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An attempt to assess the modern and the Little Ice Age climatic snowline altitude in the Tatra Mountains

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Abstract: An empirical glacio-climatic relation (Ohmura *et al.*, 1992) and meteorological data (temperature and precipitation) are employed to provide the elevation in the Tatra Mts. climate model, where conditions are suitable for hypothetical glacierisation (temperature-precipitation ELA). During the Little Ice Age (LIA) it is to have been 1.5°C colder than during the warmest decades of the 20th century (Niedźwiedź, 2004); however, some scenarios are used to define precipitation amounts related to the vertical distribution in climate model and temporal variability. The results indicate that during both considered periods – the warmest decades of the 20th century and the coolest period of LIA – the climatic snowline (cSL) was placed in most cases above the highest Tatra Mts. summits and crests. However, its spatial arrangement was unequal. In the vicinity of Kasprowy Wierch, the modern cSL is assessed to be at ca. 2,450–2,650 m a.s.l. and that during LIA at ca. 2,300–2,450 m a.s.l. In the case of Lomnicky Štit (2,634 m) it was at the level of ca. 2,700–2,800 m a.s.l. (modern times) and ca. 2,600–2,700 m a.s.l. (LIA). The discrepancies in the cSL altitude between these two locations can be explained in part by exposition to the prevailing moisture transport and orographically-induced precipitation.

Key words: climatic snowline, temperature-precipitation ELA, Little Ice Age, Tatra Mts.

Introduction

The snowline (SL) is one of the most important environmental and geoecological boundaries in the alpine ranges. Its position and changes determine the type and activity of geomorphological processes as well as the structure of geoecological belts. In the first case, it reflects the essential conditions of glaciation and, simultaneously, the upper limit of the mountain permafrost belt (Barsch, 1996). From that point, assessing the present-day and the Little Ice Age (LIA) elevation of this limit is crucial to understanding the Holocene history of the environmental changes in the Tatra Mts.

In general, a snowline is defined as a limit on terrain, above which positive balance between snow accumulation and ablation has existed for the consecutive two years. This limit is hypothetical and in reality it cannot be directly traced in the field. In the mountainous terrain, snow resedimentation by wind blowing or avalanches results in piling snow into the topographical depressions, where, if conditions are suitable, glaciers are incepting. It is often stated that, in the mid-latitude mountains, the altitude of equilibrium line of glaciers (ELA – the limit between positive and negative mass balance on glaciers; Benn & Evans, 1998) occurs at the altitude of the snowline (Jania, 1997). Thus, in most cases snowline is obtained from calculating average ELA of neighbouring glaciers in one mountain range or massif (Gross *et al.,* 1977). Such calculated snow line is less dependent on topography, thus closely related to the prevailing, long-lasting climatic condition. Therefore, the term climatic snowline (cSL) or regional climatic ELA (rcELA) can also be used in such sense of this term (Zemp *et al.,* 2007). The ELAs of individual glaciers (local topographic ELA – ltELA) can vary up to several hundreds of metres above and below this limit due to influence of local terrain and topo-climatic conditions (Benn & Lehmkuhl, 2000). In the case of unglacierised terrains, such as the Tatra Mts., only climatic based approach gives a possibility of as-

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sessing hypothetical SL grounded in temperature-precipitation condition (temperature-precipitation ELA – t-pELA).

The aim of this paper is to present the first quantitative assessment of altitudes in the Tatras climate model, where glacierisation should begin. We use empirical glacio-climatic relation (Ohmura *et al.*, 1992) and the Tatras' meteorological data to define the elevation, where climatic conditions are the same as at the modern glaciers ELAs, e.g. t-pELA. Additionally, basing on the Tatra Mts. summer temperature reconstruction (Niedźwiedź, 2004), a rough assessment of the Little Ice Age (LIA) SL position is presented.

Study area

The Tatra Mts. are located in the central part of the Western Carpathians, at the Polish-Slovak border (Fig. 1). They rise ca. 1,800–2,000 m above the surrounding Podhale-Orava and Liptov-Poprad intramontane depressions, reaching up to 2,655 m a.s.l. (Gerlachovsky Štit). The highest part of the High Tatra Mts. is built of the resistant granodiorite and granite rocks and are considered mountains with one of the best-developed Pleistocene glacial relief within the entire Carpathians (Lukniš, 1973). The deepest incised glacial cirques are located on the northern and NE slopes of the Tatra Mts. (Klimaszewski, 1960). Their bottoms lay more than 200 m lower than those on the southern slope and are constrained by the steep, several hundred metres high, rock walls and rocky slopes.

The Tatra Mts. represent a contemporary unglacierised high mountain landform system (Kotarba, 1984) with significant glacial and periglacial landforms inherited from the morphogenesis of the last cold stage. However, some small perennial snow fields or glacierets supplied by avalanches occupy niches or glacial cirques, especially below the rock walls exposed to the north (Gądek, 2008). The biggest and most investigated ones are the Medená Kotlina and the Bandzioch glacierets (Fig. 1), which are up to 0,5 ha and 22 m thick (Kłapa, 1980; Rączkowska, 2008; Gądek, 2008). They are situated at the altitudes of 2,000–2,350 m a.s.l.; however, some snow patches can survive summer tempera-

