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Air temperature changes in Toruń (central Poland) from 1871 to 2010

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Abstract

The article presents a detailed analysis of changes in air temperature in Toruń in the period 1871–2010 on the basis of homogenised monthly, seasonal and annual air temperature series which have been newly constructed (i.e. extended by the 50 years of 1871–1920). Over the 140-year study period, a sizeable and statistically significant increase of 0.1 °C per decade was found in the air temperature in Toruń. The greatest increases occurred for spring and winter, at 0.12 and 0.11 °C, respectively. A lesser warming, meanwhile, was recorded for autumn (0.10 °C/10 years), and particularly for summer (0.07 °C/10 years). The air temperature trends are statistically significant for all seasons. Air temperature differences between the monthly averages of three analysed subperiods (1871–1900, 1901–1950 and 1951–2010) and averages for the entire period under review rarely exceeded ± 0.5 °C. In all of these periods, the highest average air temperatures occurred in July and the lowest in January. The period of 1981–2010 had the highest frequency of occurrence of very and extremely warm seasons and years. Meanwhile, the highest frequency of very and extremely cool seasons and years was recorded in the 1940s and in the nineteenth century. In the period of 1871–2010, winters shortened markedly (by 7%) and summers lengthened by 3.8%. All of the presented aspects of air temperature in Toruń, which is representative of the climate of central Poland, are in close agreement with the findings of analogous studies of the same for other areas of Poland and Central Europe.

1 Introduction

Research into climate changes and variability is one of the fundamental tasks of contemporary climatology (IPCC 2013). It is of particular importance that these aspects of climatological research should be conducted on different spatial scales, from the global to the regional and local. Reliable description and evaluation are only possible after having gathered all available empirical data for a given area and having verified them for quality. This last aspect is best and most reliably done when analysis is conducted for smaller areas and by local researchers, who are best acquainted with the available data on meteorological measurement locations and methods, and changes therein (i.e. metadata). Meteorological

data series produced in this manner should be submitted for further analyses for larger areas of the globe.

Excessively short measurement series are not suited to accurate evaluation of climate change trends, as they can lead to imprecise and frequently incorrect conclusions. For this reason, among others, we have in recent years undertaken to find all available instrumental data for Toruń from before 1920, after which year continuous regular observation data exists. For researchers to take full advantage of all available data sources requires that they be knowledgeable not only of meteorology and climatology (measurement methods, the specifics of measurement for particular meteorological features), but also knowledgeable of the history of metrology and the history sensu stricto of a particular place. In the several-centuries-long history of meteorological observation, changes generally affect the location of stations, measurement periods, the exposure of instruments and instrument sensitivity and precision (e.g. Quinn and Compton 1975; Wisniak 2000; Maciążek 2005). There were also changes in measurement scales and the overall metric system (Middleton 1966; Grigull 1986).

Despite considerable advancements in research, the problem of climate change in Poland still requires further in-depth analysis. Poland's tempestuous history (numerous wars and

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partitions) has meant that finding historical climate-related sources involves searching libraries and archives not only in Poland but also in Germany, Russia, Ukraine, Lithuania and Austria. Each discovered, described and analysed source of weather and climate information represents an important addition to knowledge of climate variability in Poland. In 1918, Pawłowski pointed this out, writing: "So we would have had at least two meteorological stations in Poland in the mid-18th century [Toruń and Warsaw – supplemented by authors] whose observations are deserving of all means to be found and announced". According to this postulate, research results have been produced for the Warsaw series (air temperature, Lorenc 2000) and for the Toruń series in the present paper. Besides the Warsaw and Toruń series, other long-term air temperature series for areas of Poland have been summarised, including for Łódź (Wibig et al. 2004), Poznań (Tamulewicz 2000), Wrocław (Bryś and Bryś 2010), Kraków (Trepińska and Kowanetz 1997; Piotrowicz 2007), Puławy (Górski and Marciniak 1992), Gdańsk Wrzeszcz and Hel (Miętus 1998; Filipiak and Miętus 2010) and Bydgoszcz (Vizi et al. 2000/2001).

Meteorological measurements for Toruń have to-date mainly been subjected to analysis in short measurement series covering the post-war period. Climate conditions in Toruń have been described by, among others, Gorczyński (1955), Ziembińska (1973), Wójcik and Marciniak (1984, 1987, 1993), Wójcik and Tomaszewski (1987), Marciniak and Wójcik (1991), Wójcik (1995), Wójcik and Marciniak (1996, 2001, 2006), Wójcik and Uscka (1999), Uscka-Kowalkowska et al. (2007), Araźny et al. (2007), Przybylak (2007), Przybylak and Maszewski (2009), Przybylak et al. (2012) and Pospieszyńska and Przybylak (2013).

The main aim of the present work is to evaluate air temperature changes in central Poland in the period 1871–2010 on the basis of newly reconstructed and homogenised data series for Toruń and in the context of changes taking place over this period in other regions of Poland and in central Europe. As the basis of the climatological analyses presented herein, the homogenised data series of average air temperatures has been appended in full to the article, as appendix 1.

1.1 The history of meteorological observations in Toruń

The history of meteorological measurements and observations in Toruń has been described by Pawłowski (1918), Dunajówna (1960), Rojecki (1965), Marciniak (1990), Biskup (1996) and Ciesielski (2004). These publications have allowed additional data sources to be identified, along with the locations they pertain to. The empirical data sources from before World War I contain descriptions both of the instruments used for measurement and of the methods themselves (*Ergebnisse der Meteorologische ... 1871–1919*).

Early instrumental measurements began in Toruń in 1740 and lasted until the middle of 1767 (Pawłowski 1918). Material published in the period 1760–1767 in *Thornische Wöchentliche Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen* (TWNA, a.k.a. "Tygodnik toruński" (Eng. "Toruń Weekly")—Fig. 1) has been preserved to the present day.

In the years 1740–1767, meteorological measurements were conducted for two periods in Toruń (morning and evening). These included readings of air temperature (on Florentine and Réaumur scales), atmospheric pressure (in Rhine-inches; 1 Rhine-inch = 26.1541 mm) and wind direction (in points of the compass), as well as weather observations, including of hydrometeors (Fig. 1). These were published as weekly lists in the aforementioned TWNA (Pawłowski 1918; Dunajówna 1960; Rojecki 1965; Marciniak 1990; Ciesielski 2004). Besides meteorological data, the weekly publication also contained data on water levels in the Vistula River. The text also included additional information on extreme events (most commonly, floods on the Vistula and storms) and phenological events, such as the flowering of plants (Dunajówna 1960). The exact constructions of the measuring instruments (thermometer, barometer and anemometer) are not known.

Measurements in the period 1740–1767 were begun by Samuel Luther von Geret in the vicinity of the Gimnazjum Akademickie (eng. Academic Gymnasium) buildings in Toruń Old Town (Biskup 1996). The measurements were taken care of by Samuel Theodor Schönwald. Upon his death in 1764, there was a drop in the quality of the published data, with lists being duplicated in subsequent editions of the TWNA.

In the Toruń Branch of the National Archive, there are lists of meteorological observations for the years 1842–1858. Temperature measurements were taken at 8.00 a.m. according to the Réaumur scale. The place of measurement is not known, nor is the exposure or adjustment of the instrumentation. For the period of 1842–1850, only annual averages are available, and monthly averages for 1851–1858. This data is reprinted in a publication by Rojecki (1965).

Around the nineteenth century, Toruń spent over a hundred years in the border zone between two occupying powers and was made a Prussian fortress. Toruń owes the Prussians not only its military buildings, which were unique in Europe for the time, but also the first regular meteorological measurements which were conducted by the Royal Prussian Meteorological Institute (Königlich Preussischen Meteorologischen Instituts). The first published data on Toruń are from 1872. In the period 1872–1890, the measurements were conducted by the Royal Prussian Meteorological Institute. Political changes in the German Empire—a change in Chancellor in 1890—led in 1891 to the meteorological service changing name from the

Fig. 1 Data from the *Thornische Wöchentliche Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen* for the period 1–7.01.1760 (Geret 1760–1767)

Prussian to the German Meteorological Institute. It conducted observations almost until the end of the World War I. After the return of Toruń to Poland in 1920, in the period 1921–1939, observations in the town were conducted by the Polish National Meteorological Institute. The Second World War brought further changes in meteorological measurements—they were assumed again by the German service. After the war—from 1945, meteorological measurements and observations were conducted by Soviet army until 1947 (Zieliński, pers. comm.) and then by the National Hydrological and Meteorological Institute (PIHM). In 1971, PIHM was re-named the Institute of Meteorology and Water Management (IMGW), and again in 2010 as the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB).

