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VERY WARM AND TROPICAL NIGHTS IN VOIVODESHIP CITIES IN POLAND IN THE PERIOD 1971–2020

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Abstract. Using minimum air temperature data for the period April–September 1971–2020 obtained from 16 meteorological (synoptic) stations of IMGW-PIB located within the administrative boundaries of voivodeship cities in Poland, the temporal and spatial distribution of very warm (from >18°C to ≤20°C) and tropical (>20°C) nights was determined. The paper presents the results for thirty-year-long reference periods (1971–2000, 1981–2010, 1991–2020). A positive trend of mean minimum air temperature in all stations in each month of the period April–September was demonstrated, and was particularly pronounced in 1991–2020. Since 2010, there has been a considerable increase in the number of very warm and tropical nights, most evident in Gdańsk and Gorzów Wielkopolski. It was found that very warm and tropical nights occur most frequently as isolated cases, rarely in a series of two or three nights, and particularly rarely in a series of six and more episodes. The longest series of thermally characteristic nights was found in Warszawa in 2018 between 25 July and 5 August. Based on the earliest and latest dates, it was found that, in the analysed years, very warm and tropical nights occur earlier but also disappear later.

Key words: minimum temperature, city, variability, trends, climate change

Introduction

The upward trend in global air temperature which has been increasing at a particularly high rate since the 1970s is an important indicator of the magnitude of climate change and its possible consequences. Alexander *et al.* (2006) found that a significant decrease in the occurrence of cold nights and a marked increase in the occurrence of warm nights in a year were recorded in more than 70% of the world. In some regions, the indices have more than doubled. Moreover, the authors indicate that, in the 25-year-long period between 1979 and 2003, there was a clear increase in air temperature during warm nights. The positive trend in the minimum and maximum temperature, as well as more frequent occurrence of increasingly warmer nights has also been reported by Morak *et al.* (2011).

Results indicate that most of Europe will experience higher warming than the global average (Voutard *et al.* 2014; Christensen *et al.* 2015; Jacob *et al.* 2018). Temperatures in Europe have increased at more than twice the global average over the past 30 years – the highest of any continent in the world (Clima *et al.* 2022). The increase in air temperature results in an increased frequency and intensity of heat-waves and periods with mean temperature substantially higher than the average, particularly in the second decade of the 21st century (Krzyżewska *et al.* 2019, 2021; Liu *et al.* 2020; Twardosz *et al.* 2021; Błażejczyk *et al.* 2022; Skrzyńska, Twardosz 2023).

According to Michalska (2011), in most of Poland, the trends of mean annual air temperature for 1951–2005 were increasing and statistically significant, particularly in the north and west of the country. Additionally, air temperature is increasing rapidly; in the period 1951–2013 it was

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0.2°C per 10 years and in 1961–2018 it was as much as 0.33°C per 10 years (Kejna, Rudzki 2021). The increase in annual temperature, as well as that recorded in summer, is reflected in more frequent occurrence of extreme temperatures (Bielec-Bąkowska, Piotrowicz 2013) both during the daytime (very hot days) and nighttime (tropical nights). The trends identified with historical data (Wibig 2012; Graczyk *et al.* 2016) show that, in Poland, similarly to what has been observed throughout Europe, there is an increase in the number of hot and very hot days (and nights), as well as in the values of indices related to heat-waves. Additionally, projections for the future developed with the results of models show that the currently observed trends are to persist and the number of extreme days and nights is to increase markedly (IPCC 2023).

As has already been mentioned, the ongoing climate warming results in, among others, the increase in the frequency and extreme character of various unfavourable atmospheric phenomena. Such extreme phenomena related to heat stress include, among others, thermally characteristic nights, i.e., very warm nights (t_{min} from >18°C to ≤20°C) and tropical nights (t_{min}>20°C). The concept of tropical nights was introduced in 2005 as an important indicator of climate change (Peterson 2005). The fact that very high air temperature at night is rarely recorded in temperate latitudes is confirmed by the literature on the subject and by the absence of a definition of the term "tropical night" in the "Meteorological Glossary" (Niedźwiedź 2003).

The trend of a greater number of warm and tropical nights in the cities of Poland and their burden on human was demonstrated by, e.g. Kossowska-Cezak (2014), Krzyżewska *et al.* (2015), Więcław (2015), Twardosz, Wałach (2020). What is more, Kuchcik (2017) shows that a series of several very warm nights may lead to a considerable increase in the risk of death, particularly in women over 65 years of age.

In the last 100 years, due to climate warming, the subtropical zones in the northern hemisphere shifted ~100 km northwards, consequently moving the zone of increased night-time temperature (IPCC 2023). Such changes cause frequent occurrences of maximum daily air temperature of >40°C and minimum nighttime temperatures of >20°C as recorded in Spain, southern France, Italy and Greece (Morabito *et al.* 2017; Cantos *et al.* 2019). Cities in countries of mid- and high latitudes (e.g., Kherson, Lviv, Geneva, London) report the occurrence of tropical nights identified with different criteria adopted to meet the local conditions (Murage *et al.* 2017; Klok et al. 2023; Rippstein *et al.* 2023).

Summer periods as hot as the one reported in 2003 in Europe may occur every second year by the end of the 21st century in Central Europe, and more frequently in Southern Europe, which will result in increased heat exposure (Schär *et al.* 2004; Morabito *et al.* 2017). The increasing occurrence of heat-waves during the day and at night is considered to be a threat to public health. This has been decisively confirmed by the heat-wave of 2003 in Europe (Laidi *et al.* 2003), which initiated the development of a number of heat-wave alert systems in European countries (Casanueva *et al.* 2019).

The aim of the present paper is to determine the temporal and spatial variability of very warm and tropical nights and their duration in the period 1971–2020 and in consecutive reference periods: 1971–2000, 1981–2010 and 1991–2020 in voivodeship cities in Poland. The present study may assist in increasing awareness and providing information on heat-waves in cities by identifying the phenomenon of thermally burdensome nights.

Materials and methods

The present study makes use of the results of the daily measurements of minimum air temperature (at the height of 200 cm above the ground) obtained from 16 meteorological (synoptic) stations of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) located within the administrative boundaries of voivodeship cities in Poland in the period 1971–2020 in the warm half-year (April–September) (Fig. 1). According to *Glossary – NOAA National Weather Service* (AMS 2024), minimum temperature is the lowest temperature recorded during a specified period of time. The time period can be 6, 12 or 24 hours. The most common reference is to the daily minimum temperature, or "low".

In the first stage of the study, the linear regression method was used to analyse the trends of changes in minimum air temperature. The analysis of the time trend allowed for assessment of the direction and size of changes in the minimum air temperature over the analysed multi-year period. Figure 2 shows the course of the average and highest minimum air temperature at night in the period April–September for each year. The highest minimum air temperature means

Fig. 1. Location of meteorological stations in 16 voivodeship cities against the voivodeship borders (NUTS-2) in Poland

the highest air temperature value read from the minimum thermometer during the night from a specific period (month, season, year) (Kossowska-Cezak 2016).

