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Enhanced ground cooling in periods with thin snow cover in the Swiss National Park

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ABSTRACT: In autumn, as a result of a lack of direct radiation large mountain areas in the Alps retain a shallow snow cover. Once a shallow snow cover has built up, long-wave emissivity at the surface increases significantly and short-wave absorption decreases. The new energy balance causes snow-surface temperatures below −5°C, whereas near ground-surface temperatures remain initially between 0 and 5°C. The resulting large temperature gradient in the shallow snow cover strongly increases heat flux from the ground to the atmosphere. The assumed enhanced ground cooling processes in periods with thin snow cover in autumn in some mountain areas of the Alps could affect the distribution of high mountain permafrost. Using ground- and air-temperature data, snow depth, long-wave and short-wave radiation, first estimations of the influence of this cooling effect on the distribution of high mountain permafrost are now available.

1 INTRODUCTION

Today mountain permafrost is recognised as an important climate-driven factor for construction work, the operation of ski-runs, avalanche and flood protection, and hazards from debris flows and rock falls (Haeberli, 1992). In recent years knowledge about mountain permafrost distribution in the Swiss Alps has improved (Gruber and Hoelzle, 2001; Gardaz, 1997; Keller et al., 1998). Forecasts concerning the development of the permafrost distribution are now focused on scenarios of temperature trends and future precipitation patterns. In this context the development of seasonal snow cover may be of key importance as snow and its thermal effects have a strong influence on the energy balance at the surface (Goodrich, 1982; Hoelzle et al., 2001).

2 THERMAL EFFECTS BETWEEN SNOW COVER AND HIGH MOUNTAIN PERMAFROST

Areas with a thin snow cover in early autumn show special thermal conditions. The highest heat fluxes from the ground to the surface are to be expected when the ground is covered only by a thin snow cover with an emissivity of about 0.99 (Keller and Gubler, 1993). During cloudless nights, the energy loss through long-wave emission is distinctively higher in such areas than in areas without snow. Because of the low insulation effect of the thin snow cover, the ground is the main source of this energy. If the snow cover is more than 40 to 50 cm thick the surface temperature decreases and the long-wave radiation is reduced corresponding to Boltzman's law (Keller, 1994). With a snow depth of more than 80 cm, snow with its low thermal conductivity is a high-frequency thermal filter between the atmosphere and the earth's surface. Therefore, the Bottom Temperature of the winter Snow cover (BTS) measured in February and March by snow depth of more than 80 cm, is mainly controlled by heat flux in the uppermost part of the ground and can be used for mapping permafrost (Haeberli, 1973; Haeberli and Patzelt, 1982; Hoelzle, 1992; Hoelzle et al., 1993).

2.1 *Energy fluxes at the snow surface*

In order to estimate the energy flowing by thin snow cover from the underground to the surface, we measured the most important factors of the surface energy balance. On this basis an approximate calculation of the absorbed short-wave radiation as well as the incoming and outgoing long-wave radiation was possible.

The absorbed short-wave radiation (Q*) depends on the direct and diffuse solar radiation and the albedo of the surface:

$$Q^* = (Q + q)(1 - \alpha)$$

where Q = Direct solar radiation [W/m^2]; q = diffuse solar radiation [W/m^2]; α = Albedo.

The outgoing long-wave radiation (L↑) is given by Stefan Boltzmann's law:

$$L\uparrow = \varepsilon\sigma T^4_{Surface}$$

where ε = Emissivity ($\varepsilon_{\text{Solifluction\_Surface}} = 0.815$, $\varepsilon_{\text{Snow}} = 0.99$); σ = Stefan Boltzmann Constant; L = Long-wave radiation [W/m^2]; T_{Surface} = Surface temperature [K°].

The incoming long-wave radiation (L↓) is determined:

$$L\downarrow = \varepsilon_{Air}\sigma T^4_{Air} \approx 0.7\sigma T^4_{Air}$$

where L↓ = Incoming long wave radiation [W/m^2]; ε_{Air} = Air emissivity; T_{Air} = Air temperature [°K].

From this, $L^* = L\downarrow - L\uparrow = 0.7\sigma T^4_{Air} - \varepsilon\sigma T^4_{Surface}$, the estimated long-wave radiation is a function of the temperature difference between surface and air.

