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IMPACT OF CLIMATE CHANGE ON SNOWPACK AND AVALANCHES IN SLOVENIA: THE SOČA VALLEY CASE STUDY

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Abstract

The article discusses avalanche occurrence in the Slovenian Alps (SE Alps) in the context of climate change. It analyses the relationship between the North Atlantic Oscillation and maximum snow depth over the last two centuries, and the relationships between maximum snow depth and avalanches over the last three decades. We argue that higher temperatures lead to precipitation in the form of rain at higher elevations even in winter, so that major wet avalanches occur already in winter rather than in early spring, as was more common in the past. A case study of extreme avalanches in January 2021 is presented to support the hypothesis.

Key words

Geography • climate change • avalanche • maximum snow depth • North Atlantic Oscillation • Upper Soča Valley • SE Alps • Slovenia

Introduction

Avalanches are geomorphologically, hydrologically, and meteorologically conditioned natural phenomena (White, 1974) and become natural disasters when they cause damage or injuries and fatalities (Zorn & Komac, 2011). Globally, avalanches are the most common secondary natural hazard along with forest fires (Gill & Malamud, 2014).

Avalanches (Šegula, 1986; Stethem, 2013; Rączkowska et al., 2016b; Louchet, 2020; NSIDC 2020; Murray et al., 2021) are not only natural disasters. They also feed springs and rivers, which makes them an important part of the hydrosphere, as well as by feeding glaciers and ice caves, which a narrower sense makes them part of the cryosphere. In addition, avalanches are an important erosional and biological factor (UNESCO, 1981; Birkeland et al., 2001; Laternser & Schneebeli, 2002; Schweizer et al., 2003; Volk Bahun, 2016, 2017).

The frequency and intensity trends of climate-related natural phenomena are alarming. Global warming increases the intensity of extreme precipitation (EEA, 2021), which is also true for snow-related hazards such as extreme snow cover (Strapazzoni et al., 2011) and avalanches (Rawlins, 2022). The duration (Fischer & Knutti, 2016; Norris et al., 2019; Papalexiou & Montanari, 2019) and spatial extent of weather extremes are increasing (Benestad, 2018), redefining hazard and risk hot spots (Pelling, 2003; Wamsler et al., 2013).

However, the frequency of such events under increasingly warmer conditions remains unclear. It is known that total precipitation during these intense events nearly doubles if the average air temperature changes by one degree Celsius (Myhre et al., 2019). Because the frequency of avalanches depends on the amount of snow, the size and frequency of avalanches depend on an increase in precipitation. The expected rapid temperature changes and strong winds associated with extreme events also play an important role (Eckert et al., 2010b; Laute & Beylich, 2014, 2018; Dreier et al., 2016; Gądek et al., 2017; Ballesteros-Cánovas et al., 2018; Strapazzoni et al., 2021).

Snow occurs at altitudes around the zero-degree isotherm, so avalanches respond rapidly to climate change (Min et al., 2011), which has generally increased the frequency and intensity of gravitational flows (Stoffel & Huggel, 2012). They occur on average about 300 m lower from the altitude of 0-degree Celsius isoline.

Changes in the "snow sphere" result from climate change impacts on snowmelt, glacier and permafrost retreat, runoff regimes, and tree line changes (Keiler et al., 2010; Gądek et al., 2017). This is associated with more frequent thick snowpack and the formation of glide avalanches (Ancey & Bain, 2015; Peitzsch et al., 2015; Reiweger & Gobiet, 2019). However, future large and infrequent avalanche events are hard to predict, for example, the return period of the critical new snow depth in the case of Switzerland was about 2-5 times smaller than the return period of the avalanche (Schweizer et al., 2014).

In particular, extreme avalanches are excellent indicators of the new reality in which extremes are increasing and previously unknown relationships are being established (Berg et al., 2013; Hao et al., 2013; Ancey & Bain, 2015; AghaKouchak et al., 2018). Climate change is already having unexpected effects (Malamud, 2004) and causing a cascade of connections between previously unrelated processes (Carter et al., 2014; Kadri et al., 2014; Turner II et al., 2016) (Fig. 1), so called tsunami hazards (Suppasri et al., 2021).

This article discusses avalanches as convergent phenomena related to climate change (Adger et al., 2009; Eakin et al., 2009) and thus discusses the effects of climate factors on avalanches. It provides insights into climatic changes related to snowpack by analysing the relationship between the North Atlantic Oscillation and maximum snow depth in Slovenia over the past two centuries, the relationships between maximum snow depth and avalanches over the past three decades, and a case study of extreme snow avalanches in January 2021.

Avalanches in Slovenia

In the past, people searched for ores, grazed livestock, hunted game, and cut trees (Mikša & Zorn, 2016; Andrič et al., 2020) in avalanche-prone areas in the Slovenian mountains, whereas today human activities are expanding into hazardous areas mainly due to increased mobility and people's recreational activities (Rudolf-Miklau & Sauermoser, 2011). Although avalanches are common in Slovenian mountains, they are not comparable in magnitude to other natural disasters (Mikoš, 2014). However, in recent decades they have been in the first place when it comes to the number of fatalities caused

