Mountain permafrost in the Sølen massif, Central-Eastern Norway – first results

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ABSTRACT: Regional permafrost distribution modeling indicates that the eastern part of southern Norway represents the regional lower permafrost limit of southern Scandinavia. In order to validate this regional pattern, a permafrost mapping study was started in 2001 in the Sølen-Femunden area (62°N, 12°E) covering ground surface temperature measurement using miniature temperature loggers and BTS (bottom temperature of winter snow cover) measurements. This paper introduces the Sølen mountain area and summarises the first results and preliminary interpretations from the BTS survey. The measurements indicate a lower limit of mountain permafrost of about 1050 m a.s.l. Furthermore, there appears to be an aspect dependency, reflecting the more continental macro-climate of the area. The study so far supports the modelled regional pattern in the study area.

1 INTRODUCTION

There have been several studies of alpine permafrost mapping in southern Norway during recent years, partly within the framework of the European PACE project (Harris et al., 2001). These studies resulted locally in a detailed picture of permafrost distribution, especially in the Jotunheimen and Dovrefjell areas (Isaksen et al., 2002; Ødegård et al., 1996; Ødegård et al., 1999; Sætre, 1997). In these areas, there does not seem to be any aspect-governed differences of the lower limit of permafrost occurrence. A large-scale permafrost map of Scandinavia, derived from meteorological data and field measurements (Etzelmüller et al., 1998; Etzelmüller et al., in press), indicates that the lower limit of mountain permafrost decreases from about 1600 m a.s.l. in western southern Norway to below 1250 m a.s.l. in the eastern, more continental parts of southern Norway (Fig. 1), and increases again towards the east in the western Swedish mountains. According to these studies, the eastern part of southern Norway represents the regional minimum permafrost limit of southern Scandinavia. In order to validate this regional pattern a permafrost mapping study was started in 2001 in the Sølen-Femunden area (Figs 1, 2), covering ground surface temperature measurement using miniature temperature loggers and measurements of the bottom temperature of winter snow cover (BTS). These measurements were validated using geophysical soundings, including 1D vertical electrical soundings, DC resistivity tomography and hammer refraction seismic tests, during summer and autumn 2001 and 2002. UTL1 mini temperature loggers have been sampling ground surface temperature data since summer 2001 at eight different locations. Most of the temperature loggers were moved to lower altitudes in summer 2002. This paper introduces the Sølen area and summarises the first results and interpretations from the BTS measurements around the Sølen mountain massif. More detailed analyses of the permafrost distribution in the region including all available measurements will be given in a later paper by the same authors.

2 SETTING AND METHODS

The Sølen mountain massif (61°55’N, 11°31’E) is located on a plateau at 700–800 m a.s.l. This plateau contains scattered mountain massifs reaching altitudes of up to 1755 m a.s.l. (Figs 1, 2). According to extrapolation from surrounding climate stations the climate in the area is dominated by a continental temperature pattern (at 1200 m a.s.l. MAAT = −3.5°C, amplitude of 22°C) with low precipitation (<600 mm). The altitudinal tree line is at 900 m a.s.l., which is more than 100 m lower than in the Jotunheimen-Dovrefjell area. Above 1000 m a.s.l. organic surface material is restricted to mosses, lichens and scattered grass. The bedrock in the area is dominated by quartzite. Above 1100 m a.s.l. the mountain massifs in the area are covered by block fields, while below this limit, coarse blocky ground moraine dominates. The numerous deep melt water channels existing up to 1150 m a.s.l., built during Pleistocene deglaciation phases (Sollid & Kristiansen, 1983; Sollid & Sorbel, 1994), indicates partly deep loose surface material.

In the winters 2001 and 2002, 209 BTS measurements were carried out around the Sølen mountain massif (Fig. 1). All measurements were carried out during the first week of March in both years (6th March 2001, 5th–7th March 2002). UTL1 mini temperature logger series indicate a minimum BTS temperature during this period (Fig. 3). Only sites with snow depths greater than 80 cm were used, and two neighbouring measurements were obtained at most points. Measured BTS values above 0°C were considered as measurement errors and removed from the data-set. BTS measurements were performed on both sides of the mountain...
massif (Fig. 1), mainly between 800 and 1100 m a.s.l. (Fig. 4b). Most of the points are from slopes facing north-west and north-east since there are few south-facing slopes beneath 1050 m a.s.l. in this area (Fig. 4c). The snow cover was often thin or absent on convex windward slopes, and local peaks frequently had less than 50 cm of densely packed snow. In these areas BTS measurements were obtained in larger concave areas with sufficient snow thickness. On leeward slopes the snow cover was deep enough at most sites.
3 RESULTS AND DISCUSSION

The BTS measurements indicate permafrost limits ("probable permafrost", BTS < −3°C, (Haeberli, 1973)) as low as 1050–1000 m a.s.l. This is even lower than indicated by the MAAT-based model published earlier (Etzelmüller et al., 1998; Etzelmüller et al., in press). 1D and 2D DC resistivity soundings carried out on altitudes between 850 m a.s.l. and 1300 m a.s.l. clearly indicate permafrost, with patches of high resistivity values (>300 kΩm) from 950 m a.s.l. on northern slopes (University of Oslo, unpubl. data). These preliminary results confirm the BTS results obtained so far. The validation measurements were performed during summer 2002, but are not fully analysed yet.

