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The influence of seasonally frozen soil on the snowmelt runoff at two Alpine sites in southern Switzerland

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Abstract

In spring, snowmelt releases huge quantities of meltwater, affecting the hydrology of Alpine areas. Seasonal soil frost influences these water fluxes by locally decreasing the infiltration capacity of the soil, resulting in an increased amount of surface runoff. The main goal of this study was to investigate the spatial variability of the seasonal frost depth and to quantify by how much this seasonal soil frost affects the snowmelt discharge. For this purpose, an extensive field study was run for two winter seasons (2000/2001 and 2001/2002) at Gd St Bernard (2470 m) and Hannigalp (2090 m) in the southern Swiss Alps. The different components of the water balance (lateral runoff, deep percolation, liquid soil water content) were measured on delimited plots of 5 m^2. The two winters investigated had opposing weather and soil frost conditions: in the first winter a thick snowpack prevented the formation of soil frost, whereas in the second winter little snow fell until January, which produced a deep and persistent soil frost. We classified the snowmelt events into several classes (mid-winter, late winter, spring and post-spring) and analysed the significance of the different water flow components for each melt situation. While 90–100% of melt water infiltrated into the ground during the first winter, 25–35% of melt water ran off laterally in the second, mainly during late winter and spring snowmelt events. In that second winter, the soil infiltration capacity was primarily reduced by the presence of a basal ice sheet after mid-winter melt events.

Keywords: Snowmelt; Runoff; Seasonal soil frost; Water balance; Alps

1. Introduction

Due to the presence of glaciers and snow, mountains play an important role as water reservoirs for the lowlands. In particular, they supply the water for human activities during dry seasons, either directly through surface runoff or indirectly through infiltration and aquifer recharge. In addition to water resources management, snowmelt timing and dynamic are also relevant for hydropower generation, for agricultural production and management (soil erosion and washing away from arable land (Zuzel and Pikul, 1987; Pikul et al., 1992)) and especially for

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environmental-impact assessment, as high nutrient loads are often observed during snowmelt in rivers (Williams and Melack, 1991). Snowmelt also needs to be considered with regard to hazardous flood events and as an activating factor for landslides (Tullen, 2002). These established facts emphasize the need to better understand the snowmelt runoff processes, in particular, to specify which conditions/processes may influence the discharge pattern significantly.

A factor affecting the flow path across landscapes is seasonal soil frost. Due to its recognized influence on global hydrology, numerous studies have investigated the effect of frozen ground on the meltwater runoff in cold regions. Catchment runoff studies in areas with permafrost (Kuchment et al., 2000) or seasonal soil frost (Cherkauer and Lettenmaier, 1999) have demonstrated the hydrological effects of frozen ground at the large scale. Local process studies showed that the soil infiltration capacity is normally reduced by the presence of pore ice, which may generate considerable surface runoff and decreases the underlying groundwater recharge (Sand and Kane, 1986; Gusev, 1989; Koren et al., 1995). But it has also been demonstrated that meltwater is able to percolate through the frozen layer through air-filled pores (Stadler et al., 1996; Stähli et al., 1996; Nyberg et al., 2001).

Little is known about the effect of seasonal soil frost on the meltwater pathways in Alpine regions. Until now, most frozen soil experiments have been conducted in Scandinavia or the arctic regions, which are characterized by a different soil and snow cover type, climate and topography (Chacho and Bredthauer, 1983; Woo et al., 1982). Alpine hydrological research has predominantly been focused on snow, glacier and permafrost hydrology (Glen, 1982; Thenthorey, 1992; Singh and Singh, 2001). There is an evident and quite surprising lack of studies, as well as tools, related to small- and large-scale effects of seasonal soil frost on Alpine hydrology.

This lack of research in alpine areas was our motivation to initiate a study with the principle aim of evaluating the impact of soil frost on Alpine groundwater recharge. Special emphasis was put on winter conditions representing Alpine environments, where melting predominantly occurs at the end of the season.

The goals of the present paper are:

(a) to determine the water balance of frozen and non-frozen Alpine soils during specific snowmelt events,
(b) to assess the contribution of different runoff flowpaths for such snowmelt events,
(c) to quantify the reduction in deep percolation due to soil frost.

2. Materials and methods

2.1. Test sites

Two experimental sites representing typical Alpine regions were selected. The scientific criteria were constrained by technical criteria, as fieldwork could only take place if safety and accessibility were guaranteed all year round and infrastructure like an electrical supply or road access in summer was available. The selected sites were Hannigalp (2090 m) (46°12′; 7°52′) above Grächen and Gd St Bernard (2470 m) (45°52′;7°10′), both located in the southern Swiss Alps (Fig. 1). The experiment was carried out during winters 2000/2001 and 2001/2002.

The two sites differ markedly in their meteorological characteristics. The most important discrepancies are the yearly precipitation and the wind velocity. Hannigalp is located between two main Alpine ranges and is protected from northern and southern cyclones. The annual precipitation at Grächen (1617 m) is therefore only 512 mm.

Fig. 1. Location of the two experimental sites Hannigalp (above Grächen) and Gd St Bernard in the southern Swiss Alps.

In contrast, Gd St Bernard experiences approximately four times as much precipitation (2100 mm), due to its location on the main Alpine range, where Atlantic cyclones are more active.

The site of Hannigalp is surrounded by coniferous forest, some 100 m below the treeline, next to a ski lift and protected from external interference by a 1.5 m high fence, 100 m long. The site has an average slope of approximately 23% with eastern exposure. It belongs to a slope ranging from 2600 down to 1600 m and having an average gradient of 30%.

At Gd St Bernard, three different sub-sites were selected, differing in their orientation. The main site (the south plot) is located 30 m above the Gd St Bernard, northwest of the monastery. The site orientation is south and the mean slope is approx. 65%. The site is on the lower part of a slope ranging from 2600 down to 2470 m at the pass. It is occasionally covered by avalanches. The second site (the north plot) is located 250 m southeast of the monastery, at an altitude of 2480 m. The orientation is northwest and the slope is 58%. It is located at the bottom of a steep slope (75%). The third site (the east plot) (2420 m) is situated approximately 1 km to the south of the pass, on the Italian side. The exposure is easterly and the mean slope is approx. 63%. All sites are located approx. 600 m above the tree line.

2.2. Physical properties of the soil

The soil (i.e. the layer above the substratum) at Hannigalp is a sandy loam (Table 1) (US soil taxonomy) classified as ferric podzol. The soil is 50–70 cm thick, made up of an organic layer (5 cm), a reddish-brown horizon (20 cm) and a dark black horizon (40 cm). An old till constitutes the substratum (approx. 5–10 m thick). According to Parriaux and Nicoud (1988), the substratum saturated conductivity is estimated to range from 10^{-5} to 5×10^{-4} m s^{-1}. Below the till, the rock is formed by gneiss and schist from the Michalbel-Kristallin.

The vegetation is rhododendron (*Ericaceae*) and grass. From Porchet infiltration tests (Audry et al., 1973), the saturated hydraulic conductivity of the fine material was estimated to be approximately 3×10^{-5} m s^{-1} between a depth of 20 and 50 cm. In the upper 20 cm it varied between 10^{-4} and 10^{-3} m s^{-1}.

At Gd St Bernard, the physical properties of the soil were determined for the south site only. Nevertheless it is feasible that the same properties are valid for the east and north sites. The soil texture is similar to the one at the Hannigalp site (Table 1), and classified as ranker/rhegosol. The soil, however, differs markedly from the Hannigalp soil, due to the presence of large slate stones (diameter >5 cm) at all depths in the soil. Gneiss constitutes the underground. Soil depth varies between 40 and 80 cm. It is composed of a 5 cm-thick organic layer overlying the 50 cm-deep mineral soil. The vegetation is grass homogeneously distributed on the experimental sites. From Porchet tests, the saturated hydraulic conductivity of the soil layer between 10 and 25 cm was estimated to be approximately 5×10^{-5} m s^{-1}.

2.3. Experimental set-up

A similar set-up for measuring surface and subsurface runoff was built up at Hannigalp (Fig. 2) and at Gd St Bernard's south plot. Two gutters collected the lateral surface and subsurface runoff at the lower end of a 2 m-wide plot having an average down-slope

Table 1
Soil physical characteristics of the soils at Hannigalp (ferric podzol) and at Gd St Bernard (ranker/rhegosol)

Site	Horizon (cm)	Sand content (%)	Loam content (%)	Clay content (%)	Porosity (m^3/m^3)	Bulk density	Saturated conductivity (10^{-5} m s^{-1})
Hannigalp	5–15	63.20	30.40	6.50	55.1	1.09	
	15–25	60.55	33.65	5.85	54.1	1.12	
	25–35	57.90	36.90	5.20	50.8	1.12	3
Gd St Bernard	0–7	53.50	38.10	8.40	73	0.64	
	7–15	48.80	40.85	10.35	59	0.90	5
	15–25	44.10	43.60	12.30	57	0.90	5

