Mediterranean Geoscience Reviews (2020) 2:103–117
https://doi.org/10.1007/s42990-020-00028-3

ORIGINAL PAPER

Holocene glaciation in the mountains of Bulgaria

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Received: 14 February 2020 / Revised: 14 April 2020 / Accepted: 15 April 2020 / Published online: 30 April 2020

Abstract

This study presents a review on Holocene glacial traces in Bulgaria. Pleistocene glaciation in this territory was spread over a number of mountains above 2000 m a. s. l., while in the later time, it was restricted only to the highest areas of the two highest mountains, Pirin and Rila. Two major phases can be distinguished on the basis of field evidence—a Little Ice Age (LIA) phase, and a present-day phase. Features of present-day glaciation are only found in the Pirin Mountains, in the highest parts of Northern Pirin which are built of carbonate rocks (marble). The two glacierets in these mountains, which are now the southernmost glacial masses in Europe, occupy only c. 1.5 ha. Several permanent snow patches are also found to fill the bottoms of high altitude karst dolines in the same area, contributing to a total of 3.5 ha of firn and ice, which have not completely melted for several centuries. The post-LIA climatic warming, which has progressed with an increased pace for the last 3 decades, reduced the glaciated area in the highest mountains of Bulgaria by 58%. However, glacierets and snow patches in Bulgaria have appeared to be more stable when compared to most other locations with similar topographic setting in Southeastern Europe.

Keywords Pirin · Rila · Glacierets · Snow patches · Climate warming

Introduction

In modern science, the Holocene is considered the latest of Quaternary interglacials. As a result of numerous studies (Vavrus et al. 2018; Ruddiman 2001; Jouzel et al. 2003; Lüthi et al. 2008), it has been proved that in general, climate conditions throughout the Holocene have been quite similar to those in previous warm periods, especially what concerns the first half of the epoch. On the basis of data from the drilling of Greenland and Antarctic ice sheets, some scientists (Ruddiman 2001, 2005; Parrenin et al. 2007; Ruddiman et al. 2016) conclude that for the second half of the Holocene, temperature greenhouse gas levels (CO_2, CH_4, etc.) have started to deviate from the naturally expected downward trends, and this has been especially obvious since the beginning of industrial revolution, when human impact has globally become as strong as never before. In a reconstruction of temperatures for the final centuries of the Late glacial and the Holocene, based on marine reconstructions, Marcott et al. (2013) presented evidence and concluded that the post-LIA warming has appeared as an extraordinary interruption of the cooling trend which had started after the Atlantic optimum. CO_2 levels of 410 ppm that we have today, have not have a precedent for the whole Quaternary, as it is witnessed from the cores of Greenland and Antarctic ice sheets (Gore 2006; Bereiter et al. 2015).

Being a part of the northern periphery of the Mediterranean zone, the mountains of the Balkan Peninsula are on the margin between tropical and boreal influences, and between the warm and cold climates, respectively (Velev 2010; Burić et al. 2012). Due to this geographical position, the highest mountain areas of the peninsula have been periodically switching between glacial and non-glacial conditions. They were repeatedly occupied by extensive mountain glaciation during the coldest spells of the Pleistocene (Marjanac and Marjanac 2004; Djurović 2009; Kuhlemann et al. 2009, 2013; Hughes et al. 2006, 2007, 2010, 2011), and in some areas of the Dinaric Mountains, traces of large glaciers were documented from the cold phases of the Late glacial (Žebre et al. 2019; Çiner et al. 2019). On the other hand, during warm phases the glaciers entirely, or almost entirely, disappeared.

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In Bulgaria, the presence of classical relict traces of Pleistocene glaciers has been documented in the two highest mountains of the Rhodope Massif: Rila (2925 m a. s. l.) and Pirin (2914 m a. s. l.), and embryonic glacial landforms have also been described in Stara Planina (2376 m a. s. l.), Osogovo (2252 m a. s. l.) and Vitosha (2290 m a. s. l.) (Cvijić 1897, 1908; Janković 1903, 1908; Louis 1930; Glovnia 1958, 1962, 1968; Velchev 1995, 1999; Velchev et al. 1994, 2000 and others).

During Pleistocene ice ages Rila and Pirin were the only mountains high enough to sustain extensive glaciers. At their maximum extent (around the Last Glacial Maximum), glaciers in the Rila Mountains covered about 430 km^2 (Kuhlemann et al. 2013), which was confirmed by the dating of several moraines with cosmogenic nuclides (^{10}Be). Both in Rila and Pirin Mountains, ELA of the maximum glaciation was at about 2150–2300 m a. s. l. (Louis 1930; Georgiev 1991), and glaciers up to several km long descended down the main valleys. The longest glaciers, Beli Iskar in Rila (22 km) and Demianitsa-Banderitsa in Pirin (11 km) flew down to the north. (Kuhlemann et al. 2013; Lilienberg and Popov 1966). On northern slopes, fragments of terminal moraines are preserved down to 1100–1500 m a. s. l., and on southern slopes to 1500–1900 m a. s. l. Systems of extensive cirques, many of which with complicated configuration and staircase floors, now occupy the high mountain interiors. In Rila, there is morphological evidence for the existence of several ice caps during the Pleistocene: in the eastern, southwestern and northwestern parts of the mountain massif (Ivanov 1954; Glovnia 1968; Baltakov and Mladenova 1989; Baltakov 2004; Kuhlemann et al. 2013).

The weakness and scarcity of glacial traces in the latter mountains indicate that throughout the Holocene (even during its coldest phases) the glaciation was restricted to Rila and Pirin only, and, more strictly, in their highest parts.

As it is well known, the climate during the Holocene itself has been quite variable, especially in the last millennia (Grunewald and Scheithauer 2008b, 2011), which has reflected on the extent and forms of glaciation. On the Balkans, evidence for glaciers during the LIA was provided by Hughes (2007, 2010) for the Durmitor Mountains, by Styllas et al. (2016) for Mt. Olympus, by Wilkinson (2011), Gachev et al. (2016) and Hughes (2018) for Prokletije Mountains, by Grunewald and Scheithauer (2008b, 2011) for Pirin Mountains, by Gachev et al. (2008) for Rila Mountains. Today several very tiny, small glaciers, still manage to survive in some of the highest mountain ranges on the Balkans: for the last decades such have been documented in Prokletije Mountains (in Albania), in Durmitor (Montenegro), and Pirin (Bulgaria), and sustainable snow patches survive colder summers in the Olympus (Greece), Maglić (Bosnia and Hertzegovina), the Rila Mountains (Bulgaria) and elsewhere (Grunewald and Scheitchauer 2010; Gachev et al. 2016; Gachev 2017).

Recently, two glacierets and several sustainable snow patches have remained in Pirin, and one long-lasting snow patch in Rila. The glacierets in the Pirin Mountains have been presently recognized as the southernmost glacial masses in Europe, the only ones situated south of 42° N (Grunewald and Scheitchauer 2010). Geomorphological evidence, however, indicate that throughout the cold phases of the Holocene, mountain glaciers on the territory of Bulgaria occupied larger area (Gachev et al. 2008; Gachev and Gikov 2010; Mitkov 2020).

The aim of this paper is to summarize the data about the possible maximum Holocene glaciation in the mountains of Bulgaria, as well as to inform about the present state of glaciers and snow patches and the most recent trends in their evolution.

Study areas

The present study is focused on the highest mountain areas in Bulgaria—the Pleistocene cirques around the peaks Musala (Rila) and Vihren (Pirin) (Fig. 1). More in particular, the study areas include the cirque ensemble between the peaks Vihren (2914 m a. s. l.) and Razlozhki suhodol (2570 m a. s. l.) in the Pirin Mountains (the so called "Vihren area", or "the High Karst Ridge"), and Musala cirque in the Rila Mountains.

Kazanite cirque complex (Pirin)

The cirque complex Kazanite is situated in the northern part of Pirin Mountains, at the NE foot of Mt. Vihren (2914 m a. s. l.). It comprises two cirques, situated one above the other. Golemia Kazan ("The Big Cauldron") occupies the upper section, with the floor on altitudes 2400–2450 m a. s. l. To the southwest the cirque is bordered by Vihren peak, with its prominent 450 m high wall. To the northeast is the Kutelo peak (2908 m a. s. l.), the second highest in Pirin. Malkiat Kazan ("The Little Cauldron") is situated to the east of Golemia Kazan, and occupies altitudes between 2200 and 2400 m a. s. l. The cirque complex is carved in white–grey marble, and represents an ensemble of several glaciokarstic depressions (uvalas). Due to the karstified bedrock there are no lakes on cirque floor.

In Golemia Kazan cirque, just at the foot of Vihren's wall, is situated the Snezhnika glacieret—one of the two small glaciers in Bulgaria (the southernmost glacial mass in Europe, Grunewald and Scheitchauer 2010) with an area about 0.5 ha (80 m length × 90 m width) and aspect to the east (Fig. 2). The altitude of the glacieret is 2400–2450 m a. s. l.

