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TOPOGRAPHICAL FACTORS, METEOROLOGICAL VARIABLES AND HUMAN FACTORS IN THE CONTROL OF THE MAIN SNOW AVALANCHE EVENTS IN THE FĂGĂRAŞ MASSIF (SOUTHERN CARPATHIANS – ROMANIAN CARPATHIANS): CASE STUDIES

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Abstract

Snow avalanches are a common geomorphic process and natural hazard in the Southern Carpathians (Romanian Carpathians). The spatial distribution of avalanches is controlled by topographical factors, meteorological variables and human factors. This study examines the occurrence of avalanches in two glacial areas in the Făgăraș massif, Bâlea (on the northern slope) and Capra (on the southern slope). During the period from 1963 to 2015 a total of 27 serious avalanche accidents were recorded in the months November-June in the Făgăraș massif resulting in 76 fatalities and 50 burials/injuries. From these avalanches, we examined five major avalanche accidents: the avalanche of June, 1974 which caused 6 fatalities and 8 burials/injuries; the avalanche of April 17, 1977 which caused 23 fatalities; the avalanche of December 23, 1988 which caused 3 fatalities; the avalanche of December 28, 2002 which caused 4 fatalities and the avalanche of February 20, 2010 which caused one fatality and 2 burials/injuries. Our results indicate a good correlation between some topographical factors. On the other hand, an increase in snowfall and snowstorms in particular are factors responsible for one avalanche event; early snowfall and a sudden increase in temperature are factors responsible for two avalanche events and snowfall and a sudden increase in temperature are factors responsible for one avalanche event. Using the weather scenarios we found high snowstorm frequency in one case, early-season weak layers of faceted crystals and depth hoar in two cases and well above-average total snowfall for one case.

Key words

topographical parameters • climate variables • human factors • avalanche accidents • Făgăraș massif • Romanian Carpathians

Introduction

Snow avalanches are undoubtedly one of the major denudational processes on mountain slopes and are natural hazards that damage forests, settlements and infrastructures (Fuchs et al. 2004; Fuchs & Bründl 2005; Jamieson & Stethem 2002; Stethem et al. 2003) and cause fatalities and injuries (Höller 2007, 2009; Jamieson & Stethem 2002; Keiler 2004; Keiler et al. 2005, Voiculescu 2014).

Avalanches result from the interaction between terrain factors, climatic variables and the existence of old snowpack (Birkeland & Mock 2001). The initiation of avalanches arises from specific conditions, such as heavy snowfall combined with intense winds blowing snow directly onto leeward slopes (Birkeland & Mock 2001) that are steeper than 25° and lack forest vegetation (McClung & Schaerer 2006). The potential for avalanches is caused by the interaction between the quantity of new snow and the existing snowpack structure on a slope (Birkeland & Mock 2001). As recognised in the research literature, in several mountain regions in the world massive avalanches are created through the influence of a maritime climate, heavy snowfall and relatively high temperatures during a snow storm (Esteban et al. 2005; Lachapelle 1966; McClung & Schaerer 2006; Mock 1995, 1996; Mock & Birkeland 2000).

On the other hand it is difficult to establish a common threshold or set of factors that can trigger an avalanche. The threshold value is relevant for a certain mountain range and its climate regime (Esteban et al. 2005). Different thicknesses of snow generate avalanches. Some authors mention, in relation to the French Alps, that the moderate risk of avalanches is caused by snowfalls of more than 30 cm depth () or, for the eastern Pyrenees, falls that form a 30 cm depth in 24 hours (Esteban et al. 2005). In relation to North America, Birkeland & Mock (1996) and McClung & Schaerer (2006) mentioned the same threshold value of a 30 cm depth of snow for the initiation of avalanches. Schweizer et al. (2003) mentioned that a layer of 30-50 cm is critical for the initiation of avalanches and a layer of 1 m depth, caused by a snowstorm, is critical for the production of extreme avalanches.

Avalanche research has focused on the interactions between climate variables and avalanche activity (Birkeland et al. 2001; Castebrunet et al. 2011; Eckerstorfer & Christiansen 2011b). On the other hand, several studies have provided detailed descriptions of avalanche patterns using both topographical factors and meteorological variables (Eckerstorfer & Christiansen 2011a, 2012; Laute & Beylich 2014; McClung & Schaerer 2006; Schweizer et al. 2003). In this context, the observation of avalanche activity is an important factor for successful risk management (Laternser & Schneebeli 2002).

The scientific analysis of avalanches using terrain and climate variables, and also human factors, is absent in the Romanian Carpathians. Therefore avalanche activity is poorly evaluated, except for a recent study by Voiculescu & Ardelean (2012) and by Voiculescu et al. (2011) in the Doamnei and Bâlea glacial areas of the Făgăraș massif, Southern Carpathians.

The purpose of this study is to:

- supplement previous research on avalanche activity in the Făgăraș massif;
- outline specific topographical and climatic conditions responsible for deadly avalanche events, and
- find interconnections between topographic, meteorological and human factors and avalanche accidents.

Study area

The Bâlea glacial area is composed of a glacial cirque located at 2000 m a.s.l. and a short glacial valley located in the central part of northern slope of the Făgăraș massif, while the Capra glacial area is composed of glacial cirque located at 2000 m a.s.l. and a long glacial valley located in the central part of the southern slope of the Făgăraș massif, Southern Carpathians (Fig. 1).

