Thermal Processes in the Active Layer of the Larsbreen Rock Glaciers, Central Spitsbergen, Svalbard

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Abstract

A recent scientific focus on the thermal regime of openwork blocky deposits has lead to the conclusion that air circulation in the pore spaces and exchange with the atmosphere may be particularly important processes of heat transfer in such materials. This contradicts our data from the coarse openwork active layer of the Larsbreen rock glaciers. Visual observations and temperature data give inconsistent results on air circulation activity at this site, and we conclude that this process seems less important here compared to what is reported from other areas. Other thermal processes at the site, in addition to conduction, include water vapour transport and subsequent sublimation, and meltwater infiltration followed by several refreezing and melting events. More data is needed to understand the complex process pattern in the coarse active layer of these rock glaciers, and further instrumentation is planned as part of the IPY-project 'TSP Norway – Thermal State of Permafrost in Norway and Svalbard.'

Keywords: active layer; coarse debris; heat transfer; non-conductive processes; rock glacier; Svalbard.

Introduction

In openwork blocky debris such as rock glaciers, coarse talus deposits, and block fields, reported mean annual temperatures are often lower than in adjacent finegrained material (Harris & Pedersen 1998, Hanson & Hoelzle 2005). A recent scientific focus has lead to the conclusion that this temperature anomaly is due to air exchange between the blocky debris and the atmosphere and circulation of air within the material (Harris & Pedersen 1998). Circulation could be by free or forced convection (Nield & Bejan 2006). Free convection is driven by temperature-induced density differences of the air and may operate in gravel-sized materials or coarser if the degree of water saturation is less than about 40% (Johansen 1975), while forced convection is driven by pressure gradients as, for example, induced by high wind speeds (Ping et al. 2007). However, the general importance of this process is still largely unknown (cf. Juliussen & Humlum, in press) as many studies consider extreme cases with large pore spaces (Gorbunov et al. 2004) and steep slopes (Delaloye et al. 2003).

In this paper, we identify and discuss thermal processes operating in the coarse openwork active layer of some rock glaciers near the glacier Larsbreen in Svalbard (Fig. 1), based on visual observations from the active layer in Spring 2006 and temperature data from the active layer 2005–06.

Study Site

In Svalbard, low mean annual air temperatures (MAAT) of -5.1 to -7.1°C (1961–1990, ©Norwegian Meteorological Office) result in continuous permafrost except beneath temperate parts of glaciers. The permafrost is typically some tens of meters to 100 m thick in major valley bottoms and close to the sea, but up to 400–500 m thick in the mountains (Humlum et al. 2003).

Rock glaciers are common features in Svalbard (Sollid & Sørbel 1992). At the study site, rock glaciers are creeping out from the talus slope in front of and in a lateral position to the Larsbreen glacier (78°12′N, 15°36′E, 250 m a.s.l.) (Fig. 1). The rock glaciers in front of the glacier were deformed by the glacier advance during the Little Ice Age, but still each individual rock glacier can be traced back to the talus cone from which it is creeping, while the longitudinal furrows separating the rock glaciers are all associated with inter-cone depressions.

In the winter, snow accumulates in the depressions to depths of several meters. The rock glacier fronts, on the other hand, are covered by only a thin and sporadic snow cover. Avalanches are frequent in the study area, and cover the rooting zone of the rock glaciers with snow in the winter. By bringing snow and rock debris to the rock glacier rooting zone, they are probably a driving factor for the rock glacier development at this site (Humlum et al. 2007).

