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CHANGES IN THERMAL CONDITIONS IN THE HIGH MOUNTAIN AREAS AND CONTEMPORARY WARMING IN THE CENTRAL EUROPE

Abstract. The purpose of the report is to determine trends in thermal conditions in the Polish part of the Tatra Mountains. The results of studies were compared with the results of analogous analyses, carried out for the area of lowland Poland. The study makes use of the data from the weather stations in Zakopane and on Kasprowy Wierch Mt. from the years 1951-2006, mainly from 1966-2006. The thermal conditions in lowland Poland was determined on the basis of the area-averaged time series (45 stations). Various thermal characteristics were considered. The increase of the rate of upward trend in temperature 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. Symptoms of increase of the thermal continentality have also been observed.

Key words: contemporary warming, trend, Tatra Mountains, lowland Poland.

INTRODUCTION

Big attention during last years has been paid on the climatic changes. We are establishing their rate and spatial variations and trying to answer the questions why they happen, what are the directions of the changes and what consequences they may cause in case of the environment and human beings. Rather quick increase of the air temperature in the last years was one of the purposes why scientists started to research the climate changes also to investigate the artificial influences on these changes. The IPCC (Intergovernmental Panel on Climate Change) points in its Fourth Assessment Report „Climate Change 2007" that the global warming in the period 1956-2005 was about 0,7°C. Similar air temperature increasing occurred in the lowlands of Poland (Żmudzka, 2009a).

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; Obrębska-Starklowa, 1999). 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.

THE STUDY MATERIAL AND THE METHODS

The estimate the contemporary changes in air temperature in high mountain areas of the Central Europe is based on the data from the Polish part of the Tatra Mts: on Kasprowy Wierch Mt. (h = 1991 m a.s.l.) and from the stations IMGW in Zakopane (h = 857 m a.s.l.). The first of them is the peak station, located in a depression in the main ridge of the Western Tatras, while the second is an urban station, representing a concave landform at the foothills of the Tatras (Sub-Tatra Trough).

Two periods were considered in the study: 1951-2006 and 1966-2006. The first one served to estimate the change in air temperature on the regional scale. In this case 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 thermal conditions 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 IMGW situated below 300 m a.s.l. (Żmudzka, 2009a). These series used in the analysis can give base for synthetic evaluation of direction and scale of present evolution of climatic conditions in Central Europe (Żmudzka, 2006).

In order to document the transformations of climate on the local scale more sensitive indicators were also used, such as, for instance, extreme values of temperature, or daily and annual amplitude of temperature.

The daily data: minimum and maximum temperatures, and average, from the years 1966-2006, made it possible to determine the changes in the number of characteristic days and the sums of effective temperature (daily average of temperature >5,0°C).

The general direction and tempo of the thermal conditions changes were established on the base of linear trends. The variation range of chosen characteristics is described by extreme values.

THE 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 (Żmudzka, 2009b). The similar rate of growth of the air temperature was stated also in other mountain areas in the Central Europe, e.g. in the Karkonosze and in the Alps (see, e.g., Głowicki, 1998, 2000; Migała, 2005).

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 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.

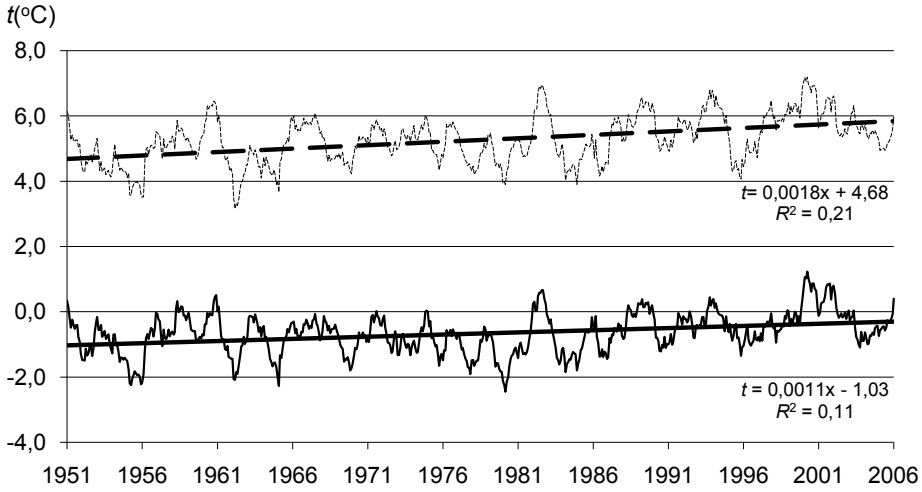


Fig. 1. Moving averages 12-monthly values of the temperature in Zakopane (--------) and on Kasprowy Wierch (——) in the years 1951-2006 and their linear trend

Warming 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 (Table 1).

