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THE LITTLE ICE AGE IN THE HIGH TATRA MOUNTAINS

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Abstract

Climate deterioration of the Little Ice Age was manifested in the most spectacular way in the glaciated high mountains, but it should also be analysed in term of a climatic concept. Spatial variation in LIA climate is illustrated also in non-glaciated areas of the Northern Hemisphere in a broader contex. Extreme climatic events were forcing factors for mountain slope deformation by geomorphic processes in the High Tatra Mountains. The old chronicles, lichenometric dating of landforms and lacustrine sediments are used to determine the beginning of "Little Ice Age – type events" (about AD 1400) and its end (about AD 1920). During this time span the set of climatic conditions responsible for triggering high-energy geomorphic processes was recognised. The catastrophic hydrometeorological events were concentrated in certain periods. Clustering of weather anomalies and natural disasters resulting from them are discussed in the paper.

Key words: geomorphic events, climate change, landform evolution, Tatra Mountains

INTRODUCTION

After the warmest phase of the Holocene, *i.e.* after the period known as Medieval Warm Period (AD 800–1200), deterioration of climate and reactivation of glaciers took place in many mountains of the world. It has been claimed that oscillations of glaciers in recent centuries were the largest during the last 5 thousand years or even the largest since the end of the Pleistocene at least in certain regions. The period of significant advances of glaciers in the late Holocene is termed the Neoglacial period, and its latest episode, which is characterised by the most extensive glacier activity, has been called the Little Ice Age (LIA). Climate deterioration of the LIA resulted in development of new forms of glacial origin and in deposition of mineral and organic sediments. Maximum extents of glacier advances in the high mountains of the northern hemisphere occurred between AD 1600 and 1850. Several concepts refer to the duration of the LIA. The onset of the climate deterioration, to which the glaciers responded, was not simultaneous. Therefore, the initiation of the LIA, derived from definite advances of glaciers, is defined differently, depending on a mountain massif where glaciological studies have been carried out. Lowell (2000), who accepted AD 1200, gives the earliest date. Other alpine researchers used to define three advances of mountain glaciers during the last 750 years, namely in: 1300–1380, 1570–1640 and 1810–1850 AD (Wanner *et al.* 2000). The International Symposium in Tokyo of 1992, devoted to the climate of the Little Ice Age, made glaciologists aware of a significant disagreement in determining the onset and the end of this period. Porter (1986) demonstrated that the LIA started after the Medieval warming, *i.e.* since AD 1250 and lasted to *ca.* AD 1920, while Lamb (1969, 1977) assigns the LIA to the years of 1550–1850 with the main phase in 1550–1700. The participants of the Symposium mentioned above, split themselves into two groups: the first one which accepted the LIA duration from 1275±60 to 1850±50 years and the second group which claimed the LIA beginning from AD 1510±50. On the other hand, the end of the LIA is not disputable and AD 1850±50 has been accepted (Grove 1988, Bradley, Jones 1992). Determination of the LIA duration does not denote that it was a single cooling episode. Historical evidences gathered in various European countries allow concluding that cooler and warmer periods were not simultaneous in the northern hemisphere. Nevertheless, several cold episodes, lasting even up to 30 years, which were synchronous on a global scale, can be identified. These were: AD 1590–1610, 1690–1710, 1800–1810, and 1880–1900. It is much more difficult to distinguish synchronous warm periods (in the 1650s, 1730s, 1820s, 1930s and 1940s – Bradley, Jones 1992). The time spans of definite cooling on the global scale, resulting from changes in solar radiation, did not always lead to increase in glacier mass gain. During the last millennium, three clear solar radiation minima occurred. They are known as: Maunder minimum (1645–1715), Spörer minimum (*ca.* AD 1500) and Wolf minimum (*ca.* AD 1200–1300). According to Wanner *et al.* (1995, fide Lockwood 2001), in the second half of the Maunder minimum, despite the distinct cooling, no significant increase of alpine glacier masses has been stated, as it was a dry period with a relatively small snowfall. For this reason, it has been accepted that in glaciological reconstruction a simultaneous analysis of thermal and humidity conditions is necessary.

