ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI ZBORNIK

2023
63
1

ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
63-1 • 2023

Contents

ISSN 1581-6613
9 771581 661010

ACTA GEOGRAPHICA SLOVENICA

63-1
2023

ISSN: 1581-6613
UDC: 91
2023, ZRC SAZU, Geografski inštitut Antona Melika

Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, p. p. 306, SI – 1000 Ljubljana, Slovenija; ags@zrc-sazu.si

The articles are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si (ISSN: 1581–8314)

Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 € for individuals/za posameznika, 28 € for institutions/za ustanove
Single issue/cena posamezne številke: 12,50 € for individuals/za posameznika, 16 € for institutions/za ustanove

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o.
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: Present, d. o. o.
Print run/naklada: 300 copies/izvodov

The journal is subsidized by the Slovenian Research Agency and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/Revija izhaja s podporo Javne agencije za raziskovalno dejavnost Republike Slovenije in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/revija je vključena tudi v: Clarivate Web of Science (SCIE – Science Citation Index Expanded; JCR – Journal Citation Report/Science Edition), Scopus, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google Scholar, CrossRef, and DOAJ.

Design by/Oblikovanje: Matjaž Vipotnik

Front cover photography: After a major storm, the carbonate Nullarbor Plain was flooded due to its impermeable layer of clay (photograph: Matej Lipar).
Fotografija na naslovnici: Po močnejši nevihti je bila sicer karbonatna ravnina Nullarbor poplavljena zaradi nepropustne plasti gline (fotografija: Matej Lipar).

Acta geographica Slovenica, 63-1, 2023, 7–22

THE NORTH ATLANTIC OSCILLATION INFLUENCE ON THE DEBELI NAMET GLACIER

Gordana Jovanović

Durmitor National Park, Montenegro, mountain peak Međed above the Crno jezero.

DOI: https://doi.org/10.3986/AGS.10834
UDC: 551.583:551.324(497.16)

Gordana Jovanović[1]

The North Atlantic Oscillation influence on the Debeli Namet Glacier

ABSTRACT: This article presents the relationship between climate variables in the Durmitor Massif (Montenegro) and the North Atlantic Oscillation (NAO). A new climate standard for temperatures and precipitation over the last 30 years has been presented. The Debeli Namet Glacier is an indicator of climate change. We have shown that the size of this glacier is affected by the NAO which mainly affects the precipitation in the accumulation period from December to March. During the ablation period from June to September, the influence of the NAO on precipitation and temperatures is less pronounced. El Niño and La Niña events are significant, especially in years with a low NAO index. The relationship between El Niño/La Niña and the NAO is still a subject of scientific debate.

KEY WORDS: The North Atlantic Oscillation, precipitation, temperatures, Debeli Namet Glacier, glacier size

Vpliv severnoatlantske oscilacije na ledenik Debeli Namet

POVZETEK: Članek predstavlja povezavo med podnebnimi spremenljivkami v masivu Durmitor (Črna gora) in severnoatlantsko oscilacijo (NAO). Predstavljen je nov podnebni standard za temperature in padavine v zadnjih 30 letih. Ledenik Debeli Namet je pokazatelj podnebnih sprememb. Pokazali smo, da na velikost tega ledenika vpliva NAO, ki vpliva predvsem na količino padavin v akumulacijskem obdobju od decembra do marca. V obdobju ablacije od junija do septembra je vpliv NAO na padavine in temperature manj izrazit. Dogodki El Niño in La Niña so pomembni zlasti v letih z nizkim indeksom NAO. Razmerje med El Niño/La Niña in NAO je še vedno predmet znanstvenih razprav.

KLJUČNE BESEDE: Severnoatlantska oscilacija, padavine, temperature, ledenik Debeli Namet, velikost ledenika

The article was submitted for publication on 20th May, 2022.
Uredništvo je prejelo prispevek 20. maja 2022.

[1] University of Montenegro, Faculty of Natural Sciences and Mathematics, Podgorica, Montenegro
gordanaj@ucg.ac.me (https://orcid.org/0000-0001-8349-4189)

1 Introduction

The last Ice Age, which ended 11,000–12,000 years ago, left its mark on the Balkan Peninsula. Thanks to the pioneering research of Jovan Cvijić traces of glaciation and interglaciation periods were discovered in the Balkans (Cvijić 1920). His discovery of an ancient glacial relief on Rila in Bulgaria, in 1896, then on Durmitor (Montenegro), Lovćen (Montenegro), Prokletije (Montenegro, Albania) and other high mountains, made him one of the greatest geographers in Europe at that time. Albrecht Penck, better known for his classic glacier work in the Alps, was another glacier pioneer who worked in the Balkans (Penck 1900). A significant contribution to glacier research was made by Louis (1926) who also worked extensively in the area. Glacier research was particularly active in the period between 1920 and 1940 (Milojević 1937; see reviews in Messerli 1967; Hughes and Woodward 2009) and after World War II, with notable research in Montenegro (Liedtke 1962; Nicod 1968; Marović and Marković 1972) and Greece (Hagedorn 1969). Looking back at the history of glacial research in the Balkan Peninsula, three distinct phases can be identified in the development of this research area (Hughes and Woodward 2016): the pioneering phase characterized by the first descriptive observations of glacial landforms, the mapping phase when the distribution of glacial landforms and sediments was first depicted on sophisticated geomorphological maps and the contemporary advanced phase characterized by the use of modern technologies (Hughes et al. 2010; Onaca et al. 2020; 2022; Gachev 2022).

Mountains with approximately the same elevation had more glaciers when they were closer to the Adriatic Sea due to higher atmospheric precipitation. The lowest Pleistocene glaciers in the Balkans, and in all of southern Europe, formed in the coastal Dinaric Alps bordering the Adriatic Sea (Penck 1900; Cvijić 1917). In these areas, moraines are present at elevations below 1000 m, and in northern Dalmatia (Croatia), glacial deposits have even been reported at sea level (see Hughes et al. 2010 and references therein). The largest glaciers on the peninsula were found in the highest Dinaric mountains – Prokletije, Komovi and Durmitor, whose peaks are above 2500 m. Traces of glaciation in Greece are described by Hughes (Hughes et al. 2010; Hughes 2018).

Today, there are 16 glaciers on the Balkan Peninsula: 13 on Prokletije, 2 on the Pirin Mountains in Bulgaria and 1 on Durmitor (Gachev 2017). Many of them are below the current snow line thanks to favorable topology and local climate. They cover an area of 0.5–5 hectares, and their thickness is estimated at 10–20 m (Onaca et al. 2022; Gachev 2017). The alternation of very warm summers and winters with low snowfall over several years can cause glaciers to retreat or melt throughout the Balkans (Nadbath 1999; Hughes 2008; Grunewald and Scheithauer 2010). The Debeli Namet Glacier (Figure 1) is the only contemporary glacier in the Durmitor massif. Scientists who have studied the Debeli Namet Glacier have been interested in its reconstruction since the Pleistocene (Djurović 2009), its dynamics from the second half of the 20th century to the present (Djurović 2012; Gachev 2017; 2020), and its response and adaptation to climate change (Hughes 2008; Grunewald and Scheithauer 2010). In this article we are interested in the causes of the climate variability and consequential glacier response. One of them is the North Atlantic Oscillation (NAO). As the dominant low-frequency atmospheric oscillation in the Northern Hemisphere it has extensive and pronounced climate impacts around the globe (Hurrell 1995; Woodward 2009; Cattiaux et al. 2010; Hurrell and Deser 2009; Cohen et al. 2012; Li et al. 2013; Li and Ruan 2018). It explains much of the observed temperature and precipitation variability over Eurasia and North America (Hurrell 1996; Wang, Liu and Lee 2010). The influence of the NAO on climate has been assessed by the NAO index defined as the difference in atmospheric pressure at sea level between the Azores and Iceland. A positive NAO index (or positive NAO phase) is associated with warmer conditions and an increase in precipitation in northern Europe and cooler conditions and a decrease in precipitation over the Mediterranean (Eshel and Farrell 2000; Criado-Aldeanueva and Soto-Navarro 2020). During the negative NAO index (or negative NAO phase) warm moist air enters the Mediterranean region and cold air enters northern Europe.

