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EMIL GACHEV (BLAGOEVGRAD)

INTER-ANNUAL SIZE VARIATIONS OF SNEZHNIKA GLACIERET (THE PIRIN MOUNTAINS, BULGARIA) IN THE LAST TEN YEARS

Abstract: Glacierets, which are in fact embryonic forms of recent glaciation, can serve as important indicators of contemporary climate dynamics in areas where classical glaciers do not exist, such as the high mountains in Southeastern Europe. Two glacierets are located in Bulgaria's Pirin Mountains: Snezhnika and Banski Suhodol. Snezhnika has been relatively well studied for the last 50 years, and in particular since 1994, when annual size measurements on a regular basis started. The present study focuses on the recent variations in the size of Snezhnika i.e. in the last ten years. Data about the area of the glacieret at the end of the ablation season (in autumn), which was obtained for each year by field measurements and analytical calculations, show that temperature can be considered as a major factor that drives glacieret fluctuations. At the current stage precipitation factor can not be evaluated properly due to the deficit of accurate climate information.

Key words: the Pirin Mountains, glacierets, size variation, climate change, climatic factors

INTRODUCTION

Although small in size and volume, in many mountain areas glacierets are natural features of sufficient value for studies of the dynamics of environmental processes, climatic variations and change. Glacierets are small bodies of perennial ice, which are smaller than glaciers but bigger and more persistent than snow patches. Glacierets are typified by a density of close-to-bottom ice of about 0.6 to 0.8 g cm^{-3}, presence of annual layers in the vertical cross-section, and long-term persistence — decades to centuries (Grunewald et al. 2008). Usually, these ice forms cover areas of at least several thousand square metres, and are up to several metres thick. Glacierets are in fact embryonic forms of recent mountain glaciation — some authors name them also microglaciers (German: Mikrogletcher, Grunewald et al. 2006).

In Europe, except for the high ranges (the Alps, the Pyrenees and the Caucasus), and the mountains in the high latitudes (in Scandinavia and Iceland),

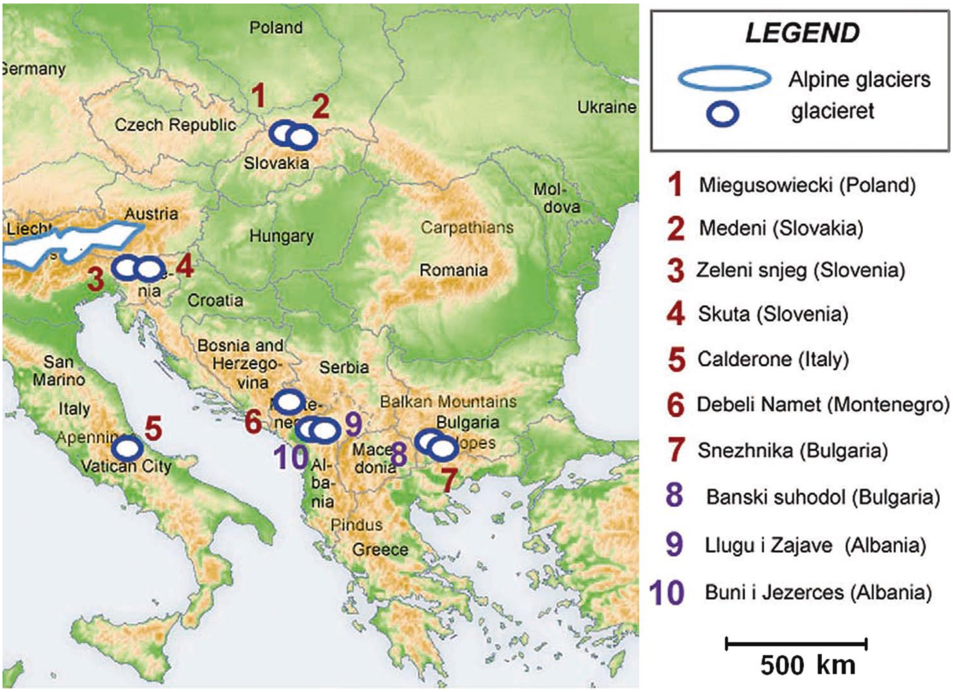

Fig. 1. Glaciers and glacierets in the mountains of Central and Southeastern Europe

small glaciers and glacierets exist also in the mountain areas of Central Europe and the Mediterranean region, where they are scattered outposts of a present glaciation (Fig. 1).

At all these sites, glacial features have been preserved up to the present in places located below the contemporary snow line, which have favorable topography and microclimate. Inter-annual changes of glaciers, glacierets and snow patches are indicative for the specifics of local climate. In most cases these specifics appear to be quite different from regional climatic patterns. In this aspect, the study of glacierets helps to reveal and estimate reaction of local high-mountain environment to climate change.

Small glacial bodies to the south and east of the Alps have been noticed, described and studied since long ago. First information about the presence of perennial snow patches in the High Tatra Mountains dates from the 17th century; some of these patches were defined as glacierets in the middle of the 19th century. First measurements were done in the 1920s and regular monitoring of several glacierets has been performed on a yearly basis since 1980 (Gądek 2008). In Slovenia, the first photograph of Triglav glacier was taken in 1897, and regular measurements have been done each year since 1946 (Čekada, Gabrovec 2008). In the mountains of Bulgaria, the presence of perennial snow was firstly mentioned in the beginning of the 20th century (Radev 1920, Louis

1930), and the first detailed study of Snezhnika glacieret in the Pirin Mountains was done in the period 1957–1961 (Popov 1964). Glaciers in Prokletije (Albanian Alps) were firstly mapped by K. Roth von Telegd (1923), and their presence in the most recent time (along with size estimation) was confirmed by M. Milivojević et al. (2008) and Ph. Hughes (2009). The Debeli Namet glacier appeared on the map of the Durmitor Mountains, Montenegro, in 1986, and regular observations have been held since 2003 (Hughes 2008).

A considerable amount of data about the morphology, dynamics and fluctuations of these small glacial forms has been collected from all these and other studies, and at most sites regular observations are going on. Comparison of the data about variation and changes of these climate-sensitive forms throughout Southeastern Europe (and possible incorporation of these data into a regional network) will help to better understand and assess the specific local and regional responses of the environment to the global climate change.

OBJECT OF THE STUDY

The present study focuses on the inter-annual variations in the size of Snezhnika glacieret, which is situated in the cirque Golemia Kazan on the northern side of the Pirin Mountains in Bulgaria. The glacieret is located on 41°46′09″ N and 23 °24′10″E, which makes it the most southern glacial mass in Europe after the extinction of Corral de Veleta glacier in the Spanish Sierra Nevada in 1913 (Grunewald, Scheitchauer 2010).