On the basis of minimum air temperature values, the occurrence of very warm nights (from >18°C to ≤20°C) and tropical nights (t_{min} >20°C) was determined according to the criteria set by Kossowska-Cezak (2014), which are widely used in the literature on the subject (Bartoszek *et al.* 2014; Krzyżewska *et al.* 2015; Więcław 2015; Mąkosza, Rawicki 2018; Twardosz, Wałach 2020; ETCCDI 2023; Yavasl, Erlat 2024).

The minimum air temperature and occurrence of very warm nights and tropical nights was recognised and presented for the whole multiannual period 1971–2020, as well as in the three reference periods adopted following the Word Meteorological Organization (WMO) and IMGW-PIB recommendations: 1971–2000, 1981–2010 and 1991–2020. The thirty-year reference periods overlap, and this is how they are adopted by WMO and IMGW-PIB. As climate change processes accelerate, the WMO recommended that the Standard Climate Norm (SCN) be calculated in periods of every 10 years (WMO 2017). If we presume a trend exists in the thirty-year data record accepted as a reference, then decadal updates become essential for monitoring the effects of such a trend on what is considered "normal" (Arguez, Vose 2011). The available literature contains publications examining changes in various meteorological elements relating to these reference periods (Dailidienė *et al.* 2023).

The present paper provides an analysis of the temporal and spatial variability of very

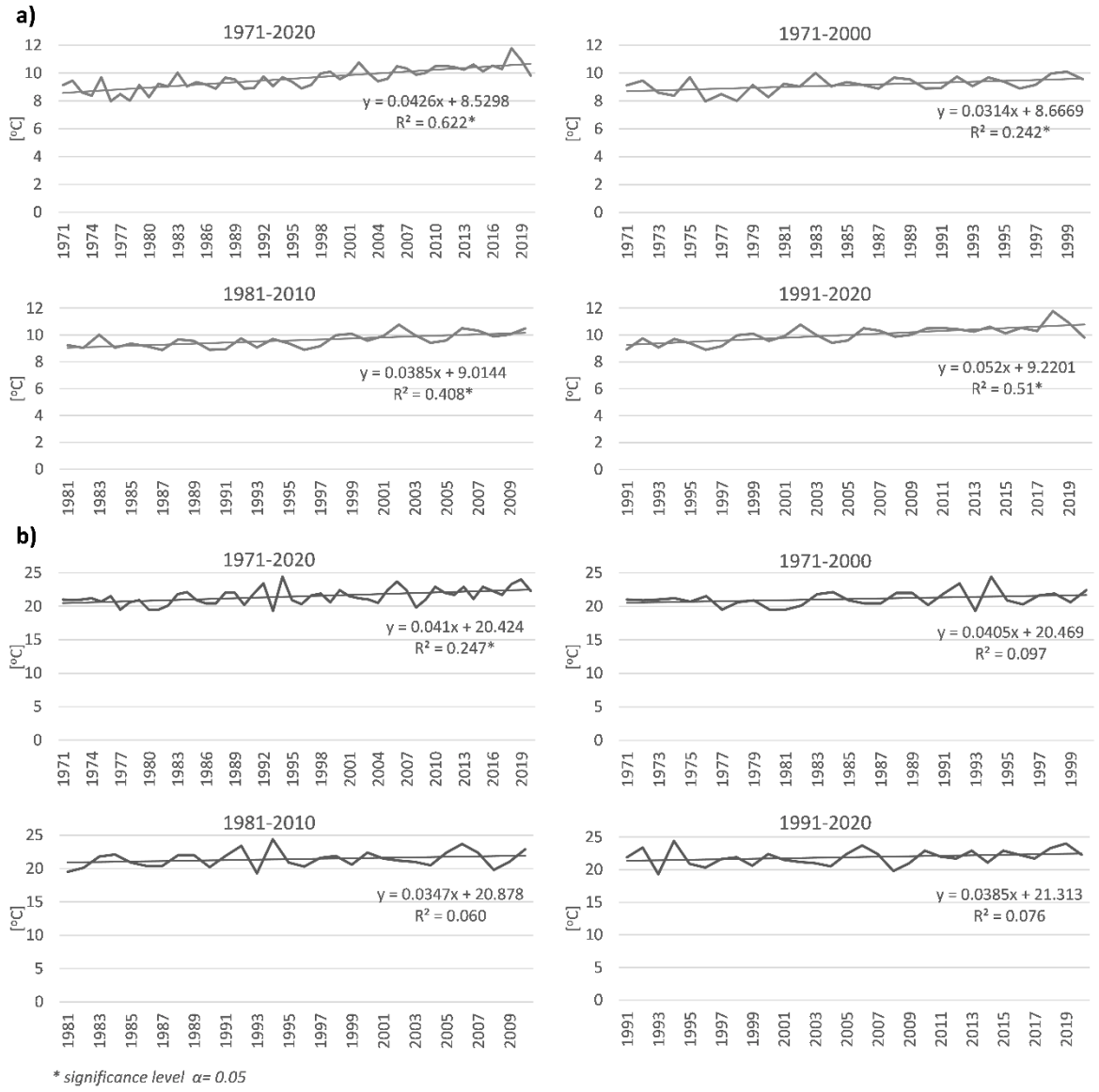

Fig. 2. Average (a) and highest (b) minimum air temperature (°C) from 16 voivodeship cities in Poland (Apr–Sep) in consecutive years in the period 1971–2020 and in the reference periods: 1971–2000, 1981–2010, 1991–2020, with trend

warm and tropical nights. For the purpose of identifying the trend of changes in a time series of thermally characteristic nights, linear regression equation were used. The rate and direction of changes were assessed by means of linear regression, and the statistical significance of trends was verified by means of a Student's t-test. The present paper identifies the change as significant (upward or downward) as the change of significance level of more than 95% ($p < 0.05$).

The analysis accounts for the length of undisrupted sequences of very warm nights and tropical nights. Moreover, the dates of the beginning and end of very warm and tropical nights for each station were determined.

To illustrate the current situation, the paper additionally provides the occurrence of very warm and tropical nights in the last years of the period 2021–2023.

Results and discussion

The analysis was based on the daily minimum temperature data (Apr–Sep), which, as shown in the figures below (Fig. 2–3), shows an increase of 0.4°C per decade in the years 1971–2020, both in terms of the average for 16 cities in Poland and for each station. Furthermore, during the considered reference periods, an increase in minimum