2 Area, data and methods

Toruń is located in the Vistula Valley in central Poland at an average elevation of 65 m a.s.l. (Fig. 2). According to the climate classification proposed by Okołowicz and Martyn (1979, 2004), Toruń lies in the Nadwiślański Region in a temperate warm zone of year-round precipitation. The area is subject to Atlantic, Baltic and continental influences. The Nadwiślański Region has a warm summer and a moderately cool winter with low precipitation.

The city's greatest population increase occurred between the nineteenth century and twentieth century (to a total population of 40,000 inhabitants), but saw its greatest surge from the 1960s until about 1995 (going from 105,000 to 205,000). Since then, the number of inhabitants in Toruń has remained more or less stable (Przybylak et al. 2017).

The locations of different categories of meteorological stations in Toruń and the range of observations were changed due to political changes, two world wars, urban expansion and a change in the number of stations themselves (Fig. 3). In the 1920s, for example, four stations were operated concurrently by the military meteorological services.

Prussian meteorological observations in Toruń began at the beginning of 1872 at the Thorn-Weisshoff station in the vicinity of the airport's Balloon School, in the area of what is presently the junction of the streets Szosa Chełmińska and Czerwona Droga (Fig. 3).

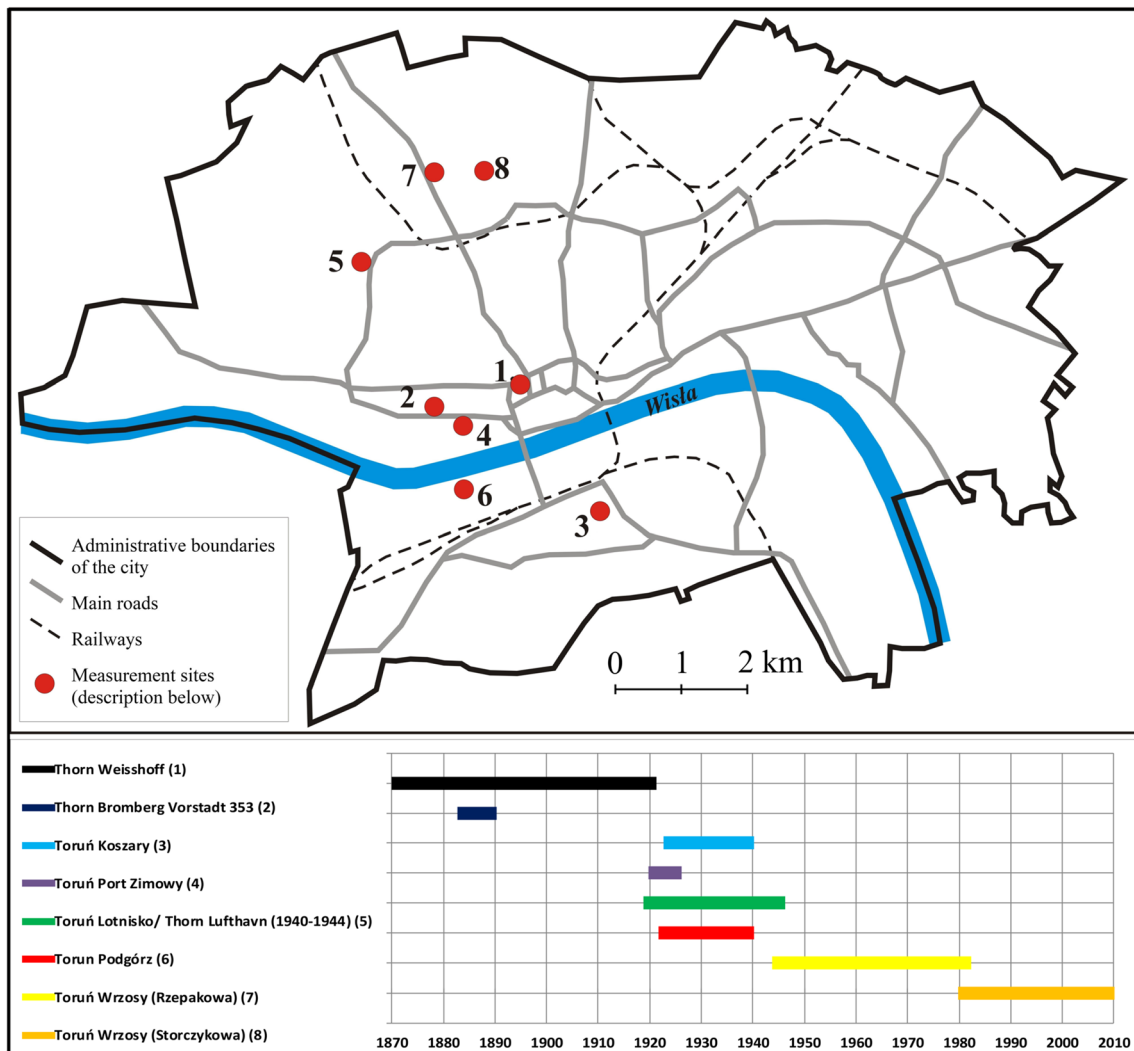**Fig. 2** Geographical location of Toruń (53°01′20″N 18°36′40″E) and reference stations (see Table 3)
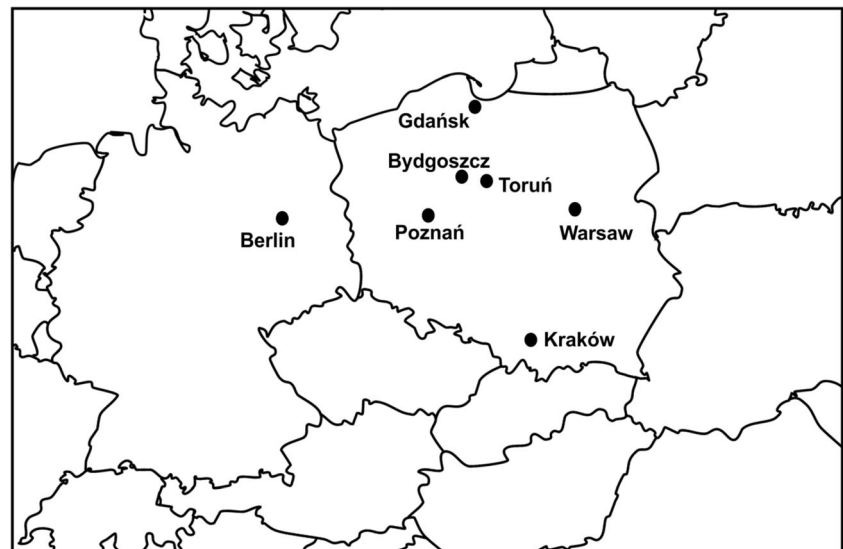

Fig. 3 Location of meteorological stations in Toruń in 1871–2010 and periods of observations

In the years 1884–1889, the Toruń station was significantly promoted, becoming a first-order station. It is known to have then been located in a building in Bydgoski Przedmieście (Bromberg Vorstadt, number 353) at what is today the junction of Bydgoska Street and Matejki Street. The data for that period are recorded at different intervals (including sub-daily). The locations of measurement points in operation in the years 1871–2010 are presented in Table 1 and Fig. 3 (map). The present location of measurement stations, which have existed uninterrupted since 1981, is Storczykowa Street 124 in a low-rise neighbourhood of detached houses. In recent years (i.e. after 2010 when the series analysed here ends) in the area bordering the station to the east a new, higher-rise residential neighbourhood called JAR has been being built, and this may interfere with the station's ability to be representative. Before this time, there was no building development around the meteorological station. Also, the urban heat island which exists in Toruń (see Przybylak et al. 2017) does not significantly influence measurements, because the station is located on the outskirts of the city. The mean annual daily difference is 0.1 °C lower here than at the rural station (see Fig. 7 in Przybylak et al. 2017). In order to construct a homogenised air temperature series for Toruń, data from four stations on the right bank of the Vistula river were used, namely stations 1, 5, 7 and 8 (Table 1, Fig. 3).

This paper uses monthly average air temperatures for 1871–2010. Data are derived from primary sources (measurement logbooks) and secondary sources (meteorological yearbooks) published first by the Prussian and then the German and Polish meteorological services (Table 2).

