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Miniature ground temperature data logger measurements 2000–2002 in the Murtèl-Corvatsch area, Eastern Swiss Alps

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ABSTRACT: Measurements of Bottom Temperatures of the winter Snow cover (BTS) constitute a well-established method to map ground freezing in winter and, hence, permafrost conditions in mountain areas. Besides information on BTS, miniature temperature loggers also provide information about, snow-cover duration, length of zero-curtain periods, onset of meltwater percolation, mean annual ground-surface temperatures, duration of ground freezing and thawing, etc. They enable a better insight into the complex high-alpine active-layer processes. Corresponding measurements are well-suited to test the snow-cover module implemented in the permafrost distribution model PERMEBAL. First results show that the main differences between the measured temperatures are caused by highly variable surface characteristics at the investigated sites and that the timing of the snow cover accumulation is very important for the interpretation of the BTS-measurements. These results provide information about possibilities and limitations of standardized long-term observations in mountain areas and their application to monitoring and modelling.

1 INTRODUCTION

Permafrost distribution in cold high-mountain areas is a function of effects from complex topography. Surface conditions like slope, aspect, altitude, ground properties or humidity, and factors influencing the energy fluxes across the earth surface such as solar radiation, air temperature, precipitation, wind, snow cover etc. often greatly vary over extremely short distances. Spatial modelling of permafrost distribution patterns and potential changes with time is a serious challenge under such conditions. Especially high requirements exist concerning calibration of models with large enough samples of measured field evidence. A major step in this direction is the use of Bottom Temperatures of the winter Snow cover (BTS), because this reliable indicator of near-surface permafrost conditions, as calibrated by numerous geophysical soundings and various boreholes, is quite easily measured at hundreds to even thousands of sites (Haeberli, 1973; Hoelzle et al., 1993; Gruber and Hoelzle, 2001). Not only are BTS measurements, by using miniature data loggers, possible at remote or dangerous sites (rock walls, avalanche slopes etc.) but the continuous recording also provides qualitative and quantitative information about important parameters such as snow-cover duration, length of zero-curtain periods, onset of meltwater percolation, duration of ground freezing and thawing, or mean annual, seasonal or daily ground surface temperatures (Figure 1; cf. Hoelzle et al., 1999). Such observations have the potential of greatly enhancing results from

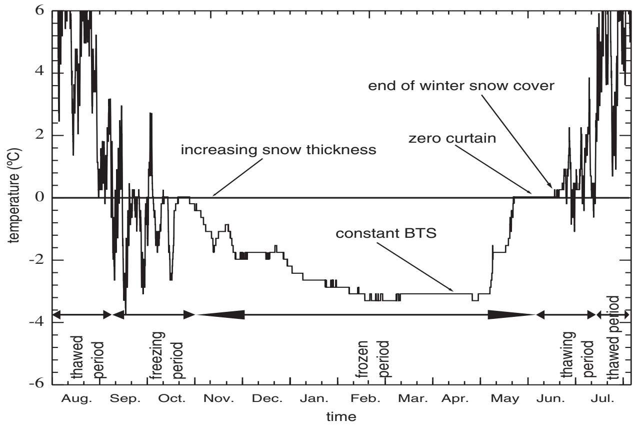

Figure 1. Typical miniature temperature data logger recording from permafrost in the Alps, indicating a set of interesting site characteristics.

past investigations on active-layer processes in different permafrost environments (e.g. Smith, 1975; Hinzman et al., 1991; Hinkel et al., 1993; Keller, 1994; Harris and Pedersen, 1998; Humlum, 1998; Ikeda and Matsuoka, 1999; Imhof, 2000; Isaksen et al., 2002).

Large amounts of data from miniature temperature data logger measurements in many mountain areas are already collected (e.g. Humlum, 1998, Imhof, 2000, Isaksen et al., 2002). To assure that this data can be reasonably handled, compared and interpreted by a wider scientific community or even the public, a suitable sampling strategy must be developed and a consensus reached about its usefulness and feasibility. The following summarizes some experiences collected within the framework of monitoring and modelling programmes in the Murtèl-Corvatsch area. The

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corresponding results provide some information about possibilities and limitations of standardized long-term observations using miniature temperature data loggers in mountain areas and their application to monitoring and model validation. Primary goals are improved process understanding, change detection and impact studies.

2 INVESTIGATION SITE MURTÈL-CORVATSCH

The Murtèl-Corvatsch area is one of the best-investigated mountain-permafrost sites of the Swiss Alps (Hoelzle et al., 2002).