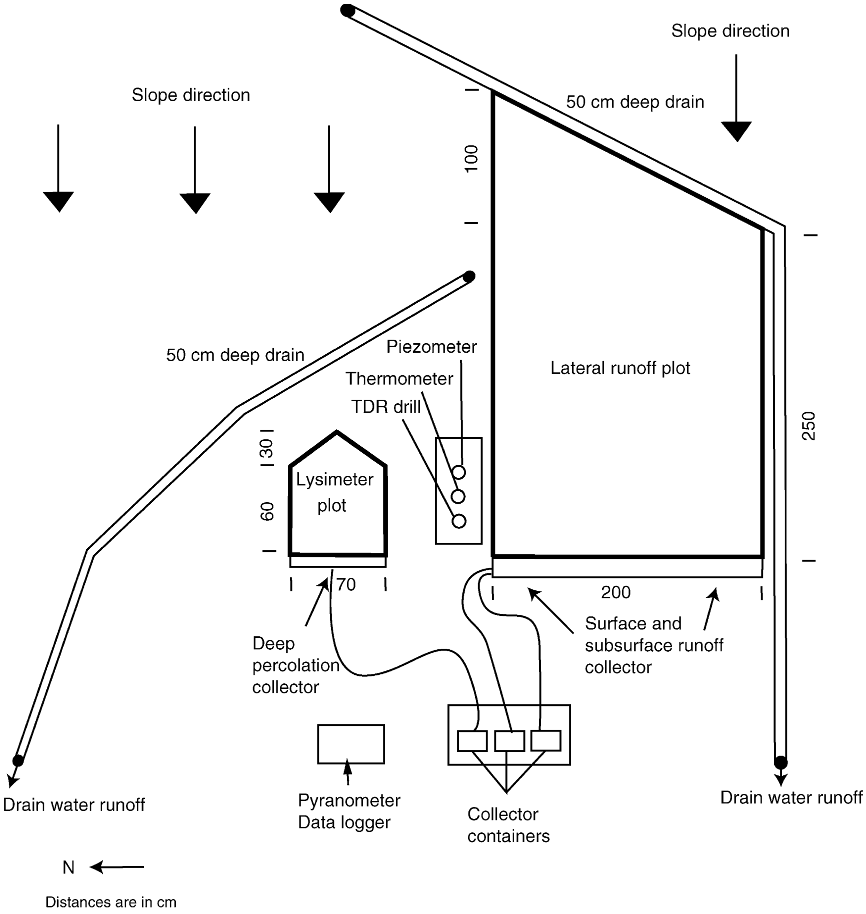

Fig. 2. Layout of the experimental site at Hannigalp.

length of 3 m. Surface runoff was collected from the surface to a depth of 3 cm, while subsurface flow was measured between 3 and 28 cm depth (Fig. 3a). The collecting containers were filled up with gravel and sand to allow water to drain to the two gutters, even under unsaturated conditions. It diminished the capillary barrier between the soil and the collecting device. The gutters were equipped with heating wires to prevent water from freezing inside them. The deep percolation was measured in an open lysimeter (Fig. 3b) with a surface area of 0.525 m^2 (Hannigalp) and 0.63 m^2 (Gd St Bernard). The bottom and outflow of the lysimeter was constructed with a metallic sheet, 70 cm wide and 90 cm long, located 40 cm under the soil. The connectivity between soil and collector was provided by a layer of gravel and sand. Both the runoff plot and the lysimeter were protected from external water inflow by 50 cm-deep drains. The discharge was measured manually in the first winter using 20 l sampling containers, whereas a 100 ml tipping bucket was used in the second winter.

Comparison between the calculated and measured deep percolation flux indicated that, at Hannigalp for winter 2000/2001, only 5% of the percolated water was collected by the lysimeter, due to the poor connection between the gravel and the sand. To take into account the non-linear response of an open lysimeter, the restitution ratio was modified using a restitution proportion calculated for high and low soil water infiltration. For winter 2001/2002, the seepage values were not readjusted as the lysimeter set-up had been improved in summer 2001 by filling the gap

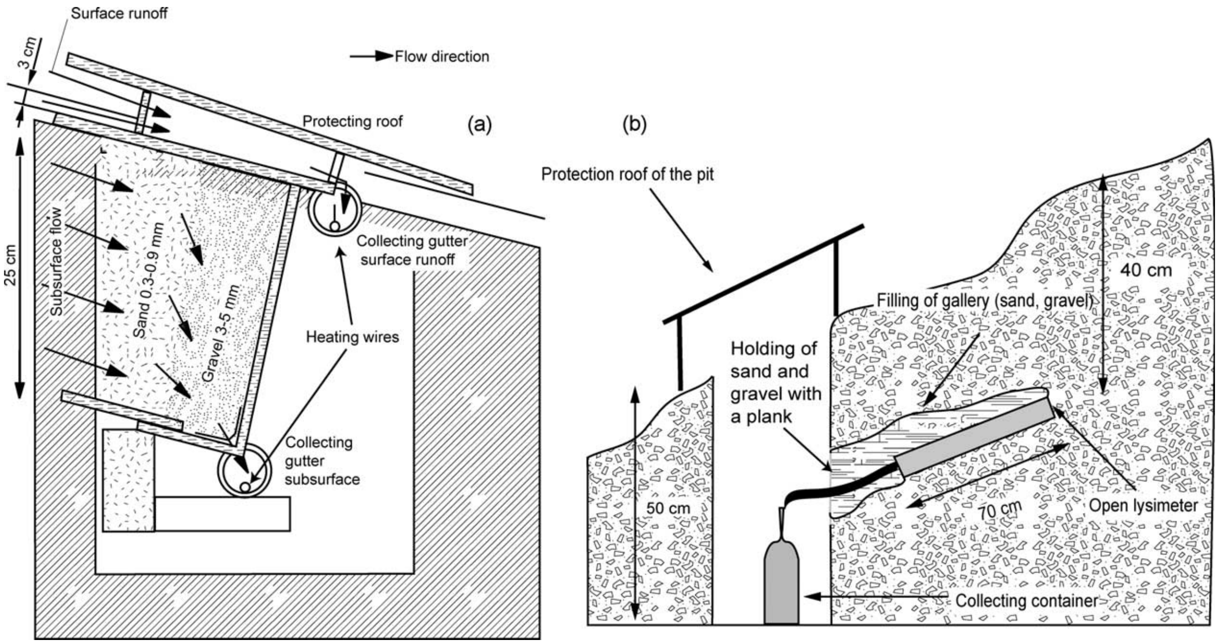

Fig. 3. (a) Cross-section of the device for collecting lateral surface and subsurface runoff. (b) Cross-section of the open lysimeter as installed at Hannigalp. A plank covered with plastic sheet held back the sand and the gravel at the outlet of the lysimeter.

between the lysimeter and the soil, hence suppressing the capillary barrier. At Gd St Bernard, approximately 30% of the total meltwater was collected by the lysimeter.

Additional measurements at Hannigalp were mainly made manually during the first winter and automatically during the second. Manual measurements were carried out daily during the snowmelt period, and bi-weekly otherwise. Automatic monitoring provided hourly mean values using multiplexers as well as a Campbell data and a Grant Data logger system. The liquid water content was measured with time domain reflectometry (TDR), using probes 15 cm in length, connected to a tektronix cable tester. To convert the measured apparent dielectric permissivity of the soil into a measure of water content, we applied the mixing model of Topp et al. (1980). TDR probes were installed horizontally at depths of 5, 10, 15, 20, 30 and 40 cm when manual collecting was carried out. During the second winter, the water content was monitored in two profiles of four probes located at depths of 5, 10, 20, and 30 cm. The soil temperature was measured automatically during both winters using thermistors, located at the same location as the TDR probes. Air temperature and solar radiation were measured at the experimental site. Other climate data, such as precipitation, wind speed, relative humidity and cloudiness were recorded at the Swiss Meteorological Institute (SMA) at Grächen (1617 m), about 3 km distant from Hannigalp (2090 m). The snow depth was recorded daily during the snowmelt period, and once or twice a week otherwise at each location. A piezometer was installed at a depth of 50 cm to detect the possible presence of a perched aquifer.

At Gd St Bernard, all measurements were carried out manually. Soil temperature and liquid water content were taken at depths of 5, 10, 20, 30 cm (south east and north plots), as well as 40 cm (south plot only). All meteorological data were taken from the SMA station located on the pass next to the south site.

2.4. Soil water balance calculations

To assess the significance of the various water flow pathways during different winter/spring situations we estimated the soil water balance for a number of snowmelt events. The soil water balance can be given with the following equations

$$q_{\mathrm{in}} = \mathrm{d}\theta_{\mathrm{w}}\Delta z_{\mathrm{soil}} + q_{\mathrm{out}} \tag{1}$$

with

$$q_{\mathrm{in}} = q_{\mathrm{prec}} - \mathrm{d(SWE)} - q_{\mathrm{subl}} \tag{2}$$

$$q_{\mathrm{out}} = q_{\mathrm{surf}} + q_{\mathrm{subsurf}} + q_{\mathrm{perc}} \tag{3}$$

where θ_{w} is the liquid soil water content, Δz_{soil} is the soil thickness, q_{prec} is the precipitation, SWE is the snow water equivalent, q_{subl} is the sublimation from the snowpack, q_{surf} is the surface runoff, q_{subsurf} is the subsurface flow and q_{perc} is the deep percolation.