The rock debris in the rock glacier is talus material composed of Tertiary sandstones and shales (Hjelle 1993). Average clast size (b-axis) is 15.0 cm at the surface and 8.5 cm close to the permafrost table, and the clasts are slabby (c:a axial ratio of 0.24 to 0.32 and b:a axial ratio of 0.66 to 0.73, see also Fig. 2). The active layer is openwork, and the pore volume is filled with air in summer and a mix of air

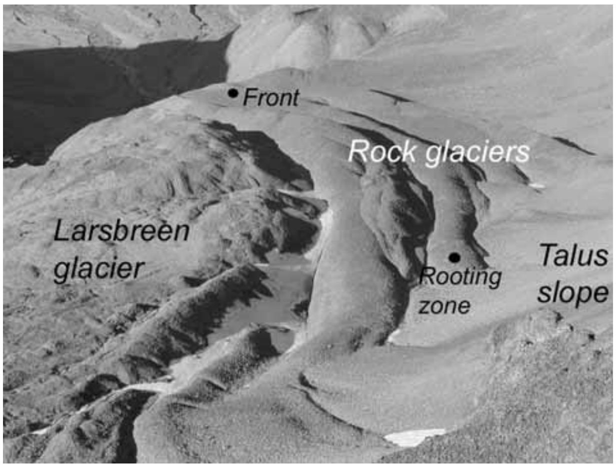

Figure 1. Photo showing the debris-covered front of the Larsbreen glacier, the rock glaciers, and the sites with active layer temperature measurements at the front and at the rooting zone.

and ice in the winter. The active layer is about one meter thick on the rock glaciers, and less than half a meter in the depressions between the rock glaciers.

Methods

Visual observations

The active layer was manually excavated at irregular time intervals during Spring 2006 to visually observe spatial and temporal changes in ice content and the structure of the ice during the melting season.

Temperature measurements

The active layer thermal regime on the rock glacier has been monitored close to the front (at the surface and at depths 0.35 m, 0.70 m, and 0.90 m) since Autumn 1999 and just below the rooting zone (at the surface and at depths 0.30 m, 0.60 m, and 1.15 m) since Summer 2005 (Fig. 1). Air temperature at the site was measured in a 0.15 m high naturally-ventilated stone cairn. Tinytag miniloggers with a precision of ±0.2°C were used both for air and active layer temperature monitoring. Temperature was logged at hourly intervals.

Since active layer temperatures were logged at two sites only, ground surface temperatures below the snow cover were measured manually at irregular time intervals through the winter and Spring 2006 to detect any spatial variability not recorded in the logger series. High spatial variability in winter ground surface temperature may reflect zones with rising and sinking pore air within individual convection cells (e.g., Goering 2002), while low variability would be against a hypothesis of effective, distinct convections cells.

Calculation of Rayleigh numbers

The potential for free air convection in a porous medium can be explored by estimating the Rayleigh number, which determines if heat transfer in a fluid is mainly by convection or conduction (Nield & Bejan 2006). It is given by:

$$Ra = \frac{C\beta gKH\Delta T}{\nu k} \tag{1}$$

where $C, \beta,$ and ν are the volumetric heat capacity, expansion coefficient, and kinematic viscosity of the pore fluid (in this case air); g is gravitational acceleration; K is the intrinsic permeability of the blocky debris layer; H is the thickness of the layer; ΔT is the temperature difference between the top and bottom of the layer (warmer boundary below); and k is the effective thermal conductivity.

Free convection can be expected if the Rayleigh number exceeds a critical value. In the case of closed upper and lower boundaries, such as represented by a continuous snow cover and the permafrost table, respectively, this critical value is $4\pi^2 \approx 40$ (Nield & Bejan 2006). When there is no snow, and the pore volume is open to the atmosphere (open boundary), the critical value is 27 (Serkitjis & Hagentoft 1998).

The Rayleigh number is estimated from the temperatures logged at the front and at the rooting zone. The effective thermal conductivity was estimated with an empirical relationship to porosity n (Johansen 1975):

$$k = 0.039n^{-2.2} \tag{2}$$

A value of 0.3 was used for the porosity. The hydraulic permeability was estimated with the approach of Fair & Hatch (1933), also used by Goering (2002):

$$K = \frac{1}{5}\left[\frac{(1-n)^2}{n^3}\left(\frac{\alpha}{100}\sum\frac{p}{d_m}\right)^2\right]^{-1} \tag{3}$$

where α is a particle shape parameter; p is the percentage of particles held between adjacent size limits; and d_m is the geometric mean size of those limits. These parameters are estimated from clast size measurements. The Rayleigh number estimates are conservative, as a minimum estimate of the hydraulic permeability was used.