Van Geel and Renssen (1998) assigned the LIA to global, abrupt climate oscillations on the Holocene scale. It is believed that such fluctuations have been related to the North

Atlantic Oscillation (NAO), and the advances of the monitored glaciers in the Alps (Aletsch and in the Grindelwald valley) were related to the course of temperature and precipitation during winter and summer seasons. However, the climate oscillations associated with NAO are overlapped by temperature and humidity variations related to volcano eruptions in the tropics. Huge volcanic eruptions were always followed by several-year-long thermal and precipitation anomalies. The facts of very cold summer seasons and "normal" winter temperatures were observed after eruptions of the volcanoes: Tambora in 1815, Cracatau in 1883, Santa Maria in Guatemala in 1902. These facts have been documented by Briffa *et al.* (1998), Wanner *et al.* (2000) and Zielinski (2000).

Although the climate deterioration of the LIA manifested itself in the most spectacular way in the glaciated high mountains, its results affected vast areas of the whole globe. It brought about significant changes in the environment and worsened living conditions of societies. The catastrophic hydrometeorological phenomena, such as intensive downpours or continuous rains, floods, hurricanes, low temperatures of summer seasons, degraded cereal yields and threatened human lives in Europe and in other continents. Therefore, the ongoing studies aiming at the reconstruction of environmental events of the LIA in non-glaciated areas are carried out in the frames of palaeogeography, palaeohydrology and palaeoclimatology, dendrochronology and other natural sciences. Historical chronicles, descriptions of catastrophic events, and the later direct measurements of climatic parameters are important sources of information about this period. A fundamental conclusion which comes out of the multi-year studies on the changes of natural environment during the last thousand years lead to the following fundamental conclusion. The term Little Ice Age should be used thoughtfully, so its meaning and duration must be always explained. Glaciological criterion cannot be a precise measure of the LIA. Jones and Bradley (1992) in their monumental work entitled *Climate Since A.D. 1500*, published in 1992, summarized the results of the studies on climatic changes of the globe. The finding that during 500 years a singular documented climate cooling did not occur is one of the most important conclusions. There were cooler and warmer episodes, but in the global scale in this time interval one can distinguish only 6 simultaneous cooling periods (1590–1610, 1690–1710, 1800–1810, 1880–1900). The periods of simultaneous warming occurred only 4 times (in the 1650s, 1730s, 1820s, 1930s and 1940s). It denoted that the periods of climatic anomalies occurred in different times in different parts of Europe and the world. Matthes and Briffa (2005) propose term "Little Ice Age-type events" for clarification in terminology of the characteristics of the LIA in the light of climatic concept. There is no one-to-one agreement between the glaciological and the climatic concepts of a "Little Ice Age". Conclusion coming from this concept says that "we need to concentrate and increase knowledge and understanding of climatic variability and of spatial variation in the Earth-atmosphere-ocean-system". Therefore, the reconstructions of climatic, hydrological and geomorphologic events need to be related to regional events. This last finding substantiates a need for more detailed studies on the LIA in the Tatras.