We estimated the accuracy of the different water balance components of Eqs. (1)–(3). These values are rough and should be taken as orders of magnitude only. At Hannigalp, the accuracy in the precipitation flux q_{prec} was estimated to be approximately 10%. At Gd St Bernard, the uncertainty of the precipitation measurements is larger (estimated accuracy 40%), due to serious wind disturbance and wind displacement, especially during snowfall. The change in the snow water equivalent was calculated from snow depth and snow density measurements (accuracy in the order of 20%). This accuracy is high, especially at Gd St Bernard, as the contrasting topography induced massive spatial snow variation and the snow pack showed strong variation in the snow density. The sublimation q_{sub} was calculated using a numerical model (Jansson and Karlberg, 2001), with an estimated accuracy of 10%. The change in soil water storage was estimated using TDR measurements between 5 and 40 cm depth (estimated accuracy 10%). The accuracy of the q_{surf} and q_{subsurf} measurements was high (estimated accuracy: ~1%), as the experimental field was isolated by a 5 cm-soil edge (on both sides) and by a 50 cm-trench (on the upper part of the field). The remaining percolation flux q_{perc} was initially treated as an unknown. Indeed the measurements from the lysimeter did not stand for the absolute discharge, but only for a fraction of it (open lysimeter). In a first step, this fraction was determined. Later on, we used this fraction to estimate the amount of percolating liquid water, with an accuracy of approx. 10% for the values thus obtained.

We divided the different snowmelt events that we observed at Hannigalp and Gd St Bernard into four classes:

A. Snowmelt events during the early stage of the winter: ‘Mid-winter snowmelt’
B. Snowmelt events during the late stage of the winter: ‘Late winter snowmelt’
C. The main snowmelt in spring: ‘Spring snowmelt’
D. The melt of a snowpack that formed anew after the winter snowpack had already disappeared: ‘Post-spring melt’.

3. Results

3.1. Weather conditions

The two winters examined showed diametrically opposed patterns. Winter 2001/2002 was characterized by early snow and large amounts of precipitation during the entire winter, whereas little snow fell during winter 2001/2002, except at the end of the winter (Figs. 4 and 5). Winter 2000/2001 resembled a ‘standard winter’, with a well-defined accumulation and ablation period. Snowmelt took place at the end of the winter only, and the entire snowpack melted within a couple of weeks. Winter 2001/2002 was more shifting, with several short melting events, and a substantial accumulation period in the ablation period. This applies to both Hannigalp and Gd St Bernard, except for the north site at Gd St Bernard, where most of the snowmelt took place in June.

3.1.1. Winter 2000/2001

At Gd St Bernard, the snowpack started to build up unusually early. On the north- and east-facing experimental sites the first persistent snow was recorded in mid-October, and on the south site at the beginning of November. A steady and intense increase in snow depth proceeded afterwards and, at the end of the winter, the maximum snow depth for all three sites varied between 3.00 and 4.70 m. The final snowmelt began on 10th May. Due to the solar exposure of the south-facing slope the snowmelt progressed more rapidly here than at the other sites.

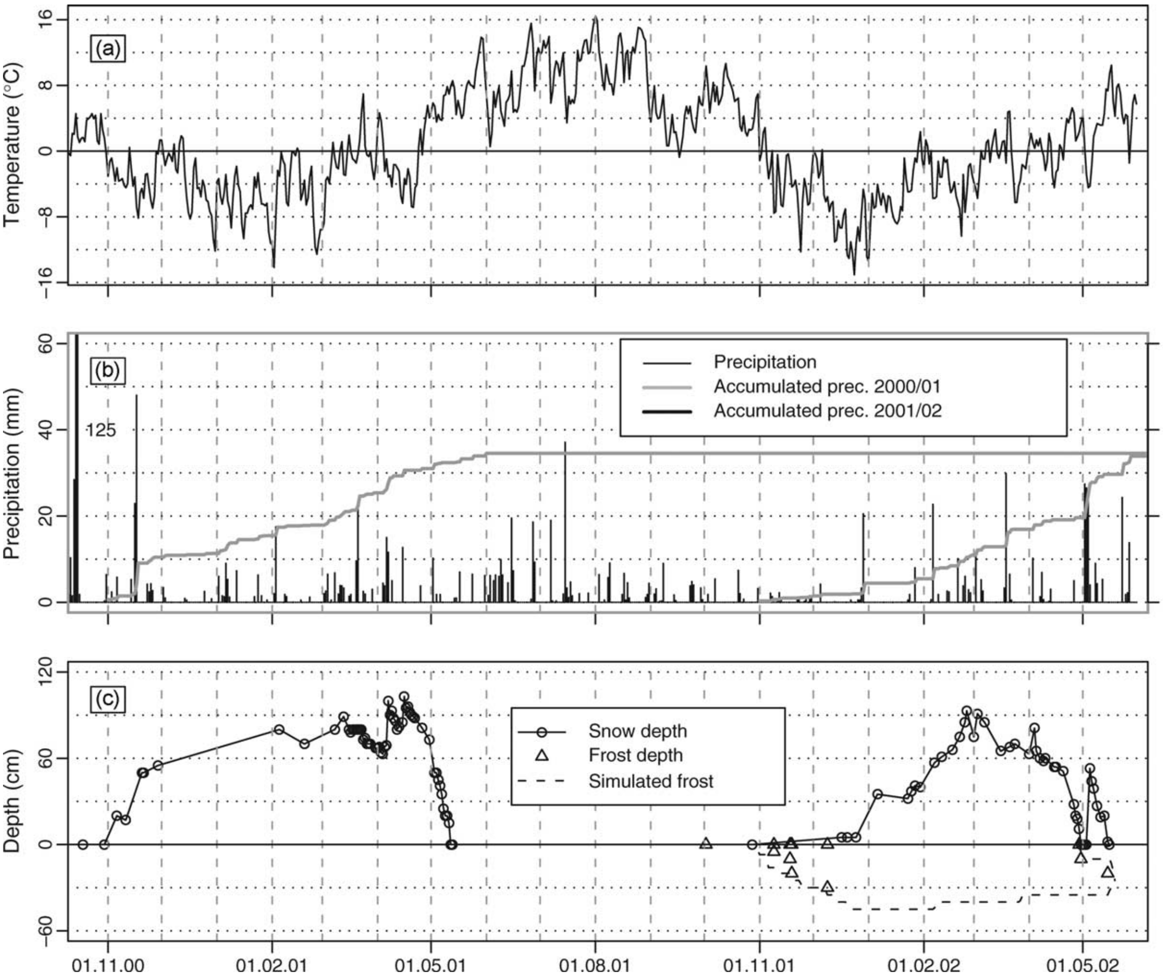

Fig. 4. (a) Mean daily air temperature and (b) precipitation (daily sums and total accumulation from 1st November to 1st June) at Grächen SMA weather station. (c) Snow depth (measured) and frost depth (measured and simulated with COUP (Jansson and Karlberg, 2001)) at Hannigalp from October 2000 to June 2002.

The snow cover disappeared 14 days and 1 month later at the eastern and northern sites, respectively.

At Hannigalp considerably less precipitation was recorded. As a result the maximum snow depth was only 103 cm. The snowpack cover period lasted from 1st November to 12th May. In mid-March a sharp increase in the air temperature created a first significant snowmelt. In April, a period of bad weather and low air temperatures delayed the snowmelt until the end of May, when the air temperature increased above 10 °C and the final snowmelt took place.

3.1.2. Winter 2001/2002

At Gd St Bernard, the snow depth did not exceed 38 cm at any of the three sites on the slope until a first significant snowfall occurred between 25th and 28th December. During this period, the snow depth increased to 50 cm on the pass (south and north plots), but remained low on the Italian side (less than 30 cm at the east plot). A warm period between 28th January and 12th February caused an early snowmelt event on the southerly exposed plot. Substantial snowmelt took place in March on the south and east plots (snow depth decreased by a third of its initial depth). On the north