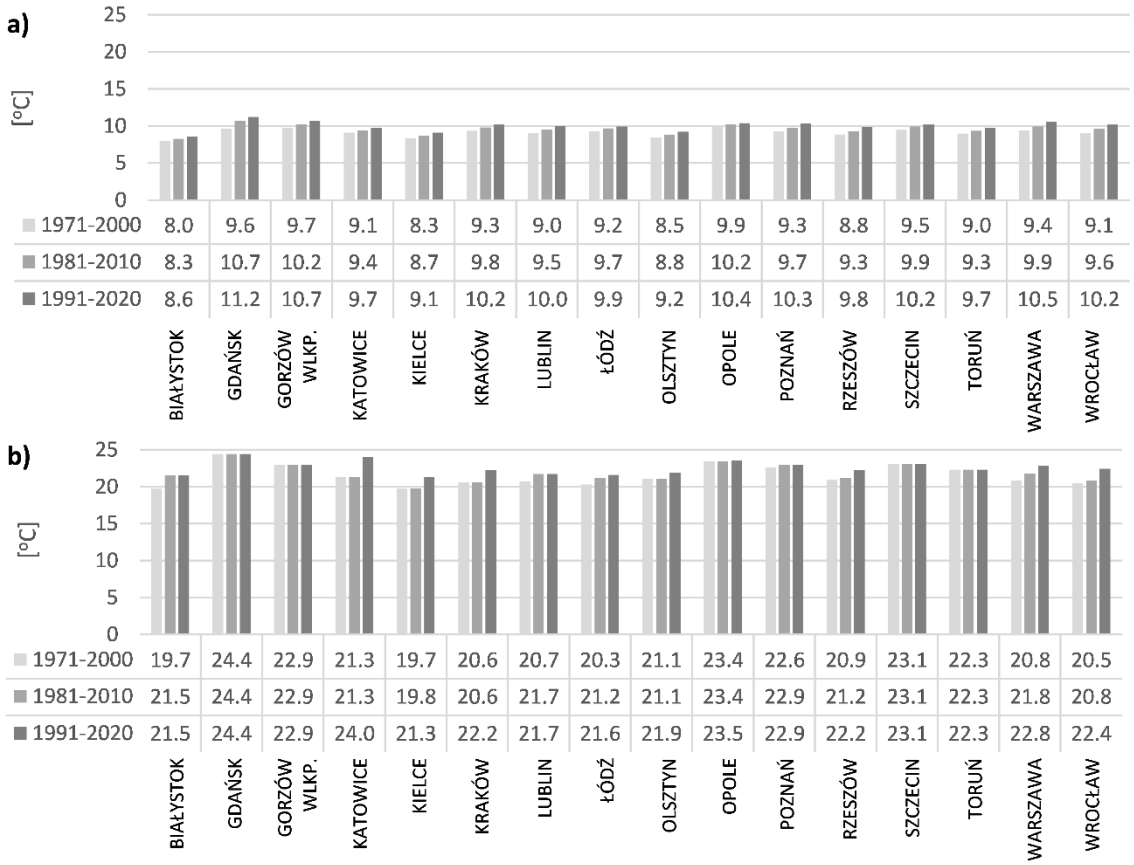

Fig. 3. Average (a) and highest (b) minimum air temperature (°C) in 16 voivodeship cities in Poland (Apr–Sep) in the reference periods: 1971–2000, 1981–2010, 1991–2020

temperature is also observed, with the greatest increase noted in the last reference period (1991––2020), amounting to 0.5°C per decade. In years 1971–2000 and 1981–2010, the increase was 0.3°C per decade. The highest recorded minimum temperature values also increase during the examined periods. The largest increase (0.4°C per decade) in highest minimum temperatures was found in the reference period 1971–2000. The highest minimum temperature (24.4°C) was recorded in the year 1994 in Gdańsk (31 July). The increasingly frequently observed high values of minimum air temperature at night in Poland clearly indicate the possibility of nights defined as very hot nights (from >18°C to ≤20°C) or tropical nights (t_{min} >20 °C). Marsz and Styszyńska (2022) indicate that the increase in air temperature over Poland began only after 1988, coinciding with changes in macrocirculation conditions forced by the changing thermal state of the North Atlantic. Bielec-Bąkowska and Piotrowicz (2013), analysing changes in extreme temperatures in Poland, demonstrated that in the years 1951–2006, changes in minimum temperature are greater than those in maximum temperature. In Poland, the magnitude of anomalous and extreme air temperatures in winter depends mainly on the distance from the Atlantic Ocean and the Baltic Sea, in summer on latitude, and throughout the year on atmospheric circulation and the type of incoming air masses, as well as physiographic conditions (Koźmiński, Michalska 2008). In the current context of climate change, the increase in minimum temperatures recorded in recent decades has received special scientific attention due to its importance for good sleep and the health of the population, among other considerations (Cantos *et al.* 2019).

In the multiannual period under analysis 1971–2020, the occurrence of very warm nights shows a statistically significant time trend (Fig. 4a). It was demonstrated that the increase in the number of very warm nights in all cities in Poland recorded in the whole period under analysis is very dynamic (20 nights per 10 years). In the period 1971–2000, on average, two very warm nights were recorded, and in 1991–2020 the number doubled to an average of four episodes

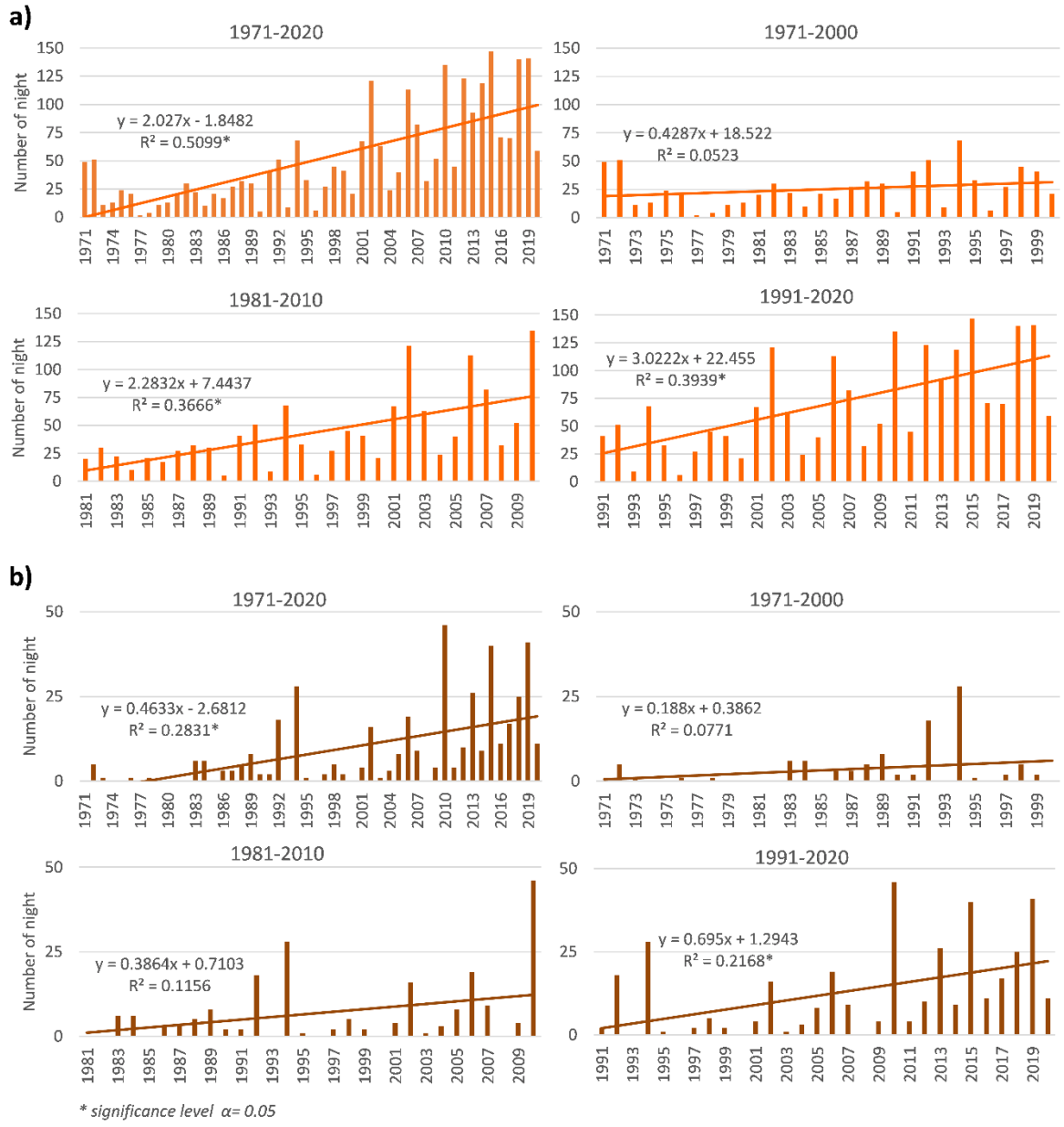

Fig. 4. The number of very warm nights (a) and tropical nights (b) in 16 voivodeship cities in Poland in consecutive years in the period 1971–2020 and in the reference periods 1971–2000, 1981–2010, 1991–2020, with trend

