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Temporal Variability of Summer Temperature Extremes in Poland

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Abstract: The aim of the study is to estimate the trend in summer maximum air temperature extremes in Poland during the period 1951–2015 by demonstrating the changes in the magnitude of temperature anomalies, temperature "surplus", as well as the area influenced by extreme temperature occurrence. To express the latter two variables, daily maps of maximum air temperature were created to calculate the total area affected by temperature extremes. To combine the effect of spatial extent and temperature anomaly, an Extremity Index was introduced. The results confirmed an increase in summer maximum air temperature of about 0.4 °C per 10 years, evidenced also in the increase of summer extremeness. Positive anomalies have dominated since the 1990s, with the largest anomalies occurring during the summers of 1992, 1994, 2010 and finally 2015, the most exceptional summer during the analyzed period.

Keywords: summer maximum air temperature; temperature surplus; Extremity Index; long-term variability; Poland

1. Introduction

The observed increase in air temperature in the northern hemisphere in recent decades is indisputable and is supported by extensive research, a summary of which can be found in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1]. Moreover, the most responsive area to climate change seems to be Europe, as shown in global or regional studies, e.g., [2–5]. A significant increase in summer temperature has been observed [5–8] for Europe and is projected to continue until the end of 21st century [5,9–12]. Extreme summer conditions have been also confirmed by changes in the frequency, intensity and duration of extreme temperature events. Studies of the variability of maximum air temperature conducted for different areas of Europe from the north: e.g., Baltic region [13], through the central-eastern countries, e.g., [7,8,14–17], western regions, e.g., [6,18] towards the Mediterranean [19,20], are in agreement that exceptionally hot summers have been common since the 1990s. Research describing heat-wave episodes in particular years in Europe have focused mostly on 2003 for the western countries, e.g., [21,22] and 2010 for the eastern countries [23,24]. For Central Europe, the most severe heat waves occurred during summer months of 1992, 1994, 2007, e.g., [16,25,26] as well as 2015 described in details by Hoy et al. [27]. Most of the research conducted for Central Europe also includes the area of Poland, e.g., [8,27].

Thermal conditions in Poland and their variability have become correspondingly a subject of local studies, raising a point of temperature extreme occurrence and principles [25,28], their long-term variability, e.g., [29–32] or extreme events, i.e., heat waves, e.g., [29,33]. As Poland, due to its location (Figure 1A), is particularly exposed to weather extremes occurrence, many papers have also been published in Polish to support security services and risk management (not cited here). All the results confirm a regional increase in maximum air temperature of about 0.26 °C per 10 years, especially in spring and summer months. A significant increase in the number of hot days as well as tropical nights in the summer has also been observed together with other changes in indices of hot extremes [33].

The aim of the study is to estimate the trend in summer maximum air temperature extremes in Poland during the period 1951–2015. The paper examines interannual variability as described by changes in anomaly magnitude, temperature "surplus", as well as the area exposed to extreme temperature occurrence. Consequently, it fulfills the need to investigate not only the aspects of air temperature itself but also the area affected, as proposed by Lhotka and Kyselý [26].