The research area lies in the Upper Engadine region in the eastern part of the Swiss Alps. The climate is slightly continental; precipitation is mainly influenced by southwesterly air masses and reaches mean values of 800 mm in the valley floors and 1,000 to 2,000 mm in the periglacial valley side belts (Schwarb et al., 2000). The altitude of the mean annual 0°C-isotherm is around 2,200 m a.s.l. The area is characterized by several well-developed rock glaciers, by glacier forefields, which became exposed during the past 150 years, and by small glaciers covering mainly the eastern slope of the Corvatsch mountain ridge. On the north-eastern side, there is a ski run of the Corvatsch ski resort. The described area extends from 1,800 to 3,400 m a.s.l. Figure 2 presents the location of the miniature temperature data logger sites. The area is characterized by periglacial phenomena, mainly rock glaciers.

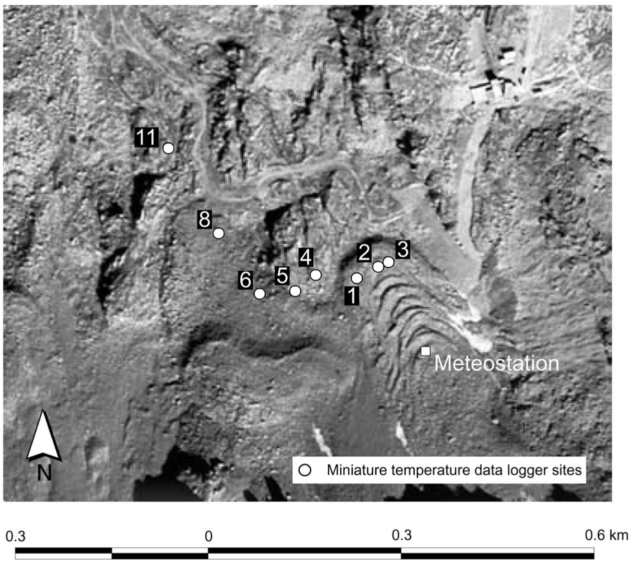

Figure 2. Measurement sites with miniature temperature data loggers in the Murtèl-Corvatsch area, Upper Engadine, Switzerland. Background: Infrared aerial (here presented in greyshading) photograph of the Swiss Office of Topography from 7.9.1988. Aerial photograph archive FD/KSL, Flightline: 061161, Image No. 4770.

3 METHODS

3.1 *Miniature ground temperature data loggers*

At different sites, continuous ground temperature measurements are performed with miniature temperature data loggers of the type UTL-1 with an accuracy of ±0.25°C (Hoelzle et al., 1999) in the Murtèl-Corvatsch. Here eleven loggers were installed in the context of the Swiss National Permafrost Monitoring Programme (PERMOS). All loggers were calibrated before they were used. The loggers were placed on a profile from SE to NW, starting at an altitude of 2668 m a.s.l. on the Murtèl rock glacier and ending at an altitude of 2535 m a.s.l. on alpine meadows.

During the first monitoring year 2000/2001, eight of the eleven loggers worked well and were used for the analyses (Figure 2). Two loggers failed because of battery problems and one logger could not be found again. The measurements all started on the 10th of October 2000 and ended on the 9th of October 2001. The second period of observation covers the following year 2001/2002.

Measurements started on the 10th of October 2001 and ended on the 9th of October 2002. In relatively fine-grained materials, the loggers, including the measurement sensors, were buried at a depth of about 2 cm below surface in order to record near-surface conditions and to protect the sensors from direct solar radiation. With the widespread coarse blocks covering rock glaciers, the exact location of the "surface" cannot be defined precisely. According to detailed field tests carried out at the same site by Raymond (2001), sensors in such situations are best placed underneath blocks where they are not directly exposed to solar irradiation, or in between smaller pieces of rock between and underneath larger surface blocks. The reason for this is the fact that the sun can heat surfaces to very high temperatures. Such extreme surface warming is not representative for the entire mixture of rock and air influenced by atmospheric fluxes; in fact, thermal diffusion of surface heat takes place within massive pieces of rock but essentially stops within the air of the large pores between the blocks. Table 1 describes the logger sites and the duration of the here-reported continuous measurements.

The snow cover depth was measured at the Murtèl climate station (see Figure 2) with an SR50 ultra sonic sensor.

3.2 *Energy balance model (PERMEBAL)*

The model PERMEBAL is an energy balance model, calculating daily surface temperatures and snow depth, based on a description of the main energy-exchange

Table 1. Description of the UTL-1 miniature temperature data logger sites at Murtèl-Corvatsch. The measurement year runs from 10th of October 2000 to 9th of October 2002.

