THE DISTRIBUTION OF PERMAFROST IN SOUTHERN NORWAY - A GIS APPROACH

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Abstract

The paper discusses the generation of a permafrost map of Southern Norway, which shows the lower limit of discontinuous permafrost at a regional scale. This map is based on field investigations of permafrost occurrence in 15 different high-mountain sites, a grid-based mean annual air temperature (MAAT) map and spatial analysis of the relationship between permafrost occurrence and MAAT. The hypothesis that regional permafrost distribution in Southern Norway can be modelled by MAAT as the main influencing factor is supported, and the proposed -4°C boundary of King (1983) and Ødegård et al. (1996) was verified. The approach opens possibilities for analyses of past and future climate change consequences on regional permafrost distribution in Southern Norway.

Introduction and setting

Detailed mapping of high alpine permafrost can be done by ground temperature measurements and through indirect methods such as Base Temperature of Snow Cover (BTS) measurements, seismic refraction and DC resistivity soundings (e.g. Barsch, 1977). For regional mapping of permafrost distribution it is necessary to establish a relationship between permafrost occurrence and macroclimatic information. Such attempts have been made, using macroclimatic parameters such as mean annual air temperature (MAAT), freeze/thaw indices and radiation values (cf. Guodong and Dramis, 1992). In Switzerland, several GIS-based programmes have been developed for mapping permafrost distribution based on combined climatic and topographic parameters, utilising either the empirical “rules of thumb” of Haebeleri (1975) (Keller, 1992; Imhof, 1996) or potential solar radiation (cf. Funk and Hoelzle, 1992) and MAAT (Hoelzle et al., 1993).

In Southern Norway, temperature measurements from the Gjuvvasshøi area, Jotunheimen, have shown a linear relationship between mean annual ground temperature (MAGT) and MAAT (Ødegård et al., 1992). Later, Ødegård et al. (1996) and Setrø (1997) concluded that BTS values in the Dovrefjell area can be explained mainly on the basis of altitude, while radiation is of minor importance. This is in contrast to the situation in the Alps where radiation is considered to be more important than MAAT (e.g., Hoelzle, 1992). These findings allow us to use MAAT to map permafrost distribution on a regional scale in Southern Norway. Previously, Ødegård et al. (1996) and King (1986) have presented permafrost maps, based on a proposed boundary of MAAT = -4°C as the lower altitude limit of discontinuous permafrost. In the present study, a permafrost map of Southern Norway is presented, based on additional field investigations (Figure 1), a grid-based temperature map produced at the Norwegian Meteorological Institute (DNMI) (Tvete and Forland, 1998) and spatial analysis of the relationship between permafrost occurrence and MAAT.

Methods and results

EVALUATION OF THE ACTUAL PERMAFROST BOUNDARY WITHIN THE STUDY SITES

The actual permafrost boundary was estimated using DC-resistivity soundings (Table 1, Figure 2). An ABEM Terrameter was employed to measure Hummel and Schlumberger configurations, with maximum AB/2-distances of 200 m to 400 m. Steel and aluminium rods were used as potential and current electrodes, respectively. Most of the profiles are located on flat or convex areas. Where this was not possible the AB direction was chosen to more or less follow contour lines. Two or more profiles at different altitude levels were recorded on each site.
In most of the areas, the geoelectrical profiles were taken both above and below the estimated permafrost limit, thus the permafrost altitude limit could be given at an order of 100 m (Table 1). In the case of the sites Haukelifjell, Sognefjell and Valdresflya, permafrost was not indicated by the DC-resistivity soundings. There, an estimated altitude limit is given, based on an evaluation of the activity of patterned ground, blockfields etc. in the area.

ESTIMATION OF THE MEAN ANNUAL AIR TEMPERATURE (MAAT) AT THE DIFFERENT STUDY SITES

Next the mean annual air temperature (MAAT) was evaluated at the different study sites. The basis was a digital map showing the MAAT in a one-km-resolution grid developed at the Norwegian Meteorological Institute (Tveito and Førland, 1998). This map was produced through reducing MAAT to datum level for all Norwegian climatic stations applying one lapse rate, spatial interpolation using kriging and combining the resulting map with a digital elevation model (DEM) to retrieve temperature at the terrain surface. In an area of 200-300 km² around each study site, the mean temperatures at different altitude intervals were calculated by comparing the DEM with the digital MAAT map. The MAAT corresponding to the estimated permafrost limit altitude could then be found (Table 1).

