Seasonal Thermal Regime of a Mid-Latitude Ventilated Debris Accumulation

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Abstract

The internal and reversible mechanism of air circulation throughout a porous debris accumulation like talus slope, relict rock glacier and rockfall deposit acts as an efficient advective conveyor of heat, which strongly influences the ground surface thermal regime during the whole year. Combining the detection of visual evidences and ground surface temperature (GST) measurements (continuous logging, winter mapping) has proved to be relevant for identifying areas affected by internal ventilation and to characterize the spatial pattern of the seasonal ground surface temperature anomalies. Five types of specific annual ground thermal regime can be defined. Vegetation, soil and micro-fauna appear to be related to these different thermal regimes. The distribution of vegetal associations is closely linked to the ground temperature in summertime.

Keywords: air circulation; seasonal thermal regimes; talus slopes; ecosystems; Swiss Alps and Prealps.

Introduction

The mechanism of deep air circulation (the so called "chimney effect" or "wind tube") is known to be a process of ground overcooling in the lower and – presumably – deeper parts of porous talus slopes (eg. Wakonnig 1996, Delaloye et al. 2003, Sawada et al. 2003). It occurs frequently in mid-latitudes, where it can generate and/or preserve extrazonal permafrost conditions up to more than 1000 metres below the regional lower limit of discontinuous mountain permafrost (Gorbunov et al. 2004, Sone 2005, Delaloye & Lambiel 2007). The process plays moreover a decisive role in the conservation of specific terrestrial ecosystems (Gude & Molenda 2003).

Detailed investigations on the thermal regime of talus slopes and other porous debris accumulations (relict rock glaciers, rockfall deposits) have been carried out since 1997 in western Switzerland (Jura mountains, Prealps and Valais Alps) in several sites located between 650 and 2000 m a.s.l with a corresponding mean annual air temperature (MAAT) ranging from +8 to +2°C, respectively (Fig. 1) (eg. Delaloye 2004, Lambiel 2006). They demonstrate that internal air circulation is a mechanism common to almost all prospected sites causing a significant annual negative anomaly of the ground surface temperature (GST) (up to more than 7°C below MAAT) at the bottom of the debris accumulation, independently of the slope orientation.

The present paper describes the seasonal spatial pattern of the ground surface thermal regime in porous debris accumulations, which are affected by the air circulation mechanism. It provides some key methods for detecting and assessing both the occurrence of a ventilation mechanism and its spatial influence. It also gives a preliminary overview on the related specific terrestrial ecosystems, in particular on the development and spatial extent of vegetal associations and soils.

Background

Cold air flow blowing out of the ground in summertime in the lower parts of scree slopes was used for centuries in mountainous or volcanic mid-latitude areas as natural fridge for the conservation of food (eg. DeSaussure 1796). Several assumptions have been advanced to explain the origin of ground cooling (Harris & Pedersen 1998). Recent studies (Wakonnig 1996, Delaloye et al. 2003, Sawada et al. 2003) and our analysis of several tens of sites investigated in Switzerland demonstrate that a deep reversible air circulation process (the so-called "chimney effect") acting throughout the whole of an accumulation of blocky material (Delaloye & Lambiel 2007) is likely to be the main factor controlling the ground surface thermal regime on these sites. The cooling effect of air circulation in a porous medium has also been used artificially in embankments to preserve permafrost conditions under highway and railway infrastructure in high-latitude or high altitude (eg. Goering & Kumar 1996, Niu & Cheng 2005).

The reversible air circulation

Variations of both the direction and the velocity of the air circulation throughout an accumulation of loose sediments are primarily controlled by the thermal contrast between the outside and inside (ground) air causing a gradient of driving pressure (Delaloye et al. 2003). The flow direction reverses seasonally. During winter, an ascent of relatively warm light air tends to occur in the upper part of the debris accumulation. It leads to a dynamic low (a depression) in the lower part, causing a forced aspiration of cold external air deep inside the ground even through a thick - but porous – snowpack. A gravity discharge of relatively cold dense air occurs during summer in the lowermost part of the debris accumulation, preventing the GST to rise significantly above 0°C in this section. As a consequence, a diffuse aspiration of external warm air occurs in the upper part of the slope.