No.	Measurement start	Measurement end	Altitude (m a.s.l.)	Site description (texture)
1	10.10	09.10	2663	coarse blocks
2	10.10	09.10	2668	coarse blocks
3	10.10	09.10	2650	coarse blocks
4	10.10	09.10	2649	soil, vegetation
5	10.10	09.10	2642	fine grained
6	10.10	09.10	2633	coarse blocks
8	10.10	09.10	2580	coarse blocks
11	10.10	09.10	2535	soil, vegetation

processes between the atmosphere and the surface (Mittaz et al., 2002a, Stocker-Mittaz et al., 2002b). It calculates short-wave net radiation, long-wave incoming radiation and turbulent fluxes as well as wind caused snow distribution (Mittaz et al., 2002a). As a physical model, the energy balance module requires an extensive set of input data describing meteorological conditions, ground surface characteristics (albedo, surface roughness, emissivity) and topography. The most important database for the model is a digital elevation model with a grid-cell size of 25 m. In addition, a set of meteorological variables such as air temperature, vapour pressure, air pressure, wind speed and direction, cloud cover, radiation at the top of the atmosphere, precipitation and global radiation for each day is needed. Available data sets from the Swiss Meteorological Service (MeteoSwiss) are used.

As a first step, the meteorological input data are extrapolated from the meteorological station to the investigated area (for detailed information about the model cf. Mittaz et al., 2002a, Stocker-Mittaz et al., 2002b). Subsequently, variables such as the albedo of snow are determined depending on the input data. The extrapolated meteorological variables provide the necessary input for the calculation – in daily time steps – of energy fluxes at each grid-point (grid cell size 25 m).

Modelling the accumulation of snow depth and snow cover duration is one of the main components within the energy balance model (Mittaz et al., 2002a). Snow cover influences the energy budget of the surface in a crucial way, by (1) insulating the ground from the cold atmosphere in winter and from the warm air in summer (Goodrich, 1982) and, by (2) changing the surface albedo and hence influencing the net radiation. Calculation of all energy fluxes allows for determination of the amount of snow-melt during winter and spring and thus for calculation of the day when a pixel becomes snow-free (see Table 2). One objective of logger measurements is to test the modelled snow cover duration with the snow-cover duration inferred

Table 2. Measured and modelled snow cover duration measured zero curtain and ground freeze duration in days for the period 2000/2001. All data in days.

No.	Meas. snow	Mod. snow	Zero curtain	Ground freeze
1	264	249	47	267
2	257	250	36	260
3	233	250	35	253
4	238	228	100	258
5	271	249	0	272
6	267	243	48	268
8	240	227	52	262
11	244	214	244	248

from continuous measurements of ground surface temperature. Once the duration of the snow-free period is known, the sum of all energy fluxes is used for the determination of the emitted long-wave radiation and thus the ground-surface temperatures. Table 3 shows the measured surface temperature at the Murtèl-Corvatsch site in comparison with the surface temperature computed using the energy balance model at this site. However, one has to bear in mind, that the simulated temperatures correspond to the temperature at the surface, i.e. at the lithosphere/atmosphere-boundary, whereas the loggers measure the temperatures a few centimeters below the surface.

4 DATA ANALYSES AND RESULTS

According to the objectives of the measurements, data analyses were carried out with respect to the local (small-scale) variability of site characteristics and to check the results from the snow-cover module of the spatial energy-balance model.

Table 2 shows a summary of the measured and modelled snow-cover duration, the zero curtain and the time period with frozen-ground conditions for the period 2000/2001.

Table 3. Measured maximum, minimum, mean annual ground surface temperatures (MAGST) and constant winter temperatures for the investigated sites and average modelled surface temperatures for the year 2000/2001. In addition the MAGST for the year 2001/2002 is given where available. All data are given in °C.

	T		MAGST			Surface T
No.	max.	min.	2000–01	2001–02	BTS-T	2000–01
1	14.4	−3.2	0.1	−2.6	−1.9	−0.2
2	16.5	−3.2	0.1	−2.1	−3.0	−0.2
3	22.3	−3.4	0.8	–	−2.5	−0.2
4	38.9	−4.5	2.2	1.2	0.0	−0.3
5	21.4	−1.6	1.2	−0.6	−0.8	−0.2
6	22.3	−3.0	0.9	−0.7	−1.9	1.0
8	19.3	−2.5	0.9	−0.8	−2.2	1.8
11	17.6	−0.8	0.3	–	0.0	2.2

The zero curtain at the different sites ranges from 0 day at logger site 5 to 244 days at logger site 11. The time period with frozen ground varies between 248 days at logger site 11 and 272 days at logger site 5. The difference is therefore only 24 days. For each temperature curve, the point in time when the temperature development started to deviate from air temperature was determined. These points were set as the starting points for a snow cover thicker than 0.5 m (Goodrich, 1982; Keller, 1994). In addition and for comparison, the energy balance model PERMEBAL was used to calculate the depth and duration of the snow cover at each measuring site by interpolating between the grid points closest to the logger sites.