The sensible heat flux (Q_H) is approximately given by:

$$Q_H = k_h v_{wind} (T_{Air} - T_{Surface})$$

where Q_H = Sensible heat flux [W/m²]; k_h = Const = 2 [N/K°m²]; v_{wind} = wind velocity [m/s] (2 m above the Surface); $T_{Surface}$ = Surface temperature [K°]; T_{Air} = Air temperature [K°].

3 INVESTIGATIONS

3.1 *Research area on Munt Chavagl*

Munt Chavagl is located in the eastern part of Switzerland in the Swiss National Park. The research area lies on a southwest exposed slope at an altitude of 2400 m a.s.l. This is about 200 m above the tree line. An alpine lawn forms an almost closed vegetation cover. Only solifluction lobes are partly free of vegetation (Furrer, 1954; Gamper, 1983). Bedrock is triassic dolomite. Keller (1988, unpubl.) mapped the permafrost for the whole Park. BTS measurements indicate the absence of permafrost in the investigated area.

Using a Campbell CR10 Logger the following parameters have been measured since 1999:

- air temperature (average, maximum, minimum) NTC-sensor in GILL radiation shield, 2 m above the surface, nonventilated.
- surface temperature (if present snow surface), infrared thermocouple sensor, calibrated from 0 to −30°C by an emissivity of 0.98, resolution ±0.5°C.
- soil temperatures at a depth of 10, 20, 40, 60 and 100 cm, NTC sensors in stainless steel tubes, layed horizontally, resolution ±0.2°C between −5 and 20°C.
- snow cover thickness, ultrasonic sensor.
- wind speed, cup anemometer, unheated, 2 m above the surface.
- reflected short-wave radiation, semi-conductor sensor with teflon diffuser.

3.2 *Measured data*

3.2.1 *October–December 1999*

The first significant snowfall occurred on October 3rd. This led to a snow cover of a thickness of 25 cm (fig. 1). This snow cover melted in 5 days. On November 1st the surface temperature decreased rapidly below 0°C. Due to the snow cover the surface temperature remained negative. On November 6th light snowfalls increased the snow layer up to an average of 15 cm over the following 17 days. This thin snow cover grew slightly by over 30 cm on November 23rd. Only after

