CAUSES AND COURSE OF CLIMATE CHANGE AND ITS HYDROLOGICAL CONSEQUENCES IN THE GREATER POLAND REGION IN 1951–2020

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Abstract: The paper presents effects of changes in climatic elements in the Greater Poland region (Poland), their causes and consequences for shaping the water balance of this area, copying with the most severe water deficit in Poland. The study period covers 70 years (1951–2020). The research identified an abrupt and significant change in the climate of Greater Poland, which started between 1987 and 1989, concerning not only air temperature but also a wider spectrum of climatic elements. The change in the state of the climate, which covers the entire Atlantic-Eurasian circulation sector, results from a sudden change in the macro-circulation conditions in the middle troposphere (500 hPa). The reason for the change in the mid-tropospheric circulation is an equally abrupt and simultaneous change in the intensity of the ocean heat transport by the North Atlantic thermohaline circulation (NA THC). Climate change observed in Greater Poland is manifested in an increase in sunshine duration (SD) and air temperature, a decrease in relative humidity, a change in the cloud structure, and an increase in the degree of sky coverage. The main, physical reason for an increase in air temperature is a rapid and strong increase in SD in the warm half-years, which began after 1988, and a significant increase in the frequency of positive North Atlantic Oscillation (NAO) phases in winters. The ongoing climate change entails various effects, among which the most important is considered to be hydrological consequences. The water balance of Greater Poland is becoming increasingly unfavourable, mainly as a result of a rapid increase in field evaporation.

Key words: rapid climate shift, cause of warming up, thermohaline circulation, water balance, Poland, North Atlantic

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Introduction

The ongoing climate change attracts a lot of attention. The manifestations of climate change and their consequences are usually discussed on a global scale (Blunden et al. 2018, Blunden, Arndt 2019) or a continental scale (IPCC 2001, 2007a, b, Ciscar 2009, Ciscar et al. 2011, Iglesias, Garrote 2015), but also, less frequently, on a sub-continental scale (Rannow, Neubert 2009, The BAAC II Author Team 2015). The scope of the analysed changes is limited to air temperature or temperature and precipitation. As a result, the picture of climate change presented in scientific papers is highly generalised and inevitably neglects a number of important features of these changes that are characteristic for individual regions.

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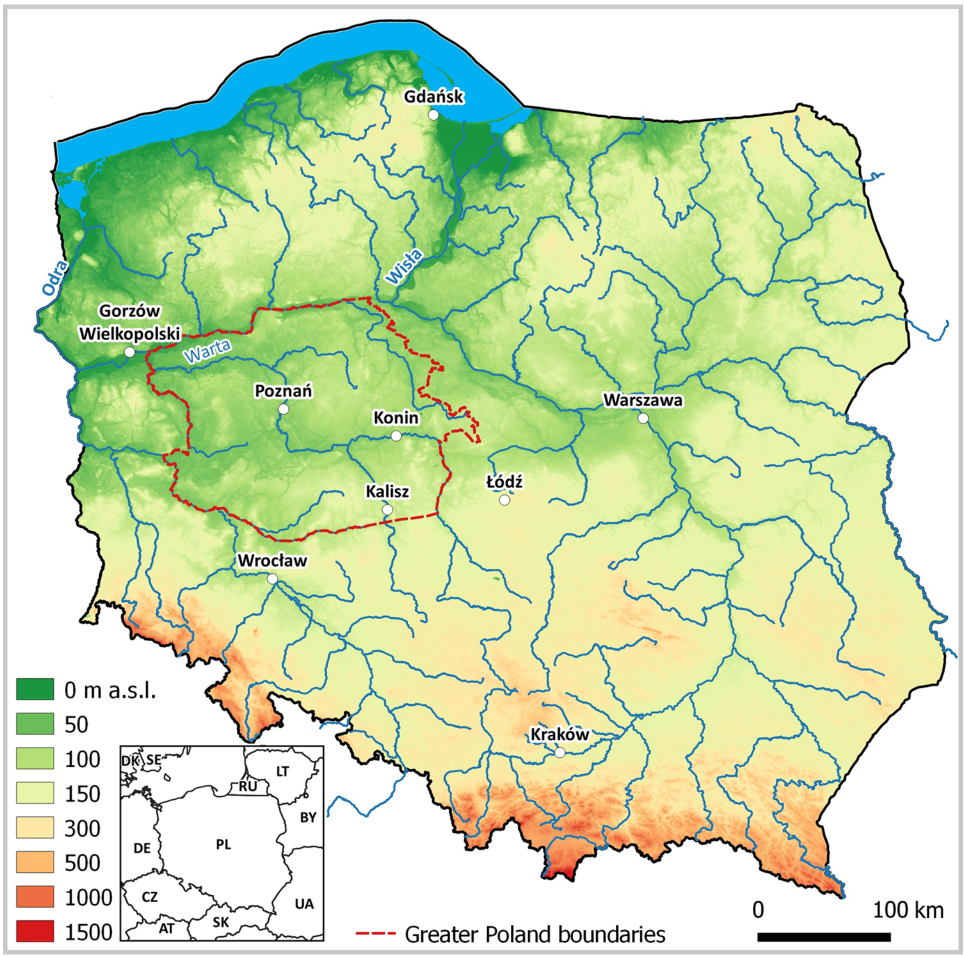

Fig. 1. Geographical position of the Greater Poland region in Poland.

Although the need to conduct more in-depth regional studies on climate change has been emphasised in the literature (Stott et al. 2010), as its course may be regionally differentiated, there is limited research on these issues. One among such regions where climate change is clearly visible and has an impact on changes of other components of the environment is Greater Poland, located in the central part of Europe.

Greater Poland is a physiographic and historical region of Poland, located in its western part (Fig. 1). It is situated on the European Lowlands, in the Warta River catchment, the third largest river in Poland after the Vistula and the Oder. Greater Poland covers about 47,000 km^2, which constitutes roughly 15% of the area of Poland, and is larger than a number of smaller European countries, such as Belgium, Denmark or the Netherlands. The city of Poznań is the capital of this region.

Greater Poland is a lowland area with small altitude variations. Apart from a few relatively elevated points, the area lies in the range of 30–140 m a.s.l. It is not shielded from any direction by the nearby heights, and thus the inflows of air masses are not obstructed. This is the reason why the climate variability of Greater Poland is shaped to a large extent by the variability of the atmospheric circulation (Woś 1994, Karolczak 2012, Szyga-Pluta and Półrolniczak 2012), while the influence of local factors on the spatial differentiation of climatic conditions is negligible. Climatic changes in Greater Poland, which have been observed in recent years, are significant and affect the entire complexity of natural processes. These changes are most strongly and clearly manifested in an increase in air temperature.

Similar to the conditions noted for most regions of the European mainland, due to the relatively small annual sums of precipitation, the increase in temperature, through the action of the entire chain of related processes, exerts considerable impact on the water balance of vast areas, creating serious threats to various sectors of the economy of the region, and especially for agriculture, which is very intensive in that area (Bartczak et al. 2014, Gawrońska 2014), forestry, energy and some industries. The ongoing climate warming also has a negative impact on the municipal economy and the quality of life of the city dwellers.

The present study aims to present the air temperature changes in the Greater Poland region in relation to the variability of other climatic elements, and to determine factors leading to the occurrence of these changes. Additionally, attention will be paid to the consequences of these changes for shaping the water balance of Greater Poland. The study period covers the last 70 years, i.e. from 1951 to 2020. It is a period long enough both to demonstrate the scale of contemporary climate change and to enable conclusions to be drawn from the statistical analyses to have a solid formal basis by which to understand the trend of the change over the mentioned 70-year period.

Materials and methods

Due to the long period of the analysis, the study will be performed on the annual basis. Average annual values of climatic elements are a synthesis of seasonal variability in a given year and describe in a proper way the tendencies and features of the long-term changes taking place in the study area.

The meteorological data used in this study come from the Poznań-Ławica station (52.41°N, 16.82°E, 88 m a.s.l., WMO Code: 12330). It is a station operating in the synoptic regime, and belongs to the state network of hydrological and meteorological services run by the Institute of Meteorology and Water Management – National Research Institute.

The Poznań-Ławica station (hereinafter referred to briefly as Poznań) is located in the western, suburban part of the city of Poznań, beyond the reach of the urban heat island (Półrolniczak et al. 2019). Throughout the period 1951–2020, the station did not change its location (Farat 1996), and changes in land development in its immediate vicinity in 1951–2020 were negligible.

Poznań has a complete measurement series of climatic elements (except for sunshine duration [SD]) for the period 1951–2020. The SD observation series, available to the authors of this paper, does not start until 1959. Due to the high quality of the data, the meteorological measurements performed at this station can be accepted as fully reliable for the analysis of climate change.

In view of the small horizontal gradients of climatic elements in the Greater Poland region, the measurement results at in Poznań can be considered fully representative for the whole area of Greater Poland. For example, the correlation coefficients between the annual air temperature in Poznań and the Kalisz station (located about 110 km SSE of Poznań), the Gorzów station (about 130 km NW of Poznań) and the Koło station (about 130 km E of Poznań) (see Fig. 1) are all equal and amount to 0.99 (1951–2020). The course of the annual precipitation totals, which differ more significantly spatially than the temperature at the aforementioned stations, is correlated with the precipitation totals in Poznań at the level of 0.70–0.75 ($p \ll 0.001$). Similarly, the courses of other climatic elements not mentioned here show a very strong correlation with the monthly and annual course in Poznań. This allows us to consider the results of analyses from Poznań as highly representative for the whole area of Greater Poland.

The values of the monthly discharges of the Warta River in 1951–2000, measured at a water gauge in Poznań ($m^3 \cdot s^{-1}$), are derived from the public, archived datasets of the Institute of Meteorology and Water Management – National Research Institute in Warsaw, Poland. Based on the daily values, the mean annual discharges were calculated in the hydrological year (November–October), and in the winter (November–April) and summer (May–October) half-years.

The values of North Atlantic Oscillation (NAO) index were downloaded from the NCAR (2022) Climate Data Guide website. The NAO PC-based indices (and not station indices) were used, as recommended by Hurrell on that website.

The values of DG_{3L} index characterising the intensity of heat transport along with water transport (Marsz 2015) were calculated from the Sea Surface Temperature (SST) values in the North Atlantic, derived from the Extended Reconstructed Sea Surface Temperature, version 5 (ERSST v.5) dataset collection (Huang et al. 2017). The description of the structure of this index and the method of its calculation were presented in Wrzesiński et al. (2019). From February

2020, the IRI/LDEO Climate Data Library discontinued the ERSST v.3b dataset (Smith et al. 2008), which is typically used for calculations of the DG_{3L} index value, and therefore it was necessary to use the SST values contained in the ERSST v.5 set. Comparison of the variations of the indices calculated from the ERSST v.3b and ERSST v.5 sets in 1951–2019 showed that their changes were strongly correlated ($r = 0.95$, $p < 0.001$). Larger differences between the indices calculated from both sets occurred only in the following time-periods: 1975–1979, 1985 and 2013–2015.

