Chapter 8
Relation Between Air Temperature and Inland Surface Water Temperature During Climate Change (1961–2014): Case Study of the Polish Lowland

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Abstract The chapter describes the relations between changes in mean annual and mean monthly (1961–2014) air and water temperatures in rivers and lakes, as well as their spatial variability in the Polish Lowland. The determination of the directions and rate of changes in air and water temperatures involved the application of linear regression. Its significance was verified by means of F test at a level of 0.05. The rate of increase in air temperature in the western part of the Polish Lowland was determined to average 0.32 °C·10 years^{-1} and decrease towards its eastern part to 0.22 °C·10 years^{-1}. In the case of rivers, the mean increase in water temperature varied from 0.26 °C·10 years^{-1} in the western part to 0.20 °C·10 years^{-1} in the eastern part, and for lake waters, from 0.30 to 0.15 °C·10 years^{-1}. Increase in water temperature in particular months throughout the analysed period was much more variable. Its highest increase occurred in May and ranged in lakes from 3.1 to 3.9 °C, and in rivers from 1.9 to 2.6 °C. The lowest increases in water temperature (usually from 0.1 to 1.0 °C) were observed in autumn and winter months, whereas water temperature in some lakes showed a negative tendency in winter months. In the case of Lake Hańcza, in November it decreased during the analysed period by 1.3 °C. During longer periods such as a year or half-year, an evident increase was found to occur in air and inland water temperature. During shorter month-long periods, the increase is not always so evident, and sometimes even a decrease in temperature is observed.

Keywords Thermal regime · Changes · Rivers · Lakes

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8.1   Introduction

Research on the relations between air and inland water temperature has a long history. It commenced already in the nineteenth century along with the popularisation of instrumental methods of hydrometeorological measurements. Due to short measurement series and a low number of sites of observations, however, the development of this kind of research occurred at the turn of the nineteenth and twentieth centuries. In the first half of the twentieth century, the investigations particularly concerned the natural relations between air and water temperature with consideration of their physical properties. This is exemplified by documenting different relations between mean monthly air and water temperatures in lakes during heat accumulation and during stagnation and heat loss (McCombie 1959). In the second half of the twentieth century, and particularly in the early twenty-first century, a rapid increase in interest in the issue occurred. This was and is related to climate warming and its increasingly visible effects in all types of inland waters.

Studies concerning changes in inland water temperature can be generally divided into two main groups. The first one includes publications discussing the rate of water temperature fluctuations and relations with air temperature (Gu and Li 2002; Dąbrowski et al. 2004; Pekarova et al. 2008; Mohseni and Stefan 1999; Jurgelėnaitė et al. 2012; North et al. 2013). The second group includes publications concerning effects of water temperature fluctuations on lake and river ecosystems with particular consideration of trophy and ichthyofauna (Caissie 2006; Hari et al. 2006; Davies 2010; Hudon et al. 2010; Leuven et al. 2011; Dugdale et al. 2013), as well as the effect of natural and anthropogenic factors on the modification of inland water temperature (among others Sridhar et al. 2004; Steel and Lange 2007; Webb et al. 2008; Xin and Kinouchi 2013). Particularly, interesting papers are those prepared based on results of observations for long measurement series (approximately 100 years), among others for the Danube River (Webb and Nobilis 1995), the Hudson and Potomac Rivers (Kaushal et al. 2010), as well as papers from the territory of Lithuania and Latvia, neighbouring with the Polish Lowland, and similar in terms of genesis (Jurgelėnaitė et al. 2012; Latkovska and Apsīte 2016). Currently, the development of measurement methods permits analysing increasingly longer observation series for different meteorological and hydrological elements. This allows for the application of modelling for simulating daily temperature fluctuations, and determining trends, among others of water temperature in lakes in periods even longer than 100 years (Magee et al. 2016). Such studies also permit the determination of the effect of other factors on the temperature of inland waters (among others wind speed and water transparency).

A review of the current knowledge on various effects of climate warming on European inland waters was presented by, among others, Dokulil (2014). The latest study results on water temperature increase in lakes around the globe and in Central Europe are included in papers by O'Reilly et al. (2015) and Woolway et al. (2016, 2017).

The majority of the aforementioned papers discuss the issues of temperature increase based on mean annual or mean seasonal values (e.g. from the warm half-

year), as well as the spatial variability of the phenomenon. The primary objective of this chapter is the determination of the relations between changes in air and inland water temperature based on mean monthly values from the period 1961 to 2014, and their variability. The issue is discussed in the context of mean annual and seasonal values. Elements modifying water temperature fluctuations are also presented.

8.2 Study Methods

Calculations and analyses were performed based on data collected in the period 1961–2014 by the Institute of Meteorology and Water Management—National Research Institute. Data concerning air temperature were obtained from the following meteorological stations: Gorzów Wielkopolski, Chojnice, Toruń, and Białystok. Data on water temperature in rivers were obtained from the Oder River (in Gozdowice), Vistula River (in Toruń), and Biebrza River (in Burzyn), and data on temperature of lake waters from the following lakes: Sławskie, Charzykowskie, and Hańcza. The meteorological and hydrological observations were performed every day in the years 1961–2014 at 6 AM GMT: first at an altitude of 200 cm above ground level and then at a depth of 40 cm.