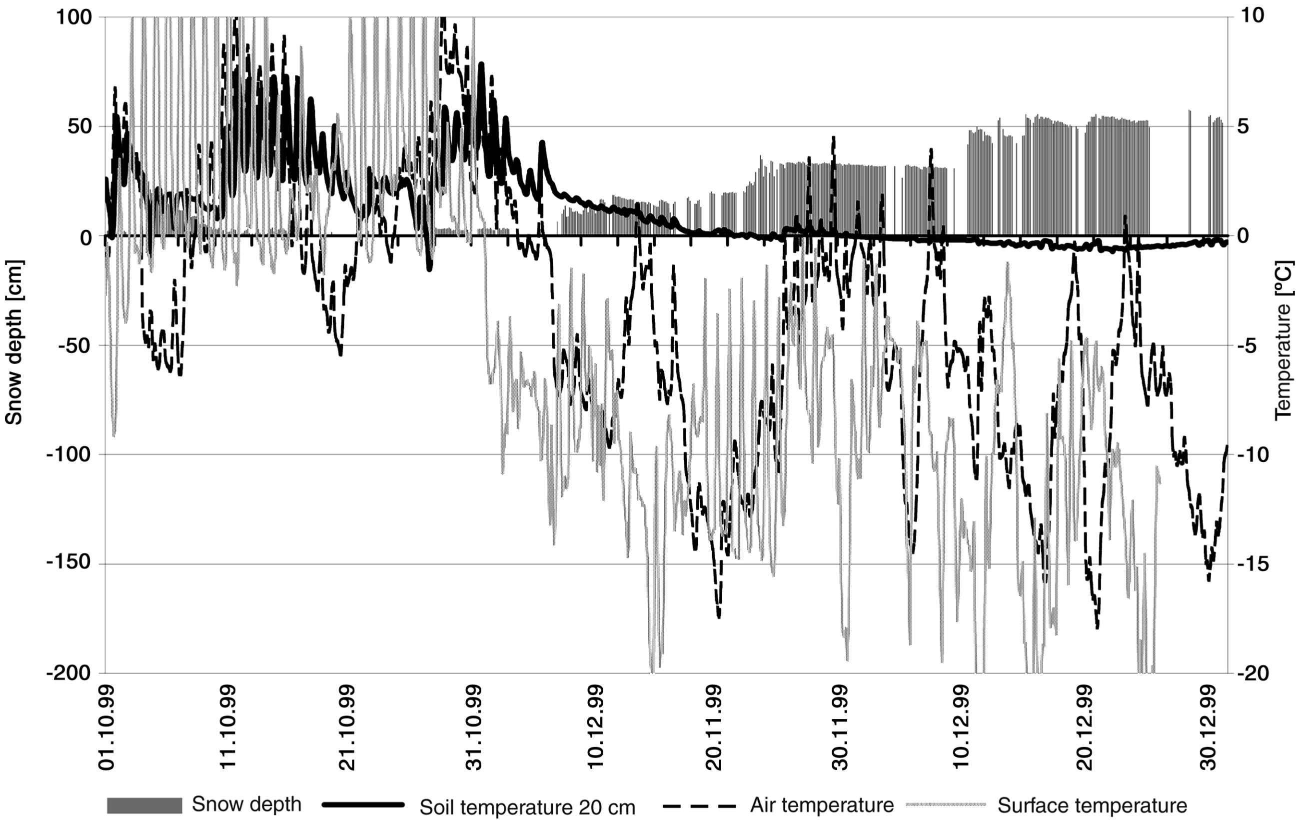

Figure 1. Snow depth and temperatures 1999.

mid-December did the snow cover reach more than 50 cm.

In the first part of October the mean air temperatures were about 0.1°C. From 10th to 25th October a warm period with mean air temperatures of 1.8°C warmed the soil. Between 26th and 31st October mean air temperatures of 5.3°C led to the last heat penetration before the winter began. The average air temperatures of the months of November (−5.3°C) and December (−7.5°C) have been about 1°C colder than in the other years since 1995. The period from November 6th to November 27th was very important for the cooling of the soil because the air temperature averaged −7.6°C during that time.

3.2.2 *October–December 2000*

Unlike 1999/2000, the winter 2000/2001 was characterized by huge amounts of snow in the whole region. On Munt Chavagl the maximum thickness of the snow cover reached 186 cm on April 21st. This was appreciably more than in 1999/2000 (102 cm on April 20th). From November 14th until May 21st the snow cover was never less than 80 cm thick, from 29th December until May 16th never less than 100 cm. The snow cover averaged from November through to May 128 cm (1999/2000: 51 cm).

Unfortunately the snow detector was defective until November 7th. However, by consulting the radiation data it is obvious that a first snowfall occurred on October 6th and a second one on October 31st. While the first snow cover did not last for more than 4 days, the snowfalls from October 31st and the following days led in a short time to a snow layer of more than 50 cm. Heavy snowfall on the 14th and 17th November raised the snow cover to over 130 cm (fig. 3). Unlike the year before there had never been a thin layer of snow cover several days.

The air and surface temperatures in the months of November and December were significantly higher in 2000 (fig. 3) than in 1999 (fig. 1). In November the mean air temperature was 0.9°C warmer than in 1999; the surface was 1.5°C warmer. In December the correspondent values were 2.8°C (air) and 2.4°C (surface). Nevertheless, the air and surface temperature remained constantly below 0°C from October 31st until November 28th.

4 ENERGY FLUXES

The calculated energy fluxes of the autumns 1999 and 2000 are shown in fig. 2 and 4. Among all energy

