Landform Analysis, Vol. 10: 140–146 (2009)

Changes of thermal conditions in the Polish Tatra Mountains

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Abstract: The purpose of the report is to determine trends in thermal conditions in the Polish part of the Tatra Mountains. The study makes use of the data from the weather stations in Zakopane and on Kasprowy Wierch Mt. from the years 1951–2006, and mainly from 1966–2006. Various thermal characteristics were considered. The increase of the rate of upward trend in temperature in the Tatras at the turn of the 21st century, as well as the change of the seasonal distribution of the warming in comparison with the preceding long-term periods, have been documented. In 1966–2006, significant trends in the changes of the mean, maximum and minimum temperatures have been observed in the Tatras in summer (respectively, 0.04, 0.05 and 0.03–0.04°C per annum). Certain symptoms of increase of the thermal continentality have also been observed (increase of the annual amplitude of temperature). Besides, important features of changes in thermal conditions at the turn of the 21st century include an increase in the number of hot days, and even appearance of the very hot days at the foothills of the Tatras, increase of the number of frost days and decrease of the number of ice days in the high mountain part of the Tatras, as well as increase of accumulated heat of the growing season and an increase of daily amplitude of temperature across the entire profile of the Tatras.

Key words: thermal conditions, trend, Polish Tatra Mountains

Introduction

Air temperature constitutes an important, though not the only factor shaping climatic conditions. It exerts a significant influence on the landscape changes and defines the limit conditions of ecosystem functioning. Temperature changes, and in particular – the impact of frost – are the main physical factors contributing to weathering of rocks and influencing pedogenetic processes. Temperature influences the course of processes in living organisms, regulates rates of their development, conditions the appearance of the morpho-physiological adaptations, and has a bearing on their behaviour. The in fluence of temperature on living organisms is also indirect – through the shaping by the climatic factors of the other, abiotic ecosystem components. Although reactions of the particular species to the changes in thermal conditions differ (Wojtuń *et al*., 1995; Obrębska-Starklowa, 1999), the essential question is to estimate the scale of variability of air temperature and directions of its changes. Determination of the climate changes is particularly important with respect to mountain areas. Mountain ecosystems are, namely, very sensitive and susceptible to climate transformations (see, e.g., Messerli & Ives, 1997). Besides, the series of data from high mountain areas constitute an especially valuable material in the study of climate changes. They are not biased with local (regional) human impact, mainly appearing through the processes of urbanisation and broadly conceived changes in land use.

Materials and methods

The objective of this report is to determine trends of changes in thermal conditions in the Polish part of the Tatra Mts. The study is based on the data from the stations in Zakopane (h = 857 m a.s.l.), located in the Sub-Tatra Trough, and on Kasprowy Wierch Mt. (h = 1,991 m a.s.l.), situated in the Western Tatras. The first of them is an urban station, representing a concave landform at the foothills of the

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Tatras, while the second is the peak station, located in a depression in the main ridge. Two periods were considered in the study: 1951–2006 and 1966–2006. The first one served to estimate the general direction and rate of change in air temperature on the regional scale. This estimate used the monthly, seasonal and annual average values of air temperature from successive years. The results of studies were compared with the results of analogous analyses, carried out for the area of lowland Poland. The trend of temperature changes in lowland Poland was determined on the basis of the area-averaged time series. It was obtained by calculating the average temperature values from 45 synoptic stations situated below 300 m a.s.l. (Żmudzka, 2004a,b, 2009). In order to document the transformations of climate on the local scale more sensitive indicators were also used, such as, for instance, average extreme values of temperature, or daily and annual amplitude of temperature. The daily data: average, minimum and maximum temperatures, from the years 1966–2006, made it possible to determine the changes in the number of characteristic days and the sums of effective temperature. In the study, the sums of average daily temperatures were calculated for days with more than +5°C. These are important characteristics for the analysis of eco-climate or the processes taking place in the ground, like weathering, conservation, transformation or disappearance of the snow cover (e.g. Kłapowa, 1980; Juraszek-Wiewióra, 2005). The source data, accounted for in the study, originate from the materials published and the database of the Institute of Meteorology and Water Management. Linear trends of changes in thermal characteristics have been determined in the study. In addition, determination coefficients were calculated, indicating what portion of the temperature variance is explained by the trends identified. Further, extreme values of seasonal and annual averages of air temperature and the years of their occurrence were determined.

