Chapter 4

The Unknown Southernmost Glaciers of Europe

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Additional information is available at the end of the chapter

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Abstract

This chapter presents the perennial firn/ice patches in the mountains of the Balkan Peninsula. The detailed study of these features in the last decades has proved that many of them are, in fact, small glaciers. They have survived without complete melting since the end of the Little Ice Age, and thus the time of their formation must have not later than in 14–15th century AD. At present, the existence of 16 small glaciers is suggested (and proved for some of them) in three mountains throughout the peninsula: Prokletije (mainly in Albania), Durmitor (in Montenegro) and Pirin (in Bulgaria), the biggest number being found in Prokletije. The two small glaciers (glacierets) in Pirin mountain are at present the southernmost glacial masses in Europe (the only located south of 42°N). Despite the registered warming of high mountain climate, small glaciers on the Balkan Peninsula have shown no trends towards shrinkage for the last 23 years.

Keywords: small glaciers, snow patches, Pirin, Durmitor, Prokletije

1. Introduction

Few mountains in Europe host classical glaciers at present: The Alps, the Great Caucasus range, the Scandinavian mountains, Polar Ural and the Pyrenees [1]. Apart from them, there are numerous small bodies of firn and ice in other mountain ranges across Europe which are still of a permanent character, with their mass moving down by gravity. Of a special interest are those in the mountains of Southern Europe [2]. They represent the furthest glacial outposts, some of which located at almost subtropical latitudes (41–43°N). Most of them exist well below the present climatic snowline, in places of favourable topography and local climate. The marginal conditions in which they still persist, and their great sensibility on short-term climate variations, make them perfect natural indicators and objects for climate change studies. The present chapter will focus on small glaciers on the Balkan Peninsula. Here, at present, the southernmost glacial masses of Europe are located [2] (**Figure 1**).

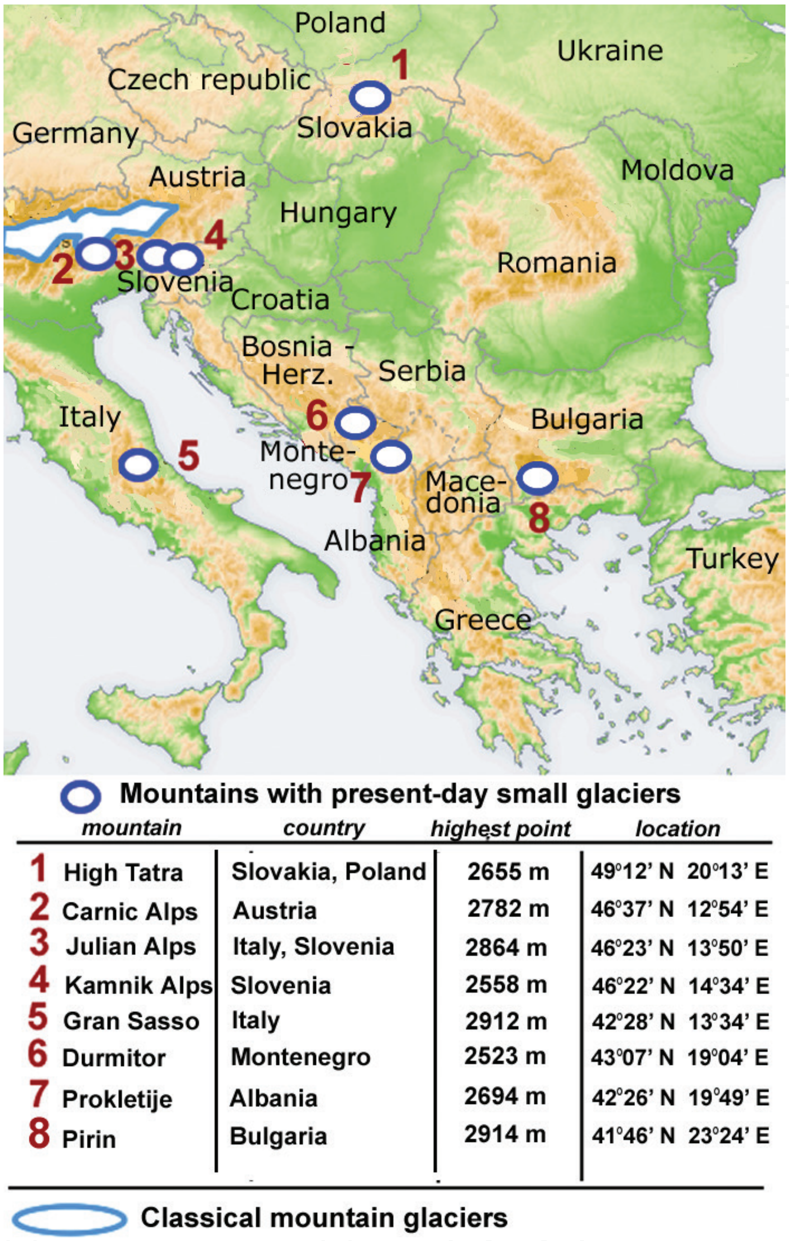

Figure 1. Mountains in Southeastern Europe with present-day small glaciers.

Scientists categorize small sustainable firn and ice features mainly in three types: small cirque glaciers, glacierets and snow patches [3].

Small cirque glaciers and glacierets occupy small sections of Pleistocene glacial cirques (usually just below tall rock walls) and can be considered as remnants of former cirque glaciers, which existed during the termination phases of the Wuermian ice age. On the Balkan Peninsula, these features occupy areas of 0.5–5 ha and have thicknesses in the order of 10–20 m. Moraine ridges have framed their lower ends. Small cirque glaciers have elongated contour, a longitudinal profile with a concave upper part and convex lower section of a tongue shape. Glacierets have simpler longitudinal cross-section (convex or concave or straight), lack of a pronounced tongue-like end and the width is often greater than length [4–6]. The presence of dynamic downward motion of firn-ice mass has been, however, proved in both types [3]. Snow patches on the other hand are not considered glaciers. They are either forms that are not permanent in a long-term sense (for more than several years), or they persist in time, but without conditions for motion. Features of the latter type often occupy karst sinkholes.

On the Balkan Peninsula, the present existence of at least 16 small glaciers has been documented and studied in three of the highest mountains: Pirin (in Bulgaria), Prokletije (mainly in Albania) and Durmitor (in Montenegro) [3–18]. Some specific conditions combine to make them possible to exist 600–800 m below the present position of the climatic snow line (estimated between 2700 m in the Western Balkans and 3200 m in the Eastern Balkans, [12, 19]): (1) altitudes between 1900 and 2600 m a. s. l. that provide for relatively low, annual, and seasonal air and ground temperatures (annual: +1 to +3°C, still too high for glaciers); (2) karstified carbonate bedrock, lightly coloured, with high albedo. It does not get warm too much in summer and allows the drainage of glacier meltwaters during ablation season, thus hindering glacier melt; (3) Shaded locations in former cirques (North or NE aspect, below high rock cliffs); (4) High winter precipitation and great contribution of avalanche and windblown snow in mass accumulation, which allows to effectively double the actual amount of snowfall.

High mountain climate conditions at these altitudes define two seasons in the annual cycle of small glaciers: accumulation season (from November to April) and ablation season (from May to October), and a balance year that can be considered similar to the hydrological year accepted for the region [20]: November 1 to October 31. Autumn (September 15 to October 31) is the best time to observe small glaciers and measure the results of the consecutive mass balance year.

2. Research of small glaciers

A wide variety of methods are applied in the research of small glaciers, many of them are specific. The knowledge about these features can be addressed as 'microglaciology', a field of science that bridges between classical glaciology and periglacial geomorphology.

Mass balance studies reveal inter-annual variations of small glaciers. The most accurate would be to measure changes of firn/ice volume. This is hard to do as it requires detailed knowledge about glacier subsurface topography, and laborious measurements after both the accumulation and ablation season. If small glaciers are to be observed mainly as climatic indicators, it is often enough to know relative changes from year to year and in longer terms. In this context, it is easier to measure the surface area of small glaciers or, as alternative (or in addition), to record fluctuations in glacier front or ice level by a measurement on the field or by photographs. It is desirable that these are done at least once a year, in autumn, to summarize the results of the ending mass-balance cycle (balance year).

On the field, glacier area is measured usually with a measuring tape (or rope) and a laser range finder. Measurements are done along glacier contour (in cases of a simpler shape) or on selected lengths and widths (in cases of irregular contours). Satellite image data can also be used if done in the exact time of the year. Distances of glacier fronts from fixed positions are measured in cases of changeable lower ends, again with the use of a tape. Current positions of firn level can be marked with paint on the rock. Measured data are then processed in a laboratory: measured lines are entered in Geographic Information System (GIS) in an appropriate scale, and then, the software calculates the exact areas. When only selected lengths and widths are measured, they are entered in the software in a proper scale. They are used as a frame, on which photographs of the glacier surface, made from distant positions, are then fitted. After that glacier contour from those images is digitized, and the area is calculated.

Spatial overlay of data from multiple measurements allows for precise comparison between glacier states of different years. Repetitive photography is also an important technique to obtain inter-annual changes. Glaciers are photographed each time from same (fixed) positions, and then images are overlayed. Precise data about area and volume cannot be obtained by using this method, but it is highly indicative when tracing the relative changes and trends in the development of small glaciers. Later, if proper scaling is done on the field, accurate absolute values for surface area and level variations can be retrieved from such photographs.

The current state of snow and firn cover is also quite indicative for the mass balance from the past year, especially for the evaluation of accumulation and ablation varieties across glacier surface. It is assessed on the field, with the use of alpine equipment (crampons, ice axe, etc.).

Effects from accumulation season only are studied in spring (April–May) by measuring snow cover thickness and density in glacier vicinities. Such observations have been rare, especially in our region, due to the high avalanche danger and limited accessibility of glacier sites in that time of the year.

