich ruchomych średnich rocznych wartości temperatury powietrza w okresie obserwacji instrumentalnych [za Przybylak 2010, zmienione]. Objaśnienia: Dane z Krakowa za Trepińska [1971] i Matuszko [2007, red.], z Warszawy za Lorenc [2000], z wybrzeża Bałtyku za Miętus [1996] oraz z Polski [za Żmudzka 2008].

world, such data only began to become used more widely in the 1990s, in which period a number of reconstructions of temperature of this kind appeared around the world [e.g. Shen and Beck 1991; Shen *et al.* 1995; Majorowicz 1996; Šafanda *et al.* 1997; Majorowicz and Šafanda 1998; Huang *et al.* 2000; Pollack and Huang 2000].

In Poland, it was thanks to a research project supported by the Committee for Scientific Research (KBN) that work of the above kind came to be undertaken, under the heading of: *Reconstruction of climate in the Polish lands in the 16th–19th century period, on the basis of historical, dendroclimatological, geophysical and instrumental sources.* This project got underway in 1999, and that same year brought the first reconstruction of temperatures at the land surface over the last 500 years in south-west Poland [Wójcik *et al.* 1999]. In subsequent years, further such reconstructions arose, albeit using varying methodologies, *i.a.* for northern Poland [Wójcik *et al.* 2000] and finally for the country as a whole beyond the mountains [Majorowicz *et al.* 2001, 2004; Przybylak *et al.* 2005].

The works in question dealt with the geothermal reconstruction methods in detail, as well as application of the research results. Thus the present study only addresses selected, most important results from the earlier research.

Fig. 6 presents four reconstructions (curves 1–3 and 5) for changes over time in mean annual ground-surface temperatures in Poland, as obtained using the functional space inversion methodology proposed by Shen and Beck [1991]. These are shown against the background of the course obtained for Warsaw mean temperatures (curve 4); and the courses

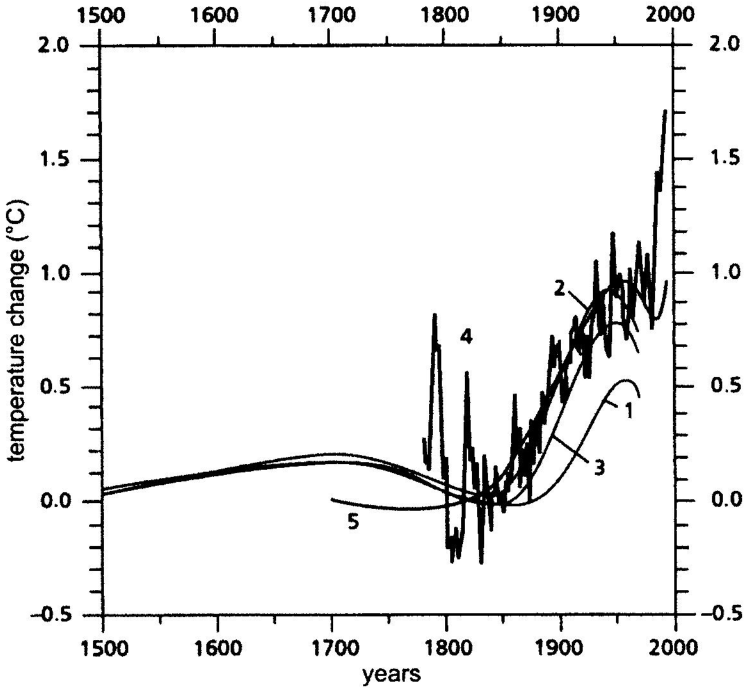


Fig. 6. Reconstructions of the ground-surface temperature history in Poland (curves 1–3) and their comparison with the analogical reconstruction (curve 5) based on the deepest point temperature profile with depth in the Grodziec borehole, as well as with air temperature (curve 4) [after Majorowicz *et al.* 2001].
Key: curve 1 – reconstruction from the continuous temperature logs which indicate minor ground-surface temperature warming, curve 2 – reconstruction derived from continuous temperature logs indicative of major warming, curve 3 – average based on the above two groups, curve 4 – homogeneous air temperature series from Warsaw (11-year running mean) [Lorenc 2000].