Results

In the area of the Tatras, an increase of the annual average air temperature was recorded in 1951–2006. It was significant at the foothills and amounted to 0.02°C per annum (Table 1). In the high mountains, the upward trend was somewhat weaker (0.01°C per annum) and was statistically insignificant. The similar rate of growth of the air temperature was stated also in other mountain areas in the central part of Europe, e.g. in the Karkonosze, in the Alps and in the Carpathian Mountains (see, e.g., Głowicki, 1998, 2000; Migała, 2005; Weber *et al*., 1997).

Moving averages 12-monthly values of the temperature (moved with the step of 1 month) changed from 3.2°C (III 1962–II 1963) to 7.2°C (II 2000–I 2001 and IV 2000–III 2001) in Zakopane, and from –2.4°C (III 1980–II 1981) to 1.2°C (IV 2000–III 2001) on Kasprowy Wierch (Fig. 1). Directional coefficient of the trend, in this case saying about the size of temperature changes per the month, means an increase temperatures in 56 years about almost of 1.2°C in Zakopane and 0.7°C on Kasprowy Wierch. It is proper to notice, that except clear growing tendency, a characteristic feature of multi-years course of temperature are over ten years fluctuations about enough large – 2–4°C – the range of hesitations (Żmudzka, *in print*).

Table 1. Directional coefficients of the trend in changes of the average values of the air temperature [°C· year^{-1}] in Zakopane and on Kasprowy Wierch Mt. and in lowland Poland in the years 1951–2006 and 1966–2006. Coefficients significant at the level of 0.05 are marked in bold (Żmudzka, 2004a, 2009)

Station/area	Months												Seasons				Year
	J	F	M	A	M	J	J	A	S	O	N	D	DJF	MAM	JJA	SON	J-D
1951–2006																	
Zakopane	0.04	0.04	0.03	0.02	**0.04**	0.01	0.02	0.02	0.00	0.02	0.00	–0.00	0.03	**0.03**	**0.02**	0.01	**0.02**
Kasprowy Wierch	0.04	0.02	0.01	0.01	0.04	0.00	0.02	0.02	-0.00	0.00	–0.01	0.01	0.03	0.02	0.02	–0.00	0.01
Lowland Poland	0.03	0.05	0.04	0.02	0.03	-0.01	0.02	0.02	0.01	0.01	–0.00	0.00	0.03	**0.03**	0.01	0.01	**0.02**
1966–2006																	
Zakopane	0.04	–0.01	–0.01	0.02	0.03	0.04	**0.05**	**0.05**	0.01	0.01	0.00	0.02	0.01	0.01	**0.04**	0.01	0.02
Kasprowy Wierch	0.04	–0.02	–0.01	0.02	0.02	0.03	0.05	0.04	0.01	0.01	0.02	0.04	0.02	0.01	**0.04**	0.01	0.02
Lowland Poland	0.06	0.03	0.01	0.05	0.03	0.01	0.05	0.04	0.02	0.02	0.00	0.02	0.03	0.03	**0.03**	0.01	0.03

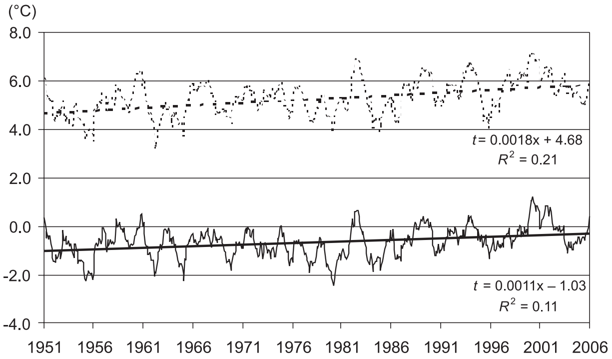

Fig. 1. Moving averages 12-monthly values of the temperature in Zakopane (- - -) and on Kasprowy Wierch Mt. (—) in the years 1951–2006 and their linear trend (based on Żmudzka, *in print*)

Temperature increase was observed in all the seasons of the year with the exception of autumn on Kasprowy Wierch Mt. The increase of temperature was the strongest in winter, and at the foothills also in spring. Yet, only the upward trends in spring and summer temperature in Zakopane were statistically significant. The scale of warming in the Tatras and its seasonal distribution is similar to the one observed in the area of lowland Poland. The basic difference consists in a stronger increase of temperature in the mountains in summer and weaker in the high mountains in the transitory seasons of the year.