The first investigation of Snezhnika was done by Vladimir Popov from the Institute of Geography — Bulgarian Academy of Sciences, in 1957–1961 in relation to the Third Geophysical Year (Popov 1962, 1964). This was the most complex study of Golemia Kazan cirque which comprised geomorphological mapping of Golemia Kazan cirque, drilling of the firn of Snezhnika, measurements of firn's temperature, physical and chemical properties, *in situ* instrumental microclimatic observations (temperature, humidity, precipitation). Instrumental measurements of the climate had been done for 4 years, but were abandoned in the period after.

Size measurements were made in the autumns of 1994, 1996 and each September from 1998 to 2007 by a group of scientists from Dresden, Germany (Grunewald et al. 2006, 2008; Grunewald, Scheitchauer 2008, 2011). Areas were obtained after analytical calculations on the basis of glacieret length and width measured on the field. Since 2006 the autumn size of Snezhnika has been measured regularly by Bulgarian scientists (Gachev 2009, Gachev et al. 2009; Gachev, Gikov 2010). Measurements were made analytically (on the basis of photographs) in October 2006 and in the field by using a rope in October 2008 (Gachev 2009), October 2009 (Gachev et al. 2009) and by E. Gachev and A. Gikov in September 2010 (data for 2010 is published here for the first time).

Golemia Kazan is one of the deepest cirques in Bulgarian mountains. It is formed at the northeastern foot of Vihren peak (2914 m a.s.l.) — the highest summit of the Pirin Mountains (Fig. 2). The cirque has an easterly exposition and a complex configuration; its southern part is a giant armchair carved in the marble of the Northern Pirin, with a base at 2400 m a.s.l.

The western and southern parts of the base are flanked by the 470 m high north wall of Vihren peak, with its lower section almost vertical and the upper one tilted to 60–65°. To the north lies the gentler southern slope of Kutelo peak (2908 m a.s.l.) with tilts in the range of 30–35°. The northern side of the cirque bottom is occupied by a large colluvial fan, fed with material from a gully sloping down from Kutelo massif. The deepest part of the cirque bottom is a complex karst sinkhole, which is opened to the east, but is dammed by a set of moraines from the Würmian glaciation. Due to the karstification there is no surface runoff.

The glacieret occupies a well-formed easterly faced hollow at the base of the wall, and from the north, east and south it is surrounded by a 2–5 m high

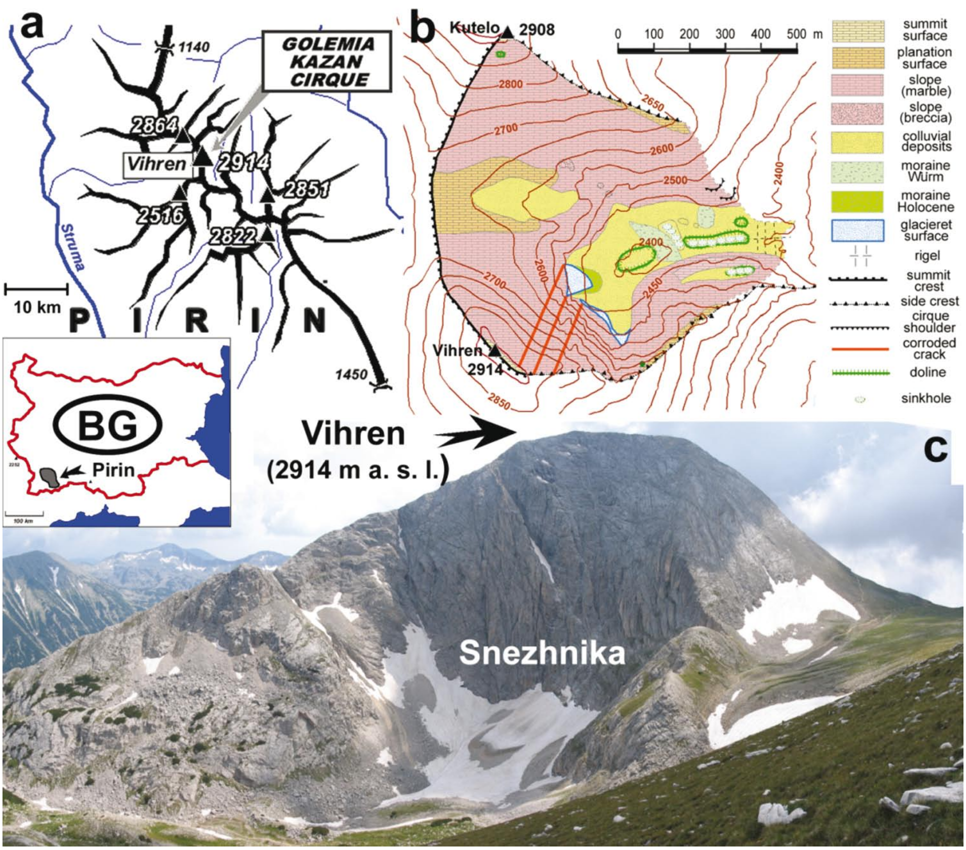

Fig. 2. Golemia Kazan cirque: a) location; b) geomorphology map, c) panorama of the cirque as seen from northeast

ridge of deposited debris, categorized by several authors as a moraine (Grunewald et al. 2008), moraine-like (Popov 1962) or protalus-moraine ridge (Gachev et al. 2009). The ^{14}C dating of the fossil soil layers of the ridge (Grunewald et al. 2008) showed that palaeosols had formed during two warmer periods in the past (the early Roman and Medieval Warm Periods). The observed inverted stratification (the older horizon above the younger) indicates that they were later redeposited. That is why the ridge is suggested by K. Grunewald et al. (2006), K. Grunewald and J. Scheithauer, (2008), K. Grunewald et al., (2008) to have obtained its present shape mainly during the Little Ice Age (15–19 c. AD).

The area of the hollow that is surrounded by the ridge and the back wall was calculated by measuring the contour along the top of the ridge and the back side of the glacieret with a rope, and then processed in GIS. As a result an area of 0.93 ha (real, not projected surface) was obtained, this should refer to the maximal extent of the glacieret during the coldest phases of the LIA. The hollow has a trapezoid shape with a length (from W to E) of about 100 m and a width (from N to S) of about 108 m in its highest part (Gachev et al. 2009).