Data are taken from sources available in the archive and library of Institute of Meteorology and Water Management, National Research Institute (IMGW-PIB), the National Library, Wrocław University Library, University of Warsaw Library, the Copernican Library in Toruń, the Nicolaus Copernicus University Library and the Nicolaus Copernicus University Environmental Library. Inquiries were expanded to include the Berlin Charité Library, the Library of the Institute für Meteorologie und Weltraumwissenschaften Freie Universität in Berlin and the Library of Zentralanstalt für Meteorologie und Geodynamik in Vienna.

The measurement instructions and organisation of the Prussian network have been determined in mid-nineteenth century, by its then director—G. J. Hellman. He was also the author of the content and template of the meteorological yearbook (Fig. 4). The yearbooks contained lists of monthly and diurnal data for the first-order station, while the second- and third-order stations contained lists of monthly averages and sums for selected meteorological features. In layout and form, these lists were the same as those later used in the yearbooks published by the Polish National Meteorological Institute of the 1920s and later. It is worth noting that the yearbooks of the German meteorological service contained an introduction with a description and characteristics of the measurement stations and a precise description of the instruments used in the measurement network, together with schematics.

From the very beginning of empirical measurements, the network conducted observations three times a day. Observation times did undergo some changes (Table 2). Until the mid-1960s, the average values of individual elements were calculated based on an equation with a weighted average—$(t7 + t13 + 2*t21)/4$—which was also used for the measurements from the German network. Since then at all synoptic meteorological stations in Poland (including Toruń), observations were made hourly and, as a consequence, daily means were calculated using the formula: $(t1 + t2 + t3 + \ldots .t24)/24$.

Until the end of World War II (WWII), the average daily temperature was measured and calculated based on an equation with a weighted average, using $(t6 + t13 + 2*t20$ UTC$)/4$. From 1946 to 1970, Polish weather services calculated the

Table 1 Geographical location of meteorological stations operating in Toruń in the years 1871–2010, with elevation a.s.l.

No.	Name	Longitude	Latitude	Elevation (m a.s.l.)	Periods of operation	Thermometers used/producer
1	Thorn Weisshoff	18°36′	53°01′	52.2	1871–1920	Unknown
2	Thorn Bromberg Vorstadt 353	18°36′	53°01′	52.0	1884–1889	Fuess
3	Toruń Koszary	18°35′	53°00′	57.8	1924–1939	Józef Jaborka
4	Toruń Port Zimowy	18°35′	53°01′	52.7	1921–1925	Balcerkiewicz
5	Toruń Lotnisko/Thorn Lufthavn	18°36′	53°00′	52.1	1920–1944	Józef Jaborka (1920–1939) Bossecker (1940–1944)
6	Toruń Podgórz	18°36′	53°00′	50.6	1923–1939	Fuess
7	Toruń Wrzosy (Rzepakowa)	18°35′	53°03′	70.7	1945–1981	Mercury thermometers produced by KWT (Kujawska Wytwórnia Termometrów)
8	Toruń Wrzosy (Storczykowa)	18°35′	53°02′	69.7	Since 1981	Mercury thermometers produced by KWT. Since 2014 temperature and humidity sensor by Vaisala

Table 2   List of available source data from instrumental air temperature measurements in Toruń, beginning in the eighteenth century

Period	Sample rate interval	Omissions	Unit	Source:
1760–1767	fixed-hours (morning, evening)	–	°Fl and °R	*Thornische Wöchentliche Nachrichten und Anzeigen nebst einem Abhange von Gelehrten Sachen*
1842–1850	annual (08.00 a.m.)	–	°C	Material gathered in the Toruń branch of the National Archive
1851–1858	monthly (08.00 a.m.)	–	°C	Material gathered in the Toruń branch of the National Archive
1872–1878	Monthly	10.1875; 10–11.1876; 9.1877; 11–12.1878	°R	Ergebnisse der Meteorologischen Beobachtungen 1871–1919, Königlich Preussisches Meteorologisches Institut, Berlin.
1884–1889	fixed-hours (6, 14, 22 UTC)	01.1888	°C	Ergebnisse der Meteorologischen Beobachtungen 1871–1919, Königlich Preussisches Meteorologisches Institut, Berlin.
1921–2010	fixed-hours (changing hours in different periods), hourly, daily	09.1922; 08.1939–02.1940; 12.1944–09.1945	°C	PIM/PIHM/IMGW/IMGW-PIB logbooks and yearbooks 1920–2010

weighted average as (t6 + t12 + 2*t18 UTC)/4. From 1970 to the end of 1995, the average was calculated from 4 values: 00:00, 06:00, 12:00, 18:00 UTC. Since 1996, the daily average has been calculated as the average of the maximum temperature (from 18:00 UTC), the minimum (from 18:00 UTC) and actual temperature from 06:00 and from 18:00 UTC. Between World War I and World War II and after WWII, the analysed data comes from the Institute of Meteorology and Water Management—National Research Institute, which is responsible for quality control. The quality control of measured (fixed hours) and mean daily data was automatic and very detailed and was done in two stages. First, for each month, the preliminary stage

included, e.g. checking of data completeness and extreme values, functional relations and time course (for more details, see Pruchnicki 1987). The second, content stage included investigation of spatial coherency data from neighbouring stations. Although there were changes in the method for calculating daily average, the Alexandersson test utilised in the present work did not register any breaks in the series, except for 1970.

In the first stage of organising the Toruń meteorological data which were gathered from the various sources described above, a computer database was created which included the air temperature analysed in this article. The average monthly air temperature values were checked first

Fig. 4 Sample page of the meteorological yearbook (*Ergebnisse... 1885*)

Table 3 Monthly correlation coefficients between Toruń air temperature series and series from stations used to make the reference series, 1871–2010

Station	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
Bydgoszcz	0.992	0.993	0.988	0.973	0.966	0.889	0.865	0.859	0.924	0.967	0.988	0.986
Kraków	0.912	0.928	0.935	0.894	0.897	0.765	0.733	0.704	0.859	0.914	0.917	0.912
Poznań	0.968	0.984	0.978	0.961	0.929	0.825	0.794	0.784	0.893	0.930	0.970	0.975
Warsaw	0.951	0.977	0.972	0.949	0.918	0.789	0.793	0.788	0.908	0.929	0.972	0.951
Berlin	0.950	0.964	0.948	0.867	0.839	0.753	0.641	0.619	0.762	0.838	0.924	0.944
Gdańsk	0.955	0.966	0.962	0.940	0.902	0.817	0.799	0.806	0.875	0.909	0.943	0.941

for completeness, and any data gaps were supplemented by the constant difference method (Pruchnicki 1987) based on the homogenised data series from the nearest station, located in Bydgoszcz. Monthly data series from Toruń and Bydgoszcz correlate closely (correlation coefficient for Sep–May in excess of 0.98, falling over the year to 0.86 in August) (Table 3). In the next stage, the monthly average air temperature data were homogenised after the method proposed by Alexandersson (1986) as well as by Alexandersson and Moberg (1997a, b). In the first stage of homogenisation, the Berlin, Bydgoszcz, Gdańsk, Kraków, Poznań and Warsaw stations were selected based on the size of correlation coefficients, and these allowed a series of reference air temperatures to be created for Toruń.

Reference series of air temperature obtained by averaging data from all stations were normalised. The zero hypothesis (that the Toruń data series is homogeneous) was verified by the equation (Alexandersson and Moberg 1997):

$$T^s_{max} = \max_{i \le a \le n-1} \left\{ a(z_1)^2 + (n-a)(z_2)^2 \right\},$$

where z_1 and z_2 are the average values of the normalised reference series in two parts of the range: from the beginning

to the ath item and from item a + 1 to the end of the range; T^s_{max} is the test statistic for the single shift test.

If the value of T^s_{max} exceeds the critical level, it means that "the null hypothesis of homogeneity can be rejected at the corresponding significance level, which means the homogeneity has been interrupted" (Alexandersson and Moberg 1997)—Fig. 5. Critical values for the measurement series were established (based on numbers of measurement series) as: T_{90}–8.05 and T_{95}–9.35. Interruptions in homogeneity most commonly result from changes in measurement methods, changes in instrumentation or changes in measurement location.