The results showed that, with the exception of two sites, most of the study areas had MAAT values close to -4°C at the permafrost limit. At Tronfjell, 1660 m a.s.l., the MAAT indicates permafrost at altitudes below 1300 m while permafrost is only present at the peak. Deep valleys surround this mountain on all sides and strong inversion effects are probable. At Gaustatoppen (1850 m a.s.l., MAAT = -4.5°C) permafrost is predicted in the model only for the peaks, whereas permafrost was found locally as low as 1400 m a.s.l. In this case there is a climatic station on top of the mountain which influences the interpolation of MAAT in the area. Inversion effects may in this case explain permafrost at low altitude. In addition, this site has extensive boulder fields at low altitude levels, which reduce ground temperatures because of Balch ventilation (cf. Liestøl, 1965).

ESTIMATION OF THE REGIONAL LOWER LIMIT OF DISCONTINUOUS PERMAFROST

Figure 1. Location of DC resistivity soundings and BTS profiles. The areas Dovrefjell (Df), Tronfjell (Tf) and Jetta mountain (Je) are described in more detail in Ødegård et al. (1996) and Sætre (1997), Engelen (1995) and Bo (in prep), respectively. Ro = Rondane mountains, If = Juvvasshytta (jotunheimen), Vf = Valdresflya (jotunheimen), Sf = Sognefjellet, Hu = Hurrungane, Au = Aurlandsfjella, Fi = Finse mountain area, Hk = Haukelifjell, Gt = Gaustatoppen.

Figure 2. The figure gives a synthesis of various types of DC-resistivity sounding curves found on the different sites. The curves show a theoretical model, fitting the data points, while the dotted line gives the most likely interpretation in terms of layer thickness and resistivity (cf. Table 1). The profiles were interpreted by the software RESIXPlus (© Interpex Lim). (a) Active layer with relatively low resistivity, underlain by ice-rich permafrost (Dovrefjell, Gaustatoppen, Jetta mountain). (b) Coarse boulder fields with high resistivity in the active layer, underlain by ice-rich permafrost, (Dovrefjell, Tronfjell, Hurrungane). (c) Water-rich layer at the bottom of the active layer, overlying permafrost layer with moderate resistivity and thickness (Dovrefjell, Hurrungane). (d) Coarse boulder fields, having a thickness (<10 m), ice-rich layer with permafrost (Jetta, ca. 1500 m a.s.l.). (e) Possible low-resistivity permafrost, but may be temperature effect. Very unsure interpretation concerning permafrost, probably close to the boundary (Midtdalsbreen, Sandalsnut, 1450-1550 m a.s.l.). (f) Boulder fields with high resistivity overly bedrock, no permafrost. (Aurlandsfjella). (g) Possible low-resistivity permafrost, but may be temperature effect. Very unsure interpretation concerning permafrost, probably close to the boundary (Midtdalsbreen, Sandalsnut, 1450-1550 m a.s.l.). (h) Sediments (e.g., coarse ground moraine or weathering residuals) with relatively high resistivities overlying bedrock, no permafrost (Valdresflya). (i) Sediment layer with relatively high resistivities overlying bedrock, causing a “permafrost curve”. These sites are covered by dense vegetation, which additionally may cause a temperature effect at depth (Gaustatoppen, Midtdalsbreen, Tronfjell ~1300 m a.s.l.).
As the final step the lower discontinuous permafrost limit in Southern Norway was estimated. As a first approach, simply all cells of the MAAT map which show values lower than \(-4\,^\circ\text{C}\) were selected (Figure 3a). In the second approach, a trend surface over the lower limit of discontinuous permafrost was calculated (Figure 3b). Here, the boundary cells of the areas \(< -2\,^\circ\text{C}\) were first selected. Based on these points a quadratic trend surface (cf. Davis, 1986) was calculated, and then 300 m was added to the results. With a lapse rate of \(0.7\,^\circ\text{C}\) (100 m\(^{-1}\)) this corresponds to a temperature drop of \(-4.1\,^\circ\text{C}\). The \(< -4\,^\circ\text{C}\) boundary cells were not used directly because they were not scattered enough to give a reliable trend surface. With this approach a goodness of fit of \(r^2=0.9\) and a RMS-error of 85 m were obtained in relation to the \(< -4\,^\circ\text{C}\) boundary. According to these results the lower permafrost altitude limit decreases from above 1700 m a.s.l. in the western part of Southern Norway down to about 1200 m a.s.l. in its eastern part.