Morphology studies involve geomorphological, glaciological and geophysical methods. Morphology analysis aims to reveal how a glacier is formed. It requires a detailed description of glacier surface geometry (contours, tilts, bergschrund, crevasses, caverns) and the character of surrounding landforms (moraines, protalus ramparts, avalanche gullies, screes). Size and roundness and lichen cover of debris are assessed. Weathering of depositional forms can be examined, e.g. with a Schmidt hammer [21, 22]. However, only relative age can be assessed with these methods.

Internal structure of small glaciers is testified with various techniques, which require investments in labour and equipment. The easier way is to excavate pits in glacier body, but this is hard to do and not much informative as pits cannot be deep. It is better to study natural outcrops of glacier body instead (bergschrund or cracks). Drilling with appropriate ice drills allows to reach depths below 10 m and to retrieve unspoiled cores for analysis in a laboratory. Radar sounding makes possible to estimate underground structure (thickness, sediment layers, patches of buried ice) without digging [23]. Both drilling and sounding, however, require carrying out heavy and expensive equipment, and this sets limitations on the application of these techniques, especially in hardly accessible high mountain areas.

Isotope composition of firn and ice along with absolute ages of formation of glaciers and their surrounding landforms (e.g. moraines) can be verified with the use of laboratory techniques after taking samples of rock, ice or organic particles. Such analyses (isotope, radiocarbon, etc.) are costly and have been applied just for two of the small glaciers on the Balkan Peninsula (in Pirin [4–6] and Durmitor [24, 25]). Absolute ages of surrounding moraines have been also retrieved by lichenometry for a glacier in Durmitor mountains [13].

3. An overview of small glaciers on the Balkan Peninsula and their research

Glacial nature has been already proved for four glaciers: two in Pirin, one in Prokletije and one in Durmitor. Twelve more features in Prokletije mountain are considered as, most probably, glaciers on the basis of their morphology and behaviour in the last decade [3].

3.1. Pirin

Pirin is the second highest mountain in Bulgaria and the third highest on the Balkans (**Figure 2**). It rises in the south-west part of the country, reaching an altitude of 2914 m a. s. l. at its highest point—Mt. Vihren. The mountain is a horst block, oriented NNW to SSE, which is built of granitic intrusions and a mantle of metamorphic rocks. A section of the northern part has on its top a thick (500–1000 m) cover of marble that composes the main ridge and the northern slope. Several gigantic glacial depressions (cirques) were formed in this area during the Wuermian ice age and subsequently have been karstified. At least four sustainable snow/firn features have been discovered and mapped in this area. Two of them have been proved to be small glaciers and, more strictly, glacierets [3, 5, 7].

Snezhnika glacieret is located at 41°46′09″N and 23°24′10″E at 2400–2450 m altitude a. s. l., just below the north-eastern marble wall of Vihren peak. The glacieret has an eastern exposure and a trapezoid shape with length of 80–100 m and width about 90 m. About 4–5 high moraine ridge surrounds glacieret body from three sides. It is considered to be formed in its present shape in the Little Ice Age [4–6] (**Figure 3**).

The first measurements and drilling of Snezhnika were done in 1957–61 by the Bulgarian karstologist Vladimir Popov, in relation to the Third International Geophysical Year [26]. The drilling reached the bottom at 8-m depth. Regular climatic measurements were performed in a meteorology station, which was equipped with a thermograph and gauge for total precipitation [27]. After the end of the programme, research was abandoned. German scientists from Dresden measured glacieret area in the autumns of 1994, 1996 and 1998–2007. In 2006, they made three drillings of the firn, the deepest reaching the bottom at 11 m. Glacier ice with a density of 0.9 Kg/l was found in the cores at depths below 10 m, and the radiocarbon dating of organic particles from these depths confirmed the ice was at least 100 years old [4–6]. This is a direct evidence for the glacial nature of Snezhnika. Since 2008, the glacieret has been also monitored by Bulgarian scientists. Its area has been measured in every autumn for the last years (2008–2016) [3, 19, 20]. After the hot summer of 2012, a cave that is 25 m long and 1.5–2.5 high opened at the bottom, reaching the back wall. There, we observed a cross-section of the glacieret body with sediment strata inside the firn [28]. While going downwards from the highest end (at the bergschrund), those layers changed their tilt from normal to reverse, indicating the presence of slow curvy digging motion, typical for the accumulation zone of mountain glaciers [3, 23].

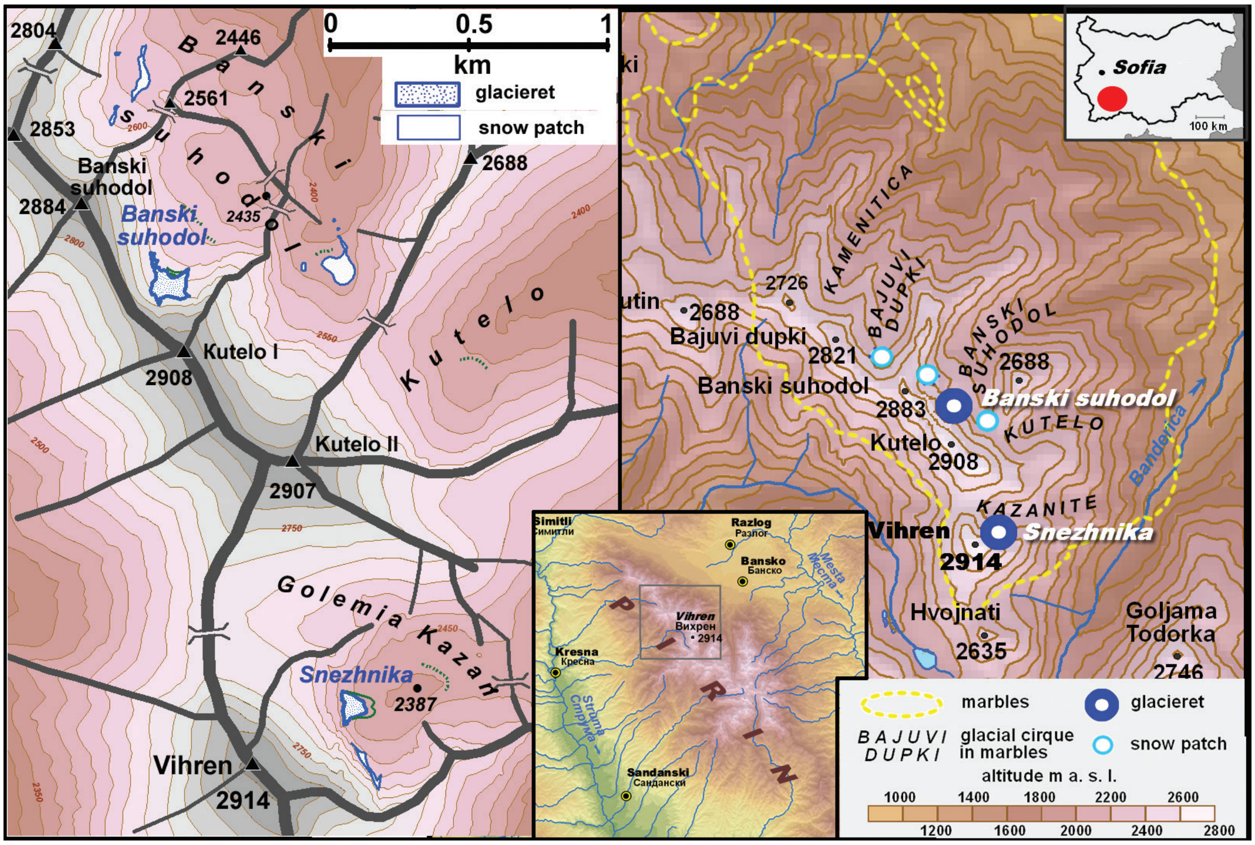

Figure 2. Glacierets and snow patches in Pirin mountains.

In these last 23 years, the area was subjected to large fluctuations, between 0.30 and 0.77 ha, without any specific trend. Average area for the period is 0.55 ha. At present, Snezhnika has been recognized as the southernmost glacial mass of Europe, being, together with Banski suhodol, the other glacieret in Pirin, the only one that is situated in south of the parallel 42°N [2].

Banski suhodol glacieret is situated 1.5 km to the north of Snezhnika, in a vast cirque below the second highest peak in Pirin, Kutelo (2908 m). It has a northerly orientation, irregular shape and an area about 1.2 ha [3, 7, 8]. The altitude of the glacieret is 2610–2700 m. It has a complicated shape, with a length 120–130 m and width 130–135 m. The surface is concave, tilted between 25 and 40°. Two moraine ridges parallel to each other are observed below glacieret front. They are more pronounced in the middle and less on the sides, as avalanche and debris flow paths pass there.

Being hardly accessible, this feature was described and mapped for the first time in 2009 [7, 8] and has been monitored annually since then [3]. Since 2011, the fluctuations of glacieret front have been measured in relation to five fixed points placed on large boulders. The inter-annual fluctuations of the surface of Banski suhodol glacieret are weakly expressed, with a maximum registered in 2010 and minimum in 2012. In October 2012, fresh glacial striations were observed on bedrock surfaces at glacieret front: a direct evidence for glacial type motion of the firn-ice mass of the glacieret.