CHANGES IN THE TATRIC ENVIRONMENT

In the mountain areas without glaciers in the Holocene, the non-glaciological criteria are to be used to define the onset and the end of LIA. The response time of large alpine glaciers to climatic changes lasted a few or even several decades, until the glaciers reached a new mass balance (Haeberli, Hoezle 1995). The aim of this paper is framed in the following questions: how did the natural environment of the Tatras, the highest and the northernmost non-glaciated mountain massif of the Carpathian arc, react to the climate deterioration of the LIA? In which period and in which way did this deterioration manifested itself most spectacularly? The answer to these questions is difficult, as Man was not a permanent resident of the Tatras, as it was the case of the Alps. During the last 600 years Man lived in the Tatras only sporadically, thus he did not documented the changes undergoing in the high mountain environment as it was done by the Alps inhabitants. In spite of that, there are historical documents allowing at least a partial answering the above questions (Generisch 1807). A real, scientific examination of the Tatras started at the turn of the 18th and 19th centuries, when the mountains became the field of interest of many local researchers and European scientists (*i.e.* Baltazar Hacquet and Robert Townson). Among the published works on the nature of the Tatras, the contribution by Christian Generisch, entitled *Reise in die Carpathen mit vorzüglicher Rucksicht auf das Tatra-Gebirge*, published in 1807, deserves a special attention. The main advantage is the chapter entitled *Meteorologische Ansicht*, which comprises all the information about the weather anomalies, *i.e.* on catastrophic precipitation and floods in the Tatras and in their foreland since the beginning of the 14th century, as available from archives and chronicles.

The turn of the 18th and 19th centuries can be identified as the beginning of systematic scientific studies. The notes about weather conditions were taken by Townson in 1793, Staszic in 1802–1805, Wahlenberg in 1813, Kořistka in 1860, while summary of their activity is given by Gustawicz (1883) and Szaflarski (1972). A chronicle of Zakopane parish for 1848–1890 by Józef Stolarczyk (Stolarczyk 1915) is a very valuable source of information about weather in the Polish Tatras and Podhale.

The available information on floods and continuous precipitation, accompanied by catastrophic short storms often changing into snowfalls in summer season, are compiled in Fig. 1. These are data records from narrative sources, *i.e.* annals, chronicles, memoirs and descriptions of travels and trips to the Tatras and the surrounding valleys.

The largest numbers of weather anomalies were registered in AD 1850–1900. In this period 29% of all the events, which have been described in the chronicles and other written documentaries for the last 400 years, took place. The second outstanding period is the time span of AD 1700–1750 (16%). The "calmest" period comprises 1750–1800 (2.7%). The differences between particular periods are very pronounced. They point to differentiation of climate during the LIA in the Tatra foreland. The historical documentaries do not allow for defining when LIA started in the Tatra interior.

Figure 1 shows the catastrophic floods and precipitation in the Tatras and at their foreland in 1600–2001 (years