The study applied standard methods of determination of the direction and rate of air and water temperature fluctuations. Linear regression was used. Its significance was verified by means of F test at a level of 0.05. For the purpose of confirming or excluding the calculated statistics (trends) from linear regression, nonparametric Mann–Kendall test was applied (Kundzewicz and Robson 2000). The test requires no preliminary assumptions, and the estimation of significance is based on the zero hypothesis of independent observations with identical distribution. Detection of significant trends in time series by means of two tests reduces the probability of making an error of the first type, i.e. detection of changes in the case of their lack. The method was adopted due to the limitations in applying linear regression which requires the assumptions of distribution normality and values independent in a time series. Mann–Kendall's sum S was divided by the root of variance:

$$S = \sum_{i=t}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$

where: $\text{sgn}(x) = 1$ for $x > 0$, 0 for $x = 0$, -1 for $x < 0$, where x denotes individual data series and n denotes the total number of years in a time series.

The analysis of the course of mean annual air and water temperature values was performed in reference to a year, seasons, and months. Dependencies between air temperature and water temperature in rivers and lakes were described by means of a Pearson coefficient of correlation, with significance at a level of 0.05 tested by t-student distribution with $n-2$ degrees of freedom.

8.3   Study Area

The study area covers the northern part of the Polish Lowland. The majority of the analysed objects are located in the young glacial area. More than half of the catchment of the Biebrza River is located in the area of the Central European glaciation, i.e. older in comparison with North Polish glaciation (Vistulian). The young glacial area is characterised by belt distribution of many geomorphological formations, deposits, and modern morphogenetic processes. The genesis of particular belts is related to the course of subsequent phases of the last glaciation. Many different relief elements occur here, including particularly: terminal moraine hills with a height of up to 328 m a.s.l., flat or undulating plateaus of the ground moraine, young network of river valleys, a dense network of subglacial channels, outwash plains, and numerous closed-drainage depressions. In addition to river valleys with usually meridional orientation, also wide and extensive Urstromtäler occurs with latitudinal orientation (Fig. 8.1). In valleys and Urstromtäler, permanent rivers occur. They are predominantly fed by groundwater and surface waters, as well as atmospheric precipitation. The majority of rivers flow through numerous lakes.

Among the rivers of the Polish Lowland, two longest ones stand out, namely the Vistula River (total length 1047 km) and the Oder River (854 km). The rivers flow out of springs in the mountains and then through uplands, and their lower sections run through the young glacial area. They are the most important rivers for the entire analysed area. They transport water to the Baltic Sea from almost all river systems of the Polish Lowland. In the lower sections of both rivers, gauging stations are located,
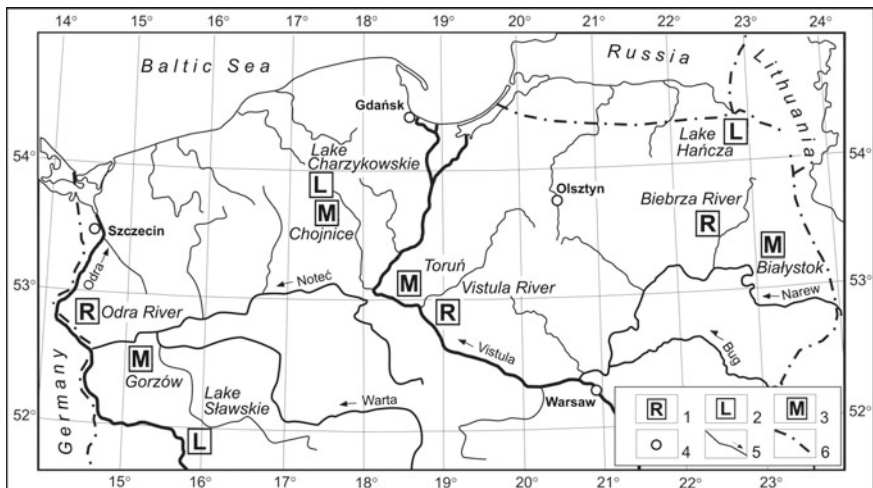

Fig. 8.1 Schematic map of the river network of the Polish Lowland with location of gauging sites. Description: 1—river gauging sites; 2—lake gauging sites; 3—meteorological stations; 4—cities; 5—main rivers; 6—country border. *Source* own elaboration

Table 8.1   Selected data on the analysed rivers

River/gauging station	Coordinates		$A \times 10^3$ km^2	Length of river		Qmean m^{3}s^{-1}
	φ	λ		L	LGS	
Oder/Gozdowice	52.764263	14.317719	109.7	855.0	645.3	523.0
Vistula/Toruń	53.008031	18.608269	181.0	1047.0	734.7	987.6
Biebrza/Burzyn	53.274332	22.459070	6.9	170.6	162.1	34.0

Description: A—catchment area; L—total river length; LGS—length of the river to the analysed gauging station; Qmean—mean discharge
Source own study based on data of the Institute of Meteorology and Water Management—National Research Institute

Table 8.2   Basic data on the analysed lakes

Lake	Coordinates		H m a.s.l.	S km^2	$V \times 10^6$m^3	Dmax	Dmean
	φ	λ					
Sławskie	51.891269	16.010868	56.9	8.22	42.66	12.3	5.2
Charzykowskie	53.778758	17.510357	120.0	13.64	134.53	30.5	9.8
Hańcza	54.264340	22.812267	227.3	2.91	120.36	108.5	38.7

Description: H—absolute height; S—surface area; V—volume; Dmax—maximum depth; Dmean—mean depth
Source according to Inland Fisheries Institute in Olsztyn data

providing data on water temperature used in this chapter. The third gauging station is located on the Biebrza River flowing through a completely different valley. Unique in Europe for its marshes and peatlands, as well as its highly diversified fauna and flora, the Biebrza Valley was designated as a wetland site of global significance and has been under the protection of the Ramsar Convention since 1995 (Frąk et al. 2008). Some data on the analysed rivers are presented in Table 8.1.