The glacieret exists here due to the favorable topographic conditions — the strong shading from south and west by several hundred metres high rock walls, the high albedo of the white marble rock and the karstified bottom of the glacieret hollow, where ice meltwaters instantly infiltrate and disappear, leaving the bottom of the glacieret dry almost all the year. The wall on the southeastern side of the cirque, at the base of which Snezhnika is located, has a configuration of a vast funnel that collects avalanche snow from large parts of Vihren's northern slope. According to V. Popov (1964), in March–April the thickness of the snow cover near the rock wall at the back of the glacieret can reach 20 m. Ph. Hughes (2008) pointed out that the existence of glaciers under the snow line in the conditions of Mediterranean climate is possible if precipitation amounts that collect over the glaciated area reach several thousand mm per year (5000–6000 mm yr^{-1} in particular for the Debeli Namet glacier in Montenegro). The deficit from the much lower annual precipitation (in the case of Snezhnika about 1000 mm yr^{-1}) is compensated by large volumes of avalanche snow.

The firn body of Snezhnika usually has a W–E length of about 70–100 m, and a N–S width ranging from 40 m (at the front) to about 90 m (at the back); the dimensions vary considerably over time. The thickness of the firn increases towards the base, where it is in the range of 8–11 m (Popov 1964, Grunewald et al. 2008). The 11 m deep vertical profile obtained in September 2006 (Grunewald et al. 2008, Grunewald, Scheitchauer 2008) revealed the following top-bottom sequence in the vertical structure: 1. old snow, 2. firn, 3. firn ice, 4. ice (below 7 m). Radiocarbon dating of organic particles from the same coring confirmed the persistence of the glacieret at least in the last decades: pollen obtained from 9.75 m depth gave approximate age of about 40–50 years, while humus material gathered from 10.03 m showed a long period of formation (between 1810 and 1924 AD). This should mean that the permanent existence of Snezhnika dates back to the Little Ice Age, and therefore it should have persisted for at least the last 500 years.

STUDIES OF INTER-ANNUAL SIZE VARIATION

Glacierets have a well-expressed annual regime of the change of snow/firn/ice mass. Unlike real glaciers, the entire volume of a glacieret is subject to accumulation in winter and to ablation in summer. In Bulgaria there are two seasons in the annual cycle of glacierets: accumulation season (usually from November to April) and ablation season (from May to October). Each year glacierets reach their minimum mass in autumn, at the end of the ablation season (most often in October). This time is accepted as the end of an annual cycle, and it is the most appropriate for measurements of the area or the volume/mass of glacierets. As the volume/mass of the firn and ice is hard to measure, a common practice in glaciology is to measure glacier length or glaciated area. Snezhnika does not have an elongated shape, so it is most appropriate to measure the total area covered by snow, firn and ice.

The balance of the volume (or mass) of a glacieret can be expressed with the equation:

$$M = (I_s + M_p) - (F_i + F_m), \quad (1)$$

where M is the current glacieret mass, I_s is snow income from snowfall and avalanches during the winter season, M_p is the glacieret mass from the previous year (after the ablation season), F_i is the glacieret mass lost in melting and sublimation during the period with temperatures above 0°C, and F_m is the glacieret mass melted away by rain precipitation during the summer. As direct data for the variables in this equation is not available, they are estimated from oblique parameters that are easier to measure. If climatic data is available, the current glacial mass can be estimated from current glacieret area, winter snow and avalanche income can be estimated from data about winter precipitation and the avalanche catchment area, glacial mass from the previous year can be estimated from the glacieret area of the previous year (autumn), whereas the loss of mass in the ablation season should be estimated from data about air and glacieret ground temperatures (especially summer temperatures), and the amount of rain in summer. At the site of Snezhnika, instrumentally measured climatic data is scarce which makes mass balance calculations difficult and researchers have to rely on data from remote locations.

Data about the area of Snezhnika in the autumn has been obtained for the period 1994–2010 (misses only in 1995 and 1997). During this period the minimal area in the annual cycle varied from 0.30 ha to 0.72 ha, or from 32% to 77% of

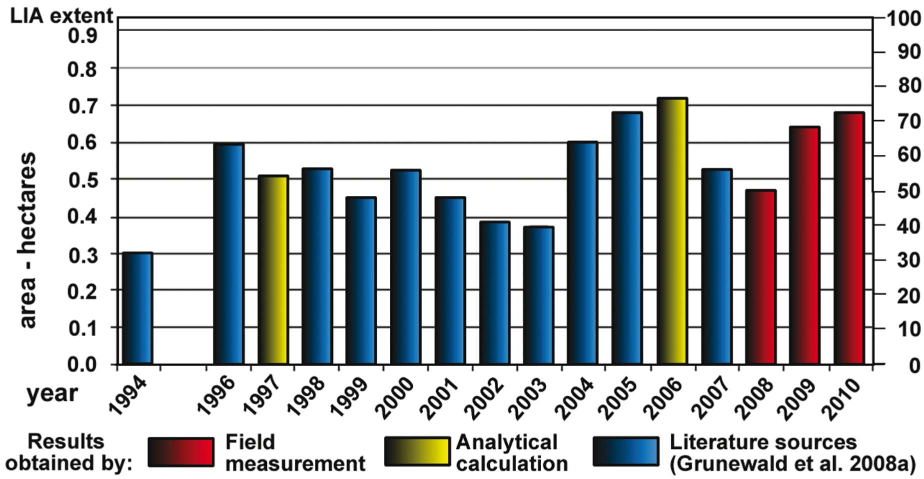

Fig. 3. Glaciated area of Snezhnika glacieret at the end of the ablation season for the period 1994–2010

the suggested extent of the glacieret during the Little Ice Age (figure 3). The analysed data indicates a high inter-annual variability in the area of the glacieret, however, no clear trend is observed in the last two decades. In general, two periods can be distinguished — an earlier period with smaller glacieret area until 2003, and a later period with a higher area from 2004 till now. This reflects the higher amounts of precipitation recorded in the last decade compared to the 1990s.

CLIMATIC FACTORS

The observed wide range inter-annual variation of the glaciated area of Snezhnika is a direct result of the variation of local climatic conditions from year to year. A challenging and important task is to evaluate the role of the main climatic factors that drive the inter-annual changes of the glacieret. As it was mentioned, the task is quite problematic due to the high uncertainty of the available data. During the observation years only the area of the glacieret in its annual minimum has been measured (*in situ* temperature measurements started already in 2009 when Karsten Grunewald installed two temperature loggers in the vicinity of the glacieret). It should be kept in mind that glaciated area is indicative of, but not strictly proportional to glacial mass and volume; as the Snezhnika has a complicated 3-D shape and the thickness in the different zones of the body of the glacieret changes each year. That is why absolute dependencies between the studied environmental variables cannot be determined or expected.

