Changing Lowland Permafrost in Northern Sweden: Multiple Drivers of Past and Future Trends

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Contribution

Paper I I initiated this paper. All authors contributed to the manuscript but I am the main author.

Paper II & III The permafrost monitoring was initiated and carried out by Jonas Åkerman from 1978 and 1980. The air and ground temperatures are part of the Abisko Station's monitoring programme. I analysed the data and wrote most parts of the papers. All authors contributed however to the manuscripts.

Paper IV This idea was developed by me, Terry Callaghan and Torben Christensen. The modeling was done by me and Elchin Jafarov. I wrote most parts of the paper, although all authors contributed to the manuscript.

Paper V This project arose from a discussion between the authors. I have had the main responsibility for the project, done the analysis for the paper and written most parts of the paper. All authors contributed though to the manuscript.

Permafrost under förändring i norra Sverige: Bakomliggande faktorer och trender

Svensk sammanfattning

Under de senaste decennierna har klimatförändringar blivit ett känt begrepp och områden i Arktis har påverkats mer än andra områden på jorden. Klimatförändringarna påverkar olika element av kryosfären och permafrost (mark som är frusen året om minst två år i följd) är ett av dessa. Permafrost är en viktig del av kryosfären eftersom den påverkar hydrologiska processer, infrastruktur, energi- och kolutbytet mellan atmosfären och marken och därför också det globala klimatsystemet. Lufttemperaturen förutspås att fortsätta öka under 2000-talet och detta förväntas ha stor påverkan på områden med permafrost runt om i Arktis. Syftet med detta arbete var att få en ökad förståelse för vad som styr förändringar av permafrost i låglänta områden i Torneträskområdet i norra Sverige idag, samt att undersöka hur permafrosten har förändrats under de senaste 1000 åren i förhållanden till olika faktorer som påverkar den.

Denna avhandling omfattar långtidsmätningar av marktemperaturer och det aktiva lagret (det lager ovanpå permafrosten som tinar och fryser årligen). Dessa visar att permafrosten i Torneträskområdet tydligt har påverkats av de uppmätta klimatförändringarna de senaste decennierna. Marktemperaturerna har ökat och det aktiva lagret har blivit tjockare. Detta kan förklaras av en ökande lufttemperatur samt i vissa fall ökande snödjup under vintern. Enligt de flesta modeller förutspås snödjupet att fortsätta öka i Torneträskområdet under 2000-talet. Snö isolerar marken och ett ökande snötäcke kan leda till att permafrosten blir varmare och slutligen tinar. Inom projektet har ett experiment satts upp för att simulera ökat snödjup och dess effekt på permafrost och vegetation. Efter bara tre års manipulation av snödjupet syntes en förändring av det aktiva lagrets tjocklek samt av vegetationen.

Modellerade marktemperaturer visade att permafrosten har tinat vid två tillfällen de senaste 100 åren. För de senaste 1000 åren indikerade de modellerade resultaten att det funnits permafrost hela tiden, men detta stämmer inte överens med proxydata (från torv och sjösediment) från området som visar att permafrosten förmodligen har bildats under den så kallade ”Lilla Istiden” (ca år 1300).

Detta arbete har ökat förståelsen för vad som orsakar förändringar i permafrosten i Torneträskområdet. Utbredningen av permafrost i området styrs av många faktorer, men lufttemperatur, snödjup, vegetation och jordmån är de dominerande faktorerna. En viktig slutsats är att förhållandet mellan snö och permafrost varierar och att det inte enbart bestäms av snöns tjocklek. Snömanipulationerna indikerade att snöns interna struktur, såsom till exempel bildning av islager under och inne i snön kan påverka avrinningen vid snösmältningen vilket i sin tur kan påverka markvattnet och marktemperaturerna. En annan viktig slutsats är att permafrosten tinar inte bara från ovan utan även underifrån, förmodligen på grund av ett ökat flöde av markvatten. Detta gör permafrosten i låglänta områden i Torneträskområdet extra känslig för klimatförändringarna som förutspås för området under 2000-talet.