Taking into consideration the period 1966–2006 one can observe that the characteristic feature of changes in thermal conditions on the entire territory of Poland was a significant increase of temperature during summer. In this period, as well, the summer warming was stronger in the Tatras than in the lowland part of Poland. In the remaining seasons of the year and on the average in the year, positive trends of air temperature changes took place, but they were not statistically significant. The increase of the average temperature in winter and in spring was somewhat weaker in the mountains than in the lowland part of Poland (0.01 and 0.03°C per annum, respectively). The more pronounced increase of the average air temperature in the warmest months of the year than in the coldest ones caused that in the period analysed the average annual amplitude insignificantly increased. The rate of this increase amounted to 0.04–0.05°C per annum. Annual course of the mean, minimum and maximum temperature in Zakopane and on Kasprowy Wierch Mt. from the years 1966–2006 is shown in Figure 2.

In 1951–2006, the year 2000 was the warmest one both in Zakopane (7.1°C) and on Kasprowy Wierch (0.8°C). Equally warm was the year 2002 (see Table 2). Among the ten warmest years in the Tatras six occurred after 1990 (1994, 1999, 2000, 2002, 2006, as well as 1998 in Zakopane and 2003 on Kasprowy Wierch Mt.). It should be noted that on Kasprowy Wierch positive annual average air temperature was recorded in all these years. Attention should to be paid to the summer seasons: as many as seven on Kasprowy Wierch and nine in Zakopane out of ten highest average air temperature values took place at

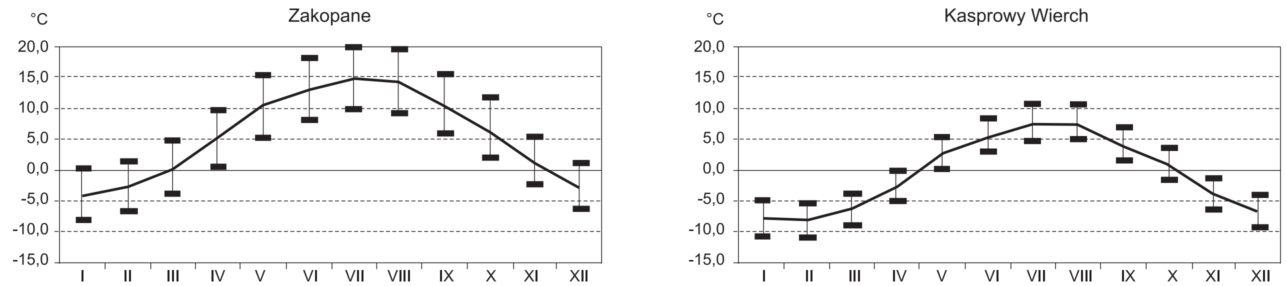

Fig. 2. Annual course of the mean, minimum and maximum temperatures in Zakopane and on Kasprowy Wierch Mt. (1966–2006)

Table 2. The lowest and highest averages of seasonal and annual temperature values and annual temperature amplitude in Zakopane and on Kasprowy Wierch Mt. (1951–2006)

Station	Value	Season				Year	Annual amplitude
		DJF	MAM	JJA	SON	J-D	
Zakopane	min	–9.2	2.0	12.1	3.7	3.5	15.9
	(year)	(1963)	(1955)	(1978)	(1956)	(1956)	(1989)
	max	0.2	7.3	16.2	9.0	7.1	28.0
	(year)	(1990)	(1983)	(1992)	(2000)	(2000)	(1956)
Kasprowy Wierch	min	–11.7	–4.9	4.3	–2.2	–2.2	12.5
	(year)	(1963)	(1987)	(1978)	(1972)	(1956)	(1989)
	max	–4.5	0.1	9.2	3.2	0.8	23.6
	(year)	(1990)	(1986)	(1992)	(1982)	(2000, 2002)	(1963)

Table 3. Directional coefficients of the trend in changes of the average values of the minimum and maximum temperatures [°C·year^{-1}] in Zakopane and on Kasprowy Wierch Mt. in the years 1966–2006. Coefficients significant at the level of 0.05 are marked in bold