TEMPERATURE

Temperature conditions play a major role for the mass balance of glaciers. The increase of air temperature is suggested to be the main reason for the globally observed retreat of glaciers in the last 150 years. While average annual temperature shows the overall thermal level of the atmosphere in a particular year, the temperatures of the summer season (i. e. the positive temperatures) determine the loss of mass in melting and sublimation to a great extent. Negative temperatures in winter set the background for snow accumulation. What is more important is the duration of the period with below zero temperatures at the site of the glacieret. On the other hand, positive temperatures are important with their particular value, which has a direct impact on the rates of ablation. That is why summer temperatures can be suitably evaluated by using either sums of temperature above 0°C or the mean temperature for the period with positive air temperatures.

As at the site of Snezhnika glacieret direct data about temperature has not been obtained except for the short period 1957–1961, data from remote locations need to be used. Few stations had been operating in the past in various parts of the mountains, however, except several recently installed loggers, at present there is no climatic station to collect data about temperature in the Pirin Mountains. That is why the climatic station at Musala peak (2925 m a.s.l.) in Rila (55 km away) that has been operating continuously since 1933 is used as a standing point for evaluating temperature. Data from the station is available on the Internet (www.stringmeteo.com). Climatic station of Bansko, located at 930 m a.s.l. at the foot of the Pirin Mountains, 7 km away from Golemia Kazan cirque, is used as a second reference point. Comparative analysis of data from Musala peak and from Golemia Kazan cirque for the period 1957–1961 (Nojarov, Gachev 2007) showed a very close correlation between the two localities (r = 0.99), which makes Musala a suitable point to estimate temperature in the highest parts of the Pirin Mountains. On the basis of climatic data from Musala peak and Bansko for the period 1973-2006 K. Grunewald and J. Scheitchauer (2008) showed that temperatures in Golemia Kazan are on average by 2.2°C higher than those at Musala peak. So in the present work temperatures and temperature sums in Golemia Kazan for the period 2001–2010 are derived by using the average daily and monthly temperatures at Musala peak with the mentioned correction. Here one must bear in mind that these are temperatures 2 m above ground, whereas ablation depends directly on ground temperatures. In this aspect more research is needed.

Summer temperatures (in this case: average air temperature for the ablation season) show quite a different pattern than annual averages. One of the most appropriate parameters for evaluation of the solar energy received by the glacieret is the sum of active temperatures (in this case the positive temperatures), because it combines both the values of temperature and the duration period of their impact. The years 2000/2001, 2007/2008, 2006/2007 and 2009/2010 were relatively the warmest, while the year 2003/2004 was the coldest (Tab. 1).

Table 1

Calculated temperature data for Snezhnika glacieret for the observation years 2000/2001 to 2009/2010 (years delimited between each two consecutive measurements in autumn)

Parameter	Year									
	2000 2001	2001 2002	2002 2003	2003 2004	2004 2005	2005 2006	2006 2007	2007 2008	2008 2009	2009 2010
Annual temperature °C	1.0	–0.3	–0.5	–0.7	–0.6	–0.3	0.5	0.3	–0.2	0.5
Summer temperature °C*	5.5	5.3	6.0	5.1	5.3	5.1	6.7	6.4	5.7	6.1
Period with positive T (days)	207	201	174	160	194	199	168	177	184	184
Sum of temp.above 0°C	1129	1072	1043	824	1019	1013	1127	1131	1051	1120

*average temperature for all the days with average air temperature above 0°C

PRECIPITATION

Precipitation is one of the most important factors for the fluctuation of glaciers. It has a two-fold impact – snow precipitation in winter adds mass to the glacier, while rain supports melting in summer. Several problems occur when trying to evaluate precipitation as a factor for the variation of glacieret size. First of all, precipitation is generally difficult to measure accurately, especially snow (Veit 2002). Second, high variability in the spatial distribution of precipitation generates huge errors if there is no rain gauge at the spot and remote stations are used. Third, it is hard to estimate the exact role of rain in ice melting, because particular temperature of rain is not measured, neither is there information about drop size and intensity of precipitation. Finally, it is hard to exactly separate snow from rain.

In the present work, data about precipitation is used from several stations depending on its availability; some data are used only for reference. For the studied period (2001–2010) data is available only for the station of Sandanski, situated at the SW foot of the Pirin Mountains (30 km away). No accurate data is available for the public from the station of Bansko, except for an older period (until 1981). The closest station to Snezhnika is Vihren hut at 1970 m a.s.l., situated 3 km to the west. It worked from 1961 to 1981 with many gaps in the record. Other stations inside the Pirin Mountains operating in the same period were those at Demyanitsa hut and at Popina laka (Fig. 4). The only station in Bulgaria for the elevation above 2400 m a.s.l. is that at Musala peak.

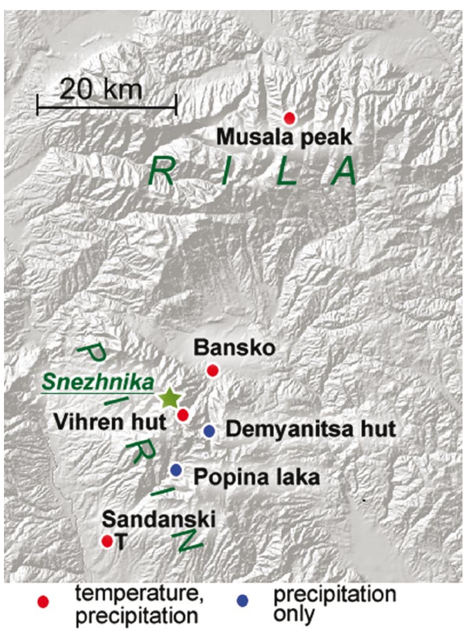

Fig. 4. Location of rain gauge stations in Pirin mountains

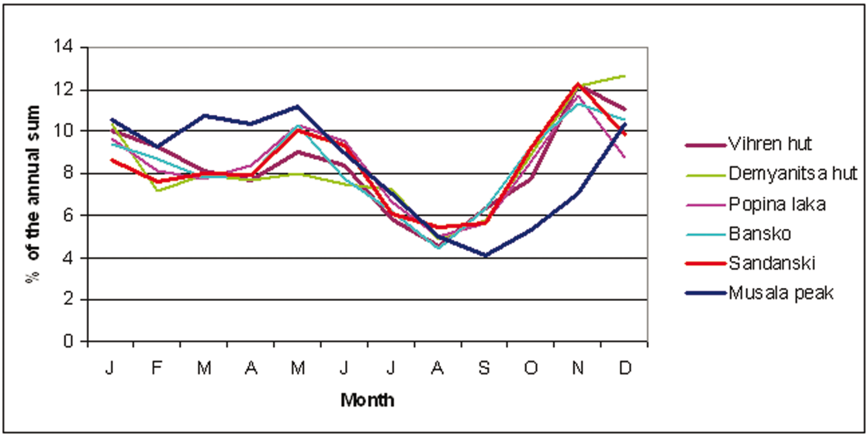

Fig. 5. Monthly distribution of precipitation (in % of the annual sum)