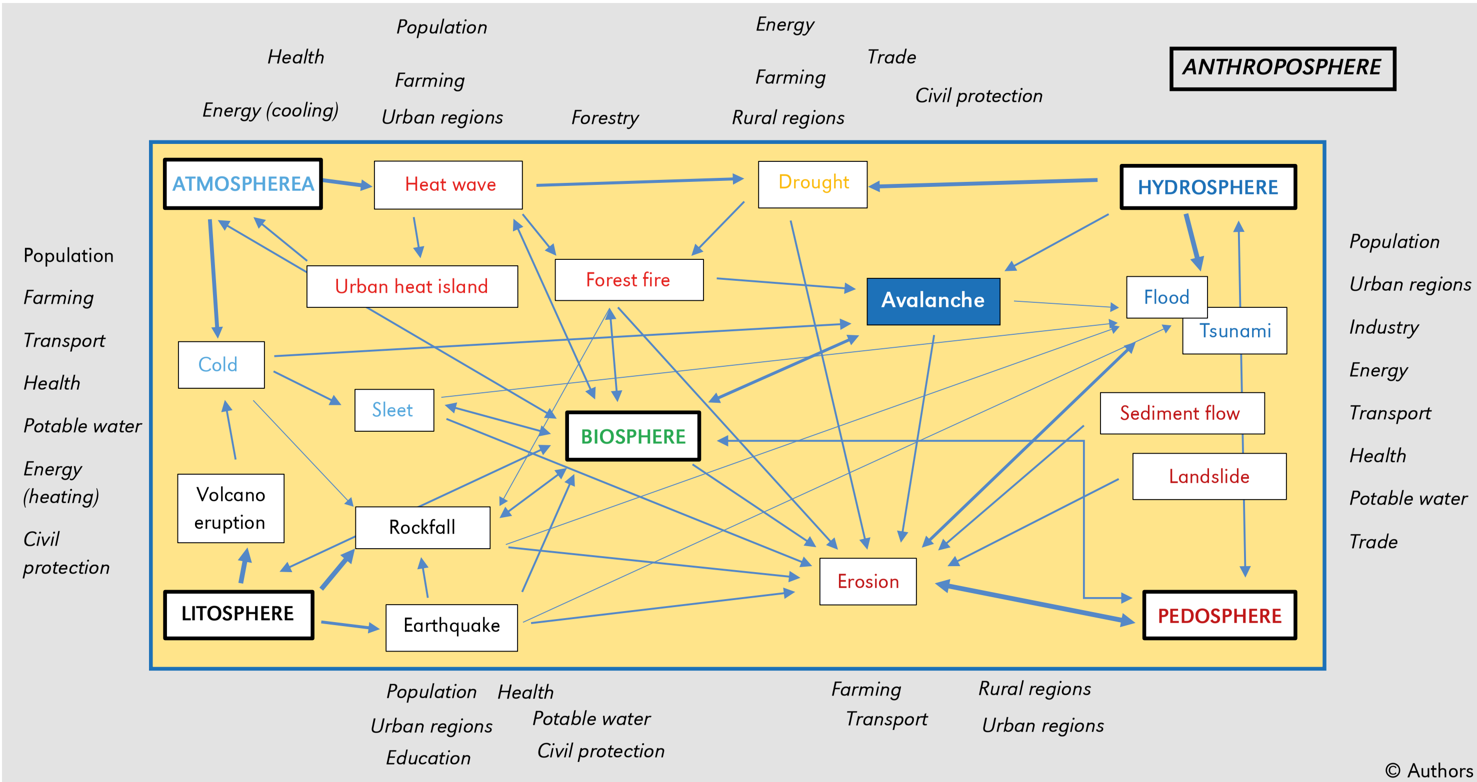

Figure 1. A diagram of the primary links between some natural phenomena shows their direct and indirect connections of avalanches with a number of factors. Erosion, floods, rockfalls, and avalanches influence the most factors

by natural disasters. They also affect tourism and transport infrastructure and cause significant damage (WSL, 2000; McClung & Schaerer, 2006; Eckert et al., 2010a; Zorn & Komac, 2011; Volk Bahun, 2020).

In Slovenia, avalanche tracks cross railroad lines at thirty-three locations, roads (of all categories) at 1,956 locations, hiking trails at 787 locations, and they pose a direct threat to 383 buildings (Volk Bahun, 2020). Infrastructure in mountainous regions was built decades ago with the expectation of a stable and predictable environment (European Commission, 2005; Cabinet Office, 2011). This prediction relied on "data" from the past and ignored possible present and future extremes that affect the cumulative risk from less frequent but more intense events (Tubaldi et al., 2017). Future planning must therefore account for higher probabilities of extreme events (Huggel et al., 2008; Ahrens & Sampson, 2011), which are complex and not well understood (Helbing, 2013). This is especially the case for low-probability events, as they are perceived as "non-events" (Kahneman, 2016). Extreme avalanches in the southeastern Alps are one such case.

Few comprehensive studies on avalanches have been published in Slovenia (Pavšek, 2002). A general-interest work on avalanches was written a century ago (Kunaver, 1921), and the first scientific study was conducted in the mid-20th century after the winter of 1951/52 (Badjura, 1953; Gams, 1955). Several studies followed (e.g., Pintar, 1968; Šegula, 1978, 1986; Bernot, 1980; Bernot & Šegula, 1983; Pintar & Mikoš, 1984; Bernot et al., 1994; Horvat & Bernot, 1994; Horvat, 1999; Vrhovec, 2002; Vrhovec et al., 2006; Pavšek, 2002; Pavšek et al., 2010, 2013; Volk Bahun 2010, 2020), of which those by Pavšek (2002) and Volk Bahun (2020) were the most thorough. This topic has been studied in several analyses and technical reports (e.g., Pintar, 1968; Bernot, 1980; Bernot & Šegula, 1983; Pintar & Mikoš, 1984; Bernot et al., 1994; Horvat, 1999), as well as in terminological studies (Badjura, 1953; Šegula, 1995). In addition, historical data on avalanches have been collected (Malešič, 2005), and some other aspects have been described (e.g., Pavšek & Velkavrh, 2005; Pavšek, 2010; Volk, 2010; Volk Bahun, 2014, 2016, 2017; Sirk, 2011; Volk Bahun et al., 2018; Oven et al., 2020; Volk Bahun & Zorn, 2020; Kobal et al., 2021; Volk Bahun et al., 2022).

An important step in the study of avalanche hazard was taken in Slovenia in 1994, when the avalanche cadastre was established (Bernot & Šegula, 1983; Bernot et al., 1994). At that time, it was found that the avalanche hazard in Slovenia was much higher than expected. The avalanche cadastre (Fig. 2) contains data on the location and extent of 1966 avalanches in Slovenia. The database consists of 45 data fields on avalanche hazard and risk. According to the cadastre, there are 845 avalanches in the Julian Alps, 370 in the Karawanks and 104 in the Kamnik-Savinja Alps. 246 of them are in the Dinaric Mountains and 5 in the Pannonian Basin (Pavšek, 2002). It should be noted that many parts of the Slovenian mountains were not included in the cadastre, so the data presented can be considered as a lower limit. Today the cadastre is also outdated, but as a spatial planning tool it is still important (Volk, 2011).

Although avalanches in Slovenia have been studied for several decades, few studies have addressed the various geographic variables that influence them (Vrhovec & Mihelič, 1992; Vrhovec & Velkavrh, 1996, 1997; Pavšek, 2002), but the effects of changing climate were not among them. Previous work has primarily examined the effects of selected geographic constants (e.g. slope, aspect, vegetation, maximum snow depth, duration of snow cover, altitude) (Pavšek, 2002) and subjective factors (Volk Bahun 2010, 2016, 2017) on avalanches.

Methodology

Methods

In this article, avalanche occurrence was related to maximum snow depth and climate. Climate-related events are represented by the North Atlantic Oscillation Index (NAO, 2019).