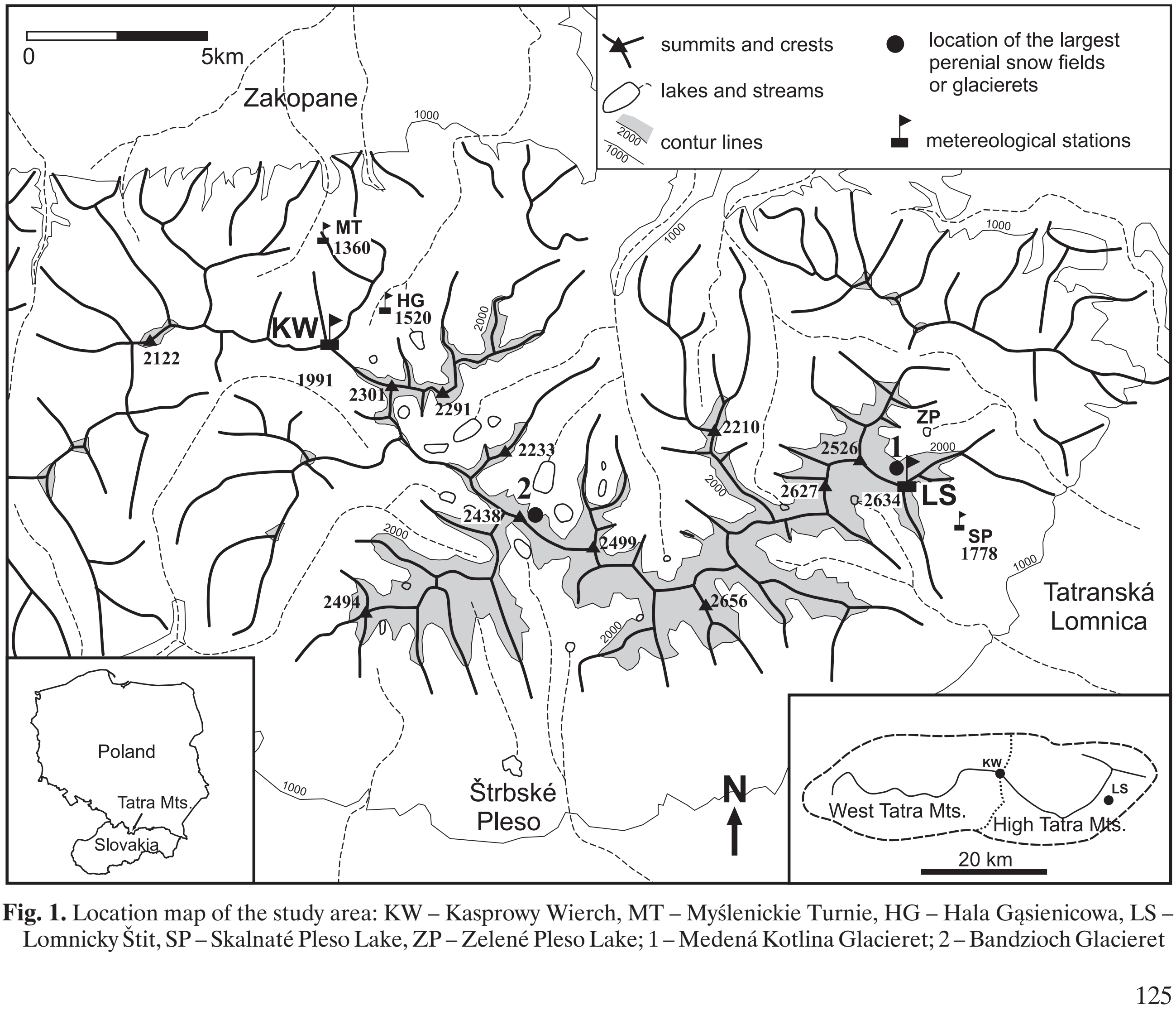

Fig. 1. Location map of the study area: KW – Kasprowy Wierch, MT – Myślenickie Turnie, HG – Hala Gąsienicowa, LS – Lomnicky Štit, SP – Skalnaté Pleso Lake, ZP – Zelené Pleso Lake; 1 – Medená Kotlina Glacieret; 2 – Bandzioch Glacieret

tures even close to 1,500 m a.s.l. (Kłapa, 1980). It is also worth noting that there are no distinct traces of morphological evidence of modern permafrost activity in the Tatra Mts. (Rączkowska, 2008).

The present-day climate conditions and air circulation patterns are dominated by the influence of the North Atlantic moisture transport. The highest precipitation totals are recorded on the northwestern slope of the mountain ridge (especially the NW fringe of the High Tatras), while the southern, lee side, is located in precipitation shadow (Niedźwiedź, 1992), which is clearly visible in the surface waters runoff (Łajczak, 2006). These spatial arrangements of precipitation are similar to those in the Alps, where the highest precipitation totals are recorded on the NW fringe of these mountains (Frei & Schär, 1998). The Tatra Mts. historical air temperature series and the dendroclimatic reconstructions (Bednarz, 1984) are also well correlated with the changes registered in the Eastern Alps (Niedźwiedź, 2004, 2006). The present-day natural timberline lies at the level of 1,550 m a.s.l. on the northern (Obidowicz, 1996), and 1,650 m a.s.l. on the southern slopes of the High Tatra Mts. (Plesník, 1971), which corresponds to the altitude of mean annual air temperature (MAAT) isotherm of +2°C (Hess, 1965). The annual isotherm 0°C lies approximately at 1,800 m a.s.l. and that of –2°C at 2,200 m a.s.l. (Hess, 1965).

Previous estimates of snowline in the Tatra Mts.

There were many attempts to estimate the modern snowline in the Tatra Mts., which revealed considerable amount of confusion about their nature and altitude (Table 1). The first snowline estimation dates back to the early 19th century (Wahlenberg, 1814). The one of the most often used criterion of snowline estimation is simple interpolation based on spatial relationships between the Tatra Mts., the Eastern Alps and the Scandinavian Mts. (Durocher, 1847; Paschinger, 1912; Vitasek, 1956). The snow line elevation has been also attributed to: (1) the theoretical lower limit of the annual preservation of snow cover on a horizontal, non-shaded surface (so called 365 level; Konček & Briedoň, 1959; Kotarba, 1976; Starkel, 1977; Gądek, 2008); in the Western Carpathians it corresponds to the elevation of MAAT –8°C isotherm (Hess, 1965); (2) the altitude

Table 1. Altitude of snowline in the Tatra Mountains according to different authors