**Discussion**

**Methodology**

**DC-RESISTIVITY SOUNDINGS**

In this work, DC-resistivity soundings were partly used alone to give an indication of the lower permafrost limit. This is problematic, as the method is indirect, and supplementary measurements are required (e.g. Vonder Mühll, 1993). However, in some control areas, both DC resistivity soundings and BTS measurements have been carried out (Ødegård et al., 1996; Engelien, 1995; Sætre, 1997). In these areas the two methods gave analogous results. We suggest that the use of one method alone can be defended for a coarse, regional mapping purpose such as presented in this study.

The high number of DC-resistivity profiles allowed us to distinguish different patterns of resistivity curves (Figure 2). Generally, extensive boulder fields, partly with high resistivities, covered the permafrost sites vi-
Figure 3. Map of permafrost distribution based on (a) grid cells with a MAAT < -4°C, (b) areas above a quadratic trend surface. The contour lines show the estimated trend surface of the lower discontinuous permafrost limit, with a contour interval of 200 m. Jostedalsbreen (Jbr), Hardangerjøkull (Hj) and Breheimen (Brh) are glacier areas. These are non-permafrost areas as most of these glaciers are throughout temperate. Parts of the Jotunheimen (Jh) mountains are also glacier covered. Permafrost is displayed in areas that have not been investigated quantitatively in the field during this study, such as Reinheimen (Rh), the Finse-Bugdalen area (FB), Hallingskarvet (Hs) and Tafjordfjella (Tf). Future permafrost prospecting is planned in these areas. (c) Map of permafrost distribution for a one degree warmer climate and (d) colder climate.
Permafrost layers in these areas seem to reach resistivities of around 100 kΩm, which indicates relatively ice-rich permafrost (cf. King, 1982). At several sites close to the possible lower margin of permafrost, a low resistivity layer appears between the active layer and the supposed permafrost table. These layers are interpreted as water-rich sediments, possibly originating from degrading permafrost (Figure 2c). Other sites lack this water-rich horizon, showing thin, ice-rich sediments (Figure 2d). Sites with exposed bedrock are difficult to interpret, because they often lack massive ice bodies at depth. This may result in lower resistivity layers in permafrost (20-30 kΩm), and in some cases the differences between upper and lower layers are so small that these can be attributed to temperature effects (Figures 2e and 2g). Boulder fields with and without permafrost were easily distinguished (Figures 2b and 2f). Sediments over bedrock profiles without permafrost gives a different response due to type of surface material, moisture etc. (Figures 2h and 2i).

**MAAT AT THE PERMAFROST LIMIT**

Our method of linking a macroclimatic parameter with the permafrost limit roughly follows that of Hoelze et al. (1993). However, we use only a simple relationship between the lower limit of discontinuous permafrost and MAAT. This dominance of MAAT is due to the more maritime macroclimate of Norway. In this regional approach, the results probably would not be greatly different if topographic or snow effects were incorporated, especially because of the coarse DTM used.

The decision to use a trend surface instead of MAAT alone was taken for two main reasons: firstly, the permafrost limit displays a macro-climatic relationship, which can be represented by a smooth surface. The second reason was the averaging effect of the statistical calculation. A coarse DEM tends to overestimate permafrost occurrence (Hoelze and Haeberli, 1995) in areas with high local relief. The trend surface filters noise created by calculation of the MAAT map and the DEMs, and should therefore give a more consistent regional picture. Areas in the western part of southern Norway, such as Tafjordfjella, Breheimen, Reinheimen and the Lesja-Eikesdal mountain area show considerably smaller areas in the trend-surface derived map than on the MAAT-map. The lapse rate used in the MAAT map appears to be too high for the maritime western areas. A lower lapse rate would give warmer temperatures in the mountains, thus decreasing permafrost area in the MAAT-map. The trend surface-derived permafrost map is therefore expected to display a more realistic regional pattern of the discontinuous permafrost in southern Norway.

**CONTRASTS ON PERMAFROST DISTRIBUTION**

Discontinuous permafrost in Southern Norway is mainly concentrated in a 50 km to 100 km wide zone between Hallingskarvet in the south and the Dovrefjell mountains in the north. East and west of this zone, only small areas have permafrost. On the western side, high mountain areas are normally covered by glaciers. Furthermore, the lower permafrost limit rises to over 1600 m a.s.l. due to increasing maritime influence. Thus, there are very few areas where permafrost can exist. On the eastern side of this zone only small mountain areas or single peaks reach altitudes above 1400 m a.s.l.

The tendency towards more continentality in the eastern part of Southern Norway is expressed through less winter precipitation and higher summer temperatures. The differences in winter precipitation at the permafrost limit between eastern and western Norway are substantial. However, snow cover does not seem to have an effect on permafrost distribution in relation to MAAT. One reason may be that even though eastern Norway has a larger potential for heat loss, this effect is counterbalanced by late-lying snow and generally cooler summers in western Norway.

