

Author responses to editor comments

We are very thankful for the comments and suggestions in the attached .pdf supplementary file and modified the manuscript accordingly. Below we provide responses to open question from the supplementary file. The responses are in *italic*.

p6, l5

“The porosity within the permafrost layer ranges from 30 to 60% and is, in some part of the talus slope, mostly sealed by ice (Scapozza 2013, Hilbich 2010).”

parts (where? at the base of the slope?)

Actually, in the Lapires talus slope ground ice is not only located at its base as one would expect. The distribution of ground ice and permafrost is quite complex and a detailed description is beyond the scope of this paper. Delaloye (2004) and Scapozza (2013) provide exhaustive information on the topic. We adapted the sentence:

“The porosity within the permafrost layer ranges from 30 to 60% and some parts of the talus slope (including the base of the slope) are sealed by ice (cf. Scapozza 2013, Hilbich 2010).”

P6, l27

meaning what? necessary for convergence?

The Courant criterion ensures that the distance that a fluid potentially travels within a time step does not exceed the distance between the different elements of the mesh. If the Courant criterion is not met, it is probable to run into numerical instabilities (see also GeoStudio, 2013a, c). To clarify this issue we adapted the sentence as follows:

“The maximum time step is 0.5 days, decreasing to 0.1 days until the Courant criterion is met to minimize numerical dispersion and oscillation (GeoStudio 2013a, c).”

P9, l14

Can you say anything about the temperature differences required for circulation to occur?

Even with (very) small temperature differences circulation occurs in the modelling results. However, a weak circulation has almost no thermal effects and the convection then only has a minor influence on the ground thermal regime. If this is also the case in reality or if there is a certain threshold value that triggers circulation remains an open question and should be addressed in a follow-up study. To be complete, we added the following sentence to the manuscript:

“Even low temperature gradients cause a circulation in the modelling results. However, a weak circulation has almost no thermal effect and thus conduction dominates.”

P10, l14

“Temperature differences between the upper and lower part of the talus slope are up to 6°C during the warm and cold years 2003-2006, which is an effect of the air circulation alone, as no significant temperature differences were obtained in the conductive reference experiment (CON, grey and black line on Fig. 6).”

unclear... are you talking about 2003 AND 2006 or about all the years between 2003 and 2006 - and which is warm and which is cold? (I thought both 2003 and 2006 were warm)

We apologize for this imprecise formulation. We wanted to highlight the exceptionally warm summer in 2003 and the two cold early winters in 2004/05 and 2005/06 causing a high temperature gradient and thus an efficient air circulation. We changed the sentence to be clearer:

“Temperature differences between the upper and lower parts of the talus slope are up to 6°C during the warm summer 2003 and the cold winters in 2004/05 and 2005/06, which is an effect of the air circulation alone, as no significant temperature differences were obtained in the conductive reference experiment (CON, grey and black lines on Fig. 6).”

Numerical modelling of convective heat transport by air flow in permafrost-affected talus slopes

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Abstract. Talus slopes are a widespread geomorphic ~~phenomenon-feature~~ in the Alps. Due to their high porosity a gravity-driven internal air circulation can be established which is forced by the gradient between ~~outside-external~~ (air) and internal (talus) temperature. The thermal regime is different from the surrounding environment, leading to the occurrence of permafrost ~~outside-below~~ the typical permafrost zone. ~~So far,~~ ~~†~~ This phenomenon has mainly been analysed by field studies and only few explicit numerical modelling studies exist. Numerical simulations of permafrost sometimes use parameterizations for the effects of convection, but mostly neglect the influence of convective heat transfer in air on the thermal regime. On the contrary, in civil engineering many studies ~~were-have been~~ carried out to investigate the thermal behaviour of blocky layers and to improve their passive cooling ~~capacityeffect~~. The present study further develops and applies these concepts to model heat transfer in air flows in a natural scale talus slope. Modelling results show that convective heat transfer has the potential to develop a significant temperature difference between the lower and the upper parts of the talus slope. A seasonally alternating chimney-effect type of circulation develops. Modelling results also show that this convective heat transfer leads to the formation of a cold reservoir in the lower part of the talus slope, which can be crucial for maintaining the frozen ground conditions ~~despite increasing air temperatures caused byunder-increased-air temperature-warming due to~~ climate change.

20 1 Introduction

Mountain permafrost is currently undergoing substantial changes due to climate change as a whole and especially due to the observed ~~and-projected~~ air temperature increase. Among the typical mountain permafrost substrates, i.e. rock, fine sediments and coarse blocky surfaces, the latter ~~play-have an~~ important role on the subsurface because of their high insulating characteristics ~~for the subsurface underneath~~ due to the low thermal conductivity of the air voids between the blocks (Harris and Pedersen 1998, Herz et al. 2003, Juliussen and Humlum 2008). In addition, natural air convection with upward transport of warmer air from the permafrost body and downward transport of cold air from the surface can take place within the coarse blocky layer, both, vertically (in flat terrain) as well as in form of a 2-dimensional ~~slope-circulation~~ within a slope. These two effects ~~firstly lead first-of-all~~ to much ~~colder-lower~~ surface and subsurface temperatures for ~~surfaces-terrain~~ with coarse blocky surface layers compared to fine-grained or bedrock surfaces (e.g. Hanson and Hölzle 2004, Schneider et al. 2012,

Gubler et al. 2011), but ~~in consequence~~then also to persisting permafrost occurrences at the lower limit of permafrost (including rock glaciers and ice-cored moraines) and ~~specifically even to~~ azonal permafrost occurrences at low altitudes elevation (e.g., Kneisel et al. 2000, Gude et al. 2003, Delaloye et al. 2003, Kneisel et al. 2015). For the latter, mean annual air temperatures may be positive and ~~no~~-permafrost would not exist without this effect. ~~These~~This permafrost ~~occurrences~~ ~~occur~~ mostly occurs in ~~form of~~ undercooled scree/talus slopes and ~~have~~has been well researched in a number of publications (Funk and Hoelzle 1992, Wakonigg 1996, Kneisel et al. 2000, Gude et al. 2003, Sawada et al. 2003, Delaloye et al. 2003, Gorbunov et al. 2004, Delaloye and Lambiel 2005, Zacharda et al. 2007, Morard and Delaloye 2008, Morard et al. 2008, Phillips et al. 2009, Gądek and Leszkiewicz 2012, Stiegler et al. 2014, Kneisel et al. 2015).

Previous review articles about mountain permafrost research have highlighted the need for improved process understanding and model studies for the complex subsurface material of Alpine terrain (Harris et al. 2009, Haerberli et al. 2010, Etzelmüller 2013). While the energy balance for the coarse blocky surface layer of rock (and debris-covered) glaciers and talus slopes has been addressed in several field and modelling studies (e.g., Hanson and Hoelzle 2004, Scherler et al. 2014, Reid and Brock 2010), the effect of the internal 2-dimensional air circulation driven by the gradient between outside (air) and internal (talus) temperature has not been treated in detail or quantified with respect to the other terms in the energy balance. Transient numerical simulations of permafrost usually neglect the influence of convective heat transfer in air on the thermal regime or parameterize it with an apparent thermal conductivity (Gruber and Hoelzle 2008), or with an artificial heat sink (Scherler et al. 2013, 2014). Only very few and idealised modelling studies of the air circulation in undercooled talus slopes exist to date (e.g., Tanaka et al. 2000, 2006).

In contrast, many studies ~~were~~have been carried out in civil engineering to investigate the thermal behaviour of artificial blocky layers (such as railroad embankments) and to improve their passive cooling capacity (e.g., Goering and Kumar 1996, Cheng 2005, Cheng et al. 2007, Pham et al. 2008, Zhang et al. 2005, Arenson et al. 2006, 2007). In this study we will adapt the modelling concepts from civil engineering to investigate the feasibility of using a commercially available finite-element modelling software (GeoStudio 2013a, b, c) to explicitly model the 2-dimensional heat transfer by air flow within an idealised talus slope and to quantify the cooling effect with respect to different sensitivity parameters. The simulations are driven by observational data from the Lapires talus slope ~~Lapires~~ in the Western Swiss Alps (Delaloye and Lambiel 2005, Scapozza et al. 2015, Staub et al. 2015).