Another important climate pattern is the El Niño–Southern Oscillation (ENSO), which is measured by the Oceanic Niño Index (ONI). The ONI is the rolling three-month average temperature anomaly in the surface waters of the eastern and central tropical Pacific Ocean. Index values of +0.5 or higher indicate El Niño while index values of –0.5 or lower indicate La Niña.

While climate responses to ENSO in the North Pacific and North America are well understood, the physical linkages between ENSO and climate variability over the North Atlantic-European region are still unclear and subject to scientific debate (Seager et al. 2010; Zhang, Mei and Geng 2018; Mezzina et al. 2019).

The combined effects of ENSO and NAO are confirmed to be more profound than the effects they produce individually (Marengo 2004). The results of recent studies show that the ENSO-NAO relationship is dominated in 1980–1982 and 1991–1993. From 2015 to 2017, the NAO showed a high correlation with the fluctuation of the ENSO (Mu et al. 2022).

In this article, the influence of the NAO and ENSO phenomena on climate variables in the Durmitor region, and thus on evolution of the Debeli Namet Glacier, has been examined. Two characteristic periods are focused on: the accumulation period from December to March, when the glacier volume increases, and the ablation period from June to September, when the glacier volume decreases (Gachev 2020).

New climate parameters for temperatures and precipitation for the last 30 years in the Durmitor region were introduced. These form the basis for the analysis in this article.

2 Glaciation in the Durmitor mountains

The massif of Durmitor, Montenegro, located at 43°26' N and 19°10' E was intensely glaciated. Carbonate rocks of different structure and age are involved in its structure (Mirković 1983). The Durmitor forms a classic glacial landscape (Cvijić 1889; 1903; 1914; Milojević 1937; 1951; Messerli 1967; Nicod 1968; Marović and Marković 1972; Djurović 2009). Deep valley troughs, separated by sharp aretes, radiate outwards in all directions from the highest central Durmitor Mountains, which culminate at Bobotov Kuk (2,523 m). Eighteen lakes are located in these valleys bounded by sedimentary or rocky ridges. The highest valley areas are characterized by armchair-shaped hollows and perennial ice is present at the head of Karlica below the peak of Šljeme (Kern et al. 2007) and also in caves such as Ledina Pećina (Veselinović et al. 2001). Two phases of Pleistocene glaciation were observed on the Durmitor mountains, the older being stronger than the younger phase. During the old phase 54% of the total surface of Durmitor was covered by ice, while during the young phase 36% of this surface was under ice (Djurović 2009). After these two phases of

© DEJAN DAJKOVIĆ

Figure 1: The Debeli Namet Glacier, Durmitor mountains, Montenegro, is one of the southernmost glaciers in Europe (August, 2010).

glaciation the present cirque glaciation phase came. It is represented by the Debeli Namet Glacier. The existence of the Debeli Namet Glacier indicates that the glaciation process on the Durmitor has not been interrupted after the Little Ice Age. This glacier is located at an elevation of 2,030–2,200 m (Djurović 2012; Gachev 2017), which is much lower than the climatic snow line estimated at 2700 m in the western (Milivojević, Menković and Ćalić 2008) and 3,200 m in the eastern part of the Balkan Peninsula (Gachev 2011). The north/northeast exposure of the terrain, as well as the highest mountain peaks surrounding this area, enabled the accumulation of significantly more snow through avalanches and blizzards than can be supplied by the atmospheric precipitation falling directly over glacier surface. Therefore, conditions still prevail in this part of the Durmitor Mountain that allow the feeding of the existing glacier. The specific position of the Debeli Namet Glacier is a factor for the smaller decrease of this glacier in comparison with other glaciers in Southern Europe during the last 50 years (Djurović 2012), regardless of the increase in temperature evident at the end of the 20th and the first decades of the 21th century (Gachev 2017).

3 Methods

For the assessment of temperatures and precipitation in the region of Debeli Namet Glacier the data from Žabljak meteorological station of the Institute for Hydrometeorology and Seismology of Montenegro (Zavod za hidrometeorologiju i seizmologiju Crne Gore) in the period from 1991 to 2021 were used. Correlations between the NAO and climate variables is evaluated by the NAO index data from the Hurrel Station-Based NAO Index (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).

The volume of the Debeli Namet Glacier is calculated on the basis of rope measurements and photographs available on the website of the Institute of Hydrometeorology and Seismology of Montenegro (www.meteo.co.me; Gachev 2020; Table 1), using the Chen and Ohmura empirical equation (1990):

$$V = 28.5S^{1.357},$$

where V is glacier volume in 10^6 m^3 and S is glacier surface area in 10^6 m^2.

Temperatures in the region of glacier (2,035 m) were calculated on the basis of extrapolated temperature data from the meteorological stationat Žabljak (1,450 m) using a lapse rate of 0.6 °C/100 m. The lowest point of the glacier was chosen for the reference point because it has the highest temperature.

Based on instrumental measurements (Weather almanacs, Institute for Hydrometeorology and Seismology of Montenegro) and statistical calculations, average annual temperature and precipitation in Žabljak were

Table 1: Average temperatures for Žabljak meteorological station in glacier accumulation period December–March (upper row) and glacier ablation period June–September (lower row) in two consecutive 30-year periods (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022).

Average temperature for December–March,1961–1990	Average temperature for December–March,1991–2020
T = –6.5 °C	T = –5.5 °C
Average temperature for June–September,1961–1990	Average temperature for June–September,1991–2020
T = 8.9 °C	T = 10.5 °C

Table 2: Average precipitation for Žabljak meteorological station in glacier accumulation period December–March (upper row) and glacier ablation period June–September (lower row) in two consecutive 30-year periods (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022).

Average precipitation for December–March, 1961–1990	Average precipitation for December–March, 1991–2020
122.1 mm	135.6 mm
Average precipitation for June–September, 1961–1990	Average precipitation for June–September, 1991–2020
97.4 mm	85.9 mm

4.7 °C and 1493.6 mm respectively during the standard climate period 1961–1990. The new climate parameters in the next 30-year period from 1991 to 2020 are different: average annual temperature and precipitation are 5.9 °C and 1505.2 mm, respectively. There is an increase in both variables, the average annual temperature increasing by $\Delta T = 1.2$ °C while the average annual precipitation increased for 11.6 mm (about 0.8%). It is obvious that the annual temperature change is significant while the annual change in amount of precipitation is negligible. The temperature of the glacier accumulation period increased for +1 °C while temperature of the glacier ablation period increased by +1.6 °C in these two consecutive 30-year periods (Table 1).

Temperatures are lower than those suggested when a lapse rate of 0.6 °C/100 m is assumed because the Debeli Namet Glacier is faced northeast and is favored by shading. Besides temperature, precipitation is another important glacier mass balance variable. Average precipitation in accumulation and ablation season in two 30-year periods is presented in Table 2. Average precipitation increased for 13.5 mm (11%) in accumulation season and decreased for 11.5 mm (12%) in ablation season over two consecutive 30-year periods. For the glaciers in the Dinaric Mountains, the winter precipitation, not the temperature, has the leading role in the glacier existence (Gachev 2020).