The annual total solar irradiation (TSI) values were taken from the Colorado University database (Kopp 2022). The TSI values used in this study are dated to mid-year. The study employs data calculated and summarised by Kopp; the methodology of their development was discussed in Kopp and Lean (2011) and Dudok de Wit et al. (2017). The TSI data series end in 2018, which makes it impossible to take them into account in the analysis of relations between the last 2 years (2019 and 2020).

The chronological series of the radiative forcing values were calculated based on the annual CO_2 concentration value. The output was a combination of the mean annual even concentration sequence with the Law Dome (Etheridge et al. 1996, 1998) from 1989–1978 with a sequence of annual CO_2 concentration values from Mauna Loa from 1958–2020 (Keeling et al. 2009). As the convergence of both series in the common observation period (1958–1978) was satisfactory, mean values from this period were used for the calculations.

Radiative forcing in *k*-th year (designated as ΔF (k), unit: $W \cdot m^{-2}$) was calculated according to the formula recommended by IPCC (2001; tab. 6.2., p. 358):

$$\Delta F(k) = 4.841 \cdot \ln (C(k) / C0) + 0.0906 \cdot (\mathrm{sqrt}(C(k)) - \mathrm{sqrt}(C0)), \quad (1)$$

where:

- C(k) denotes concentration of CO_2 in the atmosphere in *k*-th year, and
- C0 represents the concentration of CO_2 in the atmosphere in the pre-industrial era (assumed by IPCC as C0 = 280 PPM).

Standard methods of statistical analysis are used in this study, mainly the linear correlation analysis, regression analysis and analysis of variance. The calculations were performed using the StatisticaPL software (Palo Alto, California, USA) licensed by StatSoft®.

Results

Climate changes in Greater Poland

Air temperature and peculiarities of its course

The long-term average (1951–2020) annual temperature in Poznań is 8.7°C, and shows a relatively significant inter-year variability; the minimum annual temperature recorded in this period was 6.6°C (in 1956), while the maximum was 11.8°C (in 2019). Spectral analysis of the data series shows the presence of a relatively strong periodicity of about 7.7 years. This periodicity (around 7–8 years) is typical for the annual air temperature throughout Poland and has been described many times by Polish researchers, including Boryczka (1998), Fortuniak (2000), and Fortuniak et al. (2001). It can be associated with a very similar periodicity occurring in the winter changes of the NAO (Boryczka et al. 1999), which, by regulating the temperature of the winter months, exerts a strong impact on the annual temperature in the areas around the Baltic Sea, and more generally, in Central Europe.

The course of the annual air temperature in Poznań corresponding to the period 1951–2020 is shown in Figure 2A. In that period, there is a positive trend in annual temperature in the series, equal to +0.035 (± 0.005)°C $\cdot$ year^{-1} with high statistical significance (p <0.001). The temperature increases in Poznań estimated from the value of the linear trend for the analysed period of 70 years (1951–2020) is 2.4°C. Both the trend value and the resulting increase in annual temperature are greater than the global temperature and the temperature increase in the Northern Hemisphere estimated by the GISTEMP Team (Lenssen et al. 2019, NASA 2022) for this period. On the other hand, the value of the trend in Poznań is slightly lower than the value of the Northern Hemisphere trend reported by GISTEMP, which is +0.037 (±0.004)°C $\cdot$ year^{-1}.

A detailed analysis of the annual temperature series, together with the analysis of the course of the envelope of the band of its inter-annual variability, shows that this series is unstable. The

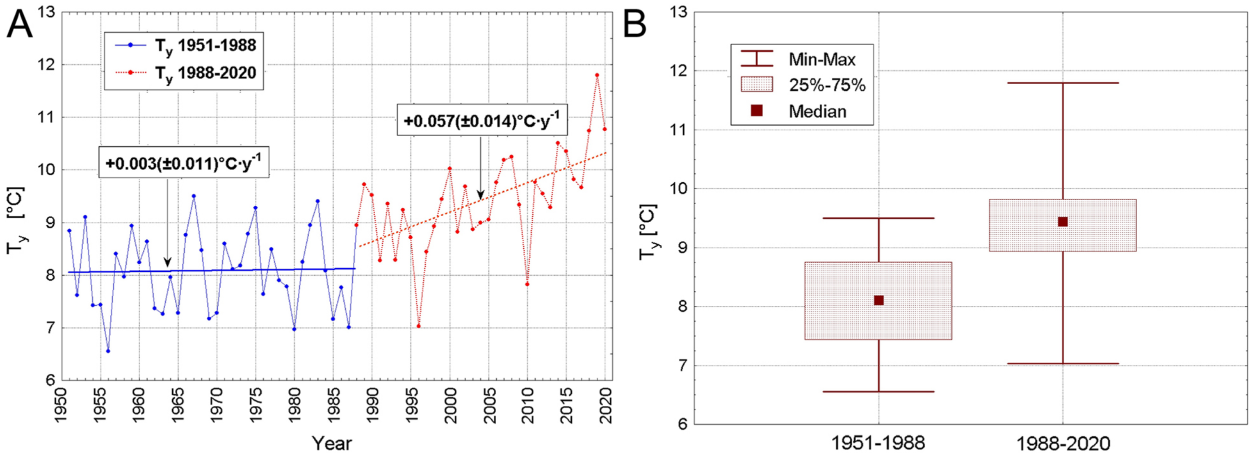

Fig. 2. The annual air temperature (T_y) with values of linear trends and the standard error of their estimation (in brackets) (A), and its variability ranges (B) in Poznań in sub-periods 1951–1988 and 1988–2020.

temperature course consists of two clearly different parts, with different ranges of variability and behaviour (Fig. 2A). The boundary between these two parts (discontinuity) is between 1987 and 1989. Next, it is arbitrarily assumed that the moment separating the two sub-periods occurs in 1988, with 1988 taken as the last year of the first sub-period and the first year of the second sub-period.

In the first sub-period (1951–1988), the inter-annual variability of temperature is significant, and there is no trend in the series – its value (+0.003 (±0.011)°C · year^{-1}) is statistically insignificant (p = 0.827). In the second sub-period, the inter-annual variability clearly decreases (Fig. 2A, Table 1) and a statistically significant positive trend appears in the course of the annual temperature (+0.057 (±0.014)°C · year^{-1}, p = 0.003). The increase in the value of the standard deviation (σ) in the second sub-period compared with the first one (Table 1) is a consequence of the occurrence of a trend in the temperature course, and not of an increase in the amplitude of inter-annual changes.

In statistical terms, the series of annual air temperature in Poznań is made up of two completely separate populations of variables, differing significantly both in terms of mean values and the distribution of values in both sub-periods. The scale of these differences is presented in Figure 2B, which shows that the lower limit of the second quartile in the second sub-period is above the upper limit of the third quartile in the first sub-period.

The temperature distribution chart shows that between 1987 and 1989, there was a noticeable change in its regime – there was a sudden, abrupt shift in the annual air temperature by about +1 degree, and then a further, still ongoing, increase began, interrupted only by two deeper chills in 1996 (7.0°C) and in 2010 (7.8°C) (see also Figure 2A).

Such an abrupt change in the structure of the temperature variability allows formulating a thesis that between 1987 and 1989, there was a change in the climate of Greater Poland. According to the definition of climate proposed by Monin (1982), climate is a certain set of multi-dimensional statistical characteristics describing the long-term state of the atmosphere over a given area. Going beyond the limits of long-term norms of even one climate element is tantamount to climate change.

The results of this analysis show that presentation of the air temperature increase in Poznań by means of a uniform trend covering the entire period in question is not correct, and such an operation does not represent the actual changes taking place in the function of time. In fact, in 1951–1988,

Table 1. Basic statistics of the annual air temperature in Poznań in the two sub-periods.

Period	Number of years	Minimum	Average	Median	Maximum	Standard deviation
		[°C]				[σ]
1951–1988	38	6.553	8.092	8.102	9.499	0.761
1988–2020	33	7.031	9.423	9.442	11.800	0.925

despite the strong inter-annual variability of air temperature, there was no temperature increase, and the warming did not start until 1988. Research conducted by Kolendowicz et al. (2019) based on the changes of temperature throughout the whole period of the measurements (i.e. from 1848) carried out by the Institute of Meteorology and Water Management – National Research Institute (Warsaw) in relation to Poznań showed that despite the strong inter-annual variability, at least from 1902 to 1987, there was no statistically significant trend in the annual temperature[1]. Thus, it can be argued that the entire temperature increase observed in Poznań in 1902–2020 took place in 1988–2020, and the warming process began only after 1988.

The aforementioned statements raise a number of further questions, some of which, considered to be the most important, need to be solved. These are:

1. Could it be that the discontinuity detected in the course of the trend in air temperature change in Poznań is not a case of a local peculiarity occurring only in Greater Poland, but possibly an observation resulting from a simple breach of the homogeneity of the dataset sequence?
2. If the discontinuity in the temperature course is not the effect of breaking the sequence of the observed values, what are the relationships of the air temperature course with other climatic elements? Have the courses of climatic elements other than temperature also changed?
3. What is the origin of the observed temperature increase – and more generally – the abrupt change in the state of the climate?

Discontinuity in the course of temperature – a local phenomenon or of a greater importance?

The analysis of the annual temperature series at weather stations in Poland shows that this discontinuity is detected at almost all stations and occurs at the same time, and also shows similar features. It is clearly visible in the changes of the annual mean area temperature, which is the average temperature from a dozen or so stations evenly distributed throughout Poland (Marsz, Styszyńska 2019). This means that the described discontinuity in the temperature changes is not a case of breaking the homogeneity of the measurement data in Poznań, nor is it a local phenomenon, limited by its occurrence to the Greater Poland region.

The so-far unpublished studies of the authors on the variability of the annual air temperature in Europe allow the conclusion that the described jump in temperature and the change in the regime of its course occur, although with some differences in the size of the jump and the value of the positive trend after 1988, over almost the entire area of Europe – from the shores of the Bay of Biscay (Merignac, France; see Fig. 3A) to the interior of

[1] Kolendowicz et al. (2019; their Fig. 5) calculated the trend value of $+0.002°C \cdot year^{-1}$ for the period 1902–1988, and its statistical significance (p) as 0.446.