For the Toruń series, interruptions within the series are mainly seen in times when stations were moved and changes were made in measurement methods: 1878, 1889, 1921, 1939, 1945, 1970 and 1981 (Table 4). Homogenisation was conducted for all months using the AnClim software (Štěpánek et al. 2009). Homogeneous Toruń air temperature series (1871–2010) are provided in extenso in appendix 1, and for January and July are also depicted in Fig. 6. All discovered inhomegeneities were corrected for using normalised series of differences between data taken from Toruń and data from Bydgoszcz (the homogenised series), located 50 km to the
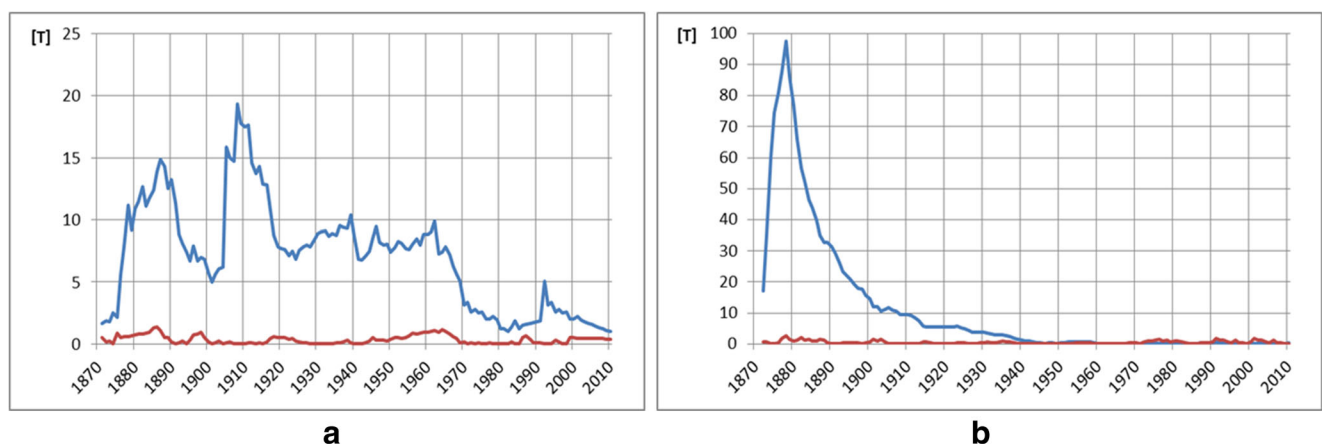

Fig. 5 The course of T^s_{max} values for **a** January and **b** July before and after homogenisation of average Toruń air temperatures, 1871–2010 (blue line: before homogenisation; red line: after homogenisation)

Table 4 Reasons for interruptions in the Toruń series in the years 1871–2010 detected by the Alexandersson test

Period of interruption	Probable/identified cause
1878	Unknown cause
1889	Unknown cause
1921	Creation of the Polish measurement network after re-gaining of independence
1939	World War II frontline operations–German service resumes measurements.
1945	World War II frontline operations–Polish service resumes measurements.
1970	Change in the method of calculating the daily average
1981	Change of station location from Rzepakowa Street to Storczykowa Street

west from Toruń and, as Table 3 shows, Bydgoszcz also correlates very closely with Toruń of all the stations analysed here.

This article uses standard meteorological data analysis methods for climatological work. For example, for year-to-year variability analysis, common variability measures such

as standard deviation and range of variability were used. In turn, the statistical significance of the air temperature trends was determined for a confidence level of 0.95 by Student's t test (Zwiers and von Storch 1995).

The highest and lowest average seasonal and annual air temperature values (t_i) were determined on the basis of

Fig. 6 The course of average monthly air temperature in January (upper chart) and July (lower chart) before filling in of gaps and homogenisation (red line) and after (blue line) (homogenised and unhomogenised data series are identical after 1980)
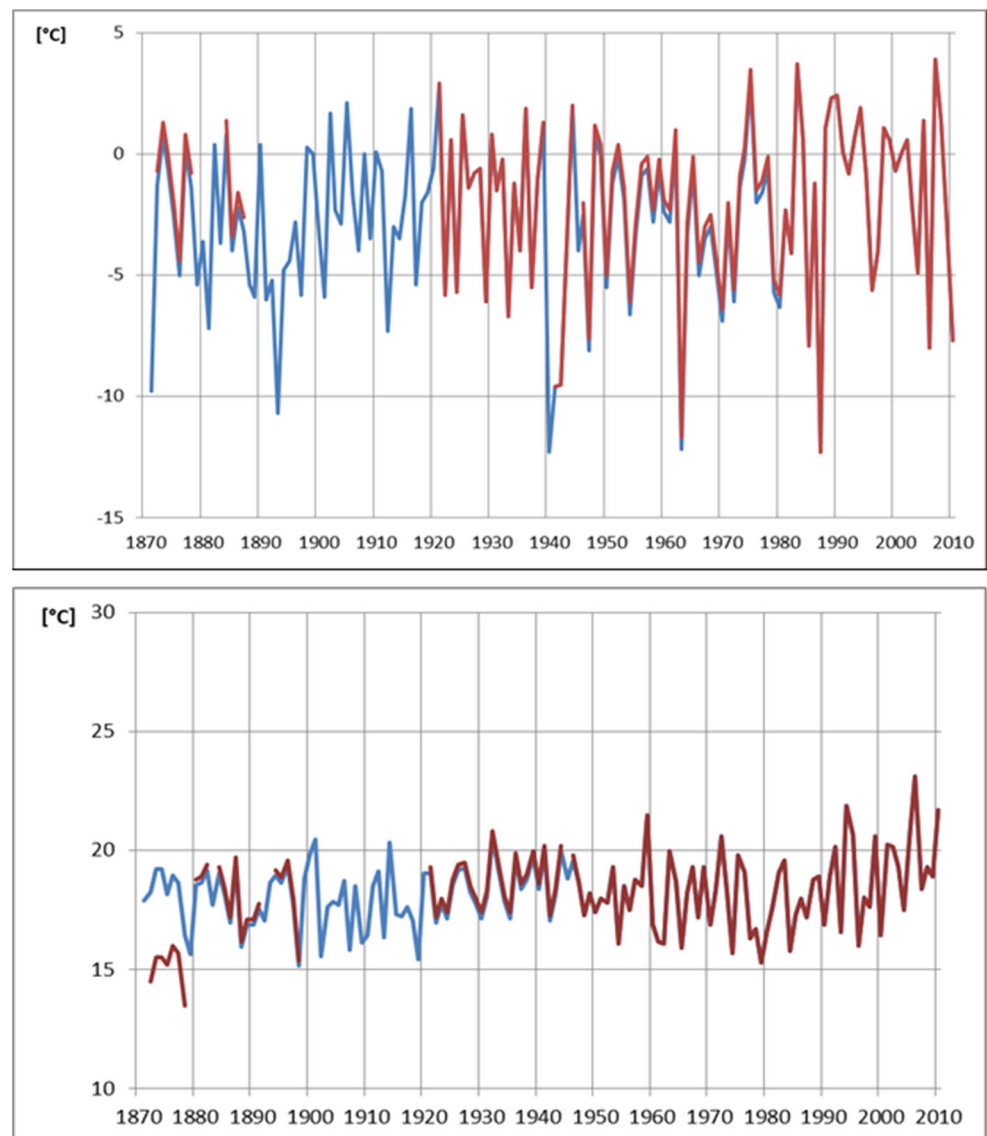
Table 5 Average seasonal and annual air temperatures (°C) in Toruń (1871–2010) for selected percentile threshold values

Percentile	YEAR	DJF	MAM	JJA	SON
99%	10.4	5.2	11.2	20.0	11.1
95%	9.5	2.9	9.9	19.0	10.0
5%	5.9	− 6.2	4.6	15.3	5.8
1%	5.0	− 8.4	3.2	14.4	4.7

the identified percentile threshold values (1, 5, 95, 99%, Table 5). Anomalous average monthly, seasonal and annual air temperatures were determined relative to the reference period 1871–2010. This method allows months, seasons and years with extremely high air temperatures to be identified and has already been used for diurnal air temperatures in Toruń (Przybylak et al. 2012). For all months, seasons and years, values and dates were provided for the highest and lowest air temperatures.

3 Results

The climate in Toruń is driven by two major baric regimes: the Icelandic Low (greater winter influence) and the Azores High (greater summer influence). The influence of the South Asian High increases in the summer, and the Asian (Siberian) High in winter. The research area's location in Central Europe means that a typical transitional moderate climate predominates, characterised by dynamic weather changes, both from day to day and from year to year, particularly in winter. The latitudinal configuration of the land is conducive to the transfer of air masses from over the Atlantic, eastwards into the continent. Continental air masses can also easily flow westwards.

Thermal conditions in Toruń are driven by many factors, including, e.g. geographic location, atmospheric circulation, insolation and cloud cover. Radiative factors dominate in summer and circulation-related factors in winter. In all seasons,

anomalies in the frequency of atmospheric circulation types can significantly disturb the annual course of air temperatures. Particularly significant in this is the role of cyclonic systems moving from west to east and carrying oceanic air, causing winter temperature increases and summer decreases.