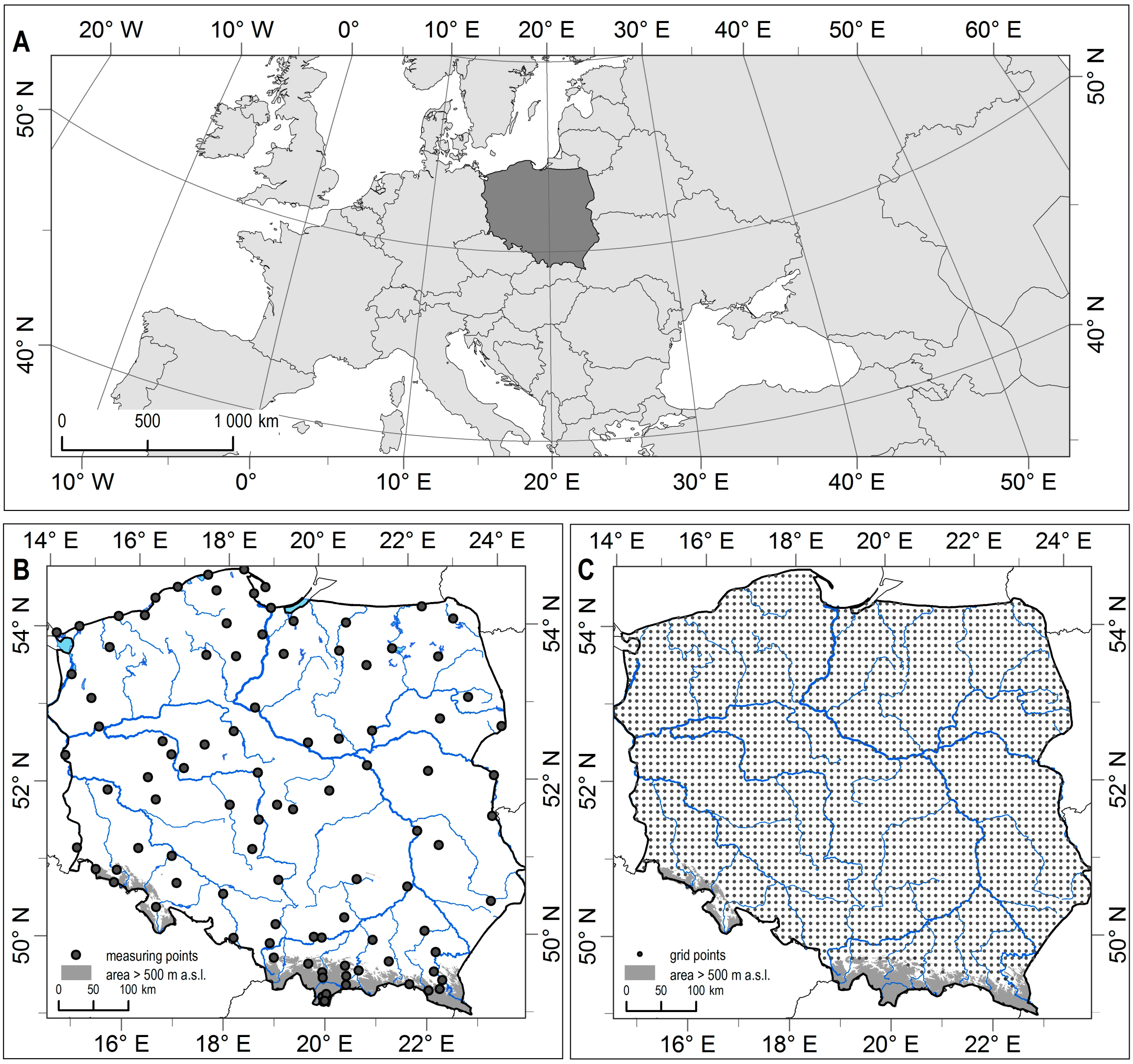

Figure 1. Study area: (**A**) location on the European subcontinent; (**B**) station distribution; (**C**) grid point locations for a resolution of 0.1°.

2. Data and Methods

Definitions of temperature extremes have been the subject of several studies, including the WMO Guidelines on the analysis of extremes in a changing climate [34] and some regional research, e.g., [28,35]. For the purpose of this paper, the probability approach has been used [36]. A maximum temperature extreme was defined as a value exceeding the seasonal (June–August) 95th percentile value calculated from daily data for the reference period of 1961–1990.

Maximum air temperature (Tx) values were obtained from 102 stations of the National Meteorological Service network, relatively regularly distributed across Poland (Figure 1B). The stations were chosen based on the series length and data quality. All the available data (more than 150 stations of the Institute of Meteorology and Water Management—National Research Institute) were thoroughly inspected and checked by quality control and weather dependent analyses [34,37]. The selected stations have data completeness of at least 90% for 1951–2015.

Station data served to create daily maps of Tx using the residual kriging interpolation method [38] with a spatial resolution of 0.01° × 0.01°. In the next step, the maps were used to produce a gridded database of maximum air temperature covering all summer days from the analyzed period with a spatial resolution of 0.1° × 0.1° (Figure 1C). Validation of the gridded data with in-situ data confirmed their significant accordance with a Pearson's correlation coefficient of R = 0.995 for the area located at or below 500 meters above sea level, whereas for high elevations, although residual kriging was used, data consistency was much lower. Therefore, for further long-term analyses, station data were used to calculate daily areal means for the mountains, areas >500 meters a.s.l. (3 percent of the territory of Poland), while the gridded data were used for the remaining area (Figure 1B,C). In addition, separate analyses were conducted for the high elevation areas of Poland to access the intensity of temperature changes in the Polish mountains, and were compared with the results obtained for other ranges as the recent warming of mountain regions, almost three times as global average, has been confirmed by several studies, e.g., [39,40].

Further analyses were conducted using two approaches. Interannual variability of the temperature extremes was examined using the gridded database and in-situ measurements for areas with elevations ≤500 m a.s.l. and >500 m a.s.l., respectively. Areal means of maximum air temperature were calculated for each day separately and were used to delimit percentiles. Long-term trends of maximum air temperature (Tx), the occurrence of summer temperature extremes (Tx95), and changes in the 95th percentile value were calculated for consecutive overlapping 30-year periods. The non-parametric Mann-Kendall test was applied to assess the trends for the entire period and sub periods and to measure the statistical significance of the changes, whereas the Theil–Sen estimator was used to calculate the trend slopes [41].

Maximum air temperature fields produced for each day for the area at or below 500 m a.s.l. provided spatial information on the area influenced by temperature extremes as well as their intensity. Temperature surplus (TS95), defined as a positive difference between daily maximum air temperature and the 95th percentile value calculated for the period 1961–1990, obtained for each 0.01° × 0.01° grid box supported the information about the magnitude of the extremes [26], whereas the number of positive anomaly grid boxes showed the total area (km^2) affected by the phenomena. Spatial resolution of the created maps (0.01°) provides the temperature information from each area of 0.78 km^2. Temperature surplus used for further analyses was expressed as the areal mean of all positive anomaly values to avoid spatial information redundancy. Interannual variability of summer temperature extremes intensity (TS95) was also calculated for mountain regions using in-situ data.

To combine spatial and intensity information, an Extremity Index EI (°C·km^2) was calculated, following the idea of Müller and Kašpar [42], simplified as (1):

$$EI = \frac{\sum_{i=1}^{n} TS95_i}{n} 0.001R \quad (1)$$

where

$$R = \sqrt{\frac{TA}{\pi}} \quad (2)$$

which is defined by the daily mean temperature surplus (TS95, n—number of grid boxes) of the total area affected by temperature extremes (TA) and radius of a circle of this area (2). The extremeness increases with increasing temperature surplus and greater area influenced by the temperature extremes. The Extremity Index, expressed by monthly and seasonal totals of EI, was calculated for each month and season separately, taking into account only the days with extreme temperature over at least 10% of the area. A constant value of 0.001 was introduced to simplify the numbers.

Trends of EI were assessed for both monthly and seasonal totals.

3. Results and Discussion

Average maximum air temperature in summer in Poland, calculated as a mean of the period 1951–2015, ranges from more than 24 °C at the western part and along river valleys to less than 14 °C at the highest peaks of the Carpathian and Sudeten mountains (Figure 2A). Mild summers are typical for the sea coast and the area under the maritime influence as well as the southern mountains (Figure 2A,B). Therefore, the central part of the country is most prone to thermal extremes. It needs to be emphasized that the long-term means differ by approximately 1 °C when the reference period (1961-1990) is taken into consideration (Figure 2B). As mentioned before, most hot summers occurred after 1990, which has a significant impact on the analyses when different averaging periods are involved. The demonstrated difference corresponds to the summer temperature increase of about 0.8 °C [43].