Changing lowland permafrost in northern Sweden: Multiple drivers of past and future trends

Abstract

Climate warming is more pronounced in the Arctic than in other parts of the world. This warming affects the terrestrial cryosphere including permafrost with consequences ranging from societal impacts to changes in hydrology and feedbacks in the climate system such as those imposed by changing greenhouse gas exchanges. Permafrost dynamics in a marginal zone for its very existence is in this context of outmost importance as it represents a very sensitive environment where changes may appear first. The main objective of this project was to understand the current status of such sensitive lowland permafrost in the Torneträsk area, sub-arctic Sweden and to explore its development over the past 1000 yrs in relation to various environmental drivers of change.

Monitoring of permafrost temperatures and active layer thickness showed that permafrost was during the last three decades degrading in the Torneträsk catchment. Increasing ground temperatures and active layer thickness were correlated with increases in air temperatures and in some cases with snow depth. A manipulation experiment that simulated future scenarios of increases in winter precipitation showed that permafrost and vegetation were sensitive to changes in snow depth after only three years of treatment.

Modelled ground temperatures showed two periods of lowland permafrost degradation during the last Century. Over the last 1000 yrs, the modelled ground temperatures at one site currently with permafrost indicated that permafrost existed throughout this period. However, this contradicts proxy data from the area that suggests that permafrost formation occurred during the Little Ice Age (around AD1300).

This study has improved our understanding of current and past dynamics of lowland sub-arctic permafrost in northernmost Sweden. The presence or absence of permafrost in the Torneträsk catchment is determined by many factors, but air temperatures, snow depth, vegetation and soil type are the most important. A major conclusion of the study is that the strength of the relationship between snow and permafrost dynamics varies considerably and is not only determined by the snow depth. The manipulation study indicated that the structure of the vertical snow profile, for example an occurrence of a bottom ice layer, could potentially affect the thermal regime of the soil via lateral runoff of melt water. Another important conclusion was that the lowland permafrost in the Torneträsk catchment is thawing from above but also from underneath, most likely caused by slightly warmer or more freely flowing ground water around and below the frozen body. This opens the possibility for permafrost degradation at the top and bottom surfaces, thereby making it very sensitive to the projected climate change during the 21st Century.

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1. Introduction

1.1 Characteristic and importance of permafrost

Climate change is ongoing and it is more pronounced in the Arctic compare to other parts of the world (ACIA, 2005). Global mean air temperatures have risen ~0.65ºC during the last four decades (Le Treut *et al.*, 2007), whereas in some parts of the Arctic the air temperatures have risen more than 4ºC during the same period (Chapman & Walsh, 2003). The recorded increases in air temperatures affect many terrestrial processes including cryospheric components such as permafrost (ground temperatures that stay at or below 0ºC for two or more consecutive years) (Anisimov *et al.*, 2007), especially in areas with a mean annual air temperature around 0ºC.

Permafrost is an important component of the cryosphere in the Arctic as it influences energy exchanges between the land and the atmosphere, hydrological processes, infrastructure, natural hazards, carbon budgets and hence the global climate system (Riseborough *et al.*, 2008). Much, 20-25%, of the terrestrial surface of the Northern Hemisphere is underlain by permafrost (e.g. Serreze *et al.*, 2000). Permafrost is widespread at higher latitudes, but also exists further south in mountainous areas. The distribution is usually defined in four sub-categories based on the percentage of land surface underlain by permafrost: continuous permafrost (90-100%), discontinuous permafrost (50-90%), sporadic permafrost (10-50%) and isolated patches (0-10%) (Brown *et al.*, 1998). The thickness of permafrost varies from a few decimetres e.g. in areas of isolated and sporadic permafrost up to more than 1400 metres in the continuous permafrost in Siberia. On top of the permafrost is an active layer that thaws and refreezes on a seasonal basis. Its thickness varies depending on climate, vegetation cover, and soil type, from a few decimetres in peat to more than several metres in areas with well-drained materials (Brown, 1997). The active layer is the layer in which current biological activity, i.e. microbial decomposition and plant root function are concentrated. Between the bottom of the active layer and the top of the permafrost is a transient layer that occasionally joins the active layer and occasionally the permafrost (Shur *et al.*, 2005). However, the permafrost below often contains records of biological activity, particularly in the form of carbon from former periods when permafrost was absent or deeper in the ground profile.