in a year per station (Tab. 1–2). The highest increase in the number of thermally characteristic nights was observed in the last two reference periods, particularly in the period 1991–2020 (Fig. 4a, 5). The maximum number of very warm nights in 16 voivodeships in Poland was recorded in 2015, the minimum in 1977 (two nights in Gorzów Wielkopolski and Poznań) (Fig. 4; Tab. 1). By a spatial system, a positive trend in very warm nights is recorded particularly in stations located in mid-western regions of the country (Fig. 5).

With respect to tropical nights (t_{min}>20°C), a statistically significant increase in number in 16 voivodeship cities in Poland in the period 1971––2020 was also recorded (Fig. 4b, 5). The values of slope coefficients of the linear trend indicate an average increase in the number of tropical nights. Between the first (1971–2000) and the last reference period (1991–2020) under analysis, the number of tropical nights showed an average increase of from 0.1 to 0.8 per year per station (Fig. 5, Tab. 1–2). Similarly to very warm nights, the most prominent increase in tropical nights was observed in the period 1991–2020, with the maximum of such nights in 2010, 2015 and 2019. In these years, there were at least 40 cases of tropi-

Table 1

Sum of very warm night and tropical night in 16 voivodeship cities in Poland in consecutive years in the period 1971–2020

Total number of very warm and tropical nights	BIAŁYSTOK	GDAŃSK	GORZÓW WIELKOPOLSKI	KATOWICE	KIELCE	KRAKÓW	LUBLIN	ŁÓDŹ	OLSZTYN	OPOLE	POZNAŃ	RZESZÓW	SZCZECIN	TORUŃ	WARSZAWA	WROCŁAW
1971	1	5	4	3	3			6	4	3	7		5	4	3	1
1972	5	6	5	1	1	1	5	4	5	4	8		1	3	6	1
1973		6						1	1	1	1		1	1		
1974		1	1	1	1	1	1	1	1	2		2			1	
1975	1		3			1		3		1	3	2	4	1	5	
1976			4			1		2	1	1	6	1	3	1	1	1
1977			1								1					
1978									1		1	1	1	1		
1979			2					3			2	1	1	2		
1980	1	1	1			1			1	1	1	2	1	1		2
1981			2			1		1		4	3	1	3	1	1	3
1982		1	5	1				1		4	3	2	7		4	2
1983		4	2	2		1		2	3	4	3		2	1	2	2
1984		4	2				1	1	2	1	1	1	2	1		
1985			2					5	2	4	1		4	3		
1986		1	1	2			1	2	1	6	3		2		1	
1987	1		2	3	2	4	3	1	2	2	1	3	2	2	2	
1988		3	2	1		4	3	3	2	5	3	2	3	2	3	1
1989	1	2	4	1				4	3	9	3	1	4	3	2	1
1990								1	1	1			2		1	1
1991		8	6		1	3		3	2	5	1	1	4	2	5	2
1992	2	9	4	4	1	2	4	6	3	6	5	2	5	7	5	4
1993		1				1		1	1	2				1	1	1
1994	1	17	13	5	3	4	1	8	2	6	5	2	9	6	7	7
1995		12	5					1	3	3	2		3	2	1	2
1996		3								1				1	1	
1997		14	2		1	1		2	2		2			2	2	1
1998	2		4	5	3	3	4	3	2	5	3	4	2	4	4	2
1999	1	8	2	3	1	1	1	4	3	4	1	2	3	6	3	
2000		1	3	3		6	1	1		3			1	1	1	
2001	5	17	2	3	2	5	1	4	4	4	3	1	3	10	6	1
2002	7	26	9	1	4	9	7	11	6	6	11	4	7	11	14	4
2003		13	7	3	1	5	1	4	3	7	5	2	4	3	4	2
2004		8	1	1	1	1		4		2	2	1	1	3	1	1
2005	1	7	4	3	1	6	2	5	2	2	2	4	1	3	3	2
2006		25	17	3	2	1	4	6	3	14	14	3	9	12	11	8
2007	4	11	8	7	2	3	6	5	5	6	7	6	6	7	6	2
2008		6	5	2				3		3	3	2	2	1	4	1
2009	1	11	2	3	3	3	4	4	3	1	4	6	1	2	7	1
2010	10	23	13	5	5	7	14	10	12	9	15	8	6	14	22	8
2011	1	6	3	5	2	2	1	2	3	5	7		3	5	3	1
2012	2	6	5	7	5	8	12	10	6	13	15	12	3	8	17	4
2013	3	6	11	7	5	6	5	7	3	9	12	4	9	10	13	9
2014	1	18	11	4	1	3	4	7	9	6	13	3	10	14	14	10
2015	2	6	15	12	8	12	9	13	5	19	15	15	11	13	14	18
2016	3	5	5	2	5	4	5	4	2	9	7	3	4	6	13	5
2017	2	3	6	5	3	4	5	7	2	9	9	8	3	5	9	7
2018	6	21	16	2	4	5	3	6	10	11	15	7	9	18	20	12
2019	3	9	15	8	5	11	4	11	10	10	21	9	11	20	20	15
2020		4	9	2	2	2	4	2	2	4	14	2	5	4	9	5
2021	7	15	11	8	8	11	10	7	12	8	10	12	11	12	18	8
2022	5	21	16	5	7	8	7	9	11	10	22	4	14	15	23	16
2023	1	7	7	3	2	9	12	6	10	11	8	10	6	10	15	11