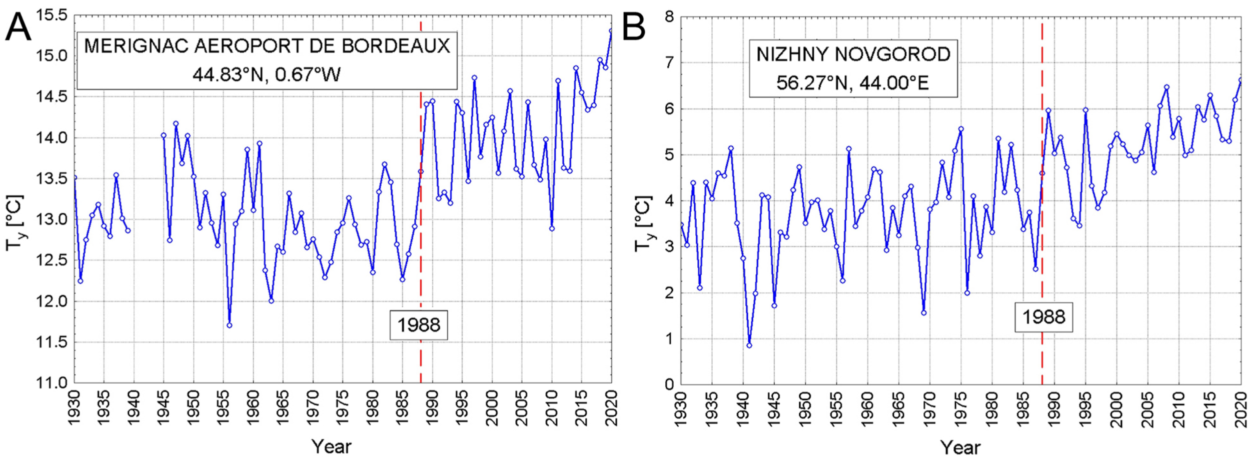

Fig. 3. The annual air temperature at Merignac Aeroport de Bordeaux (France, coast of the Bay of Biscay) (A) and at Nizhny Novgorode (the European part of the Russian Federation, around 350 km ENE of Moscow) (B) in 1930–2020. 1988 is marked with a vertical dashed line. The data in (A) are incomplete due to the Second World War.

European Russia (Nizhny Novgorod; see Fig. 3B), and from the shores of the Mediterranean Sea (Larissa, Greece) to the shores of the White Sea (Arkhangelsk, Russia).

At the majority of European stations from 1950 to 1988, the annual air temperature trend was nearly zero, and at a large number of European stations this trend has been zero since 1930. This means that also in vast areas of Europe, despite the large inter-annual temperature variability in 1930–1989, warming did not begin until 1988.

This indicates that the described change of the annual air temperature, with its discontinuity in 1987–1989, records the operation of a process of a large, macro-regional scale, covering the entire land part of the Atlantic-European circulation sector, which inevitably also appears in Greater Poland.

Variability of selected climatic elements. The scope of climate change in Greater Poland

If in 1987–1989 there was an abrupt change in the temperature regime in Greater Poland, it is important to explain how the behaviour of climatic elements other than temperature in the same period was shaped and how their relationship with temperature (T) was formed. The following were selected for the analysis: annual cloud cover (hereinafter referred to as N), annual precipitation (P), annual relative humidity (f), annual SD and the warm half-year $SD_{Apr\text{-}Sep}$, as well as annual wind velocity (Vw).

The values of the correlation coefficients between these elements in the square matrix system are summarised in Table 2. Since the measurement series of SD cover only 62 years, each time the number of correlated pairs of variables, for which the correlation coefficient was calculated, is given in the table. The *p*-values were estimated according to the number of correlated pairs of values.

When analysing the distribution of the obtained correlation coefficients, it can be seen that they represent to a greater extent dependencies found in the analysis of weather conditions occurring under typical synoptic conditions than purely physical relationships between them.

In Table 2, there are two groups of the most closely related climatic elements, namely the group associated with cloudiness and precipitation, and the group associated with sunshine and temperature. Both these groups of elements behave autonomously, and the element constituting the resultant of their opposing action is the course of air humidity.

In the course of the annual precipitation totals in the entire multi-year period under consideration (1951–2020), no trend is detectable, and its

Table 2. Values of the correlation coefficients between selected climatic elements in Poznań.

Parameter	N	P	f	SD	$SD_{Apr\text{-}Sep}$	Vw
T	*r* = −0,12 *n* = 70 *p* = 0.325	*r* = -0.05 *n* = 70 *p* = 0.691	*r* = **−0.62*** *n* = 70 *p* <<0.001	*r* = **0.71*** *n* = 62 *p* << 0.001	*r* = **0.73*** *n* = 62 *p* << 0.001	*r* = −0.21 *n* = 70 *p* = 0.078
N	1.00	*r* = **0.56*** *n* = 70 *p* << 0.001	*r* = **0.49*** *n* = 70 *p* << 0.001	*r* = **−0.44*** *n* = 62 *p* << 0.001	*r* = **−0.36** *n* = 62 *p* = 0.004	*r* = **0.25** *n* = 70 *p* = 0.041
P		1.00	*r* = **0.55*** *n* = 70 *p* << 0.001	*r* = **−0.31** *n* = 62 *p* = 0.014	*r* = **−0.26** *n* = 62 *p* = 0.038	*r* = 0,14 *n* = 70 *p* = 0.252
f			1.00	*r* = **−0.70*** *n* = 62 *p* << 0.001	*r* = **−0.68*** *n* = 62 *p* << 0.001	*r* = 0.09 *n* = 70 *p* = 0.447
SD				1.00	*r* = **0.96*** *n* = 62 *p* << 0.001	*r* = **−0.51*** *n* = 62 *p* << 0.001
$SD_{Apr\text{-}Sep}$					1.00	*r* = **−0.48*** *n* = 62 *p* << 0.001

n denotes number of the correlated pairs and *p* the statistical significance of their relationship. In the case when *n* = 70, the correlated series cover the period 1951–2020, and in the case when *n* = 61, the period 1959–2020. Significant ($p < 0.05$) correlation coefficients are marked in bold, highly significant are additionally marked with asterisk; SD, sunshine duration.

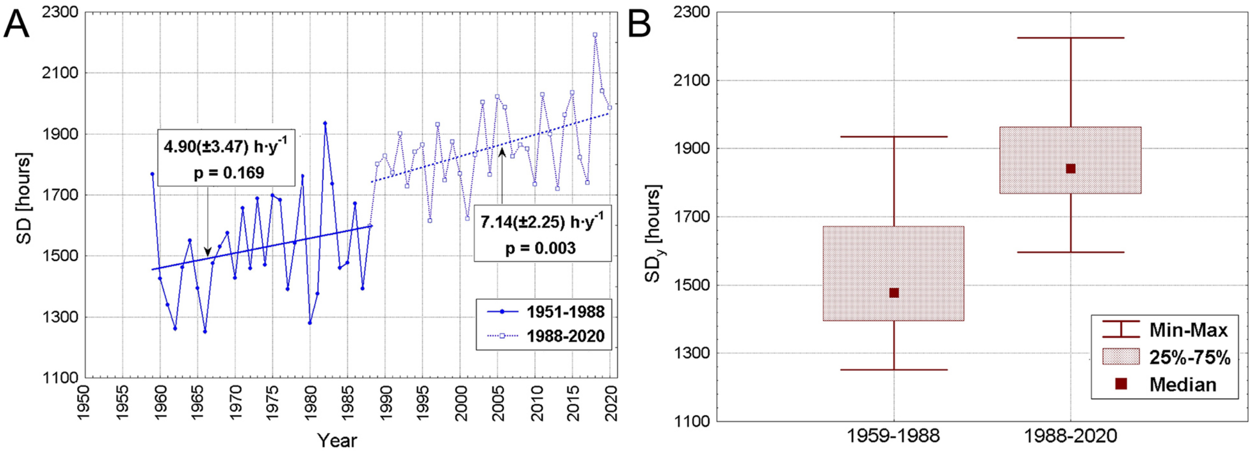

Fig. 4. The annual SD_y with marked values of trends and their statistical significance (*p*) (A), and its variability ranges (B) in Poznań in sub-periods 1959–1988 and 1988–2020. SD, sunshine duration.

characteristic feature is the occurrence of significant inter-annual variability. With the average annual precipitation of 521.2 mm, the minimum recorded value is 275.0 mm (in 1982), and the maximum is 772.1 mm (in 1967), while the standard deviation (σ) is 108.9 mm.

Total cloudiness and relative humidity are strongly positively correlated with the changes of precipitation (Table 2). The positive correlation of total cloudiness and precipitation totals is obvious, since precipitation cannot occur without cloud cover. Relative humidity is strongly positively related to the occurrence of precipitation and the process of subsequent evaporation of rainwater from the ground surface. Total cloudiness is negatively related to SD, which is also understandable, since the presence of a cloud cover limits the access of direct radiation to the Earth's surface. Precipitation and cloud cover do not show statistically significant relations with air temperature.

Temperature shows strong negative correlation with relative humidity and very weak (r = −0.12), insignificant correlation with total cloudiness. In this case, such weak relationships of the annual air temperature with cloudiness are confusing, as they can only be partially explained by the seasonal difference in the influence of cloud cover on temperature.

Air temperature is strongly related to SD – the strongest temperature correlation occurs with the warm half-year SD ($T\&SD_{Apr-Sep}$; r = 0.73). The overview of the changes of the annual SD in Poznań (Fig. 4A) reveals the presence of discontinuities in it in the same period as the temperature discontinuity. Both the range of variability in SD and the value of the trend show changes, and in 1987–1989 there is a sharp shift in SD to a higher level (Fig. 4B). This indicates that patterns of both SD and temperature change under the same factors or have the same cause.

In the first sub-period (1959–1988; 30 years) the SD_y trend is 4.90 (±3.47) h · year^{-1} and is insignificant (p = 0.169), while in the second sub-period (1988–2020; 33 years) the trend is 7.14 (±2.25) h · year^{-1} and is statistically significant (p = 0.003). The average annual SD in the two sub-periods is 1524.7 and 1856.1 h, respectively, and the difference between these averages is highly significant. The SD values in both sub-periods also represent separate populations (Fig. 4B), as is the case with air temperature (Fig. 2B).

Changes in SD are controlled by changes in cloud cover. The correlation coefficient between SD and cloud cover is highly significant, but of moderate strength (−0.42; Table 2). The analysis of the changes of total cloud cover in Poznań and its comparison with these of SD (Fig. 5) produces counter-intuitive results.