The mean measured snow-cover duration inferred from the miniature temperature data-logger measurements for all 8 sites was 252 days and the mean modelled snow-cover duration 239 days: the model under-estimated the measured snow-cover duration by 13 days or about 5%.

Figure 3 shows time series of temperatures from loggers at two sites with strongly different conditions and characteristics. Logger 2 is placed in coarse debris whereas logger 11 is buried in soil covered by vegetation. At site 11 the temperature development is quite uniform: the temperature is 0°C during the whole winter and well into spring. In contrast, to that, at logger site 2 the temperatures show fluctuations until the snow cover was around 50 cm thick (measured at the climate station). Thereafter, the temperatures decreased continuously until reaching a stable temperature of −3.0°C. Similar developments can be observed with at the sites 1, 3, 6 and 8. The temperatures at the logger sites 4 and 5 react in a similar way as at site 11.

The mean measured temperature during the summer 2001 (snow free period) is 5.4°C with a standard deviation of ±4.4°C. The mean modelled surface temperature is 22.8°C with a standard deviation of ±15.7°C. Therefore, there exists an offset of around 17°C with a considerable scatter. However, the daily cycle of the temperatures is showing a somewhat delayed, but parallel evolution (see Figure 3).

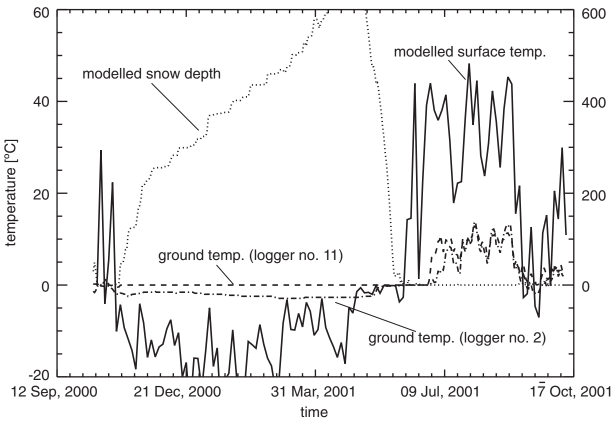

Figure 3. Ground surface temperatures at 2 different sites (no. 2 and 11), modelled surface temperatures on snow covered and snow free terrain, and modelled snow depth at site no. 2 for the period October 2000 to October 2001.

The measured temperatures at the different sites show considerable variations. In Table 3, the minimum, maximum and mean annual ground-surface temperatures (MAGST) for the whole measurement period are displayed. The lowest and highest temperatures were recorded at logger site 4 with values of −4.5°C and 38.9°C, respectively. These temperatures define a maximum amplitude of more than 43°C at an altitude of 2649 m a.s.l. The temperatures at the sites 1 and 11 show an amplitude of only 17°C and 18°C, respectively. Measured mean annual ground surface temperatures are lowest at the sites 1, 2, and 11 with temperatures between 0.1°C and 0.3°C. The warmest sites were 4 and 5 with temperatures of 2.2°C and 1.2°C, respectively. The lowest constant BTS values at site 2 reached a value of −3.0°C and the warmest had a value of 0°C.

Average modelled surface temperatures for site 4 was lowest with −0.3°C and warmest for site 11 with 2.2°C, respectively. For comparison, data from the sites 1, 2, 4, 5, 6 and 8 of the year 2001/2002 could be measured, too. Because of malfunction of the loggers 3 and 11, these annual temperature series could not be measured completely.

5 DISCUSSION AND CONCLUSIONS

The results show that the main differences between the measured temperatures are caused by highly variable surface characteristics at the investigated sites. At the logger sites 1, 2, 3, 6 and 8 are measured the lowest BTS values. All these loggers are placed in between coarse blocks, where lateral cooling effects are most effective. At site 4, located in soil covered by vegetation, recorded the most extreme ground temperatures and the highest average temperature during the whole measuring period. All other loggers have a much less pronounced temperature amplitude, ranging from 17°C to 26°C. The zero curtain lasted longest at the soil/vegetation sites (4 and 11), where latent heat effects dominate the other energy fluxes. Zero curtain at the sites 1, 2, 3, 6 and 8 are only present in spring, when snow-melt starts and percolating water freezes in the still cold snow pack, at the ground surface and in the active layer.