5 10 15 20 number of nights

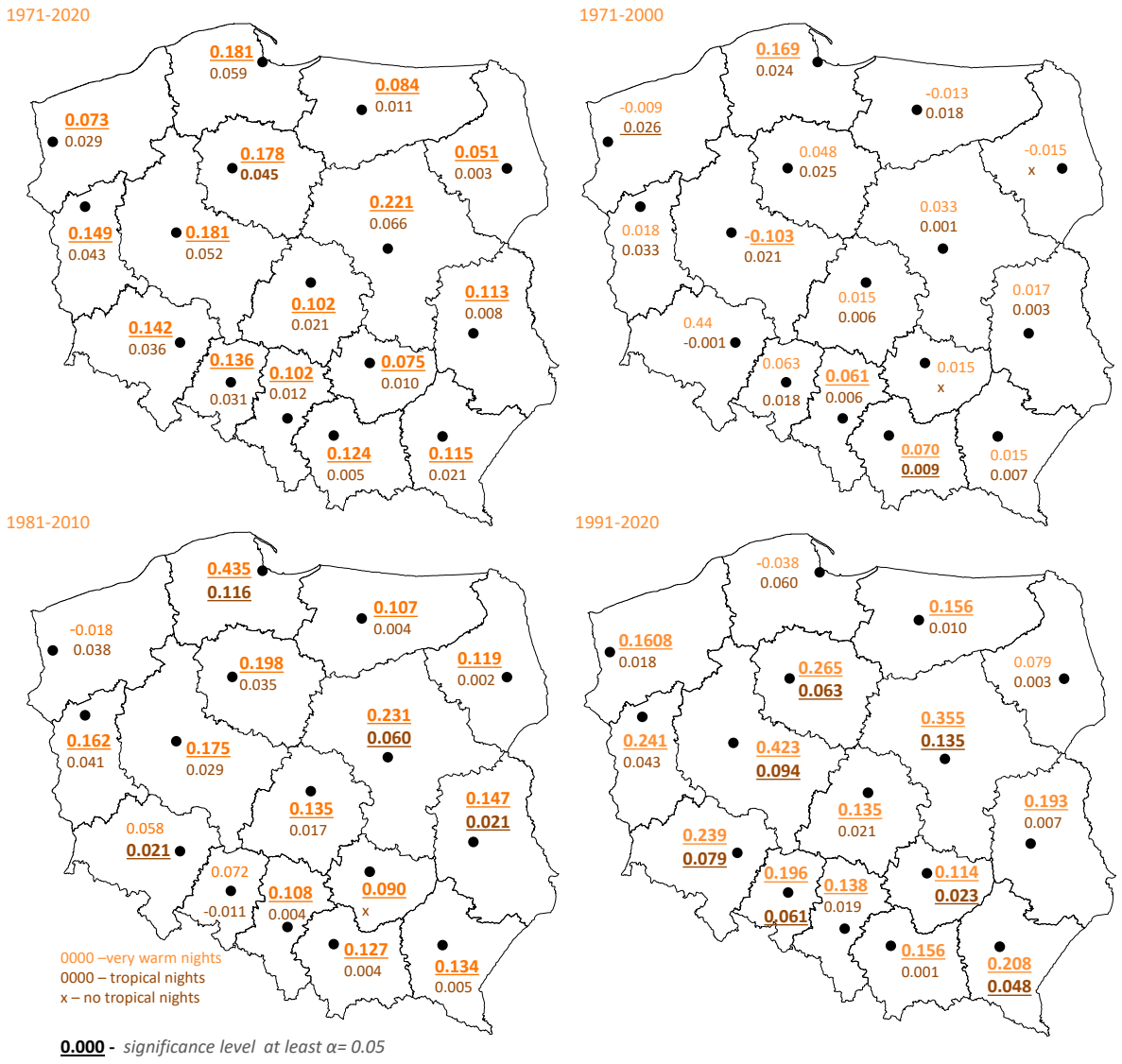

Fig. 5. Values of regression coefficients of the number of very warm nights and tropical nights in 16 voivodeship cities in Poland in 1971–2020 and in the reference periods 1971–2000, 1981–2010, 1991–2020, with trend

cal nights. What is more, since 2000, tropical nights have been recorded almost every year (with the exception of 2000 and 2008) as was demonstrated by Tomczyk (2018). However, it was found that, in the period 1971–2000, tropical nights were not recorded in as many as 13 years, and up to the year 1981, such nights had been recorded only four times (Tab. 1). Tropical nights investigated in the present paper are characterised by very high year-to-year variability, as well as high spatial irregularity of occurrence (Tab. 1). For example, in Białystok, throughout the whole period, there were only two cases of tropical nights in 2001 and 2017. In turn, in Gdańsk, tropical nights were recorded 56 times, with 95% of cases recorded in the last reference period of 1991–2020, 79% since 2002.

The total number of very warm and tropical nights in meteorological stations located within administrative boundaries of voivodeship cities is presented in Table 1. As Table 1 and Figures 4–6 show, the total number of tropical and very warm nights is evidently higher in recent years. In all cities, there was a pronounced increase in the number of the nights under analysis in particular periods, particularly in the mid-western area of the country, with the exception of Wrocław, where, due to the location of the station, the number of said nights is lower than at the neighbouring stations. Regardless

Table 2

Average number of very warm nights and tropical nights in 16 voivodeship cities in Poland (Apr–Sep) in 1971–2020 and in the reference periods 1971–2000, 1981–2010, 1991–2020

	Very warm nights				Tropical nights			
	1971––2020	1971––2000	1981––2010	1991––2020	1971––2020	1971––2000	1981––2010	1991––2020
BIAŁYSTOK	1.3	0.5	1.2	1.8	0.0	0.0	0.0	0.1
GDAŃSK	5.6	3.2	6.7	8.4	1.1	0.4	1.2	1.8
GORZÓW WLKP.	4.0	2.2	3.4	5.4	0.9	0.5	0.9	1.4
KATOWICE	2.2	1.1	1.9	3.2	0.2	0.1	0.2	0.3
KIELCE	1.5	0.6	1.1	2.2	0.1	0.0	0.0	0.2
KRAKÓW	2.6	1.1	2.3	3.8	0.1	0.1	0.1	0.2
LUBLIN	2.2	0.8	1.8	3.2	0.1	0.0	0.2	0.2
ŁÓDŹ	3.5	2.2	3.3	4.5	0.4	0.2	0.3	0.6
OLSZTYN	2.4	1.3	2.0	3.2	0.3	0.3	0.4	0.4
OPOLE	4.1	2.5	3.7	5.3	0.7	0.4	0.6	0.9
POZNAŃ	4.4	2.0	2.8	5.8	0.9	0.4	0.7	1.3
RZESZÓW	2.2	0.8	1.7	3.2	0.4	0.2	0.3	0.5
SZCZECIN	3.1	2.2	2.6	3.6	0.6	0.3	0.7	0.9
TORUŃ	3.8	1.7	3.1	5.5	0.8	0.3	0.6	1.2
WARSZAWA	4.5	1.9	3.7	6.6	0.9	0.2	0.5	1.4
WROCŁAW	2.6	1.1	1.8	3.8	0.4	0.0	0.2	0.7
Average	3.1	1.6	2.7	4.3	0.5	0.2	0.4	0.8

of the identified number of both very warm and tropical nights, as well as the spatial and local conditions of each station, there was a twofold or even threefold increase in the number of said nights in all cities between 1971–2000 and 1991––2020. A great number of cases of very warm and tropical nights was also recorded in 2021––2023 (Tab. 1) which may confirm and indicate a further increase in the number of thermally characteristic nights in the years to come. In terms of tropical nights (TN), climate change scenarios, regardless of the variant or period adopted, clearly indicate an increase in the number of such nights in Europe, including Poland (*Climate Adapt*). An increase in the number of very warm and tropical nights can also be found in other works on this topic, concerning not only Poland but also other regions of Europe and the world. For example, the results of Klok et al. (2023) directly confirm that an increase of air temperature is leading to increased numbers of tropical nights over Ukraine. Furthermore, those authors pointed out that analysis of the North Atlantic Oscillation (NAO) indices and Mediterranean Oscillation (MOI) in the context of tropical nights in Ukraine turned out to be quite effective. There is a clear connection between the rising minimum daily air temperatures and the values of global climate indices.