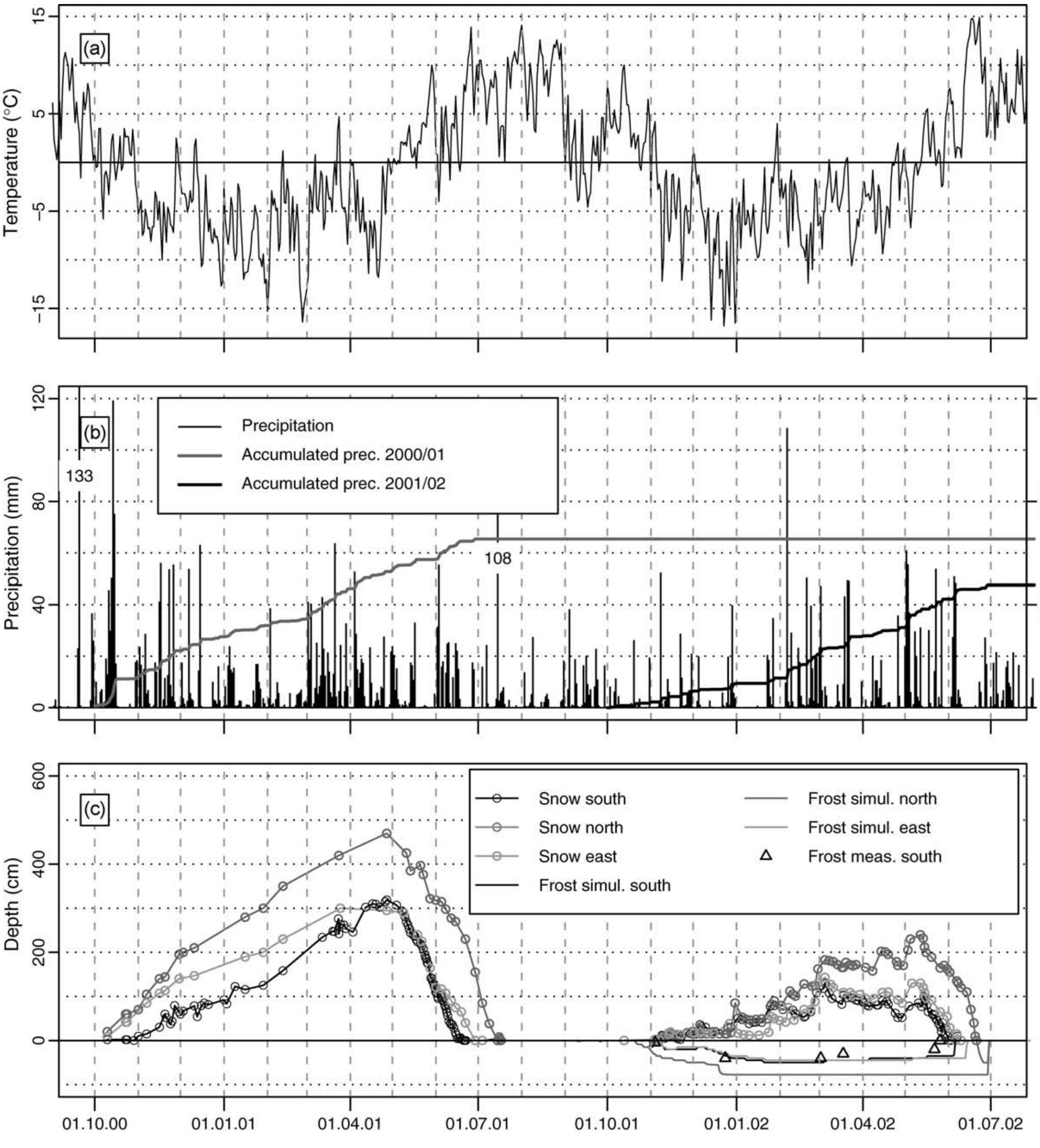

Fig. 5. (a) Mean daily air temperature and (b) precipitation (daily sums and total accumulation from 1st October to 1 July) at Gd St Bernard SMA station from September 2001 to July 2002. (c) Snow depth (measured) and soil frost depth (simulated with COUP (Jansson and Karlberg, 2001)) at the three field sites of Gd St Bernard, as well as measured frost depth at the south site.

site, however, the snow depth hardly varied. April was warm (−3.1 °C, compared to the average April temperature of −4.5 °C) and snowmelt took place on each site, except during a period of bad weather between 8th and 16th April. At the end of April, hardly any snow remained on the south plot (52 cm on 29th April). In early May, a large snowfall produced a snowpack 230 cm thick on 10th May at the north plot. Between mid-May and early June the entire snowpack melted on the south plot, which was some 14 days earlier than in the previous year. The snow remained for some 21 days and 7 days longer, respectively, on the northern and the easterly exposed plots.

At Hannigalp hardly any precipitation was recorded in November (11.4 mm) and the snow cover remained shallow (less than 5 cm). December was characterized by very cold air temperatures (−11.8 °C, compared to the average December temperature of −6.6 °C), without significant precipitation until 26th December. After that date, the snowpack steadily increased until early March. Snowmelt began on 5th March and ended on 1st May, with intermediate colder periods from 22nd March to 1st April and from 14th to 21st April. Huge amounts of precipitation fell at the beginning of May, initially as rain and, after a while, as snow. This additional snow (54 cm) stayed until 16th May.

3.2. Soil conditions

3.2.1. Winter 2000/2001: Hannigalp

Prior to the first significant snowfall on 1st November, the soil was rather wet (the liquid water content θ_w varied between 18 and 25 vol% over the studied profile) (Fig. 6a). After that date and until March, the air temperature was mostly far below 0 °C. The snow depth increased steadily with no significant snowmelt period. It is likely that no water infiltrated into the ground. During that period the liquid water content did not vary, indicating that the soil remained mainly unfrozen. This statement was confirmed by the soil temperature measurements, which remained close and mostly slightly above freezing point at all depths (Fig. 6a). During the two snowmelt periods, the liquid water content steadily increased and reached a maximum value of 35 vol% at a depth of 5 cm on 3rd May. The soil remained unsaturated, however. This result was confirmed by the piezometer measurements, as no water was found in it during the whole winter.

3.2.2. Winter 2000/2001: Gd St Bernard

The soil temperature and soil liquid water content evolution at Gd St Bernard were very similar to those found at Hannigalp. The soil was rather wet before winter ($\theta_w = 30$–55 vol% at a depth of 5 cm at all three sites). A consequence of the early arrival of snow in autumn 2000 was that the soil did not freeze (Figs. 7a

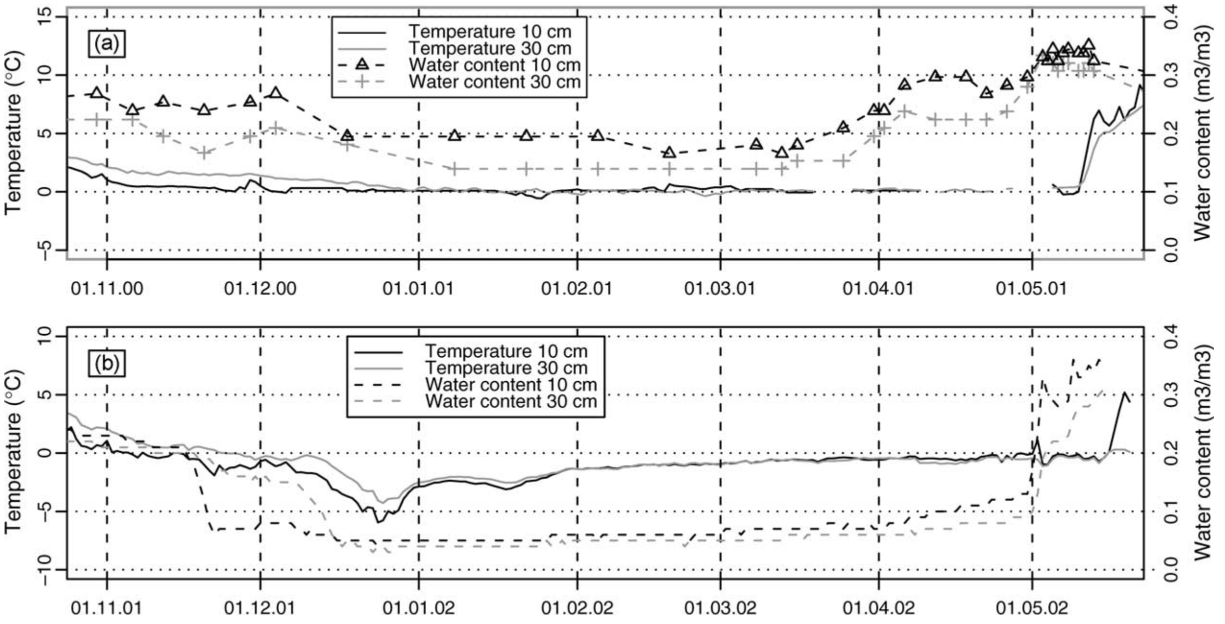

Fig. 6. Liquid soil water content and soil temperature at a depth of 10 and 30 cm for the Hannigalp-site (a) during winter 2000/2001 and (b) 2001/2002.

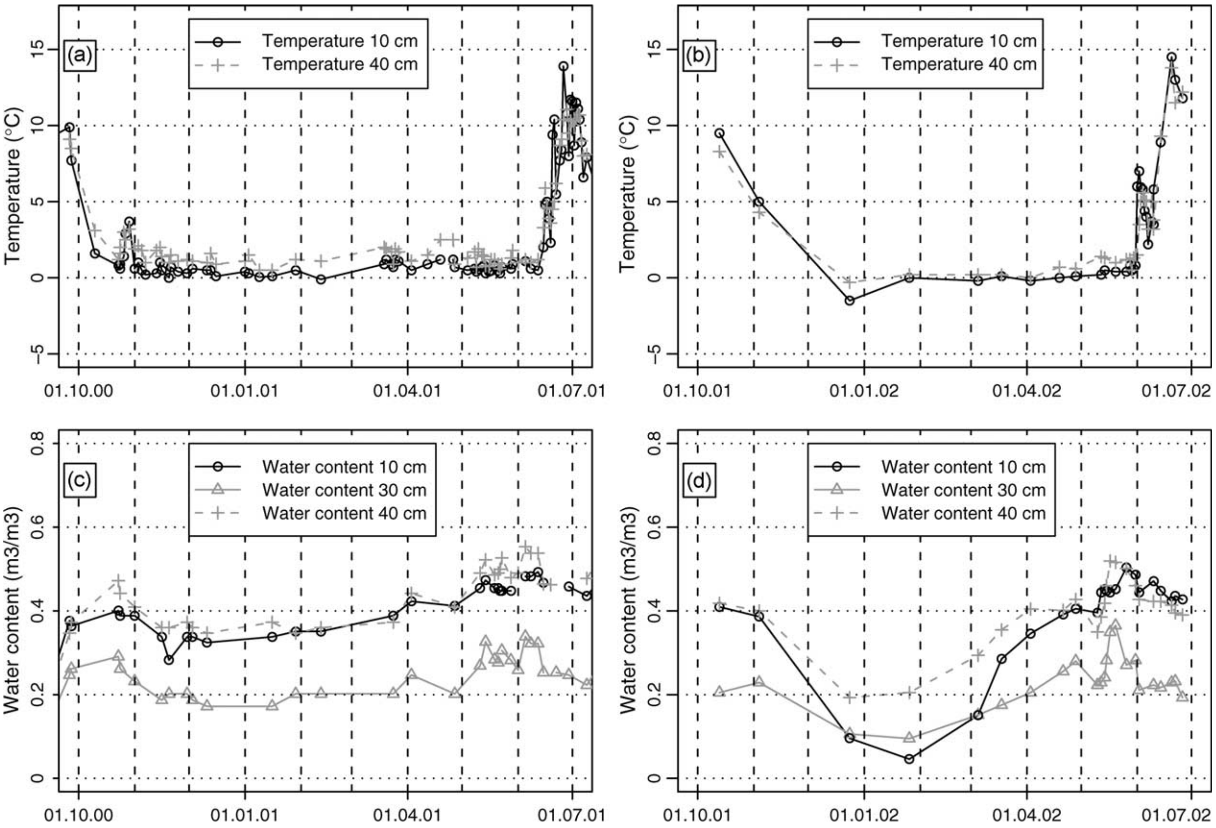

Fig. 7. Soil temperature at depths of 10 and 40 cm (a) for winter 2000/2001 and (b) for winter 2001/2002. Liquid soil water content at depths of 10, 30 and 40 cm (c) for winter 2000/2001 and (d) for winter 2001/2002 on the Gd St Bernard south plot.