The effects of snow cover thickness at the BTS readings was tested using statistical analyses (see also Fig. 4a). A correlation between BTS and snow gave a low correlation coefficient (r = 0.227), which, however is significant on a 0.01 level because of a high number of degree of freedoms (df = 198). As a second test, a stepwise multiple regression between BTS, altitude and snow depth was performed, with the latter two as independent variables. Here, $r^2$ increased only slightly from 0.444 with altitude as a variable, to $r^2 = 0.476$ when snow depth was also included. The BTS variance explained by altitude (44%) is less than in the Jotunheimen and Dovre areas, where percentages are 60% and 55%, respectively (Isaksen et al., 2002).

Figure 3. UTL1 mini temperature logger from the Søljen mountain at 1450 m a.s.l. in a northwest aspect. The arrow shows the date of BTS data acquisition.

Figure 4. (a) The relationship between BTS values and snow depth ($n = 198$). (b) The altitudinal distribution of BTS temperatures ($n = 198$). (c) The number of BTS values in different aspect settings and altitude. The markers denote different BTS classes (Fig. 1). (d) BTS gradients based on average BTS values within 50-m altitude intervals. The graph indicates 50 m to 100 m lower permafrost limits on the east side of the mountain massif.
In a similar study in Switzerland altitude explained only 31% (Gruber & Hoelzle, 2001). Below 1100 m a.s.l., the overall BTS gradient is calculated from the measurements to be 0.013°C m⁻¹. This value is comparable to those obtained in the Jotunheimen-Dovrefjell area (Isaksen et al., 2002). Furthermore, above 1100 m a.s.l. the gradient seems to decrease, with only moderately cold values at 1300 m a.s.l.

Considering only the BTS values below 1100 m a.s.l. there are some indications of an aspect dependency within the field area, in addition to the altitude dependency. When treating westerly and easterly slopes separately, BTS values show a warmer pattern on the westerly slopes (Fig. 4d). These relationships indicate a lower limit of probable permafrost at 1000 m a.s.l. on the east and north sides and at more than 1050 m a.s.l. on the western side of the mountain massif. The statistical difference of BTS values measured on the west and east side of the mountain was confirmed by a t-test, with a significance level below 0.001. All BTS measurements below the tree line were above −2°C.

On the Søylen massif, snow accumulates on eastern slopes, resulting in less snow on western slopes. This is a similar situation to that described in the Jotunheimen-Dovrefjell area where the prevailing winds are from the south-west. Isaksen et al. (2002) argue that the snow distribution balances the aspect differences, as in these regions there are little or no relationship observed between BTS values and aspect. However, this seems not to be the case at Søylen. An additional explanation is that the climate in the Jotunheimen-Dovrefjell area is more governed by advective energy exchange fluxes due to maritime climate, acting independently on slope aspect. In the more continental areas of Søylen advective energy fluxes may have a much lower influence on the surface energy balance.

The BTS gradient is larger than the atmospheric temperature lapse rate and can therefore not be explained by this alone. Snow cover evolution with an early, thin snow cover in the upper mountain areas would probably have a cooling effect, the opposite of a thick, insulating snow cover in the lower areas. Also change in surface material with altitude represents an important factor. The decrease in the BTS gradient in the upper part of the massif may be a result of temperature inversion effects on calm, cold days. A strong mixing of the air around the peaks caused by wind derived turbulent fluxes may provide a less steep temperature gradient in wind-exposed areas. Since all high altitude BTS values were measured at sun exposed sites on the leeward side of the massif, snow cover and aspect are also possible explanations. It is also important to keep in mind that there are only few BTS measurements (9 points) above 1100 m a.s.l.

Compared to the Jotunheimen-Dovrefjell area, the limit of mountain permafrost seems to be about 300 m lower, even when recognizing the patchy permafrost described as low as 1350 m in the Dovrefjell area (Sollid et al., 2003). On the Søylen massif, permafrost appears to be present close to the tree-line, while in the western parts of southern Norway permafrost starts more than 400 m above this limit. Over a distance less than 160 km this describes a substantial gradient, much steeper than that anticipated by the MAAT-based model by Etzelmüller et al. (1998). A major question is whether this gradient represents a regional gradient from the west to east in Norway, or if it is partly caused by local effects around the Søylen massif, which is a singular massif, surrounded by a flat plateau. This topographic condition may cause extremely cold weather. However, BTS measurements on the Jetta massif (Bø, 1998), a mountain east of Jotunheimen-Dovrefjell, indicate low permafrost boundaries there as well. BTS measurements have also been obtained at the Tron massif (Engelien, 1995), about 50 km north-west of Søylen. At Tron the permafrost limit is probably above 1400 m a.s.l. This can be explained by strong inversions during winter months since deep valleys, draining the cold air masses, surround this massif. Snow-conditions, with late snowfall in autumn, probably strengthen the difference from west towards east, lowering the general lower limit of permafrost in the Søylen area down to less than 1100 m a.s.l.

4 PRELIMINARY CONCLUSIONS

Based on these first field studies and analyses of permafrost distribution in south-eastern Norway the following conclusions can be drawn:

- BTS measurements indicate a lower limit of mountain permafrost of about 1050 m a.s.l. with permafrost patches below this altitude.
- There is observed an aspect dependency, probably reflecting the more continental macroclimate of the area.
- There exists a strong gradient of the lower limit permafrost altitude through southern Norway, which may be exaggerated due to local effects in the study area.
- The Søylen-Femunden area seems to represent the regional minimum mountain permafrost limit of southern Scandinavia.

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