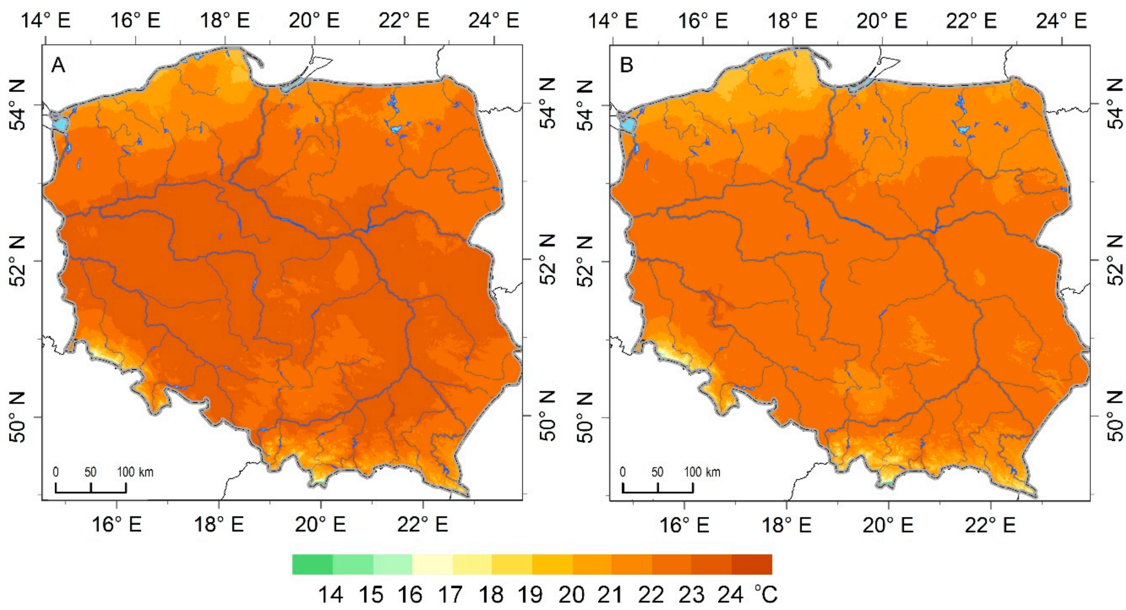

Figure 2. Summer (JJA) maximum air temperature: (**A**) mean of 1951-2015; (**B**) mean of 1961–1990.

Summer maximum temperature is mostly influenced by the thermal conditions of July and August. In June, because of the transitional location of the country, Poland can still be afflicted by late freezes, especially the NE region [44]. Daily maximum air temperatures in June do not exceed 22 °C in general, except for extreme years, as in 2000 when absolute maximum temperatures (1951–2015), reaching 30 °C, were recorded at most stations [45]. Although monthly mean maximum air temperature in July is higher than in August, most of the absolute maximum temperatures occurred at the end of July and early August [46].

3.1. Long-Term Variability of Summer Maximum Air Temperature

Interannual fluctuations of summer temperature in Poland manifest a statistically significant increase and spatial differentiation of its magnitude (Figure 3). Although the areal-averaged trend is somewhat less than 0.4 °C per 10 years, the regions located at or below 500 meters above sea level (97% of the country) warmed up much slower than the mountains (Figure 3B, Table 1). This result is consistent with previous findings of more intense warming of mountain regions, e.g., [47]. The shift to positive anomalies appeared in the mountains two years earlier and the annual deviations are larger (up to 4 °C in 2015, Figure 3). Since data gridding and averaging was reported Wibig et al. [48] as responsible for the smoothing effect, reaching −0.2 °C for summer temperature extremes (Tx95) in Poland, the results were compared with observations from two stations which represent the average conditions for the area of ≤500 m a.s.l. (Poznań, located in the Polish lowlands) and >500 m a.s.l. (high mountain observatory at Kasprowy Wierch, 1991 m a.s.l.). Analyses conducted for particular sites confirmed the trends described for the two regions (Figure 3) with smoothing effect weaker for the mountain region as fewer points were used to calculate the areal mean.

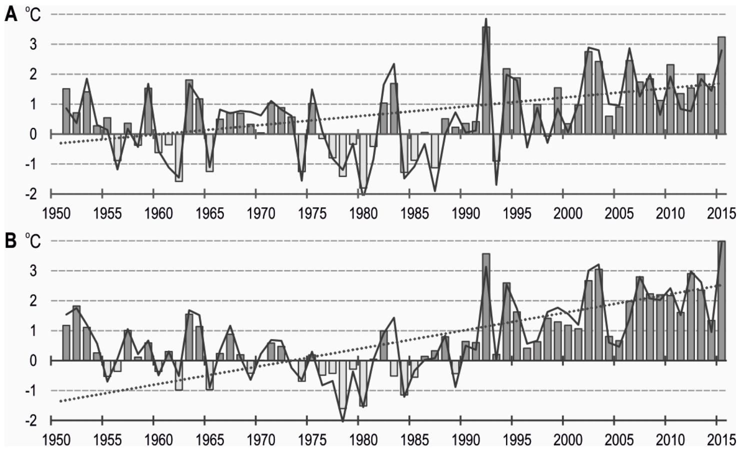

Figure 3. Long-term trend of summer (JJA) maximum air temperature anomalies with respect to the 1961-1990 period; (**A**) areal mean elevation ≤500 m a.s.l. (bars) and Poznań station (line), (**B**) areal mean elevation >500 m a.s.l. (bars) and Kasprowy Wierch high mountain observatory (line); dotted lines—linear trends.

Table 1. Trends of selected summer temperature extreme variables, elevation-sensitive (1951–2015).

