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HEATWAVES IN POLAND – FREQUENCY, TRENDS AND RELATIONSHIPS WITH ATMOSPHERIC CIRCULATION

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Abstract: The daily minimum and maximum temperatures at seven Polish stations were used in an analysis of the occurrence of heatwaves in the years 1951-2006. Heatwaves were defined as days with temperatures exceeding selected thresholds (t_{max} ≥25°C, t_{max} ≥30°C, t_{min} ≥18°C). The mean length of a wave of very warm days lasts from 2-4 days, the longest no fewer than 23 days. Waves comprising hot days and nights are shorter. The frequencies of very warm and hot days and hot nights increased in the analyzed period, especially its second half (1979-2006). The occurrence of heatwaves characteristically links up with high-pressure systems over Central Europe, along with associated blocking episodes.

Key words: extreme temperatures, Sen's slope, Lund classification, composite method, Poland

INTRODUCTION

Instrumental observations of European temperature records have revealed a warming since the end of the nineteenth century. This increase of temperature can be expressed only in terms of shifted distribution, or can also be accompanied by a change in shape. In the first case the temperature distribution is shifted towards higher temperatures, such that the frequency of days with a temperature exceeding a given threshold is greater. While the width of the distribution changes there is modification of the rate of change in the frequency of extremely warm days, enlarging it while widening and reducing it while narrowing. The changes in asymmetry could further modify the probability of extremely high temperatures occurring. So the warming corresponds with an increase in the frequency of heatwaves, but details of this increase are determined by changes in the shape of the distribution for maximum temperature.

According to Katz and Brown (1992) relatively small changes in the mean of climate variables can induce marked changes in extreme events. The frequency and severity of such events exert a considerable impact on society that is much stronger than the change in mean (Watson *et al.* 1996).

According to the IPCC (2001): "An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called extreme weather may vary from place to place."

An extreme climatic event can be defined on the basis of rarity, intensity or the impact

Table 1. Annual mean (+ standard deviation), minimum and maximum numbers of days with temperatures exceeding given thresholds in the period 1951-2006 (for Puławy 1951-1998).

Element		Hel	Chojnice	Kalisz	Poznań	Łódź	Siedlce	Puławy
mean	18°C	2.2	0.9	2.4	2.8	2.6	1.2	2.5
	25°C	10.4	25.1	39.3	39.9	37.5	36.9	38.4
	30°C	0.5	3.3	8.4	9.1	7.2	5.7	6.1
st. dev.	18°C	2.96	1.32	3.00	2.76	2.55	1.51	2.05
	25°C	6.20	10.31	11.85	12.81	12.20	11.91	10.76
	30°C	1.16	4.39	6.10	6.78	5.95	5.36	5.87
min	18°C	0	0	0	0	0	0	0
	25°C	4	15	26	26	24	23	25
	30°C	0	0	0	0	1	0	0
max.	18°C	11	6	16	16	12	6	7
	25°C	27	44	65	70	63	69	60
	30°C	5	26	28	32	27	18	24

it exerts on society (Beniston and Stephenson 2004). The definition used in this paper is based mainly on heatwave intensity.

The aim of this paper is to describe statistical properties as regards the occurrence of heatwaves over the area of Poland, to analyse the synoptic conditions accompanying them and to check if there are any trends to the frequency of occurrence of heatwaves. A heatwave is defined on the basis of maximum daily temperature and two temperature thresholds are used: 25°C and 30°C. The former is used to define :"very warm" days, the latter "hot" ones. The case of hot nights is also analysed, a threshold of 18°C for minimum daily temperature being applied as the criterion.

DATA AND METHODS

The daily maximum and minimum temperatures from seven Polish stations (Hel, Chojnice, Kalisz, Łódź, Poznań, Puławy and Siedlce) were used from the period 1951-2006 (for Puławy 1951-1998). The data from Siedlce 1999-2006 were taken from ECA&D (<http://eca.knmi.nl>, Klein Tank *et al.* 2002). The locations of these stations are as presented in Fig. 1. In addition, daily gridded geopotential heights from levels: 850, 700 and 500 hPa and sea level pressure values from NCEP/NCAR reanalysis (Kalnay *et al.* 1996) in the period 1958-2005 were used to examine the pressure systems associated with the occurrence of heatwaves.

To describe the statistical properties characterising the occurrence of heatwaves occurrence, the mean monthly numbers of days with temperatures exceeding all selected thresholds and their standard deviations were presented, together with distributions of the numbers of heatwaves in relation to their length (section 3).

The annual numbers of days and cumulative totals of temperatures exceeding given thresholds were used to characterize the temporal characteristics of heatwaves. The long-term changes were assessed using linear regression with a t-test and Sen's slope with the Kendal *tau* test (Wilks 1995). Linear regression methods assume that the distribution is normal or at least symmetrical. This assumption is not always true, so the Sen's slope method (Sen 1968) was used for comparison (section 4).