Detailed analyses of air temperatures in Toruń and surrounding areas have been conducted by Wójcik and Marciniak (1984, 1987, 1995, 1996, 2001, 2006), Marciniak and Wójcik (1991), Pospieszyńska and Przybylak (2013). In the present article, as mentioned above, the air temperature series has been extended beyond that previously available by 50 years (from 1920 back) and has been homogenised.

3.1 Long-term course

The present paper presents a climatic analysis based on newly constructed homogenised monthly, seasonal and annual air temperature series for the period 1871–2010 (appendix 1). Air temperature in this period shows similar behaviour as at other European stations. In this period, the annual average air temperature was 7.7 °C and ranged from 4.9 °C in 1871 to 9.7 °C in 2000 (Fig. 7). In the long-term course, clearly warmer periods can be distinguished (the early twentieth century and 1991–2000) as well as cooler periods (the beginning of the series and 1951–1980).

The trend in average air temperature is upwards and statistically significant. It is of around 0.1 °C per decade and is similar to that for Europe as a whole (Rebetez and Reinhard 2007; Dobrovolný et al. 2009; Leijonhufvud et al. 2010; Mikkonen et al. 2015; Niedźwiedź et al. 2015). In terms of seasons, the greatest increases in temperature were in spring and winter, being 0.12 and 0.11 °C/10 years, respectively (Table 6 and Fig. 8). A slightly lesser warming was recorded in autumn (0.10 °C/10 years), and a much lesser one in summer (0.07 °C/10 years). Trends in air temperature for all seasons are also statistically significant.

The trend values shown in Table 6 for various subperiods of the analysed long-term period clearly show a warming

Fig. 7 The course of average annual air temperature in Toruń in the period 1871–2010 (homogenised series) and its trend (red line: 10-year moving average; green line: 20-year moving average)
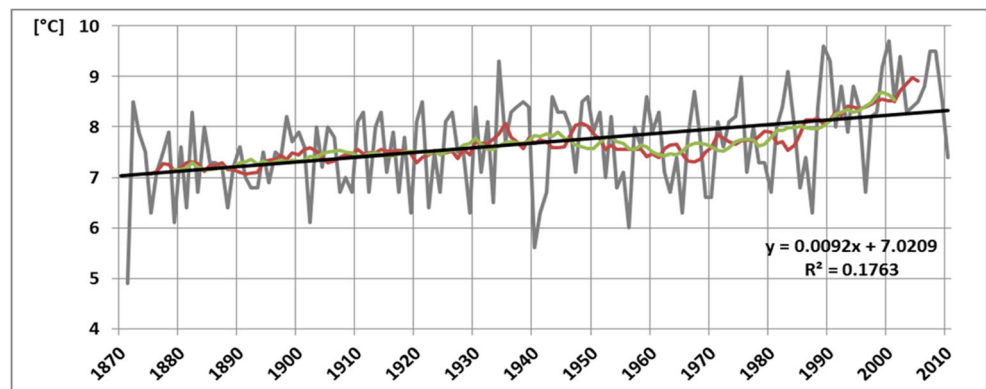
$y = 0.0092x + 7.0209$
$R^2 = 0.1763$

Table 6 Seasonal and annual directional coefficients for air temperature trends (°C/10 years) in Toruń in the periods 1871–1900, 1901–1950, 1951–2010 and 1871–2010

Period	DJF	MAM	JJA	SON	YEAR
1871–1900	0.18	0.26	− 0.05	0.13	0.12
1901–1950	− 0.22	0.17	0.28*	0.27*	0.13
1951–2010	0.15*	0.11*	0.08*	0.10*	0.11*
1871–2010	0.11*	0.12*	0.07*	0.08*	0.09*

*Trends statistically significant at the 0.95 level

which began in the 1950s. The greatest increase in seasonal and annual average air temperatures was recorded in the 60 years of 1951–2010. A growth trend was also seen in average annual air temperatures in the 1792–1995 series for Kraków, of the order of 0.05/10 years (Trepińska and Kowanetz 1997). In Kraków, all seasons have an upward trend apart from summer, for which a downward trend of − 0.01/ 10 years is seen.

The range of temperature fluctuations in Toruń in the period of instrumental measurements was 70.6 °C. The absolute maximum, which occurred on 11 July 1959, was + 38.2 °C (Table 7). Meanwhile, the absolute minimum (− 32.4 °C) occurred on 19 January 1963. Of the seasons, the greatest ranges of air temperature fluctuations are for spring (58.8 °C) and autumn (55.6 °C). In winter and summer, these ranges did not exceed 50 °C (49.5 and 39.8 °C, respectively).

Average seasonal values for winter ranged from − 8.8 to 2.8 °C (Table 7). The transitional seasons had seasonal

averages ranging from 3.8 to 10.3 °C for spring and 5.3 to 10.9 °C for autumn. Summer's lowest seasonal average was 15.0 °C, and 19.6 °C its highest. In the period 1951–1970, the seasonal average air temperatures were, respectively, − 1.7, 6.5, 17.5 and 8.0 °C (Wójcik and Ziembińska 1984).

As mentioned previously, very warm and very cool—and extremely warm and extremely cool—years are determined using percentile threshold values of 95, 5, 99 and 1%, respectively. Six very warm years were identified (1990, 1934, 2002, 2007, 2008, 1989) and 1 extremely warm year (2000), as well as 10 very cool years (1919, 1929, 1941, 1965, 1987, 1875, 1902, 1879, 1956, 1940) and 1 extremely cool year (1871). A clearly greater frequency of very warm years was recorded in the last three decades of the study period (Fig. 9).

Very and extremely warm seasons, as with whole years, have also been more frequent in the last three decades of the study period (Table 8). There was an extraordinarily warm winter in 1989/1990, with an average of 2.8 °C. Very warm winters have an average seasonal temperature range of + 1.4 to + 2.6 °C. Six of the seven warmest winters occurred in the years 1981–2010. Very and extremely warm springs and summers were also very frequent in 1981–2010 (6 out of 9 instances and 5 out of 7, respectively). Only three out of seven such autumn seasons occurred in the same 30 years.

In the case of very and extremely cool years, clearly cooler periods can be seen: 1940–1971 (5 very cool years) and 1871–1900 (2 very cool years and 1 extremely cool). In these periods, very cool winters and springs are more frequent (winters: 1939/1940, 1946/1947, 1962/1963 and 1969/1970; springs: 1877, 1883, 1942, 1955 and 1965). Very cool
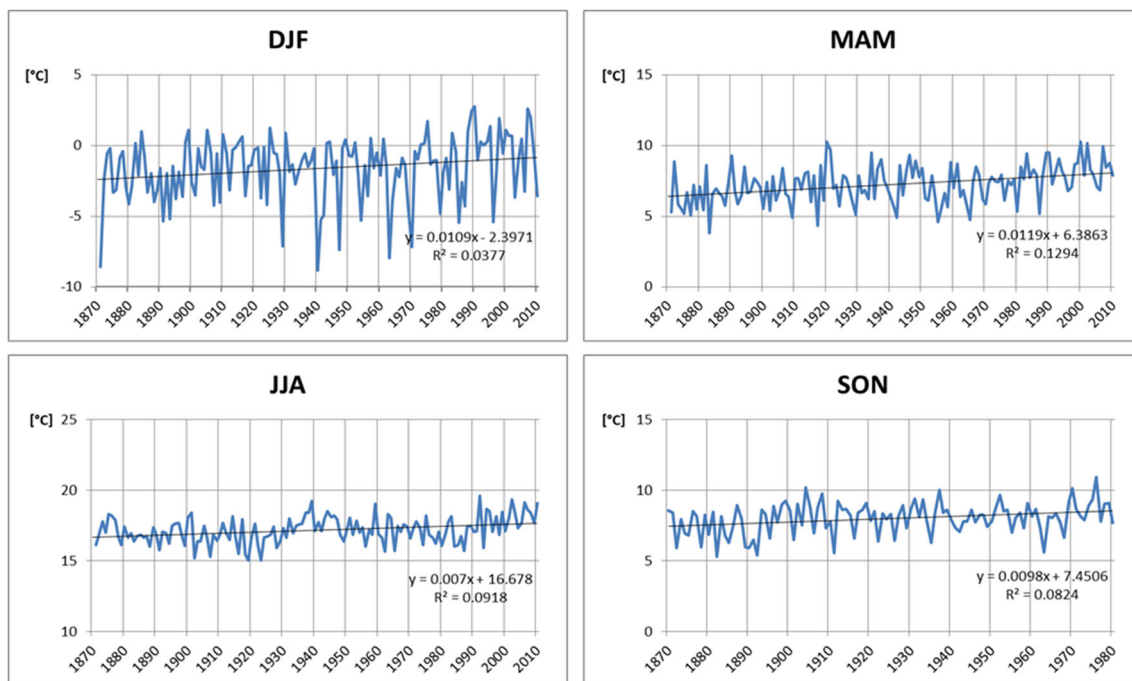