Associated with the increases in air temperatures recorded in the Arctic during the last decades, ground temperatures in areas underlain by permafrost have increased (Walsh *et al.*, 2005), by 0.5 to 2ºC at the depth of zero annual amplitude (the distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature) (Brown and Romanovsky, 2008). Permafrost thawing occurs at the southern limits of the permafrost zone (Brown & Romanovsky, 2008) and this has contributed to a northward moving of the southern boundary of discontinuous permafrost (Lemke *et al.*, 2007). Air temperatures are expected to continue to increase and as a result, thawing of permafrost in the 21st Century will likely continue or even accelerate and cause serious societal and environmental impacts (Brown & Romanovsky, 2008).

Permafrost is an integral part of many northern landscapes and has profound implications on infrastructures and economies in the North (Instanes *et al*., 2005). In areas where permafrost starts to degrade, thawing can directly affect infrastructure through ground subsidence and slope failures. Thawing of permafrost can also alter the hydrology in an area that can have direct impacts on the local population. In some areas in the discontinuous permafrost zone in Siberia, lakes are disappearing, whereas the opposite scenario with an increase in lake areas is found in more northerly areas of continuous permafrost (Smith *et al*., 2005). Changes in hydrology due to permafrost thawing can threaten water sources and their contamination while changing vegetation (e.g. Johansson *et al*., 2006; Malmer *et al*., 2005). Permafrost thawing may also lead to the release of heavy metals such as mercury from arctic soils into surface waters (AMAP, 2003).

Only a small part of the world's population lives in the Arctic, but thawing of permafrost is something that will not only affect local people but will have regional and global impacts. At a regional scale, infrastructure such as pipelines can be affected by ground subsidence: on a global scale, increased microbial decomposition of previously frozen organic soil will release more carbon to the atmosphere and hence potentially increase global warming further. This is one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in a warming climate (Schuur *et al*., 2008). Changes in hydrology occurring at a local scale can affect fauna on a global scale, for example migrating birds that lose their habitats (Luoto *et al*., 2004).

In the sub-arctic of northernmost Sweden, permafrost thawing has been reported (Christensen *et al*., 2004; Johansson *et al*., 2006, Sannel & Kuhry, 2009). In the Abisko area (68º20'E, 19ºº02'E) this has been associated with wetting of peat plateaus (Christensen *et al*., 2004; Johansson *et al*., 2006) whereas in Tavvavuoma (68º28'N, 20º54'E), northeast of Abisko, the opposite scenario was observed and thermokarst drainage has occurred during the last four decades (Sannel & Kuhry, 2009). The local impacts from thawing permafrost are mainly on infrastructures such as damage to roads and tilting electricity poles, but also potentially through the release of carbon and heavy metals. Klaminder *et al.* (*in press*) reported from two peat mires in the Abisko area that mercury export from thawing permafrost can affect the surface water in the area. At a larger geographical scale the main effect of thawing permafrost in this area is the increased radiative forcing from increased carbon release to the atmosphere through CH_4 and CO_2 emissions (Johansson *et al*., 2006).

1.2 Objectives

The main objective of this project is to understand the current status of lowland permafrost in the Torneträsk area, northern Sweden and to explore its development over the past 1000 years in relation to various environmental drivers of change.

To achieve the overall objective, a series of specific research questions were addressed:

- What determines the current presence or absence of permafrost in the Torneträsk region, northern Sweden? (Appendix I)
- What is the current status of lowland permafrost in the Torneträsk region? (Appendix II and III)
- How has permafrost varied during the last 1000 years? (Appendix IV)
- How sensitive is lowland permafrost to various environmental factors and particularly snow depth? (Appendix V)

2. Site description

The Torneträsk catchment is located in the sub-arctic environment of northernmost Sweden and covers approximately 4500 km^2 (Figure 1). The elevation in the Torneträsk region ranges from 340 to 1750 m a.s.l. Lake Torneträsk is the main water body in the catchment and covers an area of 330 km^2, has a maximum depth of 182 m and a mean depth of 52 m (Ekman, 1957). The vegetation cover in the Torneträsk region ranges from remnants of boreal pine forest through the subalpine zone dominated by mountain birch forest (*Betula pubescens ssp. czerepanovii*), through the low alpine belt which extends from the treeline up to where *Vaccinium myrtillus* no longer persists, to the high alpine belt with non-vegetated surfaces (Carlsson *et al*., 1999). The mountain birch forest covers an area of 1200 km^2 which is ~25% of the total area of the Torneträsk catchment (Appendix I).