Station	Tem-pera-ture	Months												Seasons				Year
		J	F	M	A	M	J	J	A	S	O	N	D	DJF	MAM	JJA	SON	J-D
Zakopane	min	0.05	–0.02	–0.01	0.00	0.01	0.03	**0.04**	**0.04**	0.00	0.00	0.00	0.02	0.01	0.00	**0.04**	0.00	0.01
	max	0.05	–0.00	–0.00	0.03	0.04	0.04	0.05	0.06	0.01	0.01	0.01	0.03	0.02	0.02	**0.05**	0.01	**0.03**
Kasprowy Wierch	min	0.04	–0.03	–0.02	0.02	0.01	0.02	0.05	0.04	0.01	0.00	0.01	0.04	0.01	0.00	**0.03**	0.01	0.01
	max	0.05	–0.01	–0.00	0.02	0.03	0.04	0.06	0.05	0.00	0.01	0.02	0.05	0.03	0.01	**0.05**	0.01	0.03

the turn of the 21st century. In this part of analysed period the lowest was number of the warmest autumns – only two in Zakopane and three on Kasprowy Wierch. The warmest autumns took place mainly in the 1960s in Zakopane and in the 1950s and 1960s on Kasprowy Wierch (Fig. 3).

The significant upward trends in summer temperature were revealed both for minimum and maximum values. The increase of the maximum temperatures was somewhat stronger than that of the minimum temperatures (Table 3). Weak and insignificant negative trends in the average extreme values of temperature were observed at the turn of the spring season – in February and March.

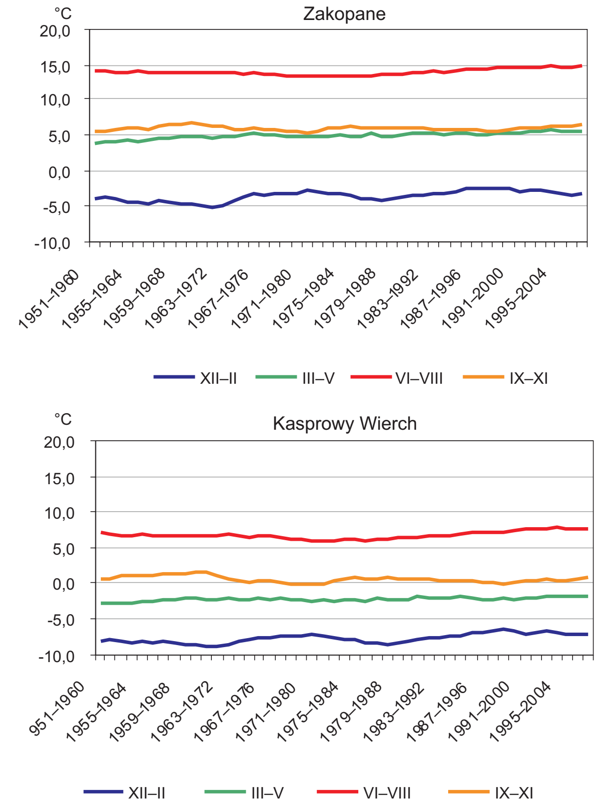

Fig. 3. 10-years moving average values of the air temperature in winter (XII–II), spring (III–V), summer (VI–VIII), autumn (IX–XI) in Zakopane and on Kasprowy Wierch Mt. in the years 1951–2006

The consequence of the stronger increase of the daily maxima than of minima was the increase in the daily amplitude of air temperature (Table 4). It appeared at both weather stations during entire year. In Zakopane, the trend of changes of average daily amplitude was significant in spring, while on Kasprowy Wierch Mt. – in summer. In both cases it amounted to 0.02°C per annum. The daily average amplitude of air temperature in Zakopane was equal 9.2°C. It ranged during the year from 7.6°C in December to 10.3°C in August (Fig. 4). The course of the averages of daily amplitude on Kasprowy Wierch was more even: from 5.1°C in April and November to 5.8°C in June – on the average in a year: 5.4°C.