Author	Altitude of snowline			Used methode/criterion
	average	N slope	S slope	
Wahlenberg, 1814	2,600**			summit method
Durocher, 1847	2,500**			comparison with the Alps and the Scandinavia
Fuchs, 1863	2,573**			(summer 0°C isotherme)
Kořistka, 1864	2,200*			altitude of snow patches
Partsch, 1882	2,300**			altitude of snow patches
Grissinger, 1888	2,300**			altitude of snow patches
Kolbenheyer, 1890	1,940**			(annual 0°C isotherme)
Paschinger, 1912	2,400			comparison with the Eastern Alps
Partsch, 1923	2,500**			altitude of snow patches
Vitásek 1956	2,300*, 2400**			comparison with the Eastern Alps
Konček & Briedoň, 1959	4,946***			altitude of 365 level
Klimaszewski, 1962; 1988		2,200	2,350	summer temp. < 6°C, annual temp. –2°C, 250 days with snow cover
Hess, 1965	3,400***	2,200**	2,350**	summer temp. < 6°C, annual temp. –2°C, 250 days with snow cover
Lukniš, 1973		2,550–2,650**	2,700–2,800**	rough estimation
Kotarba, 1984, 1996	2,150–2,300*			according to Hess 1965 and Klimaszewski 1988
Kołodziej, 1995			1,750*	lowest altitude of snow patches
Obidowicz, 1996		2,200**		600–800 m higher than the timber line
Gądek, 2008	3,400***			altitude of 365 level

*orographic snowline, **climatic snowline, ***365 level of perennial snow patches (Kořistka, 1864; Partsch, 1882, 1923; Grissinger, 1888; Gadomski, 1925), which is in fact the orographic snowline (oSL); (3) the thermal boundary, where elevation of MAAT 0°C isotherm (Kolbenheyer, 1890) or summer isotherm 0°C (Fuchs, 1863) are recorded.

The most popular opinion followed the Klimaszewski's (1962, 1967) views. He claimed that cSL lies at the altitude, where the temperature of the warmest month (July) is lower than 6°C. It was established at 2,200 m a.s.l. on the northern and 2,350 m a.s.l. on the southern Tatra slopes (Table 1). Such a boundary separates the niveo-pluvial from the nival belt (Klimaszewski, 1962; Kotarba, 1984). Hess (1965) supplemented such a view claiming that essential condition for cSL requires also annual temperature of –2°C and 250 days with snow cover. According to Klimaszewski (1962, 1988) and Hess (1965), the lack of contemporary Tatra glaciation is connected with the absence of topographically-suitable surfaces for ice alimentation. However, Kotarba (1976) and Starkel (1977) considered this boundary as the oSL.

Materials and methods

As was mentioned above, a snowline can be directly attributed to the equilibrium line of glaciers (ELA). Based on observation of 70 monitored mid- to high-altitude glaciers, Ohmura *et al.* (1992) indicated that climate at the ELA can be best described using the three summer month's (June, July, August – JJA) temperatures in a free atmosphere and annual precipitation total:

$$P_a = 9T_s^2 + 296T_s + 645 \qquad (1)$$

where: P_a is the annual precipitation total at ELA, and T_s is the summer temperature (JJA) at ELA. Some refinement of this relationship is possible by introducing global and long-wave net radiation (Ohmura *et al.*, 1992).

We assumed that that hypothetical SL in the Tatra Mts. lies at elevation, where climatic conditions are equal to the ones at ELA of modern glaciers. The extrapolation of climate model in the Tatra Mts. has been obtained by using the data from the highest summit's meteorological stations at Kasprowy Wierch (1,991 m a.s.l.) and Lomnicky Štit (2,634 m a.s.l.) (Fig. 1).

The temperature and precipitation can be expressed as a function of elevation:

$$T_s = T_{ms} + (h_{ms} - \text{t-pELA})\ \Delta T/\Delta h \qquad (2)$$

$$P_a = P_{ms} + (\text{t-pELA} - h_{ms})\ \Delta P/\Delta h \qquad (3)$$

where: h_{ms} is the elevation of meteorological station, P_{ms} is the annual precipitation total at elevation of meteorological station, T_{ms} is the summer temperature (JJA) at elevation of meteorological station, $\Delta T/\Delta h$ is the temperature lapse rate (°C/100 m), $\Delta P/\Delta h$ is the precipitation-altitude gradient (mm/100 m) and t-pELA is the elevation of cSL.

Furthermore, by combining equations (2) and (3) with equation (1) we obtained quadratic function with the only unknown parameter t-pELA. A solution is one of the roots of the equation. The simplification of calculation was made by implementing the formula in the spreadsheet (Excel application). The obtained elevation is assumed to be a cSL. It lies at the elevation, where precipitation and temperature predicted in the climate model using given laps rates satisfy the equation (1).

We use meteorological data T_{ms} and P_{ms} published by Konček & Orlicz (1974) and Chomicz & Šamaj (1974) for the decades 1951–1961, and WMO (World Meteorological Organization) climatic data for the 1991–2000 period. These periods were the warmest decades in 20th century in the Tatra Mts. (Niedźwiedź, 2004). As far as the summer temperature is concerned, its variability during the 20th century and even earlier, during the last cold phase of the Little Ice Age period, can be recalculated using the reconstructed summer temperatures from Hala Gąsienicowa published by Niedźwiedź (2004; Fig. 2). These data are assessed with larger deviation up to ±0.6°C, partially based on dendrochronological reconstruction and correlation of the remote meteorological stations and the older time series (Niedźwiedź, 2004). However, it was pointed out that the temperature series from Hala Gąsienicowa can be well correlated with those from Kasprowy Wierch and Lomnicky Štit (Niedźwiedź, 2004).

The data indicate ca. 1.5°C amplitude between the warmest and the coldest decades of the last two centuries (Fig. 2). This is in accordance with the data from southern slope of the Tatra Mts. (1.4°C; Melo, 2005). If we consider muted glacial-climatic interaction lasting more than one decade, this value represents rather the maximal cSL amplitude; hence, the most glacier-friendly scenario during the Little Ice Age. The period 1830–1890, for instance, was only 1.2°C colder than that of the 1991–2000 decade (Niedźwiedź, 2004, Fig. 2). Changes of summer temperatures with altitude can be easily predicted by using lapse rates. In the location of Kasprowy Wierch, the lapse rate of 0.70°C/100 m is used. It was obtained from differences in temperature between Kasprowy Wierch and neighbouring meteorological stations Myślenickie Turnie and Hala Gąsienicowa (cf. Niedźwiedź, 2004; Fig. 1). Similar procedure was used to assess lapse rate between the Skalnaté Pleso and Lomnicky Štit (0.67°C/100 m).