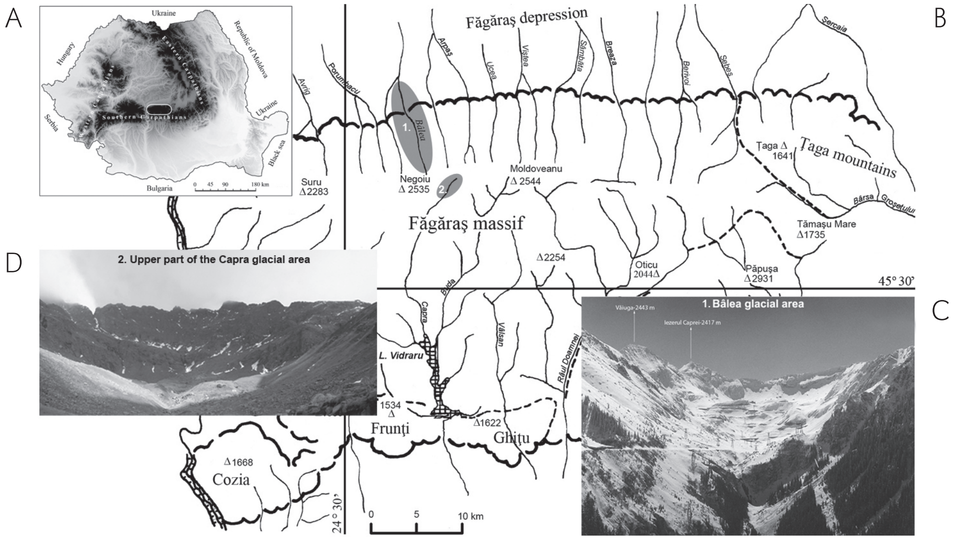

Figure 1. Location of Făgăraș massif (A and B) and of Bâlea glacial area (1 and C) and Capra glacial area (2 and D)

The local geology is rather homogenous and is characterised by metamorphic rocks, such as micaschists, gneiss and amphibolites, as well as limestone intrusions. The highest peaks reach more than 2300 m a.s.l. (Vânătoarea lui Buteanu – 2507 m a.s.l., Capra – 2494 m a.s.l., Iezerul Caprei – 2417 m a.s.l. and Paltinu – 2398 m a.s.l.). The local landscape preserves some clear landforms of Quaternary glaciations, such as a glacial cirque with a glacial lake (located at 2000 m a.s.l. in the Bâlea glacial area), glacial valleys, moraines and erratic blocks and two topographical thresholds (Germain & Voiculescu 2007; Voiculescu et al. 2011). On the other hand, the U-shaped valley is dominated by sharp ridges and periglacial landforms (scree deposits, rock glaciers, avalanche paths). The predominant geomorphic processes include avalanches, rockfalls and rock slides, debris flows in the alpine and subalpine zones and fluvial denudational processes in the forest. The main characteristics of the study areas are shown in Table 1.

Twenty-nine of the most active avalanche tracks were found (Fig. 2) in the Făgăraș massif.

Table 1. Characteristics of study areas

Characteristics	Bâlea glacial area	Capra glacial area
Geographical coordinates	45°36'14"N; 24°36'52"E	45°35'53"N; 24°38'09"E
Drainage basin area [km^2]	13.8	9.1
Min. elevation [m a.s.l.]	1,198	1,106
Max. elevation [m a.s.l.]	2,507	2,507
Mean elevation (m a.s.l.)	1,862.9	1,869.9
Mean slope [°]	34.2	32.4
Mean temperature [°C/yr] at 2044 m a.s.l.*	0.2	0.2
Mean precipitation [mm/yr] at 2044 m a.s.l.*	1,213.7	1,213.7
Elevation of the 0°C isotherm [m a.s.l.]*	2,050	2,010
Snow line [m a.s.l.]	1,700-1,750	1,800
Timberline [m a.s.l.]	1,550-1,600	1,650-1,700

* according to records from the Bâlea Lac weather station (2,044 m a.s.l.)

Twenty-one of these are located on the eastern slope of the glacial valley, five are located on the western slope of the valley and three are located in the Bâlea glacial cirque (Voiculescu et al. 2012).

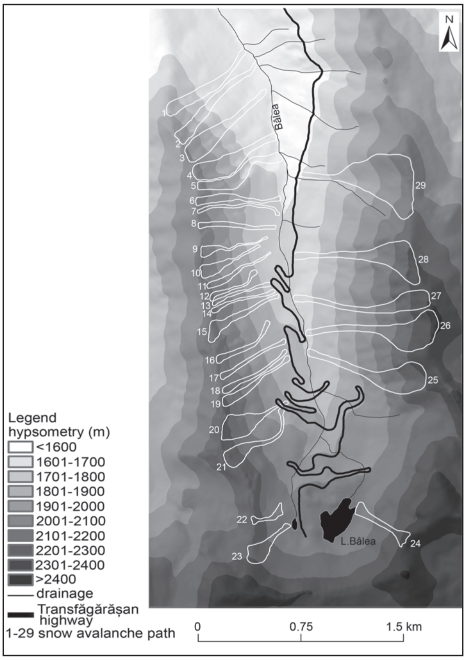

Figure 2. Location of the 29 most significant avalanche tracks (Voiculescu et al. 2012)

The timberline ranges from 1550 m to 1600 m.a.s.l. in the Bâlea glacial area and 1650 m to 1700 m a.s.l. in the Capra glacial area. Much of the floor of the Bâlea and Capra valleys is covered by trees, mainly Norway spruce (*Picea abies L., H. Karst.*) and a few common beech (*Fagus sylvatica*) and grey alder (*Alnus incana*). Dense small shrubs (*Pinus mugo*, *Juniperus communis, Rhododendron kotschy* and *Vaccinium myrtillus*) cover the subalpine zone, whereas some herbaceous species, mosses and lichens cover the alpine zone.

The high peaks of the Făgăraş massif are an important obstruction disrupting the paths of air currents. The northern slope of the Făgăraş massif is dominated by moist air from the Atlantic Ocean and cold Arctic airflows from the north associated with the highest snowfall, whereas the southern slope is dominated by warm and moist air from the Mediterranean Sea associated with abundant snow and considerable snow depths.

The climate of the Făgăraş massif is of the Dw type (a snow climate with dry winters) in the Koeppen-Geiger climate classification (Kottek et al. 2006). On the other hand, according to the seasonal snow cover classes defined by Sturm and Holmgren (1995), the Făgăraş massif has an alpine climate (Fig. 3).