The most characteristic objects of the young glacial area include post-glacial lakes. They developed cca 13 thousand years ago, after the end of the last glaciation on the northern hemisphere. They are dominated by channel and moraine lakes. The former have an elongated shape and are usually deep and narrow. Moraine lakes are usually oval, and substantially shallower. This chapter analyses channel lakes, considerably differing in terms of all morphometric parameters (Table 8.2). The maximum depth of the shallowest one—Lake Sławskie—amounts to 12.3 m and the deepest one—Lake Hańcza—108.5 m. Lake Hańcza is also the deepest lake in the Central European Lowland.

The study area is located in the moderate climate zone with evident transitional features between marine and continental moderate climate. Mean annual (1961–2014) air temperature decreases towards the east from approximately 8.7 °C in Gorzów Wielkopolski to 7.0 °C in Białystok (Table 8.3). Its higher variability (2.3 °C) is observed during the cold half-year (November–April) and considerably lower in the

Table 8.3 Location of meteorological stations and air temperature in the period 1961–2014

Meteorological station	Coordinates		Absolute height m a.s.l.	Mean temperature (1961–2014)		
	φ	λ		Year	May–Oct	Nov–Apr
Gorzów Wielkopolski	52.741231	15.277253	39	8.7	14.9	2.5
Chojnice	53.715288	17.532387	172	7.3	13.6	1.0
Toruń	53.042283	18.595451	66	8.1	14.6	1.6
Białystok	53.107221	23.162380	143	7.0	13.8	0.2

Source own study based on data of the Institute of Meteorology and Water Management—National Research Institute

warm half-year (1.1 °C). This results from more intensive influence of colder continental air masses during winter on the eastern part of the analysed area in comparison with the western part.

8.4 Relations Between Air and Surface Water Temperature

8.4.1 Western Part of the Polish Lowland

The relations between air temperature and surface water temperature in the western part of the Polish Lowland were discussed based on study results from the meteorological station in Gorzów Wielkopolski and from the gauging stations on the Oder River in Gozdowice and Lake Sławskie in Radzyń. The gauging stations on the river and lake are located at a distance of 55 and 70 km from the meteorological station, respectively.

Mean annual (1961–2014) air temperature in Gorzów Wielkopolski amounted to 8.7 °C, whereas in particular years, its high variability was observed: from 6.4 °C in 1996 to 10.7 °C in 2007. Nonetheless, an evident positive trend in air temperature occurred. During the analysed period, it averaged 0.32 °C·10 years^{-1} (Fig. 8.2). The trend is statistically significant at a level of 0.05.

Mean annual (1961–2014) water temperature in the Oder River and Lake Sławskie was higher than air temperature and amounted to 10.4 and 10.8 °C, respectively. Higher water temperature is a normal phenomenon resulting from completely different physical properties of water in comparison with air. Moreover, river valleys and lake basins are fed by groundwater which cool or warm surface waters depending on the season of the year (groundwater temperature is relatively stable throughout the year and amounts to approximately 8.5 °C). The phenomenon often occurs in young glacial areas (Jurgelėnaitė et al. 2012; Marszelewski and Pius 2016; Pius and Marszelewski 2016). It is one of the important factors due to which annual amplitudes
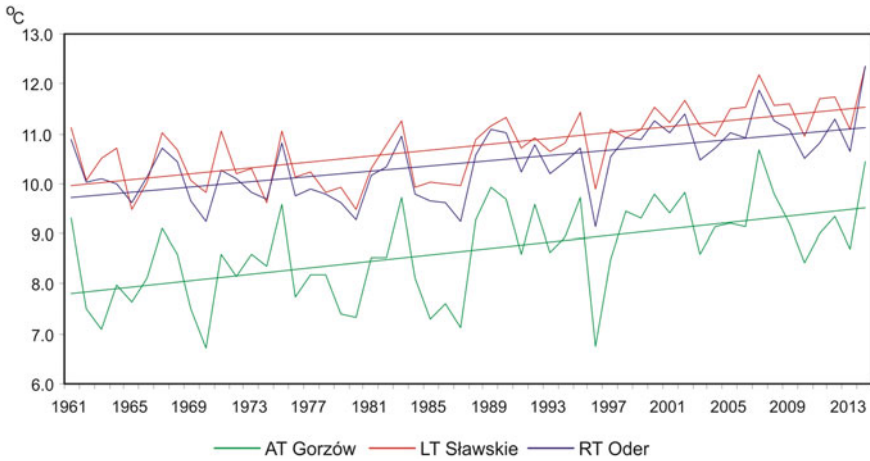
Fig. 8.2 Course of the mean annual air and surface water temperature in the period 1961–2014 in the western part of the Polish Lowland. Description: *AT*—air temperature in Gorzów Wielkopolski; *LT*—water temperature in Lake Sławskie; *RT*—water temperature in the Oder River. *Source* author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

of surface water temperature were lower than those for air and amounted to 3.2 °C in the Oder River (from 9.2 to 12.4 °C) and 2.8 °C in Lake Sławskie (from 9.5 to 12.3 °C). In the period 1961–2014, a positive and statistically significant ($\alpha = 0.05$) trend of surface water temperature was also determined (compare Fig. 8.2). In the case of the Oder River, an increase in water temperature averaged 0.26 °C·10 years^{-1} and in the case of Lake Sławskie 0.30 °C·10 years^{-1}.