The altitude ranges (Table 1) are lower limits for the discontinuous permafrost boundary. There are, however, large permafrost patches at still lower altitudes. In the Finse area for instance, permafrost occurs down to ca. 1300 m a.s.l. in relation to perennial snowbanks, and at altitudes of around 1500 m a.s.l. probably between 10-30% of the area is underlain by snow-bank related permafrost. In areas further east, radiation effects contribute to lower permafrost limits on north-facing slopes, as was found on the mountain Jetta. The limit for sporadic permafrost is even lower than 1300 m, and often combined with the occurrence of palsas.

**IMPLICATIONS TO PERMAFROST DISTRIBUTION DURING PERIODS WITH LOWER OR HIGHER MAAT**

The simple relationship between MAAT and permafrost distribution provides an opportunity to estimate past and future permafrost distribution patterns in Southern Norway by shifting the trend surface in the z-direction. This corresponds to the step change in MAAT used by Hoelze and Haeberli (1995) to simulate the effect of a climatic change on permafrost distribution and glacier size in an area of the Swiss Alps.

To illustrate such possibilities, we have shifted the trend surface, equivalent to a 1°C shift to respectively warmer and colder situations than today (Figures 3c and 3d). This may roughly correspond to a supposed future climatic warming and the colder situation during the Little Ice Age. An increase of the lower permafrost altitude leaves only small areas in the Jotunheimen,
Dovrefjell and Rondane mountains within the discontinuous permafrost zone. East of Rondane and west of Jotunheimen/Kjølen most peak areas will fall outside this limit (cf. Figure 3c). The present permafrost in the Finse-Bygdin area would disappear nearly completely. In contrast, a lowering of the permafrost limit classifies most of this mountain area and the southern margins of the Hardangervidda within the discontinuous permafrost zone (Figure 3d). These are interesting areas for studying relict permafrost and related landform features. The effect of glacier response to climatic change was not considered here. A colder MAAT would result in a glacier area increase and thus a decrease in permafrost area. A climatic warming would expose areas to permafrost aggradation due to glacier retreat. There are several implications of the estimated permafrost limits that should be studied more intensively in the future, and where the presented maps may be a helpful tool:

- Processes in relation to degrading permafrost
  Melting of permafrost alters the geotechnical properties of a slope. Landslides in the Alps are known to have occurred in areas affected by degrading permafrost (Haeberli, 1992). The warming that occurred after the Little Ice Age caused an effect similar to what might be expected from future climate warming. It is of interest to identify areas that most likely were underlain by permafrost during the Little Ice Age. These areas may have been more prone to slope failures than elsewhere. This knowledge is essential to understand landslide hazards and predict risk associated with future permafrost degradation.

- Implication for moraine formation
  Moraine formation and material stratigraphy is highly dependent on ice temperature at the glacier front (cf. Weertman, 1961; Boulton, 1974). Glaciers ending in the permafrost zone always have cold-based margins. Cold-based glacier fronts, advancing in permafrost areas, favour the formation of ice-cored moraines and push moraines (cf. Haeberli, 1979, Etzelmüller et al., 1996). Especially in the Jotunheimen mountains, these types are frequent (cf. Østrem, 1964). Previous permafrost distribution can be used to infer whether the glacier terminated in permafrost, and how moraine formation was affected.

- Distribution of periglacial landforms
  Periglacial landforms are widespread in the Norwegian mountains. However, especially well-sorted forms appear inactive today. It is possible that these forms originated during colder periods and are left today as relict features. By combining regional mapping of these forms with the present permafrost maps, such relationships can be established.

- Applied geomorphology
  The existence of permafrost has substantial consequences for human activities in mountain areas (e.g., Haeberli, 1992). Most of the permafrost in Norway is found in areas of low human activity or inside national parks with strong restrictions on human interference. However, with increasing mountain tourism (trekking, ski resorts etc.), demands for better telecommunication networks, hydropower development etc., construction work within permafrost areas may become necessary.

Conclusions

(1) This study has verified the proposed -4°C boundary of King (1983) and Ødegård et al. (1996), and supports the hypothesis that regional permafrost distribution in Southern Norway can be modelled with MAAT as the main influencing factor.

(2) The lower limit of discontinuous permafrost in Southern Norway can be modelled by a quadratic trend surface based on MAAT. The trend surface explains 90% of the variation of areas with MAAT = -4°C in Southern Norway.

(3) The approach opens possibilities for analyses of past and future climate change consequences on regional permafrost distribution in Southern Norway.

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