The northern slopes of the Făgăraş massif and the Bâlea glacial area receive moist air from the Atlantic and cold Arctic airflows from the north. According to records from the long-term weather station (Bâlea Lac at 2044 m a.s.l., 45°36′N, 24°37′E; observation period 1979-2015), the mean annual air temperature (MAAT) is 0.2°C in the alpine zone (–2.5°C on the highest ridges), 3°C at the timberline and 6.1°C in the forest belt. The coldest month of the year is February (mean temperatures of -8.4°C, –6.3°C and 3.6°C respectively). The warmest month of the year is August (mean temperatures of 8.8°C, 12.3°C and 15.3°C respectively). The mean annual precipitation (MAP) exceeds 1200 mm in the alpine zone, reaches 880 mm at the timberline and is about 770 mm in the forestry belt. The highest amount of precipitation falling in the summer, for example in June, is 206.4 mm in the alpine zone, 129.3 mm at the timberline and 112.7 mm in the forest belt. We have determined the following thermal types for the Făgăraş massif (Voiculescu 2002): very cold when MAAT < –2°C at an altitude between 2200-2300 m a.s.l. and on the highest ridges; moderately cold when MAAT varies between 0° and –2° C at an altitude between 2000 and 2200-2300 m a.s.l.; and cold when MAAT varies between 2°C and 0°C at an altitude between that of the timberline and 2000 m a.s.l. On the other hand, we have also determined the nival coefficient (%) expressed as a ratio of snowfall to total rainfall (Voiculescu 2002). From this

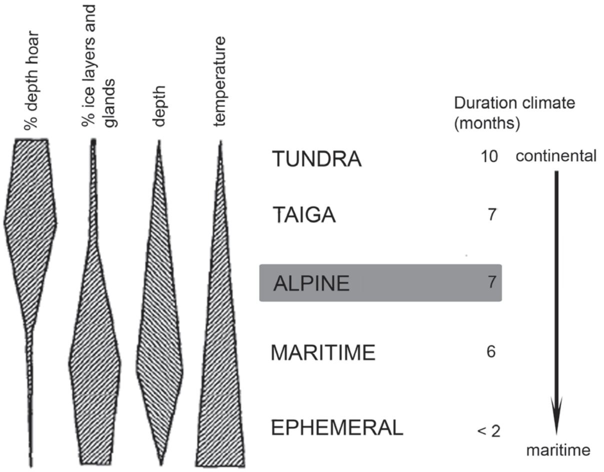

Figure 3. Seasonal snow cover classes (Sturm & Holmgren 1995); the specific alpine climate for the Făgăraş massif is shaded

viewpoint, we have determined the following types: pluvial-nival, with values between 40% and 50% at the timberline; nivo-pluvial, with values between 50% and 60% over 2000 m a.s.l.; nival-moderate, with values over 60%, over 2500 m a.s.l. In the same context, we have determined the ratio values between the annual number of days with snowfall (*sn*) and the annual number of days with rainfall (*rn*):

$$r = sn/rn$$

where:
sn is snow, snow showers and sleet and
rn is rain, rain showers and drizzle

The value of this parameter is directly conditioned by climatic influences and elevation and less by local influences: 0.80 at timberline, 1.26 at 2000 m a.s.l. and 1.50 on the highest peaks.

According to Bâlea Lac WNL, avalanches occur from the beginning of November until the end of May and even into the first half of June. Snow cover is very thick. The onset of snow cover in November is slow; it becomes continuous in early December and increases strongly in January and February reaching maximum snow depths in March and April. At higher altitudes (in the glacial cirques or on sheltered northern slopes), snow cover is persistent, lasting until the following year.

A total of 76 fatalities and 50 burials/injuries (62 fatalities and 50 injuries on the northern slope and 14 fatalities on the southern slope) have been recorded on the Făgăraş massif (Voiculescu 2014). Between the months of November and June in the years 1963-2015 (Fig. 4), 48 fatalities and 42 injuries were recorded in the Bâlea and Capra glacial areas alone.

Methodology

Our information on avalanche accidents varied according to the time period. We use different archives for the period before the founding of the Mountain Rescuers Public Services (MRPS) in 1968. These include the statements of witnesses, websites and even funerary monuments and commemorative crosses where we found information on the victims and descriptions of the locations of avalanche accidents. After 1968 we used the MRPS and database statistics of the Programme of Nivometeorology within the National Administration of Meteorology (PN-NAM). This programme was founded in 2004 in partnership with Météo France, Centre d'Études de la Neige-Grenoble

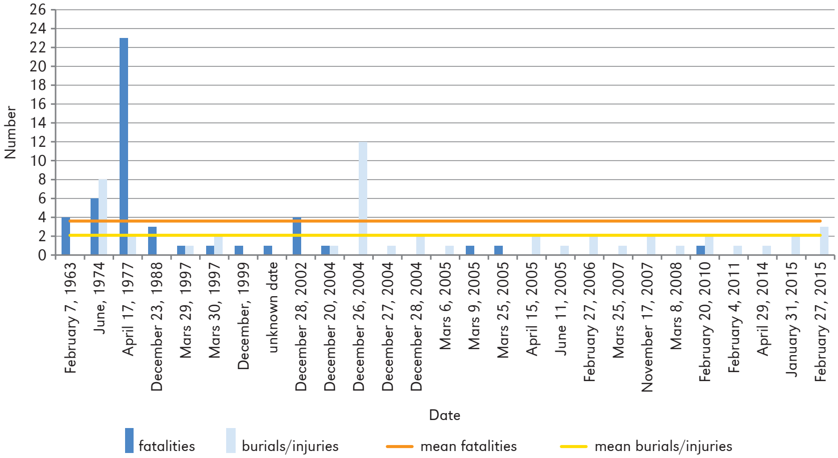

Figure 4. Number of fatalities and burials/injuries recorded in Bâlea and Capra glacial areas in the months November – June for the years 1963-2015

and includes the Bâlea Lac Work Nivology Laboratory (Bâlea Lac WNL) in the Făgăraş massif.

We considered 27 serious avalanche accidents (those which caused fatalities and/or full burials/injuries) during the 1963-2015 period (according to Techel & Zweifel 2013) (see Fig. 3). According to the literature (Jarry & Sivardière 2000), of those 27 serious avalanche accidents, four cases were considered exceptional or accidents that caused more than three deaths. Between 1963 and 2015, seven major avalanche events were recorded in the Bâlea and Capra glacial areas (Tab. 2).