Variable	H ≤ 500 m a.s.l.	H > 500 m a.s.l.
Tx (°C/10 yrs)	0.28	0.52
Tx95 (°C/10 yrs) [1]	0.41	0.54
Tx95 (days/10 yrs)	0.77	1.62
TS95 (°C/10 yrs)	1.66	2.31
TA (km^2/10 yrs)	189,500	n.a.
EI (°C·km^2/10 yrs)	489	n.a.

[1] moving window. Tx—maximum air temperature; Tx95—95th percentile of maximum air temperature; TS95—temperature surplus; TA—total area; EI—Extremity Index.

Not only is the magnitude of the warming different for the two sub-regions but the long-term pattern of the variability also differs. Figure 4 presents the trends (°C/10 years) of different multi-year sub periods with varying lengths from 15 to 65 years. The trend magnitude is shown by the intensity of colors, whereas the signature marks indicate its significance at $\alpha = 0.05$. For the periods 1951–1970 and 1956–1970, increases of 0.68 °C and 1.05 °C per 10 years, respectively, were observed in the mountains while for most of Poland (Figure 4A), the negative trend dominated in succeeding multi-year periods until 1971–1990. Negative trends are found in both sub-regions in the 1970s and 1980s followed by positive trends with the largest trends in summer maximum temperature in the period 1976–1995: 1.2 °C ($p < 0.0001$ for significance level $\alpha = 0.05$).

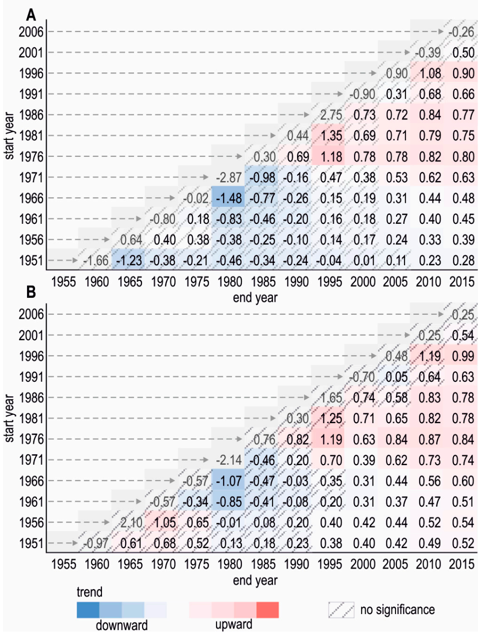

Figure 4. Multi-temporal trend analysis of summer (JJA) maximum air temperature (°C/10 years) in succeeding multi-year periods; (**A**) areal mean elevation ≤500 m a.s.l., (**B**) areal mean elevation >500 m a.s.l. Colors correspond to the positive (red) and negative (blue) trend values.

3.2. Extreme Summer Temperature Changes

Maximum air temperature extremes in summer, expressed by the 95th percentile, reach values higher than 32 °C locally in the western part of Poland and in river valleys. The lowest extremes, about 20 °C, can be observed in the Carpathians and the Sudeten (Figure 5A). For most of Poland, the threshold of a summer extreme maximum air temperature is 30 °C (Figure 5A). The period used for estimates influence the results. The 95th percentile of maximum air temperature calculated for the reference period (1961–1990) is much lower than that for the 1951–2015 period, and the spatial distribution of the 95th percentile varies between the two periods (Figure 5B).

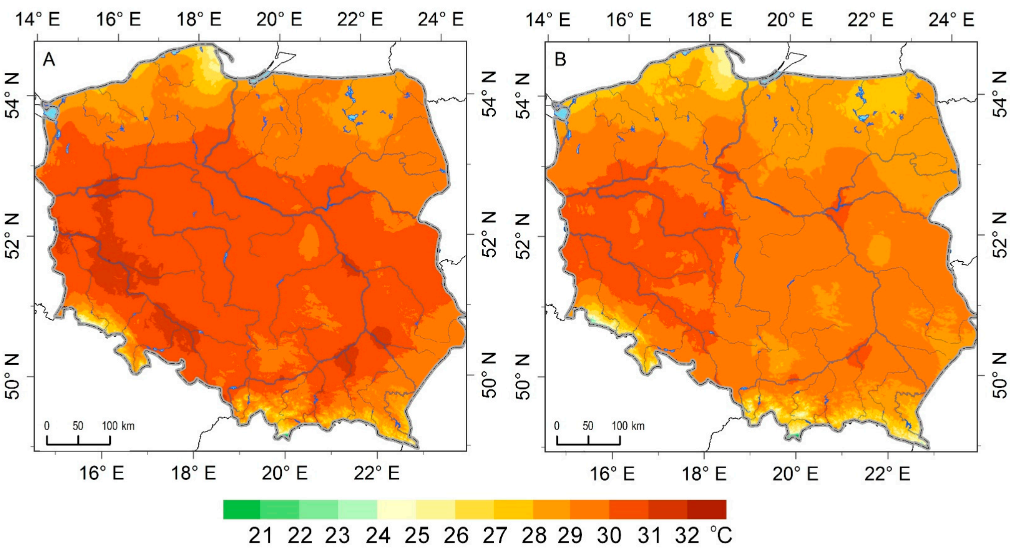

Figure 5. Summer (JJA) maximum air temperature with occurrence probability of 5% (i.e., 95th percentile): (**A**) 1951–2015, (**B**) 1961–1990.

To estimate changes in extremeness of the 95th percentiles with time, percentiles were calculated separately for both sub-regions for overlapping 30-year periods (Figure 6). The results are in accordance with the changes in magnitude of summer temperature extremes shown by Ballester et al. [4]. The value of the 95th percentile has changed by 0.41 °C per 10 years for the area at or below 500 m a.s.l. and by 0.54 °C per 10 years in the mountains (Table 1). At the beginning of the study period (i.e., 1951–1980) an extreme, when defined in terms of the 95th percentile, was a maximum air temperature value higher than 28.3 °C (low elevation areas) or 23.9 °C (mountainous areas), whereas at the end of the period (i.e., 1986–2015), the value of the 95th percentile increased to 30.1 °C and 26.1 °C, respectively (Figure 6). The more intensive warming in the mountains confirms their sensitivity to climate change as well as the nature of the process due to the low degree of human impact on these ecosystems [40,49].