The composite maps for sea level pressure (SLP) and geopotential height (GPH) of levels 850, 700 and 500 hpa and the thicknesses of levels 1000/850, 850/700 and 700/500 hPa in days with temperature exceeding the threshold were calculated to describe the influence of atmospheric circulation in the European-North Atlantic region on the occurrence heatwaves in Poland (section 5). The Lund method of field classification (Lund 1963) was used for 700 hPa GPH

Figure 1. Location of stations.

fields, to distinguish the synoptic situations accompanying heatwaves.

The objective circulation typology by Piotrowski (Piotrowski 2007) based on the subjective one from Osuchowska-Klein was also used to distinguish the synoptic conditions associated with heatwaves.

A summary and discussion of results is presented in section 6.

INTRA-ANNUAL FREQUENCY DISTRIBUTION AND LENGTH OF HEATWAVES

The mean annual number of days with maximum temperature ≥ 25°C varies from just over 10 at Hel to almost 40 in Poznań and Kalisz with standard deviations varying from 6.2 days at Hel to 12.8 days at Poznań (Table 1). Such days occurred each year in the analysed period. The smallest number of such days varied from 4 at Hel to 26 at Poznań and Kalisz. The largest annual number of very warm days varied from 27 at Hel to 70 in Poznań. Their number was at a minimum close to the seaside and a maximum in the Wielkopolska region.

Very warm days occurred from April through to October (Fig. 2). In April the average annual number of such days is close to 0.5, but in particular years their number can even reach 8. Very warm days occurred most commonly in July, when their mean number varied from 4.4 at Hel to more than 12, but in particular years it can even be 29.

Hot days are evidently less frequent. The mean annual numbers of days with a maximum temperature ≥ 30°C vary from 0.5 at Hel to more than 9 in Poznań, with standard deviation ranged from 1.2 days at Hel to more than 6.8 at Kalisz. Such days did not occur in each year of the analysed period. The highest annual number of warm days varied from 5 at Hel to 32 in Poznań.

Hot days occurred from May to September, but their mean annual frequencies in May and September did not exceed 1. They were most common in July, in which month mean frequencies vary from 0.3 at Hel to more than 4 in Poznań, but in certain years the total can reach 24 hot days.

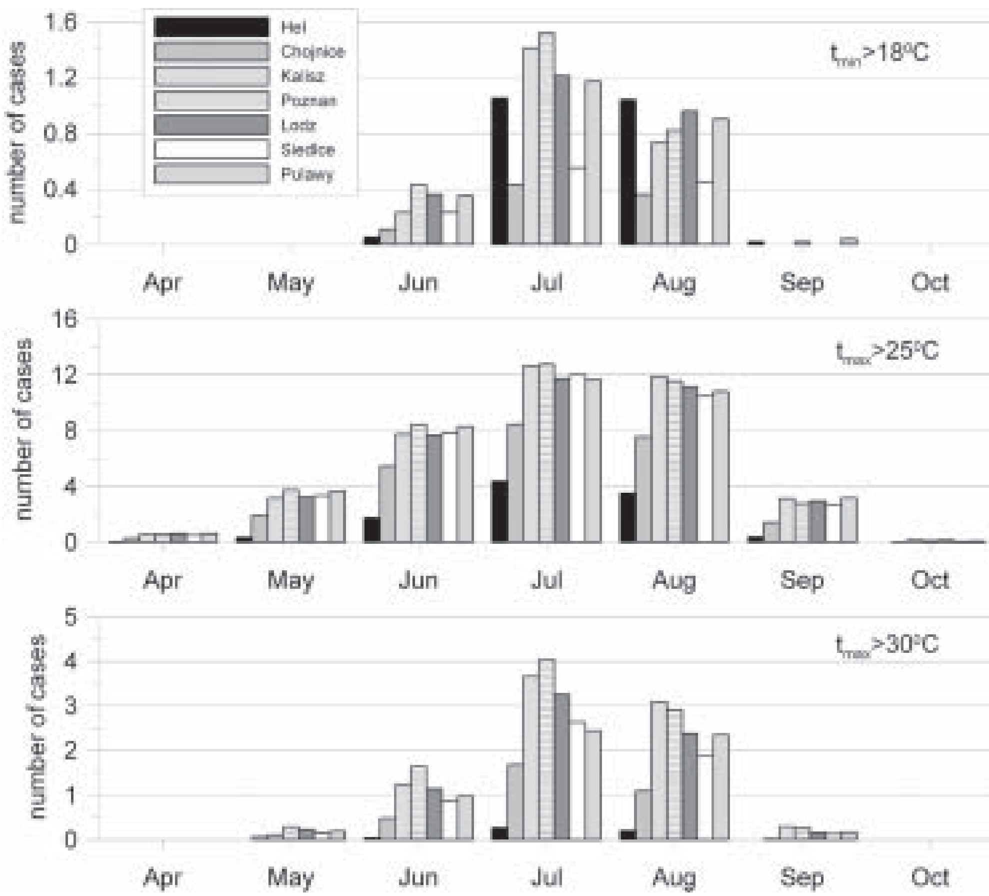

Figure 2. Mean monthly frequencies of days exceeding given thresholds at all seven stations in the period 1951-2006 (for Puławy 1951-1998).