Ryc. 6. Rekonstrukcje historii zmian temperatury powierzchni gruntu dla Polski (krzywe 1–3) i ich porównanie z analogiczną rekonstrukcją (krzywa 5) opartą na najgłębszym punktowym profilowaniu temperatury w otworze Grodziec oraz z temperaturą powietrza (krzywa 4) [Majorowicz i in. 2001].
Objaśnienia: krzywa 1 – rekonstrukcja na podstawie ciągłych profilowań temperatury, które wykazują małe ocieplenie, krzywa 2 – rekonstrukcja na podstawie ciągłych profilowań temperatury, które wykazują duże ocieplenie, krzywa 3 – średnia dla otworów z obu powyższych grup, krzywa 4 – homogeniczna seria temperatury powietrza z Warszawy (11-letnie ruchome średnie roczne) [Lorenc 2000].

of all curves make clear the existence of a period of cooling from 1700, with a minimum being reached in the early 19th century. Warming commenced from around the 1800–1850 period, this lasting up to the beginning of the second half of the 20th century, with only a slight cooling in that second half, prior to a return to an upward trend. The increase in temperature over the last 500 years in Poland is in the range 0.5–0.95°C, depending on the assumed level of conductivity, the error for the reconstruction adopted, and the groups of boreholes chosen for analysis. Most reconstructions from deep-drilled sites with measurements maintained at constant depths also point to a local maximum around 1700–1720, preceding a 19th-century minimum. A similar course to ground-surface temperatures was *inter alia* reported from central Czech Republic [Šafanda *et al.*, 1997] as well as western Canada and the USA [Skinner and Majorowicz, 1999]. The amplitude to the changes in Poland is nevertheless seen to be smaller than in the North American case.

Majorowicz *et al.* [2001] showed how reconstructed ground-surface temperature values for Poland are highly correlated with the mean annual values for air temperature that have been obtained for Warsaw. The coefficient for the correlation between the series obtained from boreholes (all holes; curve 3 – Fig. 6) and the aforementioned Warsaw series (curve 4 – Fig. 6) is of r = 0.79. A still stronger correlation occurred between the series obtained from inversion of thermal profiling with holes showing marked near-surface warming on measuring curves (Fig. 6 – curve 2) and the instrument-based Warsaw series (r = 0.89). It is worth adding that such values for correlation coefficients obtained are markedly higher than those calculated between series for annual tree growth and air temperature.

Harris and Chapman [1998] modified the method of functional space inversion, bearing in mind the most realistic possibility of it being applied to establish the mean ground-surface temperature within the time interval preceding instrumental data. The result is the POM (preobservational mean temperature) approach. The model the authors referred to adopted proceeds on the assumption that – in the period of instrumental measurements – the reconstructed ground-surface temperature is the same as the air temperature measured at a standard meteorological station.

On the other hand, in the period prior to the first measurement in a measured air temperature series, what is sought is the mean temperature value that bests approximates the course to anomalies of temperature of rocks, together with the depth denotes for thermal profiles obtained in the case of holes. Using this method, Przybylak *et al.* (2001) calculated that the increase in the ground-surface temperature between the pre-instrumental and current periods was of c. 1.5°C, and hence 0.5–0.6°C more than was calculated with the aid of the first method. In their view, one of the reasons for disparities in the results obtained may lie with differences in the assumptions underpinning the two methods.