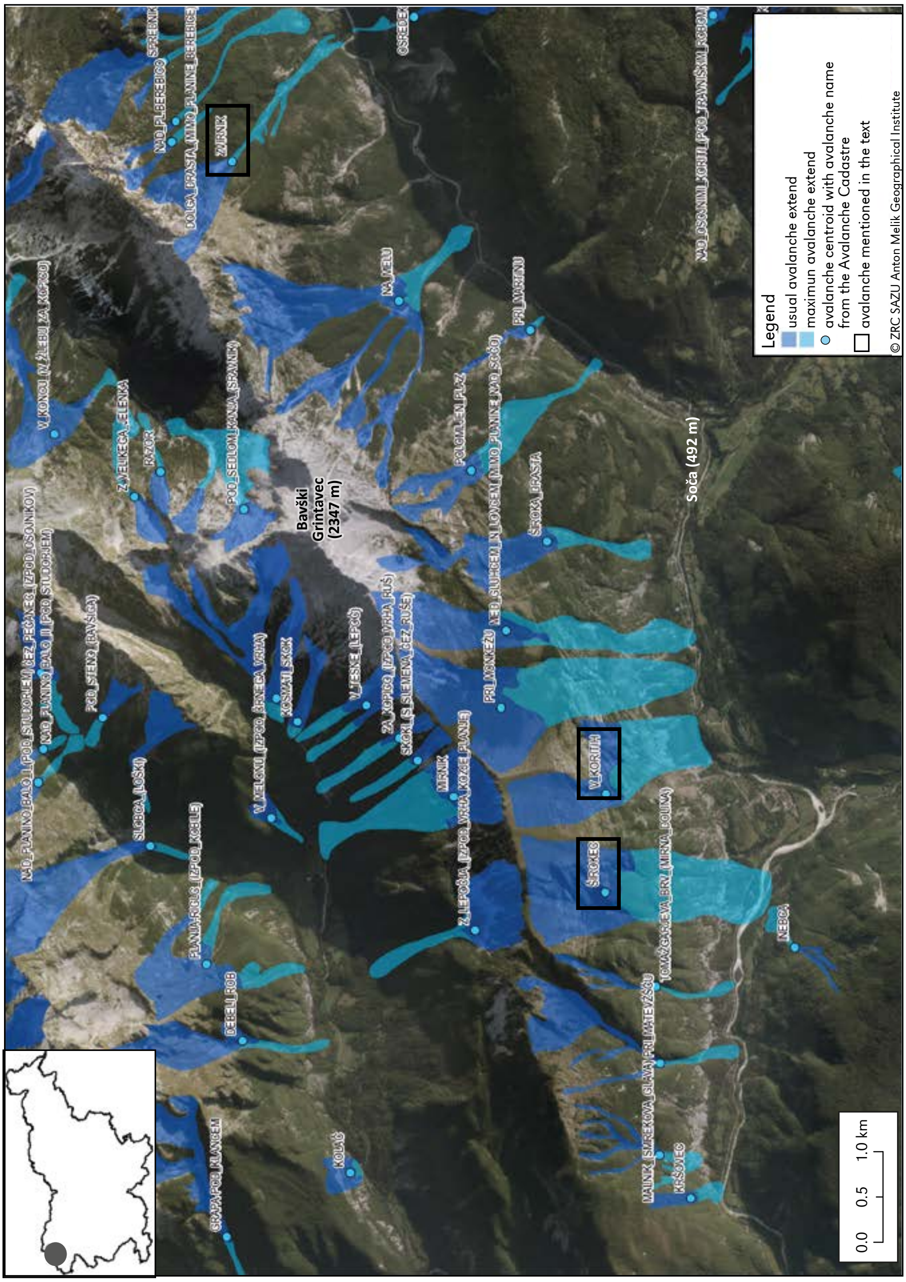

Figure 2. Part of the avalanche cadastre from the Upper Soča Valley

Source: GIAM ZRC SAZU Avalanche Archive

The North Atlantic Oscillation (NAO) is an irregular variation in atmospheric pressure over the North Atlantic that strongly affects winter weather in Europe. The changes in atmospheric pressure are an alternation between a "positive mode," where a strong subtropical high is located over the Azores, and a "negative mode," where weaker high and low pressure systems are found over the same locations (Rafferty, 2019). The influence of the NAO on avalanche activity has already been demonstrated (García-Sellés et al., 2010).

Positive values of the NAO index indicate prevailing southerly (southwesterly) winds in Slovenia, which usually bring more precipitation. In winter a strong positive phase is associated with mild but occasionally stormy conditions that bring high snow cover. Negative values of the index represent prevailing northerly winds associated with bitterly cold polar continental air flow and rare instances of maximum snow depth.

We used data on the NAO for the period 1821-2021 and compared them with data on maximum snow depth at the meteorological station on Mt. Kredarica (2,513 m) in the Julian Alps (SE Alps). The station is part of the public meteorological network of the Slovenian Environment Agency (ARSO). It has been measuring temperature, precipitation, wind, solar radiation, and snow cover depth since August 1954, with year-round data starting in 1955 (Cegnar, 2015). We used the data to reconstruct the maximum seasonal snow depth for the period 1813/1814-2020 (Fig. 3A). Values older than 1954 were calculated by regression analyses of Mt. Kredarica meteorological station (Gabrovec et al., 2014) and HISTALP data (Auer et al., 2007) (r^2 0.87 and 0.83). Values of the NAO Index were compared with the Z-score of Maximum Snow Cover Depth (MSCD) for the period 1852-2020. Data were also collected on known large avalanche events over the last 33 years (1988-2020) (Volk Bahun, 2020) and their Z-scores were compared with the MSCD data (Fig. 3B).

Study area

The Alps in Slovenia are located in the northwest and north of the country and are part of the SE Alps, which consist mainly of calcareous rocks (limestones and dolomites) of Mesozoic age. The highest are the Julian Alps, located in northwestern Slovenia, with the highest peak, Triglav (2,864 m). They are characterized by valleys up to 2,000 m deep and are snow-covered in winter, so avalanches are frequent. On Mt. Kredarica in the Julian Alps (2,513 m; just below Mt. Triglav), where the country's highest meteorological station is located, the average annual temperature increased by more than 2°C between 1961 and 2018, from −2.22°C (1961 trend value) to −0.19°C (2018 trend value). During the same period, precipitation (> 2100 mm) increased by almost 10%, while the number of days with snow cover remained more or less the same (> 260 days year^{-1}), but with a decreasing trend (Hrvatin & Zorn, 2020). The record amount of snow on Mt. Kredarica was measured in the winter of 2000/2001, with a maximum snow depth of 700 cm (Vrhovec & Velkavrh, 2001).

This article describes avalanches that occurred in January 2021 in the Upper Soča Valley (Fig. 2) in the western Julian Alps. The precipitation station in this area (Soča village, 487 m) also shows that precipitation (> 2,500 mm) increased by almost 10% during 1961-2018, but with about 46 fewer days with snow cover, i.e., about 50% less (from > 90 to < 46 days (trend values)) (Hrvatin & Zorn, 2020).

Results

On Mt. Kredarica, low NAO values were associated with high values of maximum snow depth. The variability of the data is high ($y = -0.5223x + 0.0438$; $r^2 = 0.08$; Fig. 4). However, in the last two decades (2000-2021), low NAO values correspond to high values of maximum snow depth (Fig. 5).