4 Results

4. 1 The accumulation period

The NAO index for the accumulation period refers to December–March (DJFM). In Montenegro, the amount of precipitation in this period is correlated with the NAO; when DJFM NAO indices are negative, the amount of precipitation is above the average value, and vice-versa (Burić, Micev and Mitrović 2012). This could be disturbed by ENSO. Data from the meteorological station Žabljak show that years with very low precipitation, 30%–60% lower than average, were: 1991, 1992, 1993, 1998, 2002, 2008, 2014, 2017 and 2019. They are characterized by positive DJFM NAO indices for the accumulation season (Figure 2). Years with the highest precipitation, 20%–90% higher than average, were: 1996, 2001, 2005, 2006, 2009, 2010, 2011, 2013, 2018 and 2021. These years are mostly characterized by negative DJFM NAO indices (Figure 2). The exceptions are years 2005 and 2018 with small but positive DJFM NAO indices suggesting that the NAO does not affect climate variables much. In these years El Niño (in 2005) and La Niña (in 2018) events could influence the climate variables more than NAO (Figure 3). It is also known that switches from negative to positive NAO and vice versa are followed by noticeable changes in the average precipitation (Criado-Aldeanueva and Soto-Navarro 2020). In the last 30 years there is a moderate negative correlation (Spearman's correlation $r_s = -0.55$, $p = 0.002$) between precipitation and DJFM NAO index. This means that the rising/declining precipitation trend in the Durmitor Massif is related to the negative/positive DJFM NAO index.

Relationship between temperatures in the accumulation period and DJFM NAO indices shows that the temperatures are mostly lower than average in the positive NAO phase. Namely, the years with the temperatures which are more than 1 °C lower than average for this period, were: 1992, 1993, 2000, 2003, 2005, 2006, 2012. In these years the DJFM NAO indices are mostly positive. The only exception is the year 2006 when the negative DJFM NAO was accompanied by the influence of La Niña. It seems that La Niña has a more significant impact on the temperature than on the precipitation because in 2006 the amount of precipitation was higher than average and in correlation with negative DJFM NAO index. The temperature in 2006 shows the opposite characteristic–it was lower than average in the accumulation period.

The highest temperatures in accumulation period should be expected in the years with the negative NAO, but this is not the case. Years with the highest temperatures in accumulation period, more than 1.5 °C higher than average for this period, were: 1994, 2001, 2007, 2014 and 2016. Only in 2001 a negative DJFM NAO was recorded while other years were with a positive DJFM NAO index. It seems that El Niño events in 1994, 2007 and 2014–2016, strongly influences the temperatures in the accumulation season (Figure 4). Correlation between temperatures and DJFM NAO index is low and statistically insignificant (Spearman's correlation, t-test shows $p = 0.52$). These temperatures are in connection not only with the NAO but also with the El Niño/La Niña events (Table 3).

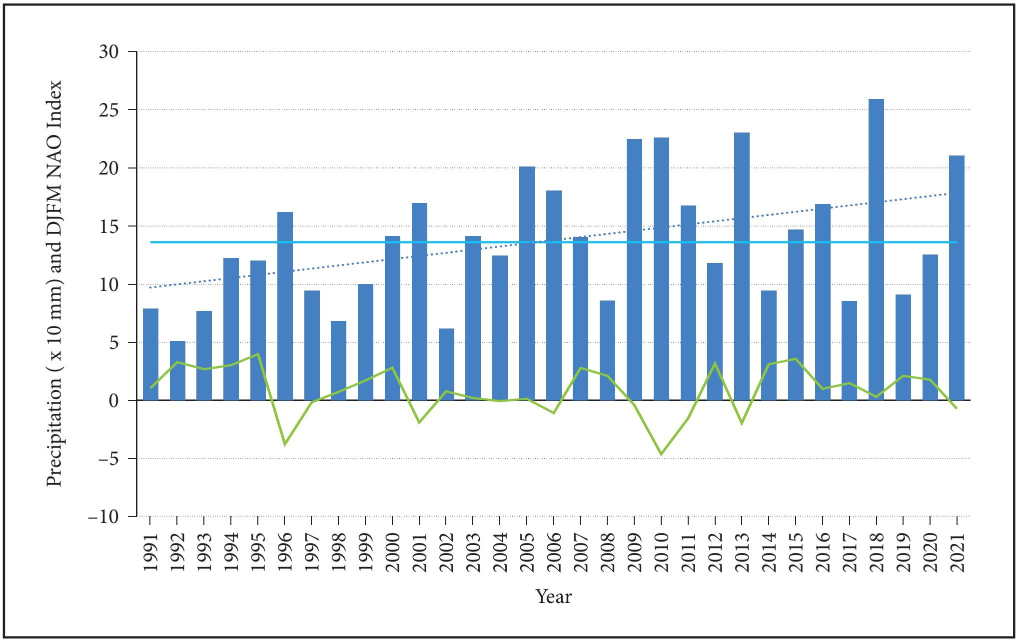

Figure 2: Precipitation for Žabljak meteorological station in accumulation period (blue columns) and DJFM NAO index (green line) for 1991–2021. The dashed blue line shows the trend of increasing precipitation, while the solid blue line represents the average precipitation (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022 and by the National Center for Atmosferic Research, USA 2022).

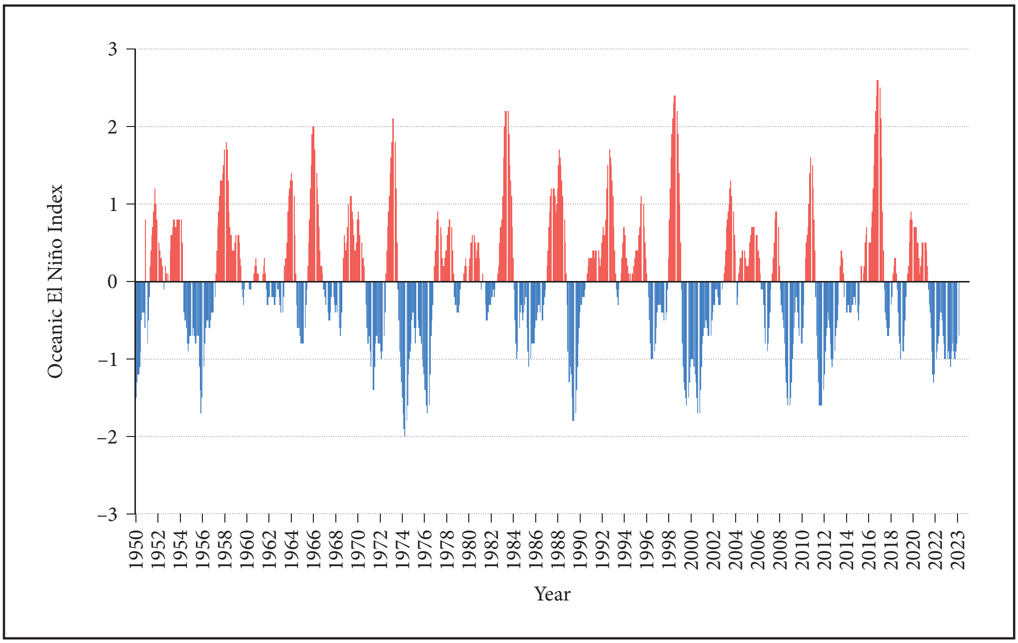

Figure 3: Warm (> +0.5 °C) and cold (< –0.5 °C) episodes for the Oceanic Niño Index_(ONI) in the period 1950–2022. The events are defined by ONI as weak (0.5–0.9), moderate (1.0–1.4) and strong (≥ 1.5) (provided by the National Center for Atmosferic Research, USA 2022 and National Weather Service, National Oceanic and Atmospheric Administration, USA 2022).