On other hand, the variations in precipitation are complex and, in contrast to temperature, they can be poorly correlated with altitude (Zemp *et al.,* 2007). In the first case some extrapolation from the calculated lapse are used. However, additional scenarios are included with the aim of outlining situation, where above the highest summits lapse rates are lower than on the mountain slopes below the crests (orographic precipitation) or precipitation totals are decreasing (inverse gradient). It can be assumed that above Kasprowy Wierch, at the level of Lomnicky Štit (ca 2,600 m a.s.l.), the precipitation total is higher than at Lomnicky Štit due to orographically-induced precipitation on the NW front of the Tatra Mts. However, it can not be ruled out that the precipitation totals are at similar level or lower than those measured in the Kasprowy Wierch station. Employed lapse rates do not exactly mean that we suspect linear change of precipitation with altitude. It can be rather treated as a means of expression of precipitation totals scenario at the level of t-pELA.

There are no data dealing with the reconstructed precipitation totals in the Tatra Mts. during the 19th century. However, plenty of detailed geomorphological investigations as well as lacustrine sedimentological studies were carried out, which suggested relatively cold and humid periods with the large frequency of catastrophic processes (floods, debris flows, rock falls) clustering into the periods of the Alpine glacier advances (Baumgart-Kotarba *et al.,* 1990; Kotarba, 2004). This statement is well in accordance with the overall depiction of the Little Ice Age climate, considered as cool and humid. Nevertheless it gives no direct quantitative information about precipitation totals during this period. On the other hand, some Alpine results suggest a slight increase in precipitation (10%) accompanied by temperature rise after the mid–19th century climatic deterioration, which reduced ELA rise caused by temperature change (Greene & Broecker, 1999). A similar trend of rising of the precipitation amounts and of temperature is observed in the Tatra Mts. (Vojtek *et al.,* 2003). Taking into account the aforementioned facts, we *a priori* assumed that precipitation totals at ELA during the Little Ice Age were similar or slightly higher than the average values of the second half of the 20th century at the stations' altitudes. This assumption also implies the most humid and glacier-friendly condition, e.g. the lowermost position of the t-p ELA. Additionally, presented scenarios up to 10–15% dryer are presented.

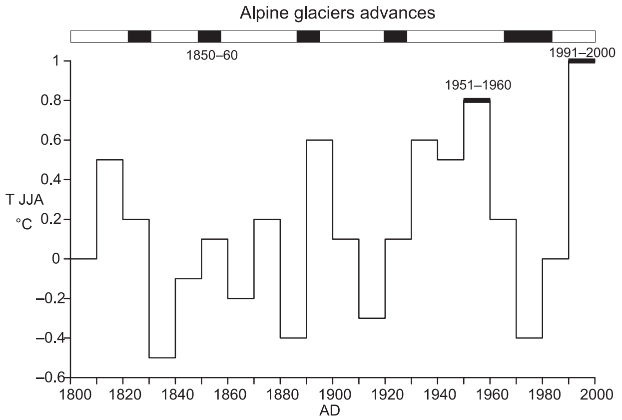

Fig. 2. Summer temperature (June, July, August) variation in the Hala Gąsienicowa 1520 m a.s.l. during the last two centuries in relation to the normal period 1961–1990 according to Niedźwiedź (2004) (part of the reconstruction). Black rectangle marks periods of moraine formation in the Alps indicating culmination of advance or stagnation of glaciers: 1820s, 1850–60, 1890–1900, 1920s and 1965–85. The most extensive advance was at 1850–60 which reaches the maximum Holocene extent (Patzelt, 1995; Zemp et al. 2008)

Results

During the warmest decades of the 20th century, at the location of Kasprowy Wierch, cSL was placed at the level of 2,500–2,600 m a.s.l. (Table 2). However, the obtained results are strongly controlled by the assumed precipitation scenario because of large vertical distance between the estimated t-pELA and meteorological station altitude (500–600 m). Depending on the assumed precipitation total (precipitation-altitude gradient), the summer temperature at ELA is there in the range of 2.7–3.7°C. In the case of the Lomnicky Štit location, differences of the ELA attitude resulting from different precipitation-altitude gradient are insignificant and the estimated ELA is in the range of ca. 2,700 to 2,800 m a.s.l., depending on the decades considered. The summer temperatures at ELA in this location are generally lower than in Kasprowy Wierch.

During the Little Ice Age, the t-pELA dropped to the level of ca. 2,300–2,450 m at the location of Kasprowy Wierch, e.g. on the NW fringe of the High Tatra Mts., while in the case of Lomnicky Štit it was in the range of ca. 2,600–2,700 m a.s.l. (Table 2).

Discussion

The presented estimates of the cSL in the Tatra Mts. are based, for the first time, on the temperature-precipitation relations. The significant problems have arisen with determining precipitation totals regarding both the present-day vertical gradient and their temporal distribution. Additionally, the precipitation distribution differences can be influ-

Table 2. Modelled elevation of climatic snowline in the Tatra Mts.