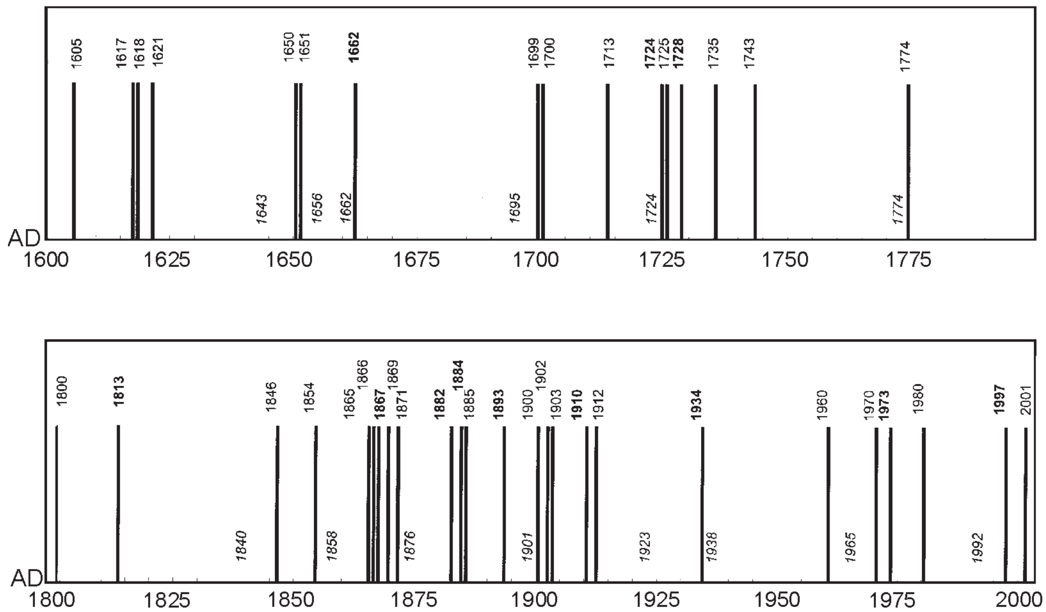

Fig. 1. Catastrophic floods and rainfalls (AD years above) and earthquakes (AD years at the bottom) in the Tatra Mountains and on the foreland from AD. 1600 to 2001 according to old documents and chronicles on the Polish and Slovak side.

marked in the upper part of figure) and the earthquakes marked in italics on the time axis (at the bottom). The figure refers to the both slopes of the Tatras.

There is a clear coincidence between catastrophic precipitation, rockfalls and earthquakes. The old chronicles often point to the earthquakes as a consequence of extreme precipitation. Rockfalls are caused by several triggers: climatic conditions (temperature, precipitation) controlling physical weathering (loosening of a rock massif), while the factor which initiates the fall is the earthquake and intensive precipitation infiltrating into the loosened rocks. These observations are confirmed by descriptions of extreme events in the Tatras. One of the largest natural catastrophes occurred in 1662. Due to the earthquake and the catastrophic precipitation in the Tatras, the summit dome collapsed and Slavkovský summit in the Slovak High Tatras has been lowered (Paryscy 1995).

The reconstruction of natural processes in the Tatras, before Man entered this region, can be done by studying the forms of relief of the slopes and valley floors formed in the earlier phases of the LIA. Absolute age of the Tatric forms has been determined by lichenometry, dendrochronology, ^{14}C dating of organic deposits and ^{210}Pb dating of mineral lacustrine deposits of the last 150 year time span.

Inferring from the lacustrine deposits of Morskie Oko and Zielony Staw Kieżmarski lakes, it has been accepted that the large frequency of high-energy rapid mass movements, characteristic of the LIA, started in the Tatras *ca.* AD 1400 and ended *ca.* AD 1860 (Kotarba 1995), yet the structures typical of this period are more numerous in the younger deposits originating from the two decades of the 20th century. Based on the above, one can accept that the rhythm of geomorphologic events of the LIA in the Tatras lasted until around AD 1925. The dates 1400–1925 can be accepted as the beginning and the ending of the LIA in the Tatras (Kotarba 2004). The beginning of the LIA in the Tatras, derived from the hillslope process recorded in lacustrine deposits of Morskie Oko lake, is additionally confirmed by secular tendencies in climatic changes in the last millennium complied using the indices of thermal and humidity conditions of Poland given by Maruszczak (1991). The 50-year mean air temperatures in the middle Poland, determined by the instrumental measurements and by extrapolation, show two minima. The first minimum, identified as the 1st phase of cooling of the LIA was *ca.* AD 1400. Earlier, Lamb (1969) showed that the 15th century was as cold as the 17th and 18th centuries. He assigned the beginning of LIA to *ca*. AD 1400.

Assuming the summer temperature variability as a criterion for defining the beginning of the LIA, it is reasonable to accept the cooling by the end of the 16th century (1576 – Niedźwiedź 2004). There is also an analogy between the climate instability in the northern hemisphere and in the Tatras. The rhythm of the mean annual temperature in Iceland, given by Bergthórsson (1985), characteristic of the LIA, lasted until 1920. Moreover, the mean annual temperatures of the northern hemisphere compiled for the 19th and 20th centuries by Mann *et al.* (2000), and presented by Bradley *et al.* (2003) explicitly illustrate the continuation of the thermal rhythm of the LIA until 1925.

The period of increased lacustrine sedimentation rate in 1905–1910 is well correlated with the phase of debris flow activity, indicated by lichenometric dating of debris flow tracks. In the time span of the last 200 years, the period 1901–1925 manifested itself by a large percent of debris flows (above 20%).