Hot nights (with a minimum temperature ≥ 18°C) are much less frequent. Their mean annual number varies from below 1 at Chojnice to almost 3 in Poznań, with standard deviation ranging from 1.3 at Chojnice to 3 at Kalisz. Hot nights did not arise in each year of the analysed period. The highest annual number of hot nights varied from 6 at Chojnice and Siedlce to 16 in Kalisz and Poznań.

Very warm and hot days as well as hot nights appear individually or in waves. Day-long waves are the most common, but the number of days in such waves account for only between 10 and 20% of all very warm days, about 20% of all hot days and as many as one half of hot nights (Fig. 3, Table 2). The mean length of very warm waves varies from 1.77 days at Hel to 3.16 in Poznań. Hot-day heatwaves are slightly shorter, and last from 1.4 days at Hel to 2.65 at Poznań. The shortest-duration phenomena are hot-night waves. They last from 1.19 days at Chojnice to 1.46 at Hel and Kalisz. The longest very warm waves in turn lasted more than 20 days (23 at Chojnice, 22 in Poznań). The longest hot heatwaves went on for 19 days. The shortest were the waves of hot nights, which never exceeded 10 days in length in the analysed period.

Table 2. Number of waves in relation to their length and number of days in these waves for very warm and hot days and hot nights at selected stations.

Chojnice	very warm days (T_{max}≥25°C)		hot days (T_{max}≥30°C)		hot nights (T_{min}≥18°C)	
	No of waves	No of days	No of waves	No of days	No of waves	No of days
1 day	197	197	44	44	35	35
2 days	100	200	19	38	6	12
3 days	87	261	8	24	1	3
4 days	43	172	5	20		
5 days	19	95	4	20		
6 days	13	78	1	6		
7 days	9	63	1	7		
8 days	8	64	1	8		
9 days	11	99				
10 days	3	30				
>10 days	10	148	1	20		
sum	500	1407	84	187	42	50
days/wave	-	2.81	-	2.23	-	1.19

Hel	very warm days (T_{max}≥25°C)		hot days (T_{max}≥30°C)		hot nights (T_{min}≥18°C)	
	No of waves	No of days	No of waves	No of days	No of waves	No of days
1 day	204	204	15	15	62	62
2 days	72	144	3	6	12	24
3 days	24	72	1	3	6	18
4 days	13	52	1	4	1	4
5 days	5	25				
6 days	7	42			1	6
7 days	2	14			1	7
>10 days	2	29				
sum	329	582	20	28	83	121
days/wave	-	1.77	-	1.40	-	1.46

Kalisz	very warm days (T_{max}≥25°C)		hot days (T_{max}≥30°C)		hot nights (T_{min}≥18°C)	
	No of waves	No of days	No of waves	No of days	No of waves	No of days
1 day	290	290	86	86	67	67
2 days	149	298	44	88	17	34
3 days	104	312	22	66	2	6
4 days	50	200	15	60	3	12
5 days	48	190	13	65	1	5
6 days	22	132	1	6		
7 days	20	140	2	14		
8 days	13	104	1	8		
9 days	7	63	1	9	1	9
10 days	10	100	1	10		
>10 days	24	323	4	58		
sum	744	2052	190	470	91	133
days/wave	-	2.76	-	2.47	-	1.46

THE LONG-TERM VARIABILITY TO HEATWAVES

Long and intense heatwaves are relatively rare. The annual number of days with temperature exceeding 30°C is an indicator for both the length and the intensity of hot heatwaves. During the period 1951-2006, a few extremely hot years can be distinguished, i.e. 1963, 1992, 1994 and 2006, with annual numbers of hot days exceeding 40 at almost all stations (Figure 4). The year-to-year variability in the frequency of very warm and hot days and hot nights is very marked (Fig. 5). Besides some extreme years, there are long-term changes to be observed. The long-term course for annual numbers of extreme days did not show any distinguishable trend in the first part of the period: 1951-1978, but an upward trend was evident in the second part – after 1978. The intensity of these trends and their statistical significance were ana-