Throughout their courses the values of cloud cover (N) and SD change – in accordance with the nature of the relationship between these elements – in the counter-phase (see Table 2). In the first sub-period, the trends in both series are close to zero and statistically insignificant. In the second sub-period the cloud cover trend becomes positive (+0.012 (±0.004) N · year^{-1}) and significant (p = 0.011), similar to the SD trend. This is a logical contradiction, since with changes in N and SD in the counter-phase (anti-correlation),

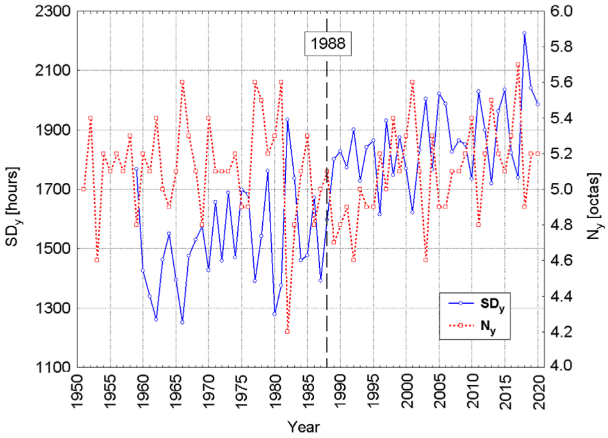

Fig. 5. The annual SD_y and annual total cloud cover (N_y) in Poznań in 1951–2020. The year of temperature and SD_y discontinuity is marked with vertical dashed line. SD, sunshine duration.

the occurrence of a positive N trend should be accompanied by a negative SD trend.

However, the presented state of dependence of both climatic elements is not an observational error – analysis of the relationship between SD and N at other weather stations in Poland confirms the common occurrence of simultaneous increases in total cloudiness and SD. This statistical paradox is relatively simple to explain. The climatic element of total cloud cover records the degree of coverage of the sky by clouds of all levels and types. Such a state is possible only when the percentage of high optical density, layered clouds gradually decreases, and the degree of sky coverage by high-level clouds with low and minimum optical density increases faster than the decrease in sky coverage. In other words, the cloud structure changes during this period, which is to a small extent related to the degree of sky coverage by clouds[2].

The occurrence of changes in the cloud structure over Poland in the second half of the multi-year period 1951–2000 and the beginning of the 21st century was concluded in a number of papers, as for example those published by Żmudzka (2007), Wibig (2008), Filipiak and Miętus (2009), and Matuszko and Węglarczyk (2018). In that period, the general tendency was a progressive decrease in the share of clouds with high optical density, especially Ns, St and As, and an increase in the frequency of Ac clouds and cirrus clouds (Ci, Cc), with a variable share of Cu clouds. Thus, one of the manifestations of the climate change that took place in Poland in 1987–1989 is also the change in the cloud structure.

Table 2 also reveals highly significant negative relationships between SD and wind speed. These relationships indicate that a decrease in wind speed in Greater Poland is accompanied by an increase in SD. This can be interpreted as an indicator of SD increases in weak-gradient and non-gradient situations. Such situations occur most often when Greater Poland is within the range of the axial parts of high-pressure wedges or within the range of an anticyclone.

Sunshine duration also shows very strong negative relationships with relative humidity. These relationships are stronger than those between temperature and humidity (see Table 2), which may indicate that an increase in SD is the most important reason for an increase in temperature and a decrease in relative humidity. The occurrence of negative trends appears in the relative humidity data series. In the first sub-period (1951–1988), this trend is close to zero ($0.0033\% \cdot year^{-1}$, $p = 0.240$) and statistically insignificant; in the second sub-period (1988–2020) it is also negative ($-0.1262\% \cdot year^{-1}$), but statistically significant ($p = 0.004$). Thus, in the second sub-period, relative humidity also decreases along with increasing SD and air temperature.

To summarise, it can be stated that the conducted analyses show that in 1951–1988 the state of the climate over the Greater Poland region was stable, and its parameters remained within the long-term standard corresponding to the average 30-year period 1951–1980, and perhaps also the norms from the period 1931–1980. In 1987–1989, there was an abrupt change in the state of the climate, in which the values of a number of elements exceeded the ranges of the previous norms. The course of SD and air temperature changed abruptly, and there was a relatively systematic increase in the value of these two elements – the period of rapid warming began. At the same time, a slow decrease in relative humidity began and the cloud

2 It is extremely difficult to correctly determine the actual cloud structure from ground-based observations. In the case of greater coverage of the sky by low-layered clouds, it is not possible to correctly determine the cloud structure in the middle and high layers. Similarly, in the presence of a middle-layered cloud (As) with a larger horizontal extent, it is not possible to determine the types of clouds and the degree of coverage of the sky by high-layered clouds.

structure changed. Within the limits of the climate norm from 1951–1980, the amount of precipitation remained unchanged, whereas total cloud cover, after a temporary decrease in 1989–1992 (Fig. 5), was increasing slowly and irregularly.

Mechanisms and causes of climate change in Greater Poland

The presented picture poses a question about the mechanisms leading to the occurrence of climate change, which is most clearly demonstrated by an increase in air temperature. For air temperature to rise, the amount of heat in the atmosphere must increase. This may occur as a result of an increase in the amount of radiation flowing into the ground, a decrease in the size of radiation losses (radiation) and/or an increase in the horizontal heat inflow over a given area along with the advection of air masses.

The analysis of the relationship between temperature in Poznań and TSI showed that the influence of changes in the solar constant on changes in air temperature can be neglected. The relationships are weak (r = 0.21) and statistically insignificant (p = 0.082; 1951–2018), and the TSI changes are nothing like the temperature changes.

Changes in the atmosphere chemistry (Anthropogenic Global Warming [AGW])

It is commonly recognised (Mann et al. 1998, IPCC 2001, 2007a, b, 2014, Hansen et al. 2007, Lacis et al. 2010, Kundzewicz 2011) that the cause of the observed global temperature increase is an increase in concentration of CO_2 and other greenhouse gases in the atmosphere, changing the radiation balance of the Earth. As a result of changes in the atmosphere chemistry, there is an additional stream of energy (long-wave radiation, reverse radiation) directed to the surface, referred to as radiative forcing (IPCC 2001), increasing non-linearly with an increasing CO_2 concentration (see Eq. [1]). As the concentration of greenhouse gases in the atmosphere increases mainly as a result of human activity, this process is referred to as AGW. As an additional factor influencing global temperature changes, besides an increase in CO_2 concentration, numerous authors point to the action of natural factors. Among them, the most frequently considered is the varying impact of heat fluxes transferred from the ocean to the atmosphere by various types of oscillations of the thermal state of the ocean surface (El Niño-Southern Oscillation [ENSO], Atlantic Multidecadal Oscillation [AMO], Atlantic Multidecadal Overturning Circulation [AMOC], North Atlantic thermohaline circulation [NA THC), Pacific Decadal Oscillation [PDO]; e.g. Kushnir 1994, Lean, Rind 2008, Compo, Sardeshmukh 2009, Foster, Rahmstorf 2011, Zhou, Tung 2013, Chylek et al. 2014, van der Werf, Dolman 2014, Willis et al. 2018, Kundzewicz et al. 2020).

In the case of the analysis of the relationship between the temperature changes in Greater Poland and the value of radiative forcing (variable ΔF), there is no other common variability than the trend occurring in both series. The variability of the monotonically increasing value of ΔF, without sharp twists and discontinuities in the course, explains a very high percentage of temperature variation (as much as 46%) in 1951–2020. The correlation coefficient between temperature (T) and radiative forcing (ΔF) in 1951–2020 is very high (r = 0.69). However, in each sub-period of the temperature course, the values of the correlation coefficients and the levels of their significance are different – in the first sub-period (1951–1988) the correlation coefficient between T and ΔF is equal to 0.03 and is insignificant (p = 0.861), while in the second sub-period (1988–2020) r reaches the value of 0.62 and becomes highly significant ($p \ll 0.001$), being, however, lower than the value of r in the entire period 1951–2020. Since the temperature increase caused by radiative forcing ($T = f(\Delta F)$) is a physical and therefore deterministic process, it is not possible for a monotonically increasing value of ΔF in one sub-period (1988–2020) to be the cause of the temperature increase, while in another (1951–1988) it was not.

Radiative forcing (ΔF) shows an even stronger relationship with SD than with temperature – for 1959–2020 the correlation coefficient between ΔF and SD is 0.76, which means that with an increase of radiative forcing, SD also increases. While, despite the above-mentioned objections, it is possible to physically justify the effect of radiative forcing on the temperature, the processes in which changes in ΔF could result in changes in SD are not known so far, and their relatively simple physical justification does not seem possible. This prompts us to consider also reasons for the increase in temperature and, more generally, climate change in Greater Poland, other than the impact of AGW.

SD, atmospheric circulation and air temperature

The high compliance between the changes of SD and air temperature suggests that both have, or may have, a common cause. While temperature changes cannot be the cause of changes in SD, changes in SD, determining changes in the amount of solar energy reaching the ground (see the Black formula in Black 1954), are the obvious cause of the air temperature changes (apart from the influence of other factors). This explains that the discontinuity of the course followed by a positive trend should be a feature of the course of SD, and the discontinuities in the course of temperature, followed by a positive trend, is a reaction of air temperature to a change in the amount of energy reaching the ground, which leads to the replication of the course of SD by the course of temperature (T).

The regression analysis shows that the change in the annual SD_y by 1 h · year^{-1} in 1959–2020 entails a change in the average annual temperature in Poznań by 0.0034 (±0.0004) C ($p << 0.001$), consistent with the change in SD. The variability of SD_y in 1959–2020 explains (adj. R^2 100%) half (50.2%) of the T_y variance at the same time. To a slightly greater extent (52%), the variability of the annual temperature is explained by the changes in SD that take place in the warm half-year (April-September; variable $SD_{Apr-Sep}$), which may be defined as the period in which the day (i.e. the theoretical time of solar operation) is on average greater than 12 h · day^{-1}. This is obviously a more reasonable explanation of the annual temperature variation than the explanation that involves radiative forcing (46%). The standard error of the estimate (SEE) is relatively small and equals ±0.74 deg.

The estimated variability of air temperature in Poznań as a function of the warm half-year SD (variable $SD_{Apr-Sep}$; Fig. 6) proves that the temperature variability quite well reproduces the SD variability, including the discontinuity in its course and the change of the trend after 1988.

Analysis of the residuals shows that in the estimation of temperature, the amplitude of its variation is lower, which indicates that the variability of air temperature is influenced by factors other than SD. More often, large residual values occur in situations with low annual temperature values.

