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

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Abstract: The daily minimum and maximum temperatures at nine stations in Poland were used in an analysis of the occurrence of coldwaves, where these are defined as days with temperatures exceeding selected thresholds ($t_{min} \leq -20°C$, $t_{min} \leq -15°C$ and $t_{max} \leq -10°C$) in the period 1951-2006. Cold nights occurred more often than very cold days and nights but the mean lengths of waves of cold nights were similar – lasting a little more than 2 days on average. The frequencies of extremely cold days revealed a slight, but statistically non-significant downward trend. The occurrence of coldwaves was associated with high-pressure systems over Central Europe and with blocking episodes, but it was always linked with a thick layer of cold air.

key words: extremely low temperature, trend, Sen's slope, least squares method, Poland

INTRODUCTION

Extreme cold events exert a strong impact on the environment and society. However, instrumental observations of European temperature records have revealed a warming since the end of the nineteenth century, while Central and Eastern Europe (and Poland) have witnessed winter minimum temperatures increasing more than maxima (Heino *et al.*, 1999, Wibig and Głowicki, 2002) Warming in the winter season in Central and Eastern Europe is strongly related to atmospheric circulation, mainly the strengthening of the North Atlantic Oscillation (NAO). While an increase in mean daily and mean minimum temperature does not necessarily affect the frequency of extreme cold weather (Walsh *et al.*, 2001), a shift in the temperature distribution towards higher temperatures, should cause the frequency of very cold days to drop considerably. However, an increase in temperature can be expressed by different changes in temperature distribution, so the influence of warming on cold-day frequency does not need to drop much.

The severity and intensity of winters in Poland have been analysed by many authors. Kosiba (1956) quoted 49 indices describing winter severity, while Paczos (1985) offered yet further ones. In the European literature, long series of extreme thermal indices were presented by Klein Tank and Können (2003), and Moberg and Jones (2005). Winter severity in Kraków since the 19th century has in turn been described by Trepińska (1976), Piotrowicz (1998, 2003a, 2003b) and Domonokos and Piotrowicz (1998). All these authors indicate that winters have been becoming more mild and less severe. Trends for the indices describing the mean severity or intensity of winters are statistically significant. But even in a warmer climate series of days with very low temperatures – the so-called coldwaves - can occur, and can exert a dramatic impact on society and the environment.

Table 1. Location of stations

Station	λ	φ	Altitude a.s.l	Lowest absolute temperature 1951-2006, with year of occurrence
Hel	18^{0}49’	54^{0}36’	1	-20.0ºC, 1956
Chojnice	17^{0}33’	53^{0}42’	172	-30.0ºC, 1956
Kalisz	18^{0}05’	51^{0}44’	140	-28.5ºC, 1987
Łódź	19^{0}24’	51^{0}44’	187	-31.1ºC, 1963
Poznań	16^{0}50’	52^{0}25’	86	-28.5ºC, 1987
Siedlce	22^{0}16’	52^{0}11’	146	-33.3ºC, 1987
Puławy	21^{0}58’	51^{0}25’	142	-31.0ºC, 1987
Zakopane	19^{0}57’	49^{0}18’	844	-34.1ºC, 1956
Śnieżka	15^{0}44’	50^{0}44’	1603	-33.9ºC, 1956

The influence of atmospheric circulation on the frequency of cold events was analysed by Domonokos *et al.* (2003), who found that northern, eastern, meridional and anticyclonic circulation types are favorable to the occurrence of cold events in southern Poland. Łupikasza and Bielec-Bąkowska (2004) found that extremely cold events are more likely to occur during anticyclonic, as opposed to cyclonic situations, with the Ka, Ea, SEa and Ca types according to Niedźwiedź’s calendar being the most favorable. Departures of temperature from mean values for days with selected circulation types according to Osuchowska-Klein during the period 1966-1980 were analyzed by Paszyński and Niedźwiedź (1991)

The aim of this paper is to describe the statistical properties of the occurrence of coldwaves across Poland.

DATA AND METHODS

Use was made of daily minimum and maximum temperatures for nine Polish stations (Hel, Chojnice, Kalisz, Łódź, Poznań, Puławy, Siedlce, Zakopane and Śnieżka), the period 1951-2006 being represented (in the cases of Łódź and Siedlce 1951-March 2006). The data from Siedlce 1999-2006 were taken from the European Climate Assessment Dataset (<http://eca.knmi.nl>; Klein Tank *et al.*, 2002). The locations of these stations are as presented on Figure 1 and Table 1. The daily gridded geopotential heights from levels: 850, 700 and 500 hPa and sea level pressure values from NCEP/NCAR reanalysis (Kalnay *et al.* 1996) were used to analyze the influence of circulation on the occurrence of coldwaves.

Three temperature thresholds were used to define extremely cold days: daily minimum temperature ≤ -15°C (hereinafter “cold” nights) and ≤ -20°C (“very cold” nights), and the daily maximum temperature ≤ -10°C (“very cold” days). The choice of such thresholds was dictated by our desire to confine ourselves to truly extreme events, with a probability of occurrence in winter below 5% at the greater part of the analysed stations. As can be seen from Table 2 there were on average almost five days per winter with $t_{min} \leq -15$°C, and under two days per winter with $t_{min} \leq -20$°C and $t_{max} \leq -10$°C. The last threshold corresponds with the so-called “very frosty” days (Paszyński and Niedźwiedź, 1991).