Logger 5 has no zero curtain, possibly because of a well-developed drainage system within the fine grained debris material preventing any storage of water. Information on the length of the zero curtain is thus useful to identify heat flux effects in the near-surface layers. Mean annual ground surface temperature at the different sites during the measurement period shows distinct differences. Loggers 1, 2, and 11 recorded mean annual ground-surface temperatures close to 0°C, whereas the loggers 3, 4, 5, 6, and 8 measured temperatures ranging from 0.8°C to 2.2°C.

Snow conditions during the two documented winters were far from normal conditions. The winter of 2000/2001 was extremely snow-rich in the investigated area as compared to normal years. Therefore, the measured winter temperatures are much warmer than during average winters and the BTS-method indicates conditions of marginal to absent permafrost for this year (Figure 4).

Ground temperatures during the following winter (2001/2002) with extremely small amounts of snow on the ground were much colder and a constant BTS could not be reached even with a snow cover developed in early March 2002. Such circumstances are not favourable for applying the BTS-method. Therefore, the BTS-method can most safely be applied in years with a 'normal' snow cover development. This implies that results from (earlier) BTS-measurements must be interpreted with due consideration of snow conditions, mainly the timing and amount of snow accumulation and melt during the measurement period.

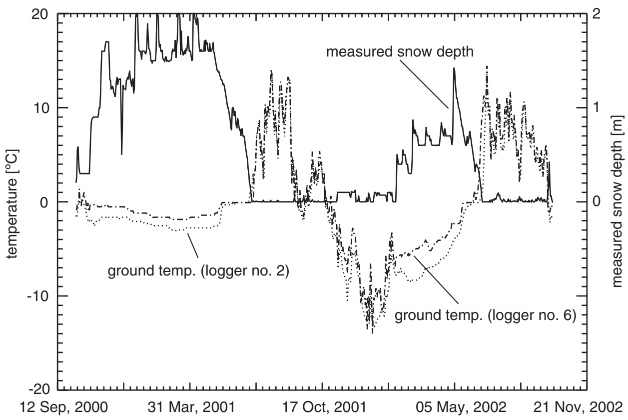

Figure 4. Measured ground surface temperatures at the sites 2 and 6 and measured snow depth at the Murtèl climate station (see figure 2) for the period October 2000 to October 2002.

During the second measurement year, mean annual temperatures at the logger sites 1 and 2 were by more than 2°C lower than in the previous year. At sites 4, 5, 6, and 8 the temperatures were by 1°C to 1.8°C lower than in the period 2000/2001 (Table 3). It should also be taken into account that temperatures below the permafrost table can be considerably colder than temperatures within the active layer, because peaks of positive summer temperatures are cut off at ice-rock layers of the perennially frozen material. In any case, mean annual surface temperatures at the investigated site are close to 0°C and indicative for warm permafrost; their interannual variability is likely to be on the order of ±2.7°C.

The presented temperatures from the miniature temperature data logger sites enables some additional validation of the snow-cover part within the energy-balance model (PERMEBAL) by comparing modelled and measured snow-cover duration. On average and for the period 2000/2001, the model calculates snow-cover duration, which is too short by 13 days or about 5% of the total duration. However, the determination of the snow cover duration with the miniature temperature data loggers involves uncertainties, which are in the same range. It can, therefore, be concluded that the snow-cover module of the model can certainly be improved but already works quite reasonably; hence the results obtained by Stocker-Mittaz et al. (2002b) appear to be realistic. Comparison between modelled and measured temperatures must be done carefully: in summer, the modelled surface temperatures are much higher than the ones measured in the ground, mainly because of the strong modelled radiative heating at the very surface of rock components. Daily mean temperatures during this time show a somewhat delayed, parallel evolution with some scatter (see Figure 3). As explained before, this offset mainly results from the difference in surface heating between air and the coarse blocks in the active layer and confirms measured thermal offset values determined by Mittaz et al. (2000). The grid-size resolution within the model of 25 m is maybe one of the important accuracy problems involved with such comparisons.

For future investigations, determination of the thermal offset between the surface and the permafrost table is the most crucial point for reasonably connecting energy balance models with the ground thermal regime.

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