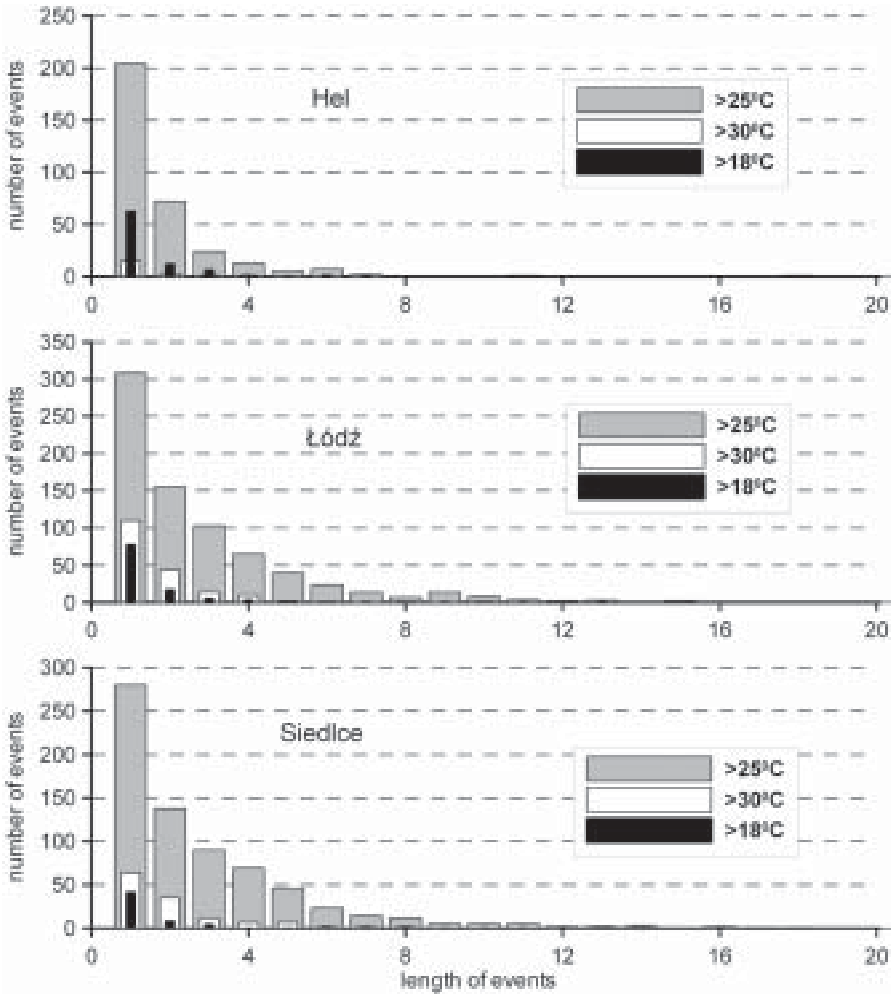

Figure 3. Distribution of waves of hot and very warm days and hot nights in relation to their length at Hel, Łódź and Siedlce.

lyzed using linear regression estimated by the least square method and Sen's slope. The first method assumes that the distribution of extreme days is close to normal or at least symmetrical and is very sensitive to outliers. The second method makes no assumptions as regards data distribution and is not sensitive to outliers. Tables 3 and 4 present the slopes and statistical significances of trends on two time scales: in the whole analyzed period (1951-2006) and in the shorter period 1979-2006, which corresponds to the strong warming in central Europe. All trends are positive indicating that heatwaves became more frequent, but trends in the second half of the analysed period are much clearer. The number of very warm days has increased evidently. At some stations the increase was of more than 8 days per decade. At the same time the increase in the number of hot days amounts only 2-4 days per decade. In turn, The most limited increase is characteristic for the number of hot nights.

The slopes calculated by both methods are similar, but those assessed using regression analysis are stronger and more often

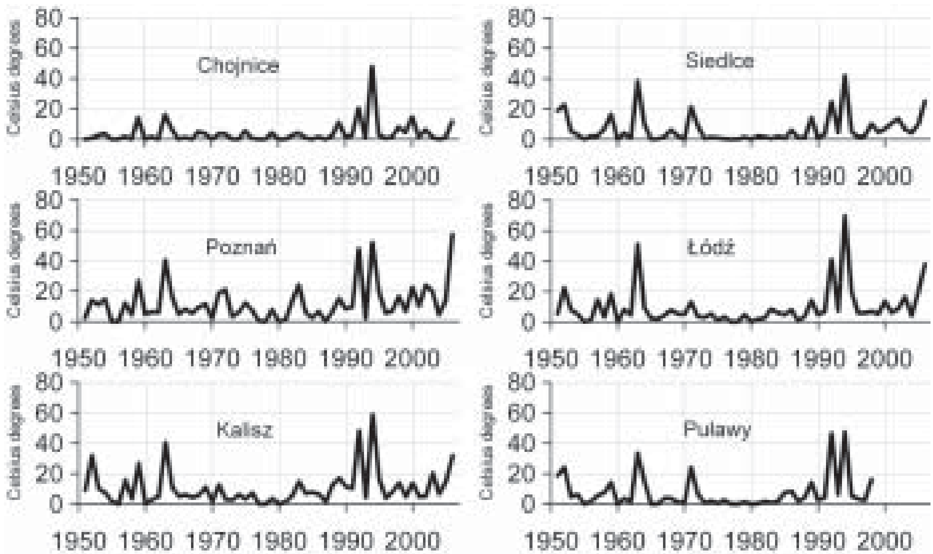

Figure 4. Annual values of the cumulative sum of Celsius degrees above the threshold (t_{max} ≥30°C) at selected stations.