An internal "cold reservoir" is build up during winter by the advection of external air (Sone 2005). The efficiency of the process depends on the intensity and duration of cold weather periods. The "frigories" are supposed to be "stored" by groundwater freezing (latent heat) and by conduction in the rocky materials and/or in the underlying finer ground (Delaloye & Lambiel 2007). The thermal conditions observed at the ground surface and in the shallow sub-surface in summertime are mainly influenced by the intensity of winter cooling and the recharge of the cold reservoir.

Specific ecosystems

The lower parts of ventilated talus slopes usually shelter specific ecosystems, whose typical distribution areas are located at higher latitude and/or higher elevation (eg. Rist et al. 2003, Gude & Molenda 2003). Besides the occurrence of boreo-alpine species, significant differences in phenological development (like dwarfing of trees, early yellowing or shorter developmental stage of vegetation) have also been highlighted between flora growing in the cold ventilated areas and those located outside (Ruzicka 1999, Körner & Hoch 2006).

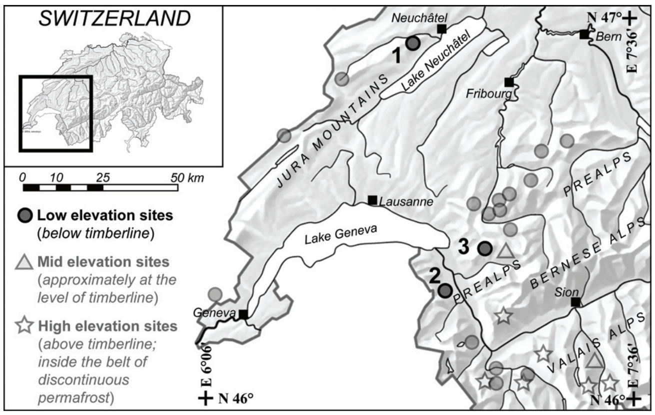

Figure 1. Location map of investigated areas with ventilated terrain in western Switzerland (after Delaloye 2004, Lambiel 2006, Dorthe & Morard 2007). Main sites: 1: Creux-du-Van; 2: Dreveneuse; 3: Bois des Arlettes.

Table 1. Topo-climatic characteristics of the investigated sites.

N°	Sites	Elevation	MAAT	Orientation
1	Creux-du-Van	1170-1290	+ 5.4°C*	N
2	Dreveneuse	1600-1800	+ 3.8°C**	E
3	Bois des Arlettes	1650-1900	+ 3.9°C***	NW

Locations are displayed on Figure 1. MAAT (Oct. 2004 to Sept. 2005) measured at: *1210 m a.s.l.; **1700 m a.s.l.(derived from Moléson, 2000 m a.s.l.); ***1740 m a.s.l.

Sites characteristics

Data from the three main sites of investigation in western Switzerland (Creux-du-Van, Dreveneuse-du-Milieu, Bois des Arlettes) are used in this paper. The sites are located between 500 and 1200 metres below the estimated elevation of the regional lower limit of discontinuous mountain permafrost (about 2200 - 2400 m a.s.l. on northern slopes) (Fig. 1 & Tab. 1).

Sites description

The Creux-du-Van (Cr) north-facing talus slope consists of limestone pebbles in the uppermost part transiting gradually to metric boulders downwards. The lower part of the slope is covered by an organic soil, and several patches of dwarf red spruces (*Tofieldio-Picetum* association) are occurring. The thickness of the blocky layer was estimated by geophysics to be about 20 m with the possible existence of a frozen body (Marescot et al. 2003). The site has been intensively studied since 1997 (Delaloye et al. 2003, Delaloye 2004).

The Dreveneuse-du-Milieu (Dr) east-facing talus slope consists of limestone pebbles and angular decimetric blocks. It is connected to a 200 m long relict rock glacier extending downward in a forested area. A few dwarf red spruces are found in the lower part of the slope as well as locally on the relict rock glacier. The thickness of the blocky layer was estimated by geophysics to be about 20 m for the talus slope and about 15 m for the relict rock glacier.

