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Climate parameters relevant for avalanche triggering in the Făgăraş Mountains (Southern Carpathians)

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Abstract

The climate conditions may contribute significantly to the generation of several hazards in mountain areas, such landslides, wildfires, flash floods and avalanches. This study examines the variation of the main meteorological parameters with impact on avalanche triggering conditions at Bâlea-Lac Meteorological Station. At the best of our knowledge, this is the first overview of the basic climate parameters which are potentially avalanche triggers in the Făgăraș Mountains (Southern Carpathians). The study is based on data from only one weather station (Bâlea-Lac) from the period 1979-2017, assuming it is consistently relevant from climatic point of view for avalanche occurrence in the area. The results demonstrate that the theoretical circumstances for avalanche triggering (e.g. snow pack, fresh snow or wind) can be captured. This paper briefly describes the nivologic monitoring system run by the National Meteorological Administration and emphasises its utility for avalanche forecasting and alerts.

Keywords: *avalanche hazards, avalanche triggering factors, mountain climate, Făgăraș Mountains*

Rezumat. Parametrii climatici relevanți pentru declanșarea avalanșelor în Munții Făgăraș (Carpații Meridionali)

Condițiile climatice pot contribui semnificativ la apariția mai multor hazarde naturale în zonele montane, precum aluncări de teren, incendii de vegetație, inundații și avalanșe. Acest studio analizează variațiile principalilor parametrii meteorologici care favorizează declanșarea avalanșelor la stația meteorologică Bâlea-Lac. Din câte cunoaștem, acesta este primul studiu al prametrilor climatici de bază are pot constiti factori declansatori pentru avalanșe în Munții Făgăraș (Carpații Meridionali). Studiul utilizează datele de la o singură stație meteorologică (Bâlea Lac) în perioada 1979-2017, considerând că este relevant din punct de vedere climatic pentru producerea avalanșelor în zonă. Rezultatele demonstrează că circumstanțele teoretice pentru declanșarea avalanșelor (stratul de zăpadă, zăpada proaspăt cazătă sau vântul) pot fi surprinse. Lucrarea descrie succinct și sistemul de monitorizare nivală condus de către Administrația Meteorologică Națională, punând accent pe utilitatea acestuia pentru prevederea avalanșelor.

Cuvinte-cheie: *riscul de avalanșă, factori declanșatori de avalanșelor, climat montan, Munții Făgăraș*

Introduction

Snow avalanches represent a major natural hazard triggering significant damages and casualties in many mountain massifs, so that avalanche forecasting services function in many countries – France, Germany, Switzerland, Norway, Poland, Austria, Italy, Czech Republic, Scotland, Iceland, Sweden, United States of America, Canada - issuing avalanche warnings. Statham et al (2018) identify four avalanche characteristics that should be considered in the assessment of avalanche hazards, related to (1) problems derived, (2) location, (3) probability of occurrence, and (4) magnitude of the event, and one can associate equal weight to each of them. Such properties should be quantitatively assessed both for current conditions and upcoming weather, as basic information for avalanche bulletins at regional and local scales.

While snow avalanches are the result of the simultaneous occurrence of different conditions related mainly to topography, climate and human activity, the efficient monitoring and accurate forecasting should equally consider all the triggering factors. Complex approaches may always deliver complete results, but studies oriented to limited aspects are also valuable since they reveal one particular facet of the avalanche phenomenon. This study investigates the climatic factors which can lead to avalanche occurrence in the Făgăraș Mountains (Southern Carpathians).

The composition and stability of the snow layer and the derived avalanche risk are evaluated based on the European Avalanche Danger Scale, and the collected information consists of information about the place, time and probability of release for a specific type of avalanches (slab or sluff, large or small, wet or dry).

Within the Romanian Carpathians, avalanches occur each winter, with an increased frequency in areas above 2,000 m, covering about 4,000 km^2, with rough topography and not permanently inhabited. Skiing fields are usually not located in areas frequently affected by snow avalanches, but the increasing number of backcountry skiers brings up the necessity of a permanent service for monitoring snow parameters and avalanches in all the mountainous areas.