2 Theory and data

2.1 Conceptual model

~~Convective processes describe~~Convection is the transport of energy by a fluid, in the present case the transport of heat by air flow through the available pore space. This is in contrast to heat transport by conduction or radiation, which are other important processes for the energy balance within coarse blocky surface layers (Scherler et al. 2014). Convective processes are responsible for the specific (cold) temperature regime in undercooled talus and scree slopes. In 1900 already, Balch

described ~~already in 1900~~ the asymmetry of seasonal air circulations in ice caves with gravity-induced descending cold air in winter, and an absence of circulating air in summer (Balch 1900). Wakonigg (1996) described the so-called chimney effect in talus slopes, where a seasonally ~~turning-switching~~ air circulation produces descending cold air in summer and ascending warm air in winter. The ~~corresponding~~ cold air exits at the foot of the slope in summer and warm air exits through melt holes in the snow cover at the top of the slope in winter, as has been observed in field studies ~~at-on~~ various talus and scree slopes (e.g., Gude et al. 2003, Sawada et al. 2003, Delaloye 2003, Delaloye et al. 2003, Zacharda et al. 2005, Zacharda et al. 2007, Morard et al. 2008, Lambiel and Pieracci 2008, Morard, 2011).

Figure 1 shows this process schematically in its most basic form (Morard et al. 2010). Here, the ~~material within sediments in~~ the talus slope ~~is-are~~ assumed to be homogeneous and the induced air circulation is most effective when the temperature gradient between the outside air (T_{ao}) and the voids in the porous substrate (T_{ai}) is ~~large-high~~ and if the voids between the blocks have a high connectivity. ~~In reality the distribution of permafrost in talus slopes is often more complex, as m~~Material composition can be heterogeneous which means that the cooling effect ~~does not affect is not affecting~~ the whole talus slope in the same way (Delaloye and Lambiel 2005). In any case, the internal air circulation can lead to rapid ground cooling, in particular at the bottom of the talus slope, where cold air is aspirated in winter.

Model studies trying to explicitly simulate this process are rare. In a 1-dimensional study of the energy balance within the coarse blocky surface layer of a rock glacier, Scherler et al. (2014) ~~could-estimated~~ the impact of this seasonally varying convective heat transfer (heat source in winter, heat sink in summer) in comparison with other elements of the energy balance, and therefore also ~~a-comparison~~ with observed data. However, this approach does not treat the underlying process and prohibits an explicit modelling of the 2-dimensional air circulation. Tanaka et al. (2000) investigated the air circulation at two sites (Ice Valley, Korea, and Nakayama, Japan) using field data, and analytical and numerical models. In their most complex 2-dimensional model they could confirm that the cooling effect in summer stems ~~indeed~~ from a gentle katabatic flow in stable stratified conditions, whereas the winter circulation is due to an unstable convective overturning ~~with-in a convection cell of around 50 m extension~~ 50 m long convection cell. In general, these convection cells form by natural convection, i.e. air movement occurs as a function of density (temperature) differences, as opposed to forced convection ~~due to e.g. caused by~~ the influence of surface (atmospheric) wind (e.g. Arenson and Segó 2007). Hereby, the air movement due to natural convection has to be ~~large-strong~~ enough with respect to the bulk thermal conductivity of the material to yield a sustained convective cell. This relation is expressed by the Rayleigh number, which relates the air permeability, the thickness of the porous layer, the thermal conductivity of the material and the ~~spatial~~ temperature gradient within the porous layer, ~~here-i.e.~~ the talus material. The higher the air permeability, the thickness of the talus and the temperature gradient with respect to the thermal conductivity, the higher the Rayleigh number and the stronger and ~~spatially-extensive~~ longer the convective cell(s) (Arenson and Segó 2007). However, as some of the important parameters of the Rayleigh number may be temporally and spatially variable, the air circulation will change in both space and time ~~as-well~~. Consequently, an explicit modelling of the air circulation in 2 dimensions is necessary to be able to simulate the development and seasonality of the occurrence of convection cells in talus slopes. Convective heat transfer in permafrost ~~context~~ was ~~also~~ explicitly modelled in

several engineering studies. First numerical simulations were conducted by Goering and Kumar (1996) and showed a passive cooling effect of convective cells within coarse grained road embankments. The same effect, corresponding to a Rayleigh-Bénard circulation was described by Guodong et al. (2007) as a thermal semi-conductor which cools road or train embankments in permafrost regions in winter, whereas no heat can penetrate in summer, due to the stable temperature stratification within the coarse material. Further engineering studies (e.g., Arenson and Sego, 2006, Arenson et al. 2007, Pham et al. 2008, Pei et al. 2014) investigated and simulated these small-scale cooling effects to optimise passive cooling systems on mine waste piles, road- and railway embankments in permafrost regions.

In the following we will describe the model set-up for an explicit simulation of the larger and natural scale lateral heat transfer by two-dimensional air circulation within an Alpine talus slope.

2.2 Governing equations

The general heat flow equation including convective transfer by water and air can be formulated as follows (GeoStudio 2013a):

$$\left(\rho_s c_{ps} + Lw \frac{\partial W_u}{\partial T}\right) \frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left[K_t \frac{\partial T}{\partial y} \right] + c_{pa} \frac{\partial(\dot{m}_a T)}{\partial y} + \rho_w c_{pw} \frac{\partial(q_w T)}{\partial y} + Q \quad (1)$$

where

	L	latent heat of water [$J m^{-3}$]
20	W_u	unfrozen water content [$m^3 m^{-3}$]
	w	volumetric water content [$m^3 m^{-3}$]
	T	temperature [K]
	y	coordinate(s) [m]
	K_t	thermal conductivity [$W m^{-1} K^{-1}$]
25	Q	boundary flux [$W m^{-3}$]
	t	time [s]
	$\rho_{s/w}$	density soil/ water [$g m^{-3}$]
	c_{ps}	specific heat capacity soil [$J g^{-1} K^{-1}$]
	$c_{pa/pw}$	specific heat capacity air/water [$J g^{-1} K^{-1}$]
30	\dot{m}_a	mass flow air [$g s^{-1}$]

q_w flow rate (Darcy) of water [$m s^{-1}$]

Water (Eq. 2) and air (Eq. 3) flow can be described as follows and have to be jointly solved, as air and water pressure are dependent variables (GeoStudio 2013b,c):

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$$m_w \gamma_w \frac{\partial H_w}{\partial t} = \frac{\partial}{\partial y} \left[K_w \frac{\partial H_w}{\partial y} \right] + m_w \frac{\partial P_a}{\partial t} + Q_w \quad (2)$$

$$\left(\frac{\theta_a}{RT} + \rho_a m_w \right) \frac{\partial P_a}{\partial t} = \frac{\partial}{\partial y} \left[\frac{\rho_a K_a}{\gamma_{oa}} \frac{\partial P_a}{\partial y} + \frac{\rho_a^2 K_a}{\rho_{oa}} \right] - \left[\frac{\theta_a P_a}{R} \frac{\partial (\frac{1}{T})}{\partial t} \right] + [\rho_a \gamma_w m_w \frac{\partial H_w}{\partial t}] \quad (3)$$

10 where

m_w slope of the water storage curve [$m^2 g^{-1}$]

γ_w unit weight of water [$g m^{-2} s^{-2}$]

γ_{oa} relative unit weight of water [$g m^{-2} s^{-2}$]

H_w total head [m]

15

K_w hydraulic conductivity [$m s^{-1}$]

Q_w boundary flux [s^{-1}]

K_a air conductivity [$m s^{-1}$]

P_a air pressure [Pa]

ρ_a density of air [$g m^{-3}$]

20

ρ_{oa} relative density of air [$g m^{-3}$]

θ_a volumetric air content [$m^3 m^{-3}$]

R specific heat capacity of dry air [$J g^{-1} K^{-1}$]

2.3 Forcing data sets

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Forcing data are used from the Lapires talus slope Lapires which is situated ~~at an altitude range between of~~ 2400– and 2700 m a.s.l. in the Valais Alps, Western Swiss Alps (e.g., Staub et al. 2015). Several long-term mean annual ground near-surface temperature data series and several-four deep boreholes with respective temperatures measurements are available from this site (Delaloye and Lambiel 2005, Scapozza 2013, Scapozza et al. 2015, Staub et al. 2015), which is ~~also~~ part of the PERMOS network (PERMOS, 2016b).