Kasprowy Wierch 1,991 m a.s.l.							Lomnicky Štit 2,634 m a.s.l.						
period	T JJA	Pa	ΔP/Δh	**t-pELA**	T ELA	P ELA	period	T JJA	Pa	ΔP/Δh	**t-pELA**	T ELA	P ELA
1951–1960	7	1,742	28**	**2,459**	3.7	1,873	1951–1960	3.58	1,651	36**	**2,695**	3.17	1,673
			0	**2,511**	3.4	1,742				0	**2,705**	3.11	1,651
			–30	**2,583**	2.9	1,564				–30	**2,715**	3.04	1,627
1991–2000	7.5	1,717	28**	**2,532**	3.7	1,868	1991–2000	4.18	1,776	36**	**2,728**	3.55	1,810
			0	**2,592**	3.3	1,717				0	**2,742**	3.46	1,776
			–30	**2,676**	2.7	1,511				–30	**2,758**	3.35	1,739
1951–1997		1,769					1951–2000	3.50	1,503	36**	**2,740**	2.79	1,541
										0	**2,756**	2.68	1,503
										–30	**2,775**	2.56	1,461
LIA	T JJA			**t-pELA**	T ELA	*P ELA*	LIA	T JJA			**t-pELA**	T ELA	*P ELA*
	6*			**2,325**	3.66	1,850		2.68*			**2,592**	2.96	1,600
				2,365	3.38	1,750					**2,635**	2.67	1,500
				2,446	2.82	1,550					**2,679**	2.38	1,400

T JJA – 3 month's summer temperature at the elevation of meteorological stations (°C), * – 1.5°C colder than the warmest decade of the 20th century; Pa – precipitation totals at the level of meteorological stations (mm/a); ΔP/Δh – scenarios of precipitation-altitude gradient (mm/100 m), ** – extrapolated; t-pELA – modelled temperature-precipitation ELA = climatic snowline (m a.s.l.); T ELA – modelled summer temperature at ELA (°C); P ELA – modelled precipitation totals at ELA (mm/a); P ELA – assumed precipitation at ELA (mm/a)

enced by horizontal gradient and topographic settings. The above mentioned problem is common in the glacio-climatic reconstructions; however, it should be emphasized that variation of precipitation has less contribution than the temperature in the ELA shifts. Ohmura *et al.* (1992) pointed out that reducing the temperature by 1°C is fully compensated by the increase in precipitation by 350 mm. In the Alps, for instance, the modelled 1°C temperature variation is balanced by 25% precipitation change (Zemp *et al.,* 2007).

The obtained results of the modern cSL altitude are ca. 300–450 m higher than those commonly used in the literature (i.a., Klimaszewski, 1962; Hess, 1965; Table 1). In all cases, it rises above the altitude of the highest Tatra summits. The calculated modern cSL lies about 450–700 m higher than the summit meteorological station on Kasprowy Wierch (1,991 m a.s.l.). In the case of Lomnicky Štit meteorological station (2,634 m a.s.l.) this vertical distance is between 60 and 120 m (Table 2).

In the neighborhood of Lomnicky Štit, the modelled cSL altitude is ca. 150–200 m higher than the location of Kasprowy Wierch. This difference can be partially explained by the scarcity of precipitation on the SE side of the High Tatras. The NW corner of the High Tatra Mts. in the surroundings of Kasprowy Wierch, Hala Gąsienicowa and Mt. Świnica is affected by the westerlies circulation, which brings high amounts of precipitation, additionally enhanced by the orographic effect. In contrast, the SE part of the High Tatra massif lies in the precipitation shadow, which causes higher cSL altitudes. However, the difference of precipitation and thus cSL altitude can also be attributed to the vertical distribution of precipitation. It can not be excluded that Lomnicky Štit stands above the zone of maximal precipitation amounts, while Kasprowy Wierch is closer to this zone. Vojtek *et al.* (2003) pointed out that in the second half of the 20th century the most pronounced increase in precipitation was noted above the level of 1,800–2,300 m. In Lomnicky Štit, the last two decades have been relatively wet in comparison to the cool and dry 1961–1990 period, which is considered as a cool and humid on the northern slopes in the lower altitudes (Niedźwiedź, 1992). This discrepancy can be a result of rising the vertical zone of the highest precipitation, which accompanied the rise in temperature. If such regularity was valid also during the LIA, we can expected even drier condition at the level of the highest Tatra summits during this cool period; hence, the amplitude of t-pELA fluctuation can be there reduced due to negative feedback between temperature and precipitation changes.

During the LIA, the calculated cSL position in Kasprowy Wierch surroundings was 150–200 m lower than the modern one. In the case of Lomnicky Štit this difference is 50–100 m. However, it should be emphasized that the modelled LIA cSL stems from the arbitrarily assumed precipitation value and precipitation-altitude gradients. Nevertheless, cSL amplitude roughly fits to the alpine ELA depression between LIA and the modern values (ca. 150–250 m; Patzelt, 1995). In the first approximation, the SL amplitude resulted simply from temperature amplitude (1.5°C) and temperature lapse rate (0.7°C/100 m), which in such a case is ca. 210 m.

The possible effects on glacierisation regarding relation between the mountain topography and cSL fluctuations are depicted in Figure 3. The modern cSL is situated at the elevation about 100–150 m higher than the highest Tatra summits and crests, what corresponds well to the situation showed in Fig. 3a; hence, during the warmest decades of the 20th century there were certainly no suitable conditions for glacierisation. Nevertheless, it was possible for perennial snow patches to survive even 750–1,000 m below the calculated cSL (cf. Table 1).

The LIA cSL position was above the level of Mt. Świnica (2,301 m a.s.l.), the highest summit in the vicinity of Kasprowy Wierch, and it was placed approximately 300–400 m above the most upper part of the north exposed, flat glacial cirque floor (2,000 m a.s.l.; Zadnie Koło cirque) (Fig. 4a). In the surroundings of Lomnicky Štit, the LIA cSL probably encompassed the elevation of the summit, but did not fall considerably under the altitude of 2,600 m a.s.l. In more dry scenarios, it was situated even several tens of metres above the summit (Fig. 4b). Likewise, the cSL altitude was placed 250–300 m above the glacial cirque floor and Medená Kotlina glacieret. In spite of general lowering of the cSL during this time, it did not fall low enough to be at the altitude of the highest cirques' floors, and it did not even reach the altitude range of the north facing rockwalls. Hence, the LIA cirque glacierisation seems to be impossible or unlikely. The conclusions reported in literature support rather the more extensive snow patches and glacierets expansion during the LIA in the Tatra Mts. than true cirque glaciation (Gądek, 2008; Rączkowska, 2008), what confirms well our results. Similarly, the results of extensive geomorphological studies as well as historical and pictorial data do not report any glaciers existence in the Tatra Mts. (Kotarba, 2004).