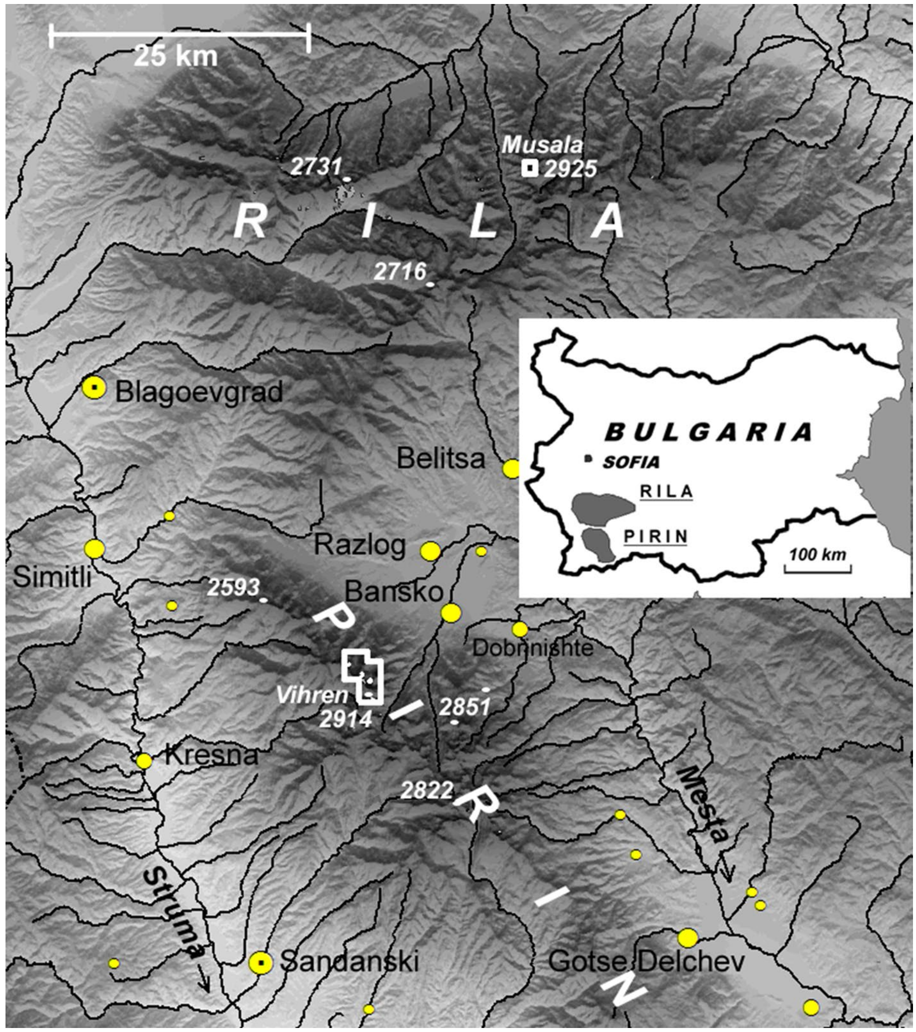

Fig. 1 Areas in Bulgaria with evident traces of Holocene glaciation

Fig. 2 Snezhnika glacieret and Vihren Peak (October 2013)

Snezhnika glacieret was first described and studied by Popov (1962, 1964). He organized a first drilling of the firn/ice that reached the bottom at 8 m depth, and conducted 4-year climatic measurements in Golemia Kazan cirque in 1957–1961. Later, in September 2006, another drilling was done by Grunewald et al. (2008) that measured 11 m depth. Pure ice was found in the core below 7 m, and the ^{14}C dating of organic material within the ice at 10 m depth gave around a 100 year age, which confirmed Snezhnika as a small glacier (glacieret).

The glacieret is surrounded by three sides (south, east, north) by a W-shaped protalus-moraine ridge, made of coarse blocks and boulders of various size, with relative height 2–4 m above the glacieret surface. Relict primitive soil is partly developed on the front side of the moraine, directed towards cirque outlet. On the basis of ^{14}C dating of these soils, Grunewald et al. (2008) came to the conclusion that the moraine is formed in its present shape during the LIA. Presently, the ice margin reaches the moraine on the front size very rarely. In most cases in the autumn, there are 15–25 m of snow free surface, filled with debris with mostly pebble size. Traces are obvious from a new ridge that has started to form, in result of the smaller glacieret extent in the recent years.

Further down the cirque, about 200 m to the east, a well-preserved crescent-shaped ridge marks a previous deglaciation stage in Golemia Kazan. It is made of marble blocks of various size, with a cover of grass over the fine grained material. Stones are covered in lichen, and bear traces of intense weathering and corrosion. The ridge, which height is 7–8 m on the internal side, and 1–2 m on the outside, is much older in age than the moraine that surrounds the present glacieret. This conclusion is also supported by the results of Schmidt hammer tests done by Mitkov (2020).

Based on the field evidence, the crescent moraine should be addressed to the next colder stage back in time before the Little Ice Age. If we take into account the climatic reconstructions done on the basis of pollen and vegetation studies, which point out that no abrupt events were registered in the high mountain environment of Pirin throughout much of the Holocene, and also the state of the moraine (strong weathering of the boulders, both physical and chemical, dense lichen cover), the most probable age for that moraine should be the Younger Dryas cold episode. The same suggestion is supported also in the works of Grunewald and Scheithauer (2008a, 2011).

Fragments of at least two moraine ridges can be suggested towards the outlet of Golemia Kazan cirque. However they are hard to determine, as part of the material there is of a rockfall origin. A huge moraine is deposited near the northeastern rim of the cirque, with a relative height of 40–45 m. Today, on top of it rests a small shelter for tourists (Kazana refuge). This moraine should belong to the previous cold phase—the Oldest Dryas.

No morainic deposits were discovered in Malkia Kazan cirque. On its almost flat, grassy floor, there is a sinkhole, above which a peat bog developed. There is a relict debris fan from the northern side that has filled the cirque depression with some material. Probably, if there were some moraines in the cirque, they were probably buried.

Kutelo cirque

This is the next cirque on the marble section of the northern slope of Northern Pirim, situated to the NW of Golemia Kazan. A long and relatively narrow glacio-karstic depression of a simple shape, the cirque lies to the north-east of Kutelo II peak (2907 m a. s. l.). The upper section of the cirque is covered by screes. There a crescent moraine from fresh blocks is situated at 2400 m a. s. l. The field between the ridge and the headwall is covered with debris, and a snow patch remains there usually until the end of July. During the Little Ice Age, a small glacier might have existed in the cirque, with length up to 250–300 m. No moraines are observed further down the cirque, except some weathered boulders at the cirque outlet, at about 2150–2200 m. a. s. l., overgrown by Pinus mugo trees and grasses.

Banski suhodol cirque

This is the largest cirque in the marble (carbonate) part of Northern Pirin (2.3 km^2) (Fig. 3). In general, it has a rhomboid shape and aspect towards NNE. To the south, it is bordered by the high main ridge of Pirin (altitudes between 2810 and 2908 m a. s. l.), and to the NE it reaches the main rigel at 2300 m a. s. l. The altitude ranges from 2908 m a. s. l. at Kutelo I peak to 2230 m a. s. l. at the lowest part of cirque floor. The cirque floor is a labyrinth of karst sinkholes, hills and low ridges. The main sinkhole, where the lowest point is located, is in the northern part near the rigel. In its upper part, the vast cirque is divided into three sections, each section resembling a separate cirque which ends in a sinkhole. The eastern section is the largest—it includes a small intra-cirque U-shaped valley with a strip of dolines at its base—which ends in the main doline of the cirque.

In Banski suhodol cirque, the setting of glacial landforms, especially moraine ridges, has much in common with that in Golemia Kazan. The uppermost part of cirque's middle section is occupied by the Banski suhodol glacieret, the largest in Pirin and Bulgaria (Fig. 3), with an average surface area of 1.1 ha for the last 10 years. The glacieret has been described, mapped and measured for the first time in 2009 (Gachev and Gikov 2010). In 2012, after a strong recession, bedrock was uncovered at the front of the firn surface, which carried fresh traces of glacial

Fig. 3 Banski suhodol cirque with the glacieret (in the centre) and snow patches (October, 2013)

abrasion (striae). This was interpreted as an evidence for glacial type of motion of the firn/ice mass (Gachev 2014; Gachev and Mitkov 2019).

A curved protalus-moraine surrounds Banski suhodol glacieret from the lower side, at 2600–2620 m a. s. l. The moraine comprises two parallel ridges, separated by a shallow trench. The outer ridge has primitive soil and vegetation developed on it, quite similar to the outer side of the ridge around Snezhnika glacieret, which suggests their ages are similar (LIA). The inner ridge is younger, probably from the twentieth century.

Some 200 m further down to the north, another ridge is observed at about 2500 m a. s. l. Its composition, appearance and weathering rate (as measured by Mitkov 2020), indicates its age should correlate to that of the crescent ridge in Golemia Kazan—most probably from the Younger Dryas.

The eastern section of Banski suhodol cirque provides another sequence of well-preserved morainic accumulations. At present, a sustainable snow patch persists on the bottom of a doline, surrounded by debris. The first ridge is situated 10–20 m from the snow at the end of ablation season. Another one is found 50 m below, perching on top of a roche moutonnee, and surrounding a doline. Both ridges are made of fresh angular blocks, whitish (not grey) in colour, with no lichens, soil or vegetation. This should be considered the LIA extent of a small glacier, which remnant is the present-day snow patch. Moraines of weathered material with soil and grass are observed further down to mark the probable Younger Dryas glacier margins.

Another sustainable snow patch also exists in the western section of the cirque. Indications in the rocks and relief show that it was much larger and thicker in the recent past. However, no moraines are recognizable around the snow patch, as it ends in a gully and a steep slope, and all materials transported by the former small glacier were pushed away and rolled down.

Bayuvi dupki cirque (Pirin)

This is the next cirque to the west of Banski suhodol. To the south, it is bordered by the main ridge (2770–2821 m a. s. l.). This is a glacio-karstic depression opened to the north, about 1700 m long and 900–1000 m wide. It has one deep uvala at its centre, near the main rigel at 2370–2390 m a. s. l. Piles of fresh morainic material, angular, with no lichens, are scattered across cirque floor, especially in its lower section, towards the uvala.