Snow avalanches have been registered since February 2004, when the Snow and avalanche monitoring network began the activity at four meteorological stations: Vârful Omu, Sinaia, Predeal and Bâlea-Lac, covering the Bucegi and Făgăraş

Mountains. Since 2018, the observational network was extended with seven meteorological stations covering most of the mountain area where avalanches frequently occur: Iezer, Călimani, Ceahlău-Toaca, Parâng, Țarcu, Vlădeasa 1800, Semenic (Figure 1).

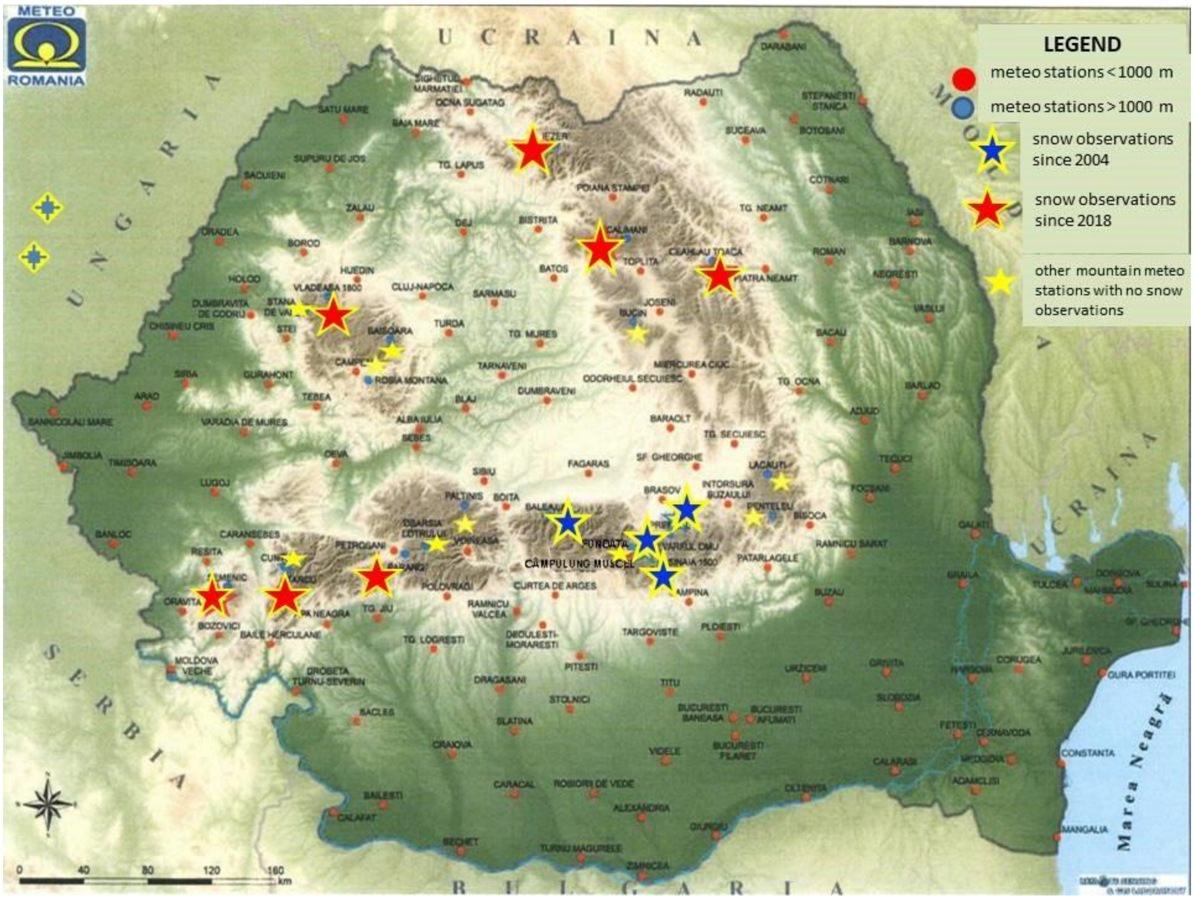

Fig. 1: Nivological network in the Romanian Carpathians

However, the information about avalanches is sparse and a consistent database covering the entire mountain area is under construction. Since January 2005, the operational work has been materialized in daily bulletins, which have been delivered to various stakeholders, e.g. Mountain Rescue Teams, District Councils, mass-media, touristic resorts and Town Halls.