Table 2. Pattern of seven major avalanche events in the Bâlea and Capra glacial areas

Avalanche events				Topographic factors	Meteorological data
date	fatalities	injuries/burials	damage		
*February, 1963	4 (climbers)	-	-	– (contradictory event place)	– (missing data)
*June, 1974	6 (highway workers)	8 (highway workers)	Transfăgărăşan highway was blocked	+	– (missing data)
*April 17, 1977	23 (off-piste skiers)	-	ice of Bâlea Lac was broken	+	+ (according to NAM databases)
**December 23, 1988	3 (off-piste skiers)	-	-	+	+ (according to Bâlea Lac weather station)
*December 28, 2002	4 (climbers)	-	-	+	+ (according to Bâlea Lac weather station)
**February 20, 2010	1 (off-piste skier)	2 (off-piste skiers)	off-piste skiing was blocked	+	+ (according to Bâlea Lac weather station)

*exceptional accidents (according to Jarry & Sivardière 2000)
**serious snow avalanche accidents (according to Techel & Zweifel 2013)

Morphometric terrain parameters

Within the ArcGIS 9.1, topographical maps were delineated showing the spatial distribution of avalanches in glacial cirques and valleys. Terrain parameters were determined for our study area and for each avalanche path and evaluated using a 10 m resolution digital terrain model (DTM) obtained from digitised contour lines (scale 1: 25,000). From the DEM, we extracted information on elevation, slope and aspect. Longitudinal profiles of the avalanche paths were produced using MICRODEM software.

We classified the avalanche tracks according to the method of Luckman (1977) and McClung & Schaerer (2006) as a large gully in the starting zone (SZ), a track zone (TZ) and a runout zone (RZ) (one case), as a cliff site with one or two large gully branches in the starting zone and as an open slope in the track and runout zones (two cases), or as an open slope in the starting, track and runout zones (two cases). In terms of the longitudinal profile, any avalanche path has three morphological sectors (McClung & Schaerer 2006; Walsh et al. 1990; Walsh et al. 2004): a starting or source zone, a track zone and a runout zone. These sectors were determined within the defined longitudinal profiles for each case, according to the international morphological avalanche classification (McClung & Schaerer 2006; EAWS 2013).

The morphometric parameters characterising the avalanche starting, track and runout zones are considered as the most relevant (Ancey et al. 2004, Butler & Malanson 1992, Luckman 1977, 1978; McClung & Schaerer 2006). The morphometric parameters were determined for each avalanche track (McClung & Schaerer 2006; EAWS 2013) as follows: the elevation (m a.s.l.) and inclination of the starting and runout zones, vertical drop, character of starting zone (from a point or line), form of avalanche track (confined/unconfined), sinuosity index (as the ratio between the length of a straight line from the highest point of the starting zone and the lowest point of the runout zone and that of the sinuous route of the avalanche flow, surface of each avalanche track, form of longitudinal profile (convex/concave), minimum, maximum and mean slope inclination (°), accessibility and any man-made infrastructure.

To define the categories of variables that characterise avalanche tracks, we used wind index, type of avalanche track, starting, track, and runout zone vegetation density and vegetation type in the starting zone, track, and runout zones according to McClung (2003).

Meteorological variables

In order to evaluate the mean winter air temperature, winter precipitation and snow depth between 01 November and 31 May for the winters from 1979-1980 to 2011-2012, meteorological data from Bâlea Lac weather station (2044 m a.s.l., 45°36′N, 24°37′E) were used. At the same time, in order to obtain correlations between different climate variables, we used databases from other weather stations which are now closed, Cozia (1577 m a.s.l., 45°18′N, 24°20′E, observation period 1980-1994) and Cumpăna (830 m a.s.l., 45°26′N, 24°37′E, observation period 1983-1996). In order to analyse the weather conditions contributing to extreme avalanche events, we used daily data (winter precipitation, maximum and minimum air temperature, snow depth and wind speed and direction) provided by the Bâlea Lac weather station for the November-May period.

The microstructural properties of the snow cover depend on the evolution and variability of the main meteorological parameters – rainfall, temperature, wind – during the cold season. Following to Eckerstorfer & Christiansen (2011b), Schweizer et al. (2003) and Teich et al. (2012) we used the short-term variations (24-72 hours) of these parameters that controlled the actual triggering of avalanches or the value of the 3-day sum of new snow depth for a given avalanche probability.

On the other hand, in order to classify wind speed, we used the wind index of the Gabl classification (1988): 0 m/s for calm, 1-3 m/s for light winds, 4-8 m/s for moderate wind; 9-17 m/s for strong wind and > 17 m/s for storm. Likewise, to evaluate the weather conditions during the avalanche events, we used specific weather scenarios according to Germain et al. (2009).

To determine the relationship between avalanche activity and climate we used the Winter Standardized Index (*WSI*) (Micu 2009) and we calculated the thermal severity of winters between 1979 and 2013 for the Bâlea Lac weather station, (Tab. 7) using the following formula:

$$WSI = t_i - t_{mean}/\sigma;$$

where

t_i is the mean winter temperature (°C),

t_{mean} is the multiannual mean winter temperature (°C) and

σ is the standard deviation.

The timing of avalanche accidents

The timing of avalanche events was defined by correlating meteorological data with avalanche activity monitored by Sibiu MRPS and Bâlea Lac WNL. In order to classify the time periods of avalanche accidents the following time periods were considered: early winter or December 1-January 31, mid-winter or February 1-March 15 and late winter or March 16 – April 31 (Grímsdóttir & McClung 2006; Spencer & Ashley 2011). In our cases, we added another time period, May 1-June 30 (Voiculescu 2014).

Results

Morphometric features of avalanches: case studies and relationships

Avalanche accidents were concentrated within the Bâlea glacial cirque (two cases, number 4 and number 20) and along the eastern slope (two cases, number 23 and number 24). The avalanche event in the Capra glacial area occurred in the upper part of the glacial valley on the eastern slope and was coded FC (*Fundu Caprei* in Romanian). The terrain parameters (Table 3) are the most important morphometric attributes controlling the spatial manifestation of avalanches.