The period of 1830–1890 was the coldest in the last 400 years in the Tatra Mts. (Niedźwiedź, 2004). It was coeval with the significant period of glacier advance in the Alps during the last cold fluctuation of the Little Ice Age (ca. AD 1850; Fig. 2). At that time, glaciers in the Alps reached once again the Holocene maximum position (Patzelt, 1995; Matthews, 2007). Hence, it can be roughly assumed that during this period the altitude of cSL in the Tatra Mts. was in the

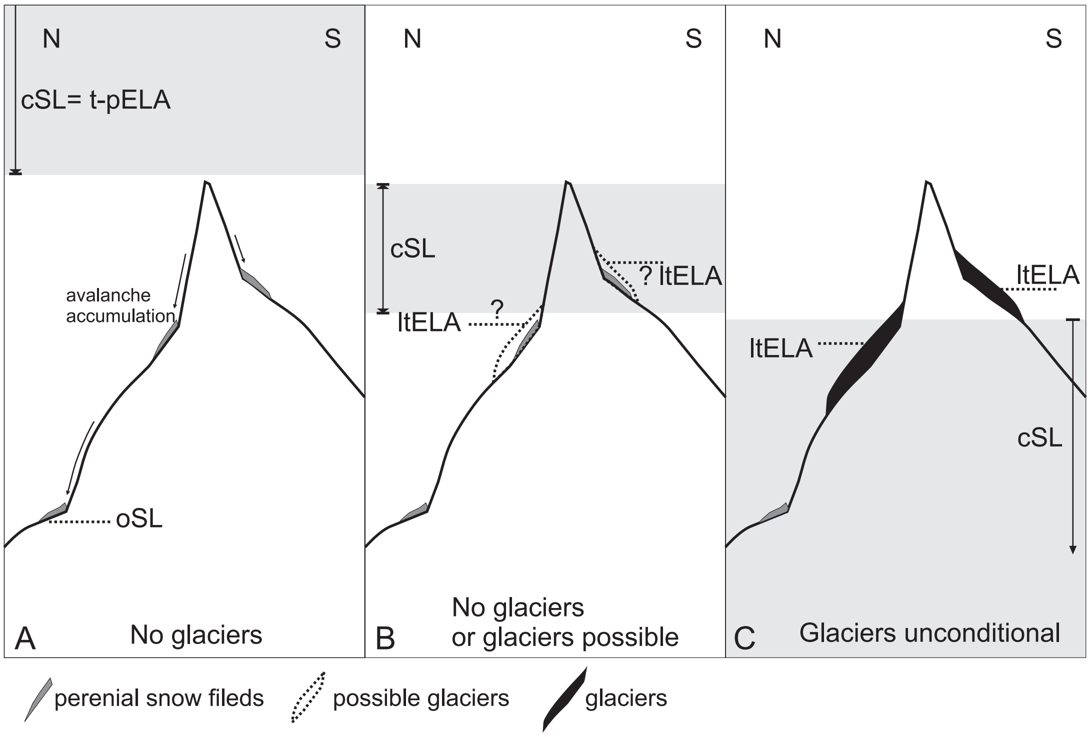

Fig. 3. Assumed relation between topography and climatic snowline (cSL) positions in respect to possibility of glaciers inception. In case where cSL (= temperature-precipitation condition at ELA, t-pELA) is above the highest mountain crests (A) there are no suitable condition for glacierisation, however perennial snow patches or glacierets can survive several hundred meters below cSL – orographic snowline (oSL). If cSL is in the range of altitudes between the highest crests and the highest north directed glacial cirque floors (B), there are no glaciers or some avalanche nourished cirque glaciers could be expected in dependence of individual topo-climatic conditions – ltELA (local topographic ELA). If cSL reaches the highest, north directed glacial cirque floors (C) it is assumed that glaciers would incept unconditional

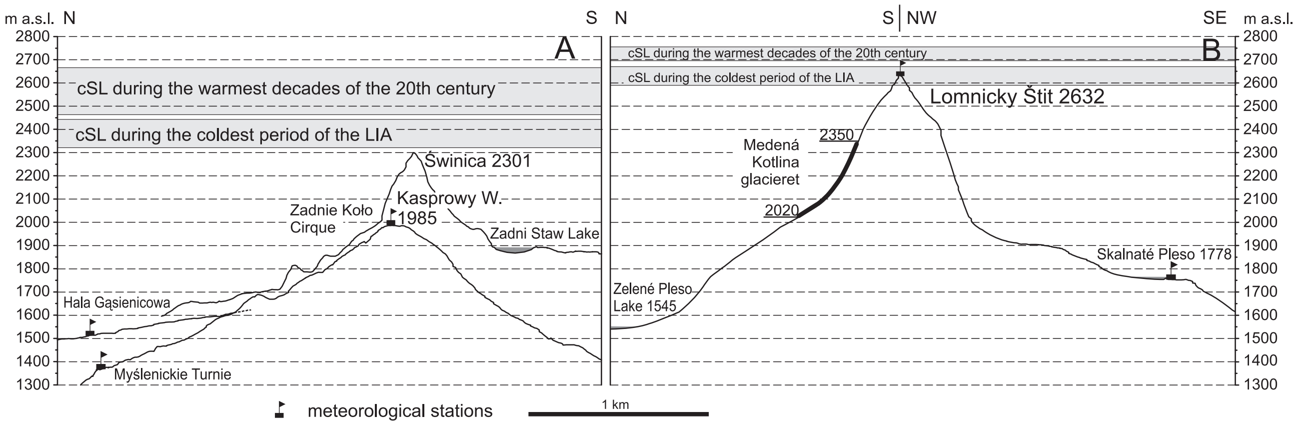

Fig. 4. Modelled climatic snowline (temperature-precipitation ELA) in relation to the topographic settings in the Kasprowy Wierch (A) and Lomnicky Štit (B) surroundings. Grey zones indicate range of snowline altitudes for the all considered scenarios (Table 2)

lowermost or close to the lowermost position during the entire Holocene. Thus, accepting the view that the Tatras' palaeoclimate did not differ significantly from that of the Eastern Alps, for instance accepting that the LIA represents one of the most pronounced Holocene climatic deterioration, the Tatra glaciation during the Holocene is unlikely. On the other hand, during the 1951–1960 and 1991–2000 decades, the cSL elevation can be suspected to be close to the highest Holocene level, if we consider that the late 20th century warming was as prominent as the earlier warm Holocene events.