and b and 8a and b). The liquid soil water content hardly changed until the onset of the melt period and the soil temperature remained slightly above freezing point at all depths. During the final snowmelt period the soil was close to saturation when lateral runoff was measured. On the east and north plot the rather low soil moisture content indicated by the TDR system (Fig. 8b) reflected the presence of large slate stones between the TDR rods, which were particularly abundant at both sites. During the snowmelt no water was measured in the piezometer, indicating that only the upper 10 cm of the soil was saturated and that the lateral runoff was not a consequence of a rising groundwater table.

3.2.3. Winter 2001/2002: Hannigalp

At Hannigalp, the soil was dry prior to the first snowfall (between 15 and 20% at a depth of 10 and 20 cm). Early winter 2001/2002 had a much thinner snow cover, which led to deep soil frost. The soil was frozen over the entire studied profile (Figs. 4a and 6b). This freezing took place in November and December. After the first significant snowfall on 25th December, the soil was insulated from the outside and warming, due to the underlying heat flux, steadily increased the soil temperature from −5 up to −0.7 °C on 10th March (at a depth of 5 cm). After that date the soil temperature stayed close to the freezing point. As shown by a nearby dye tracer experiment (Stähli et al., 2004), the soil remained frozen over the entire profile until the end of the snowmelt period. This tracer experiment allowed us also to detect an approximately 3 cm-thick basal ice sheet. During the final snowmelt most of the basal ice sheet melted. From lateral runoff measurements, we deduced that the upper 10 cm of soil was saturated during the final stage of the melt period.

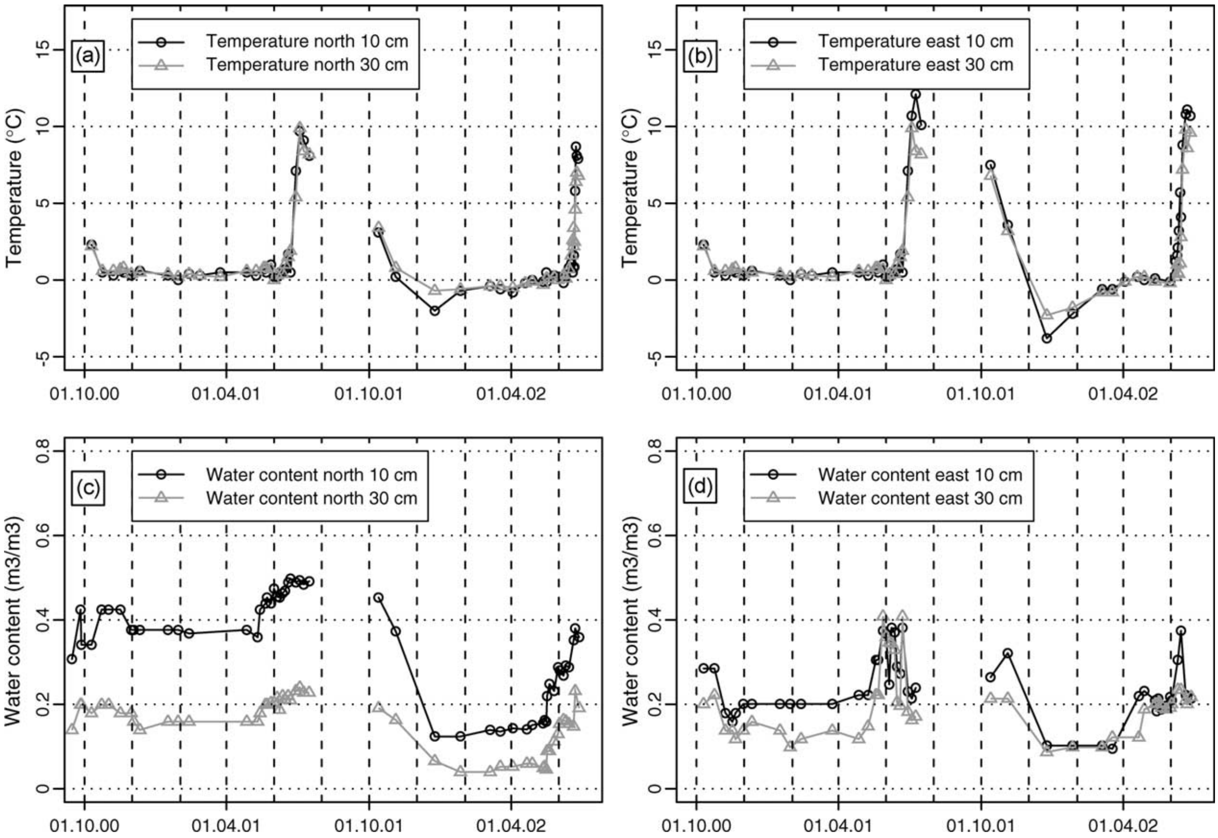

Fig. 8. Soil temperature at depths of 10 and 30 cm (a) for winter 2000/2001 and (b) for winter 2001/2002. Liquid soil water content at depths of 10 and 30 cm (c) for winter 2000/2001 and (d) for winter 2001/2002 on the Gd St Bernard north and east plots.

Between 1st and 3rd May, the ground was bare (no basal ice). The soil temperature measurements indicated that the soil was thawed to a depth of approximately 10 cm, but remained frozen below that depth. The large precipitation between 3rd and 5th May enabled monitoring of two distinctive events: (a) rain precipitation over a frozen ground, and (b) snowmelt over a partly frozen soil. During the rainfall on 3rd May, the liquid water content increased significantly throughout the entire profile, and saturation was reached when 0.2 mm of water ran off as surface flow. After this initial stage, the rain turned into snow on 4th May. The soil liquid water content decreased steadily from 45 to 26 vol% at a depth of 10 cm until 7th May, when the snowpack began to melt. The following melting period showed a similar pattern every day, with an increase in the liquid water content between 13:00 and 20:00, and a steady decrease afterwards. Below 10 cm the soil was still frozen. The soil temperature remained close to 0 °C at all depths, except during 1st and 3rd May when the temperatures steadily increased to 1 and 0.5 °C at a depth of 5 and 10 cm, respectively.

3.2.4. *Winter 2001/2002: Gd St Bernard*

At Gd St Bernard, the liquid water content of all measured profiles (except at 40 cm on the south plot) decreased to approx. 8 vol% in December (Figs. 7d and 8d) reflecting soil frost formation. From the soil temperature measurements (Figs. 7c and 8c), the frost was deepest on the east plot, due to the very thin snowpack (less than 30 cm) until end of January. On the south plot, the liquid water

Table 2
Water balance at Hannigalp for each snowmelt event in winter 2000/2001 and 2001/2002, $q_{\mathrm{in}} = q_{\mathrm{prec}} - \mathrm{d(SWE)} - q_{\mathrm{subl}}$, $q_{\mathrm{out}} = q_{\mathrm{surf}} + q_{\mathrm{subsurf}} + q_{\mathrm{perc}}$

Hannigalp	Snowmelt event type	q_{prec} (mm)	$-\mathrm{d(SWE)}$ (mm)	q_{sub} (mm)	q_{perc} (mm)	q_{surf} (mm)	q_{ssb} (mm)	$\mathrm{d}\theta_{\mathrm{w}}\Delta z_{\mathrm{soil}}$ (mm)	q_{in} (mm)	$q_{\mathrm{out}+}\mathrm{d}\theta_{\mathrm{w}}\Delta z_{\mathrm{soil}}$ (mm)
March 13 to April 5, 2001	Mid-winter	47	32	8	0	0	0	33	71 (±12)	33 (±3)
April 24 to May 12, 2001	Spring	18	345	6	330		0	27	357 (±71)	357
March 4 to March 22, 2002	Mid-winter	40	−27	13	0.2	0.1	0	3	0 (±11)	3 (±0)
April 4 to April 14, 2002	Mid-winter	40	−3	5	12	3	0.2	9	32 (±5)	24 (±2)
April 21 to May 1, 2002	Spring	5	241	12	159	44	18	26	234 (±50)	247 (±19)
May 2 to May 16, 2002	Post-spring	108	0	2	95	0.4	0.4	10	106 (±11)	106 (±11)

content at a depth of 40 cm was approx. 20 vol% in January (Fig. 7d), indicating that the soil was not entirely frozen at that depth. Between February and March, the soil temperature increased at all depths and the soil profile became isothermal at the beginning of April. The soil remained frozen until the end of the snowmelt period at all sites. Similar to Hannigalp, a basal ice sheet formed, probably after an early snowmelt event at the end of January.