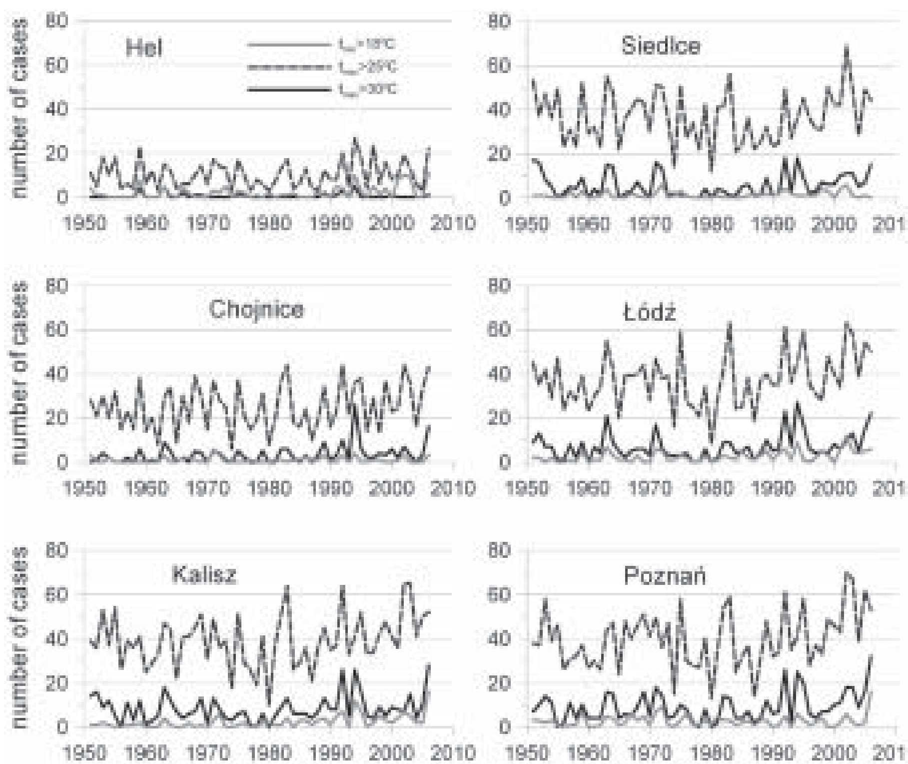

Figure 5. Long-term courses of frequencies of days with temperature exceeding given thresholds.

Table 3. Linear trends in annual number of days with temperatures exceeding given thresholds [in days per decade] based on l
* significant at 10% level, ** significant at 5% level

station	long period (1951-2006)			short period (1979-2006)		
	18 °C	25 °C	30 °C	18 °C	25 °C	30 °C
Hel	0.64**	0.49	2.34	2.18**	0.00	0.10
Chojnice	0.07	1.32	0.87**	0.11	0.37	1.34
Kalisz	0.95**	1.65	0.67*	1.77**	6.58**	2.58**
Poznań	0.18	2.08*	1.26**	0.93	8.40**	4.68**
Łódź	0.68**	1.95*	0.96*	1.48**	7.68**	3.13**
Siedlce	0.19	0.35	0.26	0.66*	6.04**	3.09**

Table 4. Linear trends in annual number of days with temperatures exceeding given thresholds [in days per decade] based on Sen's slope
* significant at 10% level, ** significant at 5% level

Station	long period (1951-2006)			short period (1979-2006)		
	18 °C	25 °C	30 °C	18 °C	25 °C	30 °C
Hel	0.00	0.20	0.00	1.67	1.79	0.00
Chojnice	0.00	1.20	0.43	0.00	0.38	0.93
Kalisz	0.57**	1.48	0.41	1.11*	6.49*	1.52
Poznań	0.00	2.03*	0.83	0.00	8.88**	4.14**
Łódź	0.54	1.67	0.67	1.32	7.43**	2.50*
Siedlce	0.00	0.00	0.43	0.00*	6.84**	2.86**

significant. Yet, because the distributions of extreme day frequencies are not close to Gaussian, the second method seems more robust.

INFLUENCE OF CIRCULATION ON HEATWAVE OCCURRENCE

The set of days with t_{max}≥30°C at at least one of the analysed stations was established. Mean sea level pressure (SLP) and geopotential heights at levels: 850, 700 and 500 hPa were then calculated and fields for mean anomalies of pressure and geopotential heights between selected days and all days were calculated for all calendar months separately. Fig. 6 presents the fields of such anomalies and mean values in the case of hot days in July, the maps for other months not differing significantly and not being shown.

Hot days in Poland occur when there is a strong high pressure system over the Northern Atlantic with a centre near 35ºN and a ridge extending far towards the north-east. The climatological low near Iceland is weak or absent and there is a low over the Middle East. Over Central and Eastern Europe the pressure is higher than normal, and the greatest anomaly, exceeding 4 hPa, is located just on the east of Poland. At higher levels, strong positive anomalies are observed over Central and Eastern Europe with maximum on the north-eastern edge of the country, exceeding 50 m at the 850 hPa level in July, 80 m at the 700 hPa level and 100 m at the 500 hPa level. At the same time, the geopotential heights of all these levels are slightly lower over the Northern Atlantic to the west of the British Isles. The height of the geopotential levels reveals a stronger-than-normal south-north gradient, and a ridge of higher values stretching from the eastern Mediterranean to