The large Bois des Arlettes (Arl) talus slopes face to the northwest and also consist of limestone debris. They dominate several sizeable relict rock glaciers. The thickness of the blocky layer was estimated to be about 25 m for the talus slope and 15-20 m for the relict rock glacier. Vegetation is almost lacking on the talus slope. The relict rock glaciers are conversely covered by a thin organic soil and a mixed forest, including some patches of azonal vegetation (*Salicetum Retuso-Reticulatae*) with alpine species such as *Pritzelago alpina* or *Dryas octopetalia*.

Meteorological conditions of the year 2004-2005

Data presented in the paper dates from the hydrological year 2004-2005 (Fig. 2).

Relatively warm conditions occurred from October to mid-January in comparison to the climatic norm 1961-1990, interspersed with a cold phase by mid-November. Two successive persistent cold periods were then recorded until mid-March, separated by a short spell of milder weather in the first days of February. Afterwards, air temperatures remained warmer than the norm, except for August.

Winter 2004-2005 was also characterized by relatively late snowfalls, the snowcover remaining thin (less than about 50 cm) until mid-February. The snowcover reached its maximal thickness (1.5 m at Creux-du-Van and probably much on the two other sites) by mid-March.

Methods

According to Delaloye (2004) and Morard et al. (2008), the observation of visual evidences (like "snowmelt windows" in the upper part of a slope in winter or ground ice occurrences in early summer in the lower part) was used to point out the activity of a ventilation mechanism through a debris accumulation (Figs. 4, 5). In addition, ground temperature measurements were carried out to assess the spatio-temporal variability of the ventilation system.

Several single-channel dataloggers (UTL-1) were installed on the different sites, mostly along a longitudinal profile crossing the whole debris accumulation. They recorded the ground surface temperature at a depth of about 10-20 cm every two hours. Atmospheric air temperatures were measured in situ (Creux du Van, Bois des Arlettes), or derived from official meteorological stations of the Federal Office of Meteorology and Climatology network using an altitudinal gradient of -0.58°C/100 m (Dreveneuse).

The comparison between ground and surrounding air temperature provides information about both the direction and intensity of the airflow. A similar relationship corresponds to an aspirating regime, while an inverse relationship indicates an expelling phase reflecting partially the thermal state of the ventilated system at a given moment (Lismonde 2002). A close non-delayed relationship between air and ground temperatures is assumed to be related to a higher intensity of the air flow.

To determine both the efficiency and the spatial pattern of a ventilation system, the winter temperature at the ground/snow interface was also mapped after a long period of cold weather in February 2005 using the BTS (Bottom Temperature of the Snowcover) technique.