Four avalanches (20, 23, 24 and FC) can be classified as high altitude ones, while avalanche 4 is an intermediate altitude event (Fig. 5). If we consider the large amount of snow and high number of fatalities, avalanches 24 and FC can be classified as large avalanches. Other avalanches were classified as a medium avalanche (20) and as small avalanches (4 and 23). All avalanches had a track length longer than 100 m but shorter than 1000 m.

Longitudinal avalanche profiles are generally characterised by a concave form, which is more pronounced in the case of the FC profile. This form of longitudinal profile, in combination with a large slope inclination, caused a high frequency of avalanches with a specific combination of parameters in the five cases examined. Two cases were confined avalanches (4 and 20), two unconfined avalanches (23 and FC), while only one avalanche combined both types (24). The vertical drop ranged from 177 m to 500 m and surface ranged from 2.23 ha to 5.91 ha. The different values are imposed by the position of avalanche tracks. Avalanche tracks located on the long and steep slopes of the glacial valleys have the largest values for vertical drop and surface area, while those located on the rock walls of the Bâlea glacial cirque, which is short and steep, have the smallest values. The sinuosity index highlights a longitudinal route rather than sinuosity. The average slope ranged from 25.4° (avalanche track number 23) to 35.4° (avalanche track number 4).

The avalanche track in the Bâlea glacial area has poor accessibility. The avalanche track of the Capra glacial area is inaccessible. One avalanche track (number 20) has elements of man-made infrastructure (a deflecting dike and snowpack support) to protect the Transfăgărășan highway against avalanches. However, according to Bâlea Lac WNL and Sibiu MRPS, this area is known to be avalanche active, with a high

Table 3. The terrain parameters of the avalanche tracks investigated

Code	Elevation (m)			Starting from a		Confined/ unconfined	Sinuosity index	Surface area [ha]	Average slope (°)			Length of avalanche path [m]	Accessibility	Man made infrastructure
	max. (SZ)	min. (RZ)	vertical drop [m]	point	line				SZ	TZ	RZ			
4	1,940 (subalpine zone)	1,412.7 (forestry zone)	527.3	+		confined	1.007	5.91	46.3	38.4	21.6	765	partially	yes*
20	2,161.5 (subalpine zone)	1,807.6 (subalpine zone)	353.9		+	confined	1.018	4.34	37.6	33.7	22	590	partially	yes**
23	2,223.1 (alpine zone)	2,046.1 (subalpine zone)	177		+	unconfined	1.008	2.63	39.2	26.9	10.1	330	yes	no
24	2,344.2 (alpine zone)	2,040 (subalpine zone)	304.2		+	both	1.010	2.23	46.9	35.6	6.5	460	yes	no
FC	230 (alpine zone)	1,980 (subalpine zone)	500.0		+	unconfined			43.3	27.5	10	700	no	no

* avalanche area display panel

** deflecting dike and snowpack support

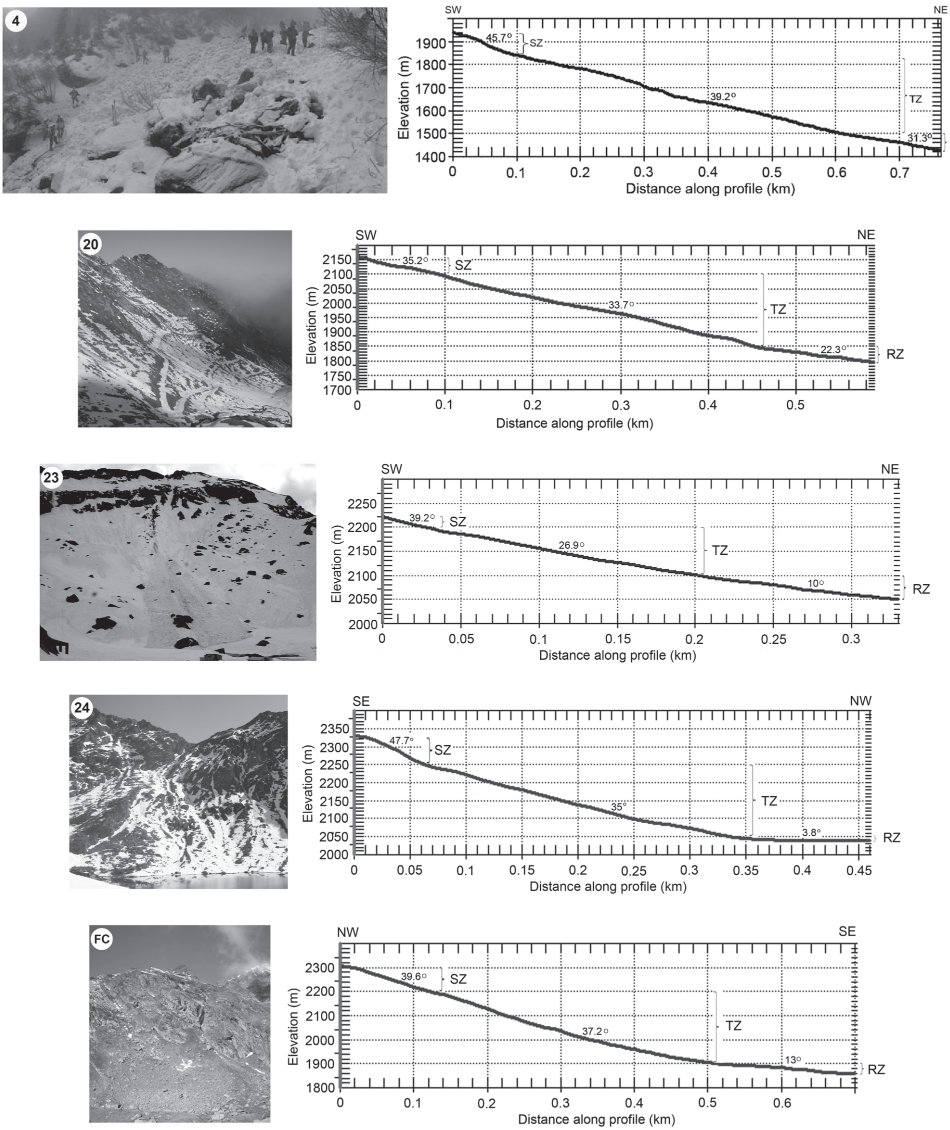

Figure 5. Longitudinal profiles of avalanches and their characteristics

frequency. Although, avalanche track number 4 is closed during the winter season (one display panel informs off-piste skiers of the prevailing avalanche situation), it is used by off-piste skiers.