The study area is located in the zone of discontinuous permafrost, i.e. 50-90% of the catchment is underlain by permafrost (Brown *et al.*, 1998). Based on many investigations in Fennoscandia, King (1986) concluded that the boundary between continuous/discontinuous permafrost corresponds approximately with the –6 ºC isotherm and the limit between discontinuous/sporadic permafrost zones corresponds approximately with the –1.5 ºC isotherm of the mean annual air temperature. At the Abisko Scientific Research Station (located in the Torneträsk region at 385 m a.s.l.; Figure 1) the mean annual air temperature for 1913 to 2006 was -0.6°C (Appendix II). The study area covers a strong climatic gradient, ranging from a maritime climate in the West to a more continental climate in the East. In general, regional precipitation decreases and seasonal temperature differences increase towards the East. The lowest precipitation is however, found around Abisko (~300 mm/yr for the period 1961-1990) due to a rain shadow and the highest precipitation is found near the Norwegian border (~900 mm/yr for the period 1961-1990) (Alexandersson *et al*., 1991). During the last decade, increases in precipitation have occurred and the total annual precipitation at Abisko has increased to 362 mm for the period 1997-2007 (Abisko Station meteorological data).

In the catchment, mountain permafrost is widespread above the treeline in the tundra zone. Jeckel (1988) concluded from ground temperature measurements, that the lowest limit of mountain permafrost occurrence was 880 m a.s.l. in the Torneträsk region. Ridefelt *et al*. (2008) modelled the probability of mountain permafrost in the Torneträsk catchment and concluded that permafrost was likely to be found in the western part of the catchment above 1300 m a.s.l. Around Abisko mountain permafrost was likely to occur above 850 m a.s.l on the north-east and east-facing slopes, above 1000 m a.s.l on the west-facing slope and above 1100 m a.s.l on the south-facing slopes (Ridefelt *et al*., 2008).

Lowland permafrost exists only in especially favourable locations in the Torneträsk catchment such as underneath wind-exposed ridges and in peat mires (Appendix I). However, permafrost can also underlay wind-swept slopes