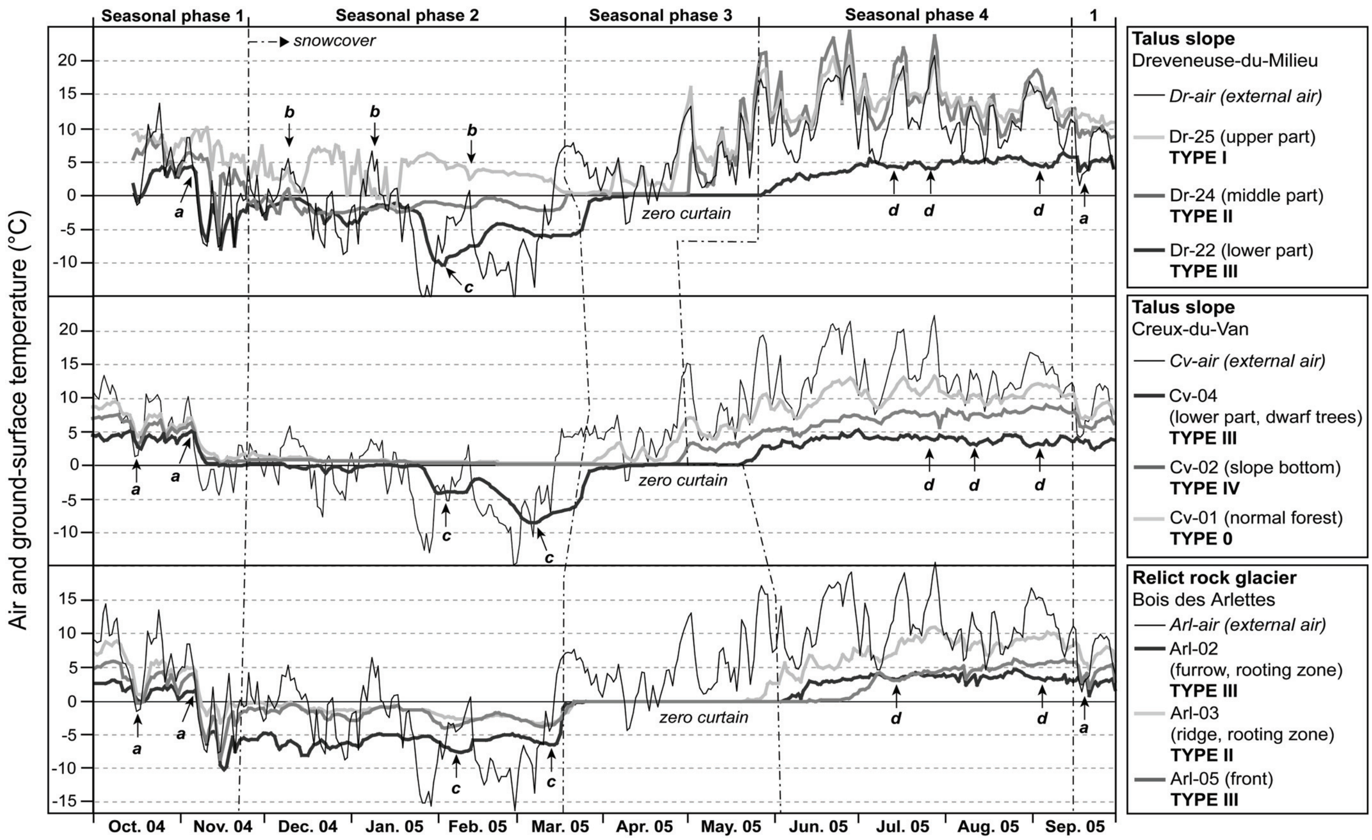

Figure 2. Thermal behaviors of the different parts of a ventilated talus slope – relict rock glacier complex. Data are daily air and ground-surface temperature. Locations of the dataloggers are shown in Figures 4 and 5. Arrows: a) inversion of the air flow direction; b) mild weather events; c) colder ground-surface temperature in January-March 2005; d) coldest ground temperature in summertime.

Results

Time series reported in Figure 2 and summed up in Table 2 illustrate the annual behavior of the GST for the three main sites of investigation along a slope profile. Four seasonal phases (1-4) can be distinguished for describing the thermal regime of the various parts of a ventilated debris accumulation, paying attention to the thermal anomalies in regard to the outside air temperature.

Seasonal phase 1: autumn and early winter conditions

The fall – early winter phase until the onset of a thick snowcover is characterized by the frequent reversibility of the ventilation system. The air flows downwards by mild weather, whereas aspiration occurs in the lower parts of the ventilated terrain when the weather becomes colder. Not only the foot of talus slopes suffers an intense cooling of the ground, but also the relict Bois des Arlettes rock glacier (arrows ‘‘a’’ in Figure 2). In all these places, this seasonal phase 1 is characterized by a negative thermal anomaly.

In November 2004, the GST in the upper part of the Dreveneuse talus slope (Dr-25) remained permanently above freezing point, with variations inversely related to those of the external air temperature. Snowmelt windows, hoarfrost, wet blocks, basal icing of a thin snowcover, condensation fog are visual evidences of the outflow of “warm” air during this phase.

During the phase 1, the lower part of the Dreveneuse talus slope (Dr-22) cooled from +4°C to -6.8°C between 6 and 10 November 2004, whereas the GST in the upper part of the slope remained as high as +8°C. At Bois des Arlettes, a rapid decrease of the GST from +1.5°C to -6.4°C and from +4°C to -6°C was also observed in a furrow in the rooting zone (Arl-02), and on the front (Arl-05) of the relict rock glacier, respectively. Where the soil is thicker and damper as in the Creux-du-Van lower talus slope (dwarf trees area), a zero curtain period can start (Cv-04).

Table 2. Temperature characteristics of the investigated sites.