Apart from the glaciers, two sustainable snow patches are also situated in Banski suhodol cirque. They have been found persistent for the last 8 years, but the low tilts and the closed

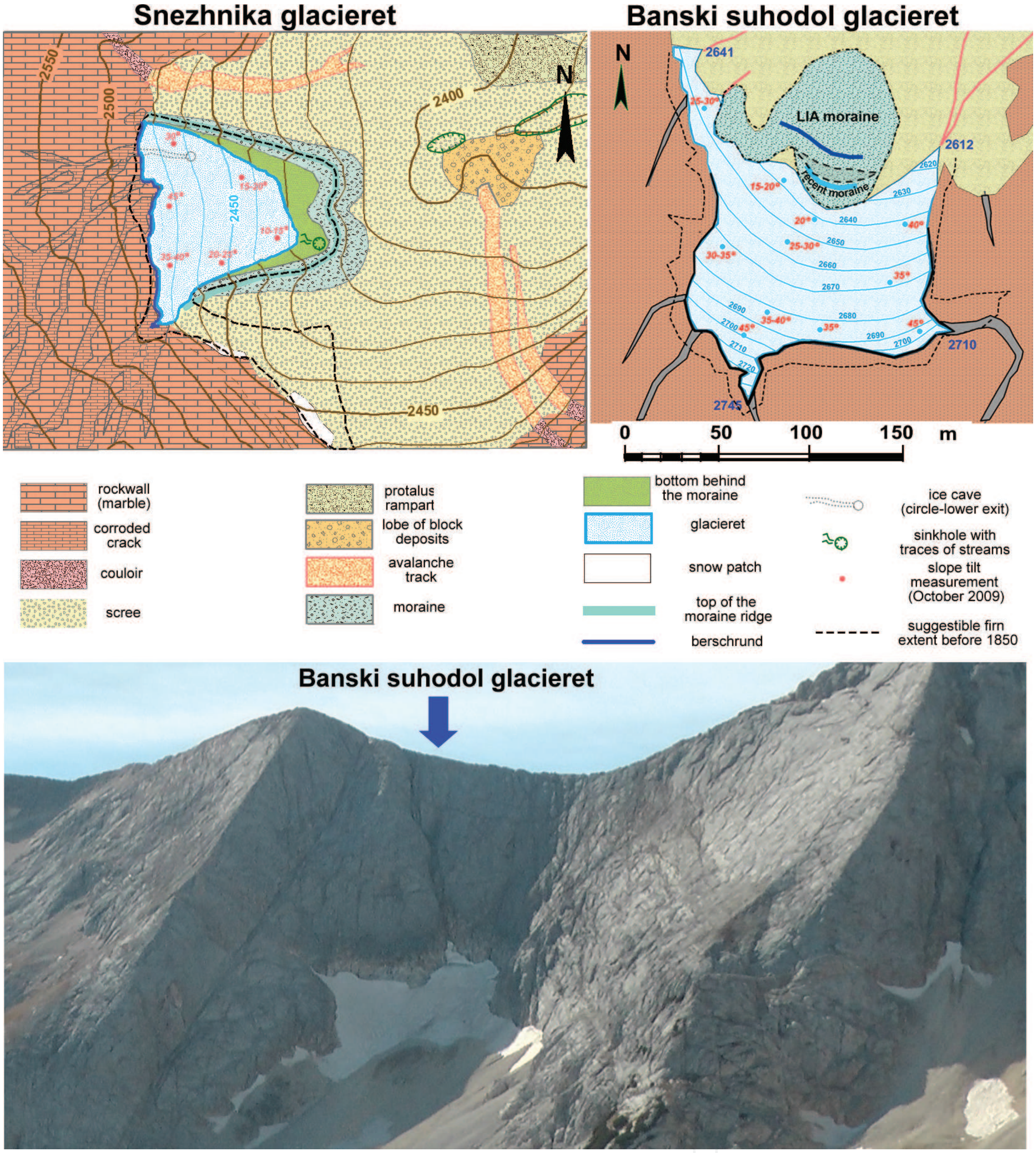

Figure 3. Snezhnika and Banski suhodol glacierets in Pirin.

depressions, where they lie, suggest they can hardly move. Their positions, however, and the moraines that surround them, indicate that they should have been glaciers in the nearly past (maybe in the Little Ice Age).

Presence of a perennial firn and ice was also reported for the cirque Bayuvi dupki, by Hristo Peev in the middle of the twentieth century [29, 30]. He reported about a 500-m long ‘firn glacieret’ that occupied the bottom of that cirque and gave information about years in which it was greater/smaller for a period of almost 2 decades. Although no figures were given for areas or lengths, this research is considered the first monitoring of a small glacier in Bulgaria. Nowadays, however, no snow remains in this cirque after hot summers. Reports for the existence of sustainable snow patches have been, however, made by enthusiast mountaineers for some locations in the Kamenitica cirque [31].

3.2. Durmitor

Durmitor is located in NW Montenegro. It is the second highest massif in the main Dinaric chain (Mt. Bobotov kuk, 2522 m a. s. l), a very small mountain, situated on a karst plateau at 1450–1550 m a. s. l. close to the deepest canyons of Europe (those of the rivers Tara and Piva [32]). The main part of the mountain is composed of thick Triassic and Jurassic limestones, which to the south overthrust Cretaceous flysch formations [33]. Four vast cirques are heritage from the extensive Wuermian glaciation. In the easternmost of them is the Debeli namet, the only present-day small glacier in Montenegro. The glacier is located on 2030–2200 m altitude; it has a northerly exposure, length about 300–320 m and width 110–135 m [34]. It has a classical elongated contour, with a wider concave upper section and bulged tongue at the front. The glacier is surrounded by a huge moraine, which rises 10–20 m above the surface. An amphitheatre of rocks and couloirs rises more than 300 m to reach the main ridge of the mountain in the south of the glacier: a grassy plateau, at 2400–2450 m a. s. l. (**Figure 4**.). Its lower section represents a surface of barren corroded rocks with a tilt steadier than the rock wall itself. This is the area where Debeli namet expands most, after years, of positive mass balances [9, 34] (in contrast to glacierets in Pirin, which fluctuate mainly in their frontal sections). Tilts of the glacier surface are in the range of 20–25°, reaching 35–40° just at the upper end. Strong mechanical weathering of rocks at the back supplies lots of debris on the ice surface, especially in the SE part.

Debeli namet was recognized as a small glacier by all researchers [2, 3, 9, 13–18]. For the first, it was mentioned in the 1960s [35]. Predrag Djurović from Belgrade, Serbia, measured glacier area in the autumns of 2003, 2006, 2008–2010, and 2015–2016 and reconstructed the size on the basis of aerial photographs for 1961, 1971, and 1981. In 1993, he tried to measure ice velocity with a stick stabbed in the middle part of the glacier. It was found at glacier front after 11 years [18]. Philip Hughes from the UK made size measurements of the glacier in 2003 and 2005–2007 and a lichenometry dating of the surrounding moraine, which addressed its age to the beginning of the twentieth century [13–16]. Accurate surface area measurements of the glacier have been done by Bulgarian scientists every year since 2011 [3]. The ice of the glacier was sampled for heavy metals and radioactive elements [24, 25]. Area observations cover a long period (since 1961) but have become already systematic since 2003. Here, it is also hard to outline any trend in fluctuations that are increasing from year to year (from 1.2 to 3.1 ha, i.e. up to three times). In the last 3 years, however, this glacier has suffered the most dramatic shrinkage on the Balkans. But it is still larger compared to its sizes during the 1990s.

There is one more perennial snow-firn feature in Durmitor, the snow patch in Snežna vrtača, a giant round sinkhole on the plateau of Šlijeme, filled with snow all year round [33].

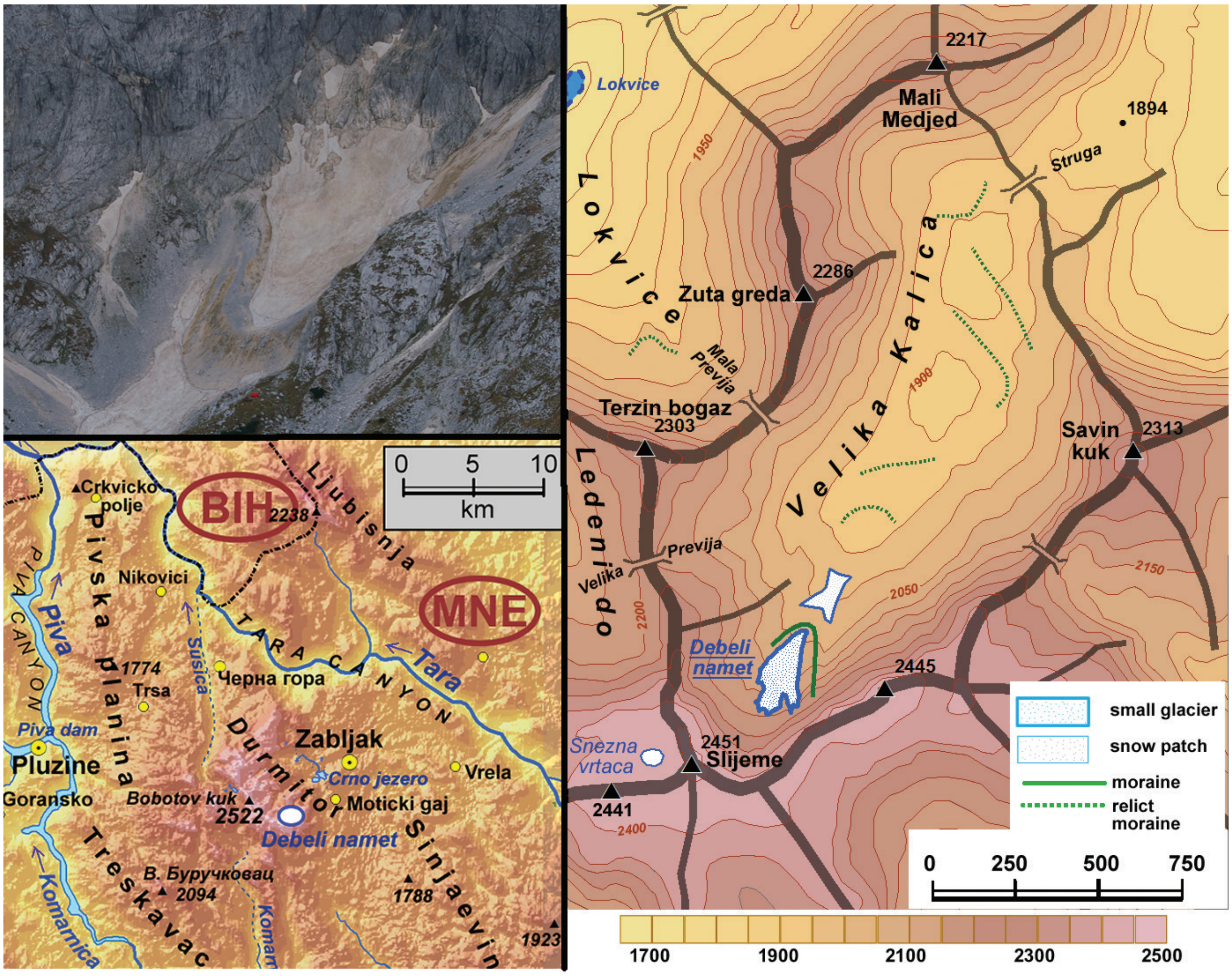

Figure 4. Maps of Durmitor and Debeli namet glacier.