Results

Visual observations

Visual observations from the active layer excavations in spring indicated that several types of non-conductive heat transfer processes had operated in the previous winter: infiltration and refreezing of meltwater, and sublimation of water vapour, the latter forming delicate hoar.

Interstitial ice was found in distinct zones, filling the open pore spaces or forming icicles (Fig. 2). Ice accumulations were largest beneath thin snow. Initially, the ice accumulations occurred in distinct zones as extensions of localized meltwater pathways through the snowpack (e.g., Conway & Benedict 1994, Albert et al. 1999). Thus, the ice formed by refreezing of infiltrating surface meltwater reaching the cold active layer. As the melting season progressed, ice accumulations became more widespread. After the snow cover was completely melted, the ice in the active layer started to melt from the surface.

Figure 2. Photos showing icicles and interstitial ice in the pore volume of the active layer. Vertical section of ruler is 17 cm. Photos taken 26.04.2006 (left) and 04.05.2006 (right).

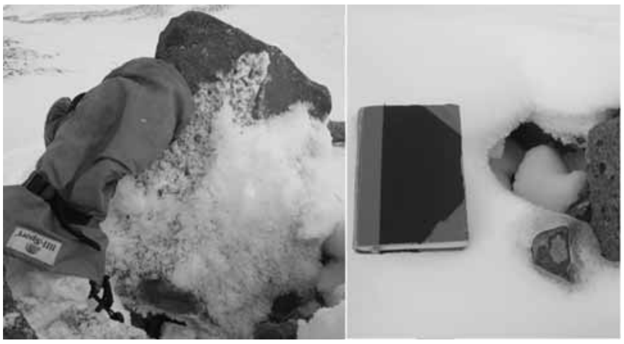

Figure 3. Left panel: Large hoar crystals occupying the pore volume and the base of the tilted block. Glove for scale. Photo taken 24.04.2006. Right panel: Funnel through the snow cover. Note the hoar on the funnel rim. Notebook (width 10cm) for scale. Photo taken 10.05.2006.

Well-developed hoar was found in the upper part of the active layer, in places filling the entire pore volume, and on snow funnel rims (Fig. 3). The hoar crystals were largest and most common near the surface of the rock glaciers where snow was thin or absent and active layer cooling was most effective. Hoar was also superimposed on some of the icicles, but not all, suggesting several episodes, both in the early winter and in the spring, of meltwater infiltration and refreezing. The prevalence of hoar suggests transport of water vapour in the pore volume towards the colder upper part of the active layer and subsequent sublimation.

Funnels through thin snow covers were frequently observed after snowfall (Fig. 3). Funnels indicate exchange of air between the pore volume and the outside (Keller & Gubler 1993).

Active layer temperatures

Average daily temperature in the air (at 15 cm height) and in the active layer at the rock glacier front and at the rooting zone for the period Sept. 2005–June 2006 are given in Figure 4. Active layer freeze-back occurred in the middle of September and was immediate, due to the lack of water in the coarse materials. At the front, negative temperatures prevailed in the active layer until May, and active layer temperatures followed the ambient air temperature throughout the winter. The shift to positive temperatures in May was immediate down to 0.35 m depth, but at 0.70 m depth there was a zero curtain period (stable temperature at 0°C) of about a week. This indicates that the upper 0.35 m was more or less free of ice, while some ice existed deeper in the active layer that required energy to melt before the temperature could switch to positive values.

At the rooting zone, the temperatures followed the air temperature until the onset of December, when the site was covered with avalanche snow. For the rest of the winter, the active layer temperatures followed only the main trends in the air temperature as high-frequency fluctuations were masked by the snow. The temperature curves from both sites show several episodes of sudden temperature increase, indicating meltwater infiltration and refreezing during the winter season, forming the observed ice accumulations (Fig. 2). These episodes occurred in periods of warm weather in the autumn, in January during an unusually warm and wet period, and in the spring melt season. In May and June, a snowmelt and zero curtain period of at least one month delayed active layer warming at the rooting zone. The zero curtain period started more or less at the same time at all depths, reflecting the abrupt nature of the infiltration process. The zero curtain period was significantly longer at 1.15 m depth, reflecting that melting occurs from the surface only and possibly indicating a higher ice content than at shallower depths.