Statistical properties of the occurrence of coldwaves were described using mean monthly frequencies of days with temperatures exceeding all the selected thresholds and their standard deviations. The frequencies of coldwaves in relation to length were also analyzed (section 3).

Very cold nights and days ($t_{min} \leq -20$°C and $t_{max} \leq -10$°C) did not arise each year at nearly all the stations. It is therefore extremely difficult to assess the temporal changes characterizing such series. The linear regression

Table 2. Statistical features of coldwaves in the period 1951-2006 (Puławy and Zakopane 1951-1998)

station	mean ± standard deviation of annual number of days			mean length of coldwaves		
	t_{max}≤-10°C	t_{min} ≤-15°C	t_{min} ≤-20°C	t_{max}≤-10°C	t_{min} ≤-15°C	t_{min} ≤-20°C
Hel	0.23±1.21	0.71±1.85	0.02±0.41	1.63	1.77	1.00
Chojnice	1.75±3.25	4.98±6.37	1.05±3.37	1.96	2.21	1.84
Kalisz	1.73±4.13	4.83±6.24	1.32±5.95	2.11	2.53	1.95
Poznań	1.38±2.78	4.58±6.48	1.27±2.67	2.03	2.29	2.09
Łódź	1.63±3.17	5.98±6.92	1.63±3.17	2.27	2.37	1.86
Siedlce	3.46±5.15	9.98±9.88	3.46±5.73	2.32	2.69	2.19
Śnieżka	12.27±8.66	11.51±8.03	1.59±3.13	2.28	2.71	2.23
Puławy	2.81±4.59	7.40±8.59	2.40±4.29	2.14	2.55	1.89
Zakopane	2.83±4.33	13.89±9.76	3.56±5.75	2.16	2.46	2.07

estimated by the least squares method is not robust in the case of such a dataset (Wilks, 1995). It emerged that the Mann-Kendall test for trend detection in the version proposed by Sneyers (1990) also gave false results. Ultimately, the Mann-Kendall test in the version described by Hipel and McLeod (1995) was applied. In this version, hypothesis H_0 - that data come from a population of independent and identically-distributed random variables - is set against alternative hypothesis H_1, that the data follow a monotonic trend over time. Under H_0, the statistic S is given by:

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

where

$$\operatorname{sgn}(x) = \begin{cases} +1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases}$$

has a distribution fast approximating the gaussian where sample size is increasing with the mean value 0 and variance Var(S), as given by the formula:

$$Var(S) = \left(n(n-1)(2n+5) - \sum_{i=1}^{k} t_i(t_i-1)(2t_i+5) \right) / 18$$

where k is the number of a tied group in the series and t_i the number of data in the ith tied group. Giving consideration to the tied groups is crucial if test significance is to be assessed.

In the case of very cold days and nights the significance of any downward trend was only assessed without an attempt at estimation of their slopes. In the case of cold nights (t_{min}≤-15°C), the assessment for the existence of a trend was augmented by slope estimation by Sen's slope and Kendall *tau* test (Sen, 1968) and the linear regression estimated by the least square method (Wilks, 1995). The last method was only used for comparison, however, because it cannot be robust in the case considered (section 4).

Figure 1. Location of stations.

The influence of atmospheric circulation in the European-North Atlantic region on coldwave occurrence in Poland was analysed using the composite maps of 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

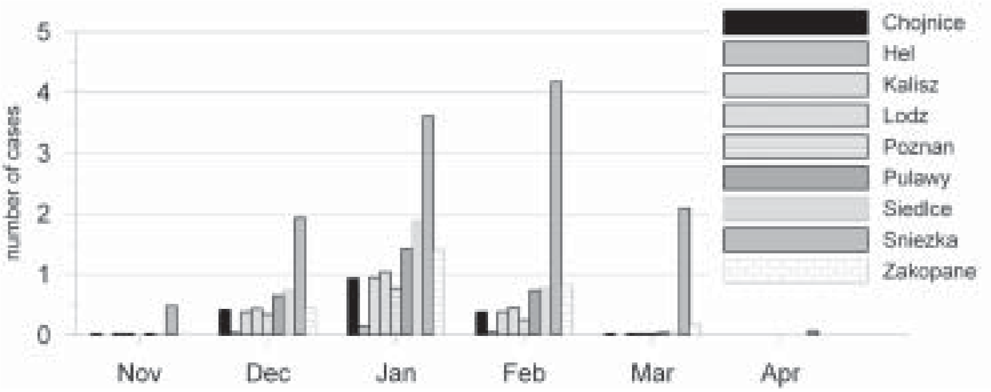


Figure 2. Mean monthly number of days with $t_{max} \leq -10°C$ at all stations in the period 1951-2006 (for Puławy and Zakopane, 1951-1998).

700/500 hPa in days with temperature exceeding the threshold (section 5). The synoptic conditions accompanying the coldwaves were distinguished by means of the Lund field classification method (Lund, 1963) applied to 700 hPa GPH fields.

The objective circulation typology from Piotrowski (Piotrowski, 2007) as based on the subjective one from Osuchowska-Klein was also used to distinguish the synoptic situations accompanying coldwaves.