In terms of annual distribution, the highest number of very warm nights (Fig. 7a) and tropical nights (Fig. 7b) is recorded in Poland in July and August, sporadically in June and only exceptionally in May and September. It is worth mentioning that very warm nights occurring in May and September were recorded slightly more frequently in the last thirty-year-long period (1991––2020). In turn, tropical nights, also exceptionally observed in May, were not recorded in the last reference period. In September, tropical nights were not identified in the first two reference periods (covering 1971–2010), yet were recorded in the period 1991–2020 in several voivodeship cities (Szczecin, Gdańsk, Toruń, Poznań, Opole, Rzeszów) (Fig. 8). In the multiannual period under analysis (1971–2020), the rate of increase in number of such nights is greater in August than in July.

In the climatic conditions of Poland, very warm and tropical nights occur mainly as isolated events, rarely in a series of two or three events and particularly rarely in a series of six or more events (which have been reported in Gdańsk, Toruń, Gorzów Wielkopolski, Warszawa, Wrocław and Opole) (Fig. 8). Single nights comprised from 31% to 61% of all very warm and tropical nights recorded (in Gdańsk and Kielce, respectively). The stations in the north (with the exception

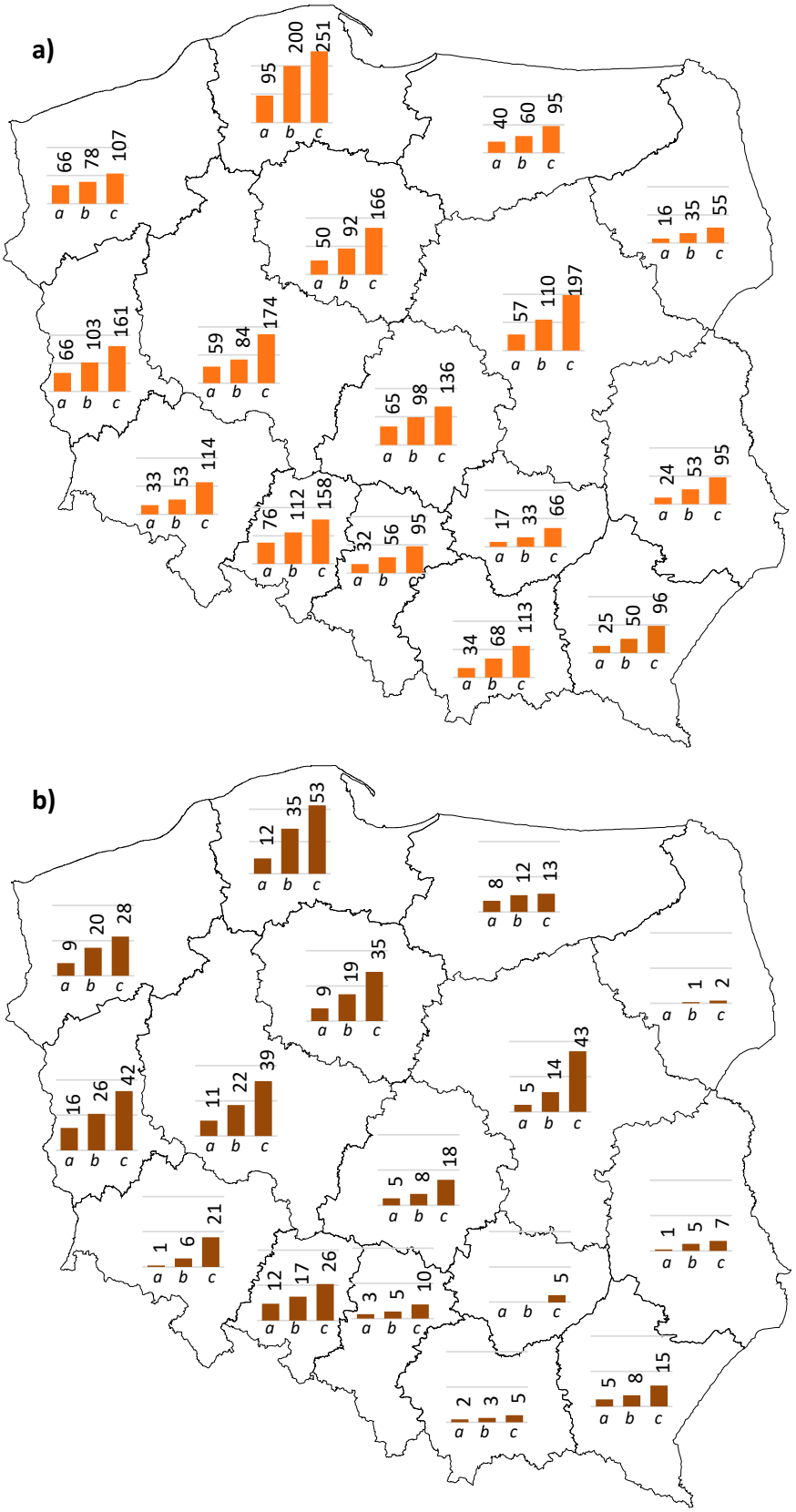

Fig. 6. Total number of very warm nights (a) and tropical nights (b) in individual voivodeship cities of Poland in reference periods: a) 1971–2000, b) 1981–2010, c) 1991–2020