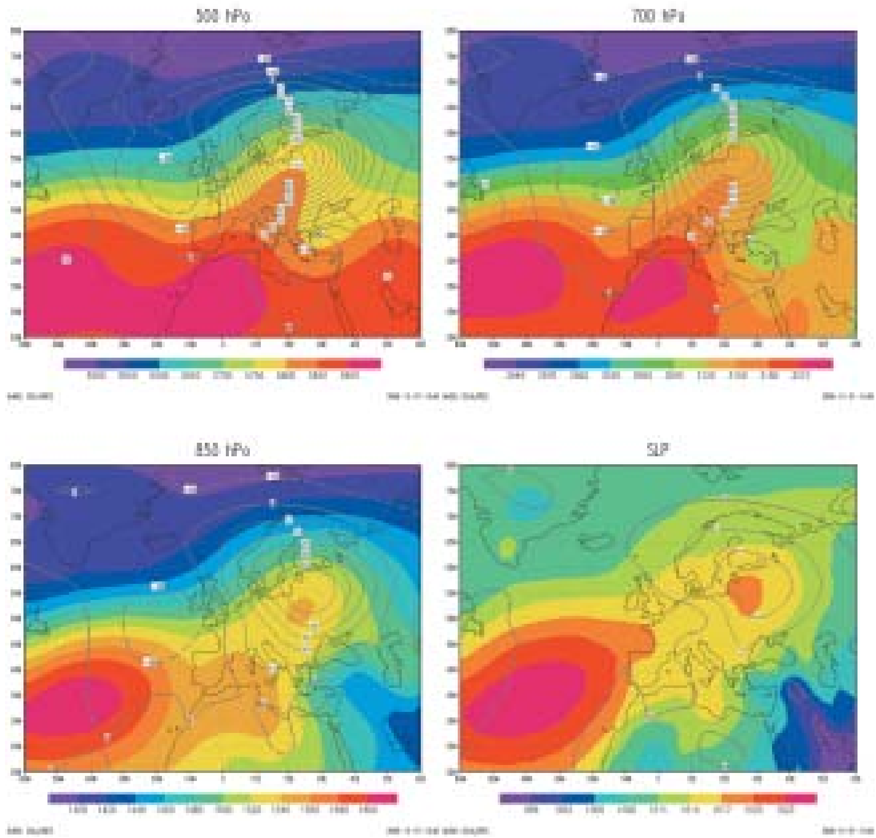

Figure 6. Mean SLP and geopotential heights at 500, 700 and 850 hPa levels on selected days (shading), and anomalies between mean values on selected or all days in given months (isolines) both in geopotential meters.

the north-east. The low over the Middle East is shallow and is not seen at geopotential levels higher than 700 hPa.

Simultaneously the thicknesses of levels 1000/850 hPa, 850/700 hPa and 700/500 hPa are greater than usual over Western and Central Europe (Fig.7). This means that a large amount of warmth is accumulated at these levels. At the same time it is easy to see that the higher the level the greater the surplus warmth. The greatest increase in geopotential level thicknesses is located just over Central Europe, and there is a small decrease over the eastern Atlantic near the British Isles.

The Lund method was used to distinguish the synoptic types accompanying heatwaves in Poland. Firstly the set of days with $t_{max} \geq 30$°C at at least one analysed station was established, there being 511 such days in the period 1958-2005 (the range of SLP and GPT data). Then the set of geopotential heights of 700 hPa level over the area ranging from 30°N to 80°N in latitude and from 60°W to 60°E in longitude with a step of 2.5° in both directions was prepared and classified using the Lund method. This level was selected because the geopotential wind at this level is close to the direction of air mass advection (Barnston and Livezey 1987). Six types were distinguished, and more than 70% of selected days shown to belong to one of these types. The model fields are presented in Fig. 8, and the details summarized in Table 5.