As shown by the above data, the rate of increase in mean annual air temperature (0.32 °C·10 years^{-1}) was somewhat faster in comparison with mean annual water temperature in the lake (0.30 °C·10 years^{-1}) and in the river (0.26 °C·10 years^{-1}). A question arises whether such dependencies are characteristic of all periods in a year (e.g. months or seasons), or only for the entire year. As shown by the analysis of relations occurring between air temperature and surface water temperature in shorter periods, such relations are much more complicated and show different patterns. It is evident both in shorter periods in a year (months) and during longer periods (half-years, seasons). In particular months of the year, the rate of increase in air temperature was not always the highest. This is particularly observed in November, when it is almost twice lower than the rate of increase in water temperature in Lake Sławskie (Table 8.4). This kind of situation results from an increase in cloudiness and reduction of insolation in that month, as well as in June and other autumn months (Żmudzka 2009). In the case of surface waters, the capacity of heat accumulation, particularly in lakes during summer and autumn, permits longer maintenance of higher than average water temperature. In the case of the Oder River (and other rivers), turbulent water movement and rapid heat exchange with the atmosphere result in lower monthly

rate of increase in temperature amounting to only 0.07 °C·10 years^{-1}. For a similar reason, a lower rate of increase in air temperature in comparison with water temperature occurred in June, as well as in May and August (compare Table 8.4). In the remaining months, the rate of increase in air temperature was faster than that of water temperature, whereas it was the highest in April, when it equalled 0.53 °C·10 years^{-1}. The value is the highest among all the remaining ones characterising the rate of air temperature fluctuations in Poland.

Substantial differences between the rate of increase in air and water temperature also occurred in longer periods in a year, and especially in particular periods (Table 8.5). The effect of physical parameters of lake waters on the rate of increase in water temperature in so-called transitional seasons, i.e. in spring and autumn, is particularly evident. In spring, a vast mass of water subject to slow mixing decreases the rate of temperature increase, and in autumn on the contrary it contributes to longer retaining of heat. As a result, during shorter periods in a year, lake waters are characterised by an evidently different rate of temperature increase in comparison with river waters; although at the scale of the entire year, the rate is approximate.

8.4.2 Central Part of the Polish Lowland

The dependencies between air and water temperature in the central part of the Polish Lowland were investigated based on the example of the Vistula River in Toruń and Lake Charzykowskie in Charzykowy. Results of research on water temperature in the Vistula River were compared to those for air temperature from the meteorological station located 6 km from the river. In the case of Lake Charzykowskie, the meteorological station is located at a distance of approximately 5 km, in Chojnice.

Mean annual (1961–2014) air temperature in Toruń was lowered by 0.6 °C than in the western part of the Polish Lowland and amounted to 8.1 °C. In particular years in the analysed period, its considerable variability was recorded: from 5.9 °C in 1970 to 10.1 °C in 2007. An evident positive trend of air temperature also occurred, averaging 0.29 °C·10 years^{-1} (Fig. 8.3). In the case of the meteorological station in Chojnice, temperature values were somewhat lower and were as follows: mean annual 7.3 °C, variability of mean annual air temperature from 5.2 °C in 1970 to 9.3 °C in 2007, and value of temperature trend 0.31 °C·10 years^{-1} (Fig. 8.4).

Mean annual (1961–2014) water temperature in the Vistula River and in Lake Charzykowskie was higher than air temperature and amounted to 10.2 and 9.5 °C, respectively. Annual water temperature amplitudes were lower than those for air and equalled 2.6 °C (from 9.0 to 11.6 °C) in the Vistula River and 3.2 °C (from 8.3 to 11.5 °C) in Lake Charzykowskie. In the period 1961–2014, positive and statistically significant ($\alpha = 0.05$) trends of surface water temperature occurred (compare Figs. 8.3 and 8.4). In this period, an increase in water temperature in the Vistula River averaged 0.27 °C·10 years^{-1} and in the case of Lake Charzykowskie 0.24 °C·10 years^{-1}. Therefore, it turns out that in spite of somewhat lower values of air and water tem-

Table 8.4 Mean monthly and annual rate of air and surface water temperature fluctuations (in °C·10 years^{-1}) in the period 1961–2014 in the western part of the Polish Lowland

Element	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
AT	0.09	0.27	0.44	0.37	0.38	*0.53*	*0.42*	0.13	*0.54*	*0.40*	0.17	0.12	*0.32*
WTL	0.17	*0.18*	*0.25*	*0.19*	*0.30*	*0.30*	*0.58*	*0.26*	*0.42*	*0.47*	*0.23*	*0.21*	*0.30*
WTR	0.07	0.10	*0.21*	0.20	*0.41*	*0.43*	*0.49*	*0.20*	*0.36*	*0.39*	0.16	0.10	*0.26*

Description: *AT*—air temperature in Gorzów Wielkopolski; *WTL*—water temperature in Lake Sławskie; *WTR*—water temperature in the Oder River. Statistically significant changes were marked with italics and bold font
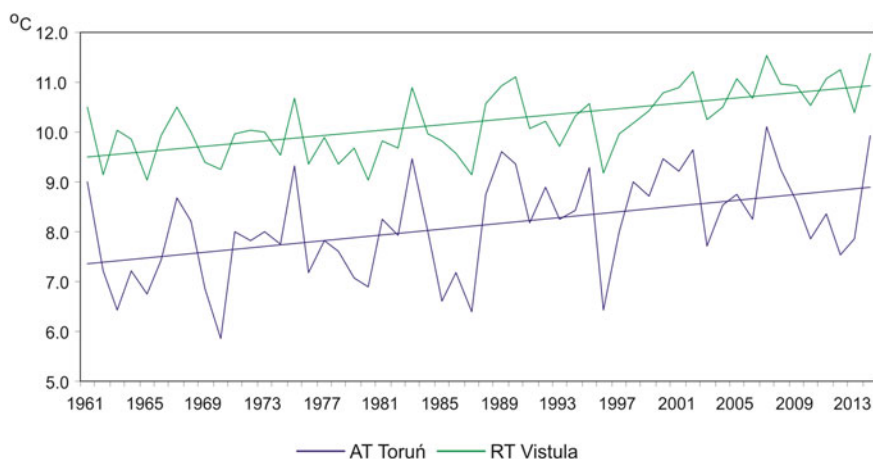
Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

Table 8.5 Mean seasonal rate of air and surface water temperature fluctuations (in °C·10 years^{-1}) in the period 1961–2014

Element	Cool half-year	Warm half-year	Winter	Spring	Summer	Autumn
AT	0.35	0.30	0.36	0.44	0.36	0.12
WTL	0.23	0.37	0.21	0.39	0.38	0.21
WTR	0.24	0.28	0.17	0.44	0.32	0.11

Description like in Table 8.4

Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

Fig. 8.3 Course of the mean annual air temperature in Toruń (*AT*) and water temperature in the Vistula River (*RT*) in the period 1961–2014. *Source* author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

perature in the central part of the Polish Lowland, the rate of its increase was almost identical as in its western part.