Precipitation

The 1001–1800 period

The reconstruction of atmospheric precipitation has met with far greater problems than in the case of air temperature, this mainly reflecting the more limited influence of the former on natural phenomena [e.g. tree rings, Zielski 1997], as well as on the life and activity of people in the temperate zone (hence the far fewer references in historical sources to precipitation conditions as opposed to thermal conditions). It is also for this reason that work to describe precipitation in Poland in the pre-instrumental period is a rarity. There are two studies [Matuszczak 1991; Przybylak *et al.* 2004] in which this issue is addressed in the case of periods lasting several hundred years, along with several [Bokwa *et al.* 2001; Limanówka 2001; Nowosad *et al.* 2007; Filipiak 2007; Przybylak *et al.* 2008; Przybylak and Marciniak 2010] that only address periods of 10–20 years or else a couple of decades.

Another significant hindrance met with in the reconstruction of precipitation is the fact that this is the most temporally and spatially variable of all the climatic elements. Maruszczak [1991] offers only very general information on (what the author judges to be) average annual humidity conditions – in a period the work does not define precisely, these being understood to be precipitation conditions. These were average in the 11th century, while the 12th century was the wettest at any point in the whole millennium. The beginning of the 13th century was marked by a decline in precipitation, to the point where this was below the norm in that century's second half. In the 14th century, quantities of precipitation increased, to the point where they were variable but close to the norm from the middle part of the 14th century through to the mid 15th century. In the subsequent 100 years there were considerable changes in humidity relations, though the author does not indicate in what direction. However, it can be judged from the context that the climate became wetter, in the years 1480–1520 at least. A hypothesis of this kind is supported in data published by Przybylak *et al.* [2004] (see Fig. 7).

In contrast, on the basis of an analysis of numbers of days with precipitation, Limanówka [2001] declared that the first half of the 16th century had far less precipitation than do contemporary times. However, it would seem that the notes compiled by the Professors of the Cracow University did not take account of the lightest precipitation, which they may well have missed altogether. A similar problem for the first two years of Chrapowicki's diaries (i.e. 1656 and 1657) was reported by Nowosad *et al.* [2007]. It therefore seems likely that the number of days with precipitation given by Limanówka [2001] should also be increased by a similar error.

The years from the mid 16th to mid 17^{th} centuries brought a preponderance of average conditions where humidity was concerned [Maruszczak 1991]. Similar results were also obtained by Przybylak *et al.* [2004] (*i.a.* see Fig. 7).

The second half of the 17th century was, according to the reconstruction by Maruszczak [1991] a time of below-average precipitation. However, it is probable that the first two decades of the period had annual precipitation within the norm, albeit with more summer rain than now, but also more limited winter precipitation (Fig. 8). High precipitation totals for June and July in this period are also documented by the reconstruction performed on the basis of dendrochronological data [see Fig. 2 in Przybylak *et al.* 2001]. This is also confirmed by an analysis of the number of days with precipitation in the years 1656–1685 [Przybylak and Marciniak 2010]. From Fig. 21.10 presented in this work, it can be concluded that the period 1677–1685 was also humid.

From the 18th century onwards there was a prevalence of within-the-norm precipitation, except in the late 18th and early 19th-century periods, when there was less [Matuszczak 1991]. In principle, the results obtained by Przybylak *et al.* [2004] confirm this, with the possible exception of the 1731–1750 period, which was most likely wetter than the norm (Fig. 7).

Reconstructions of summer and winter precipitation totals from the area of the Czech Republic [see for example Fig. 2 in Brázdil 1994] are similar to those obtained for Poland (see Table 1 and Fig. 4 in Przybylak *et al.* 2004). The most reliable results on precipitation amount over a major part of that century (years 1739–1770) come from direct measurement made in Gdańsk [Filipiak 2007]. This reveals that the first years of the period (up to 1750) were wetter, as is confirmed by results Przybylak *et al.* [2004] were able to compile for Poland as a whole. Between 1751 and 1766 there was in turn a dry period with annual precipitation in 13 years below the long-term norm calculated for the study period as a whole. However, it is noteworthy that it was at this time that there occurred the year (1755) that is considered to have been the wettest in the entire analysed period, with annual precipitation at 140%