Three avalanche tracks had their starting zones, where local drifts can form, exposed to the wind while another one had a starting zone where large amounts of snow could be moved by the wind, and another one had its starting zone protected by dense forest cover.

The highest number of fatalities was recorded on the open slope, with essentially no deep channels or gullies (three cases), followed by an avalanche track with deep channels or gullies (two cases). Vegetation type and density influence the movement

Table 4. Categories of variables of avalanche tracks

Code	Wind Index (Schaerer 1977; Smith & McClung 1997)	Type of avalanche track according to McClung (2003: 85)	Starting, track, and runout zone vegetation density, according to McClung (2003: 85)	Starting zone, track, and runout zone vegetation type according to McClung (2003: 85)
4	starting zone completely sheltered from wind by surrounding dense forest cover	deeply channelised	dense	prevailing coniferous (*Picea abies* L., H. Karst.)
20	starting zone on the lee side of open area where large amounts of snow can be moved by wind	containing a shallow gully or gullies	dense	grass, shrubs (*Pinus mugo*, *Rhododendron kotschy* and *Vaccinium myrtillus*)
23	starting zone an open slope with rolls or other irregularities where local drifts can form	open slopes with essentially no deep channels or gullies	dense	grass
24	starting zone an open slope with rolls or other irregularities where local drifts can form	open slopes with essentially no deep channels or gullies	very sparse	predominantly rocky
FC	starting zone an open slope with rolls or other irregularities where local drifts can form	open slopes with essentially no deep channels or gullies	very sparse	predominantly rocky

of avalanches. A predominantly rocky surface or sparse or very sparse grass and shrubs facilitated avalanche formation (four cases), while the presence of forest inhibited avalanche formation (only one case). In this context, we define the following categories of variables that characterise all avalanche tracks (Table 4).

Avalanche events and meteorological control

According to Sibiu MRPS and PN-NAM, avalanche accidents occur at different times. Two avalanche accidents were recorded during the early season, one case was recorded during the mid-winter season, one case during the late winter season and one case between 1 May-30 June.

Figure 6 shows the time series of daily winter precipitation, daily snow depth, daily air temperature (maximum and minimum), daily wind speed and daily avalanche activity (recorded by Bâlea Lac WNL) for four avalanche events.

The avalanche of February 20, 2010: The winter season of 2009-2010 was characterised by low snowfall (for several days) in the first half of February. There were major quantities of snowfall in mid-February. Until the avalanche event, the snow depth steadily increased, reaching 181 cm on the 18th (the average snow depth in February was 155.1 cm, while the average snow depth in the 2009-2010 winter season was 165.9 cm). The average snow depth during the snow event was 170 cm. The temperature rose continuously during February until the 20th, when it was above 0°C; afterwards it suddenly decreased, reaching –15°C. No wind was recorded. Here, we found a scenario of well above-average total snowfall.

The avalanche of December 23, 1988: The winter season of 1987-1988 was characterised by early snowfalls from the first half of December. The average snow depth was below average for the winter season: 86.6 cm (the average snow depth in the 1987-1988 winter season was 165.9 cm). During the avalanche event, the snow depth was 100 cm. No major snowfalls were record-