EXTREME HYDROMETEOROLOGICAL EVENTS AND DEBRIS FLOWS IN THE HIGH TATRAS

Time intervals in which extreme precipitation events occurred, *i.e.* particularly intensive precipitation leading to in-

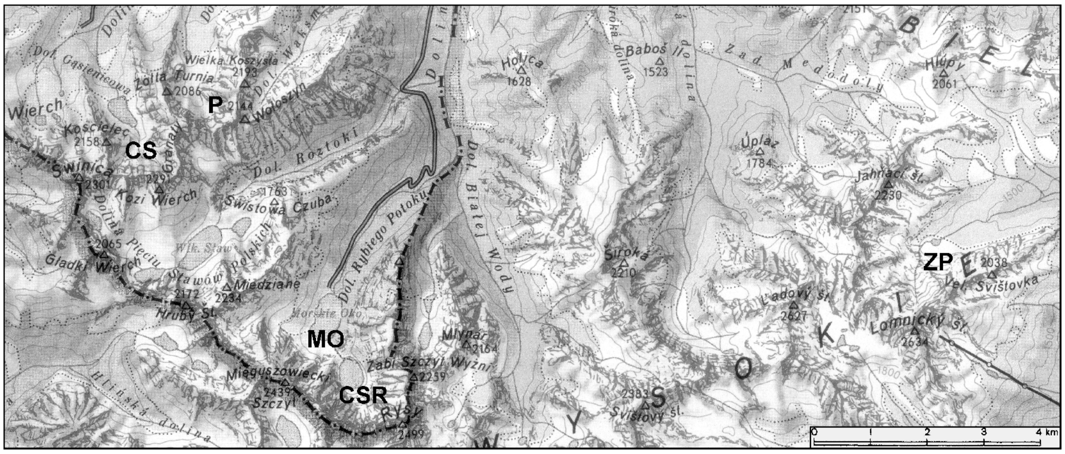

Fig. 2. Location of the test areas in the High Tatra Mountains; CS – Czarny Staw Gąsienicowy Lake, P – Pańszczyca valley, MO – Morskie Oko Lake, CSR – Czarny Staw pod Rysami Lake, ZP – Zielony Staw Kieżmarski (Zelene pleso) Lake.