While the avalanche monitoring action started in 2004, the first study about avalanches in Romanian Carpathians have been performed in 1964 and 1965 (Gaspar, 1968), following a burst of avalanches occurring at the beginning of 1963 blocking numerous roads and railway tracks in the forest massifs of the Southern Carpathians (Lotrului, Şureanu, Făgăraş) and Northern Carpahians (Maramureşului, Rodnei). The first study aimed to assess the conditions for avalanches, their characteristics, and techniques for prevention and combating.

As a result of the avalanche monitoring activity, the nivological bulletin is issued annually including information like the number, type and triggering conditions for avalanches (***, Bilanţul nivologic al sezonului de iarnă – Annual winter season report), as well as different research studies and other articles. Besides National Meteorological Administration, other research groups have analysed avalanches for specific Carpathian sectors and from different conditions, e.g. human triggering or terrain (elevation, aspect and slope angle) – (Voiculescu 2014).

This study examines the variation of the main meteorological parameters with impact on avalanche triggering conditions at Bâlea-Lac Meteorological Station, since 1979, when first observations were made, through December 2017. Bâlea-Lac is the only long-term weather station in the Făgăraș Mountains, and one can assume that the meteorological conditions are relevant for the climate of the entire mountainous area. After the introductory section (1), the paper presents (2) the triggering factors for avalanche hazards and forecast criteria, (3) meteorological data, avalanche database and climate settings at Bâlea-Lac, (4) a few climate characteristics relevant for avalanche triggering in the area of interest, and (5) concluding remarks.

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Triggering factors for avalanche hazard and forecast criteria

Most triggering factors leading to avalanche are related to the snowpack load and several classifications have been developed accordingly. Atwater (1954) proposed 10 weather and snow factors which contribute most to avalanche hazard in the Alta Ski Area, Utah, as follows: (1) old snow depth; (2) old snow surface; (3) fresh snow depth; (4) fresh snow type; (5) fresh snow weight; (6) state of accumulation; (7) wind force; (8) wind direction; (9) temperature developments; (10) snow coverage. The topography was not considered.

McClung and Tweedy, (1993), described five essential activating factors, including terrain, precipitation (especially fresh snow), wind, temperature (including radiation effects), and snowpack stratigraphy. The avalanche release probability can be assessed by estimating and weighting each contributing factor (Gubler, 1993).

Triggering factors may be stable (e.g. slope or morphology) or variable (e.g. weather conditions or snow properties) in time and they include (Ancey, 1998; de Quervain, 1981; Bernard, 1927):

• Mean slope, defined as the average inclination of avalanche starting zones, relevant between 27 and 50°;

• Roughness – a key factor in the anchorage of the snow cover to the ground;

• Shape and curvature of the starting zone. The stress distribution within the snowpack and the variation in its depth depend on the longitudinal shape of the ground. Convex slopes are generally associated with a significant variation in the snow cover depth, favouring snowpack instability;

• Slope aspect has a strong influence on the day-to-day stability of the snowpack;

• Fresh snow - an accumulation of 30 cm/day may be sufficient to cause widespread avalanching (Föhn et al., 2002; McLung and Tweedy, 1993; Ancey, 1998; de Quervain, 1981; Bernard, 1927; Gubler, 1993);

• Wind causes uneven snow redistribution (accumulation on lee slopes), accelerates snow metamorphism, form cornices which may collapse and trigger avalanches;

• Rain and liquid water content of the snow play a complex role in the snow metamorphism; i.e. the heavy rains induce a rapid increase in liquid water content, which results in a drop in the shear stress strength and leads to widespread avalanche activity (wet snow avalanches) (Conway & C.F., 1993).

• Snowpack structure. The stability of layer structure resulting from successive snow-falls depends on the bonds between layers and their cohesion. For instance, heterogeneous snow-packs, made up of weak and stiff layers, are more unstable than homogeneous snowpack (Schweizer et al., 2003).