The data show that in the case of positive NAO(+) annual values with predominant southern circulation (Quadrelli et al., 2001),

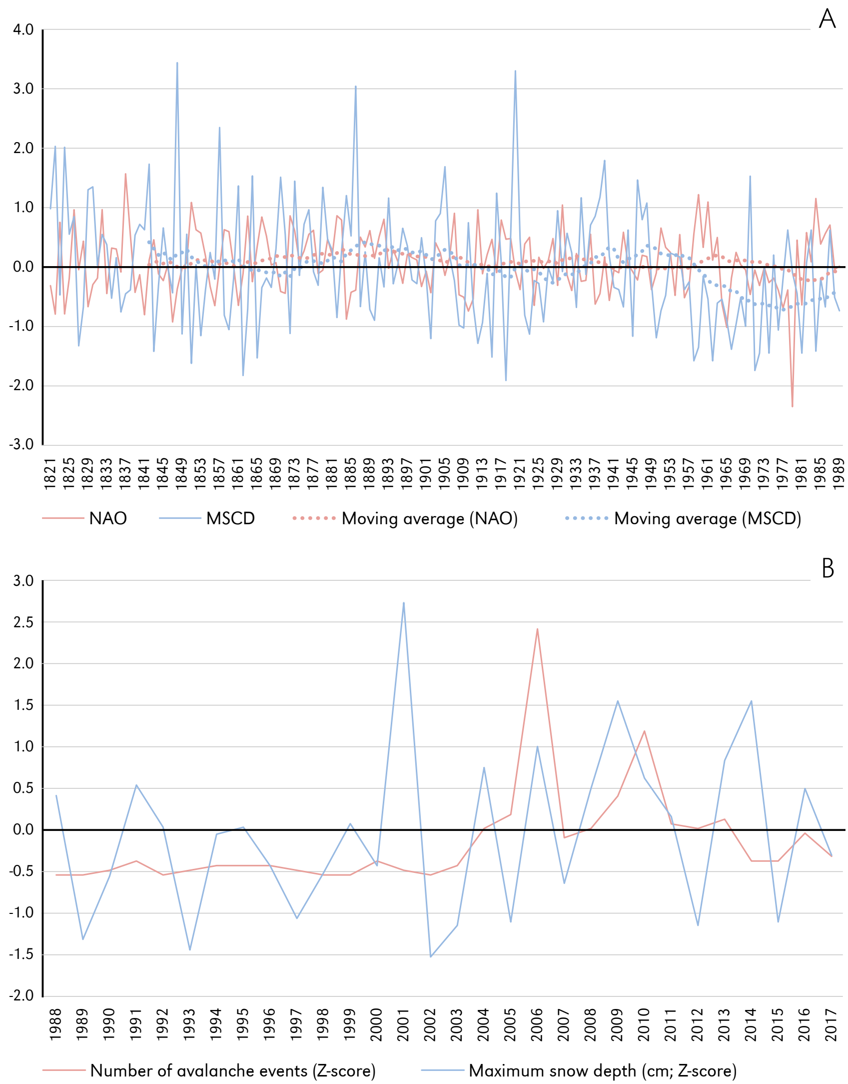

Figure 3. (A) Comparison of data on NAO and MSCD using the reconstruction of seasonal maximum snow height (cm) on Mt. Kredarica, 1852-2020 (Data sources: ARSO; Gabrovec et al., 2014). (B) Comparison of MSCD (1988-2017) and avalanche events data in Slovenia (Data sources: ARSO; Volk Bahun, 2020)

there were 34 positive (about one-fifth) and 57 (about one-third) negative values of MSCD. In the case of negative NAO(–) annual values with northerly circulation, there were 42 (about one-fourth) positive and 36 (about one-fifth) negative values of MSCD (Fig. 6A).

Cumulative values of maximum snow depth were highest (26,402 m) for negative NAO and positive MSCD and lowest (12,331 m) for negative NAO and negative MSCD, while they were about 20,000 m for positive NAO values (Fig. 6B).

The correlation between average annual data is highest for negative NAO and negative MSCD values ($N = 36$; $r = -0.32$; $r^2 = 0.10$), followed by positive (+) NAO and negative (–)

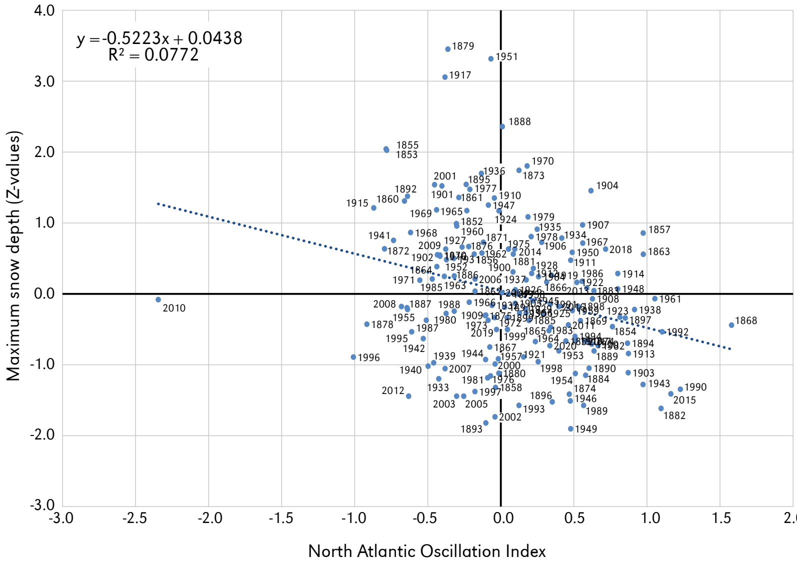

Figure 4. The relationship between NAO and MSCD (Z-score) for Mt. Kredarica for the period 1852-2020

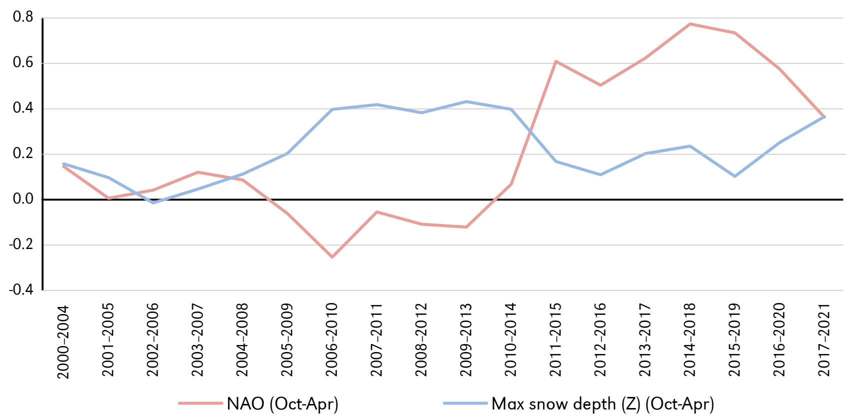

Figure 5. Z-score of maximum monthly snow depth on Mt. Kredarica from October to April, 2020-2021 (five-year moving average), show a negative correlation with NAO (Data sources: ARSO; National Oceanic and Atmospheric Administration)

MSCD ($N = 57$; $r = -0.27$; $r^2 = 0.07$), and both negative values ($N = 34$; $r = -0.19$; $r^2 = 0.04$). There is no correlation between negative NAO and positive MSCD, and in other cases NAO explains only a few percent of the variability.

Over the past 150 years (Tab. 1), we find that NAO(−)/MSCD(−) situations have more than doubled, while other combinations have remained relatively stable. For NAO(+)/MSCD(−) and NAO(−)/MSCD(+) we have observed lower values in recent decades, while NAO(+)/MSCD(+) has the highest historical variability but has remained stable over the last five decades. This means that we observed more years with northern circulation and low MSCD and fewer years with both northern circulation and high MSCD and southern circulation and low MSCD.