INTRA-ANNUAL FREQUENCY DISTRIBUTION AND LENGTH OF COLDWAVES

Very cold days and nights were extremely rare in Poland (Table 2, Fig. 2), occurring from November to March, and on Śnieżka also in April. At Hel, the minimum temperature dropped below -20°C only once in the analysed period, so its mean annual number of such events equals 0.02. Very cold days were a little more common and their number reached 0.23 days/year. In the western part of the lowlands, represented by Kalisz, Poznań, Chojnice and Lódź, the very cold days and nights occurred about one and a half times per year on average, while at Puławy, Siedlce and Zakopane about 3 days with such events were observed annually. At Śnieżka the mean annual number of very cold days exceeded 12, but the number of very cold nights was relatively small, at only one and a half. The year–on-year variability was relatively high at all stations. The standard deviations of annual numbers of occurrences at each station other than Śnieżka were at least twice as great as the mean annual values. This means that there were several years with very cold days and nights, and a large number of years without such days.

At all stations cold nights were much more common. Their mean annual frequency of occurrence ranged from 0.7 at Hel to 11.5 on Śnieżka and even 13.9 in Zakopane. Standard deviations for annual values were of the same order as the values themselves, so years without such days did occur, but were relatively rare.

All coldwaves in Poland were short. Most of them at each station did not exceed a few days. The mean length of a coldwave varied from 1.63 at Hel to 2.69 at Siedlce. The exception was one day-long wave at Hel – this being the only day with a minimum temperature below -20°C observed at this station. The longest waves occurred at Puławy and Siedlce were of 19 days' duration (Table 2, Fig. 3).

THE LONG-TERM VARIABILITY OF COLDWAVES

Very cold days and nights were extremely rare in Poland. Only on Śnieżka did cold days occur in each year of the analysed period (Fig.4), but very cold days were even more rare

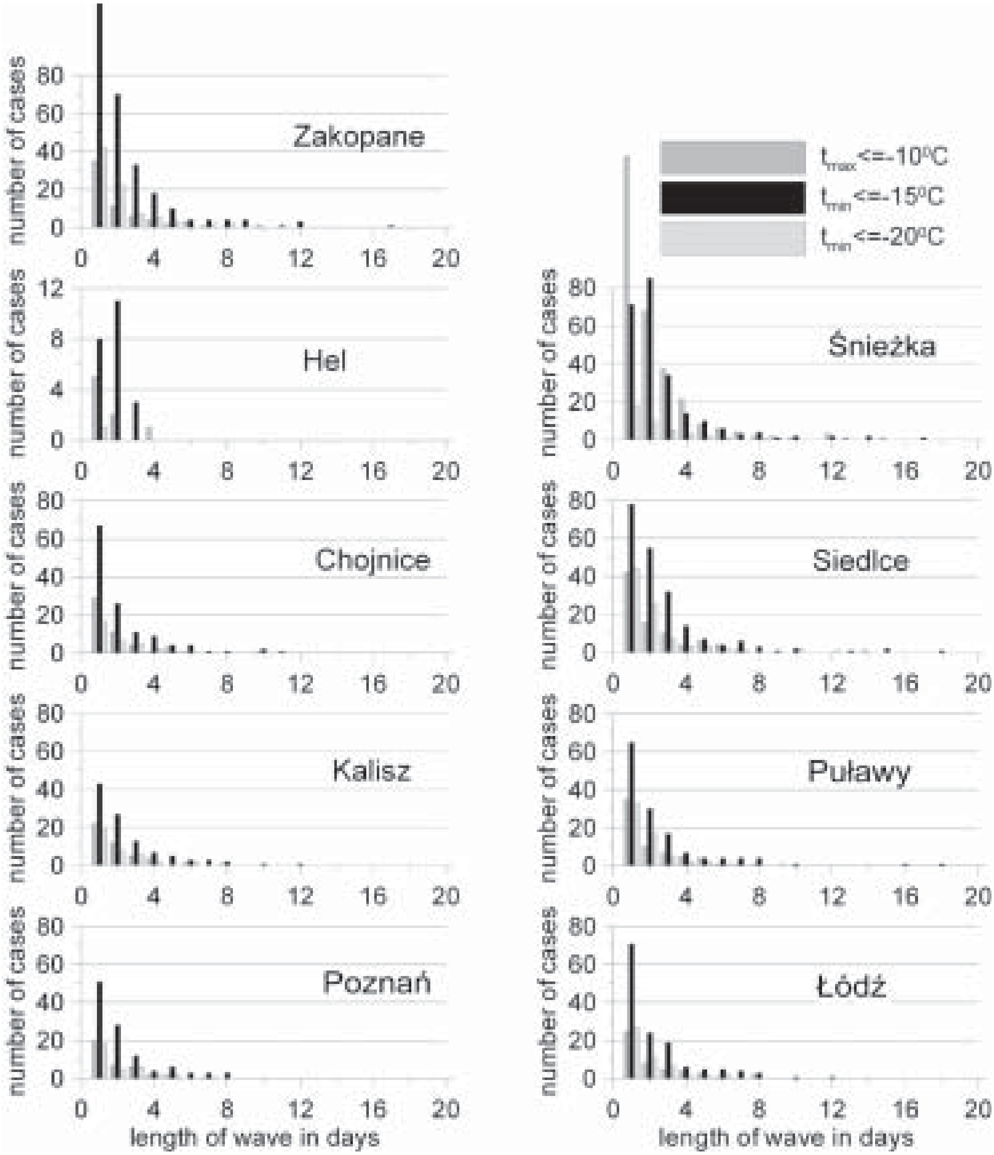


Figure 3. Distribution of waves of very cold days and nights and cold nights in relation to their length.

on Śnieżka than at other stations in Poland. During the period 1951-2006 a few extremely cold winters can be distinguished: in 1954, 1956, 1963, 1970, 1985 and 1987. The last winter 2005/2006 was very cold, but not extremely cold compared with other cold winters.