3.3. Prokletije

Prokletije is a large mountain system, situated mainly in the northern Albania, on the borders with Montenegro and Kosovo. It marks the SE conclusion of the main Dinaric chain. Strongly dissected by deep valleys, it rises to almost 2700 m a. s. l. (Mt. Jezerce, the highest of all Dinarides). The central, southern and western sections of the mountain are made of Mesozoic limestone: very thick, tectonically reworked, heavily exerted by Wuermian glaciers and deeply karstified. The present rugged morphology of the mountain reminds of the Dolomites in Italy. In the eastern flanks of the mountain system, silicate rocks prevail and the topography there is smoother and relict glacial relief is much less pronounced (**Figure 5**).

Prokletije is among the least explored mountains in Europe. First, the famous Serbian geographer Jovan Cvijić paid attention to the impressive topography, left from the Pleistocene glaciers in the area around of Plav lake [36]. The presence of perennial snow and ice in the area around the highest point Maja e Jezrecës (Jezerce, 2694 m a. s. l.) was first mentioned by an Austrian topographer, who investigated the area during WWI, and mentioned snow fields more than

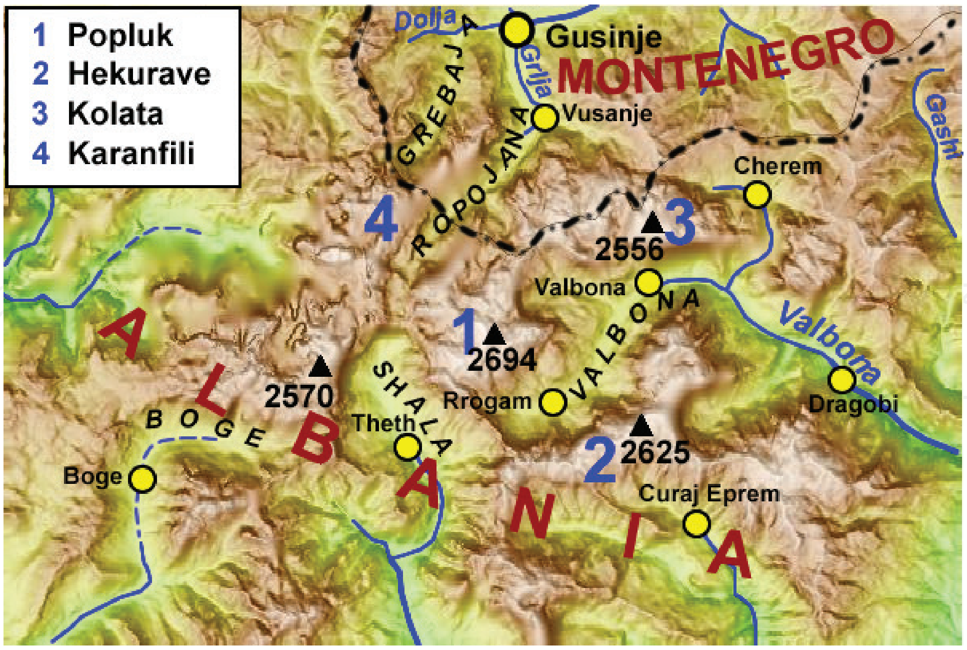

Figure 5. Prokletije mountain with locations of small glaciers.

1 km long [37]. Until the beginning of the twenty first century, geographical studies for this area were very few and not focused on present glaciation (e.g. [38, 39]). In 2007–2008, the area around Mt. Jezerce was researched for relict and present glacial evidence by Serbian geomorphologists, who reported about three 'active glaciers': the largest on the Balkan Peninsula with an area of 5 ha in the cirque Buni i Jezerces at 1980–2100 m a. s. l. and two smaller glaciers to the NE of the highest peak [12]. Soon after, another glacier with an area of 4.9 ha was described by a British expedition to lie under the eastern wall of Mt. Jezerce [15]. Since 2011 the area has been visited by Bulgarian scientists every autumn. As a result, it was revealed that the mentioned feature in the cirque Buni i Jezerces is in fact a snow patch, as it melted almost completely in 2012 and again in 2016. To compensate that, two more small glaciers were declared in the upper part of the same cirque on the basis of morphology. Bulgarian scientists have made several expeditions in other ranges within the carbonate area of Prokletije. In result, a total of 13 suggestible glaciers have been recorded and mapped in four main locations in this range, on altitudes between 2450 and 1910 m a. s. l. [3], but the presence of more is likely as many branches of this extensive mountain system are still unresearched. For the last 6 years, changes in the size of the glaciers and snow patches in the area around Mt. Jezerce have been studied in detail [3, 9–11]. The largest of them, the glacieret Jezerce III, has had an average area of 4.5 ha. Large fluctuation of the firn bodies in terms of surface area was recorded in 2011–2016, with a considerable shrinkage in the years after 2013. However, the observed thickness of some of these small glaciers (15 m and more) indicates that they are still far from complete melt.

3.3.1. Popluk range

Popluk is named the highest part of Prokletije system [38]. It includes Maja e Jezerces peak and the surrounding ridges, separated from the adjacent ranges with clearly defined cols. To the south, Valbona pass (1709 m a. s. l.) makes the transition to the high Hekurave range

(2625 m a. s. l.); to the NE is the Qafa Valbona saddle (2030 m), the pass to Bielić range (Maja e Rosit, 2524 m); to the West is the low Peja Pass (Qafa Pejes, 1690 m) that separates the valleys of Theth and Ropojana and the ranges Popluk and Karanfili. Popluk Mt. Jezerce is surrounded from three sides by large deep cirques: Buni i Jezerces (to the NW), Llugu i Zajave (to the E) and Buni i Gropavet (to the SW) (**Figure 6**).

Llugi i Zajave cirque hosts three small glaciers (glacierets). They are not situated on the bottom of the cirque but on a high terrace just under the 200–300 m high NE rock wall of Mt. Jezerce. Jezerce I (1.2 ha) and Jezerce II (2 ha), located to the NW of the summit point, are typical glacierets: they contact the rock wall, have straight surface and widths larger than lengths. Their fronts, which lie on deeply weathered and corroded limestone blocks, are bordered by moraine ridges several metres high. When they expand, both glaciers join into a single snow field. In periods of retreat Jezerce II disintegrates into several parts. The glacieret Jezerce III is situated further to the SE. It lies on a wide terrace on two levels (at 2400–2450 and 2350–2370 m,

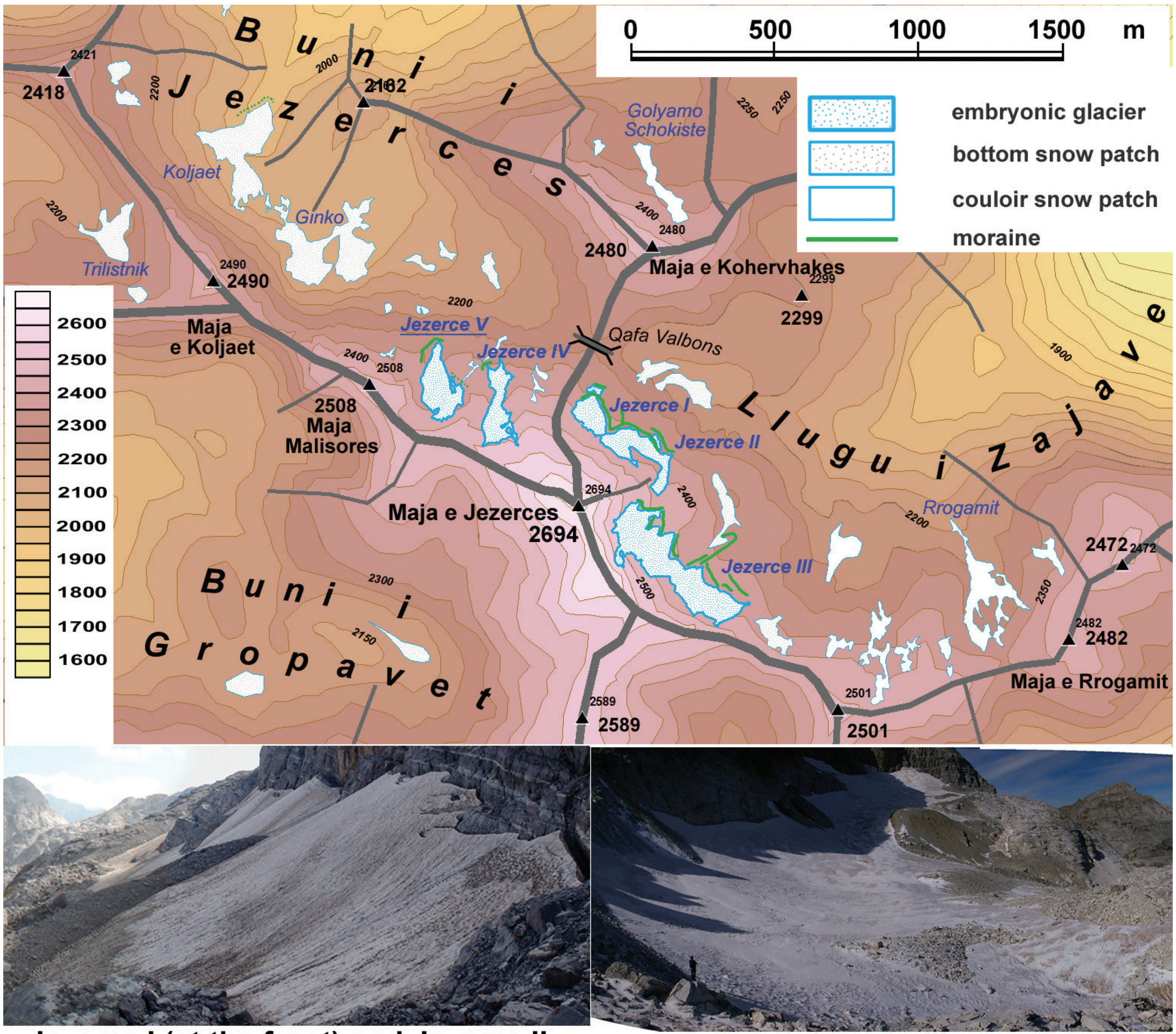

Figure 6. Small glaciers and snow patches in Popluk range.