Similarly as in the western part of the Polish Lowland, the rate of increase in air temperature was not identical in particular months (Table 8.6). The greatest differences between the rate of increase in air temperature and river water temperature occurred in as many as six months: November, May, June, August, September, and October. Air temperature in June deserves particular attention. It showed a slight, although not statistically significant, negative tendency (-0.01 °C·10 years^{-1}). Therefore, the dependencies between air and river water temperature in particular months in the central part of the Polish Lowland proved to be more complicated, although the general trend of temperature fluctuations was similar. This may result from substantially greater water mass in the Vistula River in Toruń (averaging 990 m^3·s^{-1}) in comparison with the Oder River in Gozdowice (averaging 545 m^3·s^{-1}), as well as from a slow but evident increase in climate continentalism. The disturbance of nat-
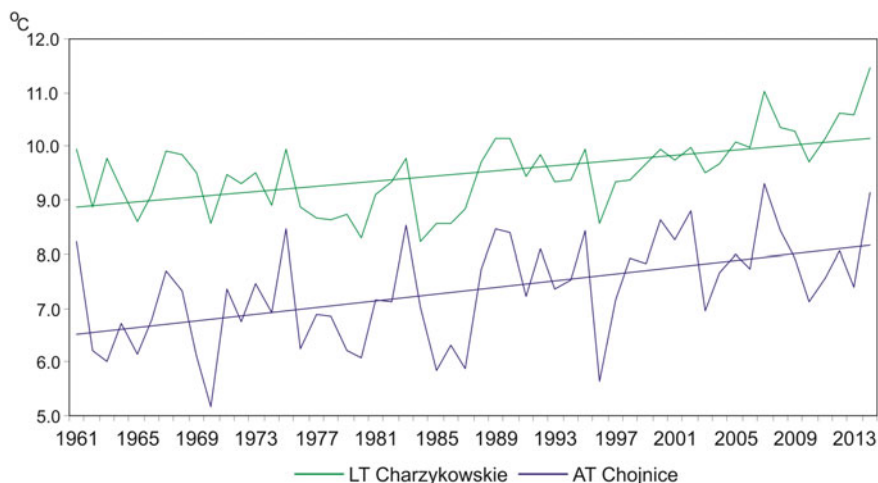
Fig. 8.4 Course of the mean annual air temperature in Chojnice (*AT*) and water temperature in Lake Charzykowskie (*LT*) in the period 1961–2014. *Source* author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

ural relations between air and river water temperatures certainly also resulted from its pollution with sewage, lasting almost until the end of the twentieth century, and from the effect of hydrotechnical facilities.

Air and lake water temperature fluctuations in particular months had an equally complicated course (compare Table 8.6). The rate of increase in air temperature was lower only in two months (May and June)—similarly as in the western part of the study area. The negative tendency of mean water temperature fluctuations in lake Charzykowskie in November draws attention (-0.08 °C·10 years^{-1}). It is an effect of only a slight increase in water temperature in October and air temperature in November, as mentioned before.

Significant differences between the rate of increase in air and water temperature also occurred in longer periods of the year, including its individual seasons (Table 8.7). The lowest rate of temperature increase was observed in autumn, particularly in Lake Charzykowskie, where it amounted to only 0.04 °C·10 years^{-1}. In this case, similarly as in Lake Sławskie, the effect of physical properties of lake waters on the rate of increase in water temperature in so-called transitional seasons is manifested. Notice also that the rate of air temperature increase in the cool half-year is substantially faster than in the warm half-year (compare Table 8.7), unlike in the case of surface waters. This also results from the physical properties of waters. Their temperature can increase only from 0 °C, and an increase in air temperature also occurs in the range of negative values.

Table 8.6 Mean monthly and annual rate of air and surface water temperature fluctuations (in °C·10 years^{-1}) in the period 1961–2014 in the central part of the Polish Lowland

Element	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
ATT	0.10	0.25	0.42	0.37	*0.37*	*0.51*	*0.35*	−0.01	*0.47*	*0.41*	0.17	0.07	*0.29*
WTR	*0.22*	*0.21*	*0.18*	0.11	*0.28*	*0.46*	*0.46*	0.15	*0.42*	*0.47*	*0.21*	*0.20*	*0.27*
ATC	0.14	0.29	0.44	*0.44*	*0.39*	*0.49*	*0.34*	0.03	*0.52*	*0.40*	0.20	0.08	*0.31*
WTL	−0.08	*0.15*	*0.20*	*0.15*	*0.30*	*0.47*	*0.65*	0.15	*0.35*	*0.35*	0.16	0.05	*0.24*

Description: *ATT*—air temperature in Toruń; *WTR*—water temperature in the Vistula River; *ATC*—air temperature in Chojnice; *WTL*—water temperature in Lake Charzykowskie. Statistically significant changes are marked with italics and bold font

Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

Table 8.7 Mean seasonal rate of air and surface water temperature fluctuations (in $°C·10$ years^{-1}) in the period 1961–2014