UTLs	MAGST (°C)	ATA (°C)	GFI (°C)	NFD (day)	ZCD (day)
Dr-air	*3.76**	*0*	*-613*	*105*	*0*
Dr-25	7.94	+4.18	-6.5	8	0
Dr-24	5.54	+1.78	-204	114	42
Dr-22	-0.01	-3.77	-601	205	48
Cv-air	*5.35**	*0*	*-441*	*85*	*0*
Cv-04	0.74	-4.91	-336	171	34
Cv-02	3.29	-2.06	0	63	63
Cv-01	4.96	-0.39	0	0	0
Arl-air	*3.96**	*0*	*-614*	*109*	*0*
Arl-02	-0.92	-4.88	-789	210	74
Arl-03	2.54	-1.41	-213	194	58
Arl-05	0.68	-3.28	-311	222	87

Location on Figures 4 and 5. * Mean annual air temperature (°C). MAGST: mean annual ground surface temperature (°C); ATA: annual thermal anomaly (°C); GFI: ground freezing index (°C); NFD: number of frozen days; ZCD: zero curtain duration (day).

Seasonal phase 2: winter conditions

Winter is often characterized by a thicker (more than 1 m) and continuous snowcover as well as by colder weather conditions. The ascending air circulation regime is prevailing.

According to the elevation, the ground surface or its close sub-surface should normally not freeze under the thicker snowcover, as it was recorded at the terminal edge of the Creux du Van talus slope (Cv-02) and in the surrounding area (Cv-01).

In the upper part of a talus slope, as in Dreveneuse (Dr-25), the GST remained warm for the whole winter, but dropped strongly for a short time by mild air temperatures (arrows ''b'' in Figure 2). The only temperature below freezing point was registered during the mildest weather period in January 2005. The GST tended however to decrease gradually from about +7°C in the beginning of November to +2°C in March. An inverse relationship to the outside air temperature is also observed. Warm air outflow is easily perceptible as well as associated phenomena like snow funneling with hoarfrost, snowmelt windows, vaulted spaces at the base of the snowpack.

GST was at or below freezing point during the whole winter in the middle and lower parts of the talus slopes (Dr-24, Dr-25, Cv-04), as well as on the relict rock glacier (Arl-02, Arl-03, Arl-05). The GST mapped in February illustrates the spatial geometry of the colder areas (Fig. 3). The thermal regime is mainly controlled by the evolution of the external air temperature (arrows ''c'' in Figure 2) with a time lag of a few days which seems to increase by the end of the winter.

Seasonal phase 3: snowmelt period

At the onset of the snowmelt phase in March, the GST rose suddenly to 0°C in the lower parts of the ventilated terrains and remained stable for 42 days at Dr-24 to 87 days at Arl-05 (Tab. 2). In the upper part of a talus slope (Dr-25), the snowmelt phase provoked a temperature drop to about 0°C. This non-constant zero curtain phase lasted for a few days only.

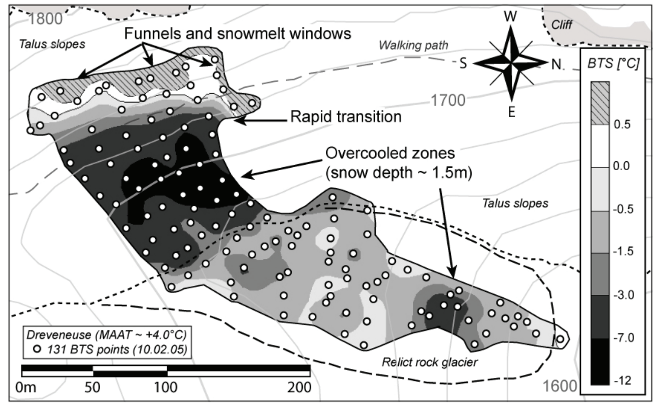

Figure 3. Ground surface winter temperature mapping (Dreveneuse-du-Milieu, 10 February 2005). Note the overcooled zone in the middle/lower part of the talus slope, the cold areas on the relict rock glacier and the rapid transition in the uppermost zone to warmer ground temperature.