Table 1. Directional coefficients of the trend in changes of the averages of seasonal and annual air temperature values [$^{o}C \cdot year^{-1}$] in Zakopane and on Kasprowy Wierch 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, 2009a, b)

1951-2006	Seasons				Year
Station/area	XII-II	III-V	VI-VIII	IX-XI	I-XII
Zakopane	0,03	**0,03**	**0,02**	0,01	**0,02**
Kasprowy Wierch	0,03	0,02	0,02	-0,00	0,01
Lowland Poland	0,03	**0,03**	0,01	0,01	**0,02**

1966-2006	Seasons				Year
Station/ area	XII-II	III-V	VI-VIII	IX-XI	I-XII
Zakopane	0,01	0,01	**0,04**	0,01	0,02
Kasprowy Wierch	0,02	0,01	**0,04**	0,01	0,02
Lowland Poland	0,03	0,03	**0,03**	0,01	0,03

Stronger increase of the temperature in spring in comparison to autumn caused the ascending trend of changes (~0,02°C per annum) in the difference between the temperature in mentioned seasons. The spring in Tatra Mountains is mostly cooler than autumn. The average difference in temperature between spring and autumn in Zakopane was –1,1°C and on Kasprowy Wierch –2,8°C.

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 (Żmudzka, 2009b). Positive trend of changes in the difference between the air temperature average in the transitory seasons of the year was slightly weaker than in the whole 56 years period. The increase of annual amplitude and lower

difference between average temperature in spring and in autumn indicate the increase of the thermal continentality.

In 1951-2006, the year 2000 was the warmest in the Tatra Mountains and in Poland. The annual average air temperature in Zakopane was equal 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 (Żmudzka, 2009b).

Table 2. The lowest and the highest averages of seasonal and annual temperature values and annual temperature amplitude in Zakopane and on Kasprowy Wierch (1951-2006) (Żmudzka, 2009b)

Station	Value	Season				Year	Annual amplitude
		XII-II	III-V	VI-VIII	IX-XI	I-XII	
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)

The annual average air temperature from lowland Poland overrun however in four times the value of 9°C what happened in 2000 (9,5°C), 1989 (9,2°C), and 1990 and 2002 years (9,1°C) (Żmudzka, 2009a), and that were the highest values of temperature from the beginning of the past century.

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 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 (Żmudzka, 2009b).

The significant upward trends in summer temperature were revealed both for minimum and maximum values. The increase of the maximum temperatures was stronger (0,05°C per annum) than that of the minimum temperatures (0,03°C on Kasprowy Wierch i 0,04°C per annum in Zakopane).