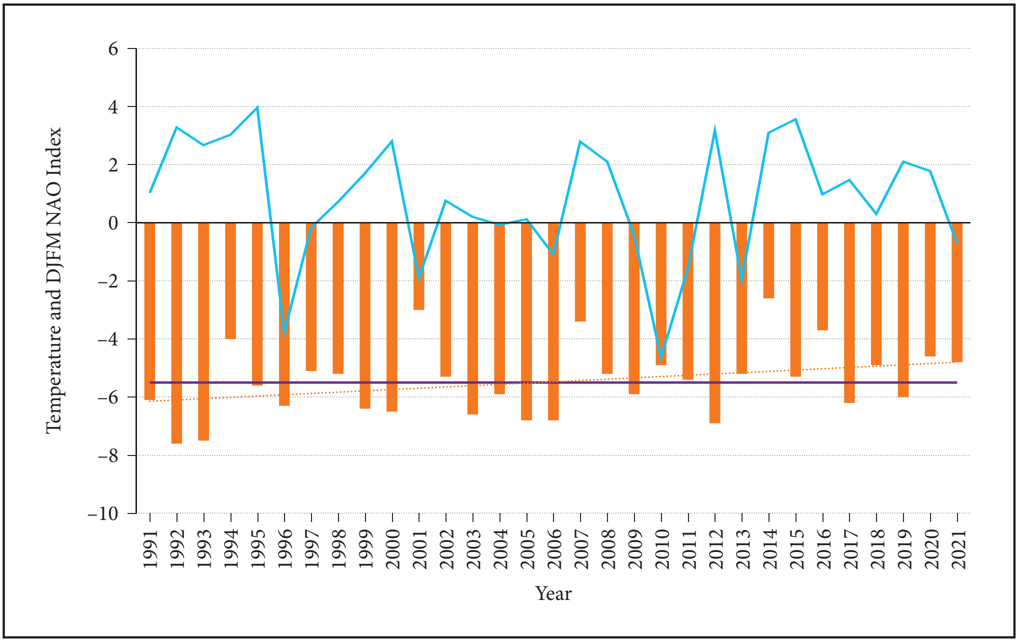

Figure 4: Temperatures for Žabljak meteorological station in accumulation period (orange columns) and DJFM NAO index (light blue line) for 1991–2021. The dashed orange line shows the trend of increasing temperature while the solid violet line represents the average temperature (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022 and by the National Center for Atmosferic Research, USA 2022).

Table 3: The influence of La Niña/ El Niño and DJFM NAO combinations on the precipitation and temperature in the Durmitor region for 1991–2021 (provided by the National Center for Atmosferic Research, USA 2022 and National Weather Service, National Oceanic and Atmospheric Administration, USA 2022).

		precipitation	temperature
La Niña	NAO +	↑	
	NAO –		↓
El Niño	NAO +		↑
	NAO –		

4. 2 The ablation period

Summer precipitation and summer temperatures are the main causes of the glacier shrinking. The NAO index for the ablation period refers to July–September (JAS). In the Mediterranean region the NAO influence in this period is less pronounced than in accumulation period. Years with precipitation above 110 mm or 30%–50% higher than average for ablation period, were: 1995, 2006, 2007, 2014 and 2020. Years with precipitation less than 70 mm, i.e. 20%–44% lower than average for ablation period, were: 1991, 1993, 1994, 1997, 2010, 2012, 2015, 2017 and 2021. These years are mostly characterized by negative JAS NAO indices (Figure 5). Exceptions are in 1997 with the strong El Niño and in 2017 and 2021 with moderate La Niña. It can be said that a negative JAS NAO is the leading factor that determines extreme precipitation in the ablation period. During the period 1991–2021 precipitation trend is almost constant.

Temperatures in the ablation season rose slightly in the considered 30-years period (Figure 6). For the temperatures above 11 °C, which are more than 0.5 °C higher than average in ablation season, the JAS NAO indices are mostly negative. Years with these temperatures were: 1998, 1999, 2003, 2007, 2010–2012, 2015,

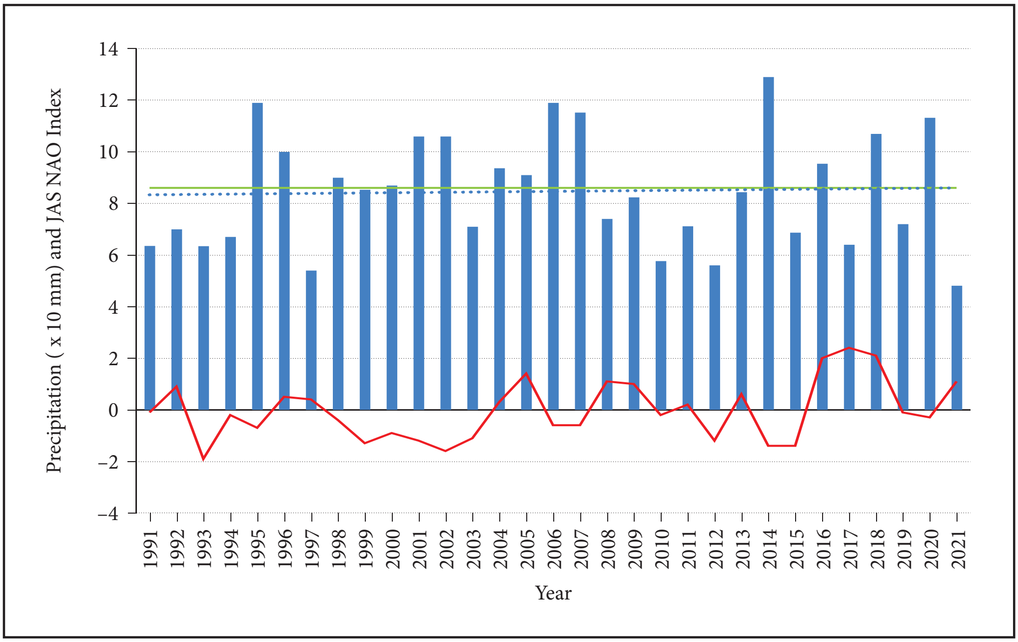

Figure 5: Precipitation for Žabljak meteorological station in ablation period (blue columns) and JAS NAO index (red line) for 1991–2021. The dashed blue line shows that precipitation tends to be almost constant, while the solid green line represents the average precipitation (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022 and by the National Center for Atmosferic Research, USA 2022).