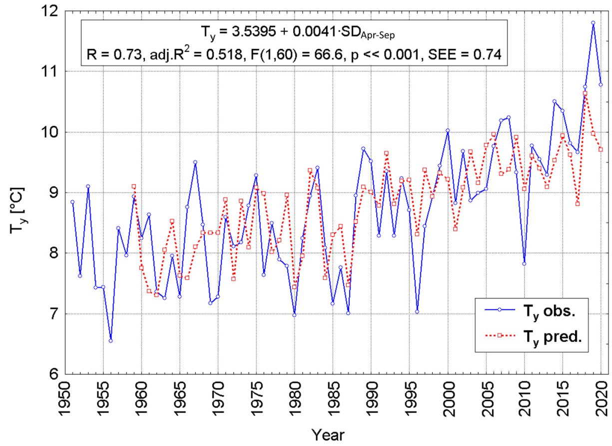

Fig. 6. The annual temperature observed (T_y obs.) and estimated (T_y pred.) in Poznań in 1951–2020 as a function of the insolation of the warm half-year.

The variable $SD_{Apr-Sep}$ may affect the annual temperature only during its operation, i.e. in the warm half-year. The equation linking the SD of the warm half-year (Fig. 6) with T_y explains only the influence of temperature of that half-year on the annual temperature (T_y). The temperature of the winter period, when – due to the long duration of the night – SD is regulated in a non-uniform manner and only to a small extent[3], is strongly regulated by the atmospheric circulation occurring in this period. Previous studies show that the variability of the winter NAO Hurrell index (Hurrell 1995) explains about 50% of the winter temperature variance (December-March) and about 35% of the annual temperature variance in Poland (Marsz, Styszyńska 2001, Kożuchowski 2011). Adding the second independent variable to the equation explaining the variability of the annual temperature in Poznań, which is the value of the winter NAO Hurrell index (the PC-based DJFM), whose variability strongly regulates the winter temperature, results in an increase of the degree of explanation of the T variance to 60% (R = 0.78) and reduction of its estimation error (SEE

[3] In the winter period, as in other seasons of the year, high daily amounts of sunshine are recorded with a cloudless sky or with strongly reduced cloudiness. However, in view of the low altitude of the sun in winter, the amount of incoming solar energy per unit surface area of the ground is small. Due to the long duration of night in winter, night radiation (long-wave radiation) in the absence or reduction of cloud cover significantly exceeds the energy supply of short-wave radiation, which in such conditions is the cause of deep temperature drops.

= ±0.68 deg). In this equation, the variability of $SD_{Apr\text{-}Sep}$ explains 52.6%, while the variability of the PC-based NAO_{DJFM} explains 8.6% of the temperature variance in Poznań in 1959–2020. The course of the observed annual temperature, and its estimation using the two-variable equation (see the framed equation and its statistical characteristics), are presented in Figure 7.

Analysis of the residuals of the temperature course calculated with the help of the two variables (Fig. 7) shows that the residual distribution is normal, the residuals and deleted residuals are closely related linearly, and there is a very weak and statistically insignificant positive trend in the residual's series. The analysis of the dispersion of the observed values and the squares of the residuals indicates the presence of three strong outliers in the set, exceeding the limits of 1.5 standard deviation of the observed temperature (1966, 1976 and 2019) and significantly reducing the precision of estimating the parameters of the equation. It was not possible to determine whether the error was caused by the temperature data (T_y) or by the independent variables ($SD_{Apr\text{-}Sep}$, NAO_{DJFM}). There is presumably another factor or other factors that are not taken into account.

The reduced value of the temperature trend estimated based on the SD value of the warm and winter half-year NAO index, as compared to the observed values, and a weak positive trend detected in a number of residuals, indicate the need

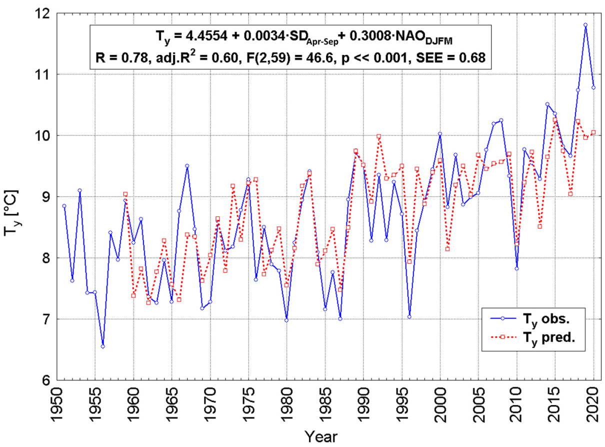

Fig. 7. The annual temperature observed (T_y obs.) and estimated (T_y pred.) in Poznań in 1951–2020 as a function of SD of the warm half-year (variable $SD_{Apr\text{-}Sep}$) and the winter PC-based NAO Hurrell index (variable NAO_{DJFM}). NAO, North Atlantic Oscillation; SD, sunshine duration.

to check whether the omission of the radiative forcing (ΔF) in the estimates is not the cause of the trend underestimation.

The equation with three independent variables ($SD_{Apr\text{-}Sep}$, NAO_{DJFM} and ΔF) is statistically significant and all its parameters (intercept, regression coefficients) are also statistically significant. The multiple correlation coefficient (R) of this equation is 0.81, the equation explains (adj. R^2) 63.87% of the T_y variance and the standard error decreased by 0.02 deg. (SEE = 0.66). In this equation, the variability of $SD_{Apr\text{-}Sep}$ is explained by 52.6%, the variability of NAO_{DJFM} by 8.6% and ΔF by 4.4% of the T_y variance. The value of the T_y trend across the 1959–2020 series increased by 0.0006 C · year^{-1}. The differences in the course of the T_y values reproduced using the three-variable equation compared to those using the two-variable equation are almost imperceptible.

Thus, the introduction of radiative forcing (ΔF) as the main factor representing AGW, together with two variables 'representing' the action of natural factors (SD in the warm half-year [$SD_{Apr\text{-}Sep}$] and the winter atmospheric circulation [NAO_{DJFM}]), increases the degree of explanation of the temperature variability by a negligible percentage (4.4%), indicating that the observed warming after 1988 is largely the result of processes related to the internal variability of the climate system.

SD, the mid-tropospheric circulation and the thermal state of the North Atlantic

Since an increase in SD is the cause of an increase in temperature, the question is what process led to the change in SD. Research by Marsz et al. (2022) showed that changes in the intensity of the North Atlantic thermohaline circulation (NA THC) controlled changes in solar radiation in Central Europe by regulating the course of the processes of the middle and lower circulation. The intensity of NA THC is characterised by the index defined by the acronym DG_{3L}. It shows to what extent the heat transport, together with the transport of water through NA THC from the Atlantic tropics to the north, is higher or lower than the 1901–2000 average.

In the changes of the DG_{3L} index, there are several decades of positive phases, in which the heat transport through NA THC is, on average, higher than the mean value, and negative phases,

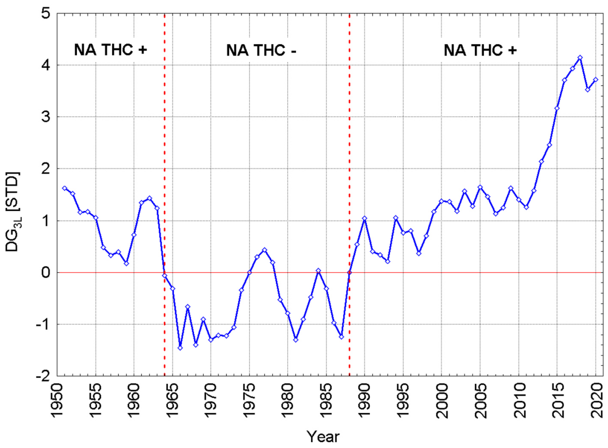

Fig. 8. The standardised DG_{3L} index characterising the intensity of heat transport through the thermohaline circulation (NA THC) from the Atlantic tropics to the Arctic. Vertical dashed lines mark the NA THC phase changes. The index values were calculated based on the ERSST v.5 dataset. NA THC, North Atlantic thermohaline circulation.

in which this transport is, on average, lower. The course of the DG_{3L} index value in 1951–2020 is presented in Figure 8. The limits of the NA THC phase change are the years 1963–1964, when NA THC changed from positive to negative, and 1988–1989, when NA THC changed from negative to positive.

The boundaries of the NA THC phases correspond with a good approximation to the boundaries of the so-called circulation periods (epochs), determined based on changes in the frequency of macrotypes of the mid-tropospheric circulation, according to the Wangengejm-Girs classification (Wangengejm 1952, Girs 1964, 1971). The period names indicate the dominant or dominant and sub-dominant macrotype in a given period. In the multi-year period 1949–2014, Savichev et al. (2015) distinguished the following circulation periods: in 1949–1965 – period E + C, in 1966–1988 – period E, and in 1989–2014 – period W. While 2014 was the last year of their analysis, it was reported by Savichev et al. (2015) that, according to their calculations, period W would continue additionally at least until 2017[4]. Very similar boundaries of the circulation periods, based on the analysis of the frequency of macrotypes W, E and C, were determined by Degirmendžić and Kożuchowski (2018, 2019).

The mechanism by which changes in the NA THC phases control the frequency changes of macrotypes of the mid-tropospheric circulation and, consequently, the boundaries of the circulation periods is explained in the papers of Wrzesiński et al. (2019) and Marsz et al. (2022).

In the periods when NA THC becomes positive, there is an increase in the frequency of the zonal macrotype W and a simultaneous decrease in the frequency of the meridional macrotype E, according to the Wangengejm-Girs classification[5], which, by shaping the appropriate weather structure, increases the value of SD (Marsz et al. 2022). These are so-called brightening periods (Wild et al. 2005, 2007, Wild 2012).

In the periods when NA THC becomes negative, the frequency of macrotype E increases, while the frequency of macrotype W decreases, leading to a decrease in sun exposure and the appearance of the global dimming periods. These processes, related to the change in the cloud structure presented in Section 3.3, occur with the changes of the circulation periods.

The relationship between changes in the annual frequency of macrotypes W and E and the annual SD in Poznań is presented in Figure 9. Due to the strong correlation of the annual frequency of macrotypes, this relationship cannot be presented in the form of linear relationships.

The value of the DG_{3L} index, which characterises the NA THC intensity, shows a strong and highly significant correlation with the annual SD in Poznań (r = 0.63, p << 0.001, see Fig. 10). Almost the same value (r = 0.62, p << 0.001) has the correlation coefficient between the DG_{3L} index and SD of the warm half-year. These values do not differ from the correlation coefficient value between DG_{3L} and the average annual SD in Central Europe (r = 0.60, p << 0.001) in 1951–2015 (Marsz et al. 2022).

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4 In order to determine the boundary of the circulation periods according to the Wangengejm-Girs classification, not less than 6–7 additional years of observation of the macrotype frequency are needed. At the moment (the last year with data is 2020) it is not yet possible to determine whether the circulation period W has ended and another circulation period has started.