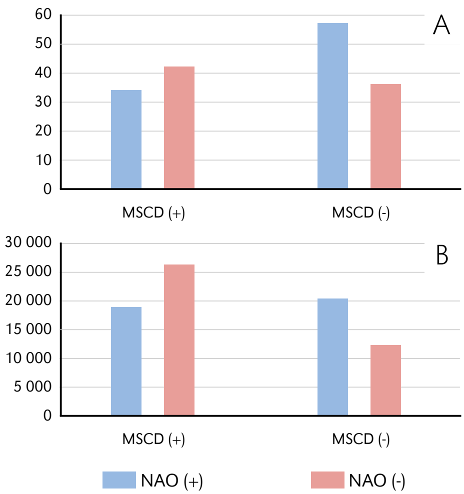

Figure 6. (A) Number of years with positive or negative MSCD with respect to average annual NAO values. (B) Cumulative values of maximum snow depth in relation to NAO over the last two centuries

Table 1. Number of years with various combinations of positive (+) and negative (–) NAO and MSCD values over the past 150 years, broken down by 50-year periods (note that the 2000-2020 category indicates a shorter time period)

	NAO(–)/ MSCD(–)	NAO(–)/ MSCD(+)	NAO(+)/ MSCD(–)	NAO(+)/ MSCD(+)	SUM
1850-1900	4	12	14	4	34
1900-1950	6	12	16	14	48
1950-2000	14	11	18	8	51
2000-2020	8	3	5	4	20
SUM	40	41	58	34	173

The changes are also reflected in the frequency of NAO/MSCD combinations. NAO(–)/MSCD(–) situations occurred on average every 4.8 years in recent decades, while they occurred less frequently in the past (every 5.8 years in the period 1850-1900 and every 7.3 years in the period 1900-1950). All other combinations show a lower frequency in the last two decades. This is true for both NAO(+) and NAO(–)/MSCD(+) combinations.

Discussion

NAO and avalanches in Slovenia

Relationships between the NAO and winter precipitation have already been studied, e.g., for the Pyrenees (Quadrelli et al., 2001; Laute & Beylich, 2018), Iceland (Keylock, 2003) and the French Alps (Jomelli et al., 2007).

Laute and Beylich (2018) have found a positive relationship between the NAO and higher winter precipitation totals. They also argue that an increase in monthly precipitation totals in winter may lead to a generally higher avalanche frequency, in part because periods with air temperatures near or above freezing are becoming more common in winter, increasing the likelihood of wet snow avalanches. In Iceland (Keylock, 2003), recent avalanches have been linked to an increase in NAO.

In Slovenia, we have recently observed fewer cases of maximum snow depth related to the southern circulation, but also cases of MSCD related to positive NAO values, manifested in a higher frequency of maximum snow depth and large avalanches. This is probably due to the higher variability of the data in recent years (cf. Šraj et al., 2016). One such case was a situation in 2021, when avalanches reached the bottom of the Upper Soča Valley. The phase diagram of the relationship between the NAO and the MSCD on Mt. Kredarica for January (for the period 2000-2021) shows that the variability of the data in 2021 was much higher than the average for the years 2000-2021. In 2021, the period January-March remained stable with positive values of NAO and positive values of MSCD. The changes occurred in April and June which approached May (with NAO(-) and MSCD(+)), while September and November approached October with NAO(-) and MSCD(-) (Fig. 7).

We have observed avalanches reaching valley floors in Slovenia in the early 1950s (Gams, 1995), 1979 (Šegula, 1980), and in 2006 (Pavšek, 2006), 2014 (Pavšek, 2014), and 2021 (Kobal et al., 2021; Komac

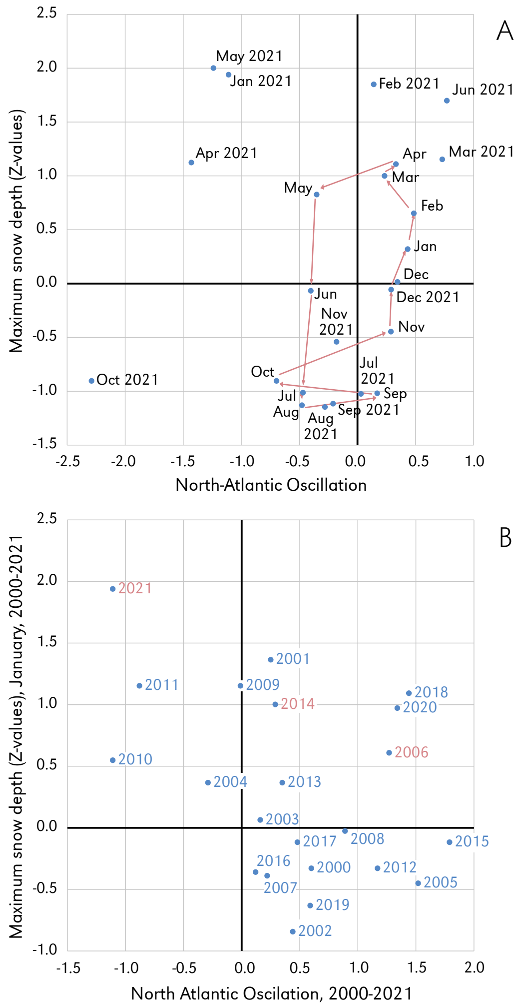

Figure 7. (A) Phase diagram showing the relationship between the NAO and the maximum snow depth (Z-values) on Mt. Kredarica (2,514 m) in January, 2000-2021. (B) A dispersion is shown for 2006, 2014, and 2021, when avalanches reached the valley floors (Data sources: ARSO; National Oceanic and Atmospheric Administration)

et al., 2021). In the last decade we observe a trend towards negative NAO values. This means that avalanches associated with high MSCD values were more strongly associated with the northern circulation in 2021 than in 2006, when the southern circulation was dominant. In 2021, we observed larger avalanches in winter (January, February) than in early spring (March), which was more common in the past (Volk Bahun, 2020). This was related to high air temperatures, which caused rainfall to overtake snowfall at higher elevations. The rain made the snowpack wetter and heavier (cf. Ogrin & Ortar, 2007) and triggered avalanches.

We argue that these more frequent extreme precipitation events are related to climate change. The trends are clear: on Mt. Kredarica, more than 100 cm of new snow has been measured within twenty-four hours three times since 1952, all in the last decade. In the last twenty years, there have been 17 days with over 70 cm of new snow – three between 2000 and 2010 and eight in the past decade alone.

When associating large avalanches with a large-scale circulation pattern such as the NAO, we should consider meteorological conditions and snowpack evolution in addition to precipitation (García-Sellés et al., 2010). The available data give us an orientation about the winters in which avalanches could reach the valley floor under the new conditions. Extremely high snow depths (over 600 cm) were recorded on Mt. Kredarica in the following years: 2013, 2009, 2006, 2001, 1985, 1977, 1978, 1979, 1975, 1970-1972, 1965, 1961-1963, 1952, 1951, 1950, 1948, 1946 in 1945-1946, 1934, 1927-1930, 1919-1920, 1917, and 1909-1911 (Gabrovec et al., 2014; Volk Bahun et al., 2018). The distribution is not linear as such events occur in cycles (Birkeland & Mock, 2001; Höller, 2009; Valt & Cianffarra, 2013) that depend on meteorological factors. As the climate warms (Hrvatin & Zorn, 2020), winter rain tends to occur more frequently in the high mountains.