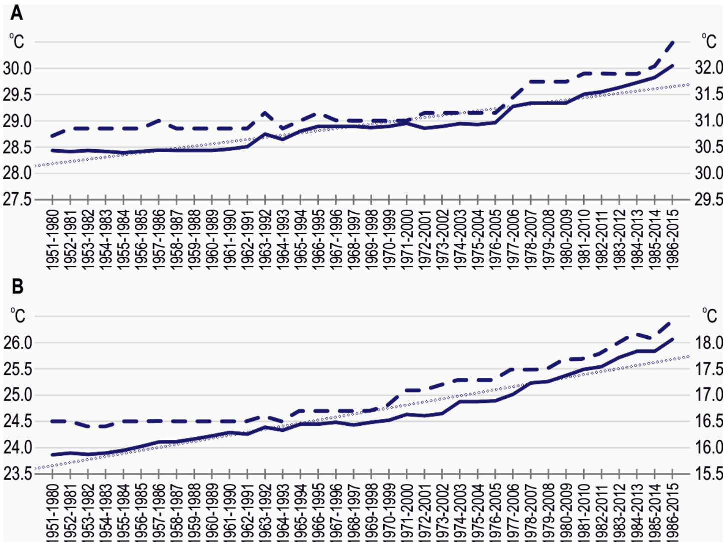

Figure 6. Long-term trend of the 95th percentile of summer (JJA) maximum air temperature values calculated for consecutive 30-year periods; (**A**) areal mean elevation ≤500 m a.s.l. (continuous line) and Poznań station (dashed line), (**B**) areal mean elevation >500 m a.s.l. (continuous line) and Kasprowy Wierch high mountain observatory (dashed line); dotted lines—linear trends.

Except for mountain regions, the largest changes in the 95th percentiles exceeding 0.4 °C per 10 years are generally observed in southern Poland compared to northern part of the country (Figure 7). The thermal burden of southern Poland has already been described by Wypych et al. [32] in the context of an increase in growing degree days.

The reference period of 1961–1990 was solely used for further analyses presented below, although the influence of the choice of reference period needs to be kept in mind when interpreting the results. The interannual variability of the areal mean of the number of days with summer temperature extremes was examined for both sub-regions. Figure 8 shows that since the 1980s the mountains experienced a slightly higher, statistically significant at $\alpha = 0.05$ level, number of extremes (as a result of increasing summer maximum air temperature) (Figure 8B, Table 1). The number of extremes within the last decade (2006–2015) is 20 days, which constitutes 20% of all summer days. In summer 2015, one-third of all days was extreme. Spatial differentiation of the trend in the occurrence of extremes (Figure 9) proves that the increasing number of extremes (up to 2.5 days per 10 years) refers mostly to southern and eastern Poland. Since the most significant temperature changes have been already confirmed for continental parts of Europe, leading towards increasing climate continentality [50], hotter summers manifested for the area provide complementary proof for contemporary Central Europe warming.

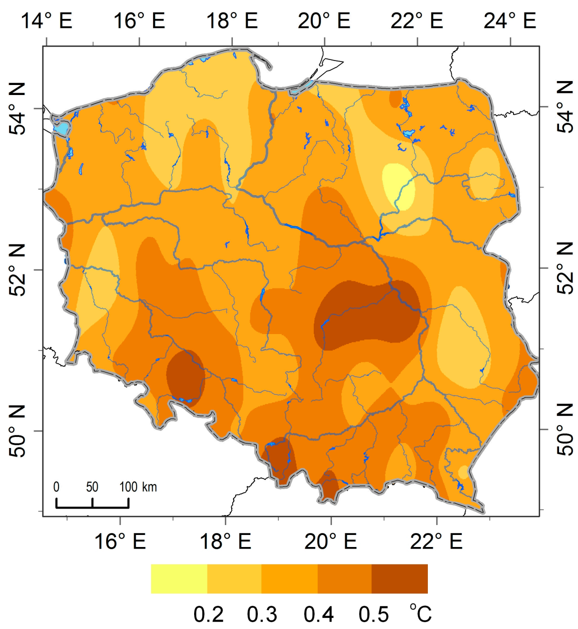

Figure 7. Spatial distribution of the trend of summer (JJA) maximum air temperature with an occurrence probability of 5% (i.e., 95th percentile, as presented in Figure 6).

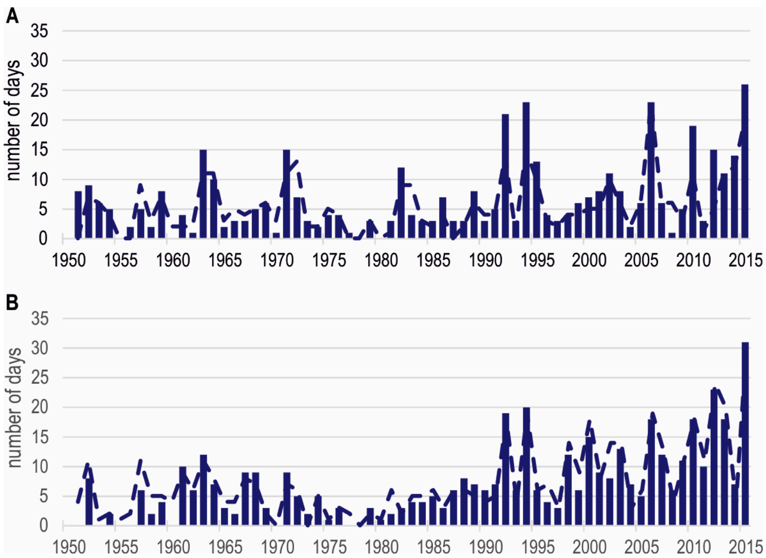

Figure 8. Long-term courses of number of days with extreme summer (JJA) maximum air temperature (**A**) areal mean for locations ≤500 m a.s.l. (bars) and Poznań station (dashed line), (**B**) areal mean for locations >500 m a.s.l. (bars) and Kasprowy Wierch high mountain observatory (dashed line).