Rapid warming leads to instability and slow warming derives snow-pack stability (according to (McClung and Schweizer, 1997)). For large (catastrophic) fresh snow avalanches, important snowfall is the strongest forecasting parameter ((Föhn et al., 2002)) and is closely related to avalanche danger (Figure 1).

Table 1: Weather-related indicators and associated greater avalanche potential (www.meted.ucar.edu/afwa/avalanche)

	Indicator	Greater avalanche potential
Precipitation	Snow accumulation rate	2.5 cm/h or more for more than 6 hours
	Water amount	25 mm or more in 24 hours
	Fresh snow density	More than 15 cm of 9% or greater density
	Storm trend	Begins cold, ends warm
	Rainfall	Any rain
Temperature	Increasing temperatures	Temperature rise >8°C in 12 hours, reaching values temperatures near or above the freezing point
	Rain/snow level	At or above avalanche starting zone elevations
	Warm temperatures	Above freezing at avalanche starting zone elevations > 24 hours
	Cold temperatures	▪ Very low temperatures (<-10°C) for long time (days) ▪ Shallow snowpack <1m deep and very low temperatures: <-10°C
Wind	Mean wind speed	▪ 9-27 m/s ▪ >27 m/s with snow density>10% ▪ 7-9 m/s with snow density<5%
	Mean wind direction	Consistent
Cloud cover	Nighttime sky cover	Clear skies with temperatures <-10°C and winds ≤ 5 m/s
	Daytime sky cover	Clear skies or thin clouds with warm temperatures and high sun angles, especially on sun-facing slopes

Accumulation of a fresh snow depth of about 1 m within a storm event is considered critical for the initiation of extreme avalanches; about 30–50 cm is critical for naturally released avalanches in general (Schaer, 1995) However, even with large amounts of

The avalanche forecast combines (1) information relevant for the snow conditions along the season of interest, and (2) short-term weather forecast for the area of interest. Avalanche forecasting is based on the joint assimilation of the weather conditions and snow coverage characteristics from the very beginning of the "winter" season. Meteorological data from the area of interest are currently used at daily scale and they should refer to:

a) Precipitation (snowfall and snow water equivalent - SWE)

b) Maximum and minimum temperatures

c) Winds near ridge-top level or at all forecast-area elevations

d) Average cloud cover

If detailed data from the past are not available, the regional weather data can be used cautiously and adapted to the area of interest. Most avalanches are associated with fresh snow falls, so that the following information should be available for any recent and/or ongoing precipitation event: (a) amount of fresh snowfall, (b) rate of accumulation, (c) SWE, and (d) fresh snow, the combined release probability of a group of avalanche paths is frequently than 50% (Schaer 1995). This shows that the fresh snow depth alone is not sufficient to explain avalanche activity (Schaer 1995).

density of the fresh snow. Further, the avalanche potential is estimated based on a threshold exceedance procedure (Table 1).

Meteorological data, avalanche database and climate settings at Bâlea-Lac

Meteorological data and metadata

This study is based on daily meteorological records from Bâlea-Lac Meteorological Station (45°36'11"LN, 24°37'44"LE, 2044 a.s.l.) from 1 January 1997 to 1 December 2017. The location of the station is in the northern part of the Făgăraș Mountains, Bâlea glacial valley, in the vicinity of Bâlea Lake (Figure 2, 3), near the Transfăgărășan road. The station began observations since January 1978, after a huge avalanche stroke, when 23 victims died. Until august 1995, the meteorological platform was situated near Bâlea-Lake chalet, then, after the chalet burned, the station was moved into the Paltinul chalet (Figure 3).