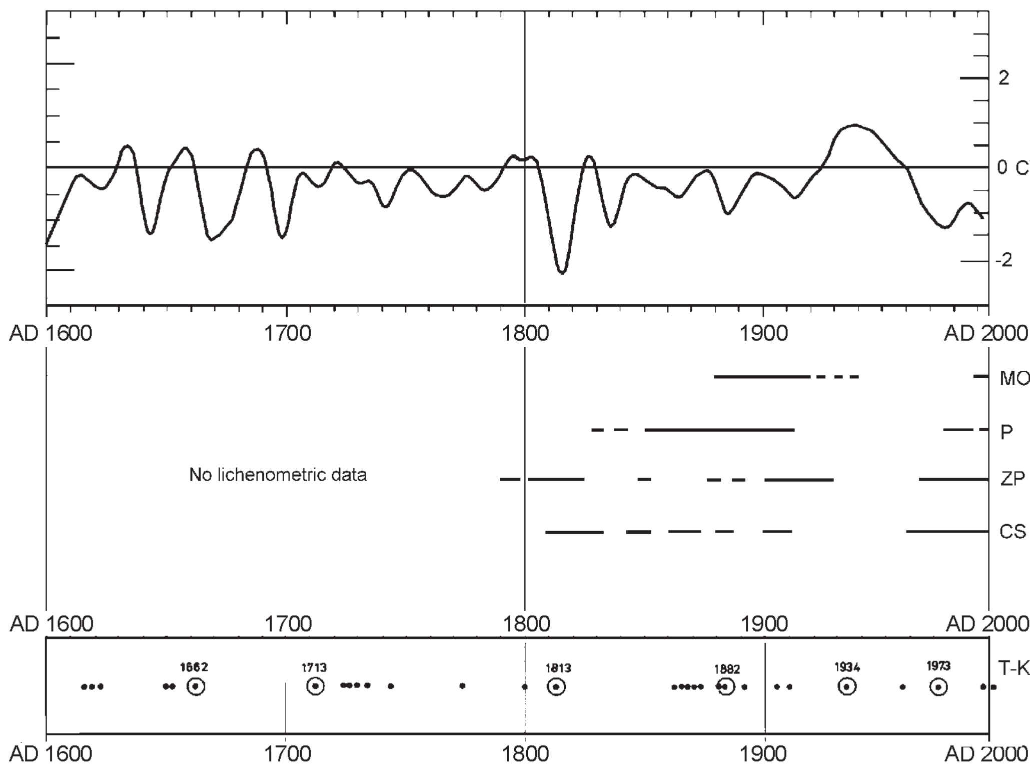

Fig. 3. Catastrophic floods and rainfalls in the Tatra Mountains and adjacent basins according to historical notes and documentaries (T-K), debris flows inside the High Tatra Mountains – Morskie Oko valley (MO); Pańszczyca valley (P); Zielony Staw Kieżmarski valley (ZP) and Czarny Staw Gąsienicowy Valley (CS). Periods of debris flow activity are based on lichenometric dating for the last 200 years; CV – hemispheric cooling based on normalized mean tree ring density anomaly of the northern boreal forest (Briffa 2000, Briffa *et al.* 1998).

tensified formation of debris flows, have been determined. The analyses of this type have been performed for the surroundings of Morskie Oko lake (MO), the Pańszczyca valley (P), the vicinity of Czarny Staw Gąsienicowy lake (CS), Zielony Staw Kieżmarski - Zelene pleso (ZP) (Figs 2, 3). In general, it can be accepted, that the entire 19th century was characterised by high slope dynamics, although it is not evidenced in all the valleys. The steeper and the shorter the slopes, the worse are the possibilities to preserve the older surfaces. The period of the 19th century intensified debris flows lasted until the 1930s. Then, a calmer period occurred which prolonged itself until the beginning of the 1970s. During the recent 30 years, next extreme geomorphologic events of an increased frequency caused by heavy downpours are observed.

The debris flows in the final phase of the LIA were much larger (10–20 m wide) than the contemporary tracks (Fig. 4), and had a high percentage of blocks whose maximum axes