Detecting trends in series with a standard deviation much greater than the mean value is extremely difficult. Series of annual numbers of days with $t_{min} \leq -20°C$ and $t_{max} \leq -10°C$ include many zero values. For this reason, the Mann-Kendall test for trend detection in the version proposed by Sneyers (1990) is not useful, while the other version described in section 2 can be applied. The values for this test are brought together in Table 3. They

Table 3. Analysis of trends: estimation of significance and slope.
* values significant at the 90% level, ** values significant at the 95% level

station	Mann-Kendall test			trend (t_{min} ≤-15°C)	
	t_{max} ≤-10°C	t_{min} ≤-15°C	t_{min} ≤-20°C	Sen's slope	linear regression
Hel	0.22	-0.46	-0.33	0.00	-0.19
Chojnice	-0.17	-0.22	0.26	0.00	-0.25
Kalisz	-0.59	-1.78	-1.08	-0.38*	-0.89*
Poznań	-0.34	-1.17	-1.01	0.00	-0.63
Łódź	-0.90	-0.93	-0.90	-0.27*	-0.64
Siedlce	0.12	-1.52	-0.95	0.00	-1.01
Śnieżka	-1.56	-1.58	-0.62	-1.05*	-0.96
Puławy	0.08	-1.37	-0.68	-0.91*	-1.13
Zakopane	-0.15	-3.56**	-2.68**	0.00	-2.66**

all indicate a downward trend, though in no case except Zakopane, are these statistically insignificant.

Series of annual numbers of days with t_{min} ≤ -15°C are a little better. The number of 0 values is small, but the standard deviation is still of the same order as the mean value. In the case of these series, the Mann-Kendall test for trend detection was supplemented by estimation of the linear slopes using the Sen's slope and least squares methods. Almost all the slopes point to a downward trend, but only some of these achieve significance at the 90% level (Table 3).

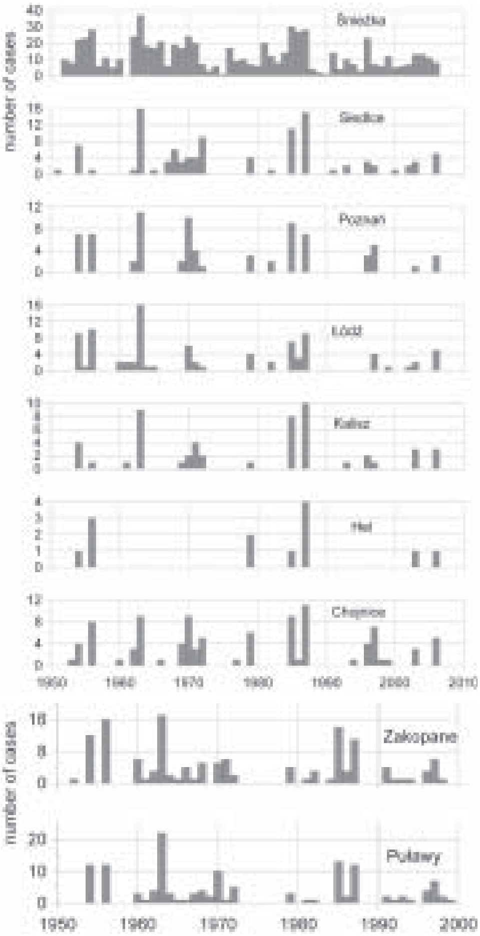
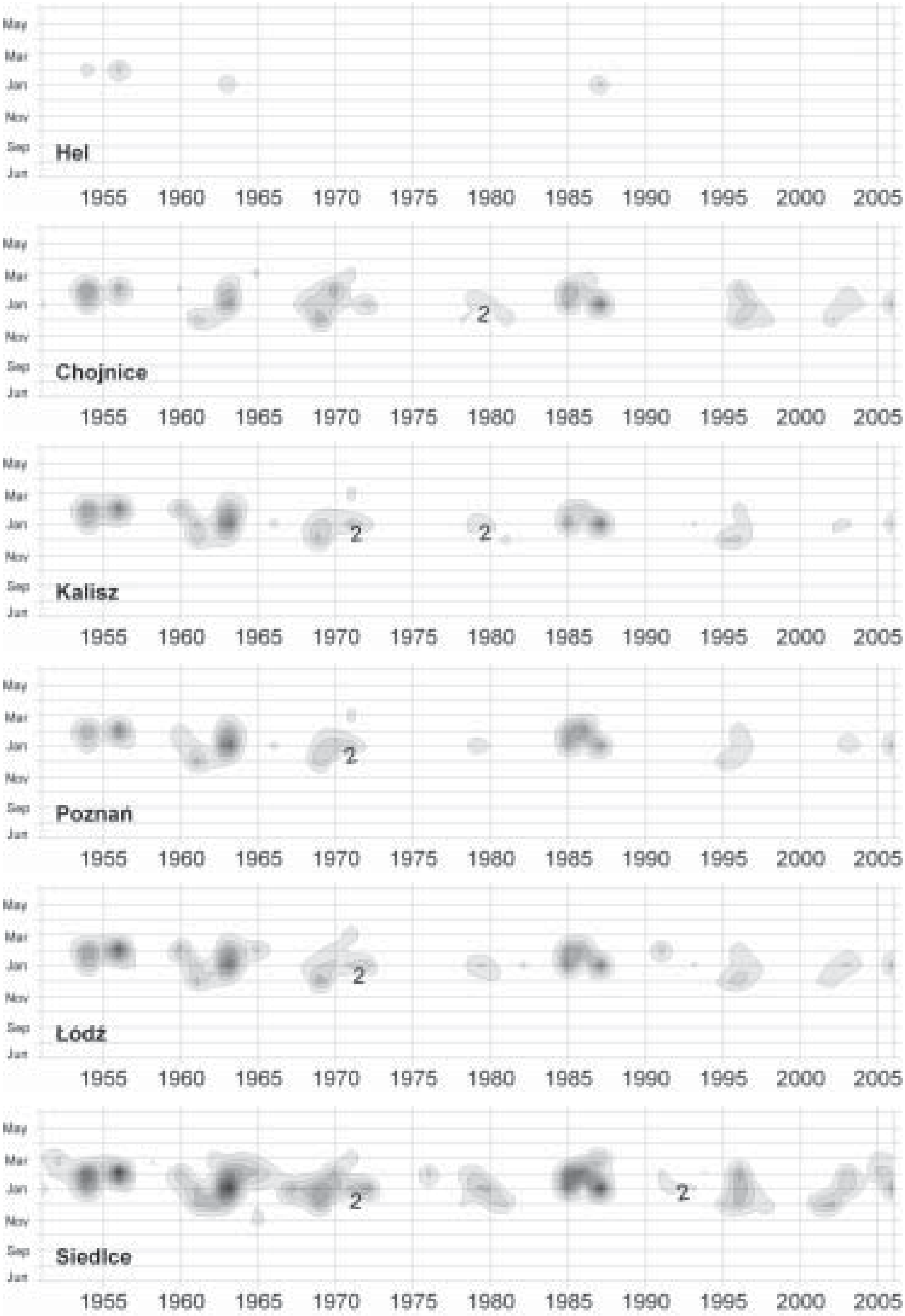