Element	Cool half-year	Warm half-year	Winter	Spring	Summer	Autumn
ATT	*0.34*	*0.25*	0.34	*0.41*	*0.29*	0.11
WTR	*0.22*	*0.32*	*0.16*	*0.36*	*0.35*	*0.21*
ATC	*0.36*	*0.26*	*0.39*	*0.41*	*0.32*	0.14
WTL	*0.19*	*0.28*	*0.16*	*0.48*	*0.28*	0.04

Description as in Table 8.6
Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

8.4.3 Eastern Part of the Polish Lowland

Air and surface water temperature fluctuations in the eastern part of the Polish Lowland are discussed based on results of research from the meteorological station in Białystok, as well as the Biebrza River (site Burzyn) and Lake Hańcza. The meteorological station in Białystok is located at a distance of approximately 40 km from the Biebrza River in Burzyn and approximately 100 km from Lake Hańcza.

Mean annual (1961–2014) air temperature in Białystok was the lowest among the analysed sites and amounted to 7.0 °C. The lowest mean annual temperature (5.1 °C) occurred in 1987 and the highest (8.8 °C) in 2007. Similarly as at other sites in the Polish Lowland, an evident, statistically significant, positive trend of air temperature was recorded, averaging 0.22 °C·10 years^{-1} (Fig. 8.5). It is worth emphasising that it is the lowest rate of temperature increase throughout the analysed area, lower by 0.1 °C·10 years^{-1} than in Gorzów Wielkopolski.

Mean annual (1961–2014) water temperatures in the Biebrza River and in Lake Hańcza were higher than air temperature and amounted to 9.1 and 8.5 °C, respectively.

Notice that in this case, unlike in the previous cases, higher mean annual water temperature occurred in the river, and not in the lake. This is related to their specific morphometric properties. The Biebrza River is sometimes described as a "wetland river". It is shallow, with slow water flow in a wide valley through numerous wetlands and flooded meadows. Due to this, water temperature during the summer season can reach much higher values than in a deep river with fast current. Due to the considerable depth and water volume, Lake Hańcza (compare Table 8.2) is characterised by a substantially longer period of water temperature increase in comparison with the remaining ones. Moreover, it is located in a region where the summer season lasts the shortest among all the regions of the Polish Lowland. For the above reasons, conditions for water temperature increase in Lake Hańcza in the warm half-year are unfavourable. As a result, water in the lake is characterised by temperature lower than in the river. It is a rare phenomenon.

Annual amplitudes of water temperature were lower than those for air and equalled 2.7 °C (from 7.9 to 10.6 °C) in the Biebrza River and 2.5 °C (from 7.2 to
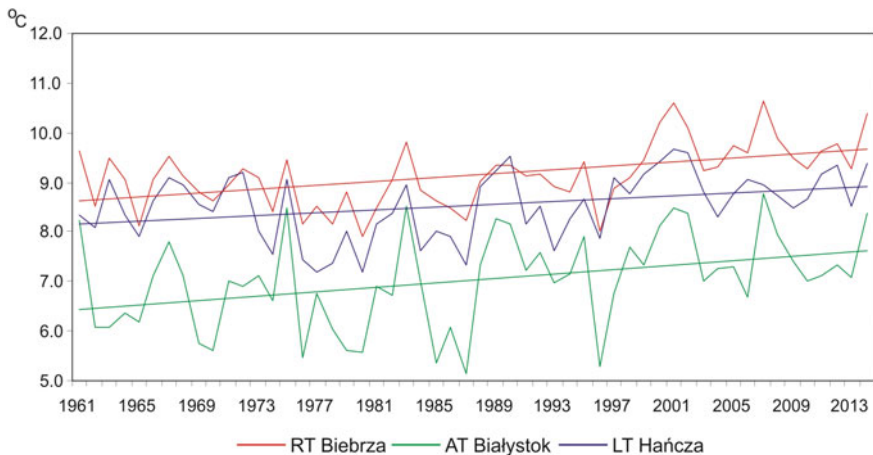
Fig. 8.5 Course of mean annual air temperature in Białystok (*AT*), water temperature in Lake Hańcza (*LT*), and water temperature in the Biebrza River (*RT*) in the period 1961–2014. *Source* author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

9.7 °C) in Lake Hańcza. In the period 1961–2014, positive and statistically significant ($\alpha = 0.05$) trends of surface water temperature occurred (compare Fig. 8.5). In this period, an increase in water temperature in the Biebrza River averaged 0.20 °C·10 years^{-1} and in the case of Lake Hańcza 0.15 °C·10 years^{-1}. The rate of its increase, however, was the lowest among all analysed hydrological objects in the Polish Lowland.

The directions and rate of air temperature fluctuations in particular months were largely variable. In three months of the year (June, September, October), a slight negative tendency of mean air temperature fluctuations was recorded (Table 8.8), although such fluctuations were not statistically significant. Among the remaining months, the fastest increase in air temperature occurred in winter months, particularly in January, when it amounted to 0.58 °C·10 years^{-1}. Throughout the winter season (from December to February), mean air temperature increase reached 0.43 °C·10 years^{-1}, proving winter to be the season with the fastest temperature increase (Table 8.9). It is worth emphasising that the fast increase in air temperature during winter did not contribute to an increase in surface water temperature, because it occurred in the range of negative air temperatures. This is evidenced by a negative, although not statistically significant, trend of water temperature (-0.08 °C·10 years^{-1}) in Lake Hańcza during the winter season (compare Table 8.9).

The above hydrometeorological situations determined strong variability of the rate of air and water temperature fluctuations also in the winter half-year, namely: 0.35 °C·10 years^{-1} for air temperature, 0.19 °C·10 years^{-1} for river water temperature, and -0.01 °C·10 years^{-1} for Lake Hańcza. An opposite situation was observed during the warm half-year (compare Table 8.9).