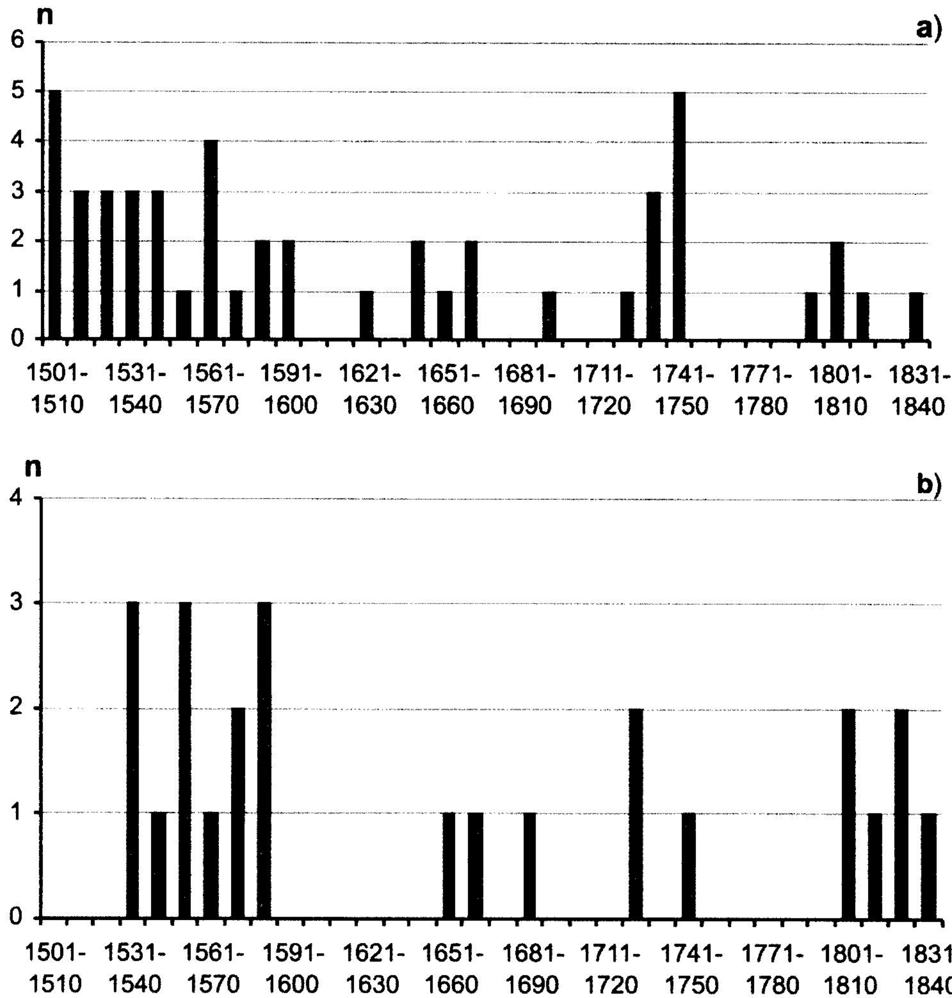


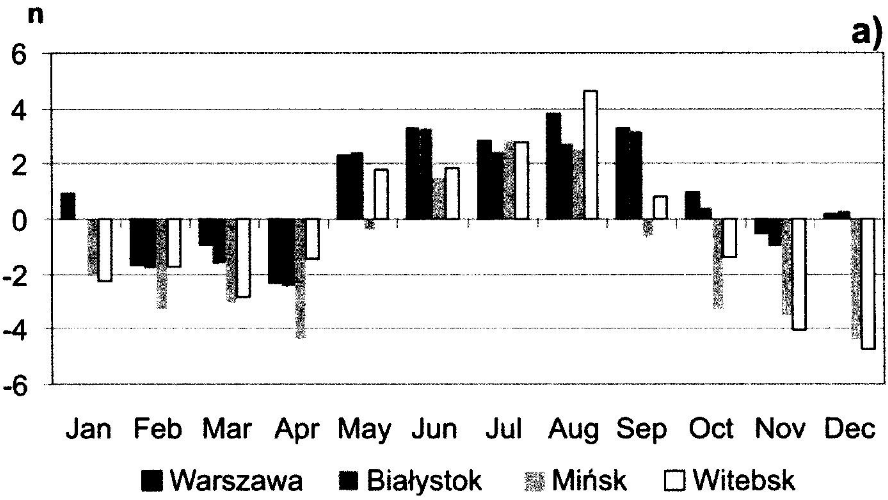
Fig. 7. Decadal frequencies of occurrence of summers (JJA) that were: a) extremely wet and very wet (indices 3 and 2) and b) extremely dry and very dry (indices –3 and –2) in Poland between 1501 and 1840 [after Przybylak *et al.* 2004].

Ryc. 7. Częstość występowania (n – liczba przypadków na 10 lat) sezonów letnich (VI–VIII): a) skrajnie wilgotnych i bardzo wilgotnych (indeksy 3 i 2) i b) skrajnie suchych i bardzo suchych (indeksy –3 i –2) w Polsce w okresie 1501–1840 [Przybylak i in. 2004].

of the norm. Interestingly, the driest year of all came in 1762, reporting just 63% of the norm).

The post-1800 period

Przybylak [2010] summarised the state of knowledge of courses for precipitation in Poland during the instrumental-observation period. Thus, all that are present-



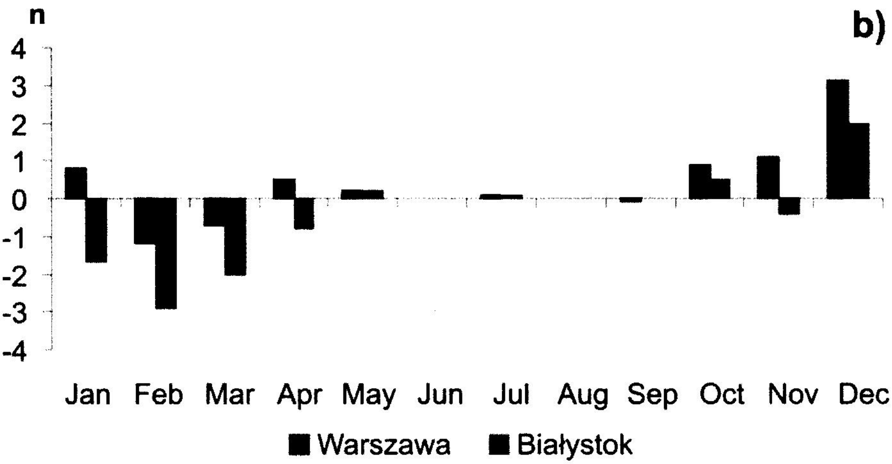


Fig. 8. Differences in numbers of days with precipitation (a) and with snowfall (b) in Poland between periods that are historical (1657–1667, J.A. Chrapowicki's diary) and modern (1961–1990, selected meteorological stations) [after Nowosad *et al.* 2007].

Ryc. 8. Różnice liczby dni z opadami (a) i ze śniegiem (b) w Polsce między okresami: historycznym (1656–1667, diariusz J. A. Chrapowickiego) i współczesnym (1961–1990, wybrane stacje meteorologiczne) [Nowosad i in. 2007].

ed here in this sub-chapter are selected most important results from that earlier work. Most publications concerning variability to precipitation in Poland relate to small areas only, or even to a single station [e.g. Gorczyński 1912; Trepińska 1969; Hohendorf 1970; Kożuchowski 1985; Twardosz 1999, 2007; Twardosz and Niedźwiedź 2001]. A large number of studies also discuss variability using data from across Poland, or certain regions thereof [e.g. Kaczorowska 1962;

Kożuchowski 1985; Miętus 1996; Kożuchowski and Żmudzka 2003; Twardosz and Cebulska 2010].