Nowadays, the cirque floor of Bayuvi dupki is usually snow free in August–September. But the presence of a small glacieret on this place until the 1960s was documented by Peev (1960, 1961), who described it in detail. Moreover, he conducted regular observations on the site between 1934 and 1958, and, although not making exact size measurements, he pointed out the years, in which the glacieret was larger in summer, and the years when it was smaller. Peev's work has now been considered as the first glaciological monitoring in Bulgaria.

Musala cirque (Rila)

This cirque is located in the eastern part of the Rila Mountains (Fig. 1). It has a northern aspect and altitudes between 2925 and 2389 m a. s. l. It is developed entirely in granite. The complex cirque is a cascade comprised of several smaller cirques (cirque sections). Seven lakes are spread on cirque floors (Fig. 4).

The uppermost cirque section lies to the NE of Musala peak, and has altitudes between 2925 and 2709 m a. s. l. Here is situated the highest lake in Rila—Ledeno ezero (Icy lake)—with size 170 × 100 m and maximum depth 14.3 m. A moraine composed of three parallel ridges of granitic boulders dams the lake on the NE side. Another ridge is found on lake bottom, about 2 m below water level (Gachev et al. 2008). The underwater ridge lies near the SW shore of the

Fig. 4 Musala cirque (September, 2006)

lake, surrounding a shallow depression on the bottom with a maximum depth of 4.1 m. The discussed ridge has a crescent configuration, and is supposed to have marked the extent of a small glacieret (snow patch) which existed on the NE slope of Mt. Musala. Probably, the glacieret was persisting during the LIA, and its summer-round existence was evidenced in the beginning of the twentieth century (Radev 1920). On the slope of Musala, above the lake, there is a lobe of boulders with grass cover on it, a lobate relict rock glacier, which during the LIA was definitely not under ice. Rather the glacieret had a V-shape, with ice descending from two sides and merging at lake's end (Fig. 5).

The state of the moraine damming the lake at 2700–2710 m a. s. l. indicates that it is much older than the LIA, most probably formed during the Younger Dryas. It was not excluded, however, that this moraine dates from

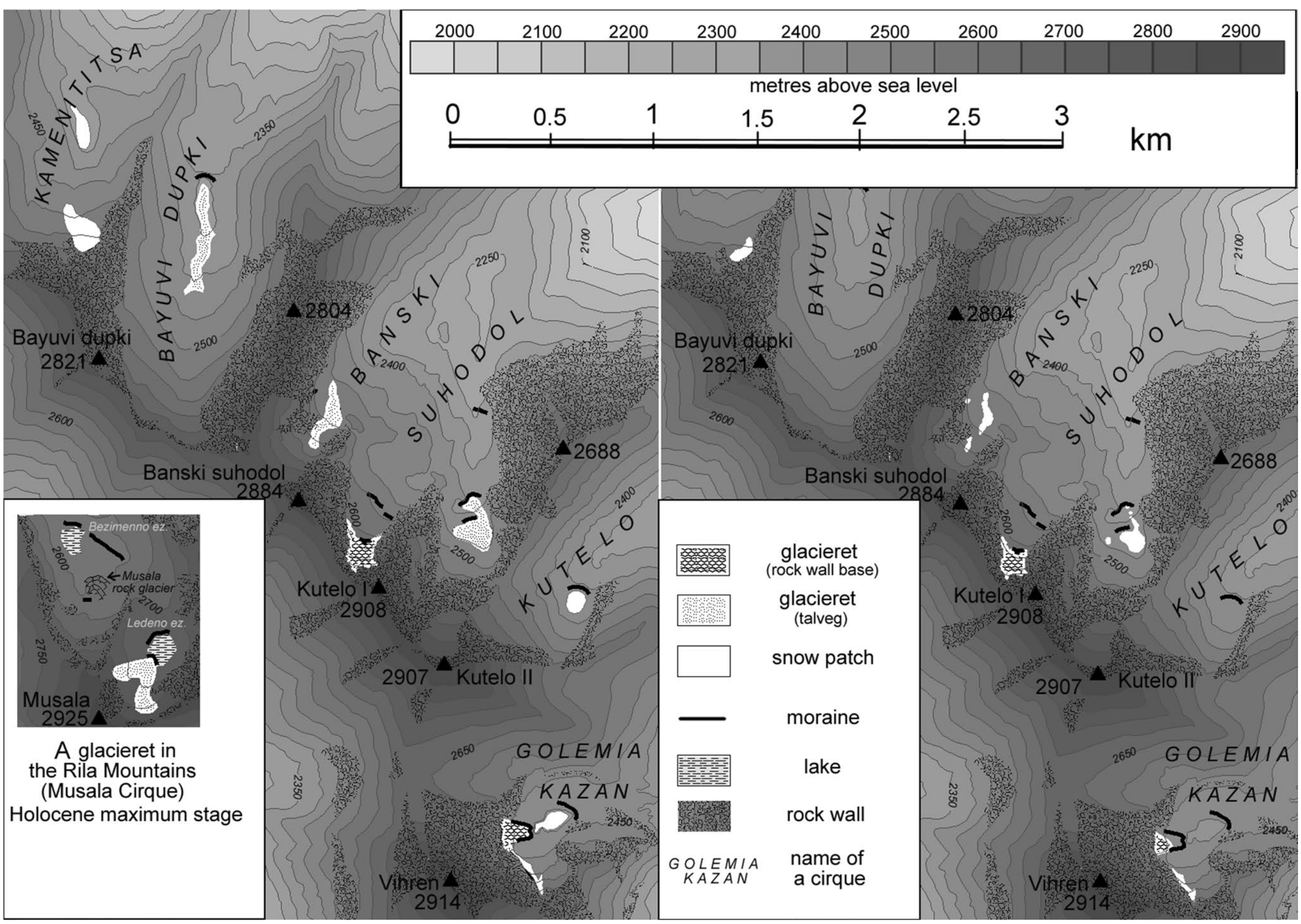

Fig. 5 Holocene glacier extent in Pirin Mountains (maximum stage to the left, present-day stage to the right) and Rila Mountains (maximum stage only)

some cold phase in the first millennia of the Holocene (piotino/Kromer stage?), because the altitude is very high and here even a slight disturbance in climate could lead to glacier formation.

The next cirque section is situated to the north of Mt. Musala, from the peak to the lake Bezimenno at 2580 m a. s. l. It encompasses the northern slope of Musala peak and the eastern slope of the ridge that descents from the peak to the north. The southern part is occupied by the Musala rock glacier, a complex body of granitic boulders. The rock glacier consists of two parts, formed separately during discrete time episodes, which has been supported by geomorphological evidence and Schmidt hammer testing (Gachev 2018).

There are traces of a small moraine ridge situated right behind (to the SW of) the last of the five ridges of the rock glacier's lower part. This moraine indicates that a small glacier (glacieret) might have existed in the beginning of the Holocene. However, the state of the lobate upper part of Musala rock glacier suggests that definitely there was no ice there during the LIA (Gachev et al. 2017; Gachev 2018). Only permafrost and some cryogenic replacements might have taken part.

Methods

Geomorphological mapping was applied to identify traces from deglaciation stages in the highest areas of Pirin and Rila Mountains. Mapping was done on the field, as well as with the use of various remote sensing techniques. Present-day glacierets and snow patches have been measured on a regular basis every autumn (in September–October) with the use of measuring tape (rope) and, in more recent years, with a laser range finder. Field measurements have been entered in GIS software, where surface areas for the particular years are calculated. The moraine ridge at the bottom of Ledeno ezero in Rila was mapped and measured with bathymetry methods, using a boat, a measuring rope, and a GPS receiver.

Suggestible extent of glaciers during the maximum Holocene stage has been outlined and digitized in ArcGIS 10 on the basis of topography maps, satellite and land based images. This allowed for the calculation of total and partial surface areas.

On Vihren peak (the highest of the Pirin Mountains), climatic data have been collected since 2014 by automatic equipment, but for the analyses in the present study daily and monthly data from the meteorological station at Musala peak (Rila) has been used (Nojarov 2008; http://www.stringmeteo.com), with extrapolation for the altitude of Snezhnika glacieret.

Results

Extent of Holocene glaciation

Summarizing the above detail description of glacial traces, on the basis of the location, morphology and state of moraines, and of data from previous studies, a conclusion can be made that two major stages of Holocene glaciation can be outlined in the highest mountain areas of Bulgaria: maximum stage, and present-day stage. Greatest extent during both stages had the glaciation in Northern Pirin, especially in the part made of carbonate rocks (marble). This demonstrates the importance of bedrock as a factor for glacier persistence in marginal areas such as the Mediterranean, where climate in general does not favour a year-round preservation of snow and ice at 2000–3000 m altitude. In the Rila Mountains, Holocene glaciers had much smaller extent, and existed only in the maximum phase. No glaciers are found there today, although the absolute altitude of the highest peaks and cirque floors reaches bigger values.

The glacier extent of the two mentioned stages is shown in Fig. 5.

According to geomorphological and glaciological evidence, during the maximum stage glacierets covered approximately 11.8 ha (9.2 ha in Pirin and 2.6 ha in Rila). At present, their total area (based on average surface size for the last 10 years) is about 1.7 ha (18.3% of the maximum stage extent) and glacierets remained only in Pirin. During the maximum stage, sustainable snow patches in the marble part of Northern Pirin occupied over 6 ha, while now their average size is 3.55 ha (58% of the maximum stage extent). In the two areas researched in details, the area occupied by summer-round ice and snow had decreased by two-thirds (Table 1, Fig. 6).