30

For this study we used ground surface temperature (GST) data as the surface atmosphere boundary condition. Moreover, snow height data from the nearby snow-weather station Les Attelas (Swiss IMIS network) was used to model the seasonal

decoupling of the ground from the atmosphere by the snow cover. Borehole temperature data ~~was-were~~ used to compare the modelled temperature distribution to the measured temperature series in the borehole.

Validation and ground truth data are available from four boreholes, ~~both~~-regarding temperature, ~~as well as~~-material composition and ~~layer-structurestratigraphy~~ of the sediments (Delaloye et al. 2001, Scapozza 2013, Scapozza et al. 2015), and ~~from~~ geophysical measurements for the analysis of spatial heterogeneity (Delaloye 2004, Lambiel 2006, Hilbich et al. 2008, Hilbich 2010). The porosity within the permafrost layer ranges from 30 to 60% ~~and some parts of the talus slope (including the base of the slope) are sealed by ice and is, in some part of the talus slope, mostly sealed by ice~~ (cf. Scapozza 2013, Hilbich 2010). The bedrock consists of gneiss and is ~~located at 40 m depth at least at least 40 m deep~~, as observed in borehole cores (Scapozza 2013, Scapozza et al. 2015).

10 3 Model setup

The commercially available software GeoStudio has already been applied to coarse blocky permafrost substrates ~~in the context for~~ of different engineering purposes, such as the investigation of the passive cooling effect in road embankments (Arenson et al. 2006) or the heat convection in coarse mine waste rock piles (Arenson et al. 2007). Furthermore, Mottaghy and Rath (2006) used it to validate their own model approach in a study of paleoclimate permafrost in porous media. In the engineering sciences modelling approaches of convective heat transport by air and the resulting passive cooling effect are numerous (e.g., Goering and Kumar 1996, Guodong et al. 2007, Lebeau and Konrad 2009). Such ~~previous studies were able to show showed~~ the important influence of convective heat transport on the ground thermal regime at fine scales..

In this study we pick up these concepts and adapt them to a natural scale talus slope. With ~~in~~ GeoStudio we use a finite element modelling approach that solves the partial differential heat equations, including convective heat transfer over a 2-dimensional domain. The numerical domain is divided into sub-domains with different material properties (Fig. 2). Measured daily temperature values (see Sect. 2.3) were used as temperature forcing ~~data~~ at the surface-atmosphere boundary for the transient modelling. This 2-dimensional approach allows an explicit modelling of the air flow and the resulting convective heat exchange over the spatial domain of a natural scale talus slope, allowing to analyse its influence on the ground thermal regime.

25 3.1 Mesh gGeometry (mesh)

Figure 2 shows the numerical domain with its four sub- domains. Each sub- domain represents a different material and ~~has~~ therefore ~~has~~ different physical material properties (Sect. 3.2). The ~~entire~~ domain represents an idealised talus slope with a talus thickness of 17 m and a constant slope angle of 33°. An unstructured mesh of quadrilateral and triangular elements was used with a mesh size of 1.2 m in the talus ~~inde~~creasing to 3 m in bedrock and air domain. An adaptive time stepping scheme was used. The maximum time step is 0.5 days, decreasing to 0.1 days until the Courant criterion is met ~~to minimize numerical dispersion and oscillation~~ (GeoStudio, 2013a, c). Convergence is met when the results of two different iterations

differ by less than 0.01°C or do not differ by more than 0.1% for temperature and 0.001% for pressure. The maximum number of iterations was set to 30, and our experiments showed that the model is numerically stable and produced interpretable results under these numerical conditions. Numerical configuration proved, however, to be a crucial and delicate point in defining the model boundaries and running the model.

5 3.2 Material properties

Table 1 summarises the material properties of the sub-domains shown in Fig. 2 which were used in our simulations. The ~~heat~~ conductivities and heat capacities are taken from Schneider (2014), who empirically established the different values for several blocky periglacial landforms in the Murtèl-Corvatsch region. It can be assumed that these values are more accurate for natural-scale talus slopes than published values from laboratory experiments. The volumetric heat capacity for bedrock exposed at the surface is given by Schneider (2014) as 275 kJ m⁻³K⁻¹ which is approximately eight times ~~smaller~~ lower than other published values for deep seated bedrock in permafrost (e.g., 1600 kJ m⁻³K⁻¹ in Gruber and Hölzle 2008, > 2000 kJ m⁻³K⁻¹ in Arenson and Sego 2006, 2000 kJ m⁻³K⁻¹ in Nötzli et al. 2008, 2063 kJ m⁻³K⁻¹ in Wegmann et al. 1998). Considering that the model is ~~representing~~ simulating bedrock at depth and not at the surface, the volumetric heat capacity is set to 2500 kJ m⁻³ K⁻¹. Arenson et al. (2006) point out, that the heat capacity has a less prominent influence on the temperature distribution than other parameters in Table 1, especially the air conductivity.

The porosity is set to 0.5 for the material within the talus slope. This value corresponds to measured porosity values in the drill cores (Scapozza et al. 2015) and model fitted values for the Lapires site (Marmy et al. 2016) as well as previously published studies-values for other coarse grained permafrost material (Gruber and Hölzle 2008, Scherler et al. 2014). The porosity of bedrock is assumed to be very small-low compared to the talus slope and is therefore set to a near-zero value ~~for~~ numerical-reasons. The so-called air conductivity is an intrinsic permeability which can be understood as a theoretical value of the potential air flow within the material. As Arenson et al. (2006) ~~pointed~~ pointed out, the chosen air conductivity has to be in accordance with the other numerical parameter settings (time step, mesh size) to guarantee numerical stability and convergence. In our study, the air conductivity in the bedrock was set to a near-zero value, assuming that no air circulates within the bedrock. The air conductivity within the talus and in the air was set to a value of 10⁴ m day⁻¹. This value was obtained through numerical test simulations, as in Arenson et al. (2007), who obtained the same value. Higher air conductivity values did not result in numerical convergence and lead to clearly unrealistic results. In comparison to that of the rock material, the heat capacity of the air above the surface is low. Air movement in the atmosphere and its influence on the talus are simplified. There are no turbulent atmospherical fluxes or external wind sources included in the model set-up. This is of course a simplification ~~to~~ of real-world conditions, but helps to isolate the process of the internal air circulation within the talus slope without the existence of external forcing by wind.

Finally, the effect of snow is simulated in an indirect way. The thermal effect of snow on the ground is represented through the explicit GST boundary condition at the atmosphere-surface boundary. However, the decoupling of the subsurface from atmospheric circulation regarding the air flow is not represented by this boundary condition. To account for this de-coupling

of air movement, the air conductivity above the surface is parameterised as a function of snow height. Snow height data from the IMIS station Les Attelas (~~in close proximity~~ to the Lapires site, with representative snow data, cf. Staub et al. 2015) was used to parameterise air conductivity. For a snow height ~~lower than~~below 0.2 m the snow layer does not restrict the circulation. ~~From a snow heights of between~~ 0.2 m ~~to and~~ 0.8 m air conductivity linearly decreases from 10^4 to 0 m day^{-1} and thus makes the exchange between the air and the talus impossible for snow heights above 0.8 m (cf. Scherler et al. 2013). Morard (2011) ~~have has~~ shown that air aspiration is also possible through the snow, but ~~in general~~ little is known about the characteristics and importance of this effect.

3.3 Boundary and initial conditions

The lower boundary condition is set to a constant value of $+0.6^\circ\text{C}$. Temperature data from the lowermost thermistor in the Lapires borehole* LAP_1108 at 39 m ~~depth~~ show values around $+0.6^\circ\text{C}$ with no seasonal variability (PERMOS 2016a). For the surface-atmosphere boundary condition a 13-year period (2000-2012) of the GST data series from the logger S15 at Lapires (cf. Sect. 2.3, Staub et al. 2015) is used. Initial conditions are set with a constant temperature of -0.2°C in the talus and 0.2°C in the surrounding bedrock, ~~followed by a seven years~~ spin-up using the daily mean values ~~from the above mentioned~~ S15 GST data as forcing. After seven years a quasi-equilibrium state from the constant initial conditions is reached. After the seven years ~~spin-up~~ procedure the 13-year data series is used at the atmospheric boundary as forcing to show the effects of interannual variability of the driving- meteorological variables.