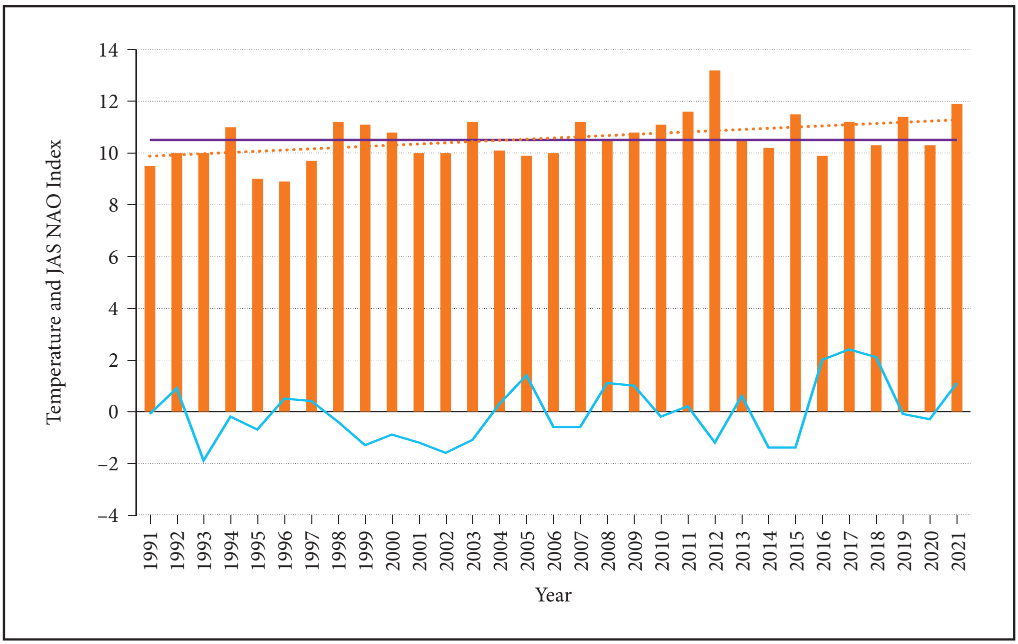

Figure 6: Temperatures for Žabljak meteorological station in ablation period (orange columns) and JAS NAO index (blue line) for 1991–2021. The dashed orange line shows the trend of increasing temperature while the purple line represents average temperature (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022 and by the National Center for Atmosferic Research, USA 2022).

2017, 2019 and 2021. Exceptions are the positive JAS NAO indices in the years 2011 (strong La Niña), 2017 and 2021 (moderate La Niña). Years with the temperatures lower than 10 °C, i.e. more than 0.5 °C less than average for this season, are mostly with the positive JAS NAO indices. These years were: 1991, 1995–1997, 2005 and 2016. In the 1991 and 1995 JAS NAO was negative and accompanied with El Niño.

Table 4 shows the exceptions when La Niña and a positive JAS NAO reduce precipitation below the average but increase the temperature above the average value as in the years 2011, 2017 and 2021. In the ablation period extreme precipitation and the highest temperatures are mainly characterized by the negative JAS NAO. On the other hand, El Niño has a great influence on the lowest temperatures regardless of the JAS NAO phase. Its influence on the precipitation is ambiguous.

Table 4: The influence of La Niña/ El Niño and JAS NAO combinations on the precipitation and temperature in the Durmitor region for Žabljak meteorological station for 1991–2021 (provided by the Institute for Hydrometeorology and Seismology of Montenegro 2022, the National Center for Atmosferic Research, USA 2022 and by the National Oceanic and Atmospheric Administration, USA 2022).

		precipitation	temperature
La Niña	NAO +	↓	↑
	NAO –		
El Niño	NAO +		↓
	NAO –		↓

4. 3 Influence of NAO on the Debeli Namet Glacier

For the further analysis, climate data were summarized in accordance with the glacier size. The size of the glacier was calculated empirically. The annual NAO index reflects both, the NAO influence in the glacier accumulation period and the NAO influence in the glacier ablation period. Therefore, it is convenient for comparison with the glacier size measured in autumn, mainly in October (Figure 7). A negative annual NAO is mainly related with the increase in glacier size, while a positive annual NAO is mainly related with the decrease in glacier size. The exceptions are years 2012, 2013 and 2018.

In the accumulation period size of the glacier increases when the DJFM NAO decreases and vice versa (Figure 8). This is in agreement with the correlation between NAO and precipitation in accumulation period. The lowest glacier size was in 2017 as a result of very low winter precipitation followed by hot and dry summer. The Spearman's correlation between glacier size and DJFM NAO index in the accumulation period is moderate negative correlation ($rs = -0.62$, $p = 0.019$).

5 Discussion

The NAO index is widely recognized as the one of the most important modes of the atmospheric variability in the northern hemisphere in the present and future (Rousi et al. 2020). There are indications that NAO is correlated not only with the geophysical phenomena but also with the solar cycle (Thiéblemont et al. 2015; Zharkova 2020; Drews et al. 2021).

In this article we present the NAO influence on climate variables in the Durmitor region. The focus is on temperature and precipitation especially in the accumulation period important for existence of the Debeli Namet Glacier. In the last 30 years there were 21 years with the positive NAO indices and only nine with the negative NAO index values. This means that about 2/3 of the considered period was characterized by the precipitation lower than average for the accumulation season. As the Žabljak meteorological station has a leeward position to the atmospheric advections from the southwest, which serve as the main sources of precipitation, it is worth to consider data from meteorological stations situated on the windward side like Nikšić and Šavnik (Figure 9). Not surprisingly, Nikšić and Šavnik receive more precipitation than Žabljak in the accumulation period but the trends are similar in all three cities, caused by the NAO influence (Burić, Micev and Mitrović 2012).

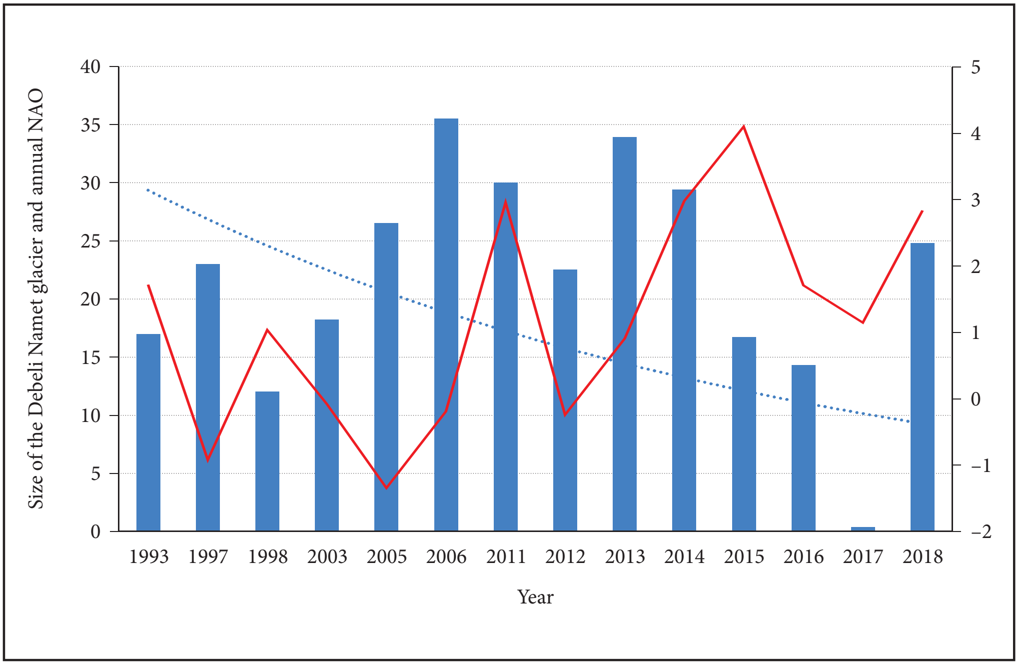

Figure 7: Size (in 106 m3) of the Debeli Namet Glacier (blue columns) and annual NAO index (red line) for the period 1993–2018. The dashed blue line shows that the glacier size tends to decrease (provided by the National Center for Atmosferic Research,USA 2022; Gachev 2020; Table 1).