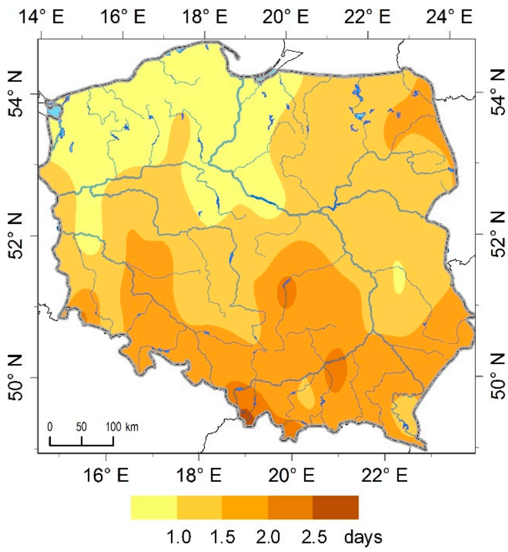

Figure 9. Spatial distribution of the trend in the number of days with extreme summer (JJA) maximum air temperature (days/10 years).

3.3. Changes in Extremeness of Maximum Summer Temperature Events

Using daily maps, maximum air temperature surplus (TS95) was delimited as the positive anomaly for each case of the 95th percentile excess. For the non-mountainous areas, maximum daily temperature surplus varies from 5 °C to 11.5 °C for individual grid boxes, whereas the daily areal mean reaches 6.5 °C (Figure 10).

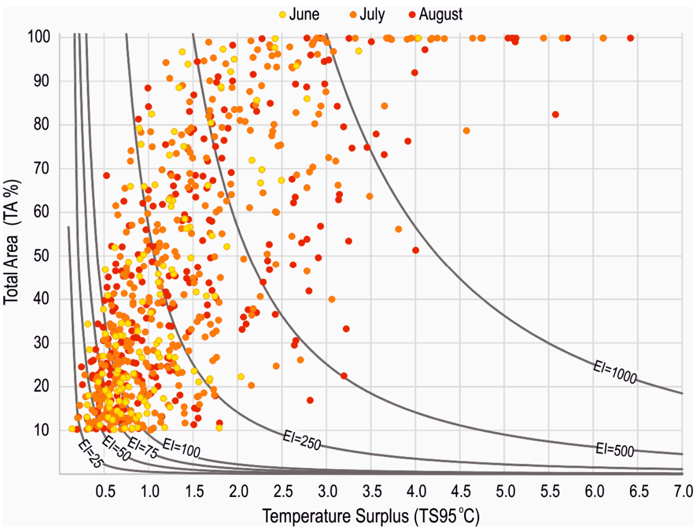

Figure 10. Relationship between two parameters of an extremity index (TS95 and TA) for extreme temperature events during 1951–2015 and the related Extremity Index (EI) ranges.

The highest TS95 values were recorded in July and August; however, there were also rare events of TS95 > 3 °C in June (Figure 10). Seasonal totals of temperature surplus vary, on average, from less than 10 °C along the Baltic sea coast (north) up to more than 13 °C in western and southeastern Poland (Figure 11A). The country has experienced a statistically significant ($\alpha = 0.05$) positive tendency of TS95, ranging from less than 0.2 °C per 10 years in the northern part to more than 0.4 °C in the south (Figure 11B). As positive temperature anomalies have been recorded mostly for the last three decades (since the 1980s) the temperature surplus amount manifests the corresponding trend (Figure 12).

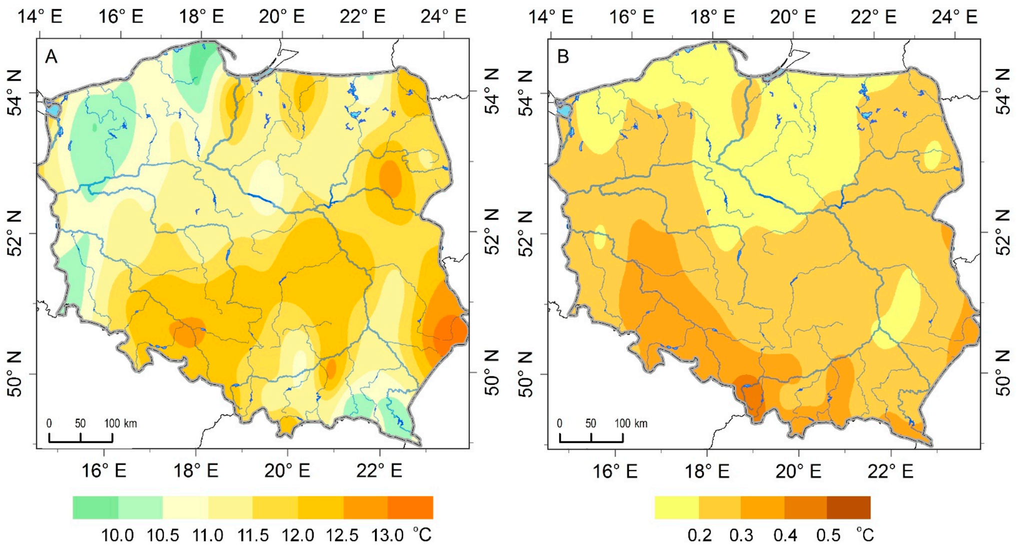

Figure 11. Summer (JJA) temperature surplus (1951–2015); (**A**) long-term mean, (**B**) trend per 10 years.