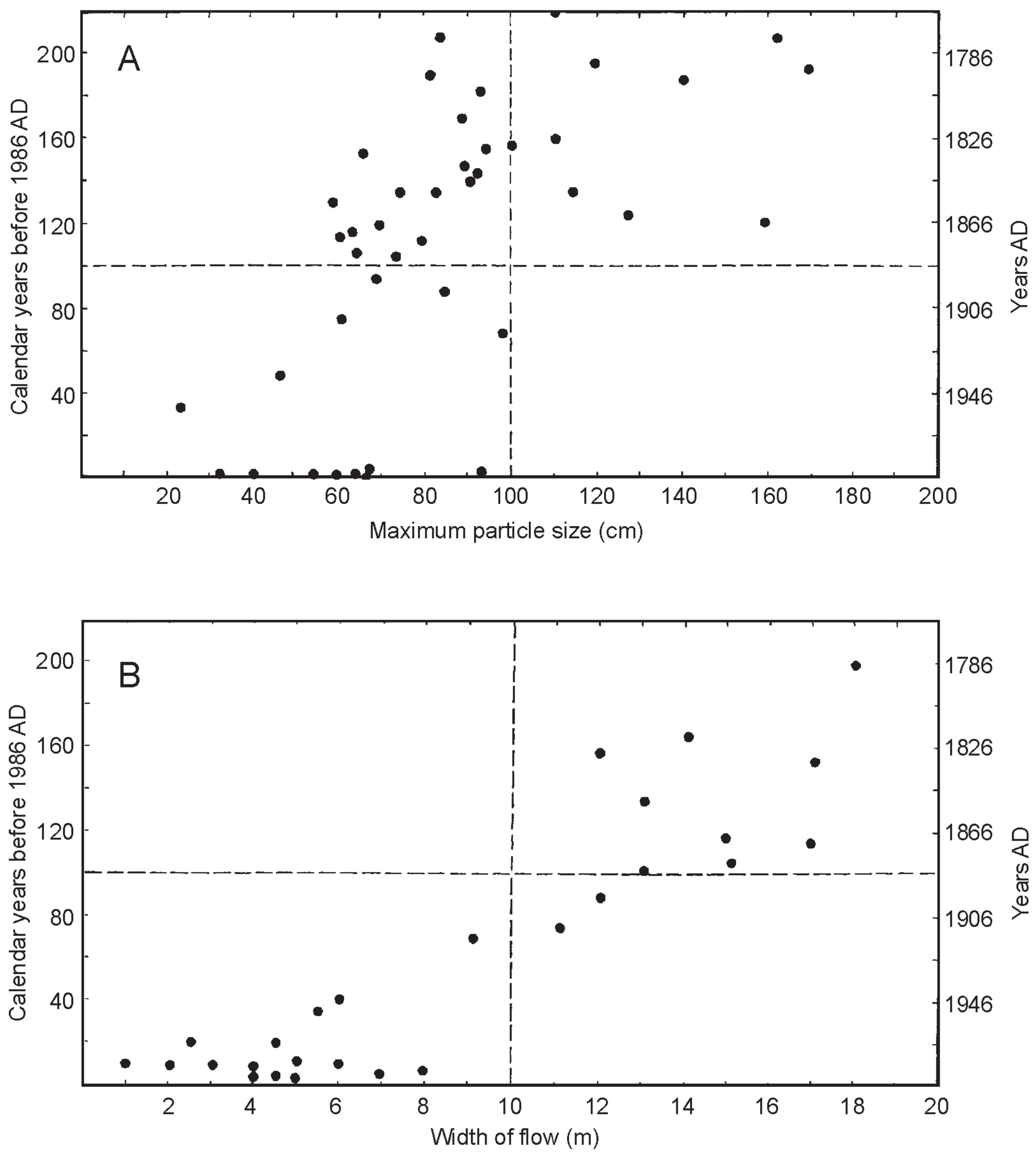

Fig. 4. Maximum boulder size (A) deposited in levees of debris flow tracks, and maximum width of hillslope debris flow tracks (B) triggered during last *ca*. 220 years (lichenometric dating) at Gąsienicowa Valley (Kotarba 1992).

exceeded 100 cm. In the 20th century flows the width did not exceed 10 m and the grain size of the material building the levees and tongues was smaller (Kotarba 1991, 1992). The transportation capacity of storm waters in the past was larger than at present, and the block sizes in the old debris flows point to a larger competence of these waters. The analyses of the old and contemporary tracks of debris flows in the Slovak part of the Tatras made by Midriak (1985) allow to conclude that in the past, under the conditions of a more severe climate, the forms were larger, longer, concentrated mainly in the major troughs dissecting the rockwalls, and descended lower than at present. The majority of the material entrained into water transportation on the slopes is an indirect measure of a relative larger intensity of hydrological events in the past, but it also shows that the increased erosional effects in some Tatric valleys in the LIA resulted from a higher sensitivity to geomorphologic processes due to the lack of stabilizing dwarf pine cover.

SUMMARISING REMARKS

The term Tatric Little Ice Age is used in this contribution for the period accepted in the world as important global climatic oscillation in the last millennium and in the Holocene scale, which has its specific imprint in the natural environment of the high-mountain Tatra massif. Both the duration and the character of the changes in the abiotic environment of the Tatras differ from the LIA concept devised in the domain of glaciology.