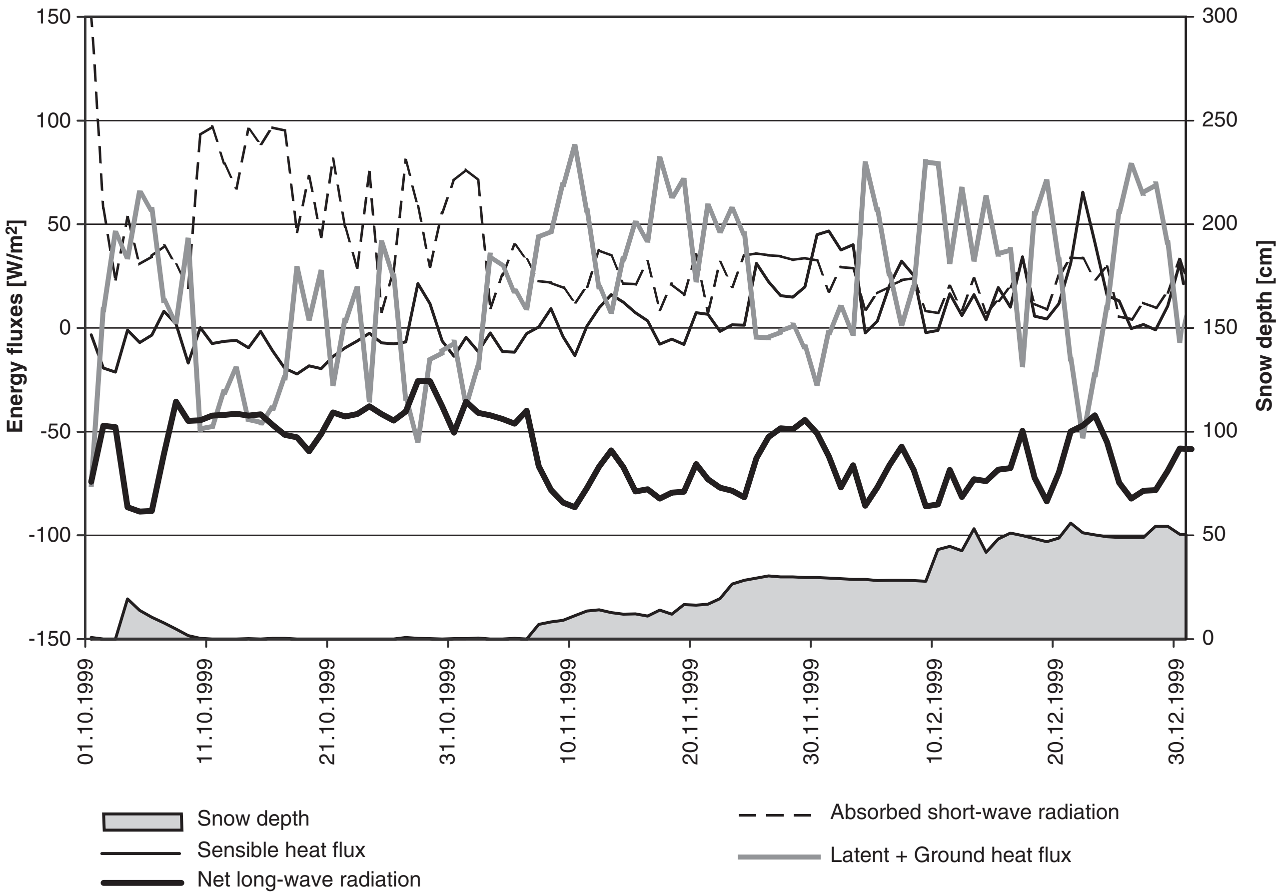

Figure 2. Energy fluxes and snow depths 1999.