respectively). However, the firn mass does not actually move down: it is mostly concentrated on the upper level (to the NW), which is on a shadier position, just below the peak. At the time of positive mass balance, all depression is filled with snow, and the glacieret obtains an impressive size (5–7 ha). Jezerce III is the largest small glacier on the Balkan Peninsula. After hot and dry years, ice masses on the lower level defragment to several snow patches occupy sinkhole bottoms, and the glacier becomes limited on the upper level. However, even in such conditions, it remains larger than the others, and ice thickness is still more than 10 m. In October 2014, surfaces of polished rock were observed by us near the firn front to evidence glacial type motion.

Buni i Jezerces is the largest of the three cirques. It is divided into two parts [12]. The lower part is wider oriented to the north. On its grassy bottom, at altitudes between 1750 and 1800 m, there is a group of six glacial karst lakes. Snow and ice features are located mostly in the upper section of the large cirque, which is narrower and oriented to WNW, with altitudes of the bottom between 2000 and 2250 m. Here, glaciers do not lie in the bottom as well but also in deep depressions on a cirque shoulder on 2400–2480 m a. l. The glacieret Jezerce IV (1.8 ha) is in a rocky depression, carved in the NW wall of Mt. Jezerce. It has an irregular shape with length of 270 m and width 70–80 m. The solid rock around produces small quantity of creep material, and in consequence, the two moraines that surround the lower end are tiny. Jezerce V lies further to the west, on the passage between Mt. Jezerce and its western neighbour Maja Malisores (2508 m). It has northern exposure and a pear-like shape of a small cirque glacier, with round upper part and narrow elongated snout. The glacier is situated in a zone of weak rocks, considerable amounts of pebble are produced especially on the SW side, and debris products are deposited as a high moraine ridge on the NW side of the tongue. To the NE of glacier end lies a rock wall, so moraine material is lacking there, and moraines at the very front of the glacier are small, as this area should serve as an avalanche track.

Several sustainable snow patches are found to be spread on the main bottom of the cirque's upper section. Ginko snow patches are in the middle part, at 2100 m a. s. l. They fill bottoms of two sinkholes, lying on a thick cover of scree material. Through years, the snow level can vary by 5–6 m and the area from 0.4 to 4 ha. When the level is high, all patches join in a single one. At the outlet of the upper section is the Koljaet snow patch, which was considered by previous researchers the largest glacier on the Balkans. And indeed, the large snow extent observed in some autumns (up to 4.5 ha for example in 2006 and 2013) and the high moraine ridges at the front can give impression of a small glacier. But regular observations have showed that in other years, the snow was actually missing there. In the small cirque to the North of Maja e Kohervhakes peak, there is another elongated snow field with NW aspect and length reaching more than 200 m in the autumns of some years (e.g. 2013). However, it was completely melted after the summer of 2016, so it is categorized as a snow patch.

The third large cirque, Buni i Gropavet, hosts several snow patches, none of them is considered permanent in long-term sense [12].

3.3.2. Hekurave range

This impressive and long range is situated to the south of Valbona valley from its beginning to its end, but the highest part lies to the west of Hekurave peak. This range has a west-east orientation and culminates in the peak Maja Gryk e Hapt (2625 m a. s. l., the third highest in

Prokletije). The northern slope is very steep and rocky, and in many regions, it rises almost vertically from Valbona valley.

Up to now, five small glaciers have been discovered in this range [3] (**Figure 7**). Three of them are on a wide terrace in the middle section of the northern slope. The big Glacieret lies at the end of the terrace, in a wide tilted couloir below the northern rock face of Maja e Zhapores (2529 m). It has a trapezoid shape and is bordered by a huge moraine. Next to the east is the Mertur glacier, a small cirque glacier of a classical shape (area around 2 ha), the most representative in Prokletije. It is situated at 2350–2450 m a. s. l. in a zone of weakened rocks

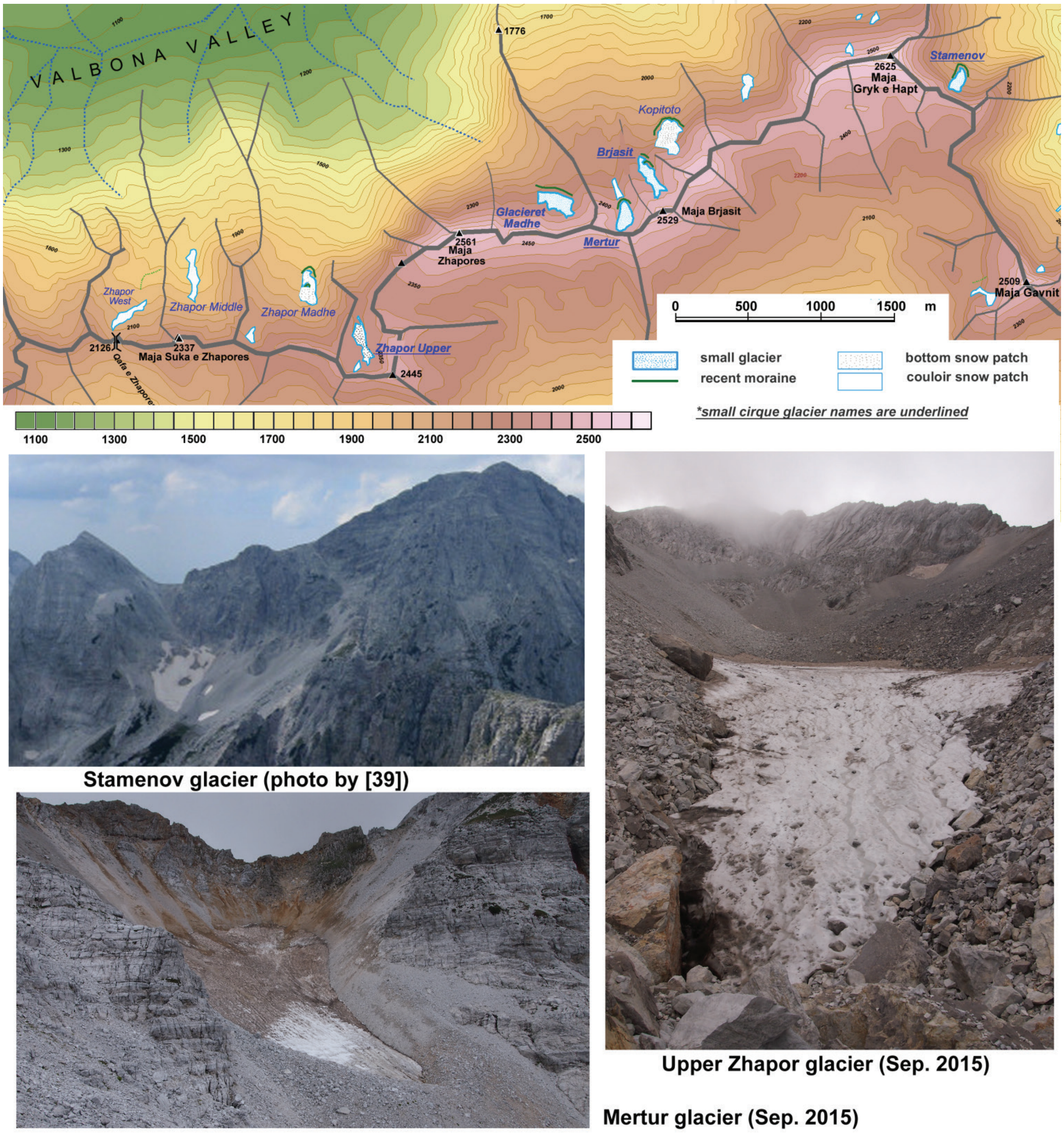

Figure 7. Small glaciers and snow patches in Hekurave range.

(limestone-marble breccia) that cross the ridge in a transverse direction. The scree behind the glacier produces large amounts of debris, which are piled up at the front as a high crescent shaped moraine. Despite that glacier surface is white and clean even after dry summers which indicates the good condition of the glacier and the active recent motion in it. A complex of three fresh stadial moraines is spread down to 500 m from the glacier, indicating its much larger size in the near past. Still further to the NE is the Brjasit small glacier (front at 2280–2300 m a. s. l.), an elongated body of firn and ice (2.5–3 ha), surrounded by moraines from three sides. This feature looks like the one that is made by a giant bulldozer. Further, another firn feature is found in the East. In September 2015, it was all covered by debris. It is obvious that there is buried ice inside, but despite the huge moraine formed behind the front, we accept this feature as a snow patch because of the lack of signs of recent activity.