Fig. 2: The Făgăraș Mountains, with Transfăgărășan Road and Bâlea Lac Meteorological Station position

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Fig. 3: Bâlea glacier Valley, the Făgăraș Mountains

Avalanche database

A number of 392 days with recorded avalanches have been collected from Bâlea-Lac meteorological station since January 1979, the beginning of the activity until January 2019. Most of the data have been collected since February 2004, when the programme of nivology began at the National Administration of Meteorology and mentioned since then into every Annual winter season report (***, Bilanțul nivologic al sezonului de iarnă). Until 2004, avalanche cases have been recorded from the literature and Mountain Rescue Services (Salvamont) – work of Walter Gutt and Reinhold, who collected informations from local papers, (as Neuer Weg, Hermannstädter Zeitung, Die Woche, Karpatenrundschau, Allgemeine Deutsche Zeitung für Rumänien, Jahrbuch der Sektion Karpaten des Deutschen Alpenverein, Kronstädter Zeitung, Clubul Alpin Român bulletins, Bukarester Tageblatt, Jahrbuch des Siebenbürgischen Karpatenvereins, Siebenbürgisch-deutsches Tageblatt). Some important avalanches happened before 1979, like the one from April 17, 1977, when 23 people were killed in an avalanche at Bâlea-Lac, but these will not be included in the study, due to the lack of meteorological observation data. All the information has been put together into a database in the Snowball project (http://snowball.meteoromania.ro/about/about-snowball).

Based on the data retrieved at the Bâlea – Lac Meteorological Station, from January 1979 through December 2017, synoptic conditions for the avalanche days have been studied and thresholds of several meteorological parameters considered to have an impact on this phenomenon has been made (Pașol et al, 2017).

Climate settings

The climate conditions at Bâlea-Lac Meteorological Station are very likely to be relevant for all the Southern Carpathians above 2,000 m, despite inherent differences related to local conditions, such as slope, exposure and land cover. The warmest period occurs during the summer months (i.e. June, July, and August) when the mean air temperature exceeds 9.0°C (e.g. 9.2°C in July and 9.5°C in August), and the maximum daily temperature reached almost 25°C (i.e. 24.8°C in 24 July 2007). The cold season (i.e. December, January, and February) has mean air temperature values around -7°C (i.e. -6.0°C in December, -7.6°C in January and February), while the lowest temperature over the period 1979-2017 was -31.7°C at 1 March 2005 (Fig. 4).

Fig. 4: Monthly average temperature (Tave), maximum (Tmax) and minimum (Tmin) daily air temperature, and mean monthly relative humidity (RH) at Bâlea-Lac meteorological station (1979-2017)

The average monthly relative humidity varies between 76-77%, in October and November, and 86-

87%, in June and July, in close correlation with the liquid precipitation influx over the area of interest (Fig. 5).

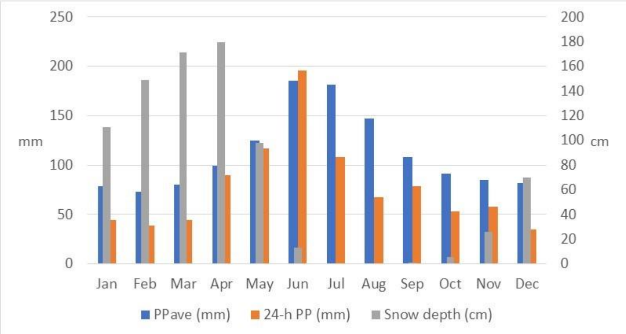

Fig. 5: Monthly average precipitation (PPave) and 24-h maximum amount (24-h PP), and mean snow depth at Bâlea-Lac meteorological station (1979-2017)

The highest precipitation amounts fall during JJA (150-190 mm as monthly average), and the highest 24-h precipitation amount was 195.6 mm, at 3 June 1988 (Fig. 5). From October to March the monthly amounts are below 100 mm. The snow cover is present almost all year round. The minimum values are in July (0.2 cm) and August (0.0 cm), and the largest snow depth occurs in April, with 179.6 cm, and March, 171.4 cm, as multiannual average values over 1979-2017 (Fig 5).

The monthly average wind speed ranges between 2.0 m/s, in August, and 3.6 m/s, in November, with a distinctive seasonal regime along the year (Fig. 6).