Figure 4. Long-term course for annual frequencies of days with t_{max}≤-10°C.

INFLUENCE OF CIRCULATION ON COLDWAVE OCCURRENCE

The set of days with t_{min}≤-20°C at at least one of the analysed stations was established, then mean sea level pressure (SLP) and geopotential heights at levels: 850, 700 and 500 hPa were calculated, and fields of mean anomalies of pressure and geopotential heights between selected days and all days calculated for all calendar months separately. Fig. 6 presents fields for such anomalies and mean values in the case of cold nights in January, the maps for other months being similar and so not being shown here.

Cold nights in Poland occur when there is a well-developed high pressure system over the Baltic area (Fig.6). A region of strong positive pressure anomalies lies over the North


May
Mar
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1955
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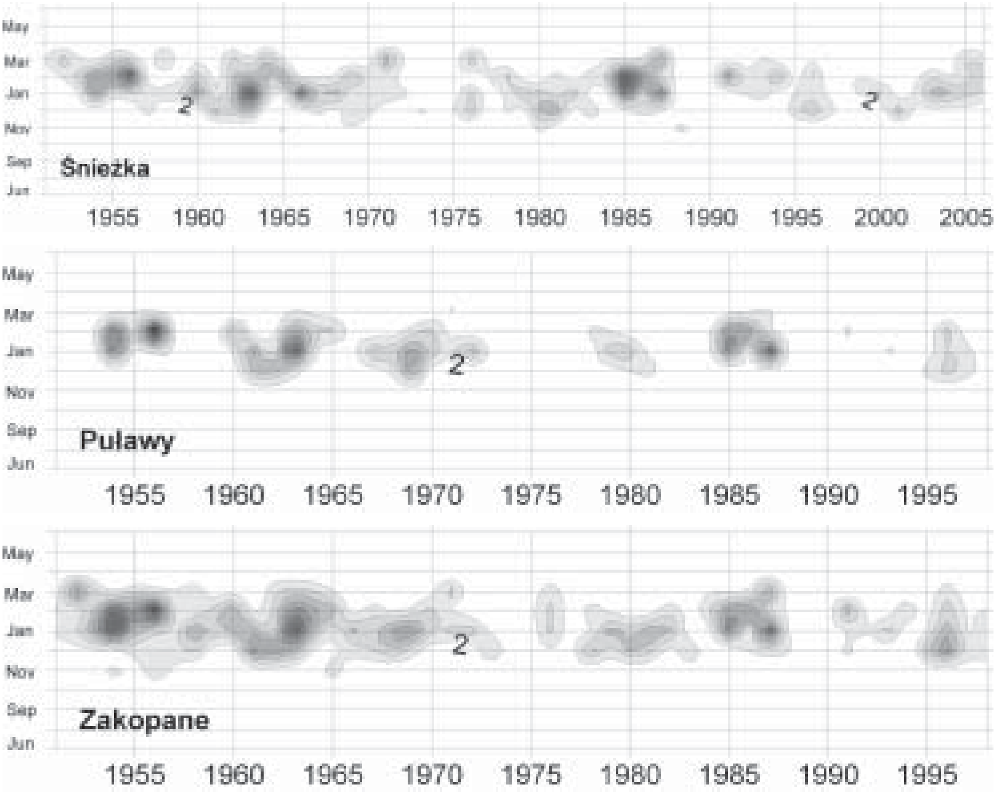

Figure 5. Long-term course for monthly frequencies of days with $t_{min} \leq -15°C$.