Table 1 Glacierets and sustainable snow patches in the highest parts of the Pirin and Rila Mountains during the maximum stage and in the present stage

Category	Location	Total area max [ha]	Total area present [ha]	Decrease, (%)
Glacieret—rock wall foot	Pirin	2.85	1.68	41
Glacieret—talveg	Pirin	6.33	0.00	100
Glacieret—talveg	Rila	2.60	0.00	100
Snow patch	Pirin	6.04	3.55	42

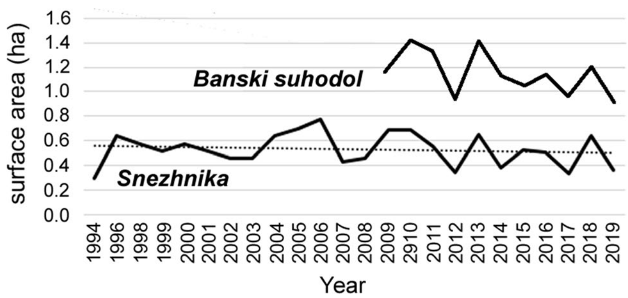

Fig. 6 Recorded areas of Snezhnika and Banski suhodol glacierets at the end of the balance year (September–October)

Recent changes in Pirin glacierets

The glacierets in Pirin have been observed regularly for the last decades. Measurements for the period 1994–2007 were presented by Grunewald et al. (2008), and for the later years by Gachev (2011, 2016) and Gachev and Mitkov (2019). For Snezhnika glacieret, the changes of area in the end of the balance year (autumn) for the period 1994–2019 have shown a slight trend towards decrease (Fig. 7). Inter-annual variations have been often great, reaching differences of two times the area. The absolute minimum was registered in 1994, in the very beginning of regular observations. Quite close to that value were the sizes for 2012, 2017 and 2019. Greatest was the size in 2006, and relatively large in 2005, 2009, 2010, 2013 and 2018.

Since the start of the annual measurements of Banski suhodol glacieret in 2009, a strong downward trend has been recorded. In fact, for the same latest period similar is observed for Snezhnika, but for the latter glacieret, the overall trend is balanced by the period 1994–2003 which was characterized by small sizes.

Discussion

Main stages of deglaciation in the Rila and Pirin Mountains during the Late glacial and the Holocene

Studied glacial evidence from the Rila Mountains (Kuhlemann et al. 2008, 2013) shows that Pleistocene glaciers in the Rila Mountains reached their maximum during the LGM. According to data from cosmogenic nuclide dating (Kuhlemann et al. 2013), glacier advances in this particular mountain massif were registered at the beginning and at the end of this stage, while at the culmination of LGM, a retreat was suggested, similar to what was found for the High Tatras (Gadek 1998; Klapyta and Zasadni 2018).

The Late glacial was marked by considerable and progressive warming, interrupted by some disturbances. Of the latter, most notable were the Oldest Dryas and the Younger Dryas cold episodes. Especially in the eastern part of the Balkan Peninsula, both phases were characterized by cold and pronouncedly dry climate, a fact, which has been proved by data from numerous pollen studies from Rila and Pirin Mountains, and from the studies of lake and Black sea levels which were situated considerably lower than today (Bozhilova 1978; Stefanova and Ammann 2003). The transition from the relatively damp and cold climate at the termination of the LGM, to the warmer and dryer conditions of the Late glacial, should have been associated with a strong glacial retreat. According to the studies of Dimitrov and Velchev (2012) and Mitkov (2020), glaciers restricted their extent within the margins of the Pleistocene cirques no later than the Oldest Dryas. For the very large cirque systems, such as Bunderishki cirque in Pirin and Seven Lakes cirque in Rila, the lowermost cirque floor sections were ice free already in the Oldest Dryas. Especially in Rila and Pirin, temperatures during the Oldest Dryas were lower than during the Younger Dryas (Stefanova et al. 2003), which

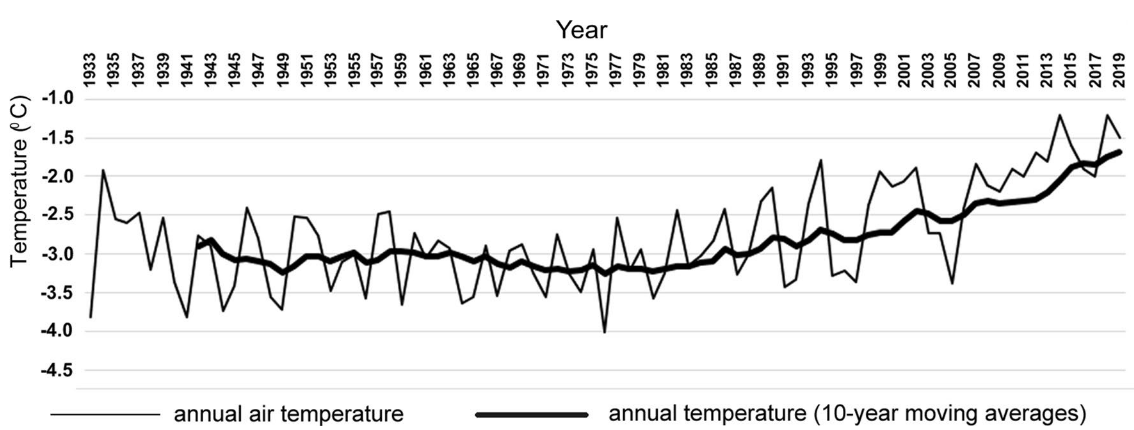

Fig. 7 Temperatures at Musala peak station (1934–2019)

resulted in the larger expression of glaciation during the first of these cold phases.

A ^{10}Be date from stadial recessions in Rila Mountains are available for the cirque of the Seven lakes—a roche moutonnee from Suhia rid yielded an age of 10 ka BP (Kuhlemann, Gachev. unpublished information), revealing that during the Younger Dryas, the ridge between the main parts of the complex cirque with an altitude 2400–2450 m a. s. l., was already free of ice. Another ^{10}Be sample taken from a moraine in Yakorudski cirque, gave an age of around 12 ka (Kuhlemann, Gachev, unpublished data).

Dry conditions continued to prevail also in the initial millennia of the Holocene, at least until 8 ka BP (Wright et al. 2003; Stefanova and Ammann 2003). The warming culminated during the Atlantic optimum (6–5.5 ka), with temperatures around 2 °C higher than the present (the last decades of the twentieth century) (Crowley 1996; Blumel 2002; Nikolov 2011). In pollen spectra, this Holocene, maximum of temperature is characterized by expansion of the fir, and rise of the timberline to 200–250 m higher than its current position (Kachaunova and Stefanova 1999; Stefanova and Ammann 2003; Stefanova et al. 2006).

In the time after the Atlantic, the climate has become changeable, with average temperatures several degrees lower (Grunewald and Scheithauer 2008a). The Early Iron Cooling, the Roman Optimum, the Early Medieval Cool Episode, the Medieval Warm Period, and the Little Ice Age were the main stages of climate history in this period. After 1850 the contemporary warming progressed, with phases of intense increase of temperatures (1860–1890, 1920–1950, 1980–present), and stages of stagnation (or slight cooling) (1890–1920, 1950–1980) (Grunewald and Scheithauer 2008b). The last time episode, since 1980, has been marked by warming on an increased pace.

Vegetation reconstructions done on the basis of pollen studies in Rila and Pirin (Bozhilova 1978; Stefanova and Ammann 2003; Stefanova et al. 2003; Tonkov and Marinova 2005; Tonkov et al. 2006, 2008) do not indicate noticeable cold phases and abrupt changes in the period from the beginning of the Holocene to the medieval times, and the Little Ice Age (LIA), which was the coldest period since the beginning of the Holocene.

On the basis of the character of climatic phases, the evolution of glaciers in the Holocene can be suggested as follows: (1) in the early millennia: retreat of Younger Dryas glaciers, ending with the minimum Holocene glacier extent during the Atlantic (glaciers may have totally disappeared); (2) the period since 3000 BP: development of microforms of glaciation, with possible disappearance during warm episodes; (3) glacier and snow patch formation and growth during the Little Ice Age; and (4) after 1850: a contemporary period with residual glacial features that show shrinking trends.

From the above description, it becomes clear that the maximum stage of Holocene glacier extent can be related to the Little Ice Age. Possible traces of earlier colder episodes throughout the Holocene were most probably overdrawn by the LIA glaciers. However, this is not 100% certain, especially in the Musala area (the highest part of Rila Mountain). In the pollen-based vegetation reconstructions in the Rila Mountains, the cold stage piotino (9 ka BP) was also recorded as a small crisis in vegetation history (Bozhilova 1978).

Relation between glaciation and post-LIA climate change

The post-LIA recession of glacierets and snow patches in Bulgaria's highest mountains can be explained with the rise of temperatures, which is clearly demonstrated by the temperature record of Musala peak meteorological station, in operation since 1933 almost without interruption (Fig. 7).

The rising trend is observed after 1980, but in the last 15 years, the warming has progressed with an increased pace. The average annual temperature for the period 1931–1970 was − 3.0 °C, for 1979–2008 − 2.7 °C, and for 1990–2019, it was − 2.2 °C. For the last decade, the average temperature reached − 1.7 °C.

The pattern of precipitation change has been much more complicated. For Musala, about 15% decrease of annual amounts was registered from the middle of the twentieth century to the first decade of our century, according to the study of Nojarov (2012). Precipitation regime, however, differs between the highest parts of Rila and Pirin, as the latter is subject to much stronger Mediterranean influence. Concerning precipitation in SW Bulgaria, Grunewald and Scheithauer (2008b) outline the following periods: 1897–1901—damp, 1902–1909—dry, 1910–1934—normal to dry, 1935–1944—damp, 1945–1953—dry, 1954–1984—damp, 1985–1994—dry. According to data from Musala station in the years since, the period 1995–1998 is moderate, 1999–2003—dry, 2004–2013—damp, 2014–2016—dry winters and damp summers, 2017–2019—dry. The variations in 10 years moving averages for the period 1990–2019 reach 200 mm (20–25%), which means that the decrease mentioned by Nojarov (2012) could originate not from a long-term change, but from the comparison between damp and dry periods.