3.4 Model experiments

Simulations with four different model set-ups have been conducted (Table 2). The first set-up (CON) allows no air circulation at all and hence only conductive heat transfer is represented, as in most permafrost models and land-surface schemes. This set-up serves as ~~a~~ reference simulation. The second setup (CLO) consists of a permanently closed domain which allows air circulation within the talus, but no exchange with the ~~modelled~~ air domain above the surface. In the third set-up (OPE) exchange with the modelled air domain above the surface is always possible, whereas the fourth set-up (SEA) allows only a seasonal circulation with the air block to represent the seasonal decoupling from talus and atmosphere by the snow cover.

4 Results

4.1 Air circulation

Figure 3 shows the simulated air circulation and temperature distribution in the full model domain for day 300 (Oct. 27) for the experiment with open boundary conditions between ~~the~~ surface of the talus slope and ~~the~~ atmosphere (OPE). The ascending air flow within the talus slope can be clearly seen, with maximum flow velocities ~~of~~ around 100 m day^{-1} , i.e.

~0.001 m s⁻¹, which is in the range of the values estimated in other model and observational studies (Tanaka et al. 2000). Meyer et al. (2016) estimated velocities of about 0.07 m s⁻¹ for air flow within an ice cave, which can be seen as the high upper porosity limit for this kind of intra-talus air circulation. The thermal effect of this circulation is clearly seen with positive temperatures around 2°C in the upper part of the talus slope and negative ~~temperatures-ones~~ around -1°C in the lower part. Note, that the near-surface layer shows homogeneously negative temperatures at this time of the year due to seasonal freezing from the surface, except for the 10 m around the exit region of the warm ascending air flow in the upper part of the slope, where ground temperatures remain positive, except for the exit region of the warm ascending air flow near 10 m horizontal distance in the upslope part.

The air circulation ~~closes the circle via the atmosphere and aspires~~causes aspiration of cold atmospheric air into the lower part of the talus slope, where ~~also~~the ~~minimum-lowest~~ temperatures ~~can be~~ found (horizontal distance 110 m). This temperature distribution is a clear effect of the induced convective air circulation. The pure conduction experiment (CON), which served as a reference experiment and ~~includes only~~ uses heat conduction as thermal transfer process for heat transfer, shows a spatially and temporally homogeneous temperature distribution ~~(both spatially and temporally)~~. The small difference between nodes A and B in Fig. 6 is due to the slightly asymmetric model geometry. The spatial variability of the temperature difference to the OPE experiment is shown in Fig. 10 in the supplementary material. ~~Additionally, no~~Neither negative temperatures ~~and therefore no~~ permafrost conditions are produced in this reference run.

Figure 4 shows the seasonal evolution of the intensity and direction of the air circulation shown in Fig. 3 ~~regarding strength and direction~~ for the different months. The seasonal reversal of the circulation, as postulated in Delaloye and Lambiel (2005) and Morard et al. (2010, cf. Fig. 1), amongst others, is clearly visible with downslope air flow within the talus slope between June- ~~and~~ September and ascending air circulation from November ~~to~~ May. The strongest circulation (snow free and therefore ~~large-high~~ temperature gradient at the atmosphere – talus boundary) is simulated in July ~~and~~ August, whereas the winter circulation is less strong, but continues over a longer time period (7 months, in contrast to only 3-4 months in summer). Even low temperature gradients cause a circulation in the modelling results. However, a weak circulation has almost no thermal effect and thus conduction dominates.

Figure 5 shows the differences of the simulated seasonal circulation depicted in Fig. 4 between the three experiments CLO, OPE and SEA. The seasons are shown as 3-month averages regarding their typical conditions at high altitude/elevation, i.e.: winter – JFM; spring – AMJ; summer – JAS; autumn – OND. The transition period with reduced air circulation between April and June is seen in all experiments, however, it has to be noted that during these 3 months the circulation reverses (cf. Fig. 4) and downslope and upslope air flow will ~~add-contribute~~ to near-zero air flow in a 3-month average. The strong downslope ~~circulation-air flow~~ in summer is seen in OPE and SEA, but much less so in CLO, as only little space in the near-surface part of the talus slope is available for the upward-directed backflow of air. In CLO the circulation is also weaker in winter, which clearly illustrates that an open boundary between atmosphere and talus slope is necessary to produce ~~an~~ stronger air circulation ~~of greater strength~~. However, it can be seen that ~~also~~ in CLO a seasonally reversing air circulation also develops.

The OPE and SEA experiments differ regarding their open and seasonally closed boundary condition, the latter resembling the ~~isolation-insulating~~ effects of the seasonal snow cover. The comparison shows that between July ~~—and~~ December almost no differences can be seen, as the snow cover is absent or not yet thick enough to dampen the air exchange between talus slope and atmosphere. On the contrary, strong damping effects can be observed between January and June, ~~corresponding~~ ~~due~~ to the presence of an up to 2 m thick snow cover (cf. Fig. 8).

4.2 ~~Ground t~~Temperature

The effect of the seasonally reversible air circulation on the spatial ~~ground~~ temperature distribution was already shown in Fig. 3. Figure 6 shows the seasonal and interannual variations of this temperature effect for all four experiments. ~~Looking at the t~~Temperature curves ~~of in~~ the upper part of the talus slope (Node A), ~~—) indicate that~~ temperatures are always positive with a seasonal variability ~~of~~ around 1°C. An exception is ~~the~~ summer 2003, where the effect of the exceptional heat wave (cf. Schär et al. 2004, Hilbich et al. 2008) ~~can be clearly seen~~ ~~is clearly shown~~ by a temperature increase between 1°C (CON) and 3°C (OPE and SEA). Apart from this anomalous year, interannual variability is small in the upper part of the talus slope. In addition, the effect of the snow cover (SEA A compared to OPE A) is small with no differences in summer and maximal temperature differences ~~in winter~~ of around 0.2°C ~~in winter~~.

In contrast, the interannual variability in the lower part of the talus slope is much more pronounced. Here, temperatures in the OPE and SEA experiments ~~develop to~~ show permafrost conditions which are almost conserved during the ~~hot~~ summer 2003 ~~heat wave~~. Temperature decreases ~~of more than~~ ~~exceeding~~ 3°C can be observed during the cold winters 2004/05 and 2005/06. After that, temperatures increase again steadily, but still show permafrost conditions at the end of the simulation period in 2012 for the OPE experiment.

The mean temperatures in the lower part of the talus at node B over the 13 years ~~s~~ modelling period decrease by 0.28 °C (CLO), 0.94°C (SEA) and 1.19°C (OPE), respectively, compared to the CON experiment with ~~no~~ ~~out~~ convective cooling. Temperature differences between the upper and lower parts ~~s~~ of the talus slope are up to 6°C during the warm ~~summer 2003 and the cold winters in 2004/05 and 2005/06~~ ~~and cold years 2003–2006~~, which is an effect of the air circulation alone, as no significant temperature differences were obtained in the conductive reference experiment (CON, grey and black lines ~~s~~ on Fig. 6). Differences between the OPE and SEA experiments are around 0.2°C for the lower part of the talus slope, demonstrating the critical role of the snow cover ~~for in~~ ~~dampening~~ the cooling effect of the talus slope circulation.

5. Discussion

The simulations ~~qualitatively~~ reproduce ~~qualitatively~~ the internal air circulation observed in low- and high ~~altitude elevation~~ talus slopes and they are consistent with many different observations. For a critical analysis of the reliability of the model approach and its results, the degree of practicality of the processes in the model, its sensitivity to model parameters, a

comparison with observed borehole temperatures in the Lapires talus slope ~~Lapires~~ as well as a discussion of the strengths and weaknesses of the model will be addressed below.

5.1 Process analysis

Figure 7 shows the velocity of the air flow within the talus slope as a function of driving GST data. It is clearly ~~seen~~ that there is a strong correlation between ~~large-high~~ positive GST data and strong downslope (positive) air flow and correspondingly, negative GST data with upslope (negative) air flow. This is in good agreement with the underlying process, where a ~~large-high~~ temperature gradient between ~~the~~ inside and outside of the talus slope leads to ascending air if the interior is warmer ~~than the outside~~, and descending air if the interior is colder than the outside air (Fig. 1). As the temperature within the talus slope is close to 0°C, a GST of 0°C corresponds roughly to zero ~~movement-air displacement~~, as ~~there is no~~ temperature gradient ~~is present~~. The high correlation coefficient (r^2) in the OPE and the SEA experiments shows that GST is a very important factor in explaining the air flow ~~in-through~~ the talus. The slightly lower r^2 in the CLO experiment is partly due to the weaker air circulation and thus greater influence of the values near the zero curtain, but may also indicate that the closed model conditions are less representative.