Seasonal phase 4: summer conditions

The gravity discharge of cold dense air prevents the GST to increase above +6°C in the lower parts of the debris accumulations as at Dr-22, Cv-04, Cv-02, Arl-02 and Arl-05. There is a more or less well established inverse relationship between the airflow temperatures and those of the external air (as indicated by arrows ''d'' in Figure 2). At these places, cold air outflow, azonal vegetation, ground ice or late-lying residual snow patches can be observed.

In the upper and middle parts of talus slope (Dr-25, Dr-24), the GST varies in close correspondence with the evolution of the surrounding air temperature. In the marginal ridges of the relict rock glacier (Arl-03) and in the areas outside the porous debris accumulations (Cv-01) this GST regime can be considered as normal: the fluctuations are smooth and depend directly on the air temperature.

Synthesis and discussion

Annual thermal regime of a ventilated system

Air circulation throughout a porous debris accumulation produces major differences in the thermal regime of areas only a few (tens of) meters from each other. Temperature anomalies occur and vary seasonally depending both on the location on the landform and the meteorological factors (external air temperature, snowcover). Indeed, five types of annual thermal regime can be defined on the basis of the four seasonal phases described above:

- Type I: positive anomaly in autumn, winter and summer. This behavior concerns the upper part of a ventilated system, where in particular the GST remains significantly higher than 0°C during winter due to the expelling of internal warm air. A positive annual thermal anomaly will result in such places (+4.18°C at Dr-25). A spell of mild weather in winter may cause the weakening or the end of the ascending airflow and consequently an episodic decrease of the GST.
- Type II: slight negative anomaly possible in winter, positive anomaly in summer. This kind of thermal

regime affects the section located immediately above the coldest area. Air aspiration occurs in late fall and winter but there is no influence of the summer gravity discharge. The annual thermal anomaly is slightly positive (Dr-24) or slightly negative (Arl-03), probably due to different ground surface properties (blocky material directly exposed to solar radiation in summer at Dr-24, thick soil and shady forest at Arl-03).

- Type III: negative anomaly in fall, winter and summer, late lying of snow. This annual type is associated to the coldest part of the system, permanently frozen during winter due to the aspiration of external air (even through the snow cover) and remaining cool in summer because of the gravity discharge of internal cold air. Such areas are located in the lower part of the talus slope as well as locally on the connected relict rock glacier – if existing. The annual thermal anomaly reached -3.28°C to -4.91°C at Dr-22, Cv-04, Arl-02 and Arl-05 (Tab. 2).
- Type IV: slight negative anomaly possible in winter, negative anomaly in summer less pronounced than in type III, late lying snow. This area is located under the coldest zone at the bottom of a talus slope and is partially affected by the summer gravity discharge. The annual thermal anomaly is slightly negative (CV-02).
- Type 0: no seasonal anomaly. During winter and in the presence of snow, the ground temperature does not drop below 0°C. This behavior concerns mainly sectors which are not affected by the air circulation and, where the heat fluxes are only conductive. The mean annual temperature is close to MAAT (CV-01).

Dissymmetry of seasonal overcooled zones

A spatial shift can be identified between the zones of maximum winter overcooling and those of minimum summer warming (Figs. 4, 5). The seasonal contrast between types II and IV shows that in a talus slope, the area affected by the winter aspiration of cold air is shifted upwards compared to the cold summer area, the seasonal gravity discharge concentrating in the lowermost parts of the slope. Such a shift has not so far been observed on the downward relict rock glaciers. However, the occurrence of thermal regimes of type III and the lack of warm areas on these landforms indicate that internal ventilation is occurring as far as the front of a relict rock glacier and should be connected to those of the upper talus slope. Figures 4 and 5 illustrate the resulting concept of air circulation throughout a talus slope – relict rock glacier complex and the possible location of permafrost within the system.

Spatial implication on related terrestrial ecosystems

Temperature is one of the key factors (with moisture) controlling the distribution of organisms and primary production (such as pedological processes) in ecosystems. The spatial distribution of vegetation and soils on a ventilated system often indicates different GST conditions.