At least two more small glaciers exist in this mountain range. One of them, Upper Zhapor glacier, occupies a high hanging cirque at 2300–2350 m a. s. l. near Zhapores peak. The glacier has a triangular shape, dictated by the topography of its bed, and in 2015, its surface was relatively fresh, with cracks in the lower part reaching 6–7 m depth. A short moraine made of huge blocks separates glacier end from the beginning of a steep couloir, which descends down to the valley of Valbona. The other feature, Stamenov glacier, lies in an easterly oriented cirque to the East of Maja Gryk e Hapt. It has an elongated shape, a clearly visible moraine that surrounds it from three sides and a relatively fresh look on all images taken in autumn.

3.3.3. Kolata range

This prominent part of Prokletije mountain system lies to the NE of Bjelić range, and is connected to it through the pass Qafa e Presljopit (2039 m a. s. l.). Rising sharply between the valleys of Valbona (to the S), Cherem (a tributary of Valbona, to the N and E) and Zarunica (tributary of Vruja and Lim rivers, to the NW), it is crossed by the Albanian-Montenegrin border and hosts the highest peaks of all Montenegro: Zla Kolata (2534 m a. s. l.) and Dobra Kolata (2528 m). The top of the range is a flattened plateau of flysch rocks, at the eastern end of which rises the highest point Ravna Kolata (2556 m), entirely in Albania. The plateau ends with almost vertical limestone cliffs from all sides. Western and southern slopes are very steep in all their height, descending almost 2 km down to the surrounding valleys. The northern and eastern slopes have staircase profiles. There are several deep and relatively narrow cirques, carved to the north of the plateau surface (**Figure 8**).

Kolata glacieret lies in the deepest cirque with a central position between the three main peaks of this range. The cirque is 200–250 m deep, with vertical walls from three sides, and looks to the north. This glacier has been among the largest and most stable in Prokletije, due to its strongly shaded position, and, possibly, the great contribution from windblown snow from the plateau. It has a triangular shape and minimum observed area about 2 ha. Series of partially developed moraine ridges surrounds it. In years of appropriate conditions, it freely expands to the north, growing to almost 4 ha. Another moraine marks the usual position of the front. Moraines at this glacier are not big, probably due to the solid rock walls that surround it, which are almost lacking wide couloirs. Three smaller features, possibly snow patches, are situated in the other cirques: to the west Malka Kolata snow patch, a remnant of

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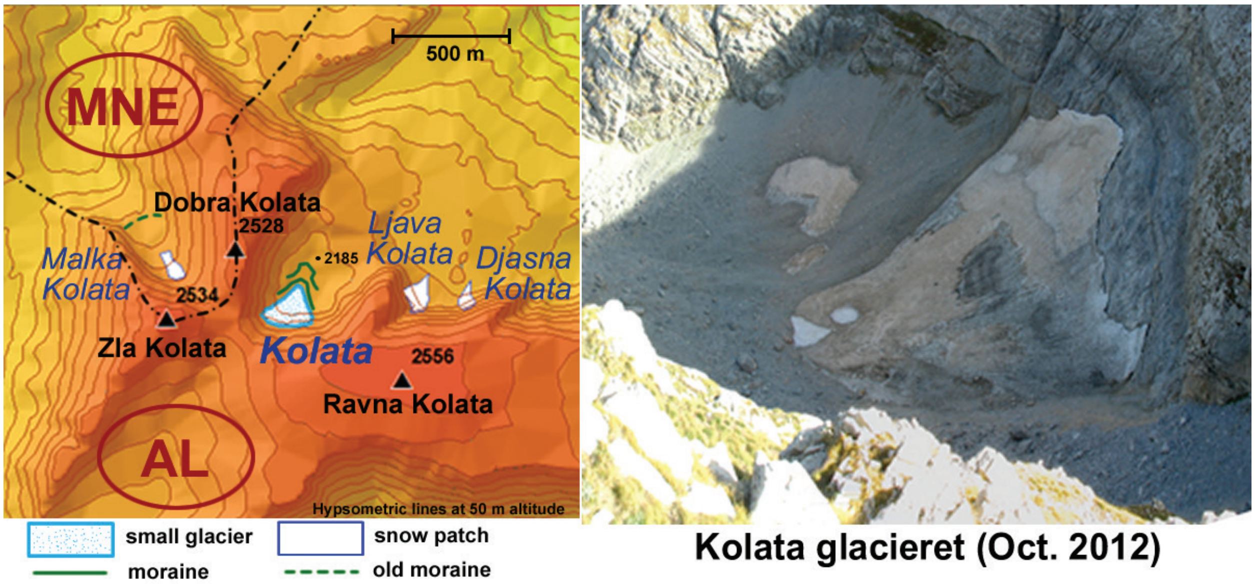

Figure 8. Small glaciers and snow patches in Kolata range.

a small glacier in the past but now looking shallow with no signs of activity; and two smaller patches to the east of the glacieret.

3.3.4. Karanfili

Karanfili range is the NE continuation of the wide Radohima massif that lies to the West of Popluk and Mt. Jezerce. To the east, Radohima share is framed by the deep Ropojana valley and the northern and western numerous ranges fork toward the valley of Vermosh (a tributary of Lim river in Albanian territory). Karanfili ridge goes narrow and sharp between the valleys of Ropojana and Grebaja, crossing the state border between Albania and Montenegro. It contains a number of peaks higher than 2400 m a. s. l., the highest being Veliki vrh (the Great peak, 2490 m) in Montenegro. At the end of Grebaja valley, which is on the NW side and is shorter, the great Grebaja cirque is formed. The two glaciers in this area are found within this cirque (**Figure 9**).

Ropojanski glacier is situated right on the state border line, to the west of the southern peak of the Karanfil (2460 m), and to the NW of the deep Ropojana pass. The altitude of this glacier is 1910–2000 m a. s. l., which makes it the lowermost on the Balkan Peninsula. It has a heart-like shape, with a 4 m high moraine at its front. Another glacier (Switzerland glacieret) has been found to the SW, under the northern wall of Vukoces peak. Framed by rocks from three sides, this feature has created short moraines only on the eastern side of its front. In 2015 the upper part was scattered by stone blocks protruding from the bottom. Several snow patches surround Mt. Vukoces from west and south (in a deep hanging cirque opened to Ropojana valley), but they all were melted in September 2016.

A number of sustainable snow patches are located further to the NE, in deep and very narrow cirques on the Montenegrin side, Kotao and Krošnja. On the bottom of the deepest cirque Kotao, carved north from the three peaks of the Karanfil (North peak, the Great peak, South

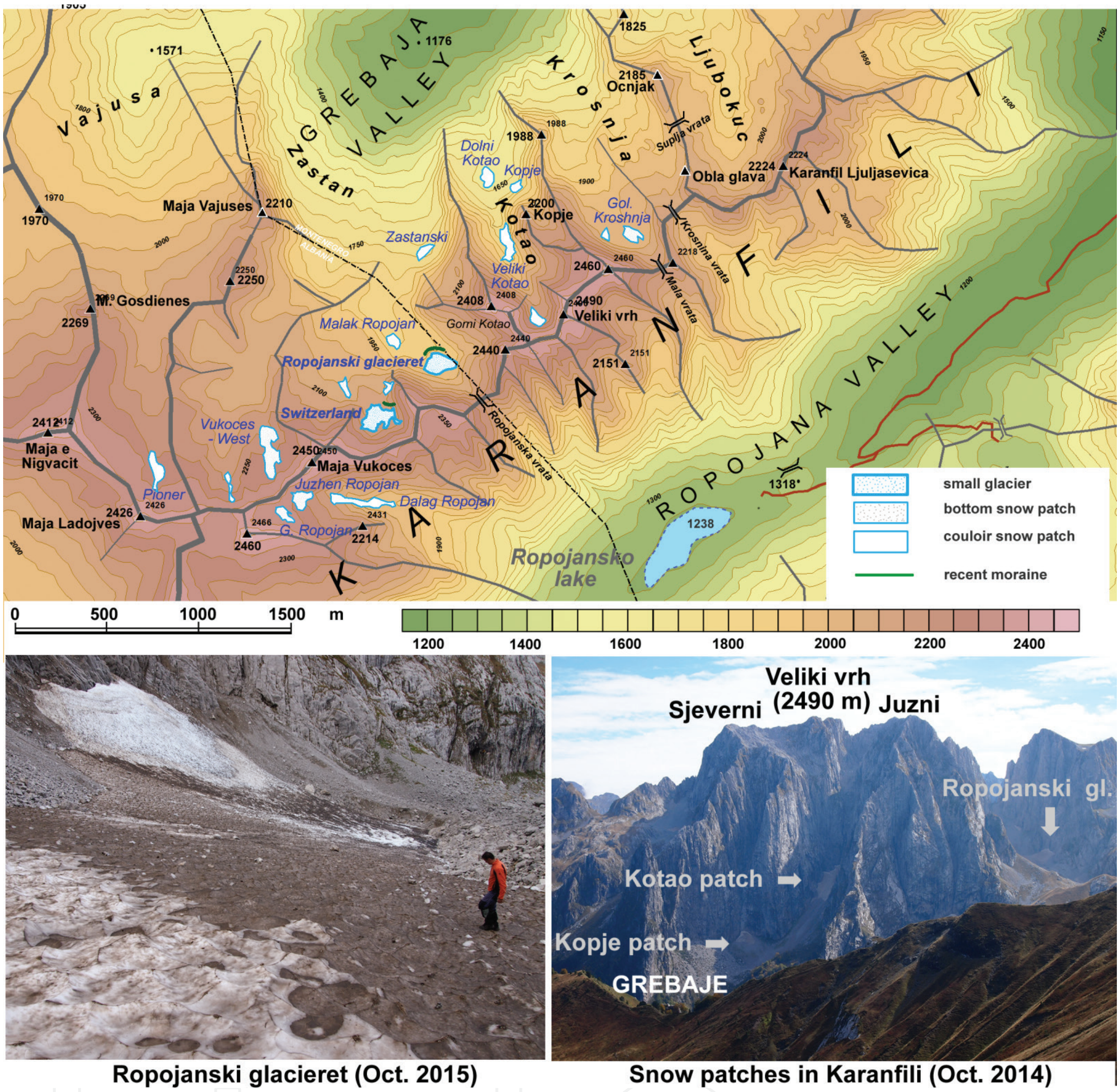

Figure 9. Small glaciers and snow patches in Karanfili range.

peak), are the two lowermost summer-lasting snow patches on the Balkans: at altitudes of 1640 m a. s. l. and 1750–1800 m a. s. l.