Table 8.8 Mean monthly and annual rate of air and surface water temperature fluctuations ($°C·10$ $years^{-1}$) in the period 1961–2014 in the eastern part of the Polish Lowland

Element	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
AT	0.09	0.28	0.58	0.42	0.40	*0.30*	0.13	−0.06	*0.37*	*0.23*	−0.02	−0.02	*0.22*
WTR	0.16	*0.16*	0.09	0.07	*0.20*	*0.47*	*0.35*	0.05	*0.37*	*0.29*	0.09	0.08	*0.20*
WTL	*−0.23*	*−0.23*	−0.01	−0.03	−0.05	*0.31*	*0.72*	*0.38*	*0.38*	*0.36*	0.02	−0.02	*0.15*

Description: *AT*—air temperature in Białystok; *WTR*—water temperature in the Biebrza River; *WTL*—water temperature in Lake Hańcza. Statistically significant changes are marked with italics and bold font

Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

Table 8.9 Mean seasonal rate of air and surface water temperature fluctuations (in °C·10 years^{-1}) in the period 1961–2014

Element	Cool half-year	Warm half-year	Winter	Spring	Summer	Autumn
AT	*0.35*	0.10	*0.43*	*0.28*	*0.18*	0.02
WTR	*0.19*	*0.21*	*0.10*	*0.34*	*0.23*	0.12
WTL	−0.01	*0.31*	−0.08	*0.36*	*0.38*	−0.07

Description as in Table 8.8

Source author's calculations based on data of the Institute of Meteorology and Water Management—National Research Institute

8.5 Correlations Between Air and Surface Water Temperature Fluctuations

The previous parts of the chapter present the tendencies of air and surface water temperature fluctuations. Attention is paid to both similarities and differences in the scope of the rate of temperature fluctuations in three analysed environments: air, river water, and lake water. It was evidenced that local conditions considerably modify the value, and even directions of water temperature fluctuations. As a consequence, the existence of many differences between temperature fluctuations of air and surface water was documented. In spite of this, a strong correlation is observed between air temperature and surface water temperature.

The strongest correlations were recorded in the scope of annual temperature values, and particularly in the western part of the analysed area. Coefficients of correlation between air and surface water temperature vary from 0.86 to 0.94. Somewhat lower coefficients of correlation occur for the central part of the area, where almost all of them are higher than 0.81. The weakest correlations occur in the eastern part of the area, particularly between air temperature in Białystok and water temperature in Lake Hańcza (0.67) (Table 8.10).

Table 8.10 Coefficients of correlation between mean annual temperatures (grey colour designates the analysed groups of objects in the western, central, and eastern part of the Polish Lowland)

	Oder R.	Gorzów	L. Sławskie	Toruń	Vistula R.	Chojnice	L. Charzykowskie	Biebrza R.	Białystok	L. Hańcza
Oder River	1									
Gorzów Wielkopolski	0.93	1								
Lake Sławskie	0.94	0.86	1							
Toruń	0.87	0.97	0.79	1						
Vistula River	0.93	0.88	0.93	0.82	1					
Chojnice	0.93	0.99	0.86	0.97	0.89	1				
Lake Charzykowskie	0.90	0.81	0.91	0.72	0.88	0.81	1			
Biebrza River	0.89	0.79	0.88	0.75	0.90	0.82	0.85	1		
Białystok	0.87	0.94	0.78	0.94	0.85	0.95	0.74	0.82	1	
Lake Hańcza	0.75	0.63	0.75	0.58	0.75	0.63	0.73	0.80	0.67	1

Source author's calculations

Table 8.11 Coefficients of correlation of mean temperature in the cool half-year (grey colour designates the analysed groups of objects in the western, central, and eastern part of the Polish Lowland)

	Oder R.	Gorzów	L. Sławskie	Toruń	Vistula R.	Chojnice	L. Charzykowskie	Biebrza R.	Białystok	L. Hańcza
Oder River	1									
Gorzów Wielkopolski	0.81	1								
Lake Sławskie	0.92	0.80	1							
Toruń	0.74	0.98	0.75	1						
Vistula River	0.86	0.63	0.85	0.57	1					
Chojnice	0.79	0.98	0.79	0.98	0.62	1				
Lake Charzykowskie	0.84	0.67	0.86	0.60	0.83	0.66	1			
Biebrza River	0.79	0.54	0.82	0.51	0.84	0.55	0.81	1		
Białystok	0.76	0.95	0.76	0.97	0.60	0.97	0.62	0.52	1	
Lake Hańcza	0.62	0.59	0.60	0.57	0.57	0.57	0.59	0.50	0.52	1

Source author's calculations

Weaker correlations were observed in the case of temperature in shorter periods, e.g. in the cool half-year (Table 8.11). The values of coefficients of correlation between air and surface water temperature in the western part of the study area range from 0.80 to 0.92, but in the eastern part only from 0.50 to 0.52. High values of correlation coefficients describe the analysed phenomena in the central part of the Polish Lowland; although in the case of Lake Charzykowskie and air temperature, the value of correlation coefficient is lower and amounts to 0.66. The causes of weaker correlations between air and water temperatures in the cool half-year are presented above.

8.6 Final Remarks

Air temperature fluctuations are the most evident element accompanying climate fluctuations. Over the last several decades, they have usually been associated with an increase in its value. Such a tendency occurs both at the global and regional scale in reference to the basic unit of time, i.e. year. In shorter periods, the rate of air temperature fluctuations, however, is very variable. This also results in the variability of the rate of water temperature fluctuations. The dependencies are evident in the scope of river waters which respond to changes in air temperature more rapidly than lake waters.