Figure 8 shows an analysis of the simulated air flow in dependence of the presence/absence of a snow cover for the three different experiments. As ~~seen-shown~~ in the previous figures, the velocities are ~~smallest-lowest~~ for the CLO experiment, and the air flows downslope in summer and upslope in winter in all experiments. In addition, velocities in summer for OPE and SEA show a similar behaviour, as no snow cover is present. Due to the more efficient ground cooling in winter, the OPE experiment shows slightly higher air velocity values. However, large differences can be seen in late autumn and during winter. Clearly, winter velocities are ~~largest-highest~~ for OPE, as ~~there is no snow cover inhibiting~~ ~~no snow cover inhibits~~ the coupling between talus slope and atmosphere in this experiment. In contrast, maximal velocities for the ascending air flow are obtained in late autumn in the SEA experiment, which can be seen as the most realistic simulation, as it includes the non-linear damping effect of the snow cover. In late autumn, air (and also ground surface) temperatures can ~~already~~ be negative due to strong radiative cooling at the surface at night. In the absence of a thick snow cover (e.g., in autumn/early winter 2005, Fig. 8) a strong air circulation can develop, as the temperature gradient between interior and outside is ~~large-high~~. As soon as the snow cover ~~completely insulates the ground, height reaches a completely isolating state~~, the air circulation is severely damped as can be seen by the increasing and then flattening velocity curve in the SEA experiment. A similar, but much weaker effect can be seen in early summer when the snow cover thickness decreases again. ~~But-However~~, as the temperature gradient is much weaker during ~~this-the main~~ snow melt period, its effect on the evolution of the air circulation is also much smaller.

5.2 Sensitivities Model sensitivity analysis

Sensitivity simulations with different slope angles showed a strong influence of the slope angle on the ~~strength-intensity~~ of the air circulation and therefore ~~the-on~~ temperature evolution. Not surprisingly, ~~larger-higher~~ slope angles lead to higher

velocities and larger temperature contrasts due to the stronger gravitational forces, as was also noted in previous studies (e.g., Guodong et al. 2007). ~~Because~~As the mesh geometry (cf. Fig. 2) changes with changing slope angles, the obtained temperature dependencies on slope angle cannot be compared quantitatively ~~in a strict sense~~. In addition, the circulation pattern changes with increasing slope angle. For the simulations with ~~comparatively large~~high slope angles (such as the 33° depicted in Fig. 2, which was used in all simulations shown above) only one 2-dimensional advection cell is present, with seasonal reversal of the flow direction (cf. Figs. 3-5). With decreasing slope angle this circulation cell ~~not only~~ decreases in strength, ~~it is also and complemented by~~ additional 1-dimensional vertical convection cells are formed, which do not extend over the full model domain (not shown). For slope angles ~~smaller~~lower than around 5° the air flow is dominated by several individual small vertical convection cells.

Guodong et al. (2007) describe a similar relation between slope angle and circulation patterns in laboratory experiments. They found a minimal slope angle of 15° for connected advection cells and a dependence on the Rayleigh number for ~~larger~~higher slope angles (cf. also section 2.1). ~~In practice and in our model simulations it is difficult to distinguish clearly between horizontal advective and vertical convection cells as there is usually a gradual transition between the two phenomena.~~In practice, and also in our model simulations, a clear distinction between advective (horizontal) and vertical convection cells is difficult to make, as usually a gradual transition between the two phenomena is observed. Using in-situ measurements, Hanson and Hölzle (2004) showed that for the case of rock glacier Murtèl, a comparatively flat rock glacier ~~that contains with~~ large furrows and ridges ~~which additionally inhibit~~inhibiting the lateral air circulation, the vertical exchange of air is more important than advective processes. A thorough observation- and simulation-based analysis of these dependencies ~~still needs to be carried out, has, however, not been undertaken yet.~~

In addition, the model is very sensitive regarding the so-called air conductivity parameter introduced above. Arenson et al. (2006) concluded that finding a physically-consistent combination of air conductivity, and temporal and spatial discretisation ~~poses the largest~~is the biggest practical problem ~~concerning~~affecting numerical stability in soil temperature simulations. In our simulations only a narrow range of air conductivities allow for convergent calculations that produce convective circulation patterns for a given mesh and time step. Similar results were obtained in GeoStudio (2013~~2~~a) and Arenson et al. (2007), which suggests that the air circulation should be used as a calibration parameter wherever subsurface temperature data are available, especially as ~~usually there are generally~~ no in-situ air velocity measurements within the talus slopes ~~are available.~~

5.3 Comparison of modelled and measured ground temperature data to borehole data

Finally, the idealised experiments discussed above can be compared to the observed temperature evolution in a borehole situated in the central part of the Lapires talus slope ~~Lapires~~. Even though the driving GST values were taken from this talus slope, this comparison can only be qualitatively ~~made~~, as no temperature calibration has been attempted in our model and there are several differences between our model setup and the real conditions ~~exist~~. ~~Most notably~~The most notable difference is the presence of a massive ice core at Lapires (Hilbich 2010, Scapozza et al. 2015), which was not included in our

simulations ~~for simplicity~~. Even ~~Al~~though technical problems ~~with the temperature measurements until 2010 prohibit~~ prevent a detailed analysis of the ~~permafrost borehole~~ temperatures ~~until 2010~~, permafrost conditions are clearly present with an active layer thickness ~~ranging~~ between 4-6 metres (PERMOS 2016a). Generally, the ~~results from the simulations~~ simulated values are similar to the observed temperatures, however, a small cold bias ~~in the model~~ can be identified ~~in the model~~ (cf. Fig. 9). ~~Correspondingly~~ As a result, the modelled active layer ~~thickness is smaller~~ is thinner and the penetration depth of the winter cooling is ~~larger~~ greater than in the observations.

This may ~~be due to~~ have several reasons. Firstly, the mean of the driving GST values of the logger LAP_S15 is colder than the mean of the uppermost temperature sensor in the borehole (Staub et al. 2015). Secondly, the massive ice core influences the ground thermal regime regarding (i) the induced air circulation patterns by blocking the air flow in a central region of the talus between 4 m and approximately 15 m depth, (ii) its different thermal properties from the air/rock material of the simulated talus slope and (iii) the latent heat necessary for phase changes. Finally, due to numerical effectivity, the depth to the bedrock was ~~chosen to be much shallower~~ much lower in the model than in reality (Scapozza et al. 2015), which may have an additional effect on the observed discrepancies.

5.4 Models strengths and weaknesses

Modelling air circulation and thus the convective heat transfer within a talus slope is an important contribution to the understanding of the complex thermal regime of a talus slope in mountainous environments. The strength of this modelling approach lies in the fact that convective heat transfer is explicitly modelled in two dimensions, and it is a first step to an explicit description of this process in more sophisticated long term permafrost models where ventilation ~~so far is~~ has so far been neglected or only parameterized (Marmy et al. 2016, Luethi et al. 2016). Weaknesses ~~foremost~~ mainly concern the lack of latent heat effects ~~caused~~ by melting/freezing of ice. The model domain in this study is assumed to be dry and hence there is no ice ~~buildup~~ formation. This allows assessment the influence of the convective heat transfer by air flow in an isolated way but neglects the interaction of water, ice and air. In ice-rich talus slopes this interaction ~~surely plays~~ may have an important role but was beyond the scope of this study and ~~might be part of~~ should be part of future model improvements. Previous studies on the effect of convective heat transfer in porous media in permafrost environments also neglect the influence of water flow and assume the numeric domain to be dry (Goering and Kumar 1996, Arenson et al. 2006, 2007, Guodong et al. 2007). The representation of snow is still quite poor. The interactions between the talus slope circulation and snow layer are complex and not yet fully understood. Melt holes due to warm air exits are frequently observed at the top of a talus slope (Morard 2011) and probably have a significant impact on the air flow path and the air velocity. The pronounced ground cooling in the lower part may also influence the snow cover, ~~especially at its base and~~ some refreezing of percolating melt water may take place. Finally, the air block above the talus slope is a very simplified representation of the atmosphere. First of all, a pressure boundary condition could have been applied to link the talus slope to the atmosphere. Air flow at the boundary is not known and would have needed further parameterizations - ~~therefore~~ so this approach was dismissed. Secondly, we assume that the ~~too~~ high thermal conductivity of air used in this study ~~compensates~~ to some extent

compensates the missing turbulent fluxes which are prevented by the actual low air conductivity. This may affect the absolute values but allows numerically consistent simulations which represent the underlying process within the talus slope. Modelling the atmospheric air flow explicitly, for example, the effect of wind speed on the intra-talus circulation, would, however, strongly increase the complexity of the model ~~strongly~~.