5 The value of the correlation coefficient between the DG_{3L} index and the annual frequency of macrotype W is +0.63, and the frequency of macrotype E is −0.61. The correlation coefficient between the annual frequency of these two macrotypes is −0.83 (all correlation coefficients are highly significant [p << 0.001]; correlation period: 1951–2015).

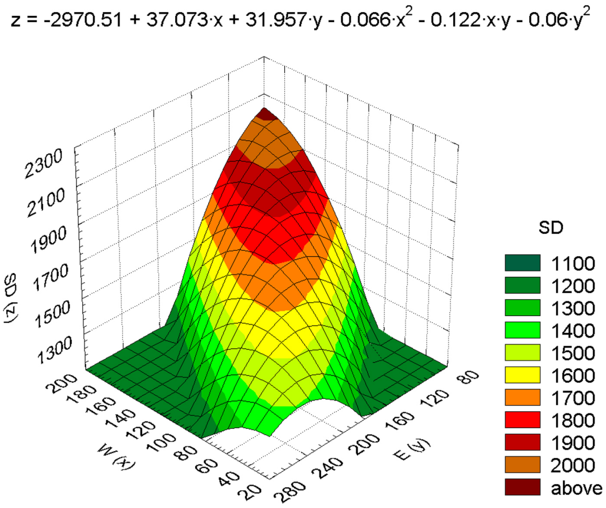

Fig. 9. Relationship between the annual SD (unit: hours) in Poznań and the annual frequency of macrotypes W and E of the mid-tropospheric circulation (unit: number of days per year) in 1959–2020. SD, sunshine duration.

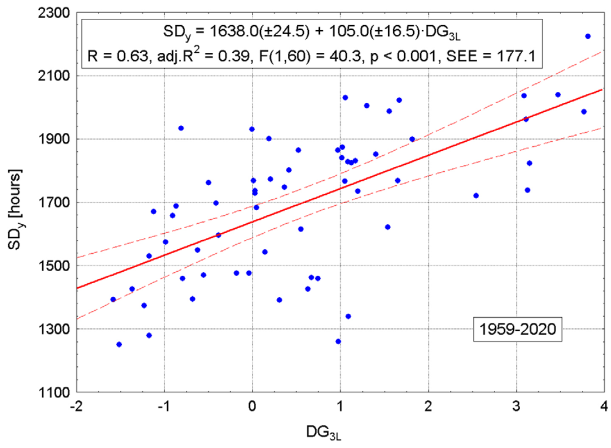

Fig. 10. Relationship between the annual SD_y in Poznań and the DG_{3L} index characterising the NA THC intensity in the North Atlantic in 1959–2020. The regression line is marked with bold solid line and boundaries of confidence level of 95% ($p = 0.05$) with dashed lines. NA THC, North Atlantic thermohaline circulation; SD, sunshine duration.

A change in the DG_{3L} index value by one unit results in an average change in the annual SD in Poznań by 105 (±16.5) h; the change is consistent with the direction of change of the DG_{3L} index (see framed equation in Fig. 10). Thus, with the variability of the DG_{3L} index in 1959–2020 in the range from about −2 to about +4, the range of changes in the annual SD in Poznań should be on average from about 1426 h to about 2026 h. These values are close to the observed values of SD_y – with the minimum of 1251 h (in 1966), and the maximum of 2224 h (in 2018).

There is a very strong positive trend in the course of the DG_{3L} index after 1988 (Fig. 8). Between 1987 and 1990, the value of that index increased from −1.58 to +1.08, and then it did not drop to negative values in the following years. This period corresponds to the period of the change of circulation periods from E to W and the occurrence of the 'jump' in the course of SD (and temperature). The positive trend after 1988 in the course of SD and temperature is consistent with the positive trend of the DG_{3L} index after 1988.

In such a situation, in the equation with two independent variables (framed in Fig. 7), it is possible to replace the variable characterising $SD_{Apr\text{-}Sep}$ directly with the variable DG_{3L}. This will allow estimation of the direct impact of the change in the thermal state of the North Atlantic on the temperature in Greater Poland, excluding intermediate stages, in the entire period 1951–2020. Estimation of the parameters of the equation, in which the annual temperature variability (T_y) is a function of the DG_{3L} index and the winter NAO index, gives the result:

$$T_y = 8.43(\pm0.09) + 0.44(\pm0.07) \cdot DG_{3L} + 0.40(\pm0.08) \cdot NAO_{DJFM}, \quad (2)$$

in which the variability of both independent variables explains a total of 57.3%, the variability of DG_{3L} is explained by 42.6%, and the variability of NAO_{DJFM} by 15.8% of the variance of T_y. The equation is highly significant ($F(2.67) = 47.4$, $p << 0.001$), since all its parameters (intercept, regression coefficients) are estimated with high significance ($p << 0.001$). The multiple regression coefficient (R) is 0.765 and the standard error of T_y estimation (SEE) is 0.70 deg. The scatter plot of the T_y values estimated using this equation in relation to the observed values is presented in Figure 11A, while the course of the observed and estimated values of T_y in Figure 11B.

Thus, Eq. (2), in which the independent variables are the DG_{3L} index and the winter NAO index, taking into account the standard error of the T_y value estimation, reproduces the course of the annual temperature in Poznań in the analysed period of 70 years, as correctly as the formula in which the independent variable (besides NAO) is represented by sunshine. The same two variables also allow estimation of the annual air temperature

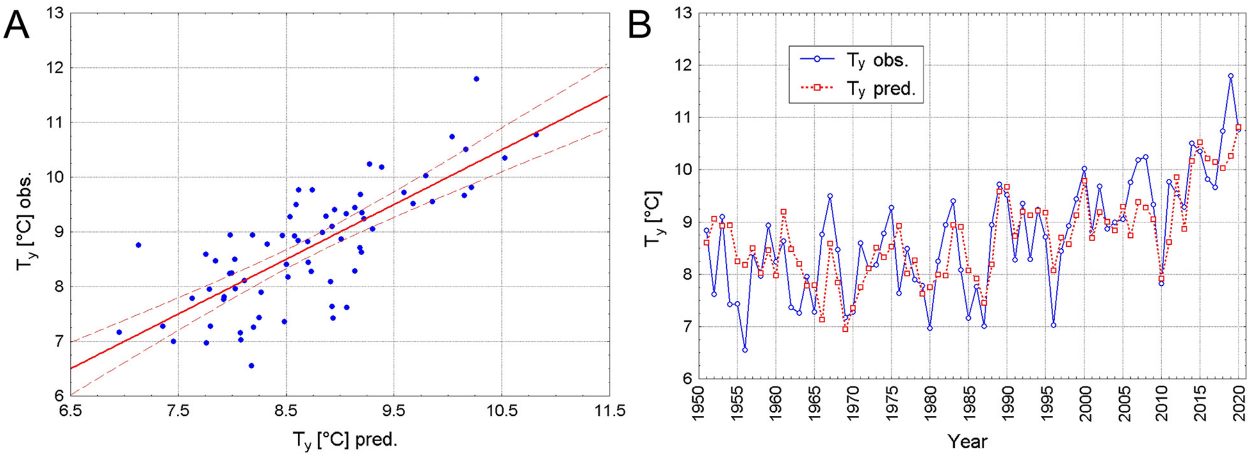

Fig. 11. Values of the annual temperature (T_y pred.) estimated using Eq. (2) in relation to the observed values (T_y obs.) (A) and their course (T_y pred.) estimated using Eq. (1) and the observed values (T_y obs.) (B) in Poznań in 1951–2020.

at other weather stations in Greater Poland. Thus, at the aforementioned weather stations in Kalisz, Koło and Gorzów, the same independent variables explain, respectively, 60.8%, 60.6% and 62.0% of the variance of their annual temperature in the period of 70 years (1951–2020) without the need to take into account radiative forcing.

It can therefore be concluded that one of the primary causes of changes in the annual air temperature, not only in Greater Poland but also over large parts of Europe, are changes in the thermal state of the North Atlantic, which, along with the change of the NA THC phase from negative to positive in 1987–1989, resulted in an abrupt change of the macro-circulation conditions in the Atlantic-Eurasian circulation sector. The change in macro-circulation conditions in the middle atmosphere led to the same change in the nature of the lower circulation (SLP), in which there was a change in the cloud structure and an increase in SD and temperature. At the same time, the structure of advection over Europe changed: along with the increase in the frequency of macrotype W and the decrease in the frequency of macrotype E in the last circulation period, the frequency and intensity of the positive NAO phases in winter increased[6]. This led to an increase in the frequency of the warm polar-maritime air masses flowing from the North Atlantic, contributing to a significant increase in temperature during the winter months.

Consequences of climate change for Greater Poland

The progressive increase in SD and an increase in temperature as well as a decrease in relative humidity in the Greater Poland region have various consequences. Among them, the most significant, specific to Greater Poland, concerns changes in the water balance. Greater Poland is characterised by the lowest values of the average annual runoff in Poland, ranging from 3 to 4 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Michalczyk 2017).

In the study area, the average runoff is 110 mm, with most of the catchments characterised by runoff lower than the national average, and with almost half of the runoff below 100 mm (Fig. 12).

Fluctuations of river runoff can be seasonal, determined by the annual cycle of the water supply changes, and random, related to the nature of meteorological phenomena. The most abundant water resources in Poland are formed in the winter-spring period, as a result of the snow cover melt. The runoff in the winter half-year (November–April) is noticeably dominant in the study area. In all river catchments of Greater Poland, its share is higher than 50%, and in the case of 14 catchments it is higher than 70%. Catchments of the Mogilnica, Bawół and Kopel

[6] Between the value of the PC-based winter NAO Hurrell index and the frequency of macrotype W in the first quarter, the correlation coefficient is 0.63 ($p < 0.001$) and the frequency of macrotype E in the first quarter is −0.49 ($p < 0.001$). Throughout the winter period (DJFM), the correlation coefficient between the frequency of macrotype W and the NAO index is 0.69 (1951–2020).