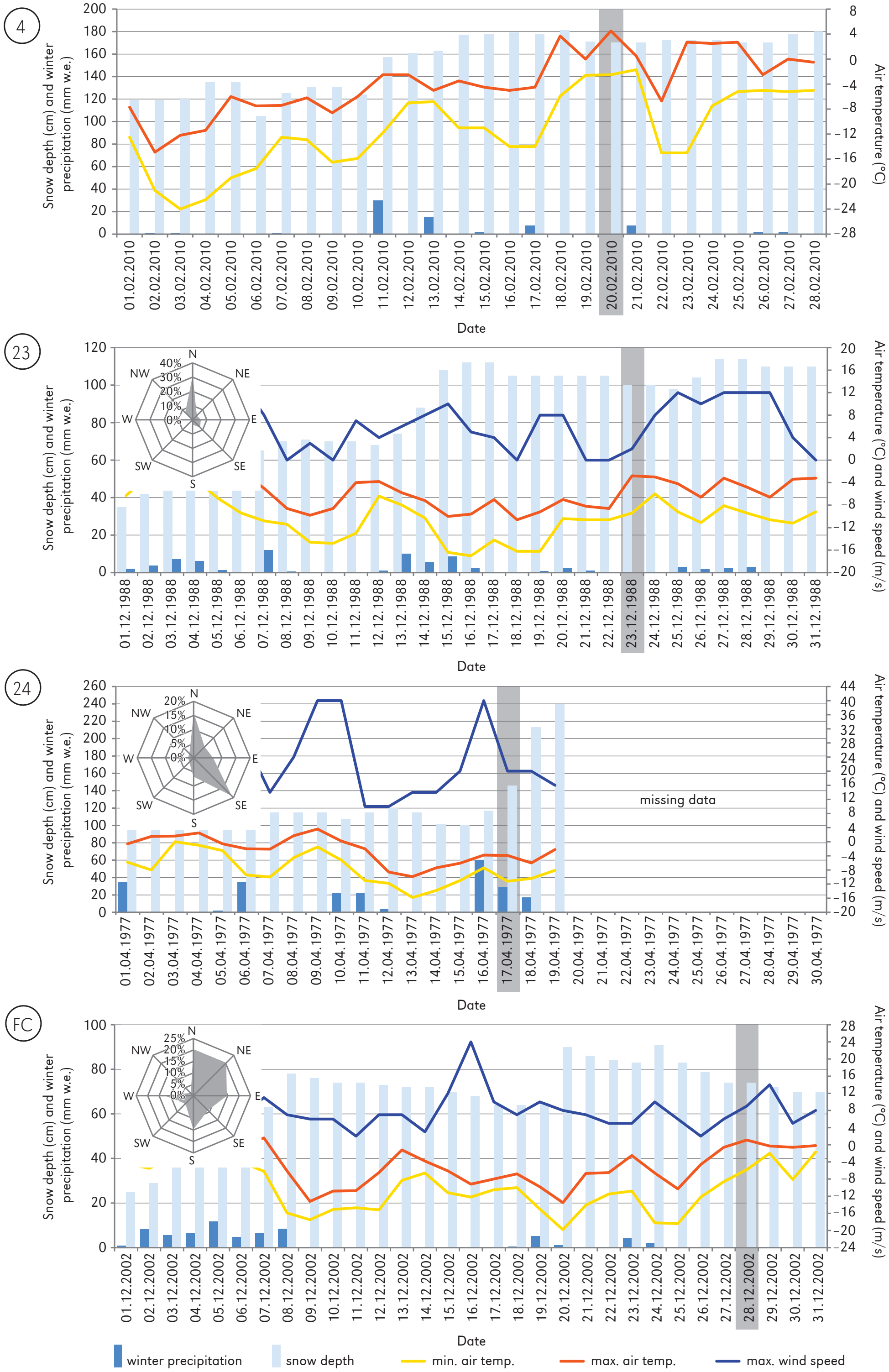

Figure 6. Time series of daily winter precipitation (mm) and snow depth (cm), mean daily air temperature (°C), mean daily wind speed (m/s) and avalanche events for four cases. Avalanche events are shaded. Meteorological data has been analysed from Bâlea Lac weather station (2044 m a.s.l.)

ed. Both the maximum and minimum temperatures were generally below 0°C during December. The average minimum temperature in December 1988 (–10.2°C) was below the multiannual average for December for the period 1979-2013 (–7.6°C). The instability of the snow cover was due to the relatively sudden increase in temperature in the last half of December and the moderate northerly winds, which increased the amount of snow cover in a metamorphic process. In this context, we identified a scenario of weak layers of faceted crystals in early-season and depth hoar.

The avalanche of April 17, 1977: This avalanche is known as the most tragic event in the history of the Romanian Carpathians and in the Mountain Rescuer Public Service records, and was triggered by 23 off-piste skiers. April 1977 saw below-average total snowfall of 125.7 cm (between 1979-2014, the average April depth was 170.4 cm). During the event, the snow depth was 146 cm. Over a six-year period, the average April depth had not exceeded the multiannual average. That April was characterised by several days with snowfall (which, for the most part, varied from the average), as well as an above-average consecutive three-day fall of fresh snow: in the first half of April – between April 10 and 12 – heavy snowfall accompanied by storm and strong winds was recorded; in the second half of April – between April 15 and 17 – heavy snowfall (snow depth increased, by 17 and 46 cm. respectively) accompanied by storms was recorded. At the end of the first part of April, the weather was sunny and warm, thus favouring the settlement and the homogenization of the layer of snow and at the same time forming ice crusts on the surface of the snow during the night. The pattern of change is as follows: between April 7 and 8, the weather began to warm (from 2°C to 10°C), subsequently, on April 10, the temperature dropped again to 5°C, and then on April 14 it dropped to 0°C. No increase in temperature was recorded up until 16 April, when it became yet colder again. During the avalanche event, the temperature was –11.2°C. Starting on April 12, a significant increase in wind speed to over 30 m/s and even 40 m/s was recorded, and during the catastrophic avalanche event, wind speed rose to over 20 m/s. This wind formed part of a storm with large snow drifts. The day after the tragic event, snow depth reached 213 cm, and even 240 cm in places (see Fig. 6). This is the context in which we identified the snowstorm frequency scenario.

The avalanche of December 28, 2002: The situation was similar to the avalanche event of December 23, 1988. The first half of the month was characterised by early snowfall. The average snow depth (88.2 cm) was below average for the winter season (the average snow depth in the 2001-2002 winter season was 97.4 cm). No significant rainfall was recorded. Both the maximum and minimum temperatures were generally below 0°C during December. The average temperature was below the multiannual average of December for the period 1979-2013 (–7.2°C). The instability of the snow cover was determined by the relatively sudden increase in temperature in the last part of December and by the moderate winds from the north, north-east to south and south-west, which increased the snow cover in a metamorphic process. In this context, we identified a scenario of weak layers of faceted crystals in early-season and depth hoar.

Avalanche events and climate relationships

In the Făgăraș massif 38.2% of winters are normal, 32.3% are cold and very cold winters, whereas 29.5% are warm and very warm winters. In this thermal context, in the Bâlea glacial area, the avalanche event of December 28, 1988 occurred in a warm winter, whereas the avalanche event of February 20, 2010 occurred in a cold winter. In the Capra glacial area the avalanche event of December 28, 2002 occurred in a cold winter (Fig. 7).

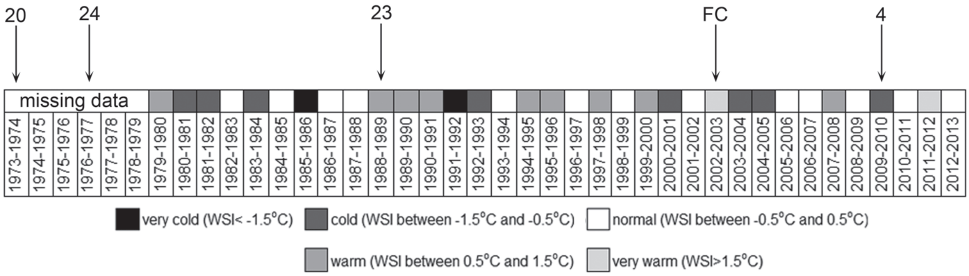

Figure 7. Relationship between Winter Standardised Index and avalanche events

Discussion

The results show that the patterns of the main avalanche events in the Bâlea and Capra glacial areas are controlled by a combination of morphometric, meteorological and human factors and are similar to patterns recorded in other mountain areas (Eckerstorfer & Christiansen 2011a,b; Laute & Beylich 2014; Schweizer et al. 2003).