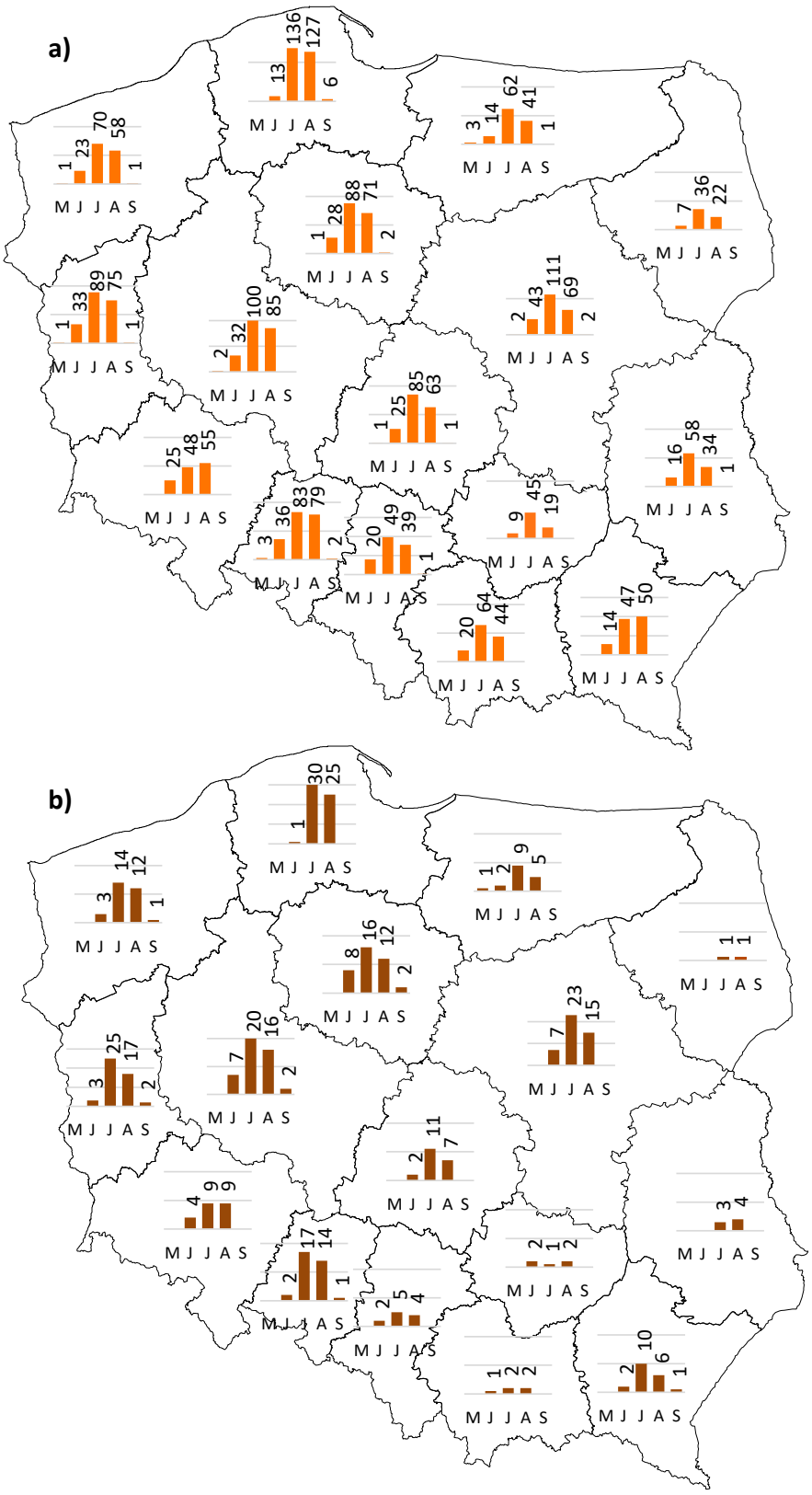

Fig. 7. Total number of very warm nights (a) and tropical nights (b) in consecutive months (Apr–Sep) in voivodeship cities of Poland in 1971–2020

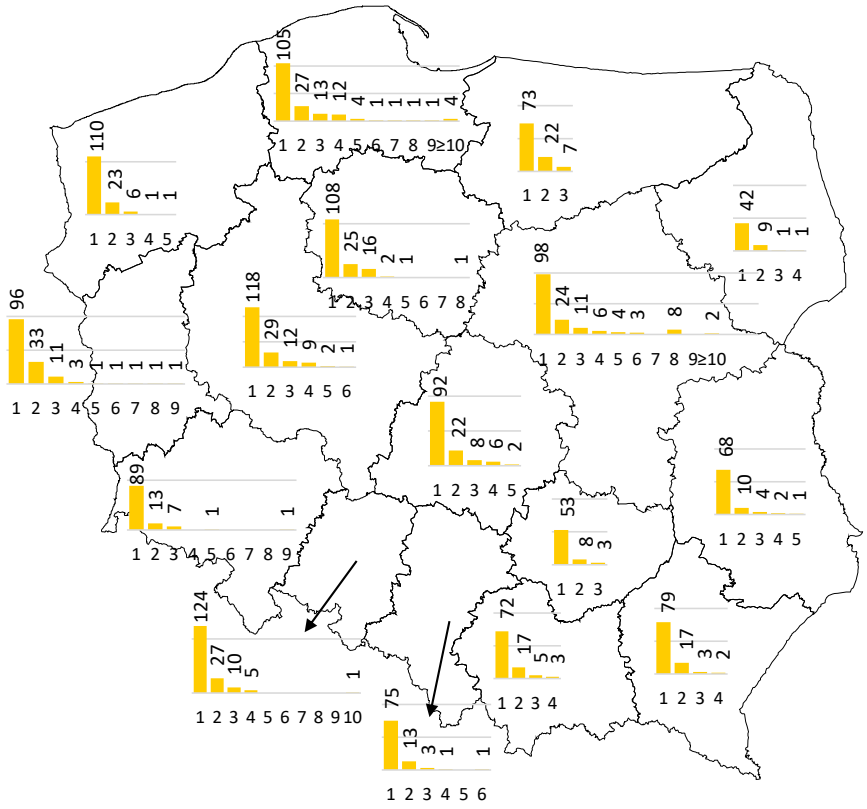

Fig. 8. Number of series of very warm and tropical nights, totalled for the period 1971–2020

of Gdańsk), east and south-east of the country generally recorded the series of very warm and tropical nights lasting up to five days, and those in the mid-western part of Poland recorded the series of ten or more days. According to Matuszko *et al.* (2023), in Kraków in the 21st century, very warm nights are being recorded in increasingly longer series, e.g. five days (from 20/21 to 24/25 July 2006) and seven days (16–22 July 2007), and a record number of tropical nights was recorded in 2006 and 2010, at nine and ten nights, respectively. Additionally, it is believed (Murage *et al.* 2017) that warm nights following hot days have the greatest effect on human health, as lack of night-time regeneration and rest aggravates the thermal stress experienced during a series of hot days.

Among the 16 cities under analysis, the longest series of very warm and tropical nights were recorded in the years 1971–2020 in Toruń from 27 July to 3 August 2018, Gorzów Wielkopolski from 26 July to 3 August 1994, Wrocław 7–15 August 2015, followed by Opole 7–16 August 2015, Gdańsk 8–18 August 2002 and 21 July and 1 August 2014, and Warszawa from 25 July to 5 August 2018. In the last series, in Warszawa (Fig. 9), there was a sequence of very warm and tropical nights reaching nighttime air temperatures of more than 22°C – the night of 1–2 August, constituting a major health risk. It should be noted that, in city centres, particularly within urban heat islands, both the frequency and duration of the nights under analysis are higher than those recorded in stations on the outskirts of cities. For example, the station in Warszawa–Okęcie is located by the airport, so it can arguably be assumed that the number of very warm or tropical nights recorded in the city centre is going to be higher – – as is also indicated by Błażejczyk *et al.* 2014. This is also confirmed by Bednorz *et al.* (2018), who argue that the values of 24-hour period minimum air temperature can be determined by local conditions and not only by circulation. The literature on the subject (Matuszko *et al.* 2023) argues that a series of hot days and nights results in malaise (fatigue, irritability), heart rate increase, reduced blood pressure and tachypnea (thermoregulatory disorders). Such series contribute to the increase in mortality due to cardiovascular and respiratory diseases, as well as increased incidence of road events and occupational injuries. Moreover, the study by Kozłowska *et al.* (2004) shows that prolonged series of very warm and tropical nights result in increased numbers of patients re-