4. Revised inventory of small glaciers on the Balkan Peninsula

As a result of all research done by now, 16 sustainable (perennial) firn/ice features in the mountains of the Balkan Peninsula can be indexed in the category of small glaciers (**Table 1**). Summer lasting snow patches have been observed also in other mountain ranges such as in Olympus (Kazania cirque), in Rila (the cirque of the Seven lakes), in Maglić, Korab and others. None of them, however, is proved to have both persistency and indications of dynamic motion.

No.	Name	Type	Mountain	Location (area, cirque)	Co-ordinates		Altitude [m] a. s. l.	Aspect	Length [m]	Width [m]	Area*	
					Lat. N	Long. E					Projec-ted [ha]	Real
1	Jezerce I	Glacieret	Prokletije	Popluk	42°26′42″	19°48′49″	2330–2420	NE	123	147	1.21	1.42
2	Jezerce II	Glacieret	Prokletije	Popluk	42°26′38″	19°48′57″	2330–2445	NE	157	222	2.06	2.61
3	Jezerce III	Glacieret	Prokletije	Popluk	42°26′27″	19° 48′57″	2375–2555	NE	188	271	6.22	7.10
4	Jezerce IV	Glacieret	Prokletije	Popluk	42°26′41″	19°48′33″	2345–2520	N	346	105	1.85	2.30
5	Jezerce V	Cirque glacier	Prokletije	Popluk	42°26′45″	19°48′25″	2330–2435	N	290	153	2.22	2.64
6	Upper Zhapor	Glacieret	Prokletije	Llugu i Silikut	42°23′27″	19°51′38″	2280–2350	N	365	100	1.60	1.70
7	Glacieret Madhe	Glacieret	Prokletije	Llugu i Silikut	42°23′58″	19°52′34″	2250–2380	N	129	263	2.21	2.64
8	Mertur	Cirque glacier	Prokletije	Llugu i Silikut	42°23′55″	19°52′57″	2360–2445	N	213	115	1.55	1.70
9	Brjasit	Cirque glacier	Prokletije	Llugu i Silikut	42°24′04″	19°53′04″	2280–2450	NW	308	84	2.60	2.94
10	Stamenov	Cirque glacier	Prokletije	Llugu i Silikut	42°24′26″	19°54′37″	2120–2270	NE	172	95	1.45	1.64
11	Kolata	Glacieret	Prokletije	Kolata	42°29′00″	19°54′05″	2190–2300	NE	300	195	3.70	4.17
12	Ropojanski	Glacieret	Prokletije	Karanfili	42°29′38″	19°46′43″	1910–2080	NNE	110	156	1.34	1.60
13	Switzerland	Glacieret	Prokletije	Karanfili	42°29′28″	19°46′29″	2130–2225	NNW	142	188	1.68	2.06
14	Debeli namet	Cirque glacier	Durmitor	Velika Kalica	43°07′20″	19°04′30″	2035–2200	NNE	275	145	2.75	3.10
15	Snezhnika	Glacieret	Pirin	Golemia Kazan	41°46′09″	23°24′10″	2400–2445	E	90	95	0.62	0.77
16	Banski suhodol	Glacieret	Pirin	Banski suhodol	41°46′54″	23°23′40″	2610–2700	N	100	127	1.15	1.40

*Area in October 2006.

Table 1. List of small glaciers in the mountains of the Balkan Peninsula.

5. Inter-annual size variations of small glaciers on the Balkan Peninsula

Precise data about size in autumn (at the end of the balance year) have been gathered for Snezhnika glacieret in Pirin for 24 different years, the 21 of which have been consecutive (1996–2016). The area of Banski suhodol glacieret was measured once (in 2009), but its size fluctuations since then are registered by repetitive photographs, and since 2011 the front advances/retreats in relation to fixed points have been recorded. Data for the surface area of Debeli namet are available for the years 1954, 1971, 1981, 1993, 1997, 1998, 2003 and 2005–2016 [3, 14, 18]. On the basis of documents, photographs and measurements information about the size of glaciers and snow patches in Popluk area of Prokletije have been gathered for the years 2006, 2007 and 2011–2016 [3, 12, 15]; for Kolata glacieret: for 2012 and 2014; for glaciers in Hekurave range: for 2006, 2011–2014 [3] and 2015; and for the snow patches in Kotao cirque: for 2006, 2009, 2013, 2015 and 2016 [3, 40].

In general, in short-term small glaciers on the Balkans, size variation of high amplitudes has been demonstrated but differences have been observed in overall amplitude, the way of expansion/shrinkage and the expression of changes. For the whole region, 2005/2006 balance year was a year of glacier growth. For the period of continuous observation in the three mountains, 2010–2014 episode was characterized by synchronous behaviour of all glaciers and snow patches on the Balkans: shrinkage in 2010/2011, 2011/2012 and 2013/2014 and expansion in 2012/2013 balance years. In the next years, different trends were observed in the Eastern and the Western Balkans: for 2014/2015 and 2015/2016 glacierets in Pirin have been stagnating (Snezhnika had even little growth in 2015), while features in Prokletije [41] and Durmitor have been strongly diminished (**Figure 10**).

For this last period, glacierets in Pirin reached their absolute minimum after 2011/2012 balance year, and the size for the years 2014–2016 was similar and at the same time much bigger. In 2015, Debeli namet glacier in Durmitor was smaller, and in 2016, it was much smaller than it was in 2012. In Popluk (Prokletije), 2012 was the minimum for the lowermost snow patches: Koljaet snow patch disappeared almost completely, then reappeared in the next year with a size comparable to that of 2007 when the Serbian scientists had visited it. Shrinkage started again in 2014, continued in 2015 and in 2016, size was again smaller but still a little larger than in 2012. In contrast, for the higher located glaciers in the area, 2015/2016 was the year of the absolute minimum with sizes definitely smaller than those for 2011/2012. For this later period, the maximum size in all the Balkans was registered in 2012/2013 balance year. In Prokletije areas, sizes were larger than those in 2005/2006, Debeli namet glacier was of same size in both the years, and Snezhnika was larger in 2006 than in 2013.

Data for a longer term, available for Snezhnika and Debeli namet, show no trend towards shrink or growth. They both reached absolute minimums in the 1990s of the last century. After 2002–2003, they stabilized and grew, but since 2010, controversial trends have been observed (**Figure 11**).

Figure 10. Inter-annual changes of Snezhnika glacieret (Pirin), Koljaet snow patch (Prokletije) and Debeli namet glacier (Durmitor) for the period 2011–2016.

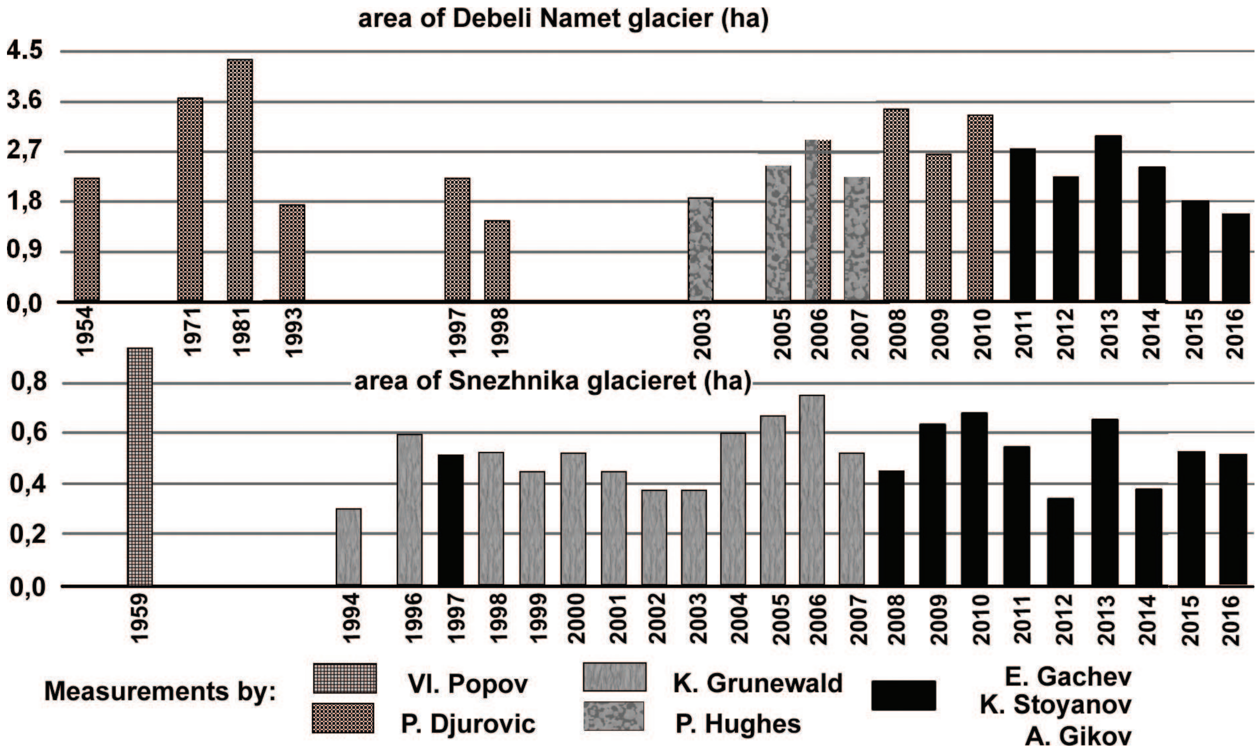

Figure 11. Area measurements for Snezhnika glacieret (Pirin) and Debeli namet glacier (Durmitor).