Fig. 8 The course of homogenised seasonal average air temperatures and their trends in Toruń, 1871–2010

Table 7 Monthly, seasonal and annual averages (t_i) (with their highest, ti_{Nw}, and lowest, ti_{Nn}) and daily maximum and minimum air temperature values (°C) in Toruń in 1871–2010, with dates of occurrence

Period	J	F	M	A	M	J	J	A	S	O	N	D	DJF	MAM	JJA	Son	Year
Ti	−2.5	−1.4	1.8	7.1	12.8	16.0	18.2	17.3	12.9	8.0	2.9	−0.8	−1.6	7.2	17.2	7.9	7.7
ti_{Nw}	3.9	4.8	6.7	12.1	17.5	19.3	23.1	21.0	16.4	12.2	6.4	4.6	2.8	10.3	19.6	10.9	9.7
$t_{max\ abs}$	12.8	17.1	23.4	29.9	32.3	35.5	38.2	37.5	32.8	28.3	19.9	13.2					
Date/year	22 1993	21 1990	30 1968	23 1968	31 1979	21 2000	11 1959	10 1992	4 1942	4 1966	1 1968	6 2006	1989/90	2000	1992	2006	2000
ti_{Nn}	−12.3	−12.6	−3.8	2.3	8.5	12.0	15.1	14.5	8.8	4.0	−2.9	−9.0	−8.8	3.8	15.0	5.3	4.9
$t_{min\ abs}$	−32.4	−30.5	−26.5	−17.0	−6.2	−1.6	2.9	1.4	−3.7	−10.1	−22.8	−26.2					
Date/year	19 1963	21 1940	8 1965	4 1929	2 2007	1 1935	1 1951	26 1973	29 1970	24 2003	24 1965	15 1933	1939/40	1883	1919, 1923	1871, 1912	1871

summers were noted mainly in the period 1902–1923, with as many as 6 (1902, 1907, 1916, 1918, 1919, 1923) of the total 7 very and extremely cool years for the full period.

Average decadal anomalies in seasonal and annual air temperatures in Toruń relative to the corresponding averages for the entire period show a clear growth trend (Fig. 10). The last two decades show positive anomalies for all seasons and for annual averages. Meanwhile, there were decidedly more negative anomalies in the beginning of the study period. In the first three decades, all four seasons and the annual average experienced negative anomalies (Fig. 10).

The maximum anomalous values (both positive and negative) range between 1.0 and 1.5 °C. Based on the size of the anomalies, it was concluded that winter and summer months have the greatest impact on annual average temperature. So, these two seasons have the greatest effect on the thermal regime in Toruń.

The air temperature in Toruń is very variable in its course from year to year (Table 9). The standard deviations of annual average air temperature range between 1.0 °C in the decades 1871–1880 and 1981–1990 and 0.5 °C in the decade 1891–1900. The highest annual average temperature stability is seen at the turn of the nineteenth to twentieth century. Beginning in the 1920s, it stays at a similar level, ranging usually between 0.8 and 0.9 °C. The last 30 years of the study period show a decrease in the variability of the annual average air temperature.

In terms of seasons, the greatest variability in air temperature from year to year is for winter—at up to about 2.5 °C in the period 1921–1950. The remaining seasons have less variable average air temperatures from year to year—with a maximum of 1–1.5 °C. Decidedly, the most stable seasonal temperature is for summer (Table 9 and Fig. 11). The greatest changes in variability are in winter, spring, autumn and the whole year—these changes are statistically significant.

The annual course of air temperature in Toruń in the period 1871–2010 is typical of stations in a temperate zone (Fig. 12). The lowest air temperatures are recorded in January (− 2.5 °C) and the highest in July (18.2 °C). Average January values for the entire study period changed from − 12.3 °C (in 1987) to + 3.9 °C (in 2007). A similar range of fluctuations, from − 12.0 °C in 1940 to 3.1 °C in 1975, was seen in Łódź (Wibig et al. 2004) for 1903–2000. The highest average decadal air temperature values for January in Toruń were recorded in the decade 1991–2000 (− 0.8 °C) and the lowest in the decade 1891–1900 (− 4.3 °C).

Average July values changed over the study period, from 15.1 °C in 1898 to 23.1 °C in 2006. A similar range of fluctuation, from 14.6 °C in 1979 to 21.5 °C in 1994, was seen in Łódź (Wibig et al. 2004). The highest average decadal air temperature values for July in Toruń were recorded in the last decade of the study period (19.9 °C), while the lowest were for the decade 1901–1910 (17.5 °C).

Fig. 9 Very warm, extremely warm, very cool and extremely cool years and seasons in Toruń, with thermal anomalies relative to the period 1871–2010. By colour: red indicates extremely warm years (≥ 99%); orange very warm years (≥ 95%); green very cool years (≤ 5%); dark blue extremely cool years (≤ 1%)
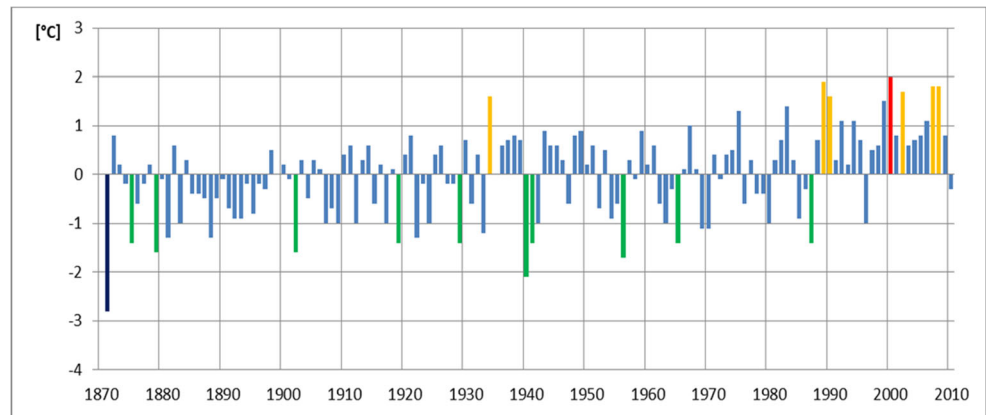
The total range of changes in monthly average air temperatures in Toruń in the years 1871–2010 ranged from 23.1 °C in July to − 12.6 °C in February.

Figure 13 shows that temperature differences between the monthly averages of the three subperiods (1871–1910, 1911–1960 and 1961–2010) and the averages for the entire study period rarely exceeded ± 0.5 °C. It can therefore be stated that the shape of the annual courses in the subperiods did not change significantly relative to the average. Clearly coolest for almost all months was the period 1871–1910, while 1961–2010 was clearly warmest.

3.2 Thermic seasons

The thermic seasons in Toruń were identified based on average diurnal air temperature, using the three thermal thresholds 0.0, 5.0 and 15.0 °C as proposed by Merecki (1914):

– winter ≤ 0.0 °C
– 0.0 °C < early spring ≤ 5.0 °C
– 5.0 °C < spring ≤ 15.0 °C
– summer > 15.0 °C

Table 8 Very warm and extremely warm, as well as very cool and extremely cool years and seasons in Toruń, 1871–2010

Percentile	Year	T (°C)	DJF	T (°C)	MAM	T (°C)	JJA	T (°C)	Son	T (°C)
≥ 99%	2000	9.7	1989/1990	2.8	2000	10.3	1992	19.6	2006	10.9
					1920	10.3				
≥ 95%	1989	9.6	2006/2007	2.6	2002	10.2	2002	19.3	1934	10.2
	2008	9.5	1988/1989	2.5	2007	10.0	1939	19.2	2000	10.1
	2007	9.5	2007/2008	2.0	1921	9.7	2006	19.2	1967	10.0
	2002	9.4	1997/1998	2.0	1989	9.5	2010	19.1	1938	9.8
	1934	9.3	1974/1975	1.8	1934	9.5	1959	19.0	1982	9.7
	1990	9.3	1994/1995	1.4	1990	9.5	1994	18.7	1872	9.5
					1983	9.5				
Percentile	YEAR	T (°C)	DJF	T (°C)	MAM	T (°C)	JJA	T (°C)	SON	T (°C)
≤ 5%	1919	6.3	1995/1996	− 5.4	1929	5.1	1962	15.6	1920	5.9
	1929	6.3	1984/1985	− 5.4	1877	5.1	1916	15.5	1902	5.9
	1941	6.3	1928/1929	− 7.1	1909	4.9	1918	15.5	1875	5.7
	1965	6.3	1969/1970	− 7.2	1942	4.9	1907	15.3	1993	5.6
	1987	6.3	1948/1947	− 7.4	1965	4.8	1902	15.2	1941	5.5
	1875	6.3	1962/1963	− 7.9	1955	4.6			1922	5.4
	1902	6.1	1871[a]	− 8.6	1917	4.3				
	1879	6.1								
	1956	6.0								
	1940	5.6								
≤ 1%	1871	4.9	1939/1940	− 8.8	1883	3.8	1919	15.0	1871	5.3
							1923	15.0	1912	5.3