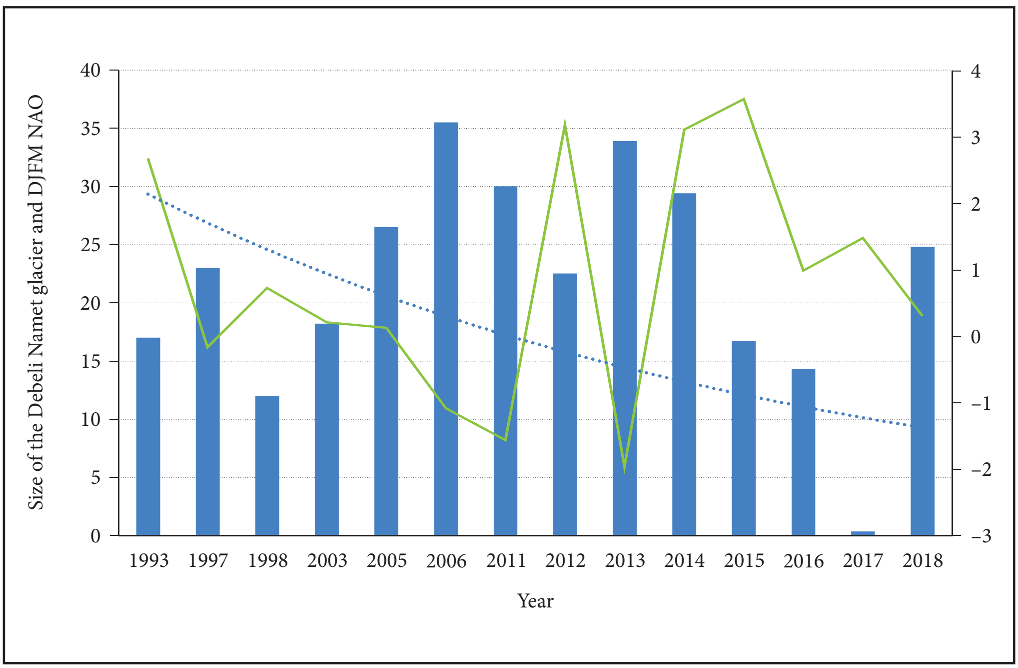

Figure 8: Size (in 106 m3) of the Debeli Namet Glacier (blue columns) and DJFM NAO index (green line) for the period 1993–2018. The dashed blue line shows that the glacier size tends to decrease (provided by the National Center for Atmosferic Research,USA 2022; Gachev 2020; Table 1).

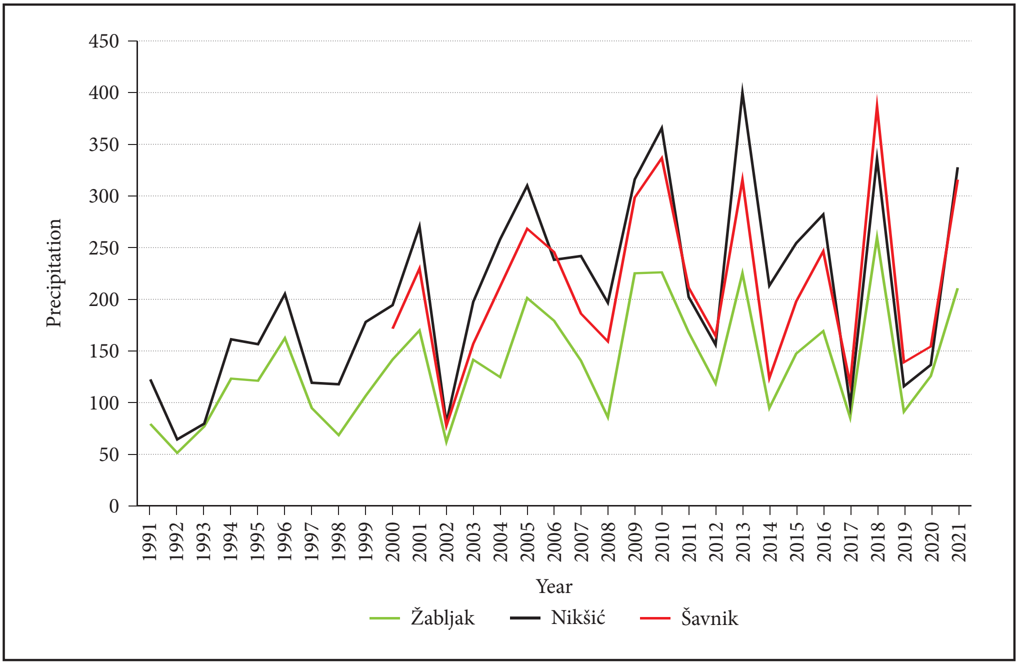

Figure 9: Precipitation in accumulation period for Žabljak, Nikšić and Šavnik meteorological stations for 1991–2021 (note that there is no data for Šavnik before the year 2000; provided by Institute of Hydrometeorology and Seismology of Montenegro).

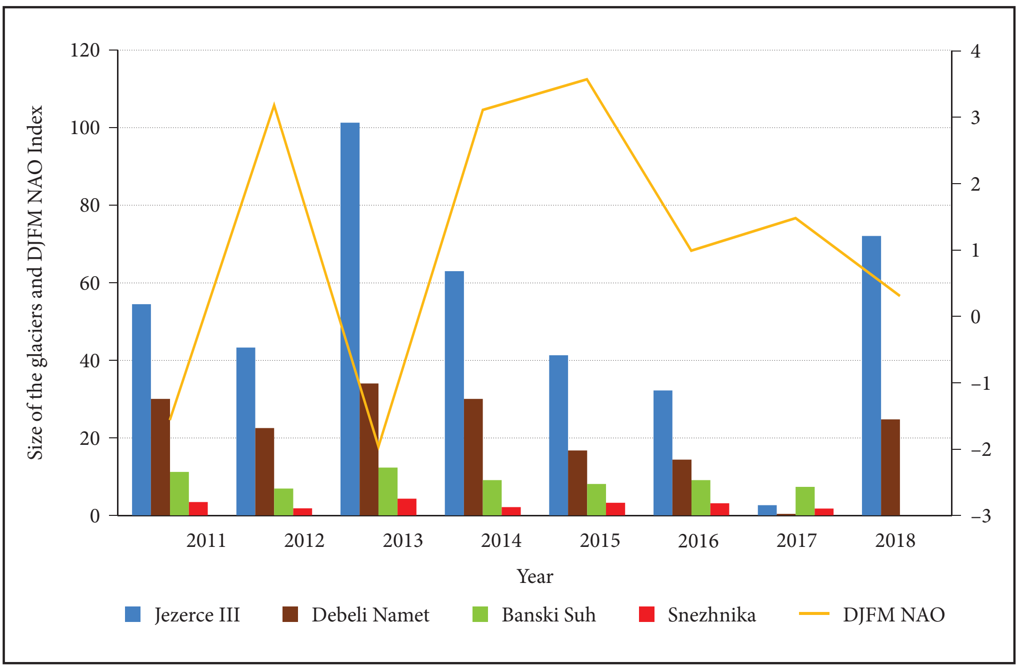

Figure 10: Size (in 106 m3) of the current glaciers in the Balkans: Jezerce III (Prokletije), Debeli Namet (Durmitor), Banski Suhodol and Snezhnika (Pirin) and DJFM NAO index for the period 2011–2018. There is no data for Banski Suhodol and Snezhnika for 2018 (Gachev 2020).

The nearest glaciers to the Debeli Namet Glacier are located in the Prokletije Mountains, Albania (Palmentola et al. 1995; Hughes 2009; Grunewalad and Scheithauer 2010; Gachev 2017). They are located below north-east-facing cliffs near the highest peak of this range, Maja Jezerce (2694 m). The largest (Jezerce III; Gachev 2020) was chosen for comparison with other current glaciers in the Balkans–Debeli Namet and glaciers in the Pirin Mountain, Bulgaria–Banski Suhodol and Snezhnika. Sizes of the glaciers are given in Figure 10.