5 | **6. Conclusions and outlook**

A numerical study of convective heat transfer by air flow in a 2-dimensional talus slope has been conducted. The results show that without forced convection a seasonally alternating circulation develops which leads to a convective heat transfer within the talus and thus to a cooling effect in the lower part of the talus slope. It therefore has a significant influence on the thermal regime in a talus slope. Sensitivity studies with a conduction model show that this cooling can be crucial to maintain
10 | the frozen state of the ground during the warm season under warming climate conditions. Furthermore, sensitivity studies, using different atmospheric boundary conditions, were conducted by simulating a closed-to-atmosphere boundary, and open-to-atmosphere boundary and a seasonally closed-to-atmosphere boundary to represent the seasonal decoupling by a snow cover. The results show that an open-to-atmosphere boundary leads to the most efficient cooling. Compared to a conduction
15 | only set-up, a cooling of 0.28 °C (CLO), 0.94°C (SEA) and 1.19°C (OPE) , respectively, was found in the lower part of the talus slope as mean value over the whole 13 years. Further sensitivity studies showed the dependence of strong cooling effects on a high air velocity in the ground as well as on an increase in slope angle. However, the circulation pattern does not change significantly in these cases.

So far, this phenomenon has mainly been documented by field studies (e.g., Delaloye et al. 2003, Gude et al. 2003, Sawada et al. 2005) and the explicit modelling of this process now confirms their findings. For simplicity, we neglected the
20 | formation of ice, which may be a reasonable assumption for low-elevationaltitude, but not for high alpine talus slopes (Delaloye and Lambiel 2005, Morard et al. 2010, Hilbich 2010, Scapozza et al. 2015). Furthermore the infiltration of melt water and precipitation as well as intra talus water flows (Luethi et al. 2016), which can lead to advective heat transfer and thus have an influence on the ground thermal regime, are neglected. This will have to be improved in a future study. Future work should therefore aim to model the internal air circulation for a specific site taking into account a more detailed structure
25 | like an impermeable ice core to get a better validation and site specific quantifications of the process. Furthermore efforts have to be made to understand the complex coupling of snow and air circulation within a talus slope.

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Table 1: Material properties used for the GeoStudio simulations in this study (based on Schneider 2014, Arenson and Segó 2006, Arenson et al. 2007 and Scapozza et al. 2015, see text). The snow layer ~~aets-only~~ only acts as an-as idealised boundary that seasonally damps and prohibits air exchange between talus and atmosphere through coupling of the air conductivity value to the snow height. See text for further explanations.

material	thermal conductivity		specific heat capacity	vol. heat capacity	porosity	air conductivity
	[W K ⁻¹ m ⁻¹]	[kJ day ⁻¹ m ⁻¹ K ⁻¹]	[J kg ⁻¹ K ⁻¹]	[kJ m ⁻³ K ⁻¹]		[m day ⁻¹]
bedrock	2.4	207	99	2500	0.01	0.01
talus	1.2	103	904	1256	0.5	10 ⁴
air	1.2	103	1	1.3	1	10 ⁴
snow	1.2	129	1	1.3	1	0 – 10 ⁴

Table 2: List and description of model experiments conducted.

Name	Processes included	Description
Conduction only (CON)	Conduction only	-
Closed (CLO)	Conduction and convection	No exchange with the air block
Open (OPE)	Conduction and convection	Unrestricted exchange with the air block
Seasonally closed (SEA)	Conduction and convection	Seasonally restricted exchange with the air block

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5 Figure 2: Model setup and mesh showing the four sub-domains used in the talus slope experiments. The points (nodes) marked by A and B are reference points which are further analysed below.

Figure 2: Model set-up and mesh showing the four sub-domains used in the talus slope experiments. The points (nodes) marked by A and B are reference points which will be further analysed in the following.

10 Figure 3: Simulated temperature distribution (colours) and air current vectors in the talus slope for the open experiment (OPE) for day 300 (winter circulation). The intensity of the circulation is marked by the grey/black colour of the vector arrows and is given in $m\ day^{-1}$.

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15 Figure 4: Mean monthly air flow of the open experiment (OPE) over the 13 modelled years. The dashed line marks the domain of the talus slope. The seasonal differences in intensity and direction of the air circulation, are clearly shown by the direction and colour of the arrows.

20 Figure 4: Mean monthly air flow of the open experiment (OPE) over the 13 modelled years. The dashed line marks the domain of the talus slope. The seasonal differences of the air circulation, both, regarding strength and direction, are clearly seen by the direction and colour of the arrows.

25 Figure 5: Modelled seasonal mean air flow for the modelled 13 years for the different atmospheric boundary conditions: (top) closed to atmosphere (CLO), (middle) open to atmosphere (OPE) and (bottom) seasonally closed to atmosphere (SEA). The dashed line is the talus slope. Figure 5: Modelled seasonal mean air flow for the modelled 13 years for the different atmospheric boundary conditions: (top) closed to atmosphere (CLO), (middle) open to atmosphere (OPE) and (bottom) seasonally closed to atmosphere (SEA). The talus slope is shown with the dashed line.

Figure 6: Temperature evolution at two different locations in the upper (node A, solid lines, see Fig. 2) and lower (node B, dashed lines, see Fig. 2) part of the talus slope for the CLO (red), the OPE (blue), the SEA (purple) and the CON (black) experiment.

Figure 6: Temperature evolution at two different locations in the upper (node A, cf. Fig. 2) and lower (node B, cf. Fig. 2) part of the talus slope for the CLO (red), the OPE (blue), the SEA (purple) and the CON (black) experiment.

30 Figure 7: Relation between velocity of the air flow at node B (see Fig. 2) and the forcing ground surface temperature (GST) for the three different experiments OPE, SEA and CLO. Positive velocities indicate downslope movement and negative velocities indicate upslope movement of air.

35 Figure 7: Relation between velocity of the air flow at node B (cf. Fig. 2) and the forcing ground surface temperature (GST) for the three different experiments OPE, SEA and CLO. Hereby, positive velocities indicate downslope movement and negative velocities indicate upslope movement.

Figure 8: Velocity of the simulated air flow at node B (see Fig. 2) in the experiments OPE, SEA and CLO for the period 2010-2013 in relation to the presence of a snow cover (grey bars). Positive (negative) velocities correspond to downslope (upslope) air flow.

Figure 8: Velocity of the simulated air flow at node B (cf. Fig. 2) in the experiments OPE, SEA and CLO for the period 2010-2013 in relation to the presence of a snow cover (grey bars). Positive (negative) velocities correspond to downslope (upslope) air flow.

Figure 9: (a) Temperature plot along a perpendicular profile through node B for the OPE simulation for the 13 year period. (b) Borehole temperature from borehole LAP_0198 at the Lapires field site (PERMOS 2016a). Missing values due to technical problems at greater depths are plotted in dark grey.