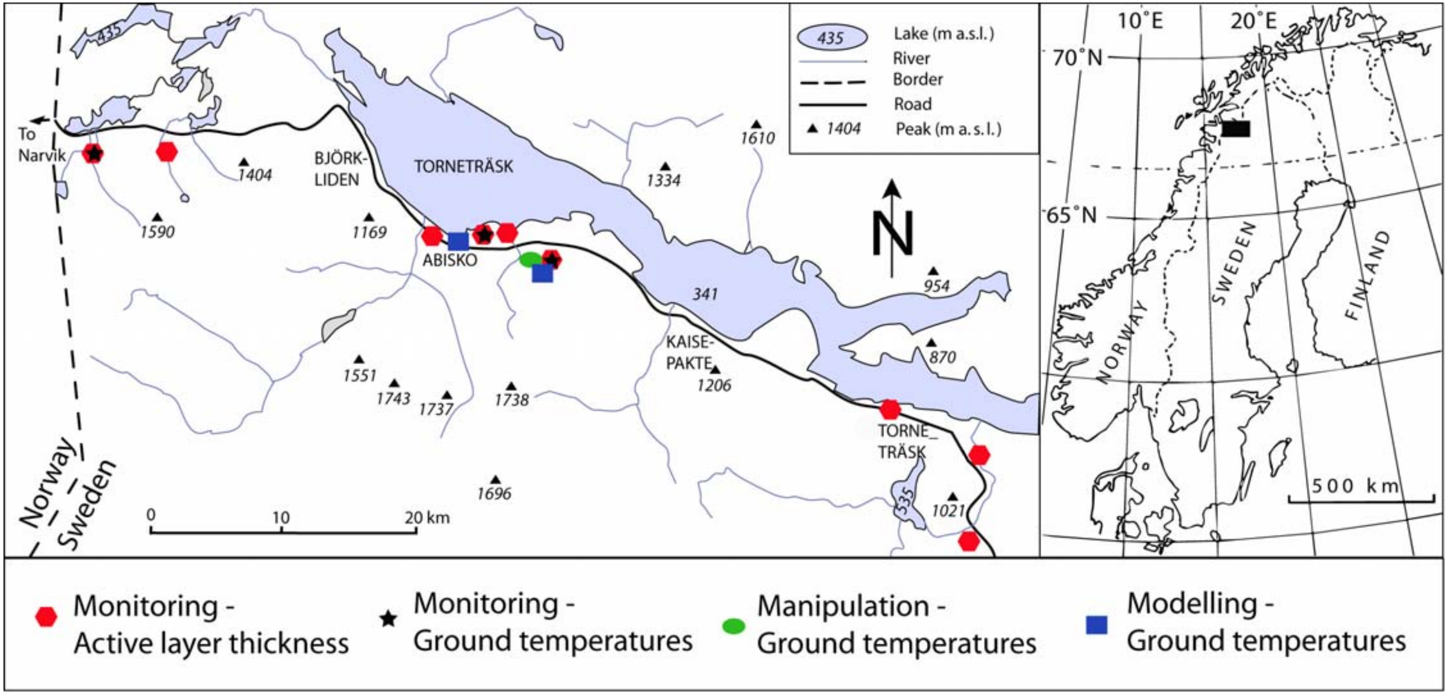

Figure 1 *Research activities and study sites in the Torneträsk region*

and exposed plateau areas due to the lack of an insulating snow cover during winter. Permafrost underlays peat plateaus and palsa mires in the study area due to a layer of organic material (i.e. the peat) that protects the ground beneath from atmospheric heating (French, 2007). Palsa is a small mound of peat in sub-arctic mires that contains a core of frozen peat and/or silt, thin layer of ice, small ice crystals and segregated ice that does not melt during the summer due to the protecting layer of peat (Seppälä, 1986).

The study presented here was carried out in peat mires along an East-West transect in the catchment (Figure 1). In general, low palsas and puonos (smaller mounds) are found in the western- and the eastern-most parts of the catchment and peat plateaus are found around Abisko. The thickness of permafrost in the mires ranges from a few to 16 meters. This thickness reflects the depth of the snow layer which varies along the transect of mires due to the strong climatic gradient discussed above. This results in relatively thick permafrost around Abisko due to little precipitation, and very thin permafrost in the westernmost mires that receive substantially more winter precipitation (Appendix III). The thickness of a peat layer is similar at all sites ~90 cm (upper 40 cm pure peat and then a mixture of peat and silt below). The thickness of peat layer needed for palsa formation in Finnish Lapland is about 50 cm (Seppälä, 1982, 1983).

Permafrost is a component of a complex geo-ecological system with both positive and negative feedbacks related to vegetation succession and changing soil properties. The permafrost at the study site is called “Ecosystem protected permafrost” (Shur & Jorgensen, 2007). This type of permafrost has formed under colder climates but can persist as patches under a warmer climate due to the ecosystem properties (peat and vegetation). “Ecosystem protected permafrost” is typically found in climates where current mean annual air temperature is approximately 2ºC to –2ºC (Shur & Jorgensen, 2007). The variability in environment along the study gradient presents a diversity of permafrost phenomena and drivers of permafrost dynamics that facilitate integrated research into long term changes in permafrost, their causes and consequences.

3. Application of multiple approaches

Three different approaches have been used in this project: monitoring, manipulation and modelling. The monitoring has been used to obtain information on the recent dynamics of permafrost and the data from monitoring have been used to validate output from a model. The monitoring results can also be used to further validate the results from the control plots in the manipulation experiments. The manipulation experiment has been used to simulate future climate effects on lowland permafrost in the catchment. In this manipulation experiment, only one climatic parameter was manipulated: snow depth that is projected to increase in the study area in the near future. The data obtained from the manipulation experiment's treatments can be used to validate model output in projections for the future and also to refine models. The manipulation results can also provide short term monitoring and can be used to refine future monitoring as it will highlight important and sensitive parameters. The modelling in this study is used to understand the past permafrost development in the area. Modelling output can identify the sensitivity of parameters to manipulate in the field (Figure 2).