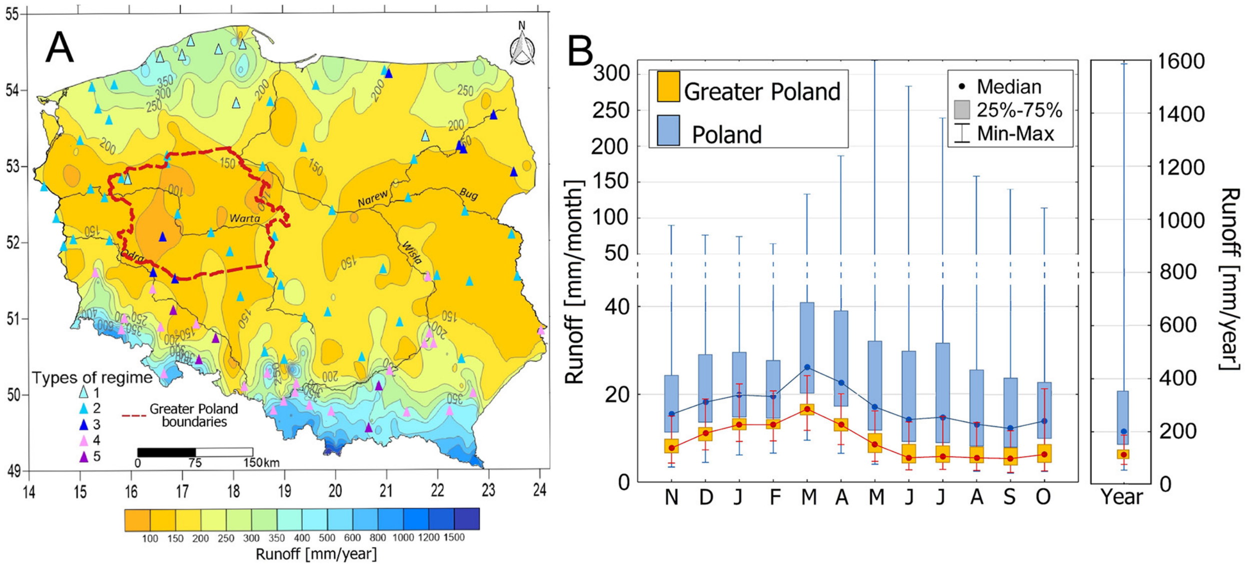

Fig. 12. River runoff and types of the river regime in Poland (A) (types of regimes: 1 – nival poorly formed; 2 – nival moderately formed; 3 – nival well-formed; 4 – nival-pluvial; 5 – pluvial-nival [after Wrzesiński 2021]), and the scope of changes in monthly and annual runoff of rivers in the Greater Poland region and Poland in 1971–2015 (B) (after Wrzesiński and Perz 2019a, b).

rivers in the Warta River basin are characterised by the highest (over 75%) share of the runoff of the winter half-year. On the seasonal basis, in all catchments the spring and winter runoffs are clearly dominant, on average taking 33% and 32% of the annual runoff, respectively. This proves the great importance of the snowmelt supply in the structure of total runoff.

On average, 20% of precipitation in the study area is transformed into runoff. For comparison, the average runoff coefficient for the whole area of Poland is 27%. The groundwater runoff coefficient (equated with effective infiltration, expressed as the ratio of groundwater runoff to precipitation) in Greater Poland is only 10%, and is much lower than the national average (17%) (Jokiel, Tomalski 2017).

The reason for a very low runoff is, besides low precipitation, high evaporation losses. As a result, even before the occurrence of climatic changes, the water balance of the region in the years with lower annual precipitation totals and higher annual temperature was often negative, keeping slightly positive values only for the long-term average (Fig. 13).

Despite the fact that there is no trend in precipitation in the study area, climate change that occurred after 1988, followed by a positive trend in air temperature and SD, changed the components of the water balance.

Total monthly water losses due to field evaporation in Poland can be estimated correctly with the help of the Ev parameter from the Ivanov climate moisture index (Kędziora 1999, 2008). The Ev parameter is calculated according to the formula (after Okołowicz 1976):

$$Ev_m = 0.0018 \cdot (25 + t_m)^2 \cdot (100 - f_m), \qquad (3)$$

where:

- Ev_m represents the amount of evaporated water in *m*-th month in the water column equivalent (mm),
- t the average air temperature of *m*-th month (°C), and
- f_m the average relative humidity of *m*-th month (%).

Evaporation for longer periods (half-year, hydrological year (November–October), calendar year (January–December)) is calculated by summing up the calculated monthly values of evaporation for a given period. The annual sums of evaporation (Ev) calculated in that way for data recorded in Poznań in the calendar year (January–December) show an increase in evaporation after 1988. While in 1951–1988 the average annual evaporation was equal to 588 (±12) mm, and the trend in the series was practically zero (+0.89 (±1.13) mm · year^{-1}), in 1988–2020 the average long-term evaporation increased to 692 (±18)

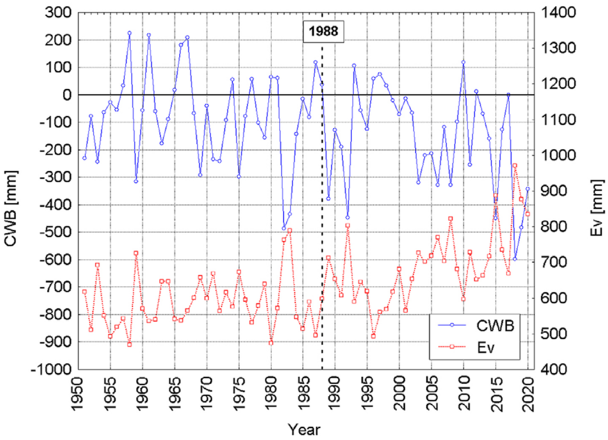

Fig. 13. The CWB in the calendar year (January–December) (CWB, unit: millimetre of water column) and the annual field evaporation (Ev, unit: millimetre of water column) in Poznań in 1951–2020. The vertical dotted line marks the year when the climate regime changed (1988). CWB, climatic water balance.

mm, and a very strong positive trend appeared in the series, amounting to 6.4 (±1.6) mm · year^{-1}; $p = 0.0003$). The importance of this trend can be illustrated by the fact that within 10 years the layer of the evaporated water increases approximately by the monthly sum of precipitation in June – the month in which the average sum of precipitation in Greater Poland is the second highest after the July maximum (average rainfall in June 59.3 mm, in July 77.9 mm).

In the simplest terms, the annual climatic water balance (CWB) can be defined as the difference between the annual sum of precipitation and the annual sum of field evaporation. The water balance calculated in this way for the calendar year (January–December) in Poznań is presented in Figure 13. As the average annual precipitation totals in Greater Poland are small, and their changes, with high inter-annual variability, do not show a long-term trend, the value of the water balance in a given year strongly depends on evaporation (Fig. 13). The correlation coefficient between CWB and Ev equals −0.84.

The positive trend of field evaporation after 1988 results in more and more frequent occurrence of longer sequences of years with a negative water balance in Greater Poland; negative CWB values deepen and the frequency of years with negative water balance increases.

This entails a number of further unfavourable hydrological phenomena. Among them, an increasing frequency of soil droughts, sometimes causing catastrophic losses in agriculture, can be mentioned. In Greater Poland, in 2006–2017, there were 9 years with drought (Wójcik et al. 2019). In other words, there were only 2 years without drought in this period. Subsequent droughts occurred in 2018, 2019 and 2020. There is a systematic lowering of the groundwater level of the first horizon, lowering of the water level in lakes (Choiński et al. 2016, Wrzesiński, Ptak 2016, 2017, Wrzesiński et al. 2018, Ptak, Nowak 2019) and eventually a decrease in the river discharges in Greater Poland (Wrzesiński 2009, Piniewski et al. 2018, Wrzesiński, Sobkowiak 2018).

The discharges of the Warta River draining the Greater Poland region, in Poznań water gauge, reveal specific changes caused by the described climatic changes. Due to the strong inter-annual variability of these discharges, the trend values do not correctly characterise their changes. The analysis of the average annual discharges of the Warta River in the hydrological year shows that they decreased from 104.2 m^3 · s^{-1} in 1951–1988 to 93.2 m^3 · s^{-1} in 1989–2020. Compared to the first sub-period, in the second sub-period both the highest average annual value of discharge (172 m^3 · s^{-1} and 157 m^3 · s^{-1}, respectively) and the lowest one (51.7 m^3 · s^{-1} and 40.4 m^3 · s^{-1}, respectively) decreased. These differences between the means are highly significant. Very significant, and dangerous from the point of view of the water resources' availability, changes also took place in the seasonal distribution of the Warta River discharges (Fig. 14).

In the 170-year long history of discharge measurements of the Warta River in Poznań, the average discharges of the winter season have approximately been twice as high as those of the summer season, accounting for about 185% of the summer discharges. On average, in Poland, groundwater flow in winter is higher than that in summer by about 37% (Jokiel, Tomalski 2017). During the warming period of 1989–2020, there was a fundamental change in the seasonal structure of the Warta River discharges. While the discharges of the warm half-year did not change much, the average winter discharges decreased very strongly and significantly (Fig. 14) (Wrzesiński, Sobkowiak 2018, Wrzesiński 2021).

In the analysed period, that is in the second half of the 20th century and the beginning of the 21st century, two periods of runoff lower than

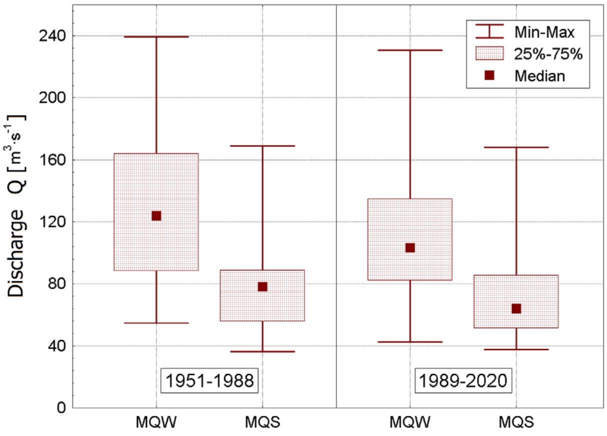

Fig. 14. Range of variability of the seasonal discharge of the Warta River in Poznań in sub-periods 1951–1988 and 1989–2020. MQW, average discharge in the cold half-year (November–April; unit: $m^3 \cdot s^{-1}$); MQS, average discharge in the warm half-year (May–October; unit: $m^3 \cdot s^{-1}$).

average can be distinguished: at the beginning and end of this multi-year period, with the period between the 1960s and 1970s with higher-than-average runoff.

In the analysed 70-year period, the runoff was lower than the average in 1951–1975, usually at the beginning of the hydrological year (by around 20%), and in the case of the Warta River mainly in winter (by 30%); the observed deviations were statistically very significant. The runoff decreased also in the summer–autumn period, mainly in July and August, and the deviations of the pentad runoff from the average values were even greater, for example in the Mogilnica and Flinta rivers by as much as 50%.

The second period of lower runoff occurred at the turn of the 20th and 21st centuries. Since the mid-1980s, most rivers in Greater Poland have been characterised by a decline in the pentad runoff by as much as 60% compared to the average values, with the greatest deviations occurring in the winter and summer seasons.