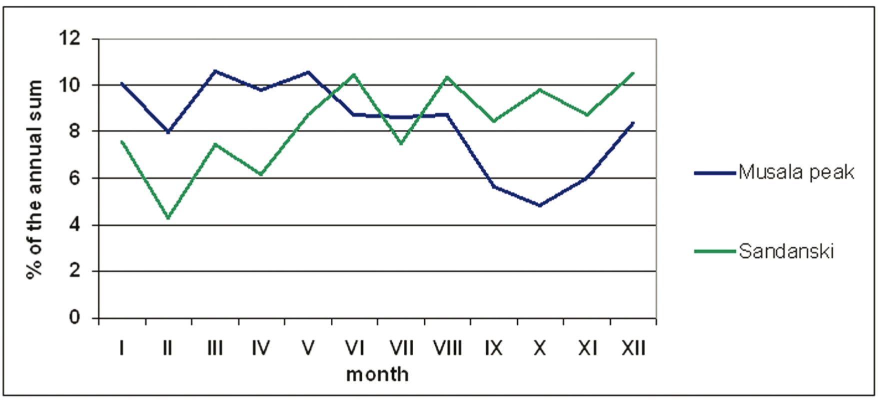

Fig. 6. Average monthly precipitation for the period October 2000–September 2010

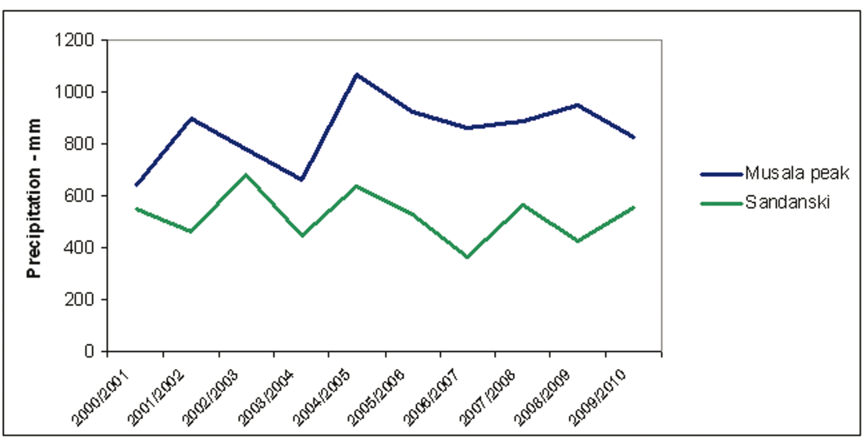

Fig. 7. Annual precipitation amounts at Musala peak and Sandanski calculated for the periods between each two consecutive measurements of the firn area of Snezhnika glacieret

Revision of data from the period 1961–1981 (Fig. 5) shows that despite considerably higher altitude, the station at Vihren hut has a regime that is very similar (almost identical) to all the other stations within the Pirin Mountains, and quite different from that of Musala peak. This means that in the present period the station of Sandanski is much more indicative for the monthly (and therefore seasonal) distribution of precipitation at the site of Snezhmika than Musala peak.

In fact, monthly differences in the precipitation as part of the annual sum between Vihren hut and Sandanski reach about 1.5% at maximum.

Similar pattern is observed when looking at the regime of precipitation for the available stations — Musala peak and Sandanski, for the study period (from the autumn of 2000 to the autumn of 2010, Fig. 6). On the other hand, the trends of the annual precipitation amounts recorded at Musala peak and those measured in Sandanski differ from each other (Fig. 7): at Musala, years after 2003 are characterized by generally higher precipitation than the years before, which to some extent matches the diagram of the glacieret areas of Snezhnika (Fig. 3). This relation is not observed in Sandanski.

The two main types of precipitation cause reciprocal effects on the changes of ice mass. An interesting result from the analysis of the available data series is that the year-to-year variations of precipitation balance (the snow — rain difference) for the periods between each two autumn measurements of the area, made on the basis of data from the station of Sandanski (i.e. the difference between the sum of precipitation at Sandanski when temperatures at the site of Snezhmika were negative, minus the sum of precipitation at Sandanski when temperatures at the site of Snezhmika were positive), provide a much better match to the changes of the area of the glacieret, than just the changes in the amount of snow precipitation between each two consecutive measurements. However the use of the balance (either in mm or in %) is to some extent abstract, because a given quantity of rain will have not equivalent but opposite effect when compared to the same quantity of snow. Precipitation balance, along with data about winter and summer precipitation derived from the station of Sandanski, is presented below, but at the present stage of the research it can only serve as a reference. Data about precipitation at Musala peak is not used in the analysis because neither calculated values for snow precipitation nor the precipitation balance have a good match (see Tab. 3).

Despite all of the described obstacles it is still reasonable to try to evaluate the precipitation factor because of its great importance for the changes in glacieret area and mass. The best solution in the case is to carry out precipitation measurements in the field. Sadly, this has not been possible in the vicinity of Snezhnika in the recent years.