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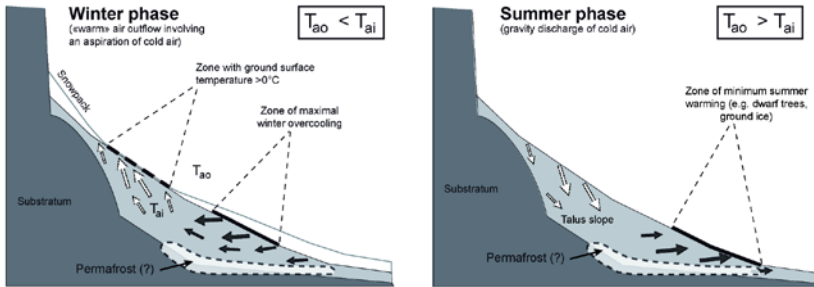


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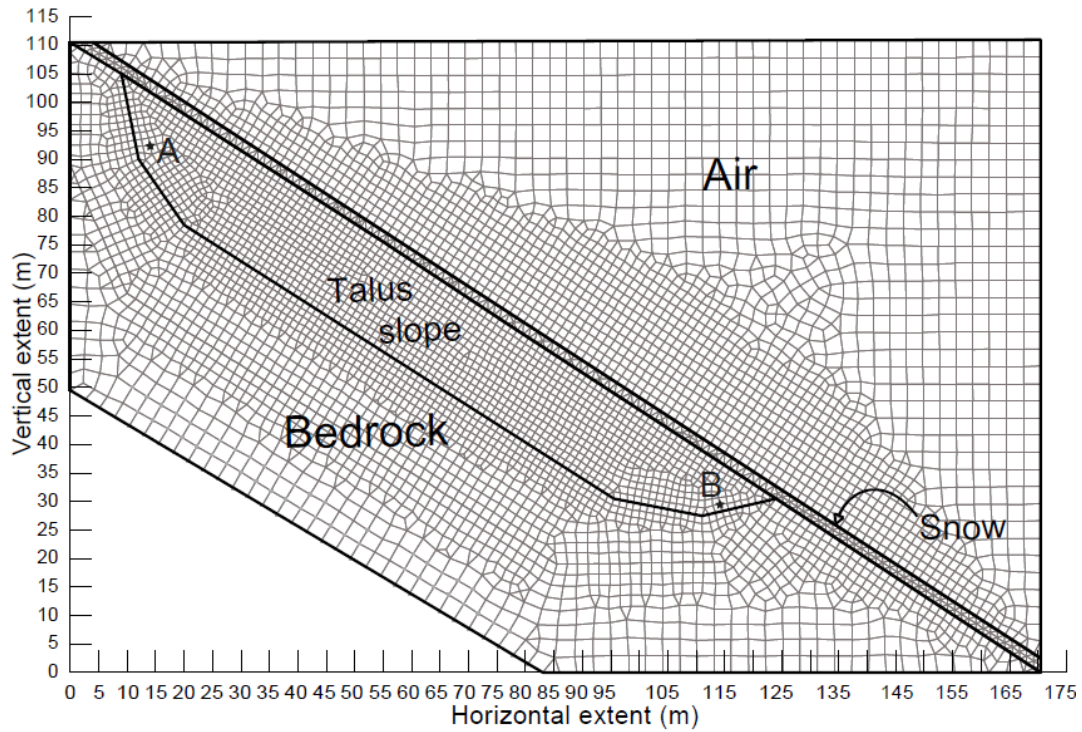


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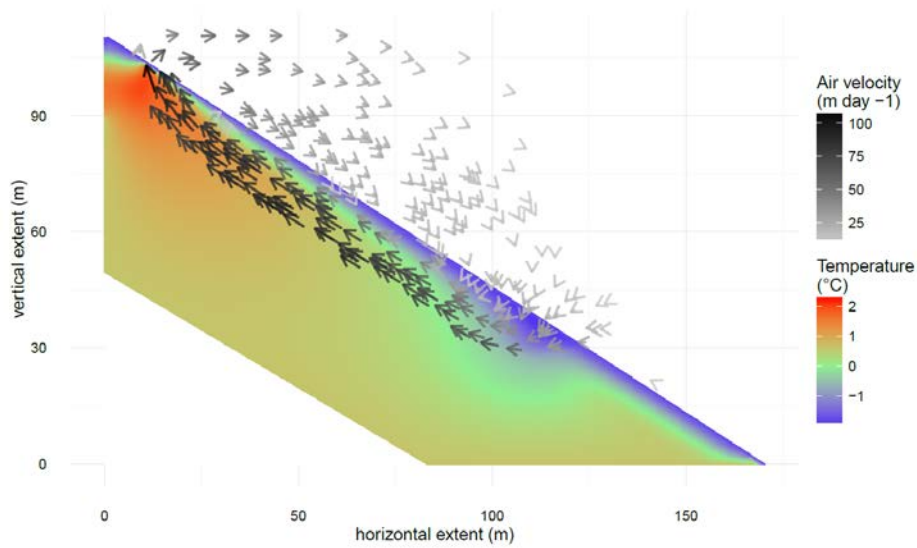


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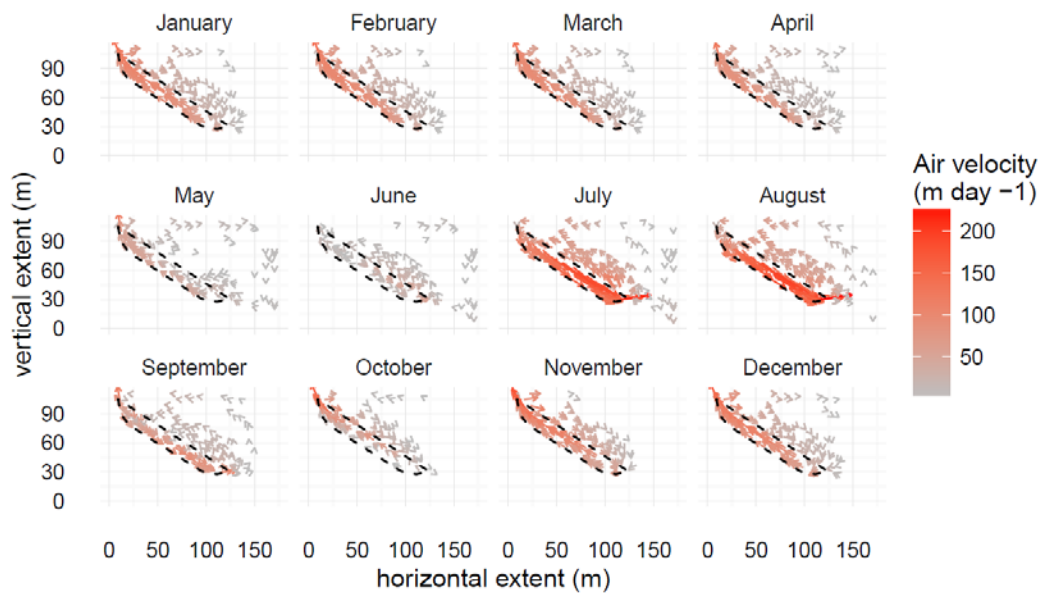


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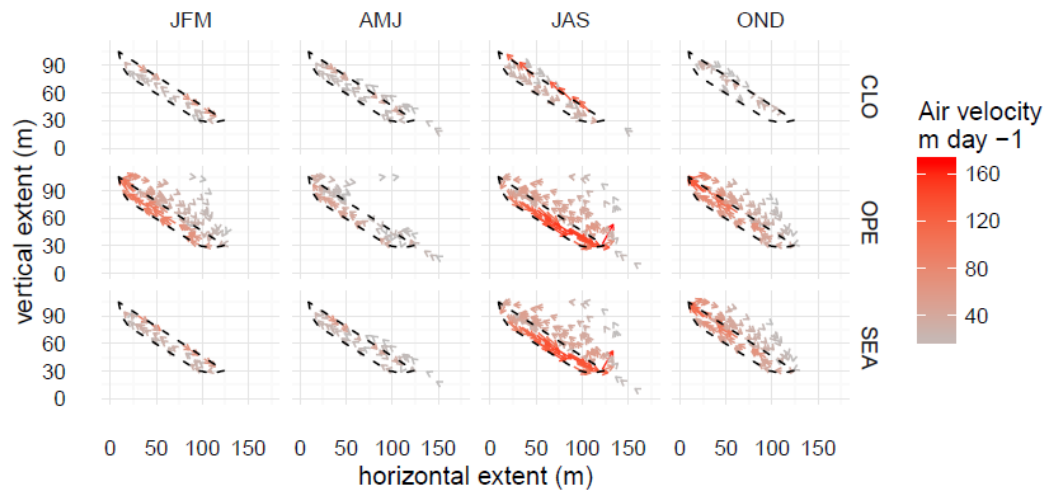