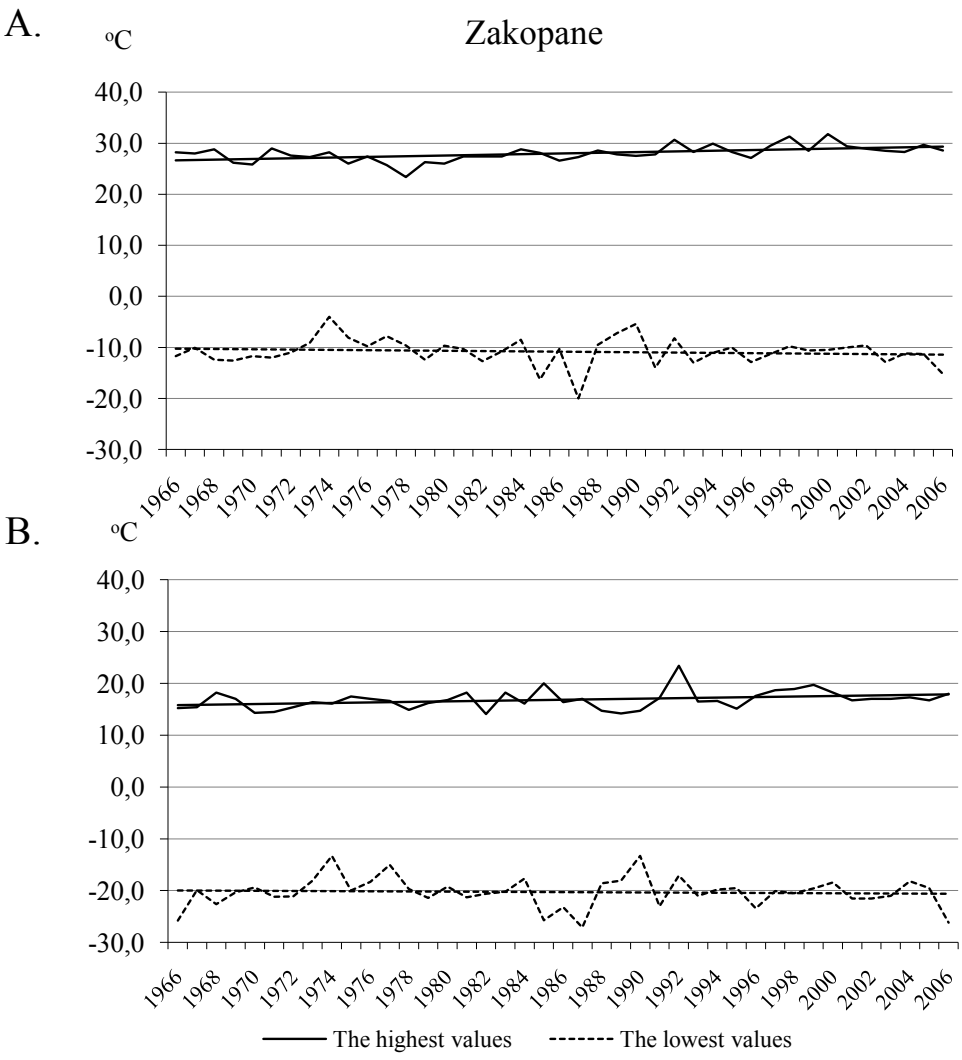
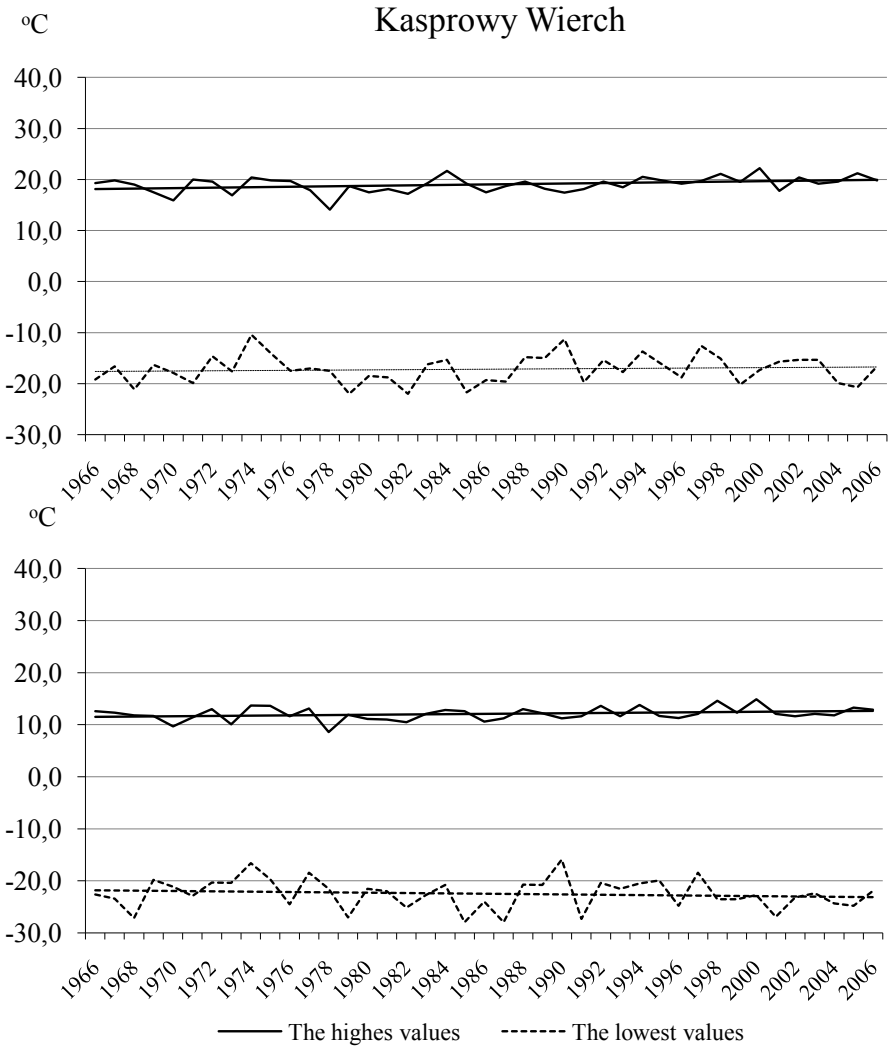


Fig. 2. Maximum (A) and minimum (B) air temperature in Zakopane and on Kasprowy Wierch in the years 1966-2006 and their linear trend

The maximum temperature was rising in average by 0,03°C per annum and minimal by 0,01°C. The positive trend of the changes in the highest maximum temperature values was also significant in Zakopane (Fig. 2). The rate of temperature changes was 0,07°C per annum in Zakopane and 0,05°C on Kasprowy Wierch (see Table 3).