Interesting observations result from the analysis of trends of changes in the numbers of characteristic days. It is worth noting that in Zakopane the most frequent were days with frost (t_{min}<0°C, t_{max}>0°C). They accounted for 28% of all days, with the maximum frequency in winter (49%, Fig. 5). On Kasprowy Wierch Mt., the most frequent were ice days (t_{max}<0°C). They accounted for 40% of days in a year. In winter this frequency raised to 86%. In the high mountain part of the Tatras neither hot days (t_{max}>25°C) nor very hot days (t_{max}>30°C) were observed. On the other hand, the very ice days (t_{min}<–10°C) did not occur only in summer (on the average they accounted for approximately 20% of days in a year).

In 1966–2006, significant increases of summer average and maximum air temperatures in Zakopane

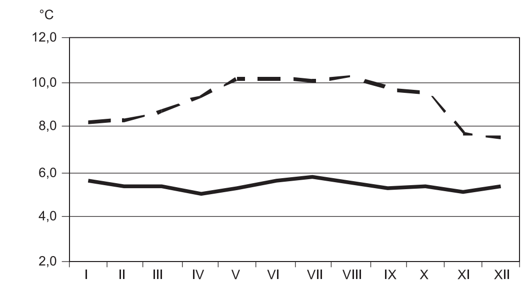

Fig. 4. Annual course of the average daily amplitude of air temperature in Zakopane (- - - -) and on Kasprowy Wierch Mt. (—) (1966–2006)

Table 4. Directional coefficients of the trend in changes of the average daily amplitude of air temperature [°C·year^{-1}] in Zakopane and on Kasprowy Wierch Mt. in the years 1966–2006. Coefficients significant at the level of 0.05 are marked in bold

Station	Months												Seasons				Year
	J	F	M	A	M	J	J	A	S	O	N	D	DJF	MAM	JJA	SON	J-D
Zakopane	0.01	0.02	0.01	0.03	0.03	0.01	0.02	0.02	0.01	0.01	0.00	0.01	0.01	**0.02**	0.01	0.01	**0.01**
Kasprowy Wierch	0.01	0.02	**0.02**	0.00	0.02	0.02	0.02	0.01	0.00	0.01	0.01	0.01	0.02	0.01	**0.02**	0.00	**0.01**

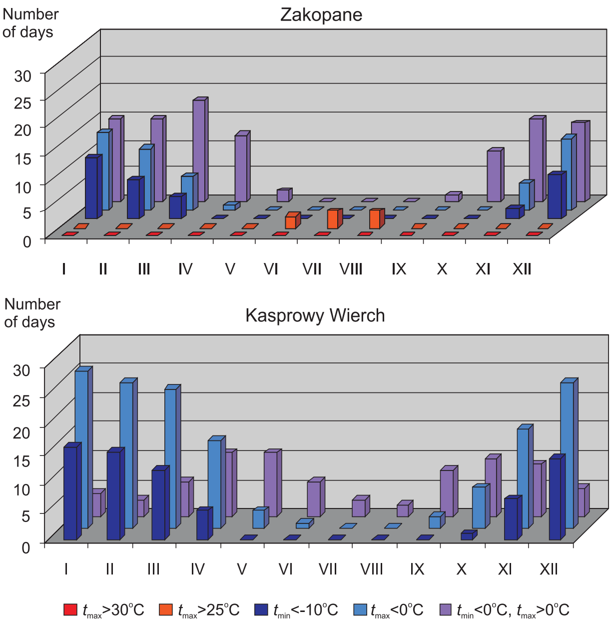

Fig. 5. The average number of characteristic days in Zakopane and on Kasprowy Wierch Mt. (1966–2000)

were accompanied by the statistically significant increases of the frequency of hot days (Table 5). In the summer 2006, there were as many as 23 such days in Zakopane. Besides, at the end of the 20th century six very hot days were observed in Zakopane, namely on 28 August 1992, 2–3 August 1998 and 19–21 August 2000.

In 1966–2006, the number of frost and very ice days decreased in Zakopane. In spring, a weak positive trend of changes in the number of ice days appeared. On the other hand, a positive trend of changes in the number of frost days, and a negative one of the number of ice days were revealed for Kasprowy Wierch. Only in summer season the number of days, during which temperature crossed 0°C decreased.

In the period considered, side by side with the shorter and milder winter seasons (in Zakopane the average air temperature in winter months in 1990 was positive, equalling 0.2°C), there was a significant increase in the accumulated heat during the growing season. The sums of the average daily temperatures exceeding the threshold of 5.0°C have been increasing at the rate of 5.8°C per annum in Zakopane and 3.4°C on Kasprowy Wierch. On the average, in 1966–2006 these sums were 1331.5°C and 320.8°C in Zakopane and Kasprowy Wierch, respectively.