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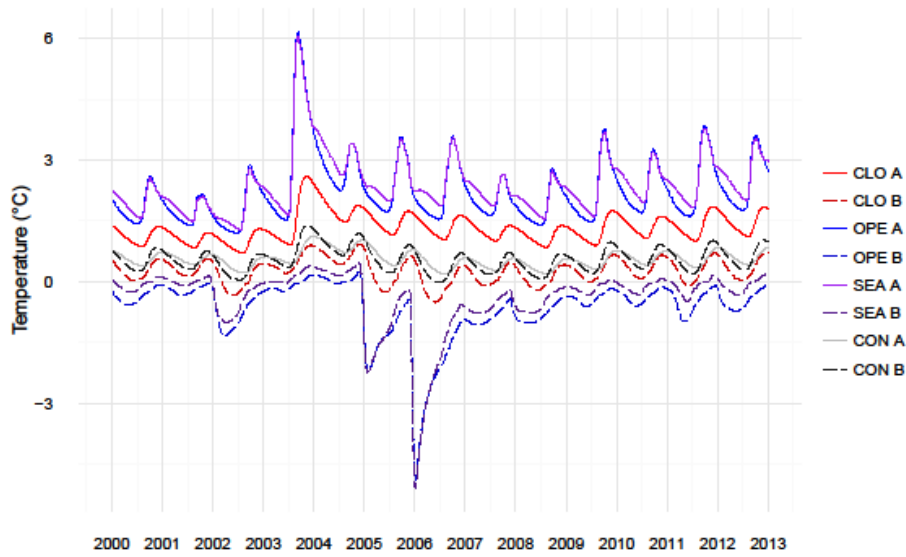
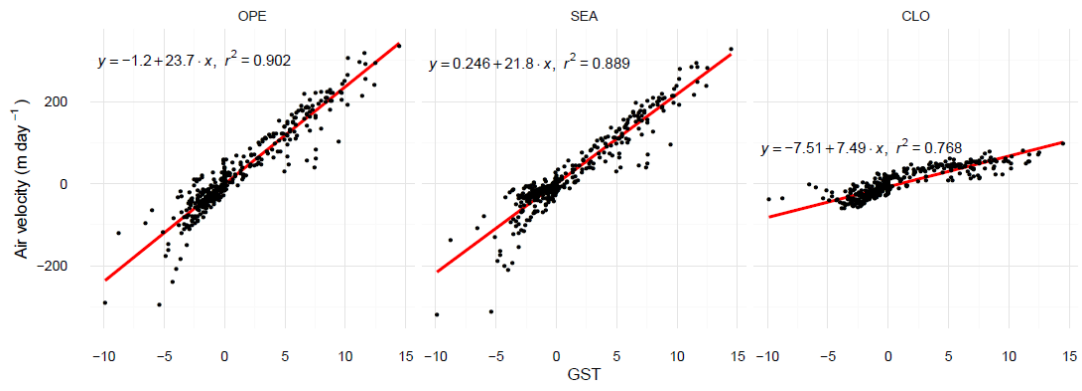
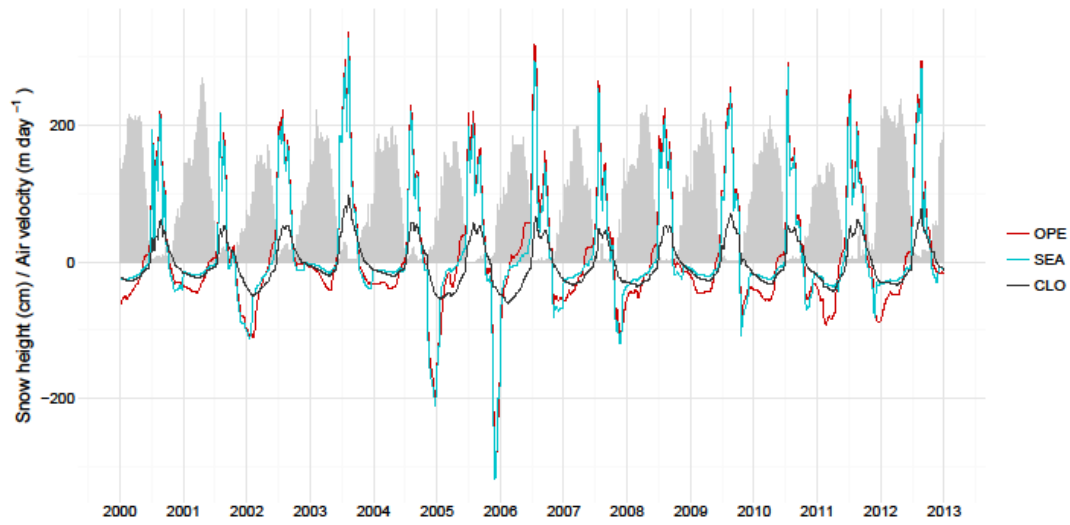


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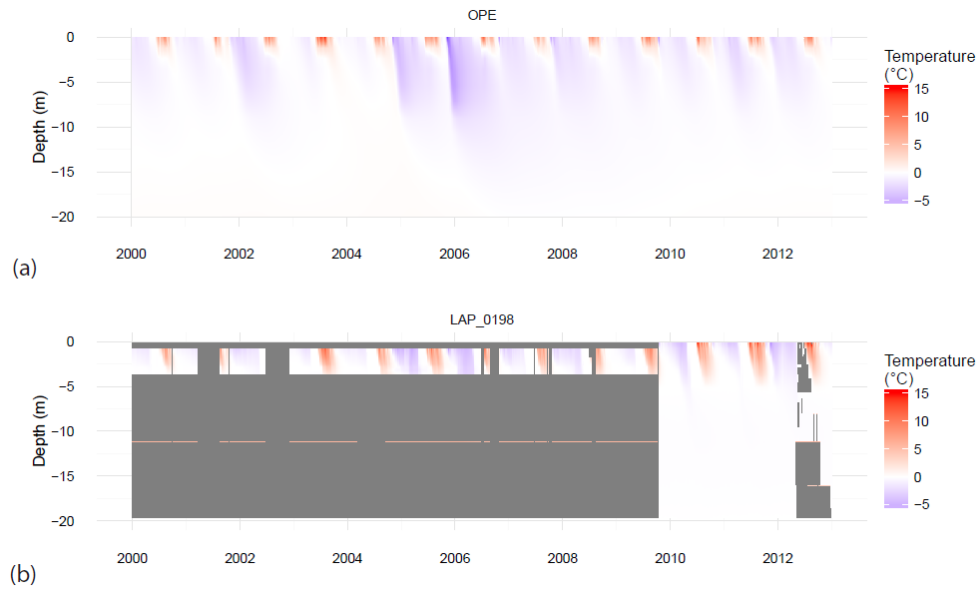


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Supplementary material

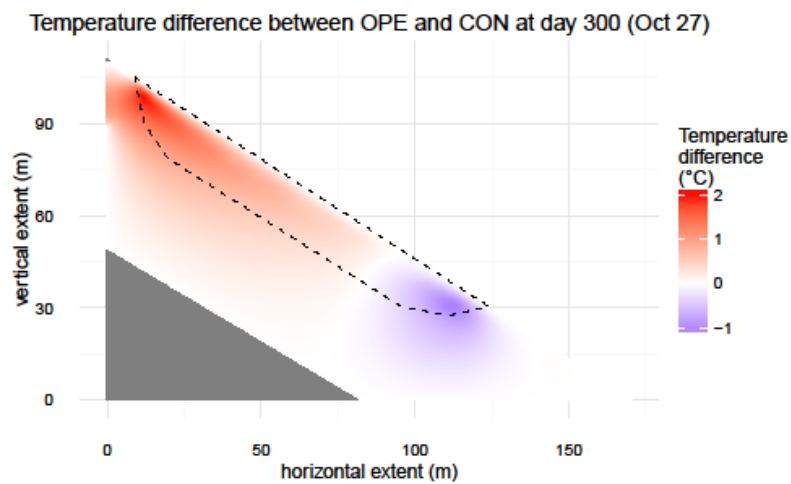


Figure 10: Simulated temperature difference (colours) in the talus slope between the open (OPE) and the conduction only (CON) experiment for day 300 (winter circulation).