Thus far, the longest series of measured precipitation totals is that available for Cracow (post 1812). That for Warsaw is just slightly shorter, having begun in 1813 (Fig. 9). Przybylak [2010] in turn stated that the precipitation totals for the years to the end of the 1820s are of limited reliability, reconstructed as they were on the basis of numbers of days with precipitation. If these are excluded from the analyses then the annual precipitation totals for Cracow do not show any more major changes over the two-century study period. It is nevertheless possible to distinguish wetter times like 1830–1860, 1900–1920 and 1960–1972, as well as the years since 1996 (Fig. 9; Twardosz 2007). The trend for annual totals in Cracow in the years 1812–2007 has been up by 23 mm per 100 years, but this does not attain statistical significance. Similarly non-significant changes over the years 1867–2007 characterise seasonal totals, other than for winters, in which the increase in the amount of precipitation has been signficant [Przybylak 2010; Twardosz, Cebulska 2010].

Courses for total precipitation similar to those recorded for Cracow are present in other precipitation series presented in Fig. 9. Particular good concordance is present between the Cracow series and the averaged series obtained for the Baltic coast, or for Poland as a whole. A good spatial correlation for precipitation in Poland was noted by Kożuchowski and Żmudzka [2003], on the basis of data for 1951–2000 (coefficients for the correlation between the averaged precipitation series for Poland and the series from particular stations assume

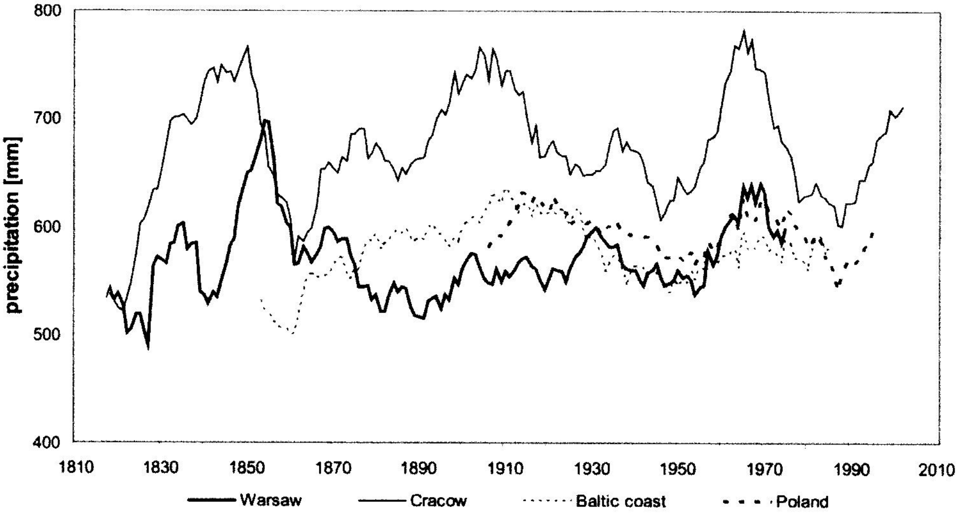


Fig. 9. Long-term courses of 11-year running mean annual precipitation in Poland during the period of instrumental observations (after Przybylak 2010, modified). Key: Data for Warsaw after Kożuchowski (ed.) (1990), for Cracow after Twardosz (1999, updated), for the Baltic coast after Miętus (1996), and for Poland [after Kożuchowski and Żmudzka 2003].