As it is seen on Fig. 8, no trend can be derived from the precipitation record of Musala peak. This is valid for the annual totals, as well as for the amounts of snow (from November to April) and rain (from May to October). In general, the periods 1997–2000 and 2005–2010 have higher winter precipitation, while they are low in 1990–1994, 2001–2004 and 2014–2019.

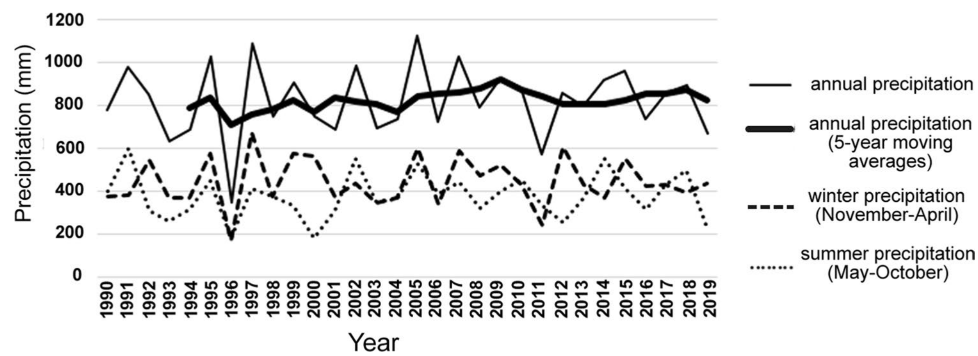

Fig. 8 Precipitation at Musala peak station (1990–2019) (http://www.stringmeteo.com)

Along with the shrinkage of Snezhnika glacieret, which bigger size was documented in numerous photographs taken between the 1950s and 1980s (about 30% reduction in area, between 1950–1980 and 1994–2007, Grunewald and Scheitchauer 2010), the change of climate since the middle of the twentieth century caused the complete disappearance of the small glacieret in Bayuvi dupki cirque, documented by Peev (1960, 1961).

Recent studies (Gachev 2016; Gachev and Mitkov 2019; Nojarov et al. 2019) have proved that the size of Pirin glacierets is mostly related to the temperature conditions during the ablation season. A correlation of − 0.73 was registered between the size of Snezhnika and the sum of positive daily temperatures, extrapolated for the site of the glacieret on the basis of meteorological data from Musala peak (Gachev 2016). This correlation remains very stable in the course of time. Winter precipitation appear as a secondary factor. The low sizes of Snezhnika during the 1990s were result of reduced snow income, especially in the first half of the decade, and the increase of snow amounts lead to the much higher sizes during the period 2004–2013. Since 2014, warm and dry winters have been predominant, and this caused another recession. Especially in this last period, the years 2017 and 2019, which combined a deficit of snow with high summer temperatures, were marked by great shrinkages of Pirin glacierets.

However, avalanche contribution has been proved to be very important for the existence of Snezhnika glacieret. The ratio between the snow catchment and the area of the glacieret is 22.28, almost entirely consisting of slopes steeper than 40°. Thus, the glacieret persists on eastern exposure, shone by the sun several hours a day even in winter. On the other hand, the same ratio of Banski suhodol glacieret is only 6.22, which is compensated by the much higher altitude (200 m higher than Snezhnika), and the northern exposure. In the years of observation, this glacieret showed greater stability and higher dependence on ablation temperature.

Regional correlations of Holocene glaciation on the Balkans

In fact, the whole territory of the Balkan Peninsula east of the Dinaric mountain range is in a position of a rain shadow to the air masses that carry the moisture from the Mediterranean (main source of winter moisture at present, and probably throughout the whole Holocene as well) (Hughes and Woodward 2008). On the other hand, air masses which invade from NW and carry moisture directly from the Atlantic Ocean, lose considerable amount of water vapour on the slopes of the Carpathians, resulting in lesser precipitation for the mountain ranges inside the Balkan Peninsula. This has determined the relatively small glacier extent in the eastern Balkans, compared to the Dinaric Mountains and the Alps.

Except in the Pirin Mountains of Bulgaria, at present, small glaciers on the Balkans have also been found, explored and described, in two more mountain ranges: Prokletije Mountains (2694 m a. s. l.) in northern Albania, and Durmitor massif (2522 m a. s. l.) in Montenegro (Djurović 1999, 2012; Milivojević et al. 2008; Hughes 2007, 2008, 2009; Wilkinson 2011; Gachev and Stoyanov 2012; Gachev et al. 2016; Gachev 2017; Gachev and Mitkov 2019; Milivojević 2019). Both mountains belong to the vast Dinaric chain, constituting its first and second highest massifs, respectively. They lie 90–110 km away from the Adriatic Sea, and receive abundant moisture from the SW. The bedrock of both is limestone.

In the central parts of Prokletije (the areas around Maja e Jezerces and Maja Gryk e Hapt peaks), traces of relatively fresh moraines without lichen cover are observed several tenths to several hundreds of meters outside of the contemporary ice margins (Wilkinson 2011; Gachev 2017). The most prominent example is the largest glacieret in Prokletije and on the Balkans as well, Jezerce III (2.5–5 ha at present), where a sequence of moraines outline the former presence of a glacier snout descending down from the upper level of the cirque. Similar sequence of very fresh moraines is also discovered around Mertur glacier, to the south of Valbona valley. All this evidence indicate the much larger extent of glaciers in those mountains during the LIA.

Hughes (2010) made a detail study of LIA glaciation in the Durmitor Massif, using mainly lichenometry. According to his findings, the current moraine that surrounds Debeli namet glacier consists of three parallel ridges, situated within 10–15 m, the outermost of which was formed around 1878 AD, soon after the end of the LIA. In contrast to this very small change, the same author found evidence for the existence of several other large glacierets in the mountain, at locations that are now completely ice free.

Throughout the northern shores of the Mediterranean, glacierets are found at topographic and climatic settings that are similar to those described on the Balkans (Gachev et al. 2009; Hughes 2009; Grunewald and Scheitchauer 2010). During the Little Ice Age, all these remnants were much larger, both in terms of volume and surface area (Hughes 2014, 2018). Since the end of the eighteenth century Calderone glacier in Gran Sasso (Apennines, Italy) has reduced its surface approximately 20 times, scattering into two glacierets in the beginning of our century (Rovelli 2006; Pecci et al. 2008). Similar has been the fate of Triglav glacier in the Julian Alps of Slovenia, which shrank from over 30 ha about 100 years ago, to only 0.4 ha in 2012, as well as that of Canin glacier in Italy (Gabrovec et al. 2013; Triglav Cekada et al. 2014). Despite the forecasts for its complete disappearance, the glacieret has been fallen into stagnation since, its size fluctuating around 1 ha. The other example from Slovenia, Skuta glacier in Grintavec massif, has lost about a third of its surface area for the last 70 years, but suffered at least 90% reduction of thickness (Pavšek 2004, 2007). For the last century, a drastic shrinkage has been observed also for the other small glaciers in the Southeastern lower flanks of the Alps (in Italy and Austria), which have similar altitude range as the highest mountains of Bulgaria (Hohenwarter 2013; Colucci 2016).

The existence of present-day small glaciers in some of the high mountains of Southern Europe is a result of favorable (and to a considerable extent accidental) combination of factors. Among them is the strong influence of topography, which modifies regional climatic conditions locally to support great snow and ice accumulation at certain locations. Topography itself is determined by the geological setting, and the impact of climate on it.

Carbonate rocks (limestone, marble, dolomite) are lighter in colour than most silicate rocks that build the high mountains on the Balkans (granite, gneiss, schist, amphibolite, gabbro, conglomerates, etc.). For instance, granites can be light grey, but the lichens that grow on them often form a dense cover of dark colour, especially when exposed on sunlight for a long time through the year. Hence, on balance, carbonate rocks reflect more light and remain colder during sunshine. Karst processes, which develop in soluble rocks, determine the infiltration of waters that are produced by glacier melt and summer rains. Disappearing underground, water is not retained at glacier bottom to support and enhance ice meltdown. Increased dissolution of carbonate rocks in vertical direction and the enhanced vertical erosion of glaciers in karst terrains favour cirque overdeepening and the formation of high vertical rock walls, which provide optimal shading conditions. Of course, sufficient altitude is needed to provide a low-temperature base. In the mountains of the Balkans, small glaciers exist on altitudes between 2700 and 1900 m a. s. l., and in the Dinarides, sustainable snow patches are observed even at 1600 m a. s. l. (Gachev et al. 2016; Gachev 2017). Also, Colucci (2016) mentioned the properties of carbonate bedrock to provide favourable conditions for snow accumulation on relatively low altitudes, due to the formation of closed karst depressions.

The influence of bedrock is well demonstrated when comparing neighbouring mountains of contrast lithology. An example already demonstrated above are the Pirin and Rila Mountains, and Pirin alone, which high area has a diverse rock composition. The highest parts of Rila and central Northern Pirin, built of granites and silicate metamorphites, do not support glacierets at present, despite the high altitude and the presence of some favourable peculiarities of topography (Gachev et al. 2009). In contrast to them is the marble part of Pirin, where two glacierets and numerous snow patches are not only present, but also have been relatively stable in the past decades. Quite similar is the comparison between the central and western parts of Prokletije mountain system, where limestone is predominant, and the eastern and northeastern sections, with a mosaic lithology of mostly silicate rocks (schists, quartzites, granite, gabbro, serpentinite etc.,) (Osnovna geološka karta SFRJ (2020) 1:100 000). No glaciers presently exist in the latter area, despite the high altitude, which exceeds 2500 m at several locations (including Djeravica peak, 2655 m a. s. l., the second highest of Prokletije). In contrast, 13 small glaciers and numerous sustainable snow patches are found in the carbonate parts (Gachev et al. 2016; Gachev 2017). In general, the much stronger influence of physical weathering on silicate rocks leads to their gradual disintegration into larger fragments (compared to limestone especially) and this leads to a greater mass movement and to a formation of steadier slopes and shallower cirques, that provide less favourable shading conditions.