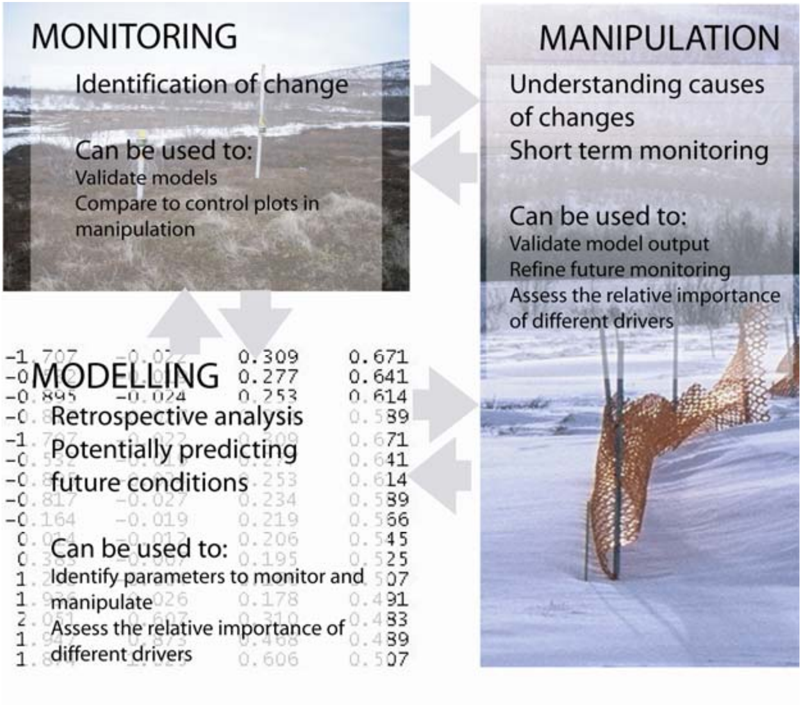

Figure 2 *The three different approaches used in this project.*

3.1 Monitoring

To monitor the recent dynamics of lowland permafrost in the Torneträsk region, active layer thickness and permafrost temperatures have been monitored in peat mires. The active layer monitoring was initiated in 1978 in the area by Jonas Åkerman and has been monitored during the third week of September, when maximum thaw depth occurs. The monitoring has been carried out at 9 mires along an east-west transect (Appendix III) extending from Katterjokk in the West to Bergfors in the East (Figure 1). Eight of the nine sites are part of the Circumpolar Active Layer Monitoring programme (CALM), which is an initiative of the International Permafrost Association. CALM archives statistical active layer thickness throughout the polar regions over time (Shiklomanov *et al*., 2008; Brown *et al*., 2000). The number of sample points at each location ranges from 40 to 121 (the latter is the CALM standard; Brown *et al*., 2000) depending on the size of the mire, and is sometimes limited by stones in the ground and the drainage system. The grids are squared and the distance between two sampling points is 10 m. The grids with 121 points are hence 110 by 110 m. The thaw depth is determined by mechanical probing. A 1 cm diameter graduated steel rod is inserted into the soil to the depth of resistance to determine the active layer thickness. It is possible to differentiate resistance due to permafrost from that due to rocks or stones. At each point, the ground was probed three to four times.

The monitoring of permafrost temperatures was initiated in 1980 in three of the peat mires (Figure 1) where active layer thickness is also being monitored. The depth of the boreholes ranges from 5 to 15 metres and reflects the different thicknesses of permafrost that exist in the Torneträsk area due to the different precipitation regimes (described above). Copper-Constantan thermocouples were installed in the boreholes (Appendix II) and ground temperatures were recorded hourly in the third week of May and September using Campbell loggers. These data give a good indication of the current status of permafrost, but the temporal resolution is scarce as the system installed in the 1980s required staff to manually record temperatures. Through the PYRN-TSP project in the Nordic Countries that is linked to the International Permafrost Association's project Thermal State of Permafrost (TSP; Brown and Christiansen, 2006), five new boreholes were installed in two of the mires (Storflaket and Kursflaket; Figure 3) in spring 2008. Hobo-loggers and sensors were installed down to 13 m depth to enable us to monitor the permafrost temperatures year round (data from the boreholes is not included in this thesis).