Ryc. 9. Wieloletni przebieg średnich 11-letnich ruchomych sum rocznych opadów atmosferycznych w okresie obserwacji instrumentalnych (za Przybylak 2010, zmienione). Objaśnienia: Dane z Warszawy za Kożuchowski (1990. red.), z Krakowa za Twardosz (1999, uaktualnione), z wybrzeża Bałtyku za Miętus (1996) oraz z Polski [za Kożuchowski i Żmudzka 2003].

values ranging from 0.6 do 0.8). The research done by many Polish climatologists also reveals that precipitation in Poland displays short-period oscillations over intervals of 2–4 years [Kożuchowski 1985; Miętus 1996; Kożuchowski and Żmudzka 2003].

In conclusion, it should be noted that, over the last 200 years, Poland has not witnessed any more significant change in amounts of precipitation.

Conclusions and final remarks

1. The existing incomplete and not fully reliable reconstructions of climate in Poland over the last millennium indicate that the first 500-year period was warmer than the second (especially as regards the first 300 years). It was mainly the warmer winters that gave this effect, since summers could even be cooler at times, if the index adopted here is the frequency of occurrence of hot summers [see Fig. 1 in Sadowski, 1991]. This was thus a period of major (and according to Sadowski [1991] even the greatest) oceanicity of the Polish climate. Thus, the history of Poland's climate needs to recognise the so-called Mediaeval Warm Period, most probably persisting through to the early 14th century [according to data from Maruszczak 1991] or the beginning of the 15th century [according to data from Sadowski 1991]. The mean air temperature then was probably higher by 0.5–1.0°C than what we experience now.

2. Beginning with the 15th century, the continentality of climate was maintained at a high level, and this continued through to the early the 19th century. As a result, this period brought winters that were markedly cooler (by c. 1.5–3.0°C in comparison with the 1901–1960 period), but also summers that were warmer (by c. 0.5°C on average). Mean annual values for air and ground-surface temperatures were most probably lower than current ones by some 0.9–1.5°C. At this point it is possible to distinguish the so-called Little Ice Age, which began more distinctly around the middle of the 16th century and most probably ended in the second half of the 19th century.

3. The reconstruction of precipitation (the most temporally and spatially variable of the meteorological elements) is burdened with much greater uncertainty than the process involving air temperature. More precipitation than average was probably present in the 12th century (especially its second half), in the first half of the 16th century, and in the first half of the 18th century. In turn, precipitation below the norm probably characterised the second half of the 13th century and the first half of the 19th century, while remaining periods probably had conditions close to average.

4. The short presented synthesis of knowledge on Poland's climate over the last millennium reveals that – despite the considerable progress made with research over the last 20–30 years – the situation remains inadequate and by no means fully certain.

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Streszczenie

Zmiany klimatu Polski w ostatnim tysiącleciu

W artykule przedstawiono aktualny stan wiedzy dotyczącej zmian klimatu Polski w ostatnim tysiącleciu. Do tego celu dla okresu przedinstrumentalnego zostały wykorzystane dostępne w literaturze przedmiotu rekonstrukcje trzech elementów klimatu: temperatury powietrza i powierzchni gruntu oraz opadów atmosferycznych. Natomiast zmiany klimatu po 1800 r. zostały przedstawione na podstawie dostępnych danych instrumentalnych. Analiza historii zmian klimatu w Polsce w ostatnim tysiącleciu pozwala wydzielić 3 charakterystyczne okresy, od dawna proponowane do opisu klimatu w tym czasie: Średniowieczny Okres Ciepły (do początku XV wieku), Małą Epokę Lodową (od połowy XVI wieku do drugiej połowy XIX wieku) i Współczesny Okres Ciepły. Ocieplenie klimatu w Polsce (o ok. 1°C) w ostatnim wymienionym okresie jest potwierdzone pomiarami termometrycznymi, jak również jest widoczne w rekonstrukcjach wykorzystujących metody geotermiczne i dendrochronologiczne. Ociepleniu nie towarzyszą istotne zmiany sum sezonowych i rocznych opadów atmosferycznych.