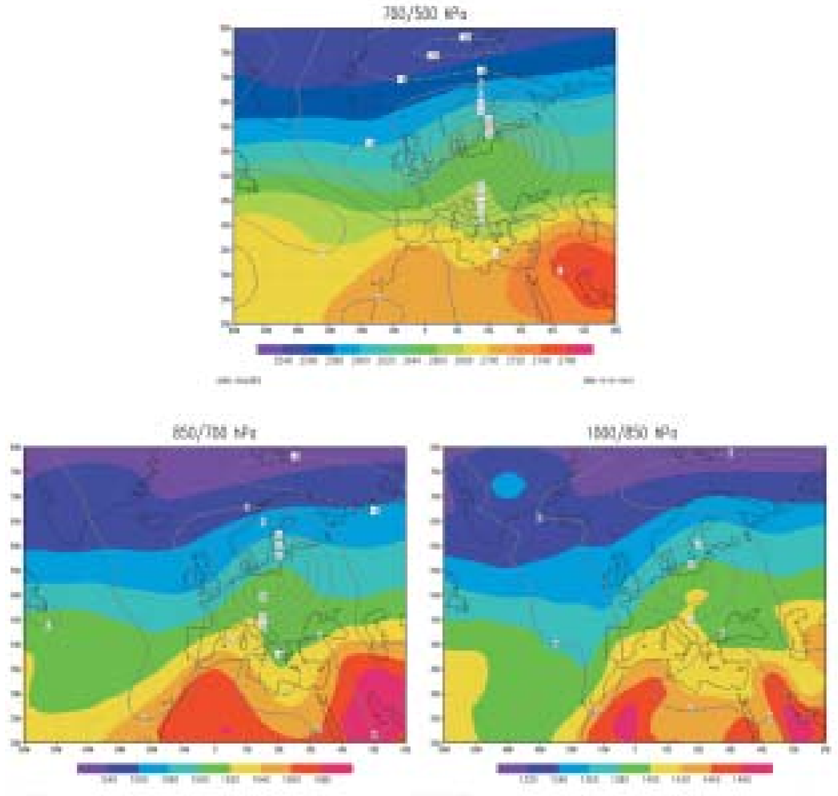

Figure 7. Mean thicknesses of 500/700, 700/850 and 850/1000 hPa levels on selected days (shading), and anomalies between mean values on selected and all days in given months (isolines) both in geopotential meters.

The first type is the most zonal circulation with the lower heights of the 700 hPa surface in the north and higher ones in the south. There is a shift of high values to the north over Central Europe, with a maximum just at the longitude of Poland. There is an advection of warm air from the south-west into the Polish area strengthening the effect of strong radiation with clear sky conditions. In the second type there are ridges of geopotential height stretching from the south-west to the north-east, and from the north-east to the south-west. The Polish area lies just between them, so there is an intense warm advection from the south-west. In the third and fourth types there are well developed Icelandic lows and Azores highs. The low is just over Iceland, the high has a ridge extending far to the north-east. Poland lies in the area of the presence of a ridge of high pressure. The strong radiation in clear-sky conditions and the blocking high are favorable to high temperatures. These two types differ in the intensity of the low-pressure system, which is stronger for the fourth type than for the third. In the case of the fifth type the low-pressure system is more elongated, but the blocking high still prevents the low from wandering to the east towards Central Europe. In the last type there is no distinct pressure system. Pressure gradients are extremely weak and a clear sky and strong radiation are the main reasons for high temperatures in Poland.

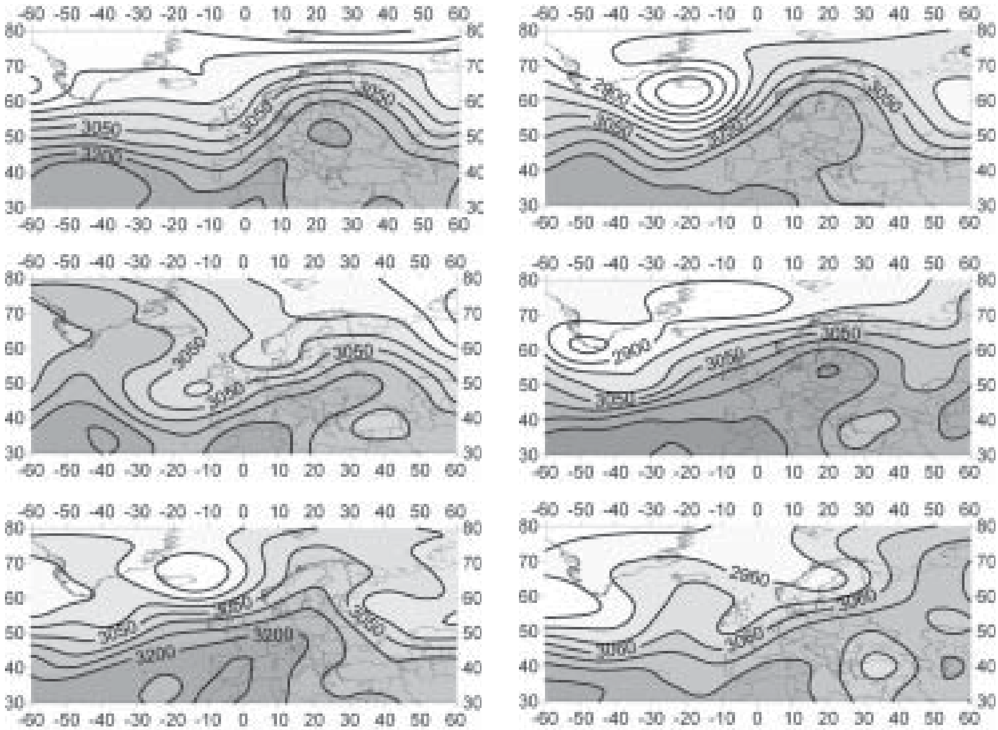

Figure 8. Geopotential heights at the 700 level (in geopotential meters) characteristic for synoptic types distinguished by the Lund method.

Table 5. Characteristics of types distinguished by Lund's method.

Type	date of model situation	number of days belonging to this type	percentage of days belonging to this type
1	16th August 2001	156	30.5%
2	7th July 1968	77	15.0%
3	17th July 1968	55	10.7%
4	26th July 1994	38	7.4%
5	24th July 1968	23	4.5%
6	14th July 1965	13	2.5%

According to objective circulation typology developed by Piotrowski (Fig. 9), on the basis of the subjective one from Osuchowska-Klein, very warm and hot days occur mainly (68.7% and 59.8% of the time) during anticyclonic conditions , especially during days with southern and south-western anticyclonic circulations (18.8 and 24.8% respectively). Hot days can also occur with a cyclonic or mixed circulation from the southern sector.