Glaciers in the Pirin Mountain with a more continental climate are less sensitive on climate change than glaciers in the Dinaric Mountains. This is in accordance with previous studies (Gachev 2020). The heatwaves in the summers in 2012 and 2017 together with the low winter precipitation caused record minimum of those glaciers (Figure 2 and Figure 6). Periods of glacier advance are characterized by a negative DJFM NAO index, while periods of glacier retreat are characterized by a positive DJFM NAO index. This situation can be changed under the influence of La Niña like in 2018, especially when the NAO index has small value.

Small glaciers respond quickly to extreme weather conditions. If warm summers follow winters with few snowfalls over several years, they shrink until they reach a new equilibrium mass balance or melt completely. Also, phases with above-average winter precipitation and cooler summers are often sufficient to stabilize small glaciers or even produce re-advance. For example, at Debeli Namet Glacier, a new moraine developed between 1994 and 2003, and between 2004 and 2006, due to small glacier advances (Grunewald and Scheithauer 2010). In the Julian Alps recent increases in winter snowfall provide resilience to very small glaciers (Colucci et al. 2021). Gachev (2022) studied response of very small glaciers in the Pirin Mountains to climate variations and found that their short-term size fluctuations are mostly related to the temperature conditions during the ablation season. Twenty-first century glaciers and climate in the Prokletije Mountains have been studied by Hughes (2009).

6 Conclusion

We analyzed the climate variables in the region of Durmitor Massif over the last 30 years and their influence on the Debeli Namet Glacier. In the first part of the article we analyzed temperature and precipitation tendencies in the periods of accumulation and ablation. Average temperature in accumulation (ablation) period in the last 30 years is 1 °C (1.6 °C) higher than average temperature in accumulation (ablation) period in 1961–1990. The lowest temperatures in the accumulation period are mainly in the years with a positive DJFM NAO while the highest temperatures in this period are driven by the combined NAO and ENSO phenomena. In the last 30 years precipitation in accumulation (ablation) period increased 11% (decreased 12%) compared to the period 1961–1990.

The main mechanism that drives precipitation in accumulation period is the NAO measured by the DJFM NAO index. In the Durmitor region the lowest precipitation is in the years with the positive DJFM NAO index while the highest precipitation is mainly in the years with the negative DJFM NAO index. We suggest that this situation may change under the influence of ENSO events, especially in the years when the NAO index is low.

In ablation period the NAO influence, measured by the JAS NAO index, is less pronounced than in accumulation period. Almost every two years since 2010 has been a year with low precipitation and above average temperatures. This fact shows that the climate variables in the ablation period have moved towards higher temperatures and lower precipitation in the last 30 years. We found that the negative JAS NAO is the leading factor that determines extreme precipitation in the ablation period. Surprisingly, there is a good correspondence between the positive JAS NAO and the lowest temperatures and between the negative JAS NAO and the highest temperatures in the ablation period.

In the second part of the article, we compared the annual and DJFM NAO with the size of the Debeli Namet Glacier. The size of the glacier increases when DJFM NAO decreases and vice versa. The situation is the same with precipitation. This result suggests that there is no significant relationship between glacier size and ablation temperatures. We found that precipitation in accumulation period has the leading role in glacier size fluctuations. Glaciers located in the Prokletije Mountains, Albania and in the Pirin Mountain, Bulgaria show similar trend in the size variations. The fact is that glaciers in the Pirin Mountain with a more continental climate are less sensitive on climate change than glaciers in the Dinaric Mountains.

ACKNOWLEDGMENT: The research and writing of this work was funded by the Montenegrin National Project »Physics of Ionized Gases and Ionized Radiation«.

7 References

Burić, M., Micev, B., Mitrović, L. 2012: Atlas klime Crne Gore. Podgorica.

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., Codron, F. 2010: Winter 2010 in Europe: A cold extreme in a warming climate. Geophysical Research Letters 37-20. DOI: https://doi.org/10.1029/2010GL044613

Chen, J., Ohmura, A. 1990: Estimation of Alpine glacier water resources and their change since the 1870s. Hydrology in Mountainous Regions. International association of hydrological sciences 193.

Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A., Cherry, J. E. 2012: Arctic warming, increasing snow cover and widespread boreal winter cooling. Environmental Research Letters 7-1. DOI: https://doi.org/10.1088/1748-9326/7/1/014007

Colucci, R. R., Žebre, M., Torma, C. Z., Glasser, N. F., Maset, E., Del Gobbo, C., Pillon, S. 2021: Recent increases in winter snowfall provide resilience to very small glaciers in the Julian Alps, Europe. Atmosphere 12-2. DOI: https://doi.org/10.3390/atmos12020263

Criado-Aldeanueva, F., Soto-Navarro, J. 2020: Climatic Indices over the Mediterranean Sea: A Review. Applied Sciences 10-17. DOI: https://doi.org/10.3390/app10175790

Cvijić, J. 1889: Glacijalne i morfološke studije o planinama Bosne, Hercegovine i Crne Gore. Beograd.

Cvijić, J. 1903: Novi rezultati o glacijalnoj eposi Balkanskog poluostrva. Beograd.

Cvijić, J. 1914. Eiszeitliche Vergletscherung der Gebirgsgruppen von Prokletije bis Durmitor. Maßstab 1:200,000. Des K.u.k. Militärgeographischen Institutes. Wien.

Cvijić, J. 1917: L'époque glaciaire dans la péninsule des Balkanique. Annales de Géographie 26-144.

Cvijić, J. 1920: Istorija geografije. Beograd.

Djurović, P. 2009: Reconstruction of the pleistocene glaciers of mount Durmitor in Montenegro. Acta geographica Slovenica 49-2. DOI: https://doi.org/10.3986/AGS49202

Djurović, P. 2012: The Debeli Namet glacier from the second half of the 20th century to the present. Acta geographica Slovenica 52-2. DOI: https://doi.org/10.3986/AGS52201

Drews, A., Huo, W., Matthes, K., Kodera, K., Kruschke, T. 2021: The Sun's role for decadal climate predictability in the North Atlantic. Atmospheric Chemistry and Physics 22-12. DOI: https://doi.org/10.5194/acp-22-7893-2022

Eshel, G., Farrell, B. F. 2000: Mechanisms of Eastern Mediterranean rainfall variability. Journal of the Atmospheric Sciences 57-19. DOI: https://doi.org/10.1175/1520-0469(2000)057<3219:MOEMRV>2.0.CO;2

Gachev, E. 2011: Inter-annual size variations of Snezhnika glacieret (the Pirin mountains, Bulgaria) in the last ten years. Studia Geomorphologica Carpatho-Balcanica 45-7.

Gachev, E. 2017: The unknown southernmost glaciers of Europe. Glacier Evolution in a Changing World. London. DOI: https://doi.org/10.5772/intechopen.68899

Gachev, E. 2020: Small glaciers in the Dinaric mountains after eight years of observation: On the verge of extinction? Acta geographica Slovenica 60-2. DOI: https://doi.org/10.3986/AGS.8092

Gachev, E. 2022: Response of Very Small Glaciers to Climate Variations and Change: Examples from the Pirin Mountains, Bulgaria. Atmosphere 13-6. DOI: https://doi.org/10.3390/atmos13060859

Grunewald, K., Scheithauer, J. 2010: Europe's southernmost glaciers: response and adaptation to climate change. Journal of Glaciology 56-195. DOI: https://doi.org/10.3189/002214310791190947

Hagedorn, J. 1969: Beiträge zur Quartarmorphologie griechischer Hochgebirge. Habilitation Thesis, Geographisches Institut der Universität. Göttingen.