The LIA in the Tatras manifested itself in a climate worsening, characterised by frequent cool and moist summer seasons. It can also be accepted that winter seasons were severe, although not all of them. However, it was not the period of the climate deterioration as significant fluctuations were observed every other year which was evidenced by numerous narrative sources. The catastrophic hydrometeorological events concentrated in certain periods. Thus, one can speak about clustering of weather anomalies and natural disasters resulting from them. There were also the periods during which the temperatures of vegetation season were similar to those of the present days.

Based on the palaeolimnological data, this contribution accepts that the Tatric LIA had started *ca*. AD 1400, which is slightly earlier than it is given in other works, mainly in European glaciological and palaeoclimatic studies. Synthesis formulated by Kreutz *et al.* (1997) documents a shift to enhanced meridional circulation around AD 1400 detected in ice cores from both Antarctica, and central Greenland. Tatric palaeolimnological evidences result from the analysis of sedimentological records of the Tatra lakes, with particular emphasis on Morskie Oko lake (Baumgart-Kotarba *et al.* 1993, Kotarba 1995, Kotarba *et al.* 2002). The onset of the intensified sedimentation of minerogenic material transported from the slopes and deposited in the lake basins is dated at the beginning of the 15th century and its end is assigned to the second decade of the 20th century.

The catastrophic floods in the direct foreland of the Tatras were initiated in the mountain interior, but their largest effects were observed outside the mountains. Historical documentaries allow AD 1850–1900 to be called the period of the largest number of the weather anomalies during the recent 400 years. The time span AD 1700–1750 manifested itself in the larger number of floods and extreme precipitation in summer seasons.

The idea that the set of conditions responsible for the high-energy geomorphic processes in the Tatras, characteristic of the LIA, lasted until the beginning of the 20th century is substantiated by the development of low pressure systems over the North Atlantic. Marsz (2004) indicated that the warm water supply to the Golf storm decreased abruptly in 1877–1886 and this state lasted until the 1920s. A change in the climatic regime, from the predominating southern circulation (which brings air masses from the north over Europe) to the zonal circulation (which brings warm Atlantic air masses from the west and south west over Europe) took place just in the first half of the 20th century, after 1905. It was also reflected in temperatures of a vegetation season. Niedźwiedź (2004) indicated that the thermal onset of the LIA in the Tatras can be assigned to AD 1575 while the end to 1895. Also selected tree-ring density series from high-latitude land areas suggest that time span of LIA climate is from AD 1570 to 1900. Matthes and Briffa (2005) demonstrate in map form "that the majority of the Northern Hemisphere experienced a relatively low mean summer temperature for more than three centuries (AD 1570 to 1900)". Regional, new glaciological studies in the mountains of Canada (Luckman 2000) and New Zealand (Winkler 2004), remote from the Tatras, also show that the LIA prolonged until the beginning of the 20th century.

The examination of the geomorphic results of the extreme weather events in the mountain interior have not provided sufficient evidences to distinguish distinct phase of climatic deterioration during the recent 200 years. The lichenometry dated sediments of the hillslope debris flows, which are assumed the effects of intensive convection precipitation, analysed in four test sites in the High Tatras, support the opinion that alluviation of the slopes in particular valleys was very individual and only the most catastrophic floods in the Tatra and Fore-Tatra were synchronous with the largest climatic cooling in the northern hemisphere (*e.g.* in 1813).

It is difficult to evaluate the degrading impact of human activity on the environment of the Tatras during the LIA. It is impossible to assess how much a common forest down cutting on the southern and northern Tatric slopes, associated with mining and metallurgy, as well as the dwarf pine felling due to sheep husbandry and local industry, contributed to intensified soil erosion in forms of washing out and creeping. There are sufficient premises to believe that influence of anthropopression on the Tatric environment emphasised natural processes during the Little Ice Age.

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