Conclusions

A comparison of the obtained results with the ones based on data from earlier and shorter periods

Table 5. Directional coefficients of the trend in changes of the number of characteristic days [days· year^{-1}] in Zakopane and on Kasprowy Wierch Mt. in the years 1966–2006. Coefficients significant at the level of 0.05 are marked in bold

Days with temperature:	Months												Seasons				Year
	J	F	M	A	M	J	J	A	S	O	N	D	DJF	MAM	JJA	SON	J-D
Zakopane																	
min<0°C, max>0°C	0.08	–0.09	–0.01	–0.10	–0.02	–0.01	–	–	–0.03	–0.00	0.02	0.02	–0.02	–0.13	–0.01	–0.01	–0.14
max<0°C	–0.09	0.10	0.06	0.02	–	–	–	–	–	0.00	–0.02	–0.03	0.00	0.07	–	–0.02	0.04
min<–10°C	–0.11	0.03	–0.01	0.01	–	–	–	–	–	0.00	–0.02	–0.03	–0.06	0.00	–	–0.02	–0.13
max>25°C	–	–	–	–	0.01	0.07	**0.12**	0.08	0.00	–	–	–	–	0.01	**0.27**	0.00	**0.28**
Kasprowy Wierch																	
min<0°C, max>0°C	0.09	0.05	0.05	0.04	0.04	–0.05	–0.05	–0.01	0.05	0.00	–0.01	0.10	0.22	0.13	–0.11	0.04	0.30
max<0°C	–0.10	–0.07	–0.02	–0.05	0.00	0.00	0.00	0.00	–0.04	–0.01	–0.03	–0.09	–0.24	–0.07	0.00	–0.03	–0.41
min<–10°C	–0.01	0.11	0.06	–0.02	–0.01	–	–	–	–	0.00	0.01	–0.05	0.04	0.04	–	0.01	0.10

(see, e.g., Niedźwiedź, 2000; Trepińska, 2004) allows for formulation of a couple of conclusions. Linear trends, depending upon the period of study, indicate different kinds of changes of air temperature, both in terms of rate and direction of change. This is due to the fact that the basic form of variability of air temperature is constituted by fluctuations. Besides, linear trends, as it is known, are very sensitive to the appearance of values strongly diverging, especially when they appear at the beginning or at the end of the series analysed. Despite these methodological limitations in application of linear trends to the assessment of climate evolution, it can be stated that the characteristic feature of contemporary changes in air temperature in the Tatras is warming. It is comparable with the one observed in the lowland areas, although it is slightly weaker and statistically insignificant in the high mountain part of the Tatras. The last years of the 20th century and the first ones of the 21st century brought a slight increase in the rate of temperature increase, as well as a change in the seasonal distribution of this process. The upward trend of temperature in the winter-and-spring season, observed in the second half of the 20th century, was joined by a significant increase of temperature in summer. It should be noted that this is not a specific feature of temperature changes in mountain areas (see, e.g., Dubicka & Głowicki, 2000). It is also visible in the lowland areas of Poland (and Europe) (Schönwiese & Rapp, 1997; Kożuchowski, 2004; *Climate Change*, 2007; Żmudzka, 2009). Extension of the period of study by the first years of the 21st century resulted in an increase of the degree of thermal continentality. This is expressed through the increase in annual temperature amplitude. The results of the study show, therefore, certain symptoms of climate evolution. If these tendencies persist in the nearest years, qualitative changes may take place in functioning of ecosystems, and an evolution of the Tatra Mts. environment would ensue.

As a result of the progressing warming up moving climatic-plant floors can pursue (Kożuchowski, 1996; Migała, 2005). Probably, the dislocation the upper border will happen and strengthen the condition of the upper mountain forest. In the European mid-mountain ranges the subalpine belt (very cold) will disappear. Where it will stay a biodiversity can reduce, and some rare species of plants can entirely become extinct (Wojtuń *et al.*, 1995; Obrębska-Starklowa, 1999). The diversified reaction of individual species to changes of climate can contribute to the disintegration of contemporary ecosystems (Boer & de Groot, 1990; Nilsson & Pitt, 1991; Obrębska-Starklowa, 1999).

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