The true cirque or valley glaciation could have taken place in the Tatra Mts. in the case of the lowering of the cSL to the highest sections of cirques bottoms, for instance, the ones presently occupied by snow patches or glacierets (cf. Fig. 3c). In the surroundings of Kasprowy Wierch, such a situation requires the cSL depression (below LIA cSL) to be ca. 300-400 m (Fig. 4a), and in the Lomnicky Štit surroundings – 250–300 m (Fig. 4b). Nevertheless, still valid is the question about threshold conditions which will cause the development of avalanche-nourished footwall or niche glaciers in the Tatra Mts. (cf. Fig. 3b).

Conclusion

The hypothetical altitude of SL in currently unglacierised mountains can be asses by using empirical glacio-climatic relations based on temperature-precipitation distribution, although with some qualification and assumption. The accuracy of results is considerably dependent on the uncertainty of precipitation distribution and elevation of meteorological stations, from which the meteorological data have been acquired.

The results indicate that the cSL during the warmest decades of the 20th century as well as during the coldest period of the LIA did not fall considerably below the elevation of the highest Tatra Mts. summits. In most cases it was placed above the highest summits of the Tatra Mts. This leads to a conclusion that even during the periods of the most glacier-friendly conditions during the Holocene (i.e., the LIA), glaciation in the Tatra Mts. was unlikely. This is in accordance with the absence of LIA glacial landsystem from the Tatra Mts. It is also concluded that the SL depression in relation to the LIA value (ΔELA), which is required for the certain cirque-valley glaciers inception in the Tatra Mts., could have exceeded 250 m.

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References

Barsch, D., 1996: *Rockglaciers*. Springer: 319 pp.

Baumgart-Kotarba, M., Jonasson, C. & Kotarba, A., 1990: Studies of youngest lacustrine sediments in the High Tatra Mountains, Poland. *Studia Geomorphologica-Carpatho-Balcanica*, 14, 161–177.

Bednarz, Z., 1984: The comparison of dendroclimatological reconstructions of summer temperatures from the Alps and Tatra Mountains from 1741–1965. *Dendrochronologia*, 2: 63–72.

Benn, D. I. & Evans, D. J. A., 1998: *Glaciers & glaciation*. Arnold, London: 734 pp.

Benn, D. I. & Lehmkuhl, F., 2000: Mass balance and equilibrium line altitudes of glaciers in high mountain environments. *Quaternary International*, 65/66: 15–29.

Chomicz, K. & Šamaj, F., 1974: Zražkovè Pomery. In: Konček, M., (Ed.) *Klima Tatier*. Vydavatelstvo Slovenskej Akademie Vied, Bratislava: 89–135.

Durocher, J., 1846: Mémoire sur la limite des neiges perpétuelles, sur les glaciers du Spitzberg comparés a ceux des Alpes, sur les phénomènes diluviens et les théories ou on les suppose produits par des glaciers. *Géographie Physique, Géographie Botanique, Botanique et Physiologie*. Paris, 1, 2: 237–408.

Frei, Ch. & Schär, Ch., 1998: A precipitation climatology of the Alps from high-resolution rain-gauge observations. *International Journal of Climatology,* 18: 873–900.

Fuchs, F., 1863: Die Centralkarpathen mit den nächsten Voralpen. Pest: 318 pp.

Gadomski, A., 1925: *Morfologia glacjalna północnych stoków Wysokich Tatr.*, Cieszyn: 150 pp.

Gądek, B., 2008: The problem of firn-ice patches in the Polish Tatras as an indicator of climatic fluctuations. *Geographia Polonica*, 81, 1: 41–53.

Greene, A. M. & Broecker, W. S., 1999: Swiss glacier recession since the Little Ice Age: reconciliation with climate records. *Geophysical Research Letters*, 26: 1909–1912.

Grissinger, K., 1888: Die Schneegrenze in der Hohen Tatra. *Bericht des Vereins der Geographen*, Wien, 14: 44–49.

Gross, G., Kerschner, H. & Patzelt, G., 1977: Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 12: 223–51.

Hess, M., 1965: Piętra klimatyczne w Polskich Karpatach Zachodnich. *Zeszyty Naukowe UJ*, *Prace Geograficzne*, 11: 267 pp.

Jania, J., 1997: *Glacjologia. Nauka o lodowcach*. Wydawnictwo Naukowe PWN, Warszawa, 359 pp.

Klimaszewski, M., 1960: On the influence of pre-glacial relief on the extension and development of glaciation and deglaciation of mountainous regions, *Przegląd Geograficzny*, 32: 41–49.

Klimaszewski, M., 1962: Zarys rozwoju rzeźby Tatr Polskich. In: Szafer, W. (Ed.), *Tatrzański Park Narodowy*. Kraków: 105–125.

Klimaszewski, M., 1967: Polskie Karpaty Zachodnie w okresie czwartorzędowym. *Czwartorzęd Polski*. PWN, Warszawa: 431–497.

Klimaszewski, M., 1988: *Rzeźba Tatr Polskich.* PWN, Warszawa: 667 pp.

Kłapa, M. 1980: Procesy morfogenetyczne oraz ich związek z sezonowymi zmianami pogody w otoczeniu Hali Gąsienicowej w Tatrach. *Dokumentacja Geograficzna, IG i PZ PAN*, 4: 1–53.

Kolbenheyer, K., 1890: Die klimatischen Verhältnisse der Zentralkarpathen. *Jahrbuch Ungarischen Karpathen-Vereins,* 17: 235–246.