Atlantic between Iceland and the Scandinavian peninsula, whereas negative anomalies are located near the Azores. Such a position of SLP anomalies point to a negative phase of the North Atlantic Oscillation (NAO). Higher geopotential levels lay higher than usual over the North Atlantic and Greenland, and lower than usual over Europe, except for its northern part. A tongue of warm air stretches to the north over the eastern part of the North Atlantic and a tongue of cold air stretches to Central Europe from the north-east.

Tongues of cold and warm air can also be seen in Fig. 7, showing the thicknesses of selected geopotential levels (1000/850, 850/700 and 700/500 hPa) on selected days, and anomalies associated with them. Anomaly fields make it clear that the air is much colder over the whole of Europe, with extreme coldness over Poland, and much greater warmth over south-eastern Greenland. Such a picture confirms the temperature seesaw between western Europe and eastern Greenland described previously by many authors.

The set of 216 days with $t_{min} \leq -20°C$ in the period 1958-2005 (full range of SLP and GPT data) at at least one of the analysed stations was established together with the appropriate set of geopotential heights of 700 hPa level over an 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. The synoptic types accompanying the coldwaves in Poland were then classified using the Lund method. Four types were distinguished and more than 86% of selected days belong to one of these. The model fields are presented by Fig. 8, and the details are summarized in Table 4.

Table 4. Characteristics of types distinguished by Lund's method.

Type	date of model situation	no. of days belonging to type	% days belonging to type
1	7th February 1960	100	46.3%
2	19th January 1963	44	20.4%
3	29th January 1963	34	15.7%
4	2nd January 1963	12	5.6%

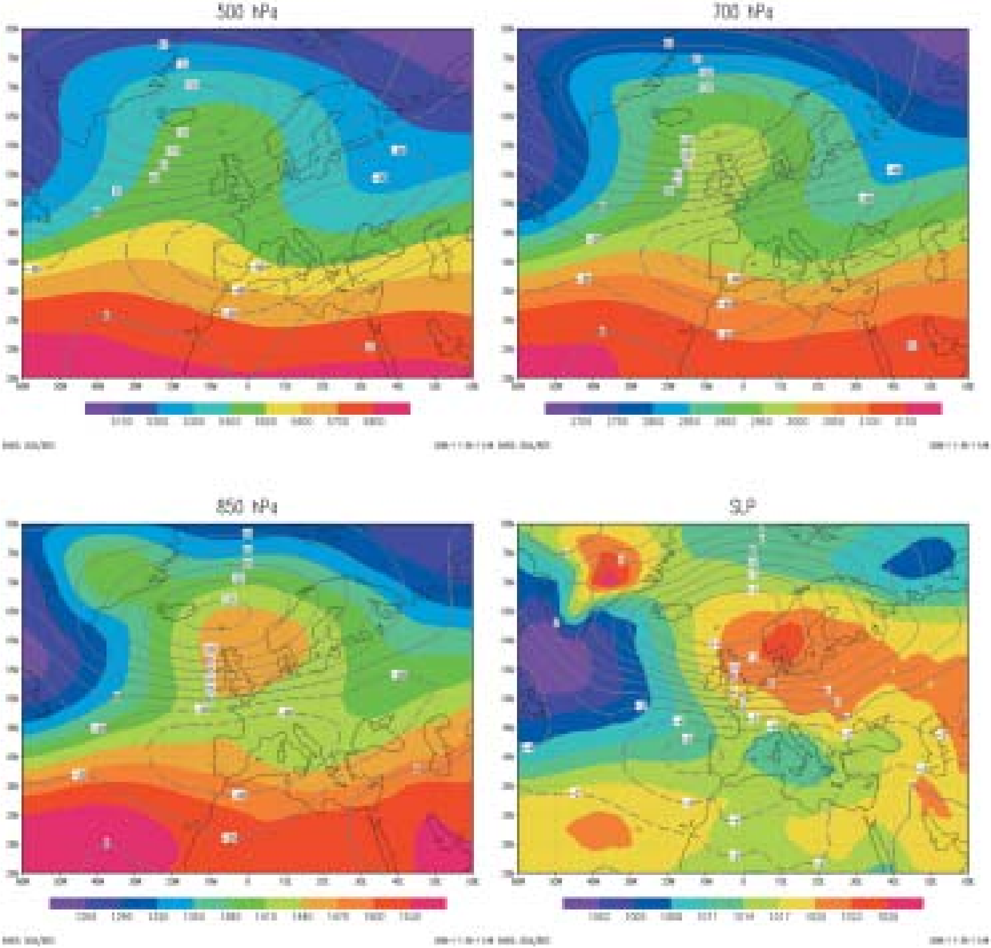

Figure 6. Mean SLP and geopotential heights at 500, 700 and 850 hPa levels in selected days (shading) and anomalies between mean values in selected and all days in given months (isolines).