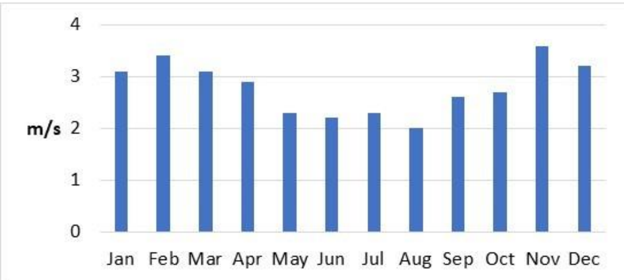

Fig. 6: Monthly average wind speed at Bâlea-Lac meteorological station (1979-2017)

Climate characteristics relevant for avalanche triggering

The climatic background enables specific climate characteristics which may favour the development of avalanches. This section depicts simple linkages between avalanche cases and (1) snow depth and water input, (2) air temperature, and (3) wind speed characteristics at Bâlea-Lac weather station. A more detailed study using this general setting is under preparation.

Snow depth and water input

There is an inherent relation between avalanche occurrence, snow depth and water input, as no snow avalanche can start without a snow cover, and the precipitation represent the main triggering mechanism. At Bâlea-Lac, the highest avalanche frequency is due to the consistent snow cover, generally exceeding 100 cm as an average for the days with avalanches during the period December-May, while the off-season avalanches (June, and September-November) depend more on the 24-h precipitation than on the existing snow cover (Figure 7).

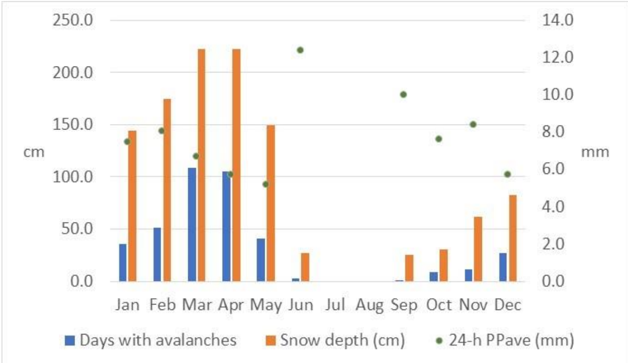

Fig. 7: Avalanche occurrence and corresponding snow depth and average 24-h precipitation (24-h PPave) at Bâlea-Lac meteorological station (1979-2017)

The snow accumulation rate and the amount of fresh snow in 24 hours is an important marker signposting potential avalanche activity, as 2.5 cm/h or more for over 6 hours and 30 cm or more in 24 hours are considered as a great avalanche indicator. (Föhn et al., 2002; McClung and Tweedy, 1993; Ancey, 1998; de Quervain, 1981; Bernard, 1927; Gubler, 1993).

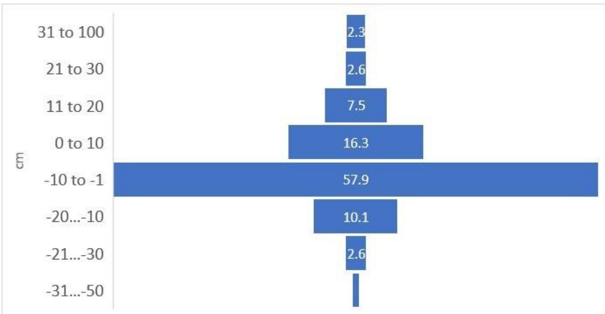

Fig. 8: Distribution of avalanche occurrence (%) depending on snow depth variation in 24-h

The distribution of avalanches based on snow depth is shown in Figure 8. Most cases occur when the snow depth decreases along 24 h with different rates (e.g. 57.9% for 1 to 10 cm decrease or 2.6% for 21 to 30 cm decrease), while snow addition over the existing cover generate avalanches in about 30% of cases (e.g.

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4.9% for 21 to 100 cm). The snow cover variations depend on the precipitation influx along certain time intervals. Over the Bâlea area high precipitation amounts lead to increasing snow depth (Figure 9), and the daily snow cover accumulation or shrinkage is well corelated with the 24-h precipitation amounts (R2 = 0.35). Temperature is also an important control factor for snow depth, explaining some negative snow depth variations along 24 h even when precipitation happen.