The estimated Rayleigh numbers are also given in Figure 4. Since the Rayleigh number is a function of the active layer temperature gradient, it fluctuated in rhythm with the active layer temperatures through the winter. At the front, the theoretical critical Rayleigh number (open boundary) was frequently exceeded, indicating possible episodes of free convection at this site. The estimated Rayleigh numbers for the period 2000–2005 were of comparable size (not shown).

At the rooting zone, the Rayleigh number fluctuated in rhythm with that at the front and with the ambient air temperature, with the highest values well above the critical value (open boundary), until the site was covered by avalanche snow. Below avalanche snow, the Rayleigh number increased to a maximum just above the critical value (closed boundary) and showed less fluctuation than at the snow-free site. Keeping in mind that the Rayleigh number estimate was conservative, there is a potential for free convection also at this site.

Ground surface temperatures (GST)

The manually measured ground surface temperatures are displayed in Figure 5 as average values for each date with one standard deviation. Between 7 and 22 measurements were made at each visit. Continuous ground surface temperature measurements at two sites within 20–30 m from the rooting zone profile are also given (GST1 and GST2), along with the surface temperatures at the rooting zone and air temperature. The standard deviation of the manual measurements was mostly below 1°C, even when Rayleigh number estimates show a potential for convection. This suggests that there were no highly effective convection cells. Moreover, the temporal evolution of the ground surface temperatures was