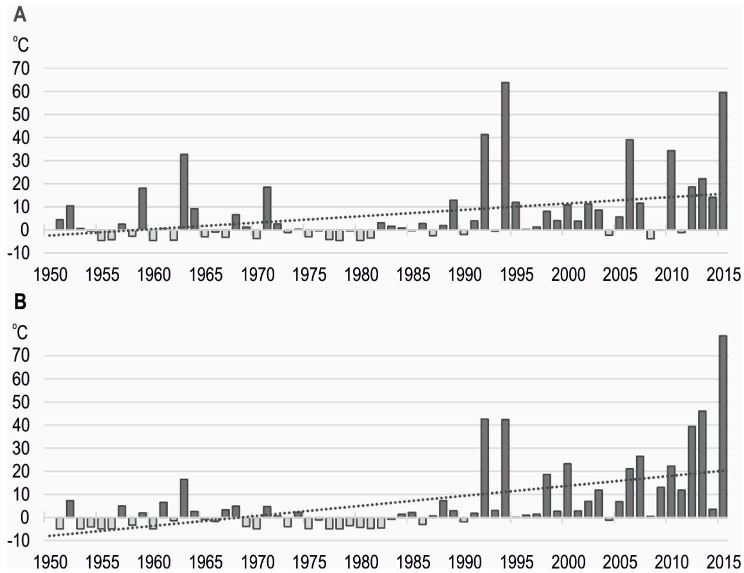

Figure 12. Long-term trends of areal mean summer (JJA) temperature surplus—anomalies with respect to the 1961-1990 period; (**A**) areal mean elevations ≤500 m a.s.l., (**B**) areal mean elevations >500 m a.s.l. (dotted lines—linear trends).

The increase in the amount of heat has been more intensive in the mountains, reaching 2.31 °C per 10 years; however, positive anomalies of the summer temperature surplus have been recorded only since 1987 (with a few exceptions, not larger than 20 °C before that date) (Table 1, Figure 12B). Lower altitudes experienced a smaller trend of less than 2 °C per 10 years (Table 1) but with several significant positive anomalies (up to 30 °C) in the 1960s and at the beginning of the 1970s. The last decades have been considerably more thermally burdened apart from location. The exceptional summers of 1992 and 1994, described by Kyselý [51]; 2006—especially at lower altitudes; and 2015, hazardous mostly for the mountains (TS > 80 °C), are remarkable (Figure 12).

The spatial extent of the area affected by extremes gives additional information about the extremity of the event [30,43,52]. Daily maps of maximum air temperature (excluding high elevation region) were used to calculate the total area influenced by temperature anomalies (Tx > Tx95). The most extreme events affected the entire area (Figure 10). These were mostly (as previously stated) July and

August events with only three June episodes. Climate warming in Poland is characterized not only by an increase in temperature but also an increase in the spatial extent of extreme temperatures. Within the study period, a positive trend, indicating an enlargement of the territory affected by extreme temperatures each season, can be observed especially after 1988 (Figure 13A). The large area affected by temperature extremes in particular years also confirms the "wave" nature of the event. To reach the total of 7 million km^2, the temperature extremity must have lasted for 23 days, covering the whole area of the country, i.e., 313,000 km^2 (Figure 13B). As already mentioned, widespread temperature extremes occurred mostly in July with some August events, especially in 1992 and 2015 (Figure 13B).

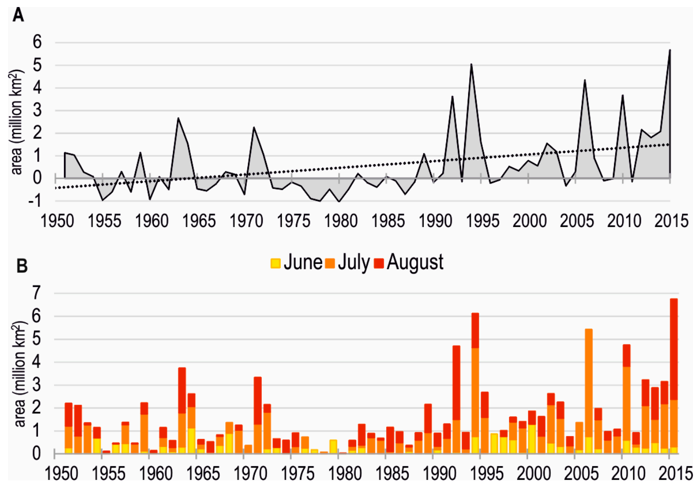

Figure 13. Long-term courses of the total area affected by extreme summer (JJA) maximum air temperature (1951–2015); (**A**) anomalies with respect to the 1961–1990 period (dotted line—linear trend), (**B**) inter seasonal differentiation.

To access the joint effect of the temperature anomaly and the spatial extent of extremes, an Extremity Index (EI) was calculated for each summer day during 1951–2015. To avoid situations when the temperature extreme occurs only at a few locations, the calculations were performed only for days with the temperature extremity affected more than 10% of the study area. The approximate values of EI for individual events are presented on Figure 10. The highest values exceeding EI = 1000 correspond with the episodes of high temperature anomalies over a large area of the country. If any of the two variables (TS95 or TA) fails, i.e., high air temperature extreme is not widespread or the temperature anomaly is not large enough despite 90% of the total area affected, the values of EI are much lower (Figure 10).