Table 2

Parameters of the inter–annual dynamics of Snezhnika glacieret

Year	Area [ha]	Area [% of LIA]	Δarea [%]	Sum of T > 0°C	Precipitation — Sandanski [mm]			Precipitation — Musala peak [mm]		
					Balance	Winter	Summer	Balance	Winter	Summer
2000/2001	0.45	48	–8	1129	–70	141	211	+55	348	293
2001/2002	0.38	42	–6	1072	–54	206	260	–89	404	493
2002/2003	0.38	40	–2	1043	–46	320	366	+53	413	360
2003/2004	0.60	64	+24	838	+69	260	191	+200	428	228
2004/2005	0.68	72	+8	1019	+60	349	289	+86	604	518
2005/2006	0.72	77	+5	1013	+13	271	258	+70	463	393
2006/2007	0.53	56	–21	1127	–8	181	189	+240	553	313
2007/2008	0.47	50	–6	1131	+193	380	187	+397	643	246
2008/2009	0.64	68	+18	1051	+100	264	164	+286	620	334
2009/2010	0.68	73	+5	1120	+110	333	223	+90	460	370

Table 3

Correlation between inter-annual changes of the glaciated area of Snezhnika (Δarea) and climatic parameters

Parameter	Correlation coefficient: *r*
Sum of temperatures for the period with positive temperatures	–0.76
Average annual temperature	–0.61
Average temperature for the period with positive temperatures	–0.60
Percentage of winter precipitation based on data of Sandanski	+0.41
Precipitation balance based on data of Sandanski	+0.39
Winter precipitation based on data of Sandanski	+0.27
Percentage of winter precipitation based on data of Musala peak	+0.15
Precipitation balance based on data of Musala peak	+0.10
Annual precipitation — Sandanski	+0.05
Annual precipitation — Musala peak	+0.02

RESULTS

Table 2 shows the main parameters of the inter-annual variations in the size of Snezhnika glacieret for the last 10 years.

From the comparison of data about precipitation from the stations of Sandanski, Vihren hut and Bansko, a conclusion can be made that precipitation regime in fact does not change significantly across the Pirin Mountains. That is why the proportion of monthly precipitation at Sandanski for all the months of the observation period is considered acceptable also for Golemia Kazan cirque. There is no sufficient data to extrapolate accurate precipitation amounts in Golemia Kazan, but according to the measurements of Popov (1964) it is suggested that they are about 100% higher than those at Sandanski. Analysis here exploits just the proportions of different monthly amounts and different types of precipitation (snow/rain), not the absolute values recorded in Sandanski.

Here follows a short year-to-year interpretation of inter-annual variation in the area of Snezhnika for the years 2000/2001–2009/2010 based on the data from Table 2.

Year 2000/2001: the area dropped by 8 % from the previous year due to a negative precipitation balance and high sum of positive temperatures.

Year 2001/2002: Temperatures were lower, but the negative balance of precipitation still caused a further decrease of the area by 6%.

Year 2002/2003: Precipitation balance was still negative, but temperatures continued to decrease and the drop of area was insufficient.

Year 2003/2004: A great drop in temperatures and a slightly positive precipitation balance in addition resulted in an increase by 24%, the greatest fin the studied period.

Year 2004/2005: Temperatures almost reached the levels of 2001–2003, but the precipitation balance was positive. This caused a further increase of the area by 8%.

Year 2005/2006: Temperatures remained similar to the previous year, but smaller precipitation balance resulted in a smaller increase of the area: by 5%. In the autumn of 2006 the glacieret had the largest post-ablation area in the whole 10 year period (Fig. 8).

Year 2006/2007: The sum of positive temperatures increased by 11% and the precipitation balance turned to negative. This resulted in a 21% decrease of glaciated area.

Year 2007/2008: Precipitation balance was strongly positive, but the sums of temperature reached their maximum. The result was a further 6% decrease of the area (Fig. 8).

Year 2008/2009: Although with a lower value than in the previous year, precipitation balance was positive. In combination with the serious drop in temperature this lead to a considerable expansion of the glacieret: 21% increase of the area.

Year 2009/2010: Precipitation balance kept positive, similar to the last year. Temperatures rose and the increase of the area was only 5%.

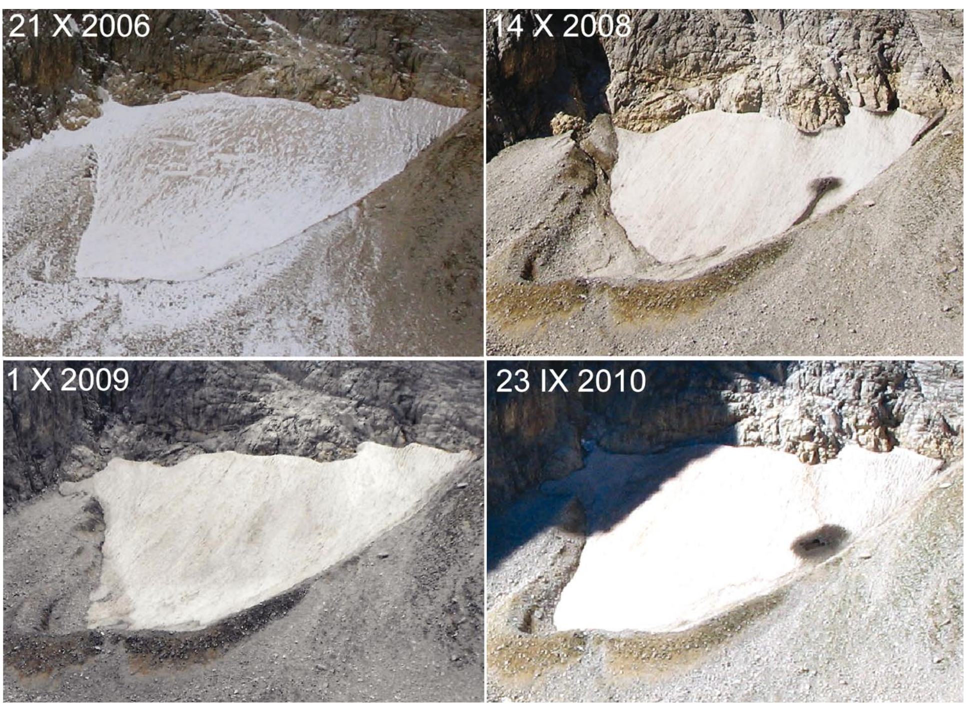

Fig. 8. Snezhnika glacieret in the autumns of 2006, 2008, 2009 and 2010 (pictures presented in an equal scale)

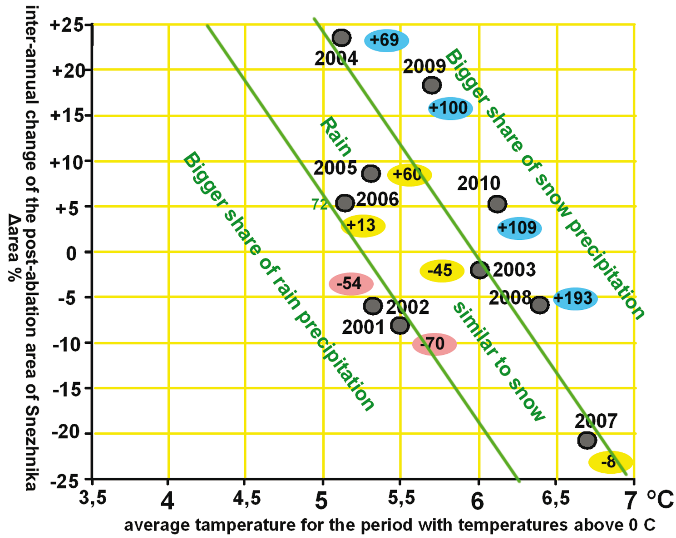

Fig. 9. Observed approximate dependencies between inter-annual changes of glacieret area, levels of summer temperature and precipitation balance based on available climatic data