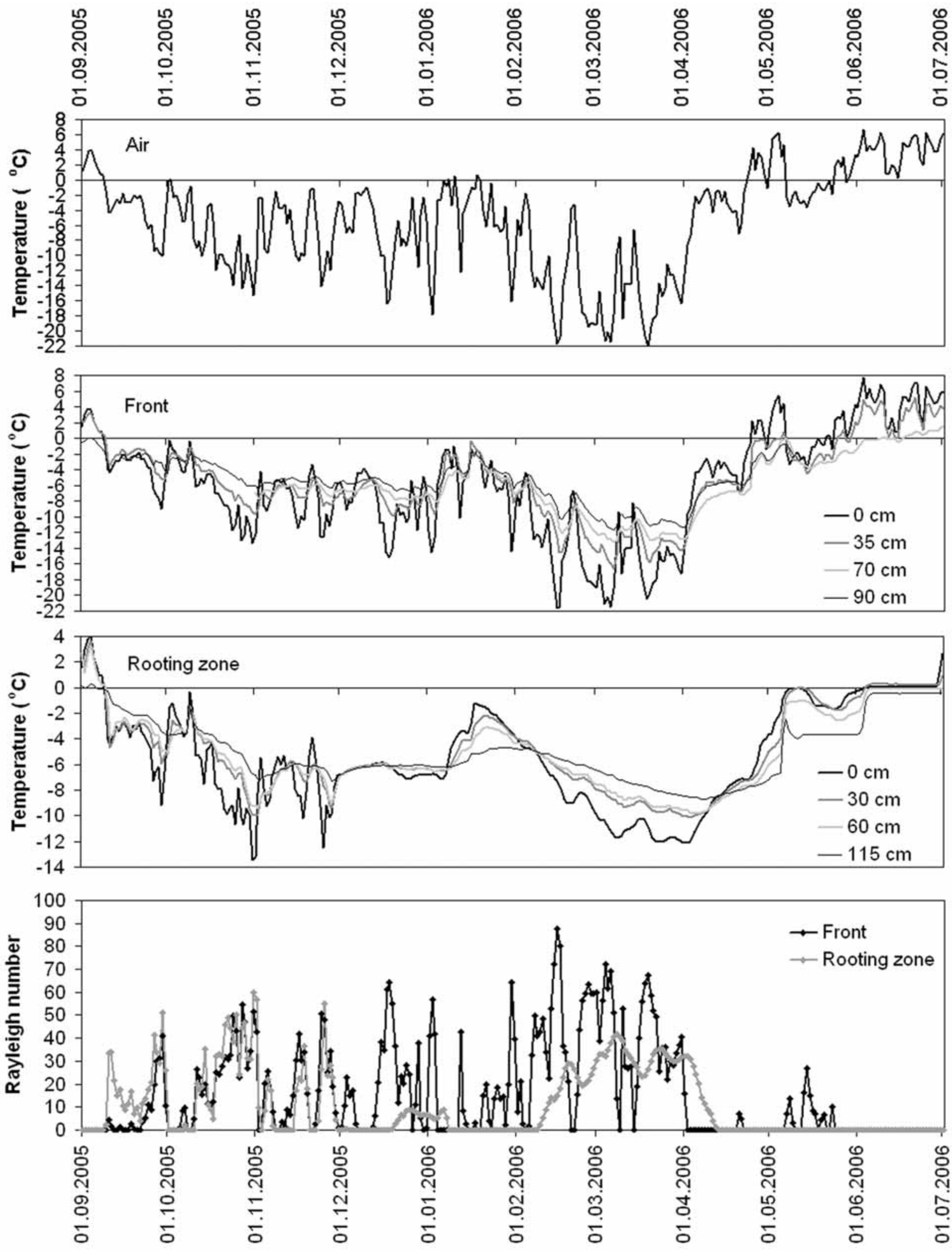

Figure 4. Daily air temperatures (at 15 cm height), active layer temperatures and estimated Rayleigh numbers at the front and at the rooting zone for the period Sept. 2005 – June 2006.

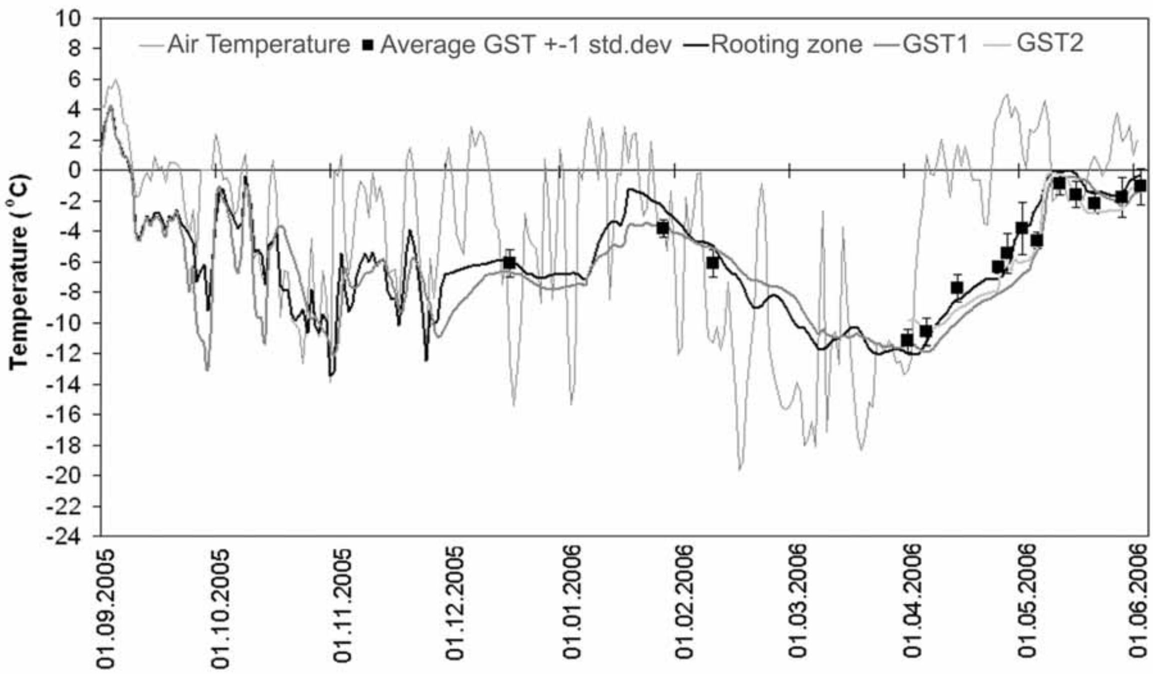

Figure 5. Average GST ± one standard deviation, based on measurement campaigns at irregular time intervals. Continuous ground surface temperatures at two sites with thick snow (GST1 and GST2), surface temperature at the rooting zone and air temperature (official temperatures from Svalbard airport, provided by the Norwegian Meteorological Office) are also given. GST2 starts on April 1.