The consequence of the stronger increase of the daily maxima than of minima was the increase in the daily amplitude of air temperature. It ap-



peared 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. 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 (Żmudzka, 2009b).

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

Station	Zakopane	Kasprowy Wierch	Zakopane	Kasprowy Wierch
Temperature	maximum		minimum	
Average	**0,03**	0,03	0,01	0,01
The highest	**0,07**	0,05	0,05	0,03
The lowest	-0,03	0,02	-0,02	-0,03

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%). 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) (Żmudzka, 2009b).

Significant increases of summer average and maximum air temperatures in Zakopane were accompanied by the increases of the frequency of hot days. Number of this days have been increasing at the rate of 0.27 day per annum (Fig. 3). 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 (0.14 and 0.13 day per annum, respectively). In spring, a weak positive trend of changes in the number of ice days appeared (0.07 day per annum). 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 (0.30 and -0.41 day per annum, respectively). Only in summer season the number of days, during which temperature crossed 0°C decreased.

The characteristic feature of the period considered was the shorter and milder winter seasons. For example, in 1990 in Zakopane the average air temperature in winter months was positive, equalling 0.2°C. Warm, "coreless" winters are mostly regarded as the manifestation of contemporary warming and occur as seasons when the snow cover is very impermanent or even absent. The significant increase in the accumulated heat during the growing season was common during last years which is evidenced by a positive trend of the sums of the average daily temperatures exceeding the threshold of 5.0°C. In 1966-2006, these sums increased at the rate of 5.8°C per annum in Zakopane and 3.4°C on Kasprowy Wierch. Unusual small sums occurred in

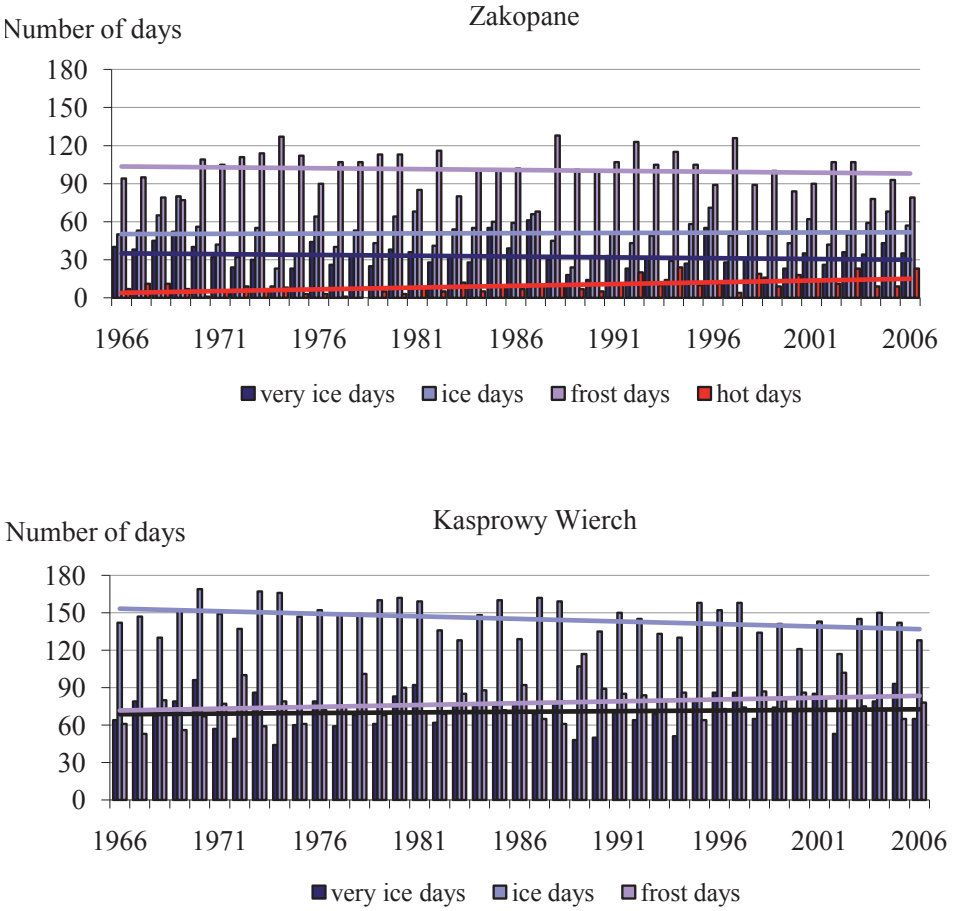


Fig. 3. Multi-years course of the number of characteristic days in Zakopane and on Kasprowy Wierch in the years 1966-2006