In contrast to the north and east plots, the liquid water content increased drastically below a depth of 5 cm at the south plot between January and March. As no significant melting was observed during that period, we believe that this increase arose from thawing pore ice. On the north and east plots, the water content hardly changed until the end of the melt period. Consequently, the soil remained deeply frozen until the end of the snowmelt period.

Table 3
Water balance at Gd St Bernard south plot for each snowmelt event in winter 2000/2001 and 2001/2002, $q_{\mathrm{in}} = q_{\mathrm{prec}} - \mathrm{d(SWE)} - q_{\mathrm{subl}}$, $q_{\mathrm{out}} = q_{\mathrm{surf}} + q_{\mathrm{subsurf}} + q_{\mathrm{perc}}$

Gd St Bernard	Snowmelt event type	q_{prec} (mm)	$-\mathrm{d(SWE)}$ (mm)	q_{sub} (mm)	q_{perc} (mm)	q_{surf} (mm)	q_{ssb} (mm)	$\mathrm{d}\theta_{\mathrm{w}}\Delta z_{\mathrm{soil}}$ (mm)	q_{in} (mm)	$q_{\mathrm{out}+}\mathrm{d}\theta_{\mathrm{w}}\Delta z_{\mathrm{soil}}$ (mm)
March 23 to April 3, 2001	Mid-winter	78	20	4	0	0	0	22	94 (±36)	22 (±2)
May 19 to June 17, 2001	Spring	264	900	11	1035	80	43	−5	1153 (±287)	1153
January 26 to February 12, 2002	Mid-winter	67	−34	6	0	0	0	31	27 (±34)	31 (±3)
March 8 to March 21, 2002	Mid-winter	64	−1	5	0	20	2	30	58 (±26)	52 (±3)
April 1 to April 7, 2002	Late-winter	5	47	3	7	14	2	23	49 (±12)	46 (±3)
April 21 to April 30, 2002	Late-winter	40	64	4	33	51	4	9	100 (±29)	97 (±5)
May 15 to May 31, 2002	Spring	145	405	8	302	214	27	44	542 (±140)	587 (±37)

3.3. Soil water balance during specific snowmelt events

For both sites, the water balance measurements from winter 2000/2001 showed zero to low surface and subsurface flow. The high soil permeability enabled most water to infiltrate into the ground. During the next winter, the lateral runoff (mainly surface runoff), increased from 0 to 25% at Hannigalp and from 10 to 35% at Gd St Bernard. The magnitude of lateral runoff depended on when the snowmelt occurred in the course of the winter (Tables 2 and 3).

3.3.1. Mid-winter snowmelt

Such events were characterized by relatively low snowmelt intensities taking place mainly between January and March. At both sites, the first snowmelt event in winter 2000/2001 (Figs. 9 and 11) and the two first events in winter 2001/2002 (Figs. 10 and 12) were mid-winter snowmelt events.

During these melt periods, the water did not infiltrate deeper than into the uppermost 30 cm of soil, and no deep percolation was measured. The soil infiltration capacity was probably reduced by refreezing of meltwater in the frozen soil and on the soil surface. This may explain why surface runoff was recorded after the first snowmelt event. During the next snowmelt event lateral water runoff (surface and subsurface flow) was measured (8% of the snow water discharge runoff ran off laterally at Hannigalp during the second snowmelt event 2002 against 41% at Gd St Bernard).

3.3.2. Late winter snowmelt

Such events were observed in April 2002 at Gd St Bernard (third and fourth snowmelt events, 2002 in Fig. 12). They were characterised by intense melting (approximately 10 mm day^{-1}) over a short time period (less than 10 days).

During the third snowmelt (50 mm of SWE in 1 week) lateral runoff made up only 30% of the melted snow, denoting a probable early alteration to the basal ice sheet. The next snowmelt event at the end of April was more intense (100 mm of SWE in 9 days).

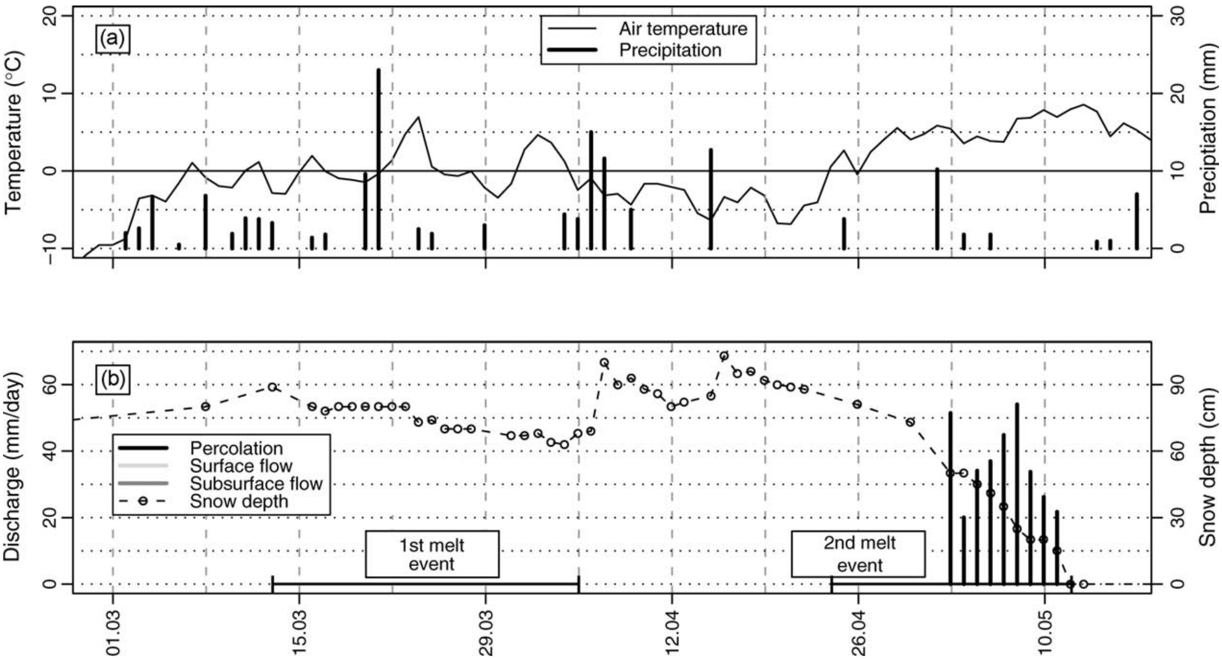

Fig. 9. (a) Daily air temperature at Hannigalp and precipitation at Grächen during the snowmelt 2001. (b) Snow depth, and daily percolation, surface flow and subsurface flow on the experimental plot during the snowmelt 2001. The discharge rates are expressed per unit area of the runoff plot.