Figure 3 *Two new boreholes were installed at "Kursflaket" in spring 2008 close to the borehole installed in 1980 (Photo: J. Åkerman).*

Monitoring of climate has been ongoing at the Abisko Scientific Research Station since 1913. In this study, air and ground temperatures and snow depth and summer precipitation data from the Station has been used. Air temperatures have been recorded manually at the Abisko Scientific Research Station since 1913 until present (using the same method as used at the Swedish Meteorological and Hydrological Institute, 2m screen air temperature). In 1984 an automatic weather station was installed and air and ground temperatures have been recorded automatically every 10 minutes since then. Ground temperatures were recorded using resistance temperature sensors Pt100.

Snow depth measurements started in 1913 from a line of 10 stakes made usually every 5th day, year round, when appropriate. Since 1956 daily snow measurements have been carried out at a single stake (Kohler *et al.*, 2006). Precipitation has been monitored since 1913 and the daily accumulated precipitation is measured at 07:00 every day.

3.2 Manipulation

To simulate the effects of a future possible climate scenario on the lowland permafrost, a manipulation experiment was set up on one of the peat mires (Figure 1; Appendix V). As the presence of permafrost in the mires is determined by insulation from peat and snow and as snow depth is determined by vegetation, the effects of increased snow depth on both permafrost and vegetation were investigated. The manipulation experiment was set up on the western part of the peat plateau where 12 plots were established and active layer thickness, species composition, soil (at 15 and 50 cm) and air temperatures (2 m), soil moisture and snow depth were recorded. Six of the sites were randomly chosen and at those, snow fences (10 m long and 1 m tall) were erected before the snow onset (mid October) and removed at the end of the snow season after the snowmelt (beginning of June). The snow fences were erected perpendicular to the dominant wind direction (easterly and westerly winds, hence in N-S direction). The other 6 sites were set up to be control plots without snow fences.

There are a large number of parameters that affect ground temperatures apart from climate and one is the effect of vegetation (Appendix I) and plant functional types. The vegetation on the mires in the Torneträsk region affects the ground temperatures by having different insulating capacities, different albedo and different capacities to trap snow. To investigate how different plant functional types (dwarf shrubs, graminoids, mosses and lichens) affect ground temperatures, a vegetation removal experiment was set up in summer 2007, where all species within a plant functional type were removed separately in six 1x1 m replicate square per treatment. The different insulating effects of the various plant functional types and also the albedo effect are being recorded (data not included in this thesis).

3.3 Modelling

In this project, the modelling has been used to hindcast permafrost development during the 20th Century in the Torneträsk region and also to estimate possible scenarios for the development of permafrost during the last 1000 years. Two sites were modelled, one currently with and one without permafrost. The model used in this study, the GIPL-2.0 model was developed at the Geophysical Institute, Permafrost Lab (GIPL) University of Alaska Fairbanks and simulates soil temperature dynamics and the depth of seasonal freezing and thawing by solving 1-D non-linear heat equation with phase change numerically (Marchenko *et al.*, 2008). Input data required for the model is climate data preferably with daily resolution for air temperature and snow depth and also a description of the soil (number of layers, their thicknesses, textures and moisture contents). To model ground temperatures during the last Century, input climate data recorded at the Abisko Scientific Research Station was used (Appendix II). To simulate possible permafrost development during the last 1000 years, proxy data was used for mean annual air temperatures (Moberg *et al.*, 2005), and different levels of snow depth (+20, ambient, -20% and -50% relative to the 1961-90 mean in the study area). Soil temperatures records available were used for the calibration of the model. (Appendix IV).

4. RESULTS AND DISCUSSION

4.1 Drivers of permafrost changes over time

There is a range of parameters that determines the presence or absence of permafrost in the Torneträsk catchment, e.g. climate (air temperature, snow depth and wind), topography, glaciers, water bodies, vegetation, soil type and human activities (Appendix I). Considering the time perspective used in this study, 100 years during the instrumental period and 1000 years overall back in time, there are a few of the above mentioned parameters such as topography and soil type that will not have changed much, while others such as climate and vegetation have varied.

The main drivers of lowland permafrost development in the Torneträsk region are air temperatures and snow. Past air temperatures have been important for the formation of lowland permafrost in the Torneträsk catchment while current air temperature determines the present temperatures in the upper part of the permