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Unprecedented loss of surface and cave ice in SE Europe related to record summer rains in 2019

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Abstract. Glaciers worldwide are shrinking at an accelerated rate as the climate changes in response to anthropogenic influence. While increasing air temperature is the main factor behind glacier mass loss, changing atmospheric circulation patterns and the distribution of precipitation also plays a role, though these are not as well understood. Furthermore, while the mass balance of surface glaciers (from large polar ice sheets to small alpine glaciers) is relatively well documented and continuously monitored, little to nothing is known about the response of cave glaciers (perennial ice accumulations in rock-hosted caves) to atmospheric warming. In this context, we present the response of cave and surface glaciers in SE Europe to synoptic conditions in summer 2019. Our investigation shows that extreme precipitation events occurring between May and July 2019 led to catastrophic loss of ice at levels unprecedented during the last century. As climate models predict that such extreme precipitation events are set to increase in frequency and intensity, the presence of cave glaciers in SE Europe and the paleoclimatic information they host may be lost in the near future. Moreover, the same projected continuous warming and increase in precipitation extremes could pose an additional threat to the Alpine glaciers in southern Europe, resulting in faster than predicted melting.

1 Introduction

The recent *IPCC Special Report on the ocean and cryosphere in a changing climate* highlighted the worldwide shrinking of the cryosphere, with ice sheets, mountain glaciers, snow cover and Arctic sea ice all losing mass (IPCC, 2019). Rising temperatures account for most of the recent widespread ice loss (Marzeion et al., 2014) and climate models suggest that warming will continue leading to unabated glacier melting over the next decades. Small glaciers are most impacted by this recent melting, with climate scenarios suggesting losses of up to 80 % by the end of this century (IPCC, 2019) for glaciers in several regions, including Central Europe. Nevertheless, the cited IPCC report does not include information either on glaciers in SE Europe, the region hosting Europe's southernmost glaciers (Snezhnika and Banski Suhodol glaciers, in the Pirin Mountains, Bulgaria) or on the dynamics of perennial ice accumulations in caves. The latter are the least visible and investigated components of the global cryosphere.

Ice caves occur in mountain regions across the Northern Hemisphere, between 30° N and 77° N, and from sea level to 3300 m above sea level (a.s.l.), in areas where a combination of favorable cave morphology, local topography and climatic conditions allow for the perennial accumulation and preservation of ice (Persoiu and Lauritzen, 2018). The accumulation of cave ice is the result of either snow diagenesis or freezing of water, or a combination of the two (Persoiu and Pazdur, 2011). Snow diagenesis occurs at the bottom of vertical shafts, in which snow falls and accumulates during winter months. In such caves, ice forms by a combination of snow diagenesis (compaction under its weight) and freezing of meltwater from the surface of the snowpack. Freezing of water occurs in caves with descending morphology (usually caves with entrances at their upper parts only), in which negative air temperatures result in freezing of infiltration water. As a direct consequence of the descending cave morphology, negative air temperatures occur throughout the year resulting in continuous accumulation and preservation of ice. Several studies have shown that in caves in Europe such ice accumulations are older than 1000 years (Spötl et al., 2014; Gradziński et al., 2016; Kern, 2018; Kern et al., 2018), preserving important clues on past environmental variability. Over the past decade, various proxies in cave ice have been used to reconstruct temperature variability during the Holocene (Persoiu et al., 2017; Sancho et al., 2018; Badaluța et al., 2020), vegetation dynamics (Feurdean et al., 2011; Leunda et al., 2019) and atmospheric composition (Kern et al., 2009; Kern et al., 2011). Additionally, other studies have targeted the microbial and fungal communities harbored by cave ice, identifying dormant new species (Brad et al., 2018; Itcus et al., 2019, Paun et al., 2019; Mondini et al., 2019).

Whereas ice loss in surface glaciers is mostly due to melting related to rising temperatures (e.g., Marzeion et al., 2014), cave ice ablation is primarily due to drip water delivering heat to the ice (Persoiu et al., 2011a). Therefore, whereas the projected increase in air temperature in mountain areas would result in enhanced mass loss for surface glaciers, the same rising temperatures might only marginally affect ice mass balance in caves. Most of the caves hosting perennial ice are found in Central and South-Eastern Europe, a region that has experienced some of the fastest loss of glacier ice (Zemp et al., 2019, Sommer et al., 2020) over the past decades. For this region, climate models suggest a mixed response to the general global warming, albeit with a general decrease in annual precipitation, an increase in winter precipitation and in the frequency and intensity of extreme summer precipitation events (Planton et al., 2012).

Consequently, cave ice deposits are facing the risk of disappearing completely within a decade (Kern and Persoiu, 2013; Kern and Thomas 2014), leading to the irreparable loss of the diverse records of past climate, environmental conditions and microbial life (with unique antibacterial potential) they record. While accumulation is a slow process (~1-20 cm/year), annual ablation rates could reach values double or even triple of that (Kern et al., 2013, Lauritzen et al., 2018). In this context, here we present the response of surface and cave glaciers in Eastern and South-Eastern Europe to the weather conditions in winter 2018-2019 and summer 2019. We have studied ice caves in Greece, Croatia, Romania, Slovenia and two surface glaciers in Bulgaria and analyzed the ice mass balance in response to climatic conditions during the 2018-2019 winter season and the spring and early summer of 2019, a period characterized by anomalous atmospheric circulation corroborated with heavy winter snowfall, extremely high summer temperatures and extreme rainfall.

2 Glaciers in Central and South-Eastern Europe

Our investigation targeted Central and South-Eastern Europe (Fig. 1), a region which hosts numerous ice caves in the rugged karst topography of the Carpathian, Dinaric and Rhodope Mountains, including the five largest underground glaciers in the world (Buzjak et al., 2018; Mihevc, 2018; Pennos et al., 2018, Persoiu and Lauritzen, 2018).

Scărişoara Ice Cave (46°29′23.64″ N, 22°48′37.68″ E) is located in the Western Carpathian Mountains (Romania), at 1165 m a.s.l. The cave opens to the surface through a ~60 m wide, 47 m deep shaft which continues with a wide chamber that hosts one of the largest (>100,000 m^3) and oldest (>10,500 years) underground glaciers in the world (Persoiu et al., 2017). This ice body primarily formed by freezing of liquid water every early winter, adding a layer of up to 20 cm of newly formed ice to the existing ice body each year. The mass balance of the ice is controlled by the amount of water available in autumn and early winter and by the melting occurring due to rainwater infiltrating inside the cave in summer. Monitoring of ice dynamics since 1947 (Persoiu and Pazdur, 2011) showed a rapid melt of ice during the 1950s due to changes in the morphology of the ice block, followed by equilibrium conditions since ~1975, with net annual accumulation or ablation rates between 0 and 5 cm.

Chionotrypa Cave (Mt. Falakro, hereafter Chionotrypa (Falakro), 41°17′39.9″ N, 24°05′24.2″ E) is a 111 m deep alpine cave located at 2080 m a.s.l. in the Rhodope Mountains, Northern Greece (Pennos et al., 2018). The entrance of the cave is through a 50 m wide, 65 m deep shaft that allows for a large amount of snow to accumulate at its base in winter. A 3 m high, 15 m wide opening at the bottom of the eastern wall of the shaft allows access to the lower chambers of the cave. At the bottom of the shaft and continuing through the opening, a 30 m snow and ice deposit has accumulated. The upper 3 m of the deposit consists of compacted snow, while the lower part is solid, layered ice, incorporating rocks and organic matter from the surface.

Chionotrypa cave (Mt. Olympus, hereafter Chionotrypa (Olympus), 40°05′18.7″ N, 22°21′55.5″ E,) is located on the eastern slopes of Olympus Mountain (Greece), at 2560 m a.s.l. Its entrance is ca. 6.6 by 8 m wide, leading through a vertical shaft to a snow and ice mass ca. 20 m thick. In winter up to 5 m of snow can accumulate on top the existing ice block, but it usually melts during spring and summer, the level of ice reaching a minimum in September (Pennos et al., 2018).

Crna Ledenica cave is located in the Biokovo Mountains (southern Croatia), 6 km from the Adriatic Sea. The cave has four vertical entrances located at elevations between 1477 and 1503 m a.s.l. (Buzjak et al., 2018): two northern (15x10 m and

7.5x5 m), one middle (5x4 m) and one southern (11x6 m). These wide entrances ensure a constant snow accumulation at the bottom of a 60 m long, 25 m wide chamber, as well as cold air circulation during winter (HBSD, 2019, last access: 25 May 2020). The snow, firn and ice deposit occupies an area of about ~450 m^2, its thickness ranging from 12 m below the northern and middle entrances to 0.5 m in the more distal parts of the cave. The upper part of the deposit is covered by fresh snow and organic matter collapsing from the surface during winter. Deeper in the cave, the snow is metamorphosed to firn and finally layered ice with embedded rock particles and organic matter. The mass balance of the ice deposit is controlled by the circulation of cold air between the cave's chamber and the four entrances, snow accumulation and water inflow during warmer, wetter periods (from spring to early autumn).

Velika ledena jama v Paradani is located on Trnovski gozd karst plateau in western Slovenia (45°59′19.70 ″N, 13°50′40.24″ E). The cave is 6534 meters long and 858 meters deep with the main entrance located at 1135 m a.s.l. The entrance opens at the bottom of a doline and leads to a series of interconnected halls, with the first and second containing the perennial ice block. This block has a layered structure, including clear ice alternating with detritus derived from the surface, and it changes from firn to congelation ice with increased distance from the entrance. The maximum depth of the ice block is unknown, but is estimated to an average of 3 meters, suggesting a maximum volume of 8,000 m^3 (Mihevc, 2018). The main ice growth periods are in winter (as snow accumulates in the entrance doline) and spring, when snowmelt water freezes to form congelation ice. The main ice loss occurs in summer and autumn following heavy infiltration of rainwater.

In addition to these underground glaciers, we have also studied Europe's two southernmost glaciers, *Snezhnika* and *Basnki Suhodol*, located in the Pirin Mountains (Bulgaria) below the northern cliffs of Vihren (2914 m) and Kutelo (2908 m) peaks (Gachev et al., 2016). Snezhnika glacier (41°46′09″ N; 23°24′12″ E) is located on an eastward-facing slope and lies at 2440-2490 m a.s.l., whereas Banski Suhodol (41°46′09″ N; 23°23′40″ E) faces north and lies at 2620-2700 m a.s.l. Both glaciers are a legacy of the Little Ice Age (Hughes, 2009) and occupy less than 1 ha (Grunewald and Scheithauer, 2010) with recent geophysical investigations revealing maximum ice thickness of 14 m and 17 m, for Snezhnika and Banski Suhodol, respectively (Onaca et al., 2019).

3 Methods

In 2018, we initiated a research program aimed to preserve the climate memory of vanishing Eastern Mediterranean subterranean glaciers. Ice levels in caves were measured against fixed points on the cave walls and/or mass balance changes were estimated using photogrammetry.

In Scărişoara Ice Cave, ice level changes were recorded monthly using a dual approach. Firstly, we measured that distance between the ice surface and a fixed point in the rock ceiling directly above the ice and secondly, we measured the surface ice level changes against a marker embedded in the ice. The results of the first measurement record the sum of changes at the surface as well as bottom of the ice block, whereas the later registers only the changes at the surface of the ice block. Subtracting the latter from the first enables us to disentangle changes at the surface likely resulting from the influence of external climate from changes at the bottom, the later influence by long-term basal melting, independent of climatic conditions. In Chionotrypa Cave (Falakro Mountain), annual ice level fluctuations were intermittently recorded at the end of the ablation period over the past five years. Changes in ice volume are continuously monitored in Ledena jama v Paradani since September 2009, with the method of wall to ice distance measurements made twice annually.

To analyze in detail the surface changes of Snezhnika and Banski Suhodol glaciers, two UAV (DJI Phantom 4 Pro drone equipped with 20 megapixel camera) surveys were performed at the end of the ablation season (October 2018 and September 2019). High-density point clouds and high-resolution ortophotos produced from the drone surveys were further processed with Agisoft Photoscan Professional software using the Structure from Motion (SftM) algorithm to generate a digital elevation model (DEM) with 22.5 cm pixel^{-1} resolution and an orthophoto-mosaic with 2.8 cm pixel^{-1} resolution for Snezhnika glacier, and a DEM with a 18.7 cm pixel^{-1} resolution and an orthophoto with a 4.6 cm pixel^{-1} resolution for Banski Suhodol glacier.

As most of the investigated caves are located far from meteorological stations, or existing station data covers inappropriate time periods for this study, we extracted meteorological data from the E-OBS dataset (Cornes et al., 2018). In order to link climatic parameters with large scale circulation patterns, we have computed the anomalies of the mean air temperature (TT) and geopotential height at 500 mb (Z500) and we analyzed the conditions of snow cover and extreme precipitation (monthly maximum consecutive 5-day precipitation, RX5day) for both the ice accumulation (December 2018–February 2019) and ablation (May–July 2019) periods. The Z500 file was extracted from the NCEP/NCAR 40-year reanalysis project (Kalnay et al., 1996). The snow cover data were provided by MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG, Version 6 (Hall et al., 2006). The Highest 5-day precipitation amount (RX5day) was computed based on the EOBS-v20e data set (Cornes et al., 2018). The ranking maps of 2019 were made for RX5day using the six first ranks. The rank maps are obtained by comparing the magnitude of the variable of each month (May–July 2019 for the present study) relative to the same month in each year from 1950. A rank of one implies record-breaking precipitation in 2019; a rank of two indicates that 2019 had the second most extreme value in that month (since 1950) etc.

4 Results

4.1 Ice mass balance changes

Ice level was constant in *Scărişoara Ice Cave* between July 2018 and September 2018 when a shallow lake started to form on top of the ice block. The water of this lake froze in early December 2018, adding a layer of 15 cm to the existing ice. Heavy snowfall in the 2018-2019 winter and subsequent melt in spring 2019 led to rapid infiltration of large volumes of water inside the cave, resulting in ca. 5 cm of ice being formed in the still undercooled cave environment. Between May and July 2019, the ice level in Scărişoara Ice Cave dropped by ca. 35 cm (Fig. 2), due to continuous infiltration of surficial warm water. This catastrophic melt event spread across the entire upper surface of the 3000 m^2 ice block, resulting in the loss of ca. 1050 m^3 of ice.

In *Chionotrypa Cave* (Mt. Falakro), a gradual decrease of the ice volume was evident since 2014, reaching a minimum in September 2019 (Fig. 3). The ice level at the bottom of the entrance shaft fell ~3 m and receded ~1 m from the cave walls between July 2018 and September 2019. A rough estimation suggests that >600 m^3 of cave ice were lost during this period.

In *Chionotrypa Cave* (Mt. Olympus), the mass balance of the snow and ice deposit was strongly positive in winter 2018/2019, but steadily decreased in summer 2019. Compared to the situation in 2018, ice and snow were lost both at the surface of the deposit and in the rimayes surrounding it, amounting to a loss of ca. 5-10 % (15–30 m^3) of the total ice volume.

In *Crna Ledenica* observations in 2019 show that following the cold and wet 2018–2019 winter large amounts of fresh snow accumulated below the entrance shafts. Further, meltwater infiltration in spring originating in thick winter snowpack led to the development of numerous ice speleothems and ice crusts. However, heavy summer rains and subsequent infiltration of warm water resulted in the complete melting of these ice crusts by September 2019. The ice-covered area and the total volume of perennial ice also retreated in summer 2019. In some parts of the cave, the ice thickness dropped by up to ~2 m, and the total area covered by perennial ice and snow dropped by ca. 200 m^2, resulting in a loss of about 150-200 m^3 during summer 2019.

The deeper parts of *Ledena jama v Paradani* cave were less affected by ice volume loss, compared with the entrance area. The ice slope connecting the inner part of the cave with the entrance has retreated by several meters towards the cave's entrance and an almost continuous surface of broken host rock developed on the former ice surface. Since June 2013 the ice surface lowered by 220 centimeters, of which 41 centimeters were lost between June 2018 and June 2019.

In October 2018, Snezhnika glacier extended over 5700 m^2, compared with 4600 m^2 in September 2019 (Figs. 4A and 4B), while Banski Suhodol glacier extended over 11600 m^2 in October 2018 (Fig. 4C) and 9600 m^2 in September 2019 (Fig. 4D). Between 1959 and 2008 Snezhnika glacier lost almost half of its surface (from 13000 to 7000 m^2, Grunewald and Scheithauer, 2010), and between 2008 and 2018 lost another 1300 m^2 while during 2019, lost 1100 m^2. The average annual retreat of Snezhnika glacier between 1959 and 2018 was rather constant between 122 and 130 m^2 $year^{-1}$, but dramatically increased by one order one of magnitude (1100 m^2 $year^{-1}$) in 2018-2019. Aerial footage indicates a general retreat at the lower end of the two glaciers and the increase in the width of the rimaye separating them from the cirque headwall. Additionally, in 2019 a small glaciated area became separated from the main ice body of the Banski Suhodol glacier, and two more indentations are likely to cause rapid disintegration of the main ice body in the near future (Fig. 4D).

Summarizing the observations above, in 2019 two distinct and exceptional periods of ice mass balance changes were identified: 1) important (in terms of volume) growth of underground ice and snow deposits between December 2018 and February 2019, especially in those caves in which direct snow accumulation occurs; and 2) rapid and massive loss of cave ice, starting in May 2019.

4.2 Meteorological data

Meteorological data (Fig. 5) show that 2019 was exceptionally wet in SE Europe. At all investigated sites, precipitation amounts exceeded the long-term (1971–2000) average by more than 150 %. Following a relatively dry early spring (compared to the 1971–2000 average), precipitation amount started to increase in April 2019, peaking in May, June and July (Fig. 5). Overall, in May 2019 all the analyzed cave ice locations received more than 100 % of the climatological mean precipitation for the respective month, with Crna Ledenica and Chionotrypa (Falakro) receiving more than 250 % and 200 %, respectively.

In December 2018, the geopotential height anomalies at 500 mb level were characterized by a wave-train like structure with negative Z500 anomalies (indicative of a low-pressure system) over the central North Atlantic Basin, positive Z500 anomalies (indicative of a high-pressure system) over the central part of Europe extending northwards, and negative Z500 anomalies over the eastern part of Europe (Fig. 6a). The low-pressure system over Eastern Europe, which was carrying moist air from the Black Sea together with cold and dry air from the north, led to snowfall events over the high altitudes in the Carpathian Mountains and some parts in Ukraine (Fig. 6d). Overall, December 2018 was warmer than normal over the whole European region with some exceptions in the Alpine areas and Bulgaria (Fig. 6g).

In January 2019, the large-scale atmospheric circulation was characterized by a dipole-like structure with positive Z500 anomalies centered over the central North Atlantic basin and negative Z500 anomalies centered over Europe (Fig. 6b). This dipole-like structure led to several episodes of snowfall in the Alps and the Carpathian Mountains, due to the advection of northerly cold air from the Arctic region coupled with moist and warm air intrusions from the Atlantic basin. In January 2019 most of Central and Eastern Europe were snow covered (Fig. 6e) and the Alpine region was up to 5 °C colder than normal (Fig. 6h).

In February 2019, the prevailing large-scale atmospheric circulation was reversed compared to the previous month. A low-pressure system prevailed over the central part of the North Atlantic basin, while Europe was under the influence of a high-pressure system (Fig. 6c), resulting in dry and warm weather (Fig. 6i). Snow was present only over the mountain regions in the Alps and the Carpathian Mountains (Fig. 6f). Overall, February 2019 was exceptionally warm in the northern and eastern part of Europe (European State of the Climate, 2019).

In May 2019, the central and south-eastern parts of Europe were characterized by below average air temperatures. The prevailing large-scale atmospheric circulation featured a Rossby wave guide with negative Z500 anomalies over the eastern U.S. coast, positive Z500 anomalies over the central North Atlantic basin and western part of Europe, negative Z500 anomalies over the eastern part of Europe and positive Z500 anomalies over Russia (Fig. 7a). Concurrently, Italy, the Alpine regions, Croatia and the northwestern part of Romania experienced extreme rainfall (Fig. 7b). Rainfall records were broken over small areas in the Alps and Ukraine (Fig. 7c). Most of the intense and record-breaking rainfall was recorded over the regions were the investigated glaciers are located (Fig. 1).

In June 2019 most of the European continent was under the influence of a high-pressure system (Fig. 7d) that led to the advection of warm and dry air from Africa and subsequent development of record-breaking heat wave over the south-eastern and central parts of Europe (European State of the Climate, 2019). June 2019 was dry over large areas of Europe, with some small exceptions over the Alpine region and the southeastern region (Fig. 7e), with record rainfalls in Bulgaria and Greece limited to relatively small areas (Fig. 7f). The precipitation in the southern part of Europe was mainly occurring during heavy thunderstorms, resulting in one-day rainfall amounts of ~50 mm/day locally.

As in June 2019, in July 2019 most of Western Europe was under the influence of a high-pressure system (Fig. 7g) and was very dry over large parts of Europe (particularly the western half). Wetter conditions, with enhanced rainfall, were recorded in South-Eastern Europe (including Croatia and Slovenia). The rainfall over these regions was mainly due to heavy thunderstorms (Fig. 7h).

5 Discussion

All ice caves in the investigated region are located well below the 0 °C isotherm. Contrary to high-altitude glaciers, underground glaciers have both the accumulation and ablation zones in the same location, in most cases at the bottom of vertical shafts where snow and ice accumulates in winter but also melts in summer, thus making them extremely sensitive to both short and long term climatic changes.

The 2018-2019 winter was extremely favorable for ice accumulation in caves in SE Europe. In December 2018 and January 2019, heavy snowfalls in the eastern half of Europe (Figs. 6b, 6e) resulted in the large accumulation of snow in Chionotrypa (Falakro), Chionotrypa (Olympus) and Crna Ledenica caves and likely on the surface glaciers in Bulgaria. In Romania and Slovenia, higher than average temperatures in February 2019 (Fig. 6i) led to the rapid melt of the surface snowpack resulting in melt water infiltration in Scărișoara Ice Cave and Ledena jama v Paradani, where thermal conditions were still negative, resulting in rapid formation of ice layers (Persoiu et al., 2011b). Overall, in the 2018-2019 winter northerly cold air advection and westerly and southerly moisture transport (Fig. 6) resulted in rapid ice accretion in caves in SE Europe, both as direct snow accumulation and water freezing.

Contrary, the 2019 extremely wet late spring and summer led to rapid cave ice ablation. Direct rain-on-snow events resulted in heavy mass loss in Crna Ledenica (Croatia) and Chionotrypa (Falakro) caves as well as in the surface glaciers in Bulgaria. At all these three locations precipitation amounts between May and July 2019 exceeded the multiannual mean (Fig. 5), mainly during extreme thunderstorm events (Figs. 7b, e, h). These extreme events delivered large volumes of warm water directly on the surface of glaciers, leading to rapid melting. In the case of Scărișoara Ice Cave (Romania) and Ledena jama v Paradani (Slovenia), where the main ice blocks are not located directly below the caves' entrance shafts, similarly extreme summer thunderstorms (Figs. 5 and 7) resulted in high volumes of water entering the caves through fissures in the host rock, leading to enhanced melting through heat delivered to the surface of the glaciers by percolating water (Perşoiu and Onac, 2019). On Mt. Olympus (Chionotrypa cave), summer 2019 was warm and dry (Fig. 7). In this cave, the surface of the ice is just 6 m below the cave entrance (Pennos et al., 2018) and thus the glacier responds to climatic variability in a manner similar to surface glaciers. The thermal inversion layer inside this shallow entrance shaft was easily destroyed during the prolonged warm spell, triggering he rapid melt of the surface and sides of the glacier. A similar behavior was observed in the case of the surface of Snezhnika and Basnki Suhodol glaciers, where, in addition to the heat delivered directly by rainwater, melting was enhanced by the warm and moist conditions resulting from turbulent heat fluxes near the surface of the ice (Marks et al., 1998; Pomeroy et al., 2016). The relative area loss of Snezhnika glacier was ~ 0.94 % a^{-1} between 1959 and 2008, similar to the average global value of 1 % a^{-1} (Vaughan et al., 2012), but increased to 1.86 % a^{-1} between 2008 and 2018 and 1.93 % a^{-1} between 2018 and 2019. For Basnki Suhodol glacier, the relative area loss between 2018 and 2019 was close to that of Snezhnika glacier at 17.2 % a^{-1}. Similarly, perennial snow patches on Mt. Olympus, remnants of glaciers from the last glacial cycle (Styllas et al., 2018), began to disintegrate in 2019 under the prolonged heat wave. These cases mirror recent findings from SW Europe, where Moreno et al. (2020) have shown that glaciers surviving warm periods of the past 2000 years are rapidly melting, being at the risk of disappearing within the coming decade(s).

Cave ice deposits are similarly prone to rapid disintegration once melt-water channels start to develop on their surface, channels that 1) drain away water before it would freeze to form new layers of ice (Persoiu and Pazdur, 2011) and 2) enhance melting and fragmentation leading to rapid loss of ice (e.g., Lauritzen et al., 2018). The cumulative ice loss in summer 2019 for the four analyzed caves is ~1300 m^{-3}. This loss ad to the long-term worldwide melting of cave ice (Kern and Persoiu, 2013), but it is unprecedented over the past century (Fig. 8). Several studies (Kern et al., 2009; Persoiu and Pazdur, 2011) of long-term links between ice mass balance and climate in caves have shown that cave glaciers have a non-linear response to air temperature changes, extreme warming events playing an insignificant role in the melting of ice, with warm water infiltration and the length of the warm season being by far the most important factors causing melting.

All surface glaciers in southern Europe are out of balance with present-day climatic conditions, but the slow melting occurring at their termini results in gradual re-equilibration with local climatic conditions (Zekollari et al., 2020). However, recent rapid warming leads to an increase in the altitude of the 0 °C isotherm (Rottler et al., 2019) thus further increasing the imbalance between glaciers and climate and enhanced melting. Our results suggest that, adding to the melting under increased temperatures, heavy summer precipitation events result in enhanced melting of both cave and surface glaciers. With increasing temperatures, the altitudinal rise of the 0 °C isotherm (Rubel et al., 2017) would bring more glaciated terrain under warming conditions, and thus yet more susceptible to heat transfer during heavy summer thunderstorms and extreme summer heat waves. Accelerated warming of the Arctic (Holland and Bitz, 2003) would result in meridional amplification and slower propagation of the Rossby waves, leading to an increase in the frequency of blocking conditions and associated extreme events (Francis and Vavrus, 2012; Liu et al., 2012; Screen and Simonds, 2014). The increased frequency, duration and intensity of both heat waves (e.g., Spinoni et al., 2015) and heavy rainfall events (Púčik et al., 2017; Rädler et al., 2019) would thus lead to a higher ablation rate of surface and cave glaciers than that expected from increased temperatures alone. Especially vulnerable are cave glaciers, already located in areas subject to both warming and extreme summer thunderstorms, and surface glaciers close to the 0 ° isotherm, thus resulting in the loss of ice faster than predicted by the most recent estimates (IPCC, 2019; Paul et al., 2020).

6 Conclusions and outlook

We have investigated the response of cave and surface glaciers to extreme summer rain events in SE Europe during 2019 and unraveled unprecedented ice mass loss over the observational period (the last 120 years). Surface glaciers in the Northern Balkan Mountains lost on average nearly one fifth of their surface, a rate at which mountains in SE Europe could be glacier free by the end of the decade (AD 2030). The ice mass loses are related to enhanced melting resulting from outsized amounts of water reaching the caves and delivering large amounts of heat directly to the ice. The synoptic conditions leading to these extreme events were induced by the persistence of blocking conditions over Western Europe leading to extreme heat waves in southern Europe and record-breaking amounts of rainfall. While cave and surface glaciers in mountains across Europe are sensitive to increasing temperature, our observations show that extreme summer rains result in rapid melting and disintegration of ice bodies, rendering them even more sensitive to temperature changes. As climate models suggest future changes in the dynamics of Rossby waves leading to more extreme events, disappearance of both surface and cave glaciers in SE Europe (and elsewhere) will occur earlier than predicted.

The ongoing and predicted loss of recently accumulated ice threatens the possibility to accurately reconstruct past climate variability using various proxies harbored in cave ice. In order to generate (semi)quantitative reconstructions it is crucial to collect ice that grew during the instrumental period (the last ~50-100 years) and compare the reconstructed variables with measure ones. The accelerated melting of ice is quickly reducing the possibility to perform such studies, thus leading to the additional loss of invaluable climatic information.

Author contributions. AP designed the study and wrote the manuscript with input from all authors. MI analyzed the climate data. CP, YS and SZ collected data and YS reconstructed the dynamics of ice in Chionotrypa Cave (Falakro), NB and VB made measurements in Crna Ledenica Cave, MS collected data from Chionotrypa Cave (Olympus), JK measured ice dynamics in Ledena jama v Paradani and AO and AH collected and analyzed data from the surface glaciers in Bulgaria.

Competing interests. The authors declare that they have no conflict of interest.

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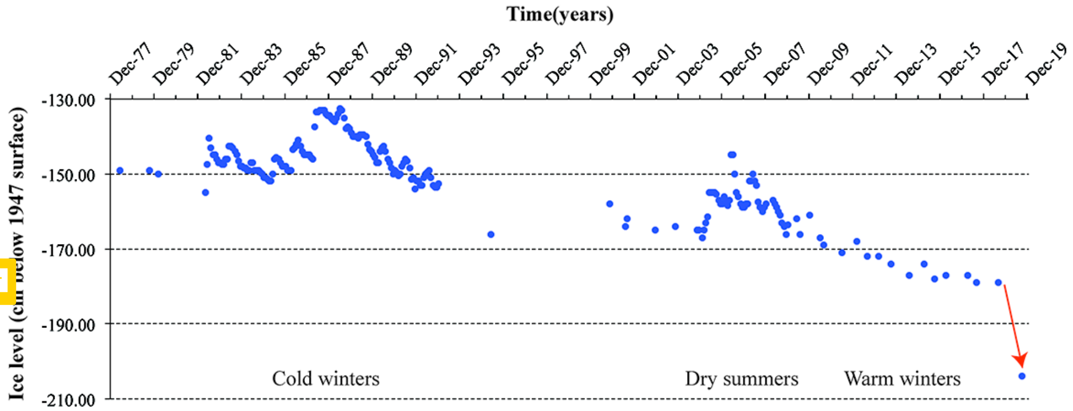
Figure 1. Location of investigated cave and surface glaciers. Base map © OpenStreetMap contributors 2020. Distributed under a Creative Commons BY-SA License.



490 **Figure 2: Upper surface ice level changes of the glacier in Scărișoara Ice cave, Romania, between 1975 and 2019. The red arrow points to the unprecedented annual melt in 2019.**

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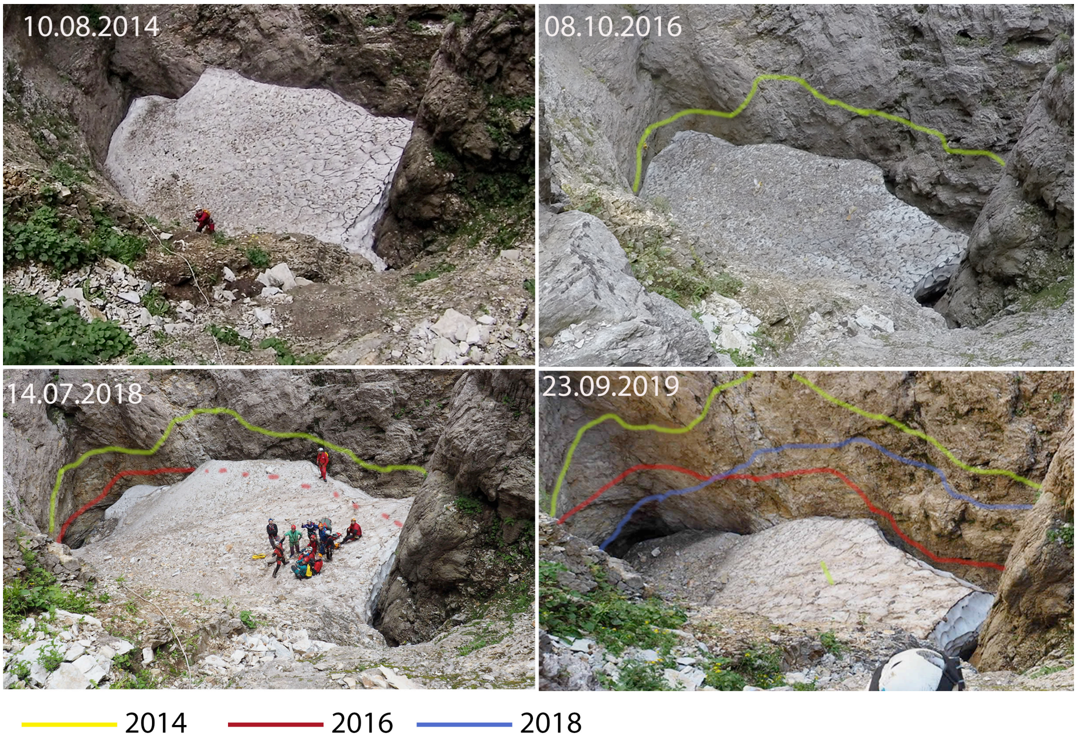

Figure 3. Changes in the surface morphology of snow and ice in Chionotrypa Cave (Falakro Mountain, Greece) since 2016.

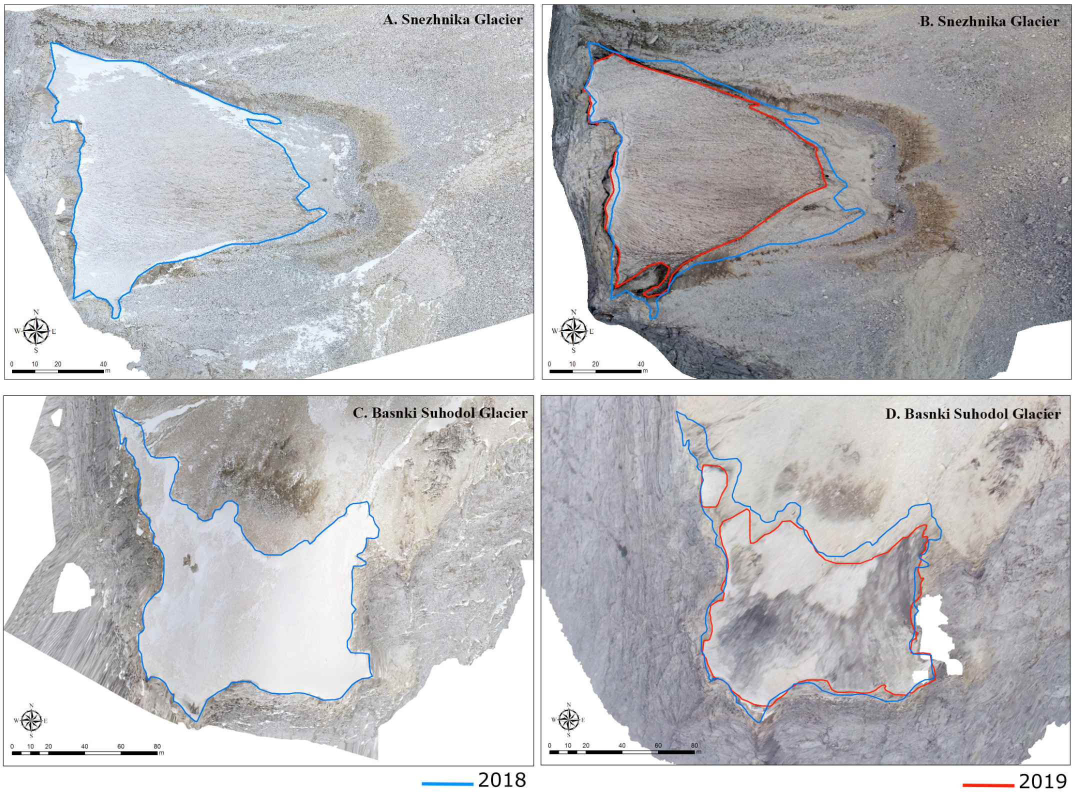

Figure 4. Ice surface changes for Snezhnika (A and B) and Basnki Suhodol glaciers (C and D), Bulgaria, between 2018 (A and C) and 2019 (B and D).

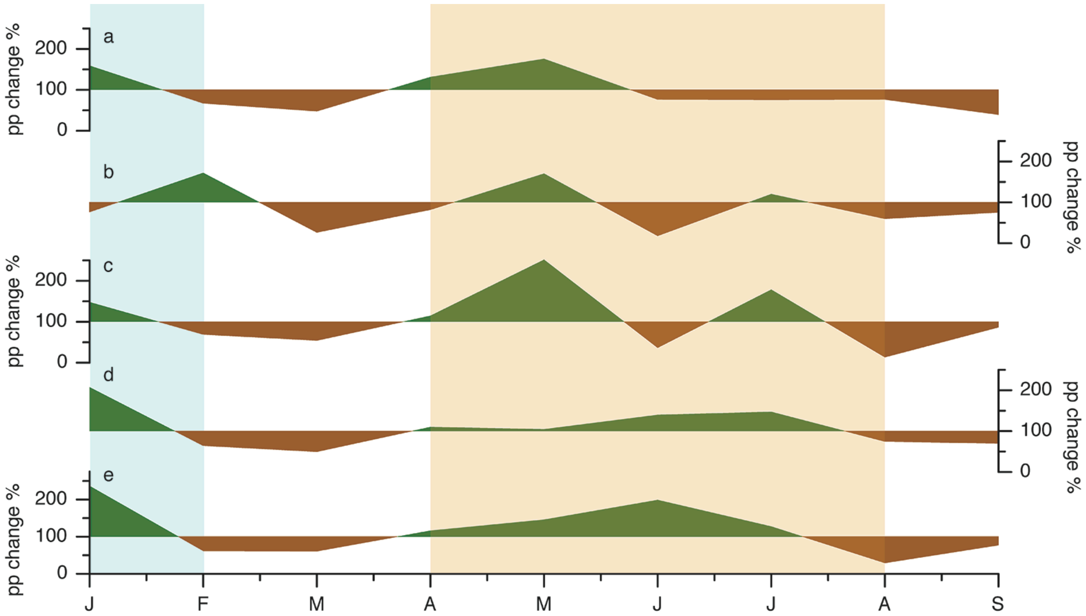

Figure 5. Monthly precipitation amount recorded from January to September 2019 at a) Scărișoara Ice Cave (ROU), b) Ledena iama v Paradani (SLO), c) Crna Ledenica (CRO), d) Vihren (BG) and 3) Chionotrypa (Falakro, GRE). The data is shown in percentage deviation from the 1971-2000 average (represented by the 100 % mark). Green shading on the charts indicates precipitation above average and brown shading indicates precipitation below average. The blue rectangle shows the period of ice accumulation and the orange rectangle the ice ablation period of the investigated glaciers.

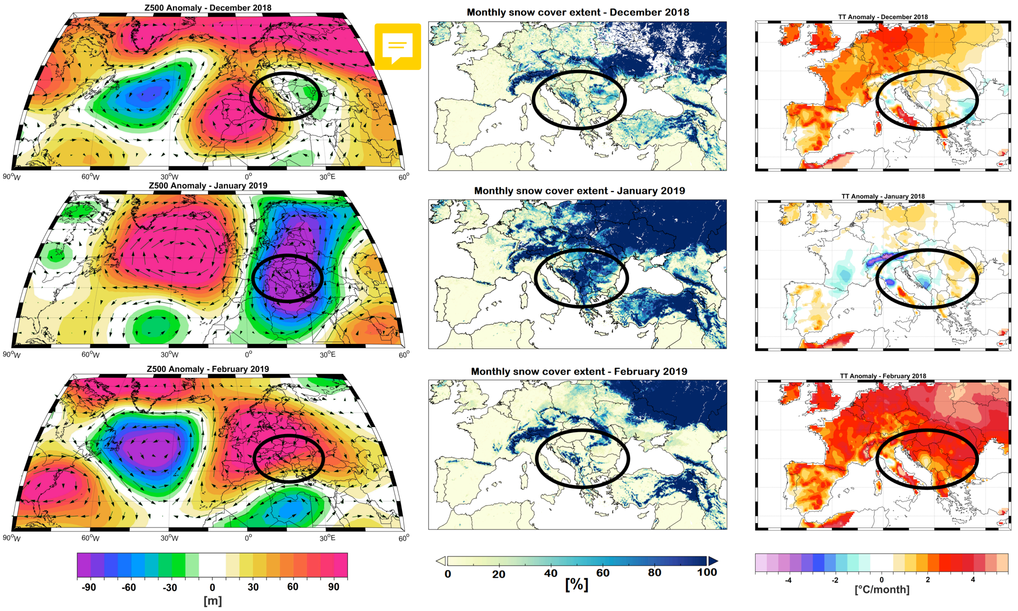

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Figure 6. Left column: Geopotential height anomalies at 500mb level (Z500) [a) December 2018; d) January 2019 and g) February 2019]. Middle column: snow cover extent across Europe [b) December 2018; e) January 2019 and f) February 2019]. Right column: mean air temperature anomalies [c) December 2018; f) January 2019 and i) February 2019]. For all the analyzed variables the anomalies are computed relative to the climatological period 1971 – 2000. Black ellipses indicate the study area.

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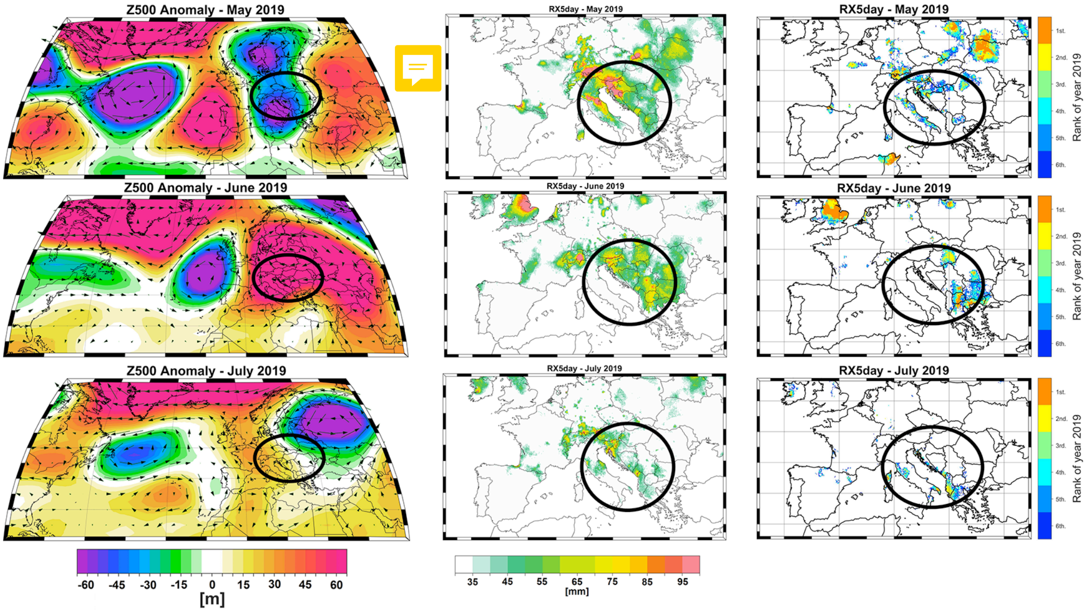

Figure 7. Left column: Geopotential height anomalies at 500mb level (Z500) [a) May 2019; d) June 2019 and g) July 2019]; Middle column - Highest 5-day precipitation amount (RX5day) [b) May 2019; e) June 2019 and h) July 2019] and right column – Top-six ranking of 2019 monthly RX5day [c) May 2019; f) June 2019 and i) July 2019]. A score of 1 represents the wettest month since 1950, a score of 2 represents the second wettest, and so on; all ranks greater than 6 are shown in white. Analyzed period: 1950–2015. For the Z500 the anomalies are computed relative to the period 1971 – 2000. Black ellipses indicate the study area.

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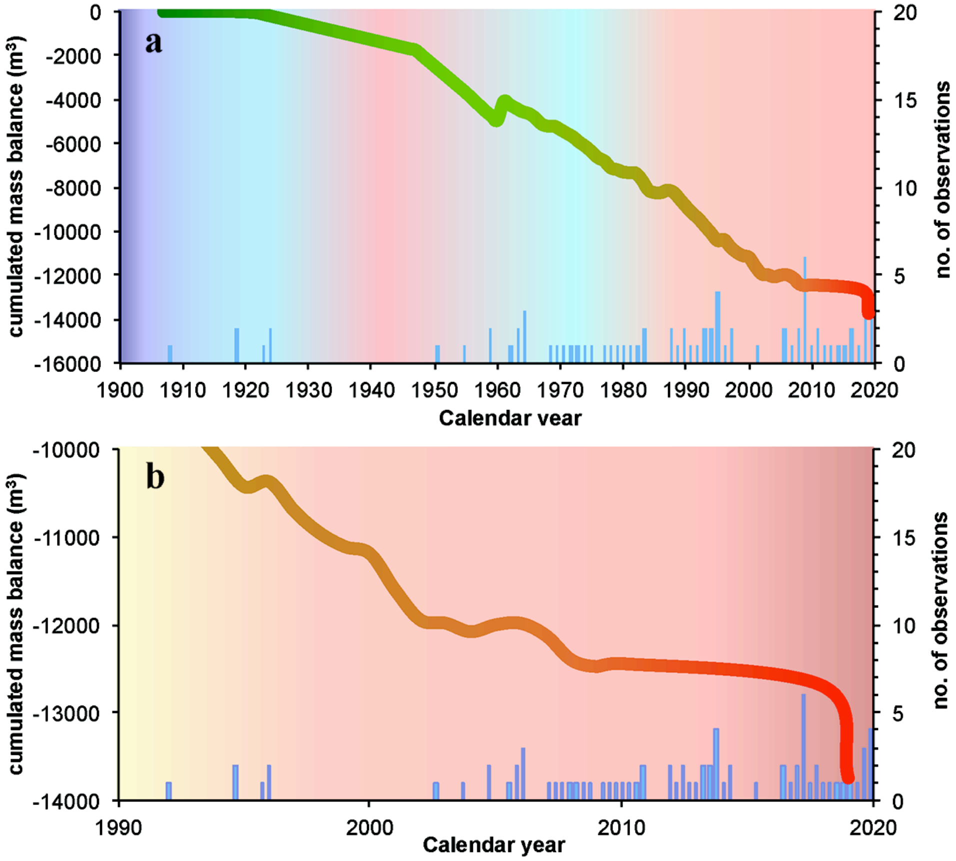

555 **Figure 8. Cumulative ice volume loss for European cave glaciers since 1900 (panel a, modified from Kern and Perşoiu, 2013) and over the past 30 years (panel b). Blue bars indicate the number of observations (caves) and the background colors show the average global temperature changes.**