We also linked data on snowpack height and avalanche events (N = 299) over the period 1988-2020. Of course, the correlation is not direct, as avalanches depend not only on maximum snow depth but also on its stability not to mention other factors such as relief, vegetation, weather, and human factors (Techel et al., 2020). Nevertheless, the correlation coefficient 0.32 (N = 33) between MSCD and annual avalanche data (Z-scores) shows some dependence in Slovenia. The correlation is more evident in recent years, but this could also be due to a more comprehensive database of avalanche events. A higher MSCD value often indicates a higher number of avalanche events, but the relationship is not clear-cut.

The 2021 avalanches in the Upper Soča Valley

In late January 2021, seven avalanches with heavy wet snow reached valley floors in the Upper Soča Valley, blocking regional and local roads. Two were triggered in the Koritnica Valley (Bovec–Predel Pass road), four in the Soča Valley (Bovec–Vršič Pass road), and one blocked the local Soča–Vas na Skali road (Tab. 2).

In the Koritnica Valley (the Koritnica River is a right tributary of the Soča River), two avalanches occurred on January 22. The *Velika Kanja* avalanche (Fig. 8) below Mt. Rombon (2,208 m) also reached the valley floor in the winters of 2005/2006 and 2008/2009. The second from Mt. Vrh Krnice (2,234 m) blocked the Bovec–Predel Pass road over a length of about 50 m to a height of about 6 m (Fig. 8A).

In the Soča Valley, the about 30 m long and up to 5 m high *V Koritih* avalanche (Fig. 9A) was triggered the same day. It crossed and buried the nearby Great Soča Troughs. The *Širokec* avalanche (Fig. 9B), which blocked the road over a length of more than 100 m and a height of about 5-6 m, is one of the largest avalanches in the avalanche cadastre: area 1.5 km^2, length 2.5 km (Fig. 2). Another avalanche was triggered while road workers were still clearing the road, and more avalanches blocked the road during the night.

The 150 m long and 7-8 m high *Zvirnik* avalanche reached the road three times, while the *Pod plazom* avalanche blocked 50 m of the road with 5 m height. The Soča–Vas na Skali road was also blocked by the 50 m long and 5 m high *Pod Rušo* avalanche.

The avalanche material was extremely saturated with water. From 21 January 2021, 7:00 p.m. to 24 January 2021, 7:00 a.m. almost 110 mm of precipitation fell on Mt. Kredarica (2,514 m), and the snow cover increased by 140 cm (Tab. 3), reaching 510 cm. It exceeded the highest January snowpack record from 1977 by 76 cm.

Avalanches were triggered on bare steep slopes above the tree line up to the level of zero isotherm at about 1700-1800 m. The snow was very wet and the load increased sharply in a very short time. In one day, the density of the snow doubled from about 200-300 $kg{\cdot}m^{-3}$ to about 500 $kg{\cdot}m^{-3}$ (cf. Wever et al., 2016.).

Table 2. Key data on avalanches blocking roads in the Upper Soča Valley at the end of January 2021 (Data sources: GIAM ZRC SAZU Avalanche Archive; Podjetje za urejanje hudournikov)

Avalanche name	Velika Kanja	Grapa – Pod klancem	Širokec	V koritih	Zvirnik	Pod plazom	Pod rušo
Road Section	Bovec–Predel Pass	Bovec–Predel Pass	Bovec–Trenta	Bovec–Trenta	Bovec–Trenta	Trenta–Vršič Pass	Soča–Vas na Skali
Avalanche area (ha)	38.1	62.5	149.4	104.5	48.0	6.9	30.8
Upper triggering altitude (m)	1,900	2,150	1,890	1,930	2,100	1,350	1,700
Lower triggering altitude (m)	850	1,300	1,350	1,400	1,550	1,100	1,300
Common deposition altitude (m)	700	850	1,100	1,100	1,300	780	920
Common avalanche altitude difference (m)	1,200	1,300	790	830	800	570	780
Common avalanche track length (m)	1,921	2,344	1,274	1,262	1,242	792	1,559
Common avalanche path inclination (degrees)	39	34	38	41	40	46	30
Maximum avalanche altitude difference (m)	1,400	1,650	1,460	1,455	1,550	600	960
Maximum avalanche track length (m)	2,401	3,337	2,558	2,238	2,732	849	2,040
Maximum deposition altitude (m)	500	500	430	475	550	750	740
Maximum avalanche track inclination (degrees)	36	30	35	41	35	45	28

Table 3. Data on precipitation, snow cover depth and new snow depth in 12/24-hour intervals from the automatic weather stations Bovec, Predel Pass and Vršič Pass and the main meteorological stations Mt. Kredarica from 21 to 24 January 2021 (Data source: ARSO)

	Precipitation (mm)					Snow depth (cm)			New snow depth (cm)
Measurement time\ Station (altitude)	Bovec (438 m)	Predel Pass (1,156 m)	Vršič Pass (1,611 m)	Mt. Kr-edarica (2,514 m)		Predel Pass (1,156 m)	Vršič Pass (1,611 m)	Mt. Kr-edarica (2,514 m)	Mt. Kr-edarica (2,514 m)
21 January / 7:00	-	-	-	1.5		-	-	371	1
21 January / 19:00	0	0	0	-		116	178	-	-
22 January / 07:00	84	34	39	33.7		118	207	425	40
22 January /19:00	73	42	42	-		119	235	-	-
23 January / 07:00	83	43	21	55.5		118	239	505	85
23 January / 19:00	35	27	12	-		141	257	-	-
24 January / 7:00	4	5	4	17.9		141	252	510	29
Total	277	151	117	109	Increase in total snow depth	25	74	139	155