the result of heat conduction through snow, as shown by snow temperature measurements, rather than by circulation of pore air in the active layer. The highest spatial variability in manually measured ground surface temperatures was due to a differential snowmelt pattern.

Discussion

Considering air convection in the active layer, the Rayleigh number and the spatially distributed GST revealed inconsistent results. While convection should be expected according to the Rayleigh number, both under open and closed boundary situations, no distinct convection cells were identified in the GST data. Funnels indicate that air exchange with the atmosphere is operating where the snow cover is thin (<10 cm). No funnels were found in thick snow covers. A possible explanation for the discrepancy between the Rayleigh number estimate and the GST data could be that the convection process is less efficient than described by e.g., Goering (2002), so that it is not detected in the spatially distributed GST data. Preservation of the delicate hoar supports that. The convection process may, perhaps, rather be viewed as a series of releases of ‘heat bubbles’ as described by Hanson & Hoelzle (2004), having negligible influence on the thermal regime. Instead, conduction is probably the main thermal process (cf. Gruber & Hoelzle 2008).

The presence of hoar in the upper part of the active layer indicates transport of water vapour and subsequent sublimation. Transport of water vapour may be by diffusion or air convection. Test measurements of relative humidity in the active layer pore volume, show saturated conditions for most of the winter, except for three shorter periods totalling 11–12 days, when the relative humidity decreases to 93–98% in the upper 0.35 m. Some upward vapour diffusion can be expected, at least during these periods, but it is at present not known to which degree this process can explain the amount of hoar in the upper part of the active layer. The drops in relative humidity nicely give the timing of air exchange between the pore volume and the atmosphere.

As the snow melts in spring, meltwater infiltrates the highly permeable active layer. The (initially small amount of) meltwater will first refreeze close to the surface in the active layer due to the cold content of the active layer. The observed icicles and extensions of meltwater pathways through the snow pack (Fig. 2) are formed in this way. As more meltwater is released and the cold content of the active layer decreases, the meltwater may infiltrate deeper into the active layer and eventually reach the base of the active layer, where it refreezes due to the colder permafrost below. Sawada et al. (2003) measured an accumulation of about 0.2 m of ice in only a few days in a block slope in Japan. This ice requires energy to melt and further delays active layer development (cf. Woo & Xia 1996).

Other processes, such as wind-forced convection (Humlum 1997) and heat radiation (Johansen 1975), may also be important for the thermal regime of coarse-grained active layers. Lack of relevant data precluded a discussion of these processes here.

Further studies are planned at the site as part of the IPY-project “TSP Norway—Thermal State of Permafrost in Norway and Svalbard.” This involves an attempt to measure relevant energy fluxes (cf. Smith & Burn 1987, Rist & Phillips 2005).

Conclusions

Heat transfer processes in the coarse-grained active layer of the Larsbreen rock glaciers in Svalbard have been discussed based on visual observations of ice in the active layer and temperature data. The following conclusions can be drawn:

- Considering air convection in the active layer, the Rayleigh number and the spatially distributed GST data reveal inconsistent results. Convection of air in the pore volume of blocky debris seems less important here compared to what is reported from other areas. Winter air exchange between the pore volume of the blocky layer and the atmosphere may operate through snow covers thinner than about 10 cm.
- Hoar in the upper part of the active layer indicates transport of water vapour, by diffusion or air convection, and subsequent sublimation.
- Water from snowmelt infiltrates and refreezes in the active layer. Melting of this ice delays active layer development.

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