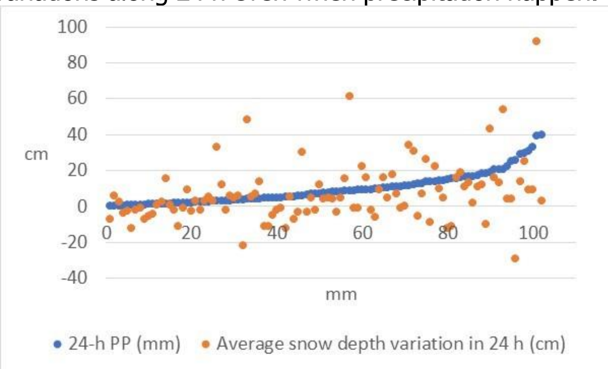

Fig. 9: 24-h precipitation amounts and corresponding average snow depth variations in 24 h for avalanche occurrence

The water amount input can increase the weight of the snow pack and 25 mm precipitation in 24 hours is considered a relevant threshold for triggering avalanches (Schweizer et al, 2003).

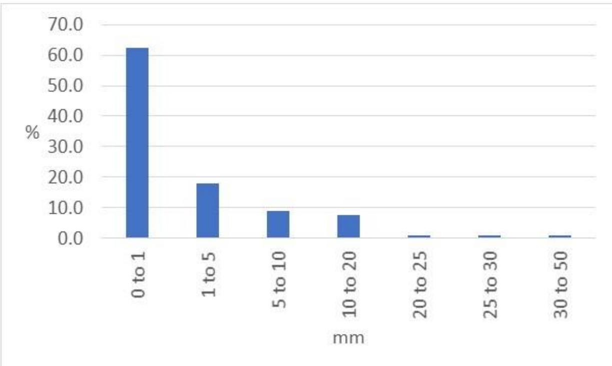

Fig. 10: Distribution of 24-h precipitation amounts (%) on different thresholds, for avalanche occurrence

Air humidity was high on most days with avalanche recordings, 53,3% at over 90% minimum relative humidity, 22,9% of cases for 70 to 90% relative humidity; 11,9% cases for 50 to 70% humidity and only 3,3% of cases for humidity lower than 50% (Fig. 4). An important number of days were recorded with fog (134) and mist (114) .

The avalanches are often associated with different weather phenomena illustrating certain humidity or temperature characteristics. For example, mist and/or fog were recorded in 319 days from the total 393 avalanche days (Fig. 11), illustrating a substantial bias of the air humidity in triggering avalanches over the Bâlea-Lac area.

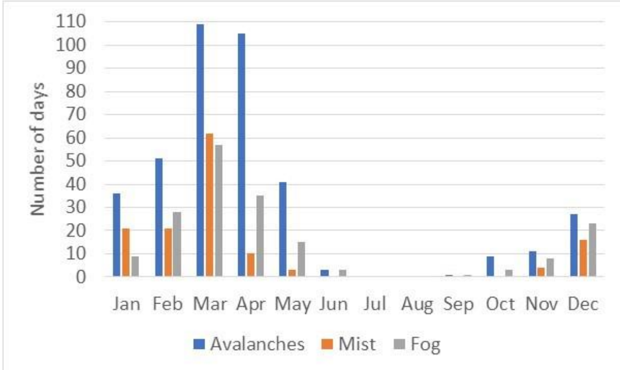

Fig. 11: Mist and fog frequency in days with avalanche occurrence

Air temperature

Near surface air temperature controls the precipitation type (e.g. rain, snow or sleet) and the persistence and steadiness of snow cover, which are basic ingredients for avalanche starting. The avalanches analysed in this study occurred between -24.0°C (daily minimum temperature 3 February 2010) and 15.9°C (daily maximum temperature 12 April 2015). The vast majority of cases are recorded in days when the minimum temperature was negative (81.7% of cases), but avalanches can also occur when the night time temperature remains positive (Fig. 12). As regards the maximum daily temperature, most avalanches happened in days with positive temperatures (60.8%). It is worth mentioning that the freeze-thaw processes are likely to play an important role for avalanches, i.e. 61.9% of the cases are noted with positive maximum and negative minimum temperature values during the same day. Moreover, the largest number of avalanches can be noticed in cold to warm season transition months (February to May), when the diurnal temperature range is higher (i.e. up to 25°C in March) (Fig. 13), and the frequency of freeze-thaw is eventually more important.