Hughes, P. D. 2007: Recent behaviour of the Debeli Namet glacier, Durmitor, Montenegro. Earth Surface Processes and Landforms 32-10. DOI: https://doi.org/10.1002/esp.1537

Hughes, P. D. 2008: Response of a Montenegro glacier to extreme summer heatwaves in 2003 and 2007. Series A, Physical Geography 90-4. DOI: https://doi.org/10.1111/j.1468-0459.2008.00344.x

Hughes, P. D. 2009: Twenty-first century glaciers and climate in the Prokletije Mountains, Albania. Artic, Antarctic, and Alpine Research 41-4. DOI: https://doi.org/10.1657/1938-4246-41.4.455

Hughes, P. D., Woodward, J. C., van Calsteren, P. C., Thomas, L. E., Adamson, K. R. 2010:

Pleistocene ice caps on the coastal mountains of the Adriatic Sea. Quaternary Science Reviews 29-27/28. DOI: https://doi.org/10.1016/j.quascirev.2010.06.032

Hughes, P. D., Woodward, J. 2009: Glacial and periglacial environments. The Physical Geography of the Mediterranean. Oxford. DOI: https://doi.org/10.1093/oso/9780199268030.003.0024

Hughes, P. D., Woodward, J. C. 2016: Quaternary glaciation in the Mediterranean mountains: A new synthesis. Geological Society London Special Publications 433-1. DOI: http://doi.org/10.1144/SP433.14
Hughes, P. D. 2018: Little Ice Age glaciers and climate in the Mediterranean mountains: a new analysis. Geographical Research Letters 44-1. DOI: http://doi.org/10.18172/cig.3362
Hurrell, J. W. 1995: Decadal trends in the North Atlantic oscillation regional temperatures and precipitation. Science 269-5224. DOI: https://doi.org/10.1126/science.269.5224.676
Hurrell, J. W. 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. Geophysical Research Letters 23-6. DOI: https://doi.org/10.1029/96GL00459
Hurrell, J. W., Deser, C. 2009: North Atlantic climate variability: The role of the North Atlantic Oscillation. Journal of Marine Systems 78-1. DOI: https://doi.org/10.1016/j.jmarsys.2008.11.026
Kern, Z., Surányi, G., Molnár, M., Nagy, B., Balogh, D. 2007: Investigation of natural perennial ice deposits of Durmitor mts, Montenegro. Proceedings of the 2nd International Workshop on Ice Caves. Demänovská Dolina.
Li, J. P., Sun, C., Jin, F. F. 2013: NAO implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability. Geophysical Research Letters 40-20. DOI: https://doi.org/10.1002/2013GL057877
Li, J. P., Ruan, C. Q. 2018: The North Atlantic–Eurasian teleconnection in summer and its effects on Eurasian climates. Environmental Research Letters 13-2. DOI: https://doi.org/10.1088/1748-9326/aa9d33
Liedtke, H. 1962: Eisrand und Karstpoljen am Westrand Lukavica-Hochfläche. Erdkunde 16-4.
Louis, H. 1926: Glazialmorphologishche Beobachtungen im albanischen Epirus. Zeitschrift der Gesellschaft für Erdkunde 9-10.
Marengo, J. A. 2004: Interdecadal variability and trends of rainfall across the amazon basin. Theoretical and Applied Climatology 78,1–3. DOI: https://doi.org/10.1007/s00704-004-0045-8
Marović, M., Marković, M. 1972: Glacijalna morfologija šire oblasti Durmitora. Geološki anali Balkanskog poluostrva 37-2.
Messerli, B. 1967: Die eiszeitliche und die gegenwartige Vertgletscherung im Mittelemeeraum. Geographica Helvetica 22-3.
Mezzina, B., Garcia-Serano, J., Blade, I., Kucharski, F. 2019: Dynamics of the ENSO teleconnection and NAO variability in the North Atlantic–European late winter. Journal of Climate 33-3. DOI: https://doi.org/10.1175/JCLI-D-19-0192.1
Milivojević, M., Menković, L, Ćalić, J. 2008: Pleistocene glacial relief in the central part of Mt. Prokletije (Albanian Alps). Quaternary International 190-1. DOI: https://doi.org/10.1016/j.quaint.2008.04.006
Milojević, B. Ž. 1937: Visoke planine u našoj Kraljevini. Beograd.
Milojević, B. Ž. 1951: Durmitor-regionalno-geografska istraživanja. Zbornik radova 9-2. Beograd.
Mirković, M. 1983: Geološki sastav i tektonski sklop Durmitora, Pivske planine i Volujka. Geološki glasnik 5.
Mu, B., Li, J., Yuan, S., Luo, X. 2022: The NAO variability prediction and forecasting with multiple time scales driven by ENSO using machine learning approaches. Computational Intelligence and Neuroscience 2022. DOI: https://doi.org/10.1155/2022/6141966
Nadbath, M. 1999: Triglavski ledenik in spremembe podnebja. Ujma 13.
Nicod, J. 1968: Premières recherches de morphologie karstique dans le massif du Durmitor (Crna Gora: Montenegro). Meditérraneé 9-4.
Onaca, A., Ardelean, F., Aredelean, A., Magori, B., Sirbu, F., Voiculescu, M., Gachev, E. 2020: Assessment of permafrost conditions in the highest mountains of the Balkan Peninsula. Catena 185-1. DOI: https://doi.org/10.1016/j.catena.2019.104288
Onaca, A., Gachev, E., Ardelean, F., Ardelean, A., Perşoiu, A., Hegyi, A. 2022: Small is strong: Post-LIA resilience of Europe's Southernmost glaciers assessed by geophysical methods. Catena 213-3. DOI: https://doi.org/10.1016/j.catena.2022.106143
Palmentola G, Baboci K, Gruda GJ, Zito G. 1995: A note on rock glaciers in the Albanian Alps. Permafrost and Periglacial Processes 6-3. DOI: https://doi.org/10.1002/ppp.3430060306
Penck, A. 1900: Die Eiszeit auf der Balkanhalbinsel. Globus 78.
Rousi, E., Rust, H. W., Ulbrich, U., Anagnostopoulou, C. 2020: Implications of Winter NAO Flavors on Present and Future European Climate. Climate 8-1. DOI: https://doi.org/10.3390/cli8010013
Seager, R., Kushnir, Y., Nakamura, J., Ting, M., Naik, N. 2010: Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. Geophysical Research Letters 37-14. DOI: https://doi.org/10.1029/2010GL043830

Thiéblemont, R., Matthes, K., Omrani, N., Kodera, K., Hansen, F. 2015: Solar forcing synchronizes decadal North Atlantic climate variability. Nature Communications 6-1. DOI: https://doi.org/10.1038/ncomms9268
Veselinović, D., Kovačević, D., Rajšić, S., Vukmirović, Z., Djordjević, D., Stanković, S., Stanković, A. 2001. The metal amounts in ice stalagmite of »ice cave« snow and water at Durmitor mountains (Yugoslavia). Journal of Environmental Protection and Ecology 2-1.
Wang, C. Z., Liu, H., Lee, S. K. 2010: The record-breaking cold temperatures during the winter of 2009/2010 in the Northern Hemisphere. Atmospheric Science Letters 11-3. DOI: https://doi.org/10.1002/asl.278
Woodward, J. (ed.) 2009: The physical geography of the Mediterranean. Oxford. DOI: https://doi.org/10.1093/oso/9780199268030.001.0001
Zhang, W., Mei, H., Geng, X. 2018: A Nonstationary ENSO–NAO Relationship Due to AMO Modulation. Journal of Climate 32-1. DOI: https://doi.org/10.1175/JCLI-D-18-0365.1
Zharkova, V. 2020: Modern Grand Solar Minimum will lead to terrestrial cooling. Temperature 7-3. DOI: https://doi.org/10.1080/23328940.2020.1796243