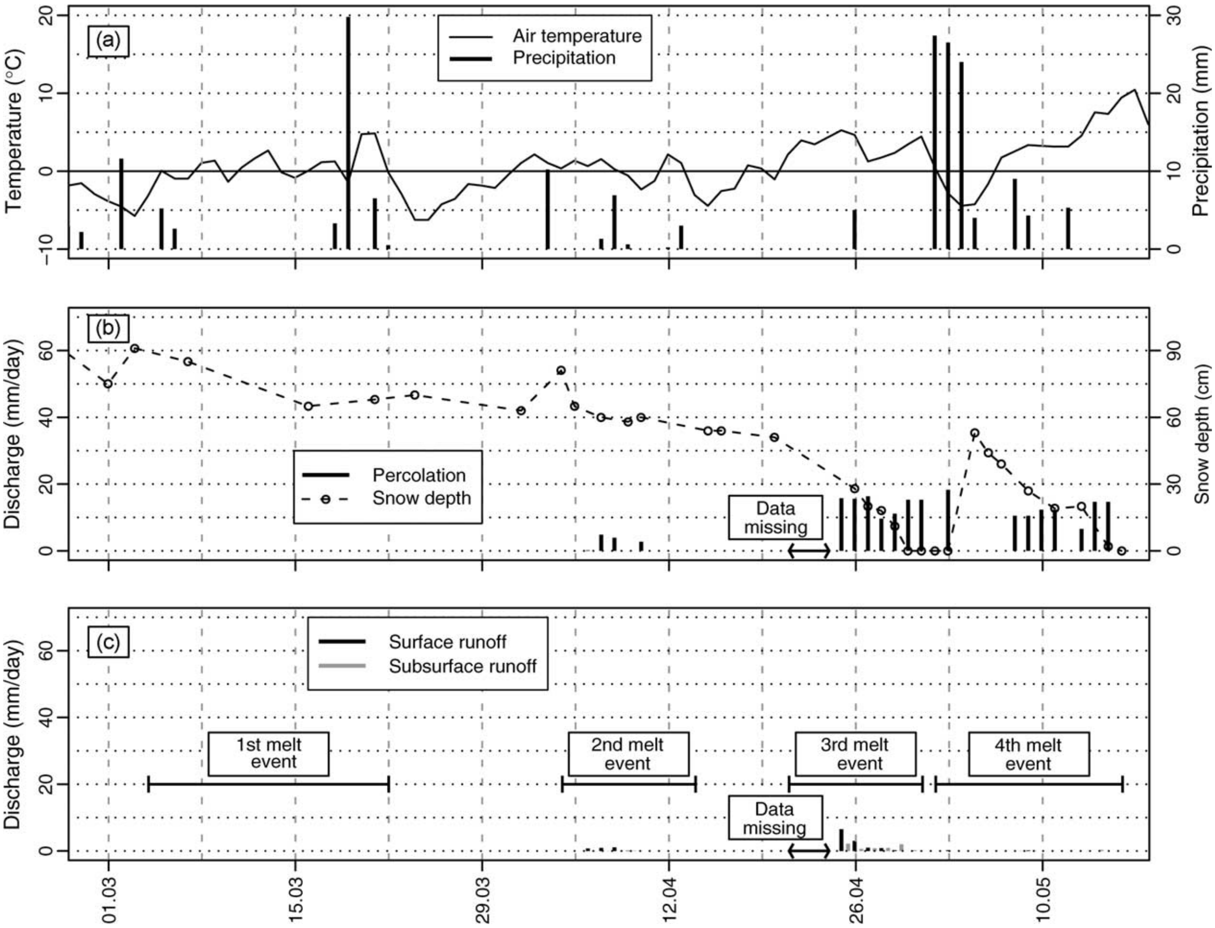

Fig. 10. (a) Daily air temperature at Hannigalp and precipitation at Grächen during the snowmelt 2002. (b) Snow depth and daily percolation, (c) daily surface and subsurface flow on the experimental plot. The discharge rates are expressed per unit area of the runoff plot.

The additional meltwater ran off mainly as lateral flow, which made up 57% of total discharge.

3.3.3. Spring snowmelt

In May and June, intense solar radiation as well as above freezing daytime temperatures produced intense snowmelt. At Hannigalp, the snowpack melted entirely within 18 days in spring 2001 and within 10 days in 2002 (second snowmelt event, 2001 in Fig. 9 and third snowmelt event, 2002 in Fig. 10). At Gd St Bernard, the exceptionally thick snowpack caused a long-lasting snowmelt period. It took 42 days to melt the entire snowpack in 2001 (second snowmelt event in Fig. 11) and 16 days in 2002 (fourth snowmelt event in Fig. 12).

In 2001, the meltwater entirely infiltrated into the ground at Hannigalp due, on the one hand, to the high infiltration capacity of the soil and, on the other hand, to the low snowmelt intensity (approximately four times less than rainfall intensity). At Gd St Bernard, the high melting intensity created surface runoff even under unsaturated conditions, and the lateral runoff made up approximately 10% of the total snowmelt.

The following spring, the measuring apparatus did not work at Hannigalp between 21st and 24th April and no data were received. Between 25th April and 1st May, most of the meltwater infiltrated into the soil (Fig. 10). 87% of the meltwater was collected by the lysimeter and 13% ran off as lateral flow. However,

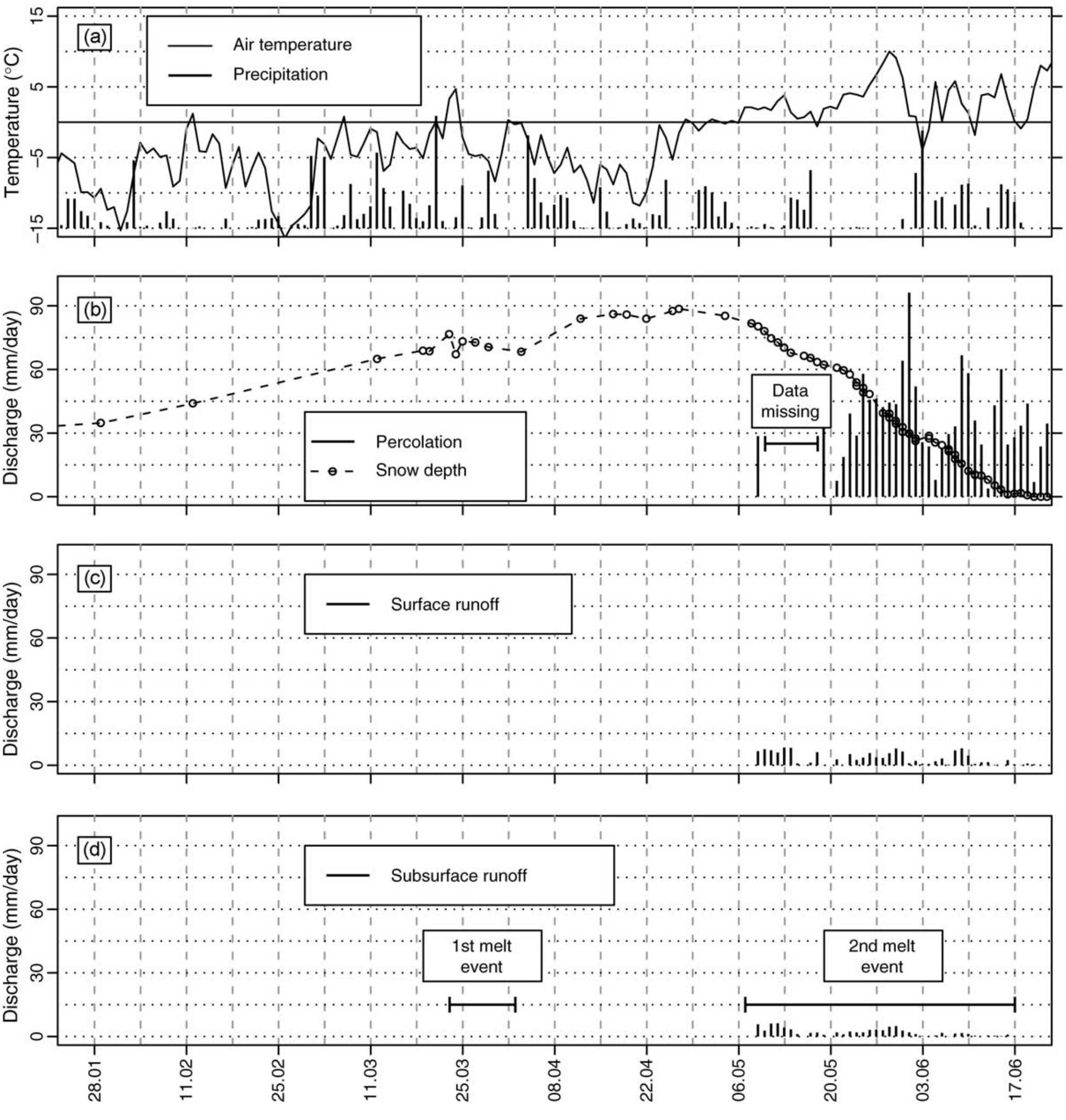

Fig. 11. (a) Air temperature and precipitation measured at Gd St Bernard during snowmelt 2001. (b) Snow depth and daily percolation, (c) daily surface flow and (d) daily subsurface flow on the Gd St Bernard south plot. The discharge rates are expressed per unit area of the runoff plot.

this percentage fluctuated with time. The relative percentage of the lateral discharge made up 31% of the total discharge on 26th May and diminished to less than 2% on 1st May, due to a steady increase of snow-free areas between these two dates. On bare areas, the upper soil frost melted, increasing the soil infiltration capacity. As more water was able to circulate in the upper unfrozen soil, subsurface flow constituted approximately 25% of the total amount of lateral flow on 27th April and 100% on 1st May.

An estimation of the water balance between 21st and 26th April was carried out. We supposed