Greater avalanche activity occurs in the upper part of the Bâlea and Capra glacial areas, whereas in the lower part, the avalanche activity decreases (Voiculescu et al., 2011; Voiculescu 2014). Avalanche accidents triggered by off-piste skiers and climbers are heavily concentrated in the glacial cirque and on the eastern slope of the glacial valleys. The spatial locations of the avalanche tracks are caused by the north-facing aspect of the long Bâlea glacial area and the south–facing aspect of the Capra glacial area. Therefore, a large number of avalanches occurred in the north-western, northern and north-eastern oriented slopes of the Bâlea glacial area (Voiculescu 2014) and in the south-eastern aspect of the Capra glacial area.

The elevation and the slope inclination of the starting zone, mean slope inclination, slope aspect and relative slope height are the most relevant terrain parameters controlling the spatial distribution of avalanches in all five avalanche paths. A very good correlation ($R^2 = 0.957$) was found between the mean avalanche track length and relative slope height and good correlation ($R^2 = 0.796$) was found between the mean avalanche path length and mean slope inclination (Fig. 8A,C).

This is characteristic of the middle and lower parts of the Bâlea glacial valley, which are steeper and narrower than the upper part of the Bâlea and Capra glacial valleys. Therefore, the longitudinal profile of avalanche paths numbers 4 and 20 and FC is longer and steeper, whereas the longitudinal profile of avalanche paths numbers 23 and 24 is shorter. On the other hand, a reasonable correlation ($R^2 = 0.498$) is found between the mean avalanche track length and the mean slope inclination of the runout zone (Fig. 8B), with the mean inclination of the runout zone varying between 3.8° (avalanche path number 24) and 31.1° (avalanche path number 4) respectively.

The difference can be explained by the different location and morphometric characteristics of the avalanche paths. Avalanche paths numbers 23 and 24 are located in the upper part of the Bâlea glacial area, originating on the high and rather steep rock walls of the Bâlea glacial cirque, and have a long and less steep runout zone. Avalanche paths number 20 and 4 are located in the upper part of the Bâlea glacial valley and in the lower part of the Bâlea glacial valley, respectively, originating on the eastern steep slope of the Bâlea glacial valley and have a short and steep runout zone. The FC avalanche has the same characteristics, originating on the high and steep eastern slope of the Capra glacial valley, with the runout zone being short and steep.

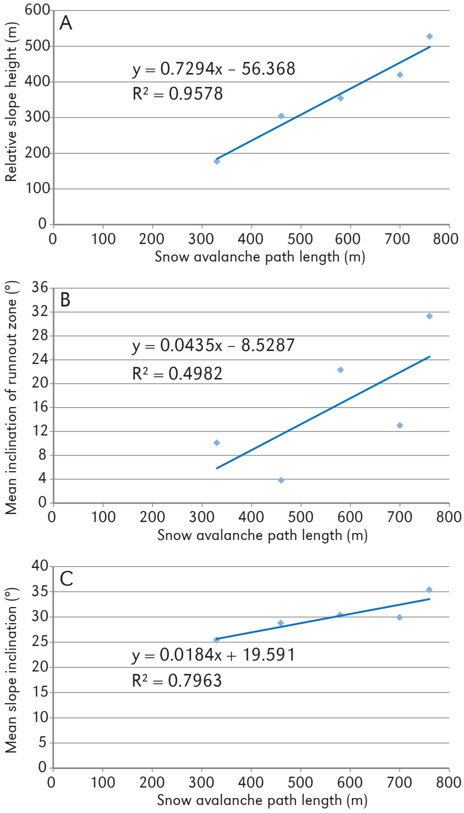

Figure 8. Statistical correlations between the avalanche track length and relative slope height (A), between avalanche track length and mean inclination of runout zone (B) and between avalanche track length and mean slope inclination (C)

Knowledge of the patterns of the morphological sectors, the only factors that are constant over time (Schweizer et al. 2003), is necessary to locate the m.a.s.l where the fatalities and/or injuries/burials occurred. The avalanche accident of December 28, 1988, was recorded in a starting zone that exceeds 2000-2100 m.a.s.l. (except for avalanche track number 4, situated below 2000 m), where the avalanche begins and accelerates. In the track zone (in the middle part of the track where the avalanche reaches maximum velocity) three avalanche accidents were recorded (on April 17, 1977, December 23, 1988, and December 28, 2002). In the runout zone (occurring on the lowest part of the path where the avalanche decelerates and leaves deposits), only one avalanche accident (on June 1974) was recorded.

For the avalanche of April 17, 1977, our results confirm the very good correlation between the triggering of the avalanche by off-piste skiers and the total winter precipitation for the three days preceding the event. This correlation is well outlined in the literature (Butler 1986; Jomelli et al. 2007). The snowfall that occurred over a short period overloaded the weak snowpack layer and increased its downslope deformation (McClung & Schaerer 2006). The new snow depth is in accordance with the values recognised by researchers (Schweizer et al. 2003): there were consecutive three-day falls of 61 cm of fresh snow, followed during the avalanche event by another 28.7 cm of fresh snow and another 17.1 cm of fresh snow the next day. The snow depth exceeded 140 cm during the tragic avalanche event and 210 cm the next day.

Conclusions

Snow avalanches are the most important geomorphic processes, causing the most fatalities and burials/injuries in the Bâlea and Capra glacial areas. This study presents the interaction of the topographic parameters, meteorological variables and human factors that control the spatial distribution of avalanches and caused accidents in the Bâlea and Capra glacial areas. Based on five major avalanche accidents, the results show the patterns of avalanche activity and their impact on human life.

The main factors triggering avalanches result from the interaction of the morphometric (elevation, length of avalanche track, slope inclination and aspect), meteorological (heavy snowfall, snow depth, sudden temperature rise or drop within short time periods, and persisting snowdrift) and human factors (off-piste skiers and climbers). On the other hand, the prevailing wind direction is governed by topographic parameters, general valley orientation (north for the Bâlea glacial area and south for the Capra glacial area) and avalanche track orientation.

A significant increase in snowfall (in the form of snow depth) and snowstorms in particular are critical factors for one avalanche event, early snowfall and a sudden increase in temperature are the critical factors for two avalanche events, and snowfall and a sudden increase in temperature are the critical factors for one avalanche event.

When we consider the high winter tourism potential of these glacial areas, we strongly believe that land managers should consider the impact of topographic and climatic conditions and warming on avalanche activity.

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

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