Winter precipitation is another very important factor for glacier formation. All the areas on the Balkans where glacierets and snow patches are concentrated, have precipitation regime with a strong Mediterranean influence, which is expressed with a great share of winter precipitation. Especially important is the avalanche and windblown snow contribution, which can increase the actual amount of snow accumulation over glacier surface several times compared to the direct atmospheric input (Hughes 2008).

Indicative cases for strong avalanche feeding are Snezhnika glacieret (in Pirin) and Jezerce III (Prokletije) which survive on eastern aspect, opened to sunshine in the morning all year round. The presence of flat plateau surfaces near deep cirques can also be a favourable condition for glacier persistence, as such surfaces accumulate much snow, which is then blown over into cirques (especially if the cirque provides shading). Such is the case with Debeli namet glacier in Durmitor, Kolata glacier in Prokletije, and, to some extent, Snezhnika glacieret in Pirin.

In general, traces from LIA glaciation from the western Balkans, Apennines and the SE Alps, indicate that the glacier recession there was much stronger than in Pirin Mountains, where the post-LIA retreat can be categorized as moderate.

Recent short-term fluctuations of glaciers have been more pronounced in areas with a damper climate and high precipitation. After several years of negative mass balance, after the summer of 2017, the glaciers in the Dinaric Mountains almost disappeared (most sites, including the Debeli namet glacier, were debris fields with exposed buried snow). A sequence of dry winters caused that drastic recession, as winter precipitation is the main factor for glacier size. On the other hand, glacierets in Pirin showed much greater stability and a weak long-term negative trend, related to temperature changes.

The role of topography is also crucial for each particular glacier. Those who are in deep and narrow rocky depressions have had smaller change in surface area, while those that occupy parts of wide cirque floors or doline bottoms, have shrunk much more. According to Colucci (2016), the damming effect of the moraine ridges, situated close to glacier margins, is also very important, as they retain avalanche snow and keep it over the glacier surface.

Some studies (Triglav Čekada and Gabrovec 2013; Scotti and Brardinoni 2018; Santin et al. 2019) confirm that the smaller is one glacier, the least dependent is it from climate change. Many glaciers in the southern and the eastern Alps have shrunk rapidly throughout the twentieth century, and, when they reached sufficiently small size (e.g. comparable to that of Pirin glacierets), they become relatively stable. Such is the case with a number of glaciers in the Julian Alps (Gabrovec et al. 2014; Colucci 2016). In Prokletije, the rapid shrinkage probably occurred also throughout the last century. At other small glaciers of the Southern Alps (Eiskar, Austria, Marmolada, Italy) the rapid reduction is still in progress (Santin et al. 2019; Hohenwarter 2013). Evidence has shown that the glacierets in Pirin were in the "small size" stage also in the LIA, and this provides an explanation why they have changed relatively little since.

On the other hand, the catastrophic situation with almost all of the Dinaric glaciers in 2017 has put a question on the proposed stability of very small glaciers. Maybe climate change is already leading them on a threshold, beyond which glacier survival is impossible.

Conclusions

The detailed study of glacial traces shows that during the Holocene, glaciation in the mountains of Bulgaria has been very restricted, and limited to the highest cirques of the highest mountains Pirin and Rila. The most favourable have been the conditions in the highest part of Northern Pirin, which is built of carbonate rocks (marble). These rocks provide optimal physical and topographical conditions: higher albedo to reduce bedrock heating by the sun, infiltration of water into karst caverns to hinder basal melting, strong shading, provided by high, almost vertical rock walls. Another important factor for the preservation of two glacierets and several highly persistent snow patches is the Mediterranean climatic influence and considerable winter precipitation, which contribute to snow accumulation not only directly, but also as avalanches and windblown snow.

During the maximum Holocene phase, which can be addressed to the LIA, the glacial extent in Bulgarian highest mountains was about as twice as big as today (in terms of surface area), which points to a much more modest post-LIA reduction than what has been observed in many other locations throughout the Mediterranean. This is addressed to the more continental climate of the eastern Balkan Peninsula, and the lesser variation in precipitation.

In the last decades, glacierets in Pirin have displayed a trend towards retreat, which reflects the increased climatic warming. Glacieret size in autumn (at the end of the balance year) depends mainly on the thermal conditions during the ablation season. The recession has been more pronounced in the years since 2006, because in this period, the temperature rise is combined with a reduction of winter precipitation.

Despite the observed tendency for glaciers to stabilize when they become very small (decoupling from climate change due to strengthening the effect of topography), the recently observed catastrophic downfall of some small glaciers on the Balkan Peninsula raises the question about the survival of small glaciers in the conditions of enhanced warming.

Acknowledgements The collection of field data for this study was done in numerous campaigns (annually from 2008 to 2019) with funding from the following projects: Projects of the South-West University—RP-A 10/15 Complex research of embryonic glaciers on the Balkan Peninsula" (2015); RP-A 13/17 Investigation of climate variations through natural indicators: small glaciers and permafrost" (2017); RP-A 4/18 Investigation of climate variations through natural indicators: small glaciers and permafrost, part II (2018); International projects—BG0034 Preservation of glacial relict plants in Bulgaria" of the Institute of Botany, Bulgarian Academy of Sciences, EEA Grants Programme, 2009–2010. Research of global changes in high mountains by the example of lake areas in Rila (Bulgaria) and the Julian Alps (Slovenia). Bulgarian Scientific Research Agency, funded organization: National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, 2012–2014.

Data availability All data and materials are available on demand.

Compliance with ethical standards

Conflict of interest There are no conflicts of interests.

References

Baltakov G (2004) Glacialna morfogeneza vav visokoplaninskia pojas na Bulgaria svarzana s kupolen tip lednici (Glacial morphogenesis in the high-mountain zone of Bulgaria associated with dome glaciers). Probl Geogr 1:71–79 **(in Bulgarian)**

Baltakov G, Mladenova V (1989) Some typical Late Glacial geomorphic phenomena in the Rila mountain. Geogr Rhodopica 1:191–193

Bereiter B, Eggleston S, Schmitt J, Nehrbass-Ahles C, Stocker TF, Fischer H, Kipfstuhl S, Chappellaz J (2015) Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present. Geophys Res Lett 42:542–549

Blumel WD (2002) 2000 Jahre Klimawandel und Kulturgeschichte—von die Eiszeit in die Gegenwart. Wechselwirkungen—Jahrbuch aus Lehre und Forschung der Universitat Stuttgart, Stuttgart

Bozhilova E (1978) Promeni na rastitelnostta v Rila prez poslednite dvanadeset hiliadi godini. Vegetation changes in the Rila Mountains in the last 12,000 years. Annual Journal of Sofia University, Fac. Biol., book-2. Botany 71:39–44

Burić M, Micev B, Mitrović L (2012) Atlas klime Crne gore (Climate Atlas of Montenegro). CANU, Podgorica

Çiner A, Stepišnik U, Sarikaya MA, Žebre M, Yildirim C (2019) Last glacial maximum and Younger Dryas piedmont glaciations in Blidinje, the Dinaric Mountains (Bosnia and Herzegovina): insights from ^{36}Cl cosmogenic dating. Mediterr Geosci Rev. https://doi.org/10.1007/s42990-019-0003-4

Colucci R (2016) Geomorphic influence on small glacier response to post Little Ice Age climate warming: Julian Alps, Europe. Earth Surf Process Landf 41(9):1227–1240

Crowley TJ (1996) Remembrance of things past: greenhouse lessons from the geologic record. Consequences 2(1):3–12

Cvijić J (1897) Tragovi starih gletcera na Rili. (Old glacier trogs in Rila). Glas Srpske Kraljevske Akademije Nauka 54, Belgrade

Cvijić J (1908) Beobachtungen uber die Eiszeit auf der Balkanhalbinsel, in dem Sudkarpathen und auf dem mysischen Olymp. Zeitschrift fur Gletscherkunde 3:1–35

Dimitrov P, Velchev A (2012) The relict rock glaciers as a morphological feature in Rila mountain's alpine zone. Ann J Sofia Univ Fac Geol Geogr Book 2 103:97–112

Djurović P (1999) Natural and anthropogenic influences as threats to pits in the Debeli namet glacier, Durmitor National park, Montenegro. Contribucion del estudio cientifico de las cavidades karsticas al conocimiento geologico. Malaga

Djurović P (2009) Reconstruction of the pleistocene glaciers of Mt. Durmitor in Montenegro. Acta Geogr Slov 49(2):263–289

Djurović P (2012) The Debeli Namet glacier from the second half of the 20th century to the present. Acta Geogr Slov 52:277

Gabrovec M, Ortar J, Pavšek M, Zorn M, Triglav-Čekada M (2013) The Triglav glacier between the years 1999 and 2012. Acta Geogr Slov 53(2):257

Gabrovec M, Hrvatin M, Komac B, Ortar J, Pavšek M, Topole M, Triglav Čekada M, Zorn M (2014) Triglavski ledenik. Geografija Slovenije, 30th edn. SANU, Ljubljana

Gachev E (2011) Inter-annual size variations of Snezhnika glacieret (the Pirin mountains, Bulgaria) in the last 10 years. Stud Geomorphol Carpatho Balcan 45:47–68

Gachev E (2014) Ima li lednitsi na Balkanskia poluostrov (Are there glaciers on the Balkan Peninsula?). Priroda 1:96–103