6. Discussion: small glaciers on the Balkans and climate variations

To understand the nature of short-term glacier variations, we have to bear in mind the climate of the mountains which contain these glaciers. All the three discussed areas are in the zone of transition between the temperate and subtropical (Mediterranean) climate. Located close to the Mediterranean sea (70–100 km away), they are not standing right on the coast, and being among the highest ranges, they are open to continental influences from mainland Europe [3, 12, 33, 42, 43]. Climatic data for these high mountain areas are also lacking. For reference, for a longer period in Pirin, the climatic station of Musala peak in Rila (2925 m a. s. l., 54–55 km away from the glacierets) is used [44]. In the last years measuring devices have been installed in the target area of Pirin such as in Golemia Kazan, close to Snezhnika, by K. Grunewald (an automatic meteorological station recording since September 2011) and on the top of Vihren peak by the South-west University of Bulgaria (logger-sensors, recording every 30 minutes air temperature and humidity since October 2014; and ground temperature since 2016). The statistically significant correlation of temperature data between Musala peak and Golemia Kazan cirque shows that the information from Musala (available also in Internet at [44]) can be used to estimate conditions in Northern Pirin [45]. However, for the last 5 years data from the station near Snezhnika have shown quite high air temperature (annual around +2°C [46]). Analysis of data from Musala enabled to calculate temperature monthly and annual averages for 1994–2016 (**Figure 12**).

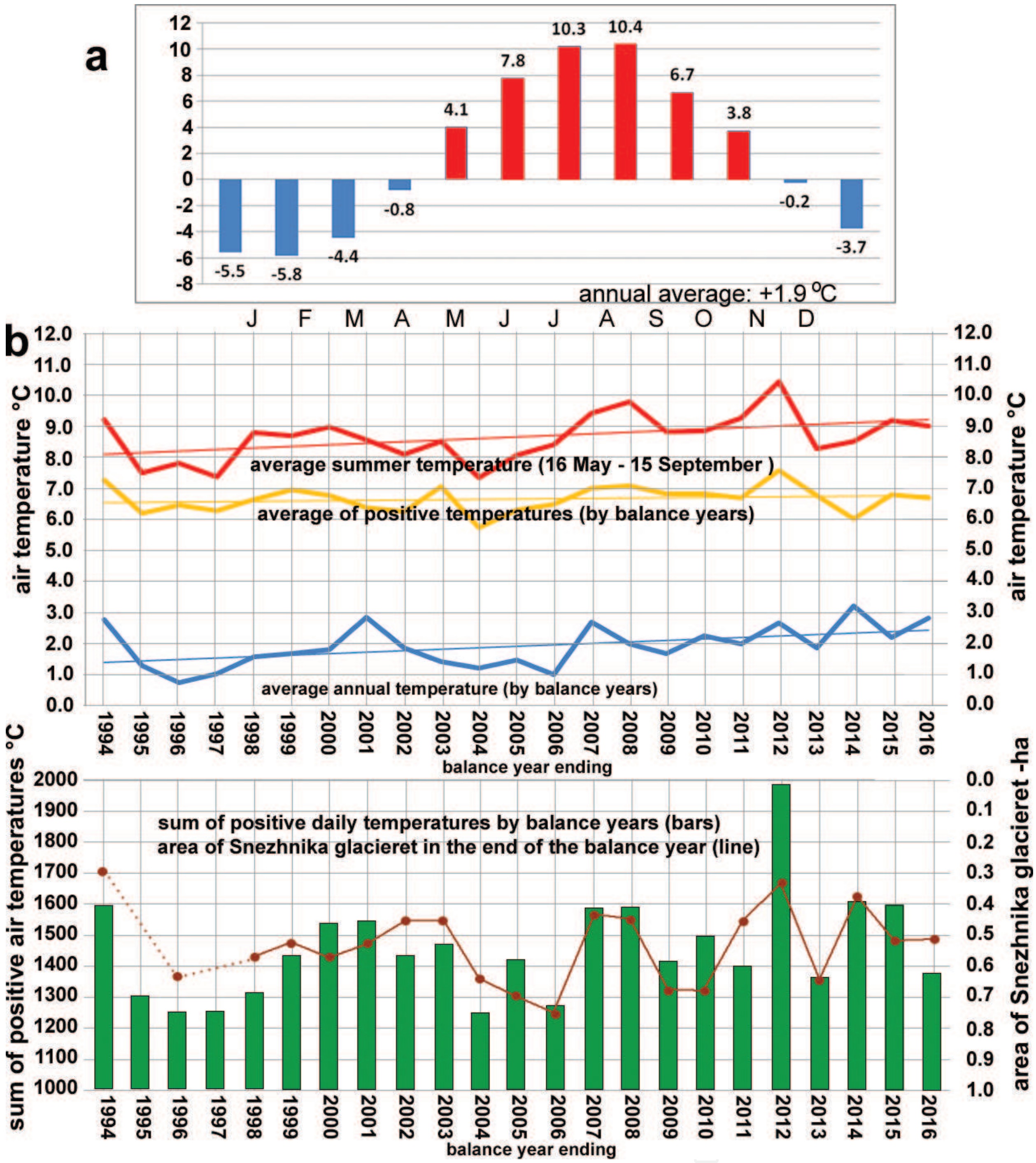

Figure 12. Climatic averages for the area of Snezhnika glacieret based on data from Musala peak: (a) monthly averages for the period 1994–2016; (b) averaged data for 1994/1995—2015/2016 balance years.

What is clear from the figure is that according to the data, there has been registered a considerable warming trend for last 23 years in annual, ablation and summer temperatures. Analyses showed that there is a relatively good correlation between thermal variables, calculated in balance years, and the area of Snezhnika glacieret. For the 23 year period the best is the correlation with the sums of positive temperatures (ablation season sums) which is −0.73.

Why is then no trend in the development of Snezhnika glacieret, if the temperature rise is a fact? The answer is sought in the influence of precipitation, but data about this climatic element are almost missing in Pirin. However, analysis of precipitation data from Musala (with lots of uncertainties) shows that the stagnation of Snezhnika can be due to the higher sums of winter precipitation, which have been registered in most of the years after 2004.

As the annual precipitation in the high parts of Pirin is suggested to be around 1000–1100 mm/year, 650–700 mm of which during the accumulation season [26, 42], Snezhnika is fed to a greatest extent by avalanche and windblown snow. Thus, it receives snow amounts much larger than the actual sum of atmospheric precipitation. On the contrary, Banski suhodol has much smaller avalanche catchment [8]. It relies most of all on shading, and its variations through years are smaller than those of Snezhnika [3]. Sadly, precipitation data from the devices installed in Pirin are not reliable [45, 47].

No climatic data are available from the high mountain areas of Prokletije and Durmitor, the closest mountain station being on Bjelašnica peak in Bosnia and Herzegovina (2067 m a. s. l.). Extrapolations of temperature for the last decade however suggest that around 2150 m a. s. l., annual temperatures are around +2°C and more, and even near the highest glaciers, they are positive [12, 14, 18]. These are however temperatures for open slopes. In negative forms, values are by no doubt lower but still high to sustain glaciers. In the Western Balkans, the existence of perennial ice is favoured by the much greater precipitation: annual amounts for the highest areas of Durmitor are about 2600 mm [18, 33], and for the central and western parts of Prokletije 2500–3300 mm, 2/3 of this amount falling in the cold half of the year [12, 43, 48]. This enables formation of glaciers even at altitudes around 2000 m in strongly shaded sites. The plateau surfaces in the south of Debeli namet and Kolata glaciers serve as great sources of snow, so the actual amount of snow can be more than twice the winter precipitation sum. Glaciers around Mt. Jezerce rely most of all on high altitude (comparable to that of Snezhnika in Pirin) and precipitation around 2500 mm/year and those in Karanfili range mainly on strong shading. Glaciers in Hekurave area, especially Mertur glacier, have always been in good condition in the last years (even in 2012 and 2016). This is due to their high altitude, and, possibly due to much higher precipitation (probably around 3000 mm/year), a result of their southern position and greater proximity to the Adriatic.

The different trends in small glaciers in the Western and the Eastern Balkans, which were observed in the last two balance years (2014/2015 and 2015/2016) can be explained with some synoptic events of accidental character that affected unevenly the territory of the Peninsula. After a relatively snowless winter, in the beginning of March 2015, a cyclone coming from Greece reached Southern Bulgaria and deposited abundant snow in high mountains, triggered avalanches and piled more than 10 m of snow over Snezhnika and smaller but still amount over Banski suhodol (as it is less prone to avalanche). At the same time, mountains in the western part of the Peninsula did not face that cyclone and remained with little snow. After the summer, melt resulted in a positive balance for Snezhnika, a slightly negative for Banski suhodol and a strongly negative for all glaciers in the Western Balkans. Similar situation occurred also after the next winter.

7. Conclusions

At least 16 small glaciers still exist in the mountains of the Balkan Peninsula. Prokletije mountain range provides the best conditions for glacier preservation in the region. Favouring factors for glaciers in the Western Balkans are the high precipitation and the greatest dissection of relief that provides optimal shading conditions. Here, the lowermost small glaciers and snow patches on the Balkans are found. Favouring factors for glacier formation in Pirin are the higher altitude and avalanche occurrence. Small glaciers on the Balkans, which are among the southernmost in Europe, still manage to survive in conditions of climate warming, proved by data from high mountain stations. Further, in a longer term (the last 20 years), they have shown no trend towards shrinkage. Although their area at the end of the balance year shows some correlation with summer temperatures, the neutral balance is reached due to the increased winter precipitation, especially in the last 12–13 years. These facts support the suggestion that small glaciers in such marginal environmental conditions may last much longer than expected.

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