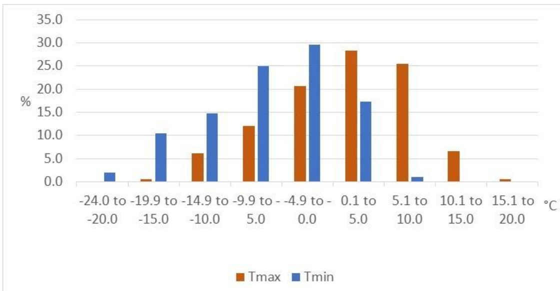

Fig. 12.: Distribution of avalanche days on maximum (Tmax) and minimum (Tmin) daily air temperature classes

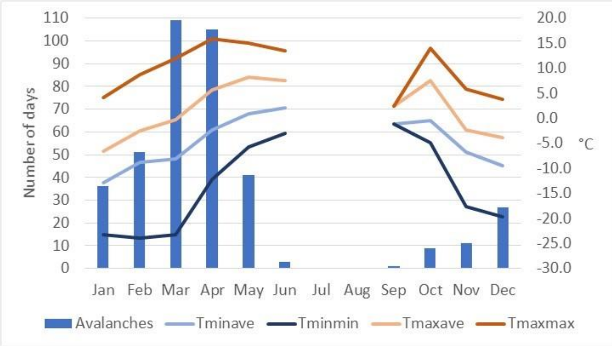

Fig. 13: Annual distribution of avalanche days and the corresponding average minimum (Tminave) and absolute minimum (Tminmin) daily temperature, and respectively average maximum (Tmaxave) and absolute maximum (Tmaxmax) daily temperature. Temperature values were computed only for days with avalanches

Wind speed

Wind can add relevant pressure on snow packs leading to avalanches. Figure 14 shows that, in the days with avalanches, the maximum wind speed measured at 10 m above the ground at Bâlea-Lac weather station is between 5 and 10 m/s in almost 75% of the cases. Sustained wind speeds are clearly an important factor in avalanche triggering processes.

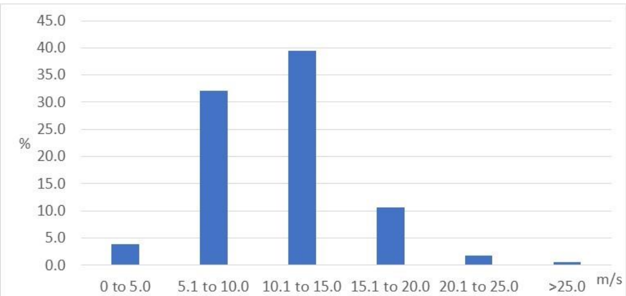

Fig. 14: Frequency of daily maximum wind speed (m/s) on different classes

Conclusions

This study reveals the value of continuous monitoring and careful collection of detailed avalanche information, which can support the research of the causes and possible impacts. At the best of our knowledge, this is the first overview of the basic climate parameters which are potentially avalanche triggers in the Făgăraș Mountains (Southern Carpathians). The study is based on data from only one weather station (Bâlea-Lac), assuming it is consistently relevant from climatic point of view for avalanche occurrence in the area. Even if such an assumption contains an inherent degree of confidence, which was not evaluated here, the results demonstrate that the theoretical circumstances for avalanche triggering (e.g. snow pack, fresh snow or wind) can be captured.

Most avalanches in the database (covering the Făgăraș Mountains) happen over steady snow depth while receiving supplementary water input, under temperature fluctuations and wind speed pressure.

Simple linkages between avalanche incidence and factors like (1) snow depth and water contribution, (2) air temperature, and (3) wind speed were evaluated and quantitative indications are provided, in good agreement with the theoretical premises for such phenomenon. Moreover, the results represent the background for more detailed investigations which are under preparation, and can contribute to enhanced avalanche forecasting in the Southern Carpathians.

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