The presented short description shows that temperature conditions can still be considered as the most important factor that causes the inter-annual size variation. This is obvious when looking at correlation coefficients obtained for the relationship between the inter-annual variation of the area of Snezhnika (%) and the main climatic parameters (Tab. 3). Here the latter are calculated for the particular periods between each two size measurements of Snezhnika in autumn.

The data shows that only direct relations between changes in area and temperature parameters can be considered as statistically significant. The type of precipitation balance (positive or negative) can be accounted as a secondary factor. Its particular value for each year sharpens or softens the trends dictated by temperature (Fig. 9).

Importantly, due to the uncertainties of data these relations are only just approximate and cannot be used for precise calculations at this stage. Errors can be minimized when climatic measurements are performed in the vicinity of the glacieret.

DISCUSSION

Although variations in the area/length of small glaciers, glacierets and snow patches are closely related to topography, the general mode of these variations, as well as some specific characteristics of their morphology, are determined by the regional climatic patterns.

The climate of the valleys and hollows around the Pirin Mountains is categorized as Continental-Mediterranean (Velev 2010), or as Mediterranean with cold winters (Rachev, Dinkov 2003). The high mountain area of Northern Pirin has a low temperature modification of this type of climate, withmaximum winter precipitation and an average precipitation of about 1000 mm yr^{-1}. Mean annual temperatures at the site of Snezhnika glacieret are in the range of –0.4 to +1.5°C (based on the data from Musala peak for the period 1994–2010).

Despite the deficit of reliable climatic data, results obtained from the systematic measurements of Snezhnika glacieret during the last 10 years suggest that variation of summer temperature is among the main driving factors for the observed year-to-year variation of glaciated area (and firn/ice mass, therefore). Long-term changes in annual precipitation seem to be responsible for the decadal shifts of prevailing high/low values of glacieret area/mass; for example, the period of low area in 1994–2003 and the period of high area in 2004–2010.

A brief regional comparison with other features of perennial ice in the region helps to better explain the observed mode of the size variations of Snezhnika. The other glacieret in the Pirin Mountains, Banski suhodol, is the largest in Bulgaria and had a surface area of 1.2 ha in October 2009 (Gachev et al. 2009; Gachev, Gikov 2010). It seems to have similar mode of variations, although in a less expressed manner (as suggested by our observations of this glacieret in the years 2009–2011). According to our field observations most of the glacial features found in the Albanian Alps (around the highest peak Maja e Jezerces, 2694 m a.s.l.) are in their appearance quite similar to the glacierets in the Pirin (Fig. 10), although they occupy areas larger than Snezhnika, and researchers (Milivojevic et al. 2008, Hughes 2009) described them as active glaciers. It should be noted that these glaciers are situated at much lower altitudes (1980–2420 m a.s.l.). The same concerns Debeli Namet glacier in the Durmitor, Montenegro, which has a morphology of a real glacier (Hughes 2007, 2008) and is situated between 2050 and 2300 m a.s.l. The presence of perennial ice at the latitudes of about 42° N and at such low altitudes is explained by the greater precipitation amounts — suggested by Ph. Hughes (2007, 2008, 2009) to be in the range of about 2500–3000 mm yr^{-1}.

However, although most glacial features in the Western Balkans show morphologies similar to that of Snezhnika, until now the studies have revealed a greater variability of the size of these forms in comparison with the glacierets in Bulgaria. The field observations of the author of the present study in the Albanian Alps in the autumn of 2011 showed that the so called “largest glacier on the Balkans” — the glacier Maja e Kolacit, as described by M. Milivojević et al. (2008) and Ph. Hughes (2009) had been disintegrated into two small and shallow ice patches. During the studies in 2003–2007, Debeli Namet glacier in the Durmitor was recorded to have an area between 1.8 ha (2003) and 5.0 ha (2006) (Hughes 2008). Photos, made during our observations of the glacier in the autumns of 1998 and 2011 (Fig. 11) demonstrate the great variability of the glacier size. This should be explained with the greater variations in precipitation in the damp Mediterranean climate such as that of the Dinaric mountains.

The small glaciers located further to the west — the Triglav glacier in the Julian Alps (Slovenia), and Calderone glacier in the Abruzzi (Italy) have a different mode of size variations — both glaciers have been steadily and continuously shrinking for the several decades (Gabrovec 1998, Gabrovec, Zakšek 2007; D'Alessandro et al. 2001), including the last 20 years – a trend that has