Gachev E (2016) Klimatichni faktori za mezhdugodishnata dinamika na mikrolednik Snezhnika v Pirin. Climatic factors for the interannual dynamics of Snezhnika glacieret in Pirin. In: Proceedings of the scientific conference "geographical aspects of spatial planning and utilization in global change conditions", Bulgarian Geographic Society, Varshets, Bulgaria, 09. 2016

Gachev E (2017) The unknown southernmost glaciers of Europe. In: Godone C (ed) glaciers. InTech Publishers, Zagreb

Gachev E (2018) Characteristics and evolution of the rock glacier near Musala peak (Rila Mountains, Bulgaria). Stud Geomorphol Carpatho Balcan 51:25–42

Gachev E, Gikov A (2010) Opisanie i parvo izmervane na snezhnika v tsirkusa Banski suhodol. (A description and a first measurement of the glacieret in Banski suhodol cirque.). Probl Geogr Bulg Acad Sci 3:90–98 **(in Bulgarian)**

Gachev E, Mitkov I (2019) Small glaciers in Pirin (Bulgaria) and Durmitor (Montenegro) as glacio-karstic features. Similarities and differences in their recent behaviour. Quatern Int 504:153–170

Gachev E, Stoyanov K (2012) Present-day perennial firn/ice patches in the mountains of the Western Balkan Peninsula. Stud Geomorphol Carpatho Balcan 46:51–70

Gachev E, Gikov A, Gacheva I, Nojarov P, Popov M (2008) Morfologia na dunoto na Ledenoto ezero (Rila) i nejnata vruzka s kvaternernata evolyutsia na relefa. Morphology of the bottom of Ledeno ezero (Rila) and its relation to the Quaternary evolution of relief. Probl Geogr Bulg Acad Sci 3:97–106 **(in Bulgarian)**

Gachev E, Gikov A, Zlatinova C, Blagoev B (2009) Present state of Bulgarian glacierets. Landf Anal 11:16–24

Gachev E, Stoyanov K, Gikov A (2016) Small glaciers on the Balkan Peninsula: state and changes in the last several years. Quat Int 415:32–54

Gachev E, Magori B, Sirbu F-S, Stoyanov K, Ivanov M (2017) Field observations of rock glaciers in the mountains of Bulgaria. Probl Geograph Bulg Acad Sci 3:55–66

Gądek B (1998) Würmskie zlodowacenie Tatr w swietle rekonstrukcji lodowcow wybranych dolin na podstawie prawidlowosci glacjologicznych. Wuermian glaciation of the Tatras in the light of the reconstruction of selected valley glaciers on the basis of glacial evidence. Prace Naukowe Uniwersytetu Slaskiego w Katowicach, Katowice, 1741 **(in Polish)**

Georgiev M (1991) Fizicheska geografia na Bulgaria (Physical geography of Bulgaria). Sofia University Press, Sofia, p 406 **(in Bulgarian)**

Glovnia M (1958) Geomorfolozhki prouchvanija v Yugozapadnia dyal na Rila planina (Geomorphological researches in Southwestern Rila mountain). Annu J Sofia Univ GGF Geogr 51(3):68–103 **(in Bulgarian)**

Glovnia M (1962) Prouchvania na glacialnata morfoskulptura v Iztochnia dyal na Rila planina (Researches of glacial morphosculpture in the Eastern share of Rila mountain). Annu J Sofia Univ GGF Geogr 55(2):1–47 **(in Bulgarian)**

Glovnia M (1968) Glacialen i periglacialen relef v yuzhnata chast na Sredna Rila (Glacial and Periglacial relief in the southern part of Central Rila mountain). Annu J Sofia Univ GGF Geogr 61(2):37–66 **(in Bulgarian)**

Gore A (2006) An inconvenient truth. Rodale Press, New York, p 328
Grunewald K, Scheitchauer J (2010) Europe's southernmost glaciers: response and adaptation to climate change. Glaciology 56:129–142
Grunewald K, Scheitchauer J (2011) Landscape development and climate change in Southwest Bulgaria (Pirin mountains). Springer, New York, p 161
Grunewald K, Scheithauer J (2008a) Holocene climate and landscape history of the Pirin Mountains (Southwest Bulgaria). In: Borsdorf A, Stotter J, Veulliet E (eds) Managing Alpine future. IGF-Forschungs-Berichte, Dresden, pp 305–312
Grunewald K, Scheithauer J (2008b) Climate and landscape history of Southeast Europe. A geoarchive based reconstruction for the Pirin Mountains (Bulgaria). Rhombos Verlag, Dresden, p 180 **(in German)**
Grunewald K, Scheithauer J, Gikov A (2008) Mikrolednitsi v Pirin planina. Glacierets in the Pirin Mountains. Probl Geogr Bulg Acad Sci 1–2:159–173
Hohenwarter G (2013) The Eiskar—115 years of measurements at the southernmost glacier in Austria. Meteorologica 102:26–28
Hughes PD (2007) Recent behaviour of the Debeli Namet glacier, Durmitor, Montenegro. Earth Surf Process Landf. https://doi.org/10.1002/esp.1537
Hughes PD (2008) Response of a Montenegro glacier to extreme summer heatwaves in 2003 and 2007. Geogr Ann 90A:259–267. https://doi.org/10.1111/j.1468-0459.2008.00344.x
Hughes PD (2009) Twenty-first century glaciers in the Prokletije Mountains, Albania. Arct Antarct Alp Res 41:455–459
Hughes PD (2010) Little Ice Age glaciers in the Balkans: low altitude glaciation enabled by cooler temperatures and local topoclimatic controls. Earth Surf Proc Landf 35(2):229–241
Hughes PD (2014) Little Ice Age glaciers in the Mediterranean mountains. Mediterrannee 122:63–79
Hughes PD (2018) Little ice age glaciers and climate in the Mediterranean mountains: a new analysis. Geogr Res Lett 44(1):15–45
Hughes PD, Woodward JC (2008) Timing of glaciation in the Mediterranean mountains during the last cold stage. J Quat Sci. https://doi.org/10.1002/jqs.1212
Hughes PD, Woodward JC, Gibbard PL, Macklin MG, Glimour MA, Smith GR (2006) The glacial history of the Pindus Mountains, Greece. J Geol 114:413–434
Hughes PD, Gibbard PL, Woodward JC (2007) Geological controls on Pleistocene glaciation and cirque form in Greece. Geomorphology 88(3):242–253
Hughes PD, Woodward JC, van Calsteren PC, Thomas LE, Adamson KR (2010) Pleistocene ice caps on the coastal mountains of the Adriatic Sea. Quat Sci Rev 29:3690–3708
Hughes PD, Woodward JC, van Calsteren PC, Thomas LE (2011) The glacial history of the Dinaric Alps, Montenegro. Quat Sci Rev 30:3393–3412
Ivanov I (1954) Geomorfolozhki prouchvaniya v zapadnata chast na Severozapadna Rila (Geomorphological researches in the western part of Northwestern Rila mountain). Izvestia na Geografskiya institut. BAN 2:7–61 **(in Bulgarian)**
Janković P (1903) Glacial traces in Pirin Glas Crpske kraljevske akademije. Belgrade 65(25):163–178 **(in Serbian)**
Janković P (1908) Der Pirin. In: Dr. A. Petermanns, Mitteilungen aus Justus perthes' geographischer anstalt. Herausgegeben von Prof. Dr. A. Supan. Ergänzungsband XXXIV (Heft 158–162). Inhalt: Nr. 162. **(in German)**
Jouzel J, Vimeux F, Caillon N, Delaygue G, Hoffmann G, Masson-Delmotte V, Parrenin F (2003) Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores. J Geophys Res. https://doi.org/10.1029/2002JD002677
Kachaunova E, Stefanova I (1999) The upper forest limit in North Pirin Mountain—past, present and future. In: Proceedings of the 1st congress of ecologists of Macedonia with International Participation. Special issues of MES, vol 5, Skopje
Kłapyta P, Zasadni J (2018) Research history on the Tatra Mountains glaciations. Stud Geomorphol Carpatho Balcan, 54, pp 43–85
Kuhlemann J, Gachev E, Gikov A, Nedkov S (2008) Glacial extent in Rila mountain (Bulgaria) as part of an environmental reconstruction of the Mediterranean during the last glacial maximum (LGM). Probl Geogr Bulg Acad Sci 3:87–96
Kuhlemann J, Milivojević M, Krumrei I, Kubik PW (2009) Last glaciation of the Sara Range (Balkan Peninsula): increasing dryness from the LGM to the Holocene. Aust J Earth Sci 102(1):146–158
Kuhlemann J, Gachev E, Gikov A, Nedkov S, Krumrei I, Kubik P (2013) Glaciation in the Rila Mountains (Bulgaria) during the last glacial maximum. Quat Int 293:51–62
Lilienberg D, Popov V (1966) Novie dannye ob oledenenii Pirin (Rodopy) New data about the glaciation of Pirin (Rhodopes). Doklady AN SSSR 167:5 **(in Russian)**
Louis H (1930) Morphologische Studien in Sudwest Bulgarien. VN Krebs, Stuttgart, p 108
Lüthi D, Le Foch M, Bereiter B, Blunier T, Barnola J-M, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker TF (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453:379–382
Marcott SA, Shakun JD, Clark PU, Mix AC (2013) A reconstruction of regional and global temperature for the past 11,300 years. Science 339(6124):1198–1201
Marjanac L, Marjanac T (2004) Glacial history of the Croatian Adriatic and coastal Dinarides. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations—extent and chronology. Part I: Europe. Elsevier, Amesterdam, pp 19–26
Milivojević M (2019) Metodologija rekonstruisanja planinske pleistocene glacijacije na primeru Dinarsko-prokletijskih planina. Methodology for a reconstruction of Pleistocene glaciation by the example of Dinaric-Prokletije Mountains. A PhD thesis. Faculty of Geography, University of Belgrade, Serbia. **(in Serbian)**
Milivojević M, Menković LJ, Ćalić J (2008) Pleistocene glacial relief of the central part of Mt. Prokletije (Albanian Alps). Quat Int 190:112–122. https://doi.org/10.1016/J.quaint.2008.04.006
Mitkov I (2020) Razvitie i savremenno sastoianie na lednikovia i kriogennia relef v izgradenite ot mramori chasti na Pirin. Evolution and present state of the glacial and cryogenic relief in the parts of Pirin built of marble. A PhD thesis. Blagoevgrad. **(in Bulgarian)**
Nikolov T (2011) Globalni izmenenia na klimatite v istoriata na Zemiata (Global changes of climates in Earth's history). Marin Drinov (BAS) Publishing House, Sofia, p 396
Nojarov P (2008) Regime of air temperature on Musala peak for the period 1933–2007. Geography 21(2):14–19
Nojarov P (2012) Variations in precipitation amounts, atmosphere circulation, and relative humidity in high mountainous parts of Bulgaria for the period 1947–2008. Theor Appl Climatol 107(1):175–187
Nojarov P, Gachev E, Grunewald K (2019) Recent behavior and possible future evolution of the glacieret in the cirque Golemiya Kazan in the Pirin Mountains under conditions of climate warming. J Mount Sci 16(1):16–29
Osnovna Geološka Karta SFRJ (1983) 1:100 000 (General geological map of Yugoslavia)
Parrenin F, Barnola J-M, Beer J, Blunier T, Castellano E, Chappellaz J, Dreyfus G, Fischer H, Fujita S, Jouzel J, Kawamura K, Lemieux-Dudon B, Loulergue L, Masson-Delmotte V, Narcisi B, Petit J-R, Raisbeck G, Raynaud D, Ruth U, Schwander J, Severi M, Spahni R, Steffensen JP, Svensson A, Udisti R, Waelbroeck C, Wolff E (2007) The EDC3 chronology for the EPICA Dome C ice core. Clim Past 3:485–497
Pavšek M (2004) Ledenik pod Skuto: ledeniški dragulj na senčini strain Kamniško-Savinjskih Alp. Geogr Obzornik 51(3):11–17