Kołodziej, T., 1995: *Charakterystyka wieloletnich płatów śnieżnych w zachodniej części słowackich Tatr Wysokich*. Unpublished MSc. thesis, Katedra Geomorfologii, Wydział Nauk o Ziemi, Uniwersytet Śląski, Sosnowiec.

Konček, M. & V. Briedoň, V., 1959: Snehové pomery Vysokých Tatier. *Geografický časopis*, 11: 3–42.

Konček, M. & Orlicz, M., 1974: Teplotné pomery. In: Konček, M., (Ed.), *Klíma Tatier*. Vydavateľstvo Slovenskej Akadémie Vied, Bratislava: 443–470.

Kořistka, K., 1864: Die Hohe Tatra in den Central Karpathen. *Petermanns Geographische Mitteilungen*, Ergänzungshelft, Gotha, 12: 124 pp.

Kotarba, A., 1976: Współczesne modelowanie węglanowych stoków wysokogórskich na przykładzie Czerwonych Wierchów w Tatrach Zachodnich. *Prace Geograficzne IG i PZ PAN*, 120: 1–128.

Kotarba, A., 1984: Elevational differentiation of slope geomorphic processes in the Polish Tatra Mts. *Studia Geomorphologica Carpatho-Balcanica*, 18: 113–17.

Kotarba, A., 1996: Współczesne procesy rzeźbotwórcze. In: Mirek, Z. *et al.* (Eds.) *Przyroda Tatrzańskiego Parku Narodowego. Tatry i Podtatrze 3.* Tatrzański Park Narodowy, Kraków–Zakopane: 125–137.

Kotarba, A., 2004: Zdarzenia geomorfologiczne w Tatrach Wysokich podczas Małej Epoki Lodowej. In: Kotarba, A. (Ed.), *Rola małej epoki lodowej w przekształcaniu środowiska przyrodniczego Tatr. Prace Geograficzne IG i PZ PAN*, 197: 9–54.

Lukniš, M., 1973: *Reliéf Vysokých Tatier a ich predpolia*. Veda, Bratislava: 375 pp.

Łajczak, A., 2006: Spatial distribution of water resources in the Tatra Mountains on the background of other mountains. In: Kotarba, A. & Borowiec, W. (Eds.), *Tatrzański Park Narodowy na tle innych górskich terenów chronionych,* Zakopane, v. 1: 19–34

Matthews, J. A., 2007: Neoglaciation in Europe In: Elias, S. (Ed.), *Encyclopedia of Quaternary Science*, Elsevier: Amsterdam: 1122–1133.

Melo, M., 2005: Warmer periods in the Slovak mountains according to analogue method and coupled GCM. *Croatian Meteorological Journal*, 40: 589–592.

Niedźwiedź, T., 1992: Climate of the Tatra Mountains. *Mountain Research and Development*, 12, 2: 131–146.

Niedźwiedź, T., 2004: Rekonstrukcja warunków termicznych lata w Tatrach od 1550 roku. In: Kotarba, A. (Ed.), *Rola małej epoki lodowej w przekształcaniu środowiska przyrodniczego Tatr. Prace Geograficzne IG i PZ PAN*, 197: 57–88.

Niedźwiedź, T., 2006: Variability of air temperature in the Tatra Mountains in comparison with the Southern Carpathians and the Alps In: Kotarba, A. & Borowiec, W. (Eds.), *Tatrzański Park Narodowy na tle innych górskich terenów chronionych*, Zakopane, v. 1: 9–17.

Obidowicz, A., 1996: A Late glacial-Holocene history of the formation of vegetation belts in the Tatra Mts. *Acta Palaeobotanica*, 36, 2: 159–206.

Ohmura, A., Kasser, P. & Funk, M., 1992: Climate at the equilibrium line of glaciers. *Journal of Glaciology,* 38: 397–411.

Partsch, J., 1882: *Die Gletscher der Vorzeit in den Karpathen und den Mittelgebirgen Deutschlands*. W. Koebner (Eds.), Breslau: 198 pp.

Partsch, J., 1923: *Die Hohe Tatra zur Eiszeit*. Leipzig, 220 pp.

Paschinger, V., 1912: Die Schneegrenze in verschiedenen Klimaten. *Petermanns Geographische Mitteilungen*, Ergänzungshelft, Gotha, 173 pp.

Patzelt, G., 1995: Holocene glacier and climate variations. In: Schirmer, W. (Ed.), *Quaternary Field Trips in Central Europe*. Verlag Dr. Friedrich Pfeil, München: 385–389.

Plesník, P., 1971. *Horná hranica lesa vo Vysokých a Belanských Tatrách*. Vydavateľstvo SAV, Bratislava: 238 pp.

Rączkowska, Z., 2008: Are there geomorphic indicators of permafrost in the Tatra Mountains? *Geographia Polonica*, 81, 1: 117–133.

Starkel, L., 1977: *Paleogeografia holocenu*. PAN, Warszawa: 362 pp.

Vojtek, M., Faško, P. & Š astný P., 2003: Some selected snow climate trends in Slovakia with respect to altitude. *Acta Meteorologica Universitatis Comenianae*, 32: 17–27.

Vitásek, F., 1956: Sněžná čára ve Vysokých Tatrách. *Geografický časopis,* 8, 4: 171–176.

Wahlenberg, G., 1814: *Flora Carpatorum principalium exhibens plantas in montibus Carpaticis inter flumina Waagum et Dunajetz, cui praemittitur tractatus de altitudine, vegetatione, temperatura et meteoris horum montium in genere.* Göttingen: 408 pp.

Zemp, M., Hoelzle, M. & Haeberli, W., 2007: Distributed modelling of the regional climatic equilibrium line altitude of glaciers in the European Alps. *Global and Planetary Change*, 56: 83–100.

Zemp, M., Paul, F., Hoelzle, M. & Haeberli, W., 2008: In: Orlove, B. *et al.* (Eds.), *Darkening Peaks: Glacier Retreat, Science, and Society*. Berkeley, US: 152–167.