SUMMARY AND DISCUSSION

Very warm days in Poland occur from April to October, whereas the hot days and nights occur from May to September only, with maximal occurrence in July or August, as with hot nights. Very warm and hot days occur most frequently in the central part of Poland (Poznań, Kalisz and Łódź), whereas the number of hot nights was relatively

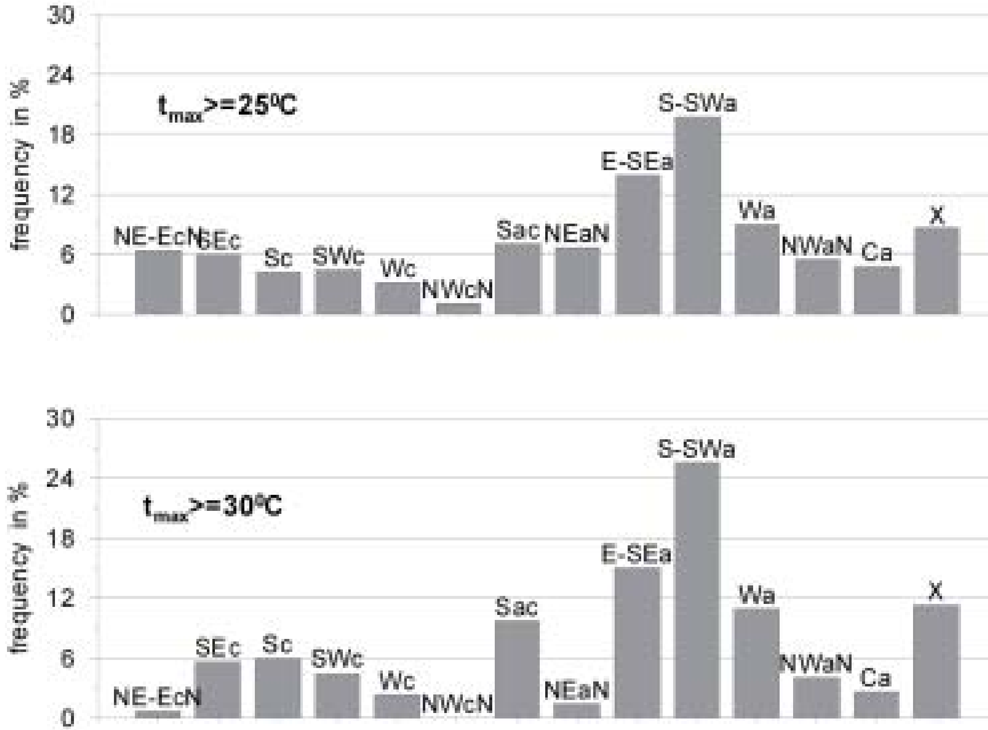

Figure 9. Distribution of synoptic types for Poland after Piotrowski's classification in days with t_{max} ≥25°C (upper graph) and t_{max} ≥30°C (lower graph).

more frequent at the seaside (Hel). There is very marked year–on-year variability in the frequency of very warm and hot days. During the analyzed period there were a few summers with really severe heatwaves arising in 1963, 1992, 1994 and 2006. Less intensive heatwaves were observed in 1952, 1964, 1971 and 1983. Overall, such a distribution indicates increasing frequency in the latter part of the analyzed period, but because of their irregular occurrence it is extremely difficult to assess the significance of the increase. The t-test applied to linear regression results has shown really marked significance, but the results are not robust if the distribution of the analyzed dataset is far from the Gaussian. The results obtained by the Sen's slope method and *tau* test seem more realistic because the methods do not demand any assumption as regards the dataset distribution. The trends obtained using this method are still positive, even though weaker.

Warming in Poland is not uniform during the year, being strongest in late winter and spring, less marked in early winter and summer. In autumn cooling is observed in some places, though this is not statistically significant (Kożuchowski 2004). At the same time, there are many places in Central Europe in which the means for extreme daily temperatures have increased more than the mean daily values (Beniston *et al.* 1994; Brazdil *et al.* 1996; Wibig and Głowicki 2002). Our results indicate that extreme maximum temperatures have increased even more, and these can affect large numbers of mid-latitude residents, especially those living in large cities – since this increase can be amplified by the urban effect.

Heatwaves occur when high-pressure systems are dominant over Central Europe, or there is strong advection from the south.

Because waves of hot and very warm days are rare across Poland, it is difficult to assess the probability of such an event on the basis of nothing more than the circulation type that occurs. Some analyses point to the role of the persistence of high-pressure systems. It appears that "more persistent circulation patterns tend to enhance the severity of heat waves and support more pronounced temperature anomalies. Recent sharply rising trends in positive temperature extremes over Europe may be related to the greater persistence of the circulation types, and if similar changes towards enhanced persistence affect other mid-latitudinal regions, analogous consequences and implications for temperature extremes may be expected" (Huth and Kyselý 2008).

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