Pavšek M (2007) Ledenik pod Skuto kod pokazatelj podnebnih sprememb v slovenskem delu Alp. (The Skuta glacier as an indicator of climate changes in Slovenian part of the Alps). Dela 28:207–219
Pecci M, D'Agata C, Smiraglia C (2008) Ghiacciaio del Calderone (Apennines, Italy): the mass balance of a shrinking glacier. Geogr Fis Dinam Quat 31:55–62
Peev H (1960) Za niakoi savremenni lednikovi formi v Pirin planina (About some present-day glacial features in the Pirin Mountain). Priroda (Nature) 1:34–41
Peev H (1961) Prinos kam vaprosa za obrazuvaneto na savremenni lednikovi formi v Pirin (A contribution to the issue about the formation of present-day glacial features in Pirin). Hidrol Meteorol (Hydrol Meteorol) 3:22–26 **(in Bulgarian)**
Popov V (1962) Morfologia na tsirkusa Golemia Kazan—Pirin planina (Morphology of the cirque Golemia Kazan—Pirin mountains). Announc Inst Geogr 6:86–99 **(in Bulgarian)**
Popov V (1964) Nabljudenia varhu snezhnika v tsirkisa Golemia Kazan—Pirin planina (Observations on the glacieret in the cirque Golemia Kazan, the Pirin mountains). Announc Inst Geogr Bulg Acad Sci 8:198–207
Radev Z (1920) Prirodna skulptura na visokite bulgarski planini. Natural sculpture of high Bulgarian mountains. Nature, Sofia **(in Bulgarian)**
Rovelli E (2006) Il Ghiacciaio del Calderone: riconstruzione delle oscillazioni recenti mediante l'analisi delle fonti iconografico-storiche e meteo-climatiche (Calderone glacier: reconstruction of recent oscillations through the analysis of the iconographic-historical and meteo-climatic sources (Gran Sasso, Abruzzo, Italy)). Terra Glac 9:9–46
Ruddiman WF (2001) Earth's climate. Past and future. Freeman and Co., New York, p 465
Ruddiman WF (2005) How did humans first alter global climate? Sci Am 3:34–41
Ruddiman WF, Fuller DQ, Kutzbach JE, Tzedakis PC, Kaplan JO, Ellis EC, Vavrus SJ, Roberts CN, Fyfe R, He F, Lemmen C, Woodbridge J (2016) Late Holocene climate: natural or anthropogenic? Rev Geophys 54:93–118. https://doi.org/10.1002/2015RG000503
Santin I, Colucci R, Žebre M, Pavan M, Cagnati A, Forte E (2019) Recent evolution of Marmolada glacier (Dolomites, Italy) by means of ground and airborne GPR surveys. Remote Sens Environ. https://doi.org/10.1016/j.rse.2019.111442
Scotti R, Brardinoni F (2018) Evaluating millennial to contemporary time scales of glacier change in Val Viola, Central Italian Alps. Geogr Ann Ser A Phys Geogr 100:1–21. https://doi.org/10.1080/04353676.2018.1491312
Stefanova I, Ammann B (2003) Lateglacial and Holocene vegetation belts in the Pirin Mountains (Southwestern Bulgaria). Holocene 13(1):97–107
Stefanova I, Ognjanova-Rumenova N, Hofmann W, Ammann B (2003) Late glacial and Holocene history of the Pirin Mountains (SW Bulgaria): a paleolimnological study of Lake Dalgoto (2310 m). J Paleolimnol 30:95–111
Stefanova I, Atanassova J, Delcheva M, Wright H (2006) Chronological framework for the lateglacial pollen and macrofossil sequence in the Pirin Mountains, Bulgaria: Lake Besbog and Lake Kremensko-5. Holocene 16(6):1–16
Styllas MN, Schimmelpfennig I, Ghilardi M, Benedetti L (2016) Geomorphic and palaeoclimatic evidence of Holocene glaciation on Mount Olympus, Greece. Holocene 26:709–721
Tonkov S, Marinova E (2005) Pollen and plant macrofossil analyses of radiocarbon dated mid-Holocene profiles from two subalpine lakes in the Rila mountains, Bulgaria. Holocene 15:663–671
Tonkov S, Possnert G, Bozhilova E (2006) Lateglacial vegetation and radiocarbon dating of Lake Trilistnika, Rila Mountains (Bulgaria). Veg Hist Archaeobot 16:15–22
Tonkov S, Bozhilova E, Possnert G, Velchev A (2008) A contribution to the postglacial vegetation history of the Rila mountains, Bulgaria: the pollen record of lake Trilistnika. Quat Int 190:58–70
Triglav Čekada M, Gabrovec M (2013) Documentation of Triglav glacier, Slovenia, using non-metric panoramic images. Ann Glaciol 54(62):2013. https://doi.org/10.3189/2013AoG62A095
Triglav Čekada M, Zorn M, Colucci RR (2014) Površina kaninskih in triglavskega ledenika od leta 1893, določena na podlagi arhivskih posnetkov i aerolaserskih podatkov. Changes in the area of the Canin (Italy) and Triglav glaciers (Slovenia) since based on archive images and aerial laser scanning. Geod Vestnik 58(2):274–313
Vavrus S, He Feng, Kutzbach J, Ruddiman WF, Tzedakis P (2018) Glacial inception in marine isotope stage 19: an orbital analog for a natural Holocene climate. Sci Rep 8:10213. https://doi.org/10.1038/s41598-018-28419-5
Velchev A (1995) Pleistocenski zaledyavaniya v bulgarskite planini (The Pleistocene glaciations in Bulgarian mountains). Ann J Sofia Univ GGF Geogr 85(2):53–65 **(in Bulgarian)**
Velchev A (1999) Glacialen i kriogenen relef v chast ot Musalenskia dyal na Rila (Glacial and cryogenic relief in part of Musala share of Rila). Ann J Sofia Univ GGF Geogr 89(2):7–21 **(in Bulgarian)**
Velchev A, Todorov N, Kostadinov K (1994) Razvitie i savremenno sastoianie na subalpiiskite landshafti v Osogovska planina. Evolution and present state of the subalpine landscaped in Osogovo Mountains. Ann J Sofia Univ GGF Geogr Book 2 Geogr 85:181–198
Velchev A, Konteva M, Penin R, Todorov N (2000) Landshaftni osobenosti na Midzhur, Chiprovska planina. Landscape peculiarities of Midzor, Chiprovska Mountain. Ann J Sofia Univ Fac Geol Geogr Book 2 Geogr 90:111–131
Velev S (2010) Klimatat na Bulgaria (The climate of Bulgaria). Heron Press, Sofia, p 190
Wilkinson R (2011) A multi-proxy study of late holocene environmental change in the Prokletije Mountains, Montenegro and Albania. A PhD thesis, University of Manchester
Wright H, Ammann B, Stefanova I, Atanassova J, Margalitadze N, Wick L, Blyakharchuk T (2003) Late-glacial and early Holocene dry climates from the Balkan Peninsula to Southern Siberia. In: Tonkov S (ed) Aspects of palynology and paleoecology. PENSOFT Publishers, Sofia, pp 127–136
Žebre M, Sarikaya MA, Stepišnik U, Yildirim C, Çiner A, (2019) First ^{36}Cl cosmogenic moraine geochronology of the Dinaric mountain karst: Velež and Crvanj Mountains of Bosnia and Herzegovina. Quat Sci Rev 208:54–75. http://www.stringmeteo.com. Bulgarian website for discussing weather

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