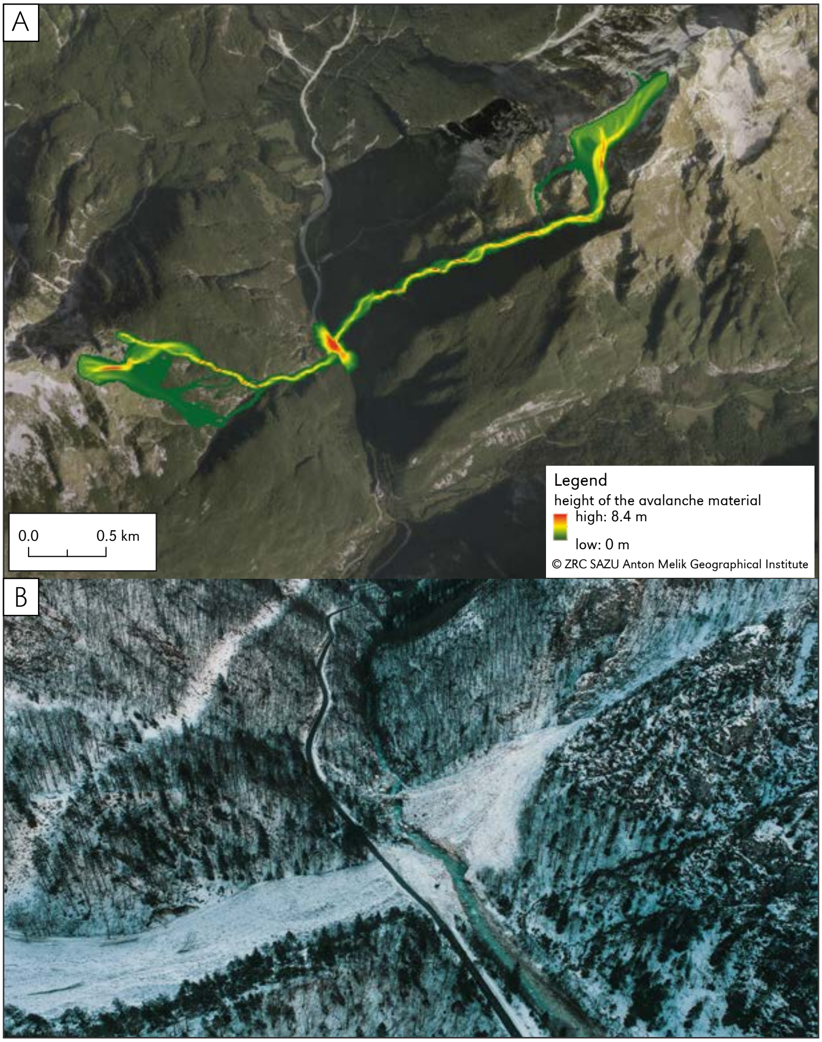

Figure 8. (A) Height of the avalanche material in the *Velika Kanja and Grapa – pod Klancem avalanches*. This (B) Twin avalanches in the Koritnica Valley near the Kluže Fortress occurred on January 22, 2021, looking northwest (Photo by Jure Tičar; GIAM ZRC SAZU Archives, 2021)

Sediments

Avalanches in steep alpine valleys are important in terms of connectivity of geomorphic systems (cf. Bollati & Cavalli, 2020). Avalanches erode and displace sediments, plant material, and contribute 0.04-131 t C km^{-2} annually to the carbon cycle (Korup & Rixen, 2014). Erosion is most severe when an avalanche moves over a frozen base with a thawed upper sediment layer.

In the case of the *Zvirnik* avalanche, sediment volume on the surface of the avalanche was measured on June 3, 2021. We made 42 measurements of sediment thickness in two random vertical and quasi-parallel profile lines. The measurements were made with a gage that allowed an accuracy of ± 0.25 mm. More sediment was measured in the lower parts of the avalanche accumulation, but, the amount of sediment was also

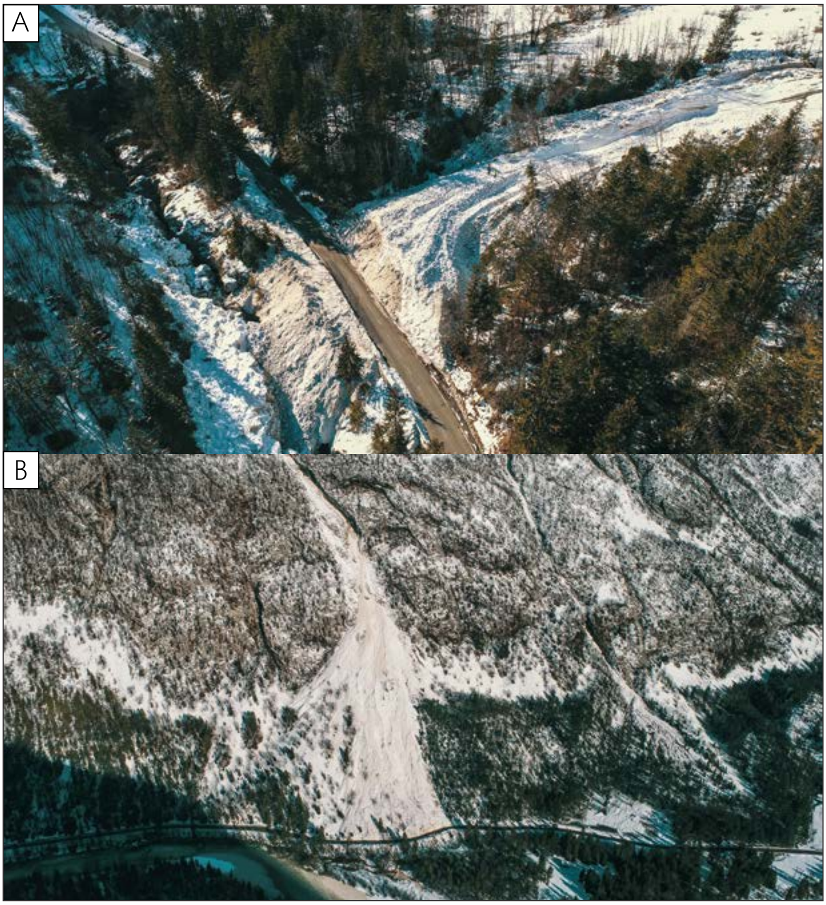

Figure 9. (A) The *V Koritih* avalanche reached the valley floor and partially buried Great Soča Troughs, left of the road (Photo by Jure Tičar; GIAM ZRC SAZU Archives, 2021). (B) The *Širokec* avalanche moved to the less vegetated, eastern part of the scree (Photo by Jure Tičar; GIAM ZRC SAZU Archives, 2021)

influenced by the slope of the micro location. The average result was 0.92 cm of sediment, with a range of 0.0 to 2.9 cm (Fig. 10). Similar accumulation rates (average 1.1 cm/year) were also reported from the Tatra Mountains in Poland (Rączkowska et al., 2016a).

According to our measurements, the app. 6000 m^2 surface of the *Zvirnik* avalanche accumulation contained 55 m^3 of sediment, which, depending on the size of the contributed hinterland, means a sediment production of app. 184 t km^{-2}. We estimate that all the January 2021 avalanches in the Upper Soča Valley displaced a total of up to 250 m^3 of sediment.

If we consider that such an event occurs in the region every 8.3 years (calculation based on MSCD), the average erosion is 22.19 t $km^{-2}a^{-1}$ and about twice as much for large events. Generally, avalanches contain between 0.01 and 1% of sediments, but they often contain also larger boulders. In Switzerland, their contribution to fine sediments ranges from 1.8 to 830 t $km^{-2}a^{-1}$. For avalanches in Erdalen (Norway), a total annual sediment/debris mass of 83 t $km^{-2}a^{-1}$ was determined in relation to the entire catchment and 196 t $km^{-2}a^{-1}$ in relation to the catchment consisting of rock walls. In Bødalen (Norway), the values 68 t $km^{-2}a^{-1}$

and 159 t $km^{-2}a^{-1}$ were determined, respectively (Laute & Beylich, 2014).

In the Upper Soča Valley, avalanches are estimated to contribute an average of 1% to annual sediment transport, and up to several percent in larger events. The ratio may be underestimated because the estimated average sediment production in the Upper Soča River basin is 2,234 t $km^{-2}a^{-1}$, while local erosion events triggered by earthquakes or rainfall can release more than 200,000 t $km^{-2}a^{-1}$ of sediment, giving a ratio of 1:89 (Mikoš et al., 2006).