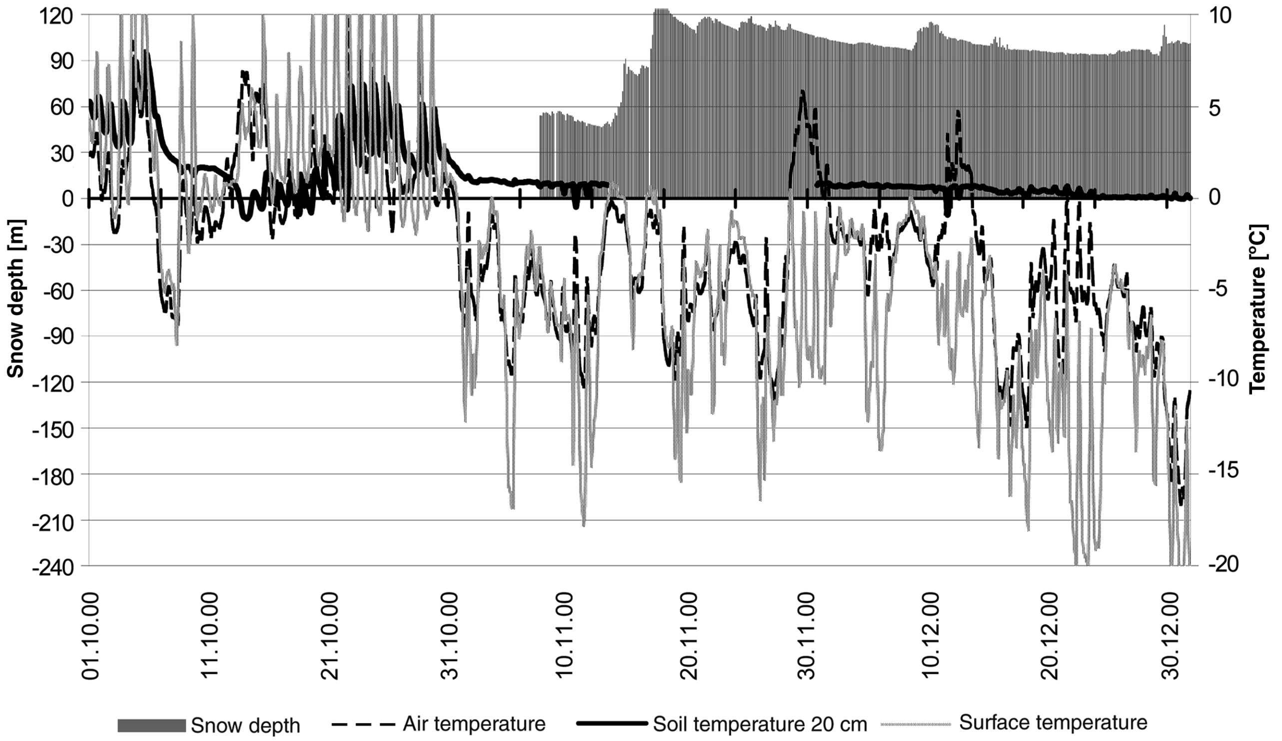

Figure 3. Snow depth and temperatures 2000.

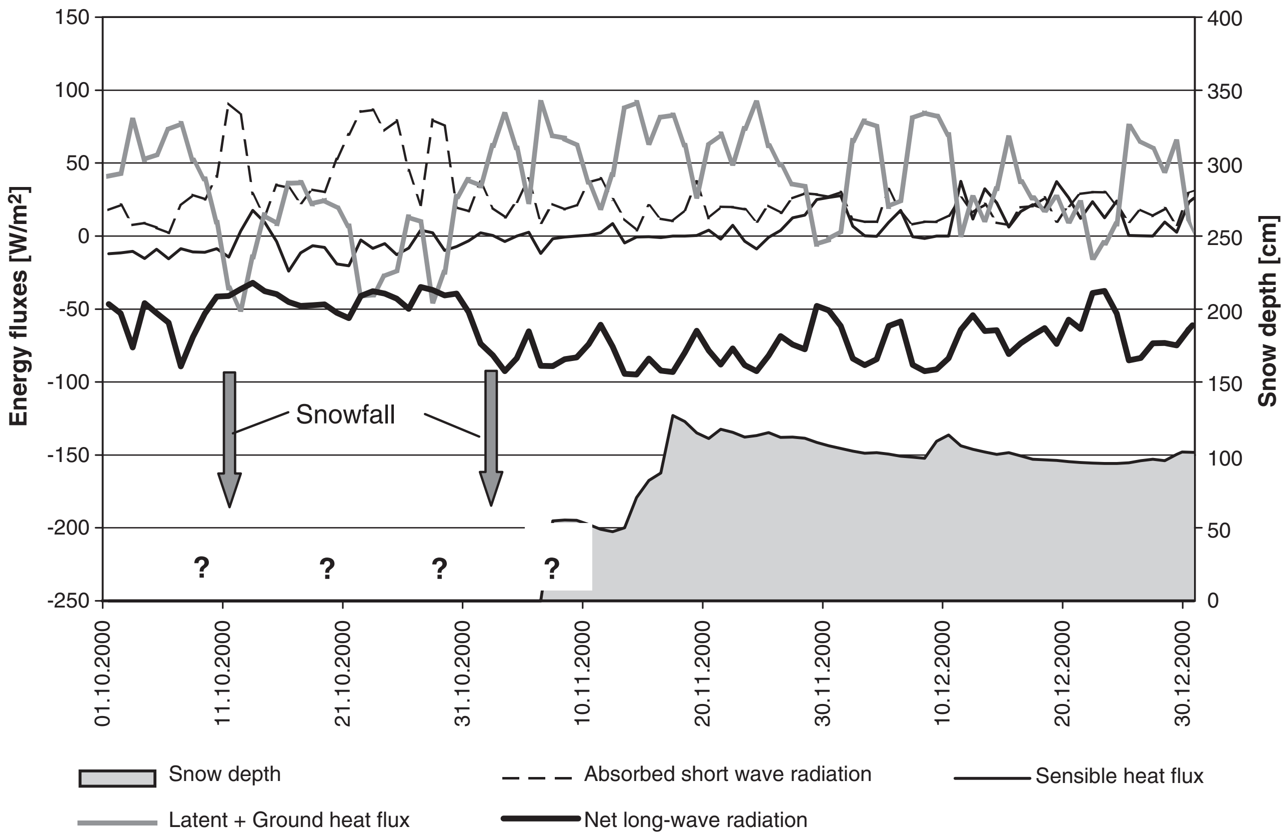

Figure 4. Energy fluxes and snow depths 2000.