The first type indicate that the 700 hPa surface lies higher over the climatological position of the Iceland Low and lower over Central Europe. It corresponds with the existence of a cold air pool over Europe and a second pool of relatively warm air over the North Atlantic. It is accompanied by the advection of cold air from the north-east. In the second type the pool of cold air is located over north-eastern Europe, whereas warm air lies over southern Europe and over the Azores. In such

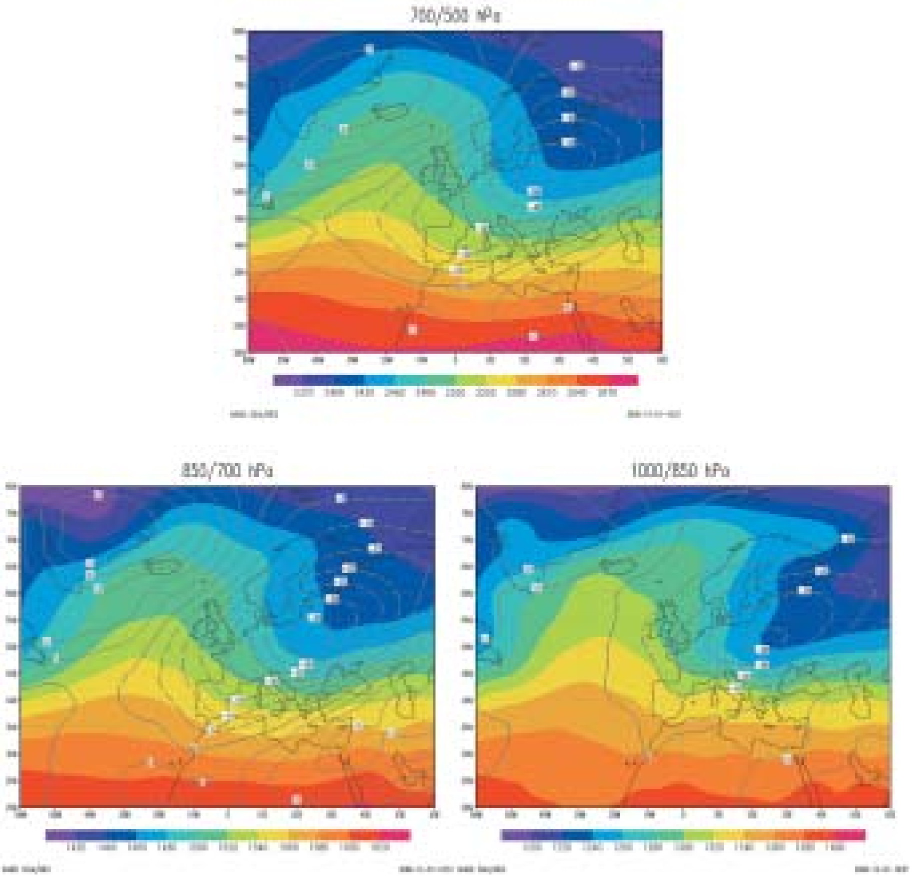

Figure 7. Mean thicknesses of 500/700, 700/850 and 850/1000 hPa levels in selected days (shading) and anomalies between mean values in selected and all days in given months (isolines).

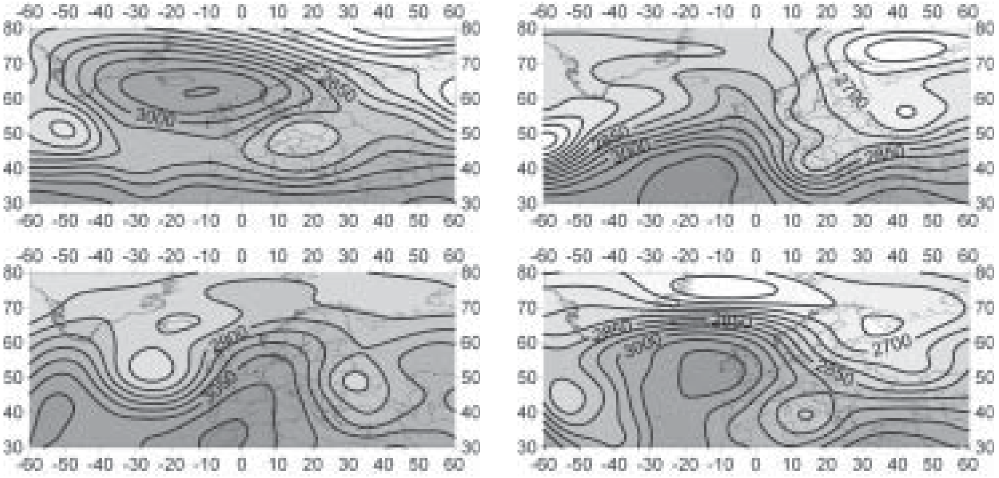

Figure 8. Characteristics of synoptic types distinguished by the Lund method at the 700 hPa level.