Avalanches in this region are characterized by high connectivity. Sediment transport to streams is rapid, because most avalanches follow the slope ravines (Fig. 2) towards the valley floor, and about one-third of the water runs off as meltwater.

Avalanche debris as a river dam

The *Velika Kanja* avalanche (Fig. 8) buried the Koritnica riverbed over a length of more than 150 m and a height of more than 10 m on January 22, 4:30 p.m. The water level of the river dropped suddenly at first, but a few dozen minutes later, when the avalanche dam was breached, the water level rose sharply and formed a snow bridge. A similar reported phenomenon, albeit on a smaller scale, occurred in 2006, as well as in early May 1979 and in February 1952 (Gams, 1955).

A temporary avalanche lake formed behind the avalanche dam in the Koritnica riverbed. Data from the gauging station 3 km downstream near the village of Kal – Koritnica show that an avalanche dan formed at 5:10 p.m. on Friday, January 22. It lasted until 5:45, and was followed by a 40-minute flood wave with a peak discharge at 6:00. Discharge data for this period are not known due to problems with the discharge curve, but we estimate that the lake contained over 30,000 m^3 and the discharge reached about 12 $m^3{\cdot}s^{-1}$. Overall, the length of the reservoir was over 100 m during the damming event. After the river broke through the dam, there was still a snow bridge on January 25.

A similar phenomenon occurred on March 5, 2006, when an avalanche dammed the river at 3 p.m. and a breakthrough occurred at 3:40 p.m. It is estimated that by 4:30 p.m., about 30,000 m^3 of water had accumulated behind the dam and drained in 50 minutes. The flood wave spread at a speed of 7.4 $km{\cdot}h^{-1}$ to the nearby gauging station (Log Čezsoški). The ratio between filling and emptying was 1:1.8, which means that the lake was emptied about 2 times slower than filled.

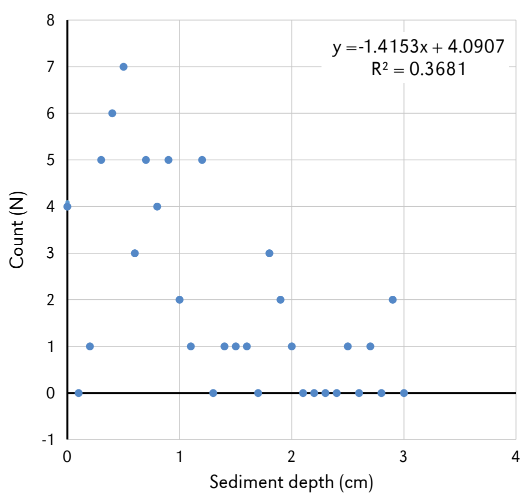

Figure 10. Sediment depth measured at the surface of the *Zvirnik* avalanche

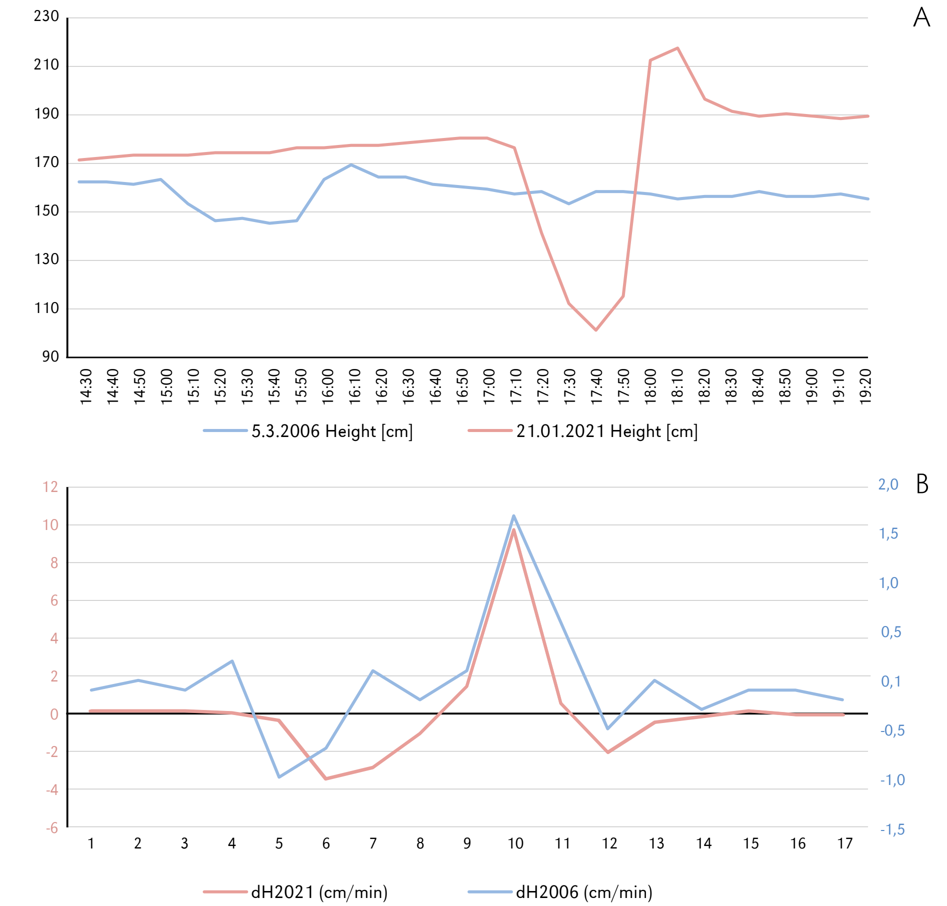

Figure 11. Water level height (A; in cm) during two avalanche river dam events in 2006 and 2021. Figure 11B shows water level height changes (in cm/min) in 10-minute intervals (for 2006, number one in the graph indicates time is 14:30, and for 2021 the starting time is 16:30)

In 2021, the ratio was 1:3. As regards the outflow discharge dynamics the 2006 and 2021 events were similar (Fig. 11).

Also in 1952, avalanches dammed the Koritnica River. At that time, the avalanche also covered the Soča riverbed (Gams, 1955), as well as in 2014 and 2021.

Conclusions

In the article, we pointed out the reasons why avalanches of heavy, wet snow, which normally tend to occur in the spring, are now also characteristic of the winter season. We note that this is one of the direct consequences of climate changes. Because of their extraordinary mass and liquidity, such avalanches can easily reach their maximum known extents. In recent years, they have occurred more frequently than usual, often reaching the valley floor and even damming watercourses.

The analysis presented was indirect because only data on maximum snow depth for a longer period are available in Slovenia (and not for avalanches). Despite declining trend in maximum snow depth, the concurrent warming of the climate and more frequent extreme weather and hydrological phenomena are causing wet snow avalanches to reach the valley floor more frequently than in the past and within the coldest winter period. Using field measurements, we also analysed the contribution of avalanches to sediment transport, which we estimate > 20 t $km^{-2}a^{-1}$ for the study area.

The results of this study indicate that avalanche prevention management must take into account the changing nature of avalanche risk in the SE Alps and incorporate the higher probability of rare extreme events. Therefore, prevention needs to focus more on low-frequency high-intensity events, while response measures need to be adapted to the temporal shift from early spring to mid- winter.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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