Tatra Mountains in 1978 when it was only 978,0 °C in Zakopane and 134,1°C on Kasprowy Wierch (Fig. 4). Extremely high sums of effective temperature were affirmed at the turn of the 21st century. The sum were higher than 1500°C in four years (1999, 2002, 2003, 2006) in Zakopane and once (2000) exceeded even 1600°C. Mentioned years and two others, 1992 and 1994, distinguish themselves in unusual high sums of temperature (more than 400°C) on Kasprowy Wierch. The year of 2003, when the sum exceeded 500°C, was in this regard very extreme. On the average, in 1966-2006 these sums were 1331.5°C and 320.8°C in Zakopane and Kasprowy Wierch, respectively (Żmudzka, 2009b). Different authors studies show, that growing shorter of the winter season as well as the growth of supplies of warmth in vegetative period is the characteristic feature of present changes of thermal conditions

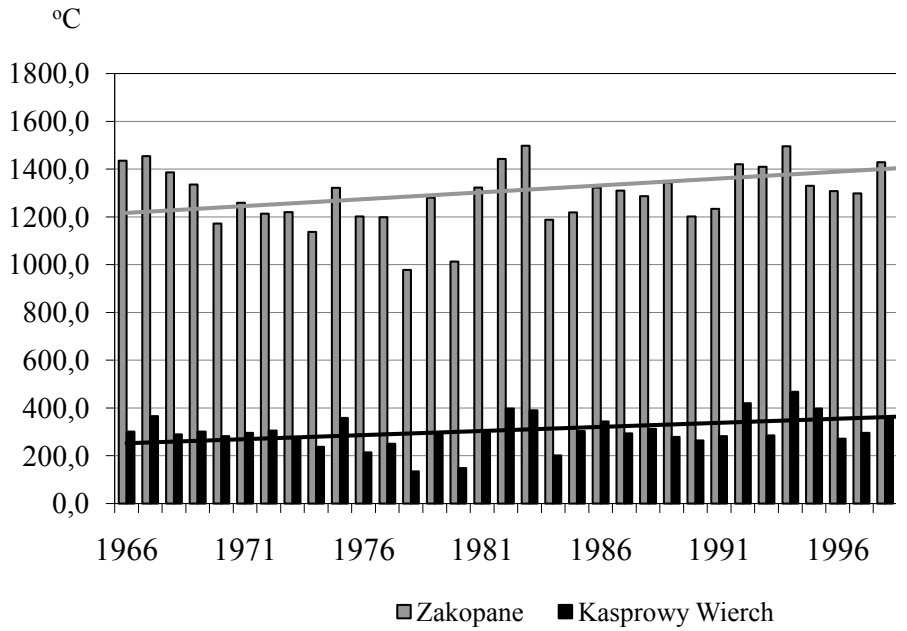


Fig. 4. Multi-years course of the sums of the effective temperature (average daily temperatures >5°C) in Zakopane (——) and on Kasprowy Wierch (▬▬) in the years 1966-2006

also in different high mountain areas and the lowland part of central Europe (Dubicka, Głowicki, 2000; Kożuchowski, 2004).

CONCLUSIONS

The contemporary warming in the Tatra Mountains is comparable to that observed in the European high mountain regions and similar to the one on lowland areas. This warming is slightly weaker and statistically insignificant in the high mountain parts of the Tatra Mountains comparing to that in the lowlands of Poland.

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. These feature also visible in the lowland areas (Schönwiese, Rapp, 1997; Kożuchowski, 2004; *Climate Change*, 2007; Żmudzka, 2009a). The similar rate of the air temperature growth and the similar seasonal distribution of the warming in the Tatra Mountains and in many areas of central Europe may suggest the reasons of this process are much more general.

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. 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.

The results of the study of the multi-years variability of the air temperature in the Central Europe show, therefore, certain symptoms of changes in climate evolution at the turn of the 21st century in comparison with the preceding long-term periods (np. Lorenc, 1994; Niedźwiedź, 2000; Kożuchowski, Żmudzka, 2001; Wibig, Głowicki, 2002; Trepińska, 2004; Żmudzka, 2004a, b). The open problem is the answer for the question if we will still be observing the increase of the air temperature or maybe the contemporary warming will be stopped.

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