Monthly and seasonal totals of EI summarize summer thermal conditions and can be used to estimate the interannual variability of summer extremeness. The long-term means for summer months vary from EI = 710 in June, EI = 2046 in August, and EI = 2760 in July. Although the probability distribution of the EI values for all months are significantly asymmetric (June: skewness $\approx$ 2.4, July: skewness $\approx$ 2.5, August: skewness $\approx$ 3.6), the median values can be used to describe the data. The medians achieve EI = 515, EI = 1676 and EI = 909, respectively. Despite the method of measuring the central tendency, an exceptional EI value occurred in June 2000, during which, as already mentioned, absolute maximum air temperature values were recorded at many stations [45]. The extremity index value reached EI = 4000 and was a result of both temperature anomaly and the spatial extent (Figure 14, Figure 10). In July, the highest EI value of 14000 occurred in 1994. A higher value, reaching EI = 15,000, occurred in August 2015, further pointing to the extraordinary nature of temperature extremes during this month. Values exceeding EI = 10000 occurred only twice more: in July 2006 and in August 1992 (Figure 14). The long-term seasonal mean of EI is equal to 5190 and the median is 2141. According to the Extremity Index, the most hazardous summers occurred in 2015 (EI > 21,000), 1994 (EI = 20,034) and 1992 (EI > 14,500). Although such extraordinary seasons happen rarely, the temporal trend of EI is positive and statistically significant ($p < 0.001$, $\alpha = 0.05$) (Figure 14). The value of the Extremity Index has increased by 489 °C·km^2 per 10 years (Figure 14, Table 1).

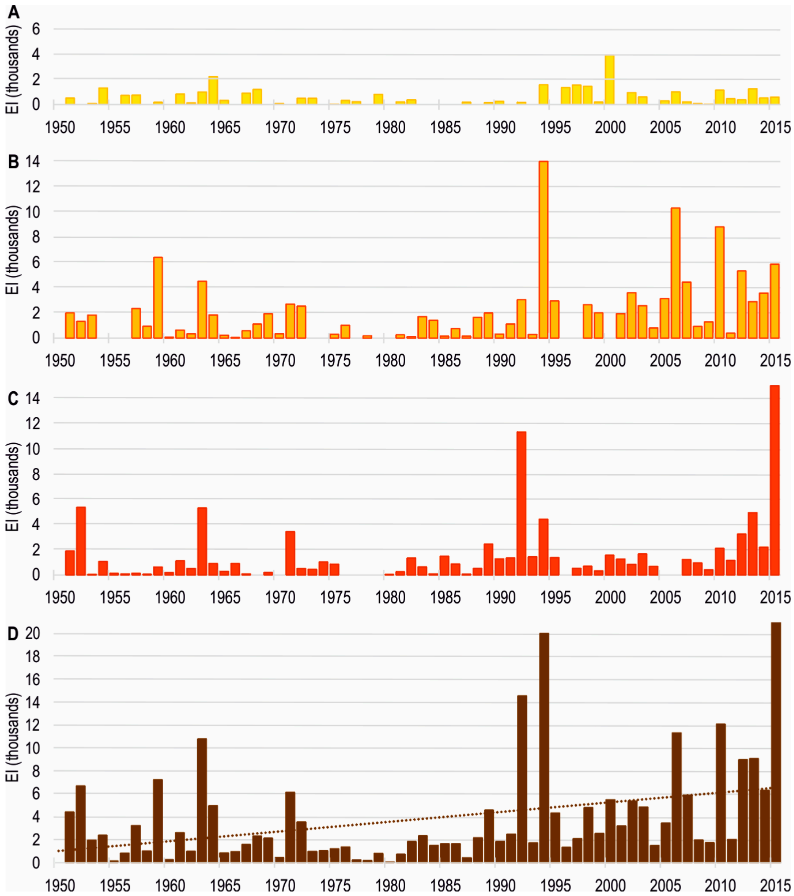

Figure 14. Long-term courses of the monthly and seasonal means of the extremity index (°C·km^2) (1951-2015): (**A**) June, (**B**) July, (**C**) August, (**D**) summer season (dotted line—linear trend).

Using the EI, we ranked the warmest 10 Polish summers during 1951–2015 (Table 2). The list corresponds to the Central European results, highlighting the summers of 2015, 1994, 1992, 2010 and 2006 [5,8,26,27]. Other summer months, which received less attention in the literature, were regionally severe and have been described by some local researchers, e.g., [53].

Table 2. Years with top 10 summer months and season in Poland (based on EI).

Rank No.	June	July	August	Summer
1	2000	1994	2015	2015
2	1964	2006	1992	1994
3	1994	2010	1952	1992
4	1997	1959	1963	2010
5	1998	2015	2013	2006
6	1996	2012	1994	1963
7	1954	1963	1971	2013
8	2013	2007	2012	2012
9	1968	2002	1989	1959
10	2010	2014	2014	1952

4. Conclusions

The study demonstrated the significant increase in summer maximum air temperature in Poland, in agreement with previous research conducted for Central Europe, e.g., [8,26,27,33]. This increase is evident from the positive temporal trend in mean seasonal maximum air temperature (0.4 °C per 10 years, on average) as well as from several indices describing the intensity and spatial extent of extreme temperature events, i.e., number of days with temperature extremes (average increase of 1.2 days per 10 years), changes in the threshold of the 95th summer maximum air temperature percentile (average trend of 0.47 °C per 10 years), changes in temperature surplus (average trend of 1.99 °C per 10 years), total area affected by the extreme and the Extremity Index. The temperature extremes have been more intense and have affected a larger area, causing more extreme summer thermal conditions. The described trends can have a large environmental impact as increasing extremeness of thermal conditions affects the water cycle leading to severe drought stress [27]. Moreover, the magnitude of the changes is larger at higher elevations, which are more sensitive to such a stimulus. This tendency has already resulted in an upward shift of plant species followed by the advancement of phenological stages [54].

The use of an Extremity Index with detailed analysis of the parameters composing the index provides important additional information about the spatial extent of extreme events. The index was used to rank Polish summers in terms of their thermal conditions, and confirmed the regional importance of the extreme heat during the summers of 1992, 1994, 2010 and 2015. As shown in earlier studies for Poland [8,33], the temperature increase has been accompanied by more frequent, long-lasting and more intense heat waves. This earlier research along with the results of extremity index analyses presented in this study indicates that Poland is vulnerable to heat stress and its consequences. Therefore, detailed analyses should be conducted to include not only the possible factors but also the multicomplex variables to identify climate-change hot spots and regions especially exposed to, and affected by, heat stress.

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