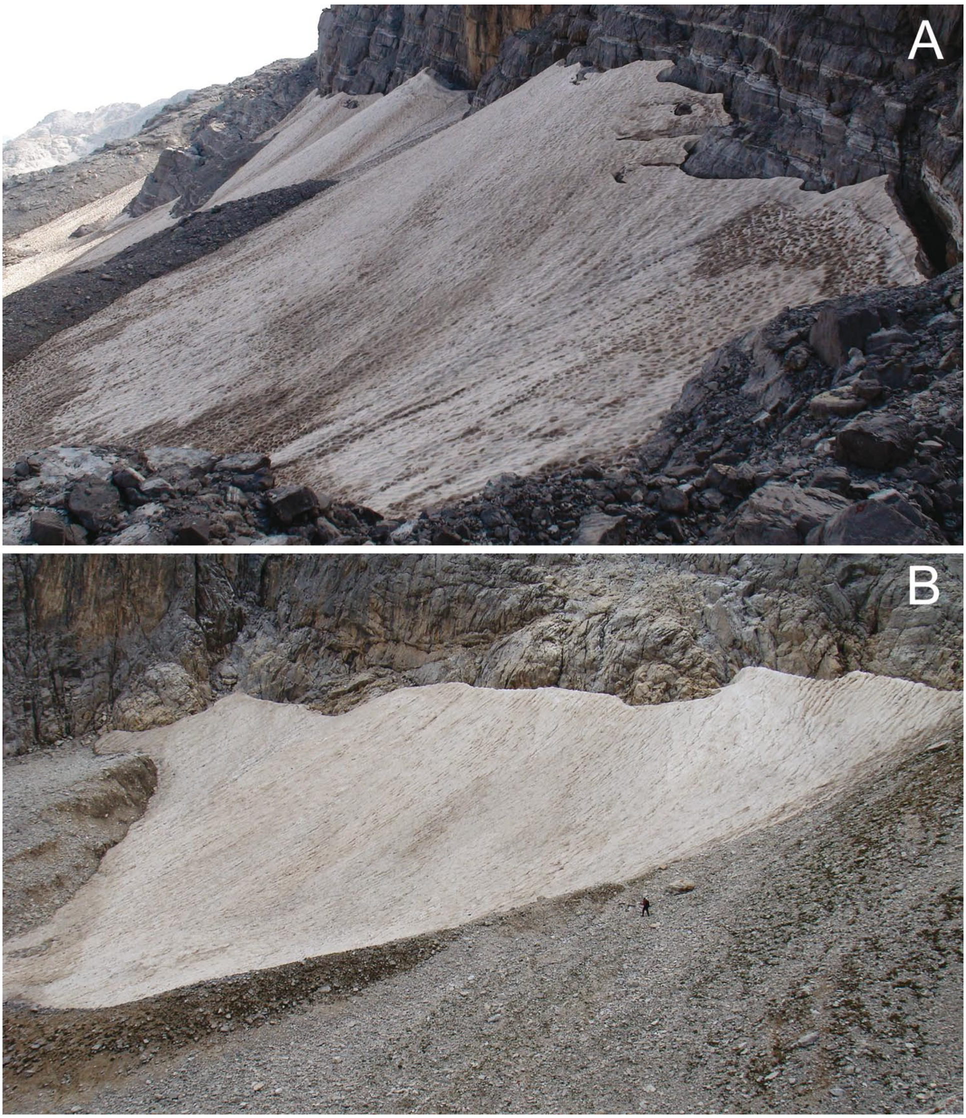

Fig. 10. Similar appearance of "Maja e Jezerces I" in the cirque Llugu i Zajave, Albanian Alps (A — described by M. Milivojevic et al. (2008) as an active glacier) and Snezhnika (B — categorized by K. Grunewald et al. (2008) as a glacieret)

not been observed neither for the glacierets in Bulgaria nor for those in Albania and Montenegro. According to M. Gabrovec and K. Zakšek (2007) between 1960 and 2006 Triglav glacier has lost 95% of its area (from 12.0 to 0.6 ha), mainly as a result of the rise in summer temperatures (it is interesting that in the period 1994–2006 Triglav glacier gradually reduced its size from 2.2 to 0.5 ha, while at the same time Snezhnika increased in size from 0.3 to 0.77 ha). Similar is the situation with Calderone glacier in Italy, which has lost 90% of its volume and 68% of its area in the period 1916-1990 (D'Alessandro et al. 2001). It seems that the progressive shrinking of both glaciers is related to their topography — although they are facing north, they are situated on higher slope sections, which are weakly shaded, especially from the east and west, and this makes them more strongly dependent on the temperatures in the free atmosphere. Moreover, temperature rise in the last three decades has led to an increase of rain precipitation and the decrease of snowfall, which supports the degradation of glaciers.

The other Slovenian glacier, situated below Skuta peak (2532 m a.s.l.) in the Kamnik Alps, is a typical cirque bottom feature, which is well shaded from three sides. M. Pavšek (2007) reported the overall shrinkage of the glacier in the last six decades (from 2.8 ha in 1950 to 1.1 ha in 2007), and especially in the last 20 years, although the process is not as rapid as at Triglav glacier, and even a small increase was registered between 2003 and 2007. It seems that the slower rates of glacier shrinkage are a result of the morphology of the glacier site, but the overall negative trend is dictated by the changes that occur in regional climate of the Southeastern Alps in the last decades.

Glacierets in the High Tatra Mountains, which, like those in the Durmitor and the the Pirin Mountains, are situated in concave forms at the bases of rock walls and rely mainly on avalanche snow, also show quite stable modes of size variation. Although some reduction of area and thickness has been observed since the 1920s (Jania 1997), the size variations in the last 50 years in general show no clear trend (especially for Mięguszowiecki glacieret; Gądek 2008). Here we have to mention that the mechanism of changes of these glacierets and the factors that determine these changes differ from those in the Mediterranean area. A. Wiśliński (2002) pointed out that the size variations of Mięguszowiecki glacieret in the period 1980-2001 had not been in relation to the changes in air temperature, although B. Gądek (2003) confirmed the strong relationship between the variables of air temperature, recorded near the glacieret, and the rates of ablation in particular. According to B. Gądek (2008), driving factors for the observed variations in the size (length) of several glacierets in the High Tatras are the intensive rains in summer (up to 166 mm per 24 h during the period 1980–2001), the formation of underground tunnels in the ice from the rain waters and the incident collapse of the latter. As the occurrence of heavy rains in summer is of an accidental character, this factor is hardly to be explained with climatic totals or averages. Although observed similarities in topography, in the case of Mediterranean small glaciers/glacierets no conditions exist for a development of underground tunnels, because the summer is usually dry. Therefore, the size changes of Snezhnika should be more temperature dependent that those of the glacierets in the Tatras, and less temperature dependent than those of Triglav and Calderone glaciers.

CONCLUSIONS

The persistence of Snezhnika in the last centuries, its relative stability in the recent time despite the strongly expressed inter-annual variety of area and mass (which seem to be much greater than the observed decadal and centennial changes of the glacieret) makes it a valuable indicator for the fluctuations of high mountain climate. The comparison between glacieret areas during the annual minimum (measured on a regular basis since 1994 and especially in the last 10 years), and available climatic data series, highlight the variations of temperature as a major factor that causes the changes of the size of the glacieret from year to year.

In a regional aspect the variations of the size of Snezhnika glacieret appear to be more temperature dependent than those of the glacierets in the Tatra Mountains, less temperature dependent than those of the glaciers in Slovenia, and more stable in mass balance than the glaciers in the Western Balkans (Albania and Montenegro).

To make these results more reliable, it is necessary to broaden the analysis to all 17 years of systematic observation. Research in the future must include in situ instrumental climatic measurements with automatic devise to retrieve local climatic data.

South-west University "Neofit Rilski",
Faculty of Mathematics and Natural Sciences
66 Ivan Mihailov str., 2700 Blagoevgrad, Bulgaria

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