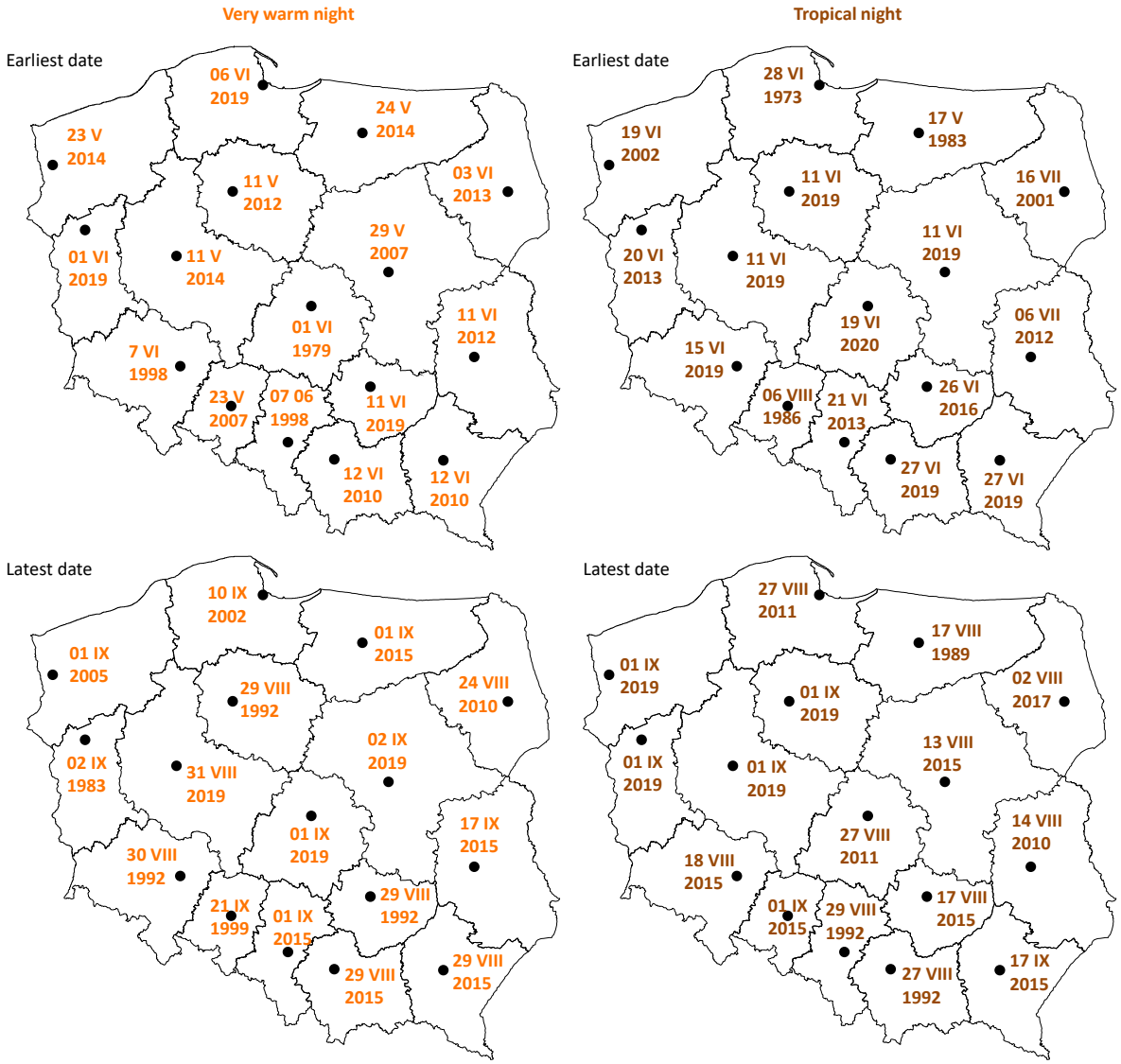

Fig. 9. Earliest and latest dates of occurrence of very warm and tropical nights in 1971–2020 in voivodeship cities in Poland

porting to outpatient clinics and deaths in Warszawa. It should be kept in mind that, in city centres, especially within the urban heat island, both the frequency and duration of said nights are greater than those recorded at stations on the outskirts of cities (Błażejczyk *et al.* 2014; Mąkosza, Rawicki 2018). According to Gabriel and Endlicher (2011) and López-Bueno *et al.* (2021), heat-related mortality is higher in urban areas than rural areas, owing to the urban heat island effect.

The present study points to the regional distribution of the series of very warm and tropical nights which is largely determined by the spatial distribution of high-pressure areas and the inflow of tropical and continental air masses, respectively. This is confirmed by Więcław (2015), who, based on surface synoptic maps of Europe, showed that very warm nights most often occur during advection of tropical air (e.g., the percentage of tropical masses during such nights is ~90% in Chojnice, 75% in Kołobrzeg and 79% in Poznań). By contrast, during hot nights, only the inflow of tropical masses was observed.

The area with the most frequent occurrence of very warm and tropical nights i.e., mid-western Poland, is generally characterised by the earliest and the latest dates of occurrence (Fig. 9). In the multiannual period under analysis, at the stations in Poznań and Toruń, very warm nights were recorded as early as in the second decade of May and tropical nights in the second decade of June. The stations in Szczecin, Olsztyn, Warszawa and Opole record very warm nights in the third decade of May, and the remaining

stations in the first and second decade of June and – with respect to tropical nights – in the third decade of June and first decade of July. As is presented in Figure 9, very warm nights can occur in the first and second decade of September, with the exception of stations in Bialystok, Kielce, Kraków, Rzeszów and Wrocław, where they are recorded at the end of August. Tropical nights were identified in mid-west of the country in the first decade of September, and in the rest of Poland in the second and third decade of August, with the exception of Rzeszów (17.09.2013) (Fig. 9). In the light of the aforementioned dates, the potential occurrence in Poland ranges from the second decade of May to the second decade of September for very warm nights and from the second decade of June to the second decade of September for tropical nights.

During heat-waves, anticyclonic atmospheric circulation predominated and advection of air masses from the north and south-east. Heat-waves were frequently recorded during non-advection events (barometric ridge). Więcław (2015) reported that importance of tropical air masses increases at the beginning and end of the season for very warm nights whereas, in July and August, cases of such nights are also observed during the advection of potentially colder air masses.

Conclusions

- In the last reference period 1991–2020 the values of minimum temperature indicates increases of 0.5°C per decade and 0.3°C per decade in the years 1971–2000 and 1981–2010.
- The number of very warm and tropical nights shows a positive statistically significant trend in 1971–2020, especially in the mid-west of the country, particularly in the last reference period 1991–2020.
- Relative to the first reference period (1971––2000), twice as many very warm and tropical nights were recorded in the last (1991–2020).
- The analysed very warm and tropical nights are recorded most frequently in August and July, rarely in June, sporadically in May and September. Tropical nights, unprecedented in September in previous years, were recorded in the last reference period (1991–2020), particularly in the west of Poland.
- The discussed very warm and tropical nights are characterised by great temporal and spatial irregularity of occurrence, particularly in the north-east of Poland. In the multiannual period under analysis, the following years are distinguished in terms of high number of such nights: 1994, 2006, 2010, 2013, 2015, 2018 and 2019.
- In the climatic conditions of Poland, very warm and tropical nights primarily occur as isolated events (31–68% cases), rarely in a series of two or three events, and series of six and more nights are exceptional.
- On the basis of the available climate change scenarios and the positive trends in minimum air temperature identified in the present paper, one can expect a further increase in the occurrence and intensity of very warm and tropical nights in voivodeship cities in Poland.

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