This chapter concerns three rivers differing in both the discharge volume and the majority of morphometric and physiographic elements. It is very interesting that in spite of the evidenced differences in the rates of temperature fluctuations in particular rivers, the general course of such changes is similar (Fig. 8.6).

Inconsiderable changes, and even negative directions of changes, were observed in the period from November to February. Over the following three months, a growing increase in the rate of water temperature fluctuations occurred. Throughout the
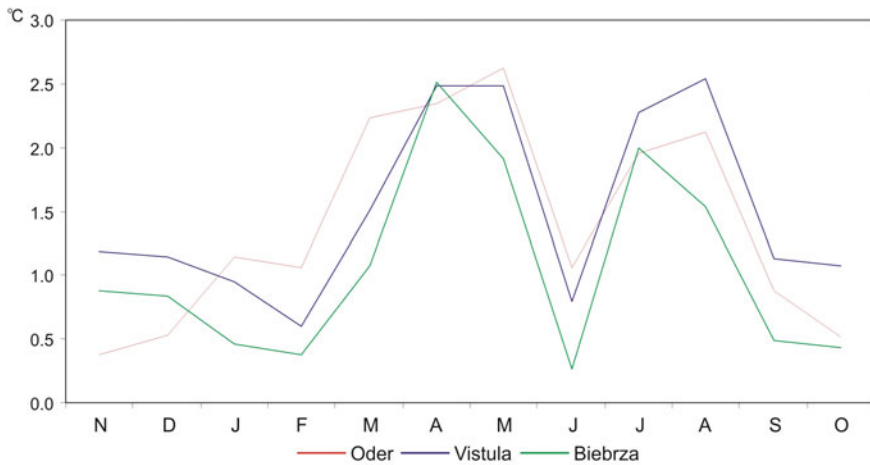
Fig. 8.6 Mean monthly (1961–2014) values of water temperature increase in rivers. *Source* author's calculations

analysed period, the highest increase in river water temperature was observed in April and May and varied from 1.9 to 2.6 °C. The evident discontinuation of the increase occurred in June as a result of a negative tendency of air temperature fluctuations. Over the following two months, another temperature increase occurred (by 1.5–2.5 °C in the years 1961–2014), and in September and October, a temperature decrease to a level characteristic of autumn and winter months (compare Fig. 8.6). In the case of rivers, in spite of the complicated course of water temperature fluctuations, a positive trend was recorded in each month; although in winter months, as well as in June, September, and October, temperature increase throughout the study period was lower than 0.5 °C.

Water temperature increase in lakes in particular months of the year showed higher regularity (Fig. 8.7). During autumn and winter months, it was low and amounted to approximately 1 °C in the case of Lakes Sławskie and Charzykowskie. In Lake Hańcza, however, a slight decrease in water temperature was recorded (to 1.2 °C), particularly in November and December. In the period from March to May, temperature increased in all lakes, even to 3–4 °C. In the period 1961–2014, the highest water temperature increase in lakes was observed in May (from 3.1 to 3.9 °C). Therefore, water temperature increase in lakes in May was by more than 1 °C higher in comparison with rivers. In June, like in rivers, an evident decline of water temperature increase occurred.

The relations between air and surface water temperature fluctuations are strong, although they are subject to modifications depending on the natural conditions and anthropo-pressure. Study results presented in this chapter confirm the earlier hypothesis that water temperature is a good indicator of climate changes, and particularly air temperature fluctuations.
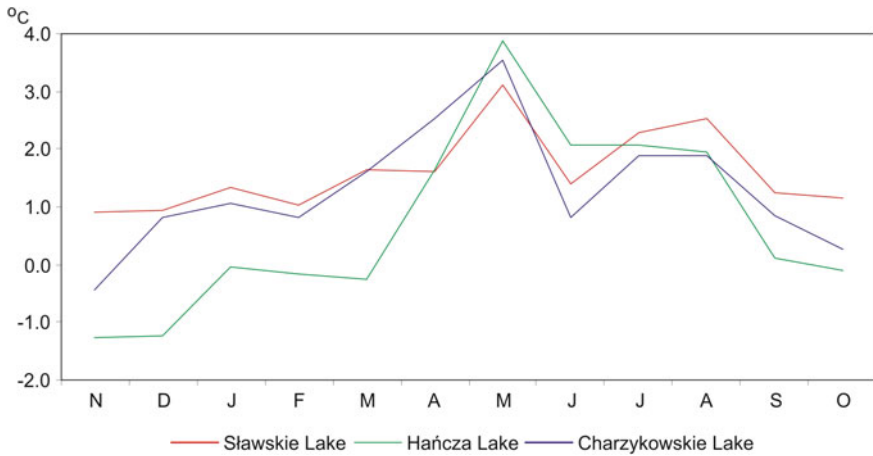
Fig. 8.7   Mean monthly (1961–2014) values of water temperature increase in lakes. *Source* author's calculations

The observed increase in the temperature of surface water results in changes in its physical properties, including among others a decrease in its density, viscosity, oxygen concentration. This is of high importance for aquatic ecosystems, because it contributes to an increase in the rate of sedimentation as a result of reduced ability of plankton to persist in the water. An increase in heat resources in inland waters also modifies the course of the development cycle of aquatic organisms (Adrian et al. 2006). Such changes show multiple directions and are difficult to determine based on research of only one element. In areas with transitional and cool moderate climate, an increase in water temperature in the winter season caused a reduction of persistence of ice phenomena and a reduction in the thickness of ice.

The research on the relations between air temperature and inland water temperature should be continued. Its results are useful for forecasting thermal conditions of rivers and lakes even until the end of the twenty-first century (Morrison et al. 2002; Ferrari et al. 2007; van Vliet et al. 2013).

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