An increase in evaporation losses, which have been concluded in the cold season, does not fully explain such a significant decrease in winter discharges of the Warta River. This decrease can be interpreted as a symptom of a decrease in the groundwater supply of rivers in the Warta River catchment above Poznań in 1989–2020. The adoption of such an interpretation means that as a result of more and more frequent occurrence of years with a negative CWB (Fig. 13), the amount of water infiltrating into the ground is diminished, which leads to the significantly reduced volume of groundwater resources. Prolonging such a situation may bring disastrous consequences for the Greater Poland region.

The changes occurring as a result of climate changes after 1988 require very quick and extensive adaptation to new conditions. Aside from the imperative need for changes in water management practices, this requirement for adaptation also refers to broad changes in industrial technologies – transition to water- and energy-saving technologies, and changes in agriculture, forestry and municipal water management.

Discussion and conclusions

Climate change that occurred in Greater Poland between 1987 and 1989 was sudden and took place within about 3 years. In the Greater Poland region, this change is not limited only to the change of the air temperature regime or the commencement of the warming process after 1988, but also covers a wider spectrum of climatic elements.

This climate change has its origin in an abrupt change in macro-circulation conditions in the Atlantic-Eurasian circulation sector observed in 1987–1989. In 1987–1989, the frequency of the meridional macrotype E, according to the Wangengejm-Girs classification, dropped suddenly, and at the same time the frequency of the zonal macrotype W increased, while the fluctuations in the frequency of macrotype C remained close to the long-term average. The circulation periods changed from period E to period W (Savichev et al. 2015, Degirmendžić, Kożuchowski 2018, 2019).

The change of the 'proportion' in the frequency structure of the macrotypes of the mid-tropospheric circulation changed the frequency of lower baric situations in an equally abrupt way, thus necessitating a change in the cloud structure and a rapid increase in SD, which led to an increase in air temperature in the warm half-year. At the same time, along with the increase in the frequency of macrotype W in winter, the number of winters with the positive NAO index increased[7],

[7] See footnote 6.

which led to a significant increase in temperature in winter, or more generally, in the cold half-year. This means that the observed warming (or, if viewed from the point of view of thermodynamics: sources of heat for the air temperature increase) does not have the same origin. One part of the temperature increase is directly induced by the increase in the amount of solar energy SD reaching the ground, while the other part by the increased transport of advective heat taken from the surface of the North Atlantic Ocean (NAO).

The reason for the change in macro-circulation conditions is the change in the intensity of ocean heat transport through the thermohaline circulation (NA THC) that occurred in 1987–1989, changing the values and location of heat flows from the ocean to the atmosphere. The value of the DG_{3L} index increased sharply in these years and was permanently positive (see Fig. 7). This factor can be considered as the root cause that triggered a chain of interrelated processes that led to climate change.

In the scientific literature (Wild et al. 2005, 2007, Wild 2012) the increase in SD over Europe observed since the end of the 1980s is associated with the impact of human activity, and more specifically with a reduction in the concentration of anthropogenic aerosols caused by the decline of industry in the 1980s in the former socialist bloc countries. The research by Stanhill et al. (2014) shows, however, that changes in SD are caused by changes in cloudiness, and not by changes in the concentration of anthropogenic aerosols in the atmosphere. The results of research on changes in the cloud structure over Poland (Żmudzka 2007, Wibig 2008, Filipiak, Miętus 2009, Matuszko, Węglarczyk 2018) indicate that the increase in SD also occurred as a result of a change in the cloud structure. The concordance in the time of an abrupt increase in SD with the change of the circulation period E into the circulation period W and with the change of the NA THC phase (see Figs 4, 5, 8 and 9) proves that the process of increasing SD, as shown in the paper of Marsz et al. (2022), is natural and unrelated to any supposed anthropogenic impact on the climate. Recent studies of Dübal and Vahrenholt (2021) show that the positive trend of the solar energy flux observed in 2001–2020 was caused by a change in the cloud structure, and not by a decrease in atmospheric aerosol concentration, and may be related to the variability of AMO. Thus, the results of the research carried out by Dübal and Vahrenholt (2021) largely confirm those concluded in the paper of Marsz et al. (2022) that long-term changes in SD result from natural processes and are related to the dynamics of the North Atlantic waters.

Both NA THC and NAO are not processes whose variability is controlled by changes in the concentration of CO_2 or other greenhouse gases in the atmosphere (e.g. Cohen, Barlow 2005, Semenov et al. 2008, Grossmann, Klotzbach 2009, Chylek et al. 2016, Parker 2016). Therefore, it can be assumed that the observed temperature increase in Greater Poland may have its main causes in the natural, and not anthropogenic factors, and more specifically in an increase in the amount of solar energy reaching the surface SD in the warm season, and an increase in the frequency and intensity of the inflows of warm-maritime air masses from the North Atlantic during the cold season.

Changes in the thermal state of the North Atlantic, driven by changes in the intensity of NA THC, as a driver of climate change in the vicinity of that ocean, have been repeatedly considered in the literature. Here only a few of the most important issues will be highlighted.

Sutton and Hodson (2005), based on model studies, demonstrated the relationship between changes in temperature and precipitation totals in the USA and Western Europe with the variability of AMO (Kerr 2000, Enfield et al. 2001)[8]; the variability of AMO is strongly regulated by thermal and precipitation conditions in the warm season. In one of their recent papers, Sutton and Dong (2012) pointed to a shift in European climate that occurred in the 1990s. According to these researchers, the reason for that change was the acceleration of AMOC and a sharp increase in the amount of heat transported to the north by NA THC, which resulted in a sudden increase in

[8] The AMO index characterises the deviation of the mean SST for the entire North Atlantic from the mean, revealing the long-term changes in its thermal state, but without informing about the intensity of heat transport to the north. The long-term changes in AMO are a consequence of the NA THC variability, which is referred to as AMOC in the North Atlantic. The DG_{3L} index shows a significant positive correlation with the AMO index.

SST in the North Atlantic (Robson et al. 2012). The time lag between the climate change indicated in our study (1987–1989) and that determined by Sutton and Dong (2012) (1990s) results from the fact that Sutton and Dong (2012) take the AMO phase change as the moment of climate change. The value of the AMO index, calculated after detrending the series of SST anomalies and with the use of strong, long-term filtration (equalisation of the 121-point consecutive mean), changes the zero-crossing moments of the AMO index and occurrence of its local minima and maxima in relation to the actual changes of the SST anomaly.

Pohlman et al. (2006) proved, also through model studies, that an increase in the intensity of heat transport to the north by the Atlantic Meridional Overturning Circulation (MOC) was the cause of the multi-decadal variability of the climate in Europe, with the strongest changes in temperature occurring in the region broadly understood as the Baltic Sea Basin. In periods of increased intensity of heat transport to the north by AMOC, strong changes take place in the winter temperature – it rises and the number of frosty days is significantly reduced. In summer, the temperature increases, as does the number of hot days (T_d > 25°C). When the heat transfer by MOC is weakened, the situation is reversed and a general cooling down occurs. Aggregating the seasonal changes, we arrive at the corresponding changes in the annual temperature that have taken place. In the case of precipitation totals, Greater Poland, according to the model proposed by Pohlman et al. (2006) (their Fig. 3b), lies in the middle of a dipole of opposing changes with centres located over the northern part of the Scandinavian Peninsula and the Alpine-Balkan countries. Thus, changes in the AMOC intensity cannot be the cause of the multi-decadal changes in precipitation totals in Greater Poland, and trends related to changes in the thermal state of the North Atlantic in the course of precipitation totals are not detected.

Thus, the analysis of empirical data on the changes of temperature in the Greater Poland region is consistent with the results of model studies carried out by Pohlman et al. (2006), indicating the control of long-term changes in climatic conditions in Europe by the variability of the thermal state of the North Atlantic. An increase in the annual temperature in Greater Poland after 1988, higher than that resulting from the model calculations of Pohlman et al. (2006), is most likely due to the fact that the warm and cold AMOC phases were determined by these researchers as exceeding the limits of ±0.44 standard deviation (σ), when in the last phase of NA THC (1989–2020) the mean value of the DG_{3L} index exceeded the limits of +1σ in relation to the entire period (1856–2020), for which its values can be calculated. However, according to the model, the stronger the deviation of heat transported by AMOC from the mean, the stronger the temperature deviation.

This allows us to conclude that the main cause of the change in the state of the climate may be the action of the internal variability of the ocean–atmosphere system, while the role of the anthropogenic factor in shaping this change may be of secondary or tertiary importance. Temperature changes in the 70-year period (1951–2020) dealt with in the present study constitute one of the most drastically altered climatic elements in the Greater Poland region in the recent past (current and preceding centuries), and while 57% of these changes are explained by the effect of natural factors, only about 4–5% are explained by an increase in CO_2 concentration. The NA THC variability plays a fundamental role in controlling changes on a multi-decadal scale, and these changes are reflected not only in changes in the atmosphere's climate, but also in the climate-controlled hydrological conditions.

Regardless of the cause of the described climate change, which took place in 1987–1989, the scale of changes in climatic and hydrological conditions in the Greater Poland region is so large that it is necessary to immediately undertake a number of adaptation measures.

Summary

The ongoing climate changes in Greater Poland merely constitute a single theatre of the large-scale climate changes affecting the Atlantic-Eurasian circulation sector. These changes originated in an abrupt change of the macro-circulation conditions in 1987–1989, forced by a strong increase in the intensity of heat transport to the north by the thermohaline circulation in the North Atlantic (Fig. 8).

Climate change that took place in Greater Poland is manifested in an increase in SD and air temperature, a decrease in relative humidity, a change in the cloud structure and an increase in the degree of sky coverage. Air temperature change, which is the most spectacular manifestation of climate change, began after 1988, and only then did the warming begin. Its main physical cause is the rapid and strong increase in SD, which started in the same period as the temperature rise.

The detected changes in the atmosphere's climate entail various effects, the most important of which are the changes in the water balance occurring as a result of the rapid increase in field evaporation. The water balance of Greater Poland in the years following 1988 more and more often becomes negative, which poses a direct threat to water supply to a number of branches of the economy, which are crucial for the region's continued commercial viability.

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Author contributions

AAM was responsible for conceptualisation, methodology, software deployment, validation, formal analysis, investigation and data curation, preparing the original draft and visualisation. LS was responsible for software deployment, preparing the original draft, reviewing and editing, visualisation and supervision. AS was responsible for conceptualisation, methodology, software deployment, validation, formal analysis, investigation and data curation, preparing the original draft and visualisation. DW was responsible for conceptualisation, methodology, software deployment, validation, formal analysis, investigation and data curation, preparing the original draft, visualisation and supervision.

Conflict of interests

The authors declare no conflict of interests.

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