[a] Average for winter 1871 calculated from January and February data only

Fig. 10 Anomalies of 10-year average seasonal and annual air temperatures in Toruń, 1871–2010 (reference period 1871–2010)
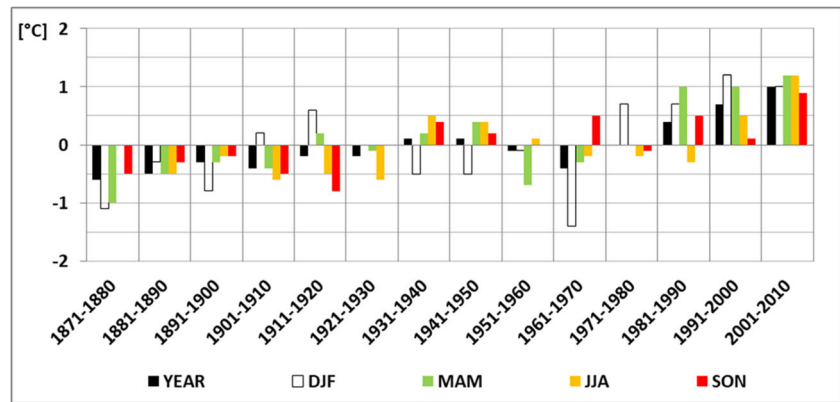
– 5.0 °C < autumn ≤ 15.0 °C
– 0.0 °C < early winter ≤5.0 °C

The analysis of Toruń for the period 1871–2010 revealed a very marked shortening of winter and a lengthening of summer in the period from the end of the nineteenth century to present day (Fig. 14). There were also significant changes in the start and end dates of individual seasons. Comparisons of the coolest and warmest decades (1871–1880 and 2001–2010, respectively) against the long-term period are presented in Table 10 and Fig. 14.

Winter ends 2 weeks earlier in the last decade than at the beginning of the study period (Table 10). The average duration of this season ranged from 65 days for the decade 2001–2010 to 94 days for 1871–1880, with an average of 81 for the whole study period. Niedźwiedź and Limanówka (1992) set the duration of winter for 1951–1980 in Toruń at 85 days. In the period 1946–2005, winter in Toruń was shorter, at only

75 days (Wójcik and Marciniak 2006). There is also a clear shortening of winter seen in Kraków (1901–2000; Piotrowicz 2007), Lublin (1951–1995; Nowosad and Filipiuk 1998) and at selected stations of south-eastern Poland (1971–2000; Skowera and Kopeć 2008).

Early spring in Toruń in the last decade ended on average a week earlier than the average for the whole study period and 10 days earlier than in the coldest analysed decade. The average duration of this season over the entire study period is 33 days. Niedźwiedź and Limanówka (1992) calculated the duration of early spring in 1951–1980 in Toruń at 29 days. This same duration for the same season was determined by Wójcik and Ziembińska (1984) for Toruń in the period 1947–1966.

Currently, spring starts 6 days earlier (27.03) and ends on average 8 days earlier (26.05) than at the beginning of the study period. This means that its duration has not changed greatly. In the period 1871–2010, spring lasted an average of 63 days, while in 1946–2005, it was 52 days (Wójcik and Marciniak 2006).

Summer in the last decade of the study period has ended on average a week later than at the beginning of the study period (respectively, 6.09 and 30.08). The average duration of this season ranged from 85 days for the decade 1871–1880 to 103 days for 2001–2010, with an average of 89 days for the whole study period. Wójcik and Marciniak (2006) determined the duration of this season at 105 days. A lengthening of this season was also noted in Kraków-Balice (by 4 days), Przemyśl (by 1 day) and in Sandomierz (by 6 days; Skowera and Kopeć 2008). In Lublin, this season lengthened by 9 days in the period 1951–1995 (Nowosad and Filipiuk 1998).

In the last decade of the study period, autumn started on average a week later than at the beginning of the study period, but ended 13 days later. The average duration of this season ranged over the whole study period from 59 days for the decade 1871–1880 to 64 days for 2001–2010. In the last decade, early winter began and ended 2 weeks earlier than at the beginning of the study period (Table 10). In the period 1871–2010, early winter lasted an average of 34 days, and its duration did not change greatly. A similar tendency was

Table 9 Standard deviation of seasonal and annual average air temperatures in Toruń (in °C) for individual decades and the whole period 1871–2010

Period	DFJ	MAM	JJA	Son	Year
1871–1880	2.4	1.2	0.8	1.3	1.0
1881–1890	1.5	1.5	0.4	0.5	0.6
1891–1900	2.0	0.8	0.7	0.6	0.5
1901–1910	1.8	1.0	0.9	0.9	0.6
1911–1920	1.3	1.6	1.0	1.2	0.7
1921–1930	2.5	1.2	0.7	1.2	0.8
1931–1940	2.3	1.1	0.7	1.2	1.0
1941–1950	2.6	1.4	0.6	1.1	0.8
1951–1960	1.7	1.2	0.8	0.9	0.8
1961–1970	2.6	1.2	0.9	1.0	0.8
1971–1980	1.6	0.8	0.7	0.5	0.6
1981–1990	2.7	1.2	0.8	0.8	1.0
1991–2000	2.0	1.0	1.1	1.2	0.8
2001–2010	2.1	1.1	0.7	1.0	0.7
1871–2010	2.3	1.3	0.9	1.1	0.9

Fig. 11 Ten-year moving average of standard deviations for seasonal and annual average air temperatures (°C) in Toruń, 1871–2010
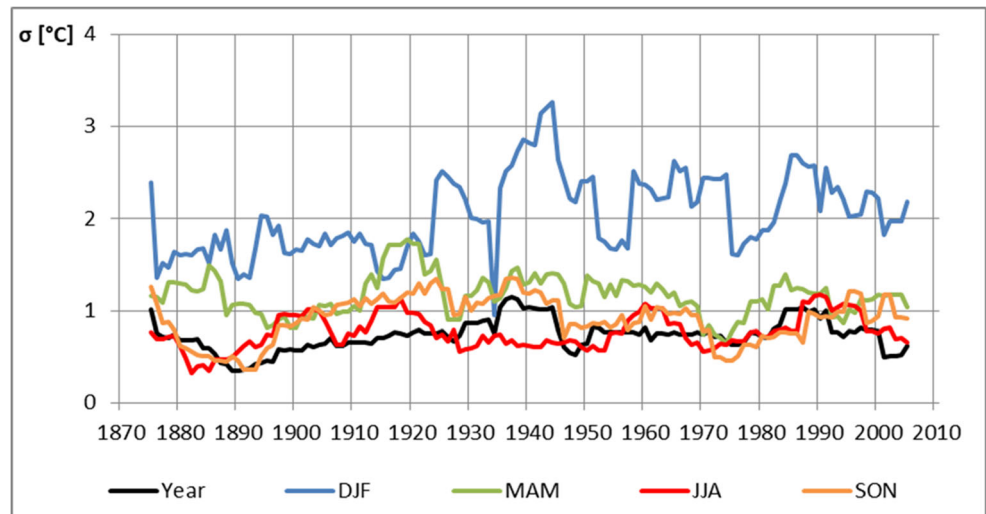