The seasonal asymmetrical position of cold zones plays an important role on the vegetal distribution. The thermal regime of type II is not associated with azonal vegetation. At Arl-03 for instance, the presence of *Rhododendro-Vaccinetum Juniperetosum* Ass. indicates normal ground thermal conditions during the vegetation period in summer. Conversely, a cold summer ground surface thermal regime of types III and IV is associated with alpine species like *Pritzelago alpina* and *Dryas octopetalia* (for instance at Arl-02) and limits the growth of tree roots (Körner et al. 2006) (Dr-22, Cv-04). The phenological development is strongly conditioned by the summer ground temperature.

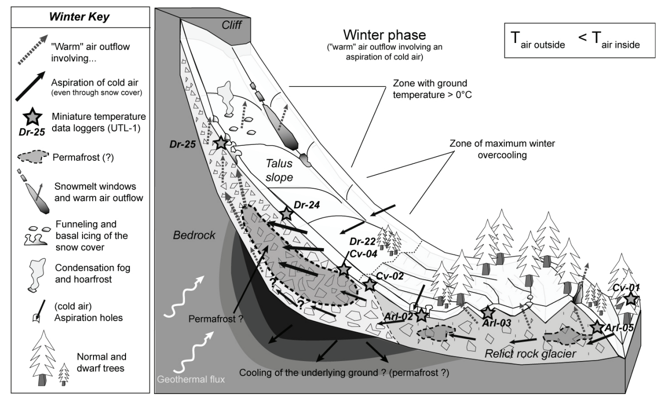

Figure 4. Model of winter ascending air circulation (in talus slope / relict rockglacier system). The stars indicate the general position of the dataloggers presented in Figure 2.

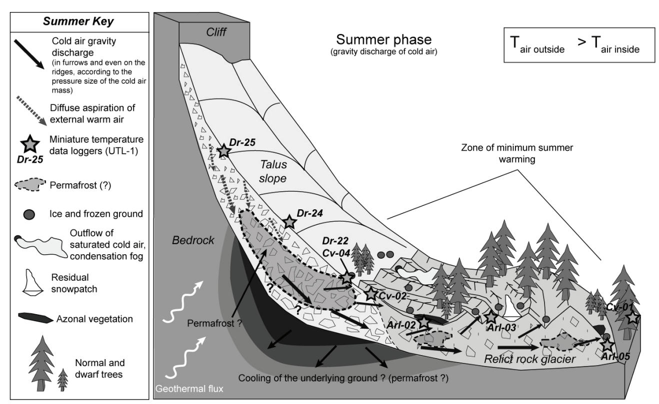

Figure 5. Model of summer descending air circulation (in talus slope / relict rockglacier system). The stars indicate the general position of the dataloggers presented in Figure 2.

Soils found in overcooled sectors evolve differently from the general pedoclimatic trend (Gobat et al. 2003). Furthermore, cold summer temperature directly influences the development of humus. Spatial variations in pH, organic texture and kind of macrorests is clearly dependent on the location of ventilated system (Rossel et al. 2004) and the GST regime.

A strong thermal stability is observed in summertime, but also from year to year (Delaloye 2004), where the cold air outflows occur. It would also provide possible favorable long term abiotic conditions for azonal and less-competitive species. Genetic DNA-analyses carried out on different separated populations of wingless beetles found in cold scree slopes have shown on the one hand an own genetic evolutionary way (island like character of this biotope), on the other hand the existence of true faunal relicts from glacial periods (Gude et al. 2003).

Conclusion

The main conclusion of our study is that thermal anomalies induced by advective heat fluxes ("chimney effect") are observed in many porous debris accumulations located below the regional lower limit of discontinuous permafrost in the Swiss mountains. An interconnection in the airflow between a talus slope and a relict rock glacier located immediately downstream has also been identified.

The combination of visual and thermal measurements has proved to be a relevant method for detecting and characterizing heterogeneous ground surface thermal regimes of a ventilated debris accumulation.

A succession of negative seasonal anomalies is typical in the lower part of a ventilated area, while in the upper part the GST regime presents usually a positive anomaly during the whole year. Other differenciated types of seasonal thermal regimes occur in the upper and lower margins of the coldest places of a debris accumulation. Moreover the occurence, development and spatial pattern of distribution of specific "cold" terrestrial ecosystems are directly influenced by the internal circulation of air.

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