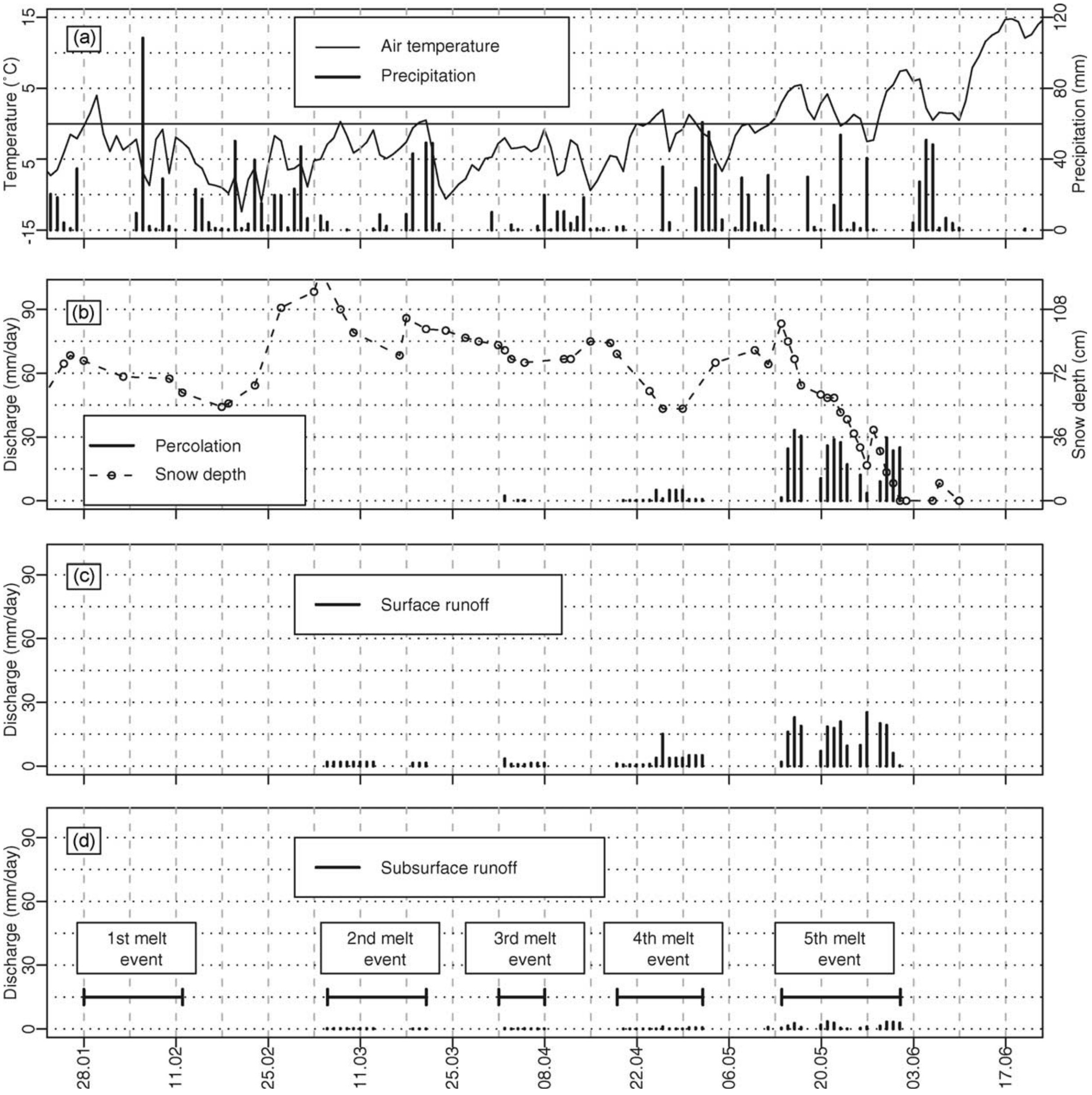

Fig. 12. (a) Air temperature and precipitation measured at Gd St Bernard during snowmelt 2002. (b) Snow depth and daily percolation, (c) daily surface flow and (d) daily subsurface flow on the Gd St Bernard south plot. The discharge rates are expressed per unit area of the runoff plot.

the soil infiltration capacity to be constant and we used the measured deep percolation value between 26th and 30th April to estimate the amount of deep seepage water. We were hence able to estimate the lateral flux, which made up 37% of total meltwater runoff. This proportion should, however, be more important, as the soil water infiltration capacity increased with time. Most of the water infiltrated into the ground.

At Gd St Bernard, the basal ice was spoiled during the final snowmelt and, between the 15th and the 30th April, lateral runoff was reduced to 40% of total discharge, despite the intense melting due to warm weather.

3.3.4. Post-spring melt

Such an event was recorded at Hannigalp in May 2002 after an intense snowfall (corresponding to a SWE of 108 mm) when the winter snowcover had disappeared. During this post-spring melt, the discharge was little affected by the remaining pore ice. Most of the ice had melted before when the ground was bare, so that almost all meltwater infiltrated into the soil.

4. Discussion and conclusion

For both sites studied, the water balance characteristics for the four different snowmelt events are summarised in Table 4.

The snowmelt dynamic was closely related to the exposure and the altitude. In particular, high solar radiation enabled mid-winter snowmelt even in January at high altitude locations like Gd St Bernard's south plot. In contrast, no snowmelt runoff was recorded for the same period at Gd St Bernard's north plot or in January 2000 at the protected site of Hannigalp, in spite of a very warm air temperature (daily mean air temperature of 2 °C for several days). At these two locations, late winter melt events were rare, as in March and May, respectively, the continued low air temperature and the reduced solar radiation inhibited intense snowmelt. In May and June, respectively, continuous melting started, as the air temperature remained mostly above freezing point, matching the onset of the spring snowmelt.

During the unfrozen winter 2000/2001, all meltwater infiltrated into the ground, except at Gd St Bernard's south plot during the main melt (Table 4). Here, the lateral flow was probably favoured by the steepness of the terrain and by the very intense snowmelt. It is feasible that during the most intense melt in the afternoon the soil was locally saturated, causing this surface runoff. The subsurface flow was probably due to lateral flow through the relatively porous organic upper soil layer, and the lateral deviation of infiltrating water by large stones close to the collecting gutter. A similar type of saturated lateral flow at the bottom of the snowpack has been observed by Waldner et al. (2000).

During the frozen winter 2001/2002, variation in the pore and basal ice content controlled the different parameters of the water balance. The surface runoff and subsurface flow increased by up to 30% under frozen conditions (Table 4). The presence of a basal ice sheet was mainly responsible for this change. It acted as a barrier, inhibiting the meltwater from infiltrating into the ground. During early snowmelt events, this barrier was particularly effective as, in spite of the low melt intensity, surface flow was recorded. Later, the soil infiltration capacity increased steadily between each snowmelt event. We believe that the main reason was the alteration of the basal ice

Table 4
Water balance characteristics for the four snowmelt events, under frozen and unfrozen soil conditions

	Winter snowmelt event	Spring snowmelt event	Final snowmelt event	Snowmelt event after final snowmelt
Sublimation (% of total water loss of the snowpack)	>10	5–10	<5	<5
Water snowpack runoff (% of total water loss of snowpack)	<90	90–95	>95	>95
Water snowpack runoff (mm/day)	<5	5–15	15–40	15–40
Soil infiltration frozen soil (% water snowpack runoff)	60–100	40–70	60–75	80–100
Lateral runoff frozen soil (% water snowpack runoff)	0–40	30–60	25–40	0–20
Soil infiltration unfrozen soil (% water snowpack runoff)	100	100	90–100	90–100
Lateral runoff unfrozen soil (% water snowpack runoff)	0	0	0–10	0–10

by the incoming meltwater (Woo et al., 1982), and the biological activity beneath snowpack (Richardson and Salisbury, 1977; Jones et al., 2001). Indeed, meltwater contributes to ice destruction through thermal and mechanical erosion. This alteration of the ice sheet becomes more important with increasing snowmelt, explaining why the basal ice sheet lost its blocking capacity with time. On the other hand, the penetration of visible light through the snowpack affects many plant processes, in particular germination and emergence. Plants are able to melt the surrounding snow or ice, in particular, when the snowpack is shallow (<20 cm), increasing markedly the soil infiltration capacity, and partly explaining why lateral runoff decreased greatly between 16th and 29th May.

During the post-spring melt 2002 at Hannigalp, the soil infiltration capacity was little reduced by the pore ice below 10 cm. The absence of a basal ice sheet may partly explain this behaviour. Another reason arose from the fact that the upper organic soil, with a high water retention capacity and hence a great blocking effect, was already unfrozen, in contrast to the mineral soil, where only a little pore ice was present and the ice blocking effect reduced.

Variations in the altitude and in the exposure also affected the physical state of the profile studied in winter. In particular, warming from underneath proved to be a dominant mechanism at the southerly exposed plot at Gd St Bernard. In contrast to the other locations of Gd St Bernard, a distinct melting from below was observed here in winter 2001/2002. Probably heat from the preceding summer was stored in the ground, which then provided a considerable heat flux from underneath towards the frozen layer in winter. The strong ice melting may also have been caused by soil warming from adjacent rock formations. These rocks covered an area of 10 m^2 and were free of snow at the end of February. In spring they were heated during the day, melting the surrounding snow, and possibly affecting the underlying pore ice.

Main differences in the hydrological behaviour of Gd St Bernard and Hannigalp were caused by differences in steepness and snowmelt intensity, rather than textural changes, as at both sites the infiltration capacity was approximately similar. However, the texture had a dominant influence on the thermal processes. The thermal properties of the soil control the heat diffusion in the soil. At Gd St Bernard, we would expect a fast soil freezing, due to the presence of conductive slate stones. At the other site, the soil retention capacity, and hence the amount of latent heat, depends on the texture. The soil retention capacity was particularly important at Gd St Bernard's south site (approx. 40 vol%) and freezing was slowed down by the high water content. In contrast, at Hannigalp the dry sandy soil enabled a fast freezing.

In conclusion, the main results from this study can be summarized as follows.

- Despite the thick snowpack building up in Alpine regions, soil frost is present during specific winters. This soil frost may remain until the end of the winter, reducing the amount of deep percolation and therefore also the groundwater recharge by up to 25%.
- For the development or absence of soil frost, the late autumnal and early winter meteorological weather conditions are decisive for the altitude range observed. In mid-winter, the snowpack is mostly thick enough to insulate the soil from the cold air and the weather conditions do not influence the extent of the soil frost depth any further.
- Surface runoff, subsurface runoff and percolation were influenced mainly by the presence or absence of pore and basal ice as well as the snowmelt intensity. Despite the steady increase in the snowmelt intensity with time, the lateral runoff did not increase accordingly. This was due to the alteration of the basal ice sheet and the pore ice, with time modifying the soil infiltration capacity.
- In spite of the harsh meteorological conditions at the two experimental sites, the different components of the soil water balance could be determined with satisfactory accuracy. The largest uncertainty was related to (a) the deep percolation measurements, and (b) the precipitation measurements, especially at Gd St Bernard, due to strong wind disturbance.

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