Fig. 12 The annual course of air temperature in Toruń in the period 1871–2010 (key: M: monthly average; Hst: selected highest monthly average; Lst: selected lowest monthly average)
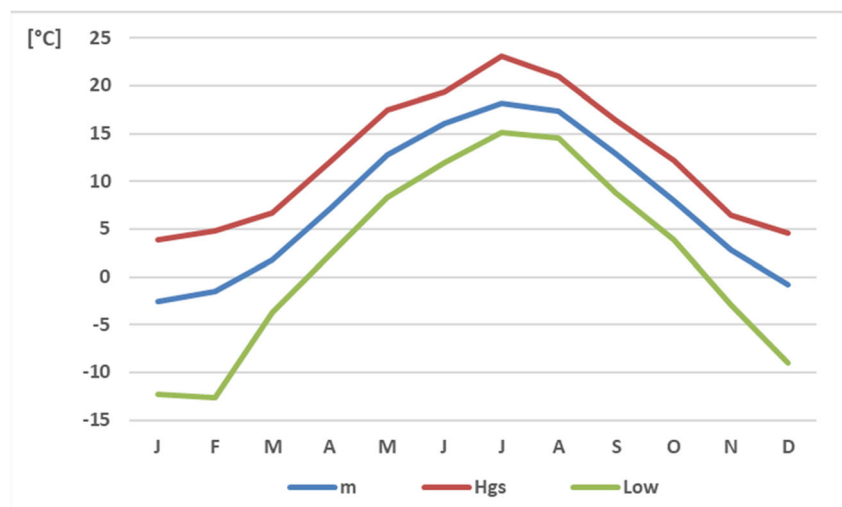

Fig. 13 Annual course of air temperature differences in Toruń in the periods 1871–1910, 1911–1960 and 1961–2010, relative to the period 1871–2010
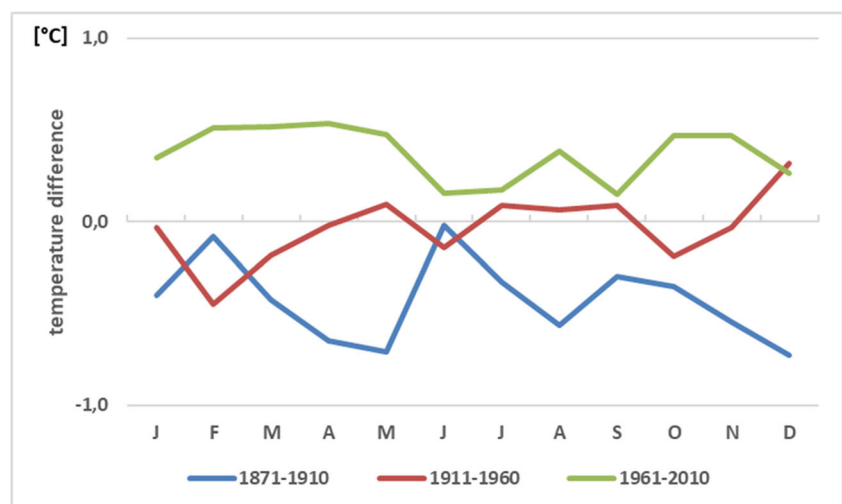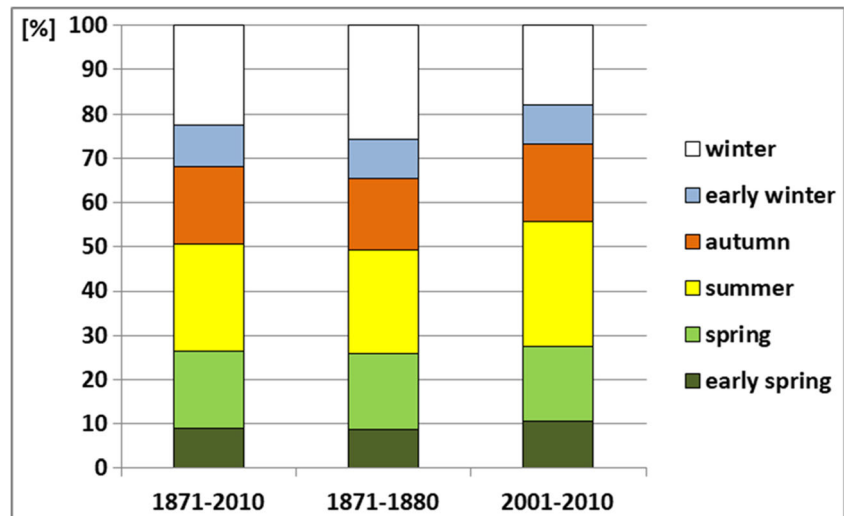
Fig. 14 Time of occurrence (as %) of thermic seasons in Toruń in the period 1871–2010 and in the coolest (1871–1880) and warmest (2001–2010) decades

noted by Nowosad and Filipiuk (1998) for Lublin (1951–1995), where the average duration of this season ranged from 26 to 30 days.

4 Conclusions

The aim of the research was to reconstruct the longest possible air temperature series for Toruń based on all the available sources containing empirical data, and then to homogenise them. Until now, climate studies of this area have mainly been based on data from years covering various post-war periods.

The rich meteorological data gathered (including newly discovered data from the turn of the nineteenth to twentieth century) and available weather descriptions were used to build the computer database used in the paper. The gathered empirical data were checked for correctness. Gaps in monthly average air temperature in Toruń for the period 1871–2010 were supplemented from data available for Bydgoszcz, which showed the strongest correlation with the Toruń series (correlation coefficient > 0.8–0.9).

Next, the thus-completed series was homogenised using Alexandersson's test.

In the period 1871–2010, a significant increase in air temperature was recorded in Toruń. The results agree with similar analyses in the literature for the whole of Poland and the selected Polish regions. A great similarity was noted between the increase in temperature observed in the modern period in Toruń and that in Europe.

The most significant research results are as follows:

1. A statistically significant increase in annual average air temperature in Toruń was noted for the period 1871–2010 at a rate of 0.1 °C per decade. The annual average air temperature ranged from a minimum value of 4.9 °C in 1871 to a maximum of 9.7 °C in 2000, compared to an average for the whole study period of 7.7 °C.
2. In terms of seasons, the greatest increase in air temperature was in spring and winter, respectively, 0.12 and 0.11 °C/10 years. A lesser warming was recorded in autumn (0.10 °C/10 years), and a much lesser one in summer (0.07 °C/10 years). The air temperature trends are statistically significant for all seasons.

Table 10 Start and end dates and duration (in days) of thermic seasons in Toruń in the period 1871–2010, and in the coolest and warmest decades (1871–1880 and 2001–2010)

Thermic seasons	1871–2010			1871–1880			2001–2010		
	beginning	end	duration	beginning	end	duration	beginning	end	duration
Early spring	28.02	1.04	33	4.03	4.04	32	16.02	26.03	39
Spring	2.04	3.06	63	5.04	6.06	63	27.03	26.05	61
Summer	4.06	31.08	89	7.06	30.08	85	27.05	6.09	103
Autumn	1.09	3.11	64	31.08	28.10	59	7.09	9.11	64
Early winter	4.11	7.12	34	29.10	29.11	32	10.11	12.12	33
Winter	8.12	27.02	82	30.11	3.03	94	13.12	15.02	65

3. The average seasonal values in winter ranged from − 8.8 to 2.8 °C. The transitional seasons had seasonal averages ranging from 3.8 to 10.3 °C for spring and 5.3 to 10.9 °C for autumn. Summer's lowest seasonal average was 15.0 °C, and 19.6 °C its highest.

4. The turn of the 20th to twenty-first century had the highest frequency of very and extremely warm years. Meanwhile, a higher frequency of very and extremely cool years was seen in the 1940s and before 1900.

5. In terms of seasons, the greatest variability in air temperature from year to year is for winter—at up to about 2.5 °C in the period 1921–1950. The remaining seasons have less variable average air temperatures from year to year—with a maximum of 1–1.5 °C. Decidedly, the most stable seasonal temperature is for summer. The greatest changes in variability are in winter, spring, autumn and the whole year—these changes are statistically significant.

6. The annual course of air temperature in Toruń in the period 1871–2010 is typical of stations in a temperate zone. The lowest air temperatures are recorded in January (− 2.5 °C) and the highest in July (18.2 °C). Average January values for the entire study period changed from − 12.3 °C (in 1987) to + 3.9 °C (in 2007). The highest air temperatures for January in Toruń were recorded in the decade 1991–2000 (− 0.8 °C) and the lowest in the decade 1891–1900 (− 4.3 °C). The shape of the annual courses in the subperiods did not significantly change, and it can be considered to have been stable over the long term. The clearly coolest period was 1871–1910, while 1961–2010 was clearly warmest.

7. Over the entire period of regular meteorological observations (1871–2010), a marked shortening of winters was noted (by 29 days). The duration of spring did not change, and summer lengthened by 19 days. The vegetative period was extended by 18 days (to 228 days). Early spring and spring start on average 10 days earlier, and early winter and winter start 10 days later.

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