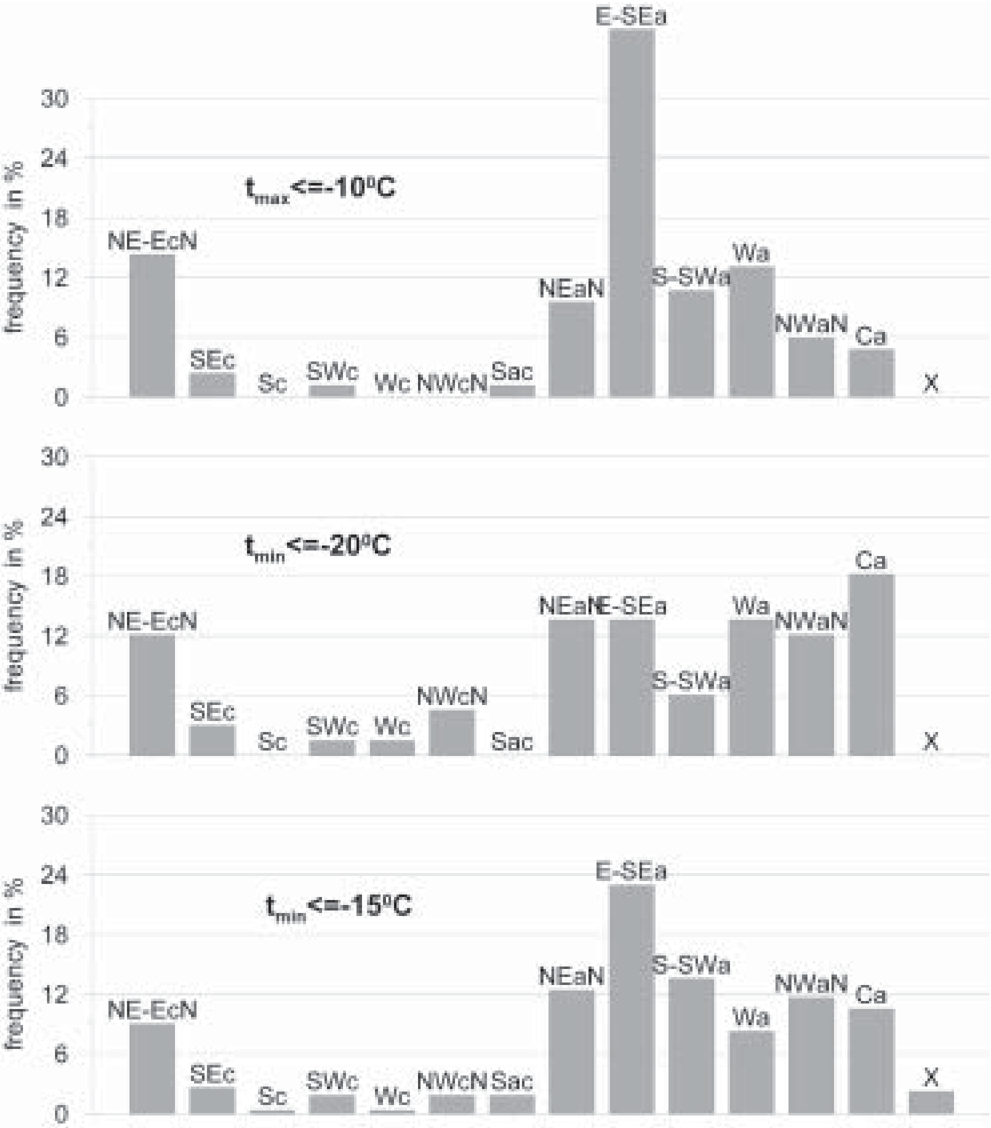

Figure 9. Distribution of synoptic types for Poland according to Piotrowski's classification in days with t_{min} ≤-10°C (upper graph), t_{max} ≤-20°C (middle graph) and t_{max} ≤-15°C (lower graph).

a situation there is an advection of cold air from just to the north of the Polish area. In the third type there are two regions of low positions of 700 hPa level. One of them is located over the central part of the North Atlantic, the second just to the south-east of Poland. Between them there is a ridge of high values of 700 hPa over Western Europe. Cold air comes to Poland from the north-west. The fourth type is slightly similar to the second. The highest values of 700 hPa level concentrate over the Atlantic to the west of the British Isles, while low values occur over the White Sea. Cold air from the north-west comes to Poland in this case.

According to the objective circulation typology from Piotrowski (Fig. 9), as based on the subjective one by Osuchowska-Klein, the very cold and cold nights and very cold days occur mainly during anticyclonic days (79.5%, 77.3% and 80.9% of cases), and during days with northeastern and eastern cyclonic circulation (9.1%, 12.1% and 14.3% of cases respectively).

SUMMARY AND DISCUSSION

Very cold days and nights and cold nights can occur in Poland from November through to March, while in the mountains they also arise in April. They are most frequent in the east and in the mountains, and rarest by the sea. The year-on-year variability in the number of coldwaves is much greater than the mean values, so the estimation of trends and their significance is extremely difficult and it is not possible to state that the apparent downward trend is significant. Kyselý (2008) has shown that persistence of circulation patterns has a strong impact on the severity of heat and cold events. Greater persistence causes the greater frequency and the greater severity of heat and cold waves.

Mean daily temperature and mean minimum and maximum temperatures in winter reveal a significant upward trend (Kożuchowski 2004; Wibig and Głowicki 2002). The extreme coldwaves display a downward trend but this is not yet significant. However, in milder winters coldwaves that do occur can exert a dramatic effect on the environment. During mild winters, trees that are not hardened are much more sensitive to moderate frost than those during a cold winter are to severe frost.

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