exchange processes, net radiation and effects of the snow cover appear to play the determining role for the soil temperature. In both winters the net long-wave radiation varies with values of around −25 to −94 W/m^2. The short-wave radiation balance during the snow covered time is due to its high albedo (0.8 with snow, 0.3 without snow) in a range of 20 to 40 W/m^2. The daily mean of the estimated sensible heat flux varies in 1999 between −22 and 66 W/m^2 respectively in 2000 between −24 and 37 W/m^2. Using short- and long-wave radiation balances and the estimated sensible heat flux, the sum of latent and ground heat flux is calculated by setting the energy balance to zero. As expected, these values, between −54 and 87 W/m^2 in 1999 respectively −50 W/m^2 and 91 W/m^2 in 2000, correlate strongly with the air temperature. In both winters the energy balance regime changed completely after snowfall. In every case the amount of net long-wave radiation (L↓ + L↑) increased, whereas the sum of latent and ground heat flux changed in general from minus to plus. As long as the snow cover is less than about 40 cm thick, this leads to a cooling process in the ground. Effects of ground cooling due to snow cover melting near the ground surface cannot be determined with the available data.

5 INTERPRETATION

In winter 1999 two different ground cooling periods can be distinguished (fig. 1). At the first snowfall on October 3rd a significant cooling occurred in the soil. In 30 hours the temperature at 20 cm cooled from 3.3 to −0.9°C. The mean surface temperature on October 4th was calculated at −4.3°C. Within the 20 cm of snow depth the resulting temperature gradient was 21.5°C/m. Using a thermal conductivity of 0.3 W/°Cm the resulting mean heat flux through the snow cover was about 7 W/m^2. This situation illustrates the autumn- snow-effect postulated in Keller (1994). The next snowfall of 15 cm occurred on November 6th and is characterized by a cooling of the soil, too. With mean surface temperatures of −8.3°C the soil temperature at 20 cm decreased in 10 days from 3.3°C to about 0.4°C, even though on November 13th positive air temperatures were measured. In both periods the ground cooling is a result of heat flux through the snow cover and snow melting at the base of snow cover due to positive ground temperatures.

Regarding the development of the snow cover, autumn 2000 was completely different to the year before. Nevertheless, similar cooling processes did take place. On October 6th 2000 the first snowfall led immediately to a cooling of the soil-temperature at 20 cm from 5.6°C to 0°C in 6 days. On October 31st after the second snowfall the soil-temperature at 20 cm cooled in a few days from 2.8°C to 1°C. But this cooling process probably slowed significantly not only because the snow depth reached more than 40 cm (no data available), but also because the ground surface froze and no more snow melting at the base of the snow cover occured. In both situations the sum of latent and ground heat flux was higher than 50 W/m^2.

6 CONCLUSIONS

- In autumn heat fluxes through a thin snow cover (Snow depth <40 cm) and snow melting near the ground surface can cool down positive ground temperatures efficiently.
- It was possible to get an idea of the autumn-snow effect postulated in Keller (1994) using a small data basis over two autumns. In periods with thin snow cover in autumn ground heat fluxes in the magnitude of 7 W/m^2 can cool the soil very efficiently.
- The effects of snow melting near the ground surface while the ground surface temperature is positive could be determined measuring the moisture content in the ground.
- With regard to possible global warming effects, the investigated autumn-snow effect could play an important role on the permafrost distribution pattern. Today it is not clear what the future snow cover in a warmer climate will look like. In locations with extremely smaller snow depths the investigated effect could cause colder permafrost temperatures, even though air temperatures are increasing.
- Measurements should be continued. After the analyses of two or three further autumns, the knowledge will be sufficient for the implementation of this effect in GIS-based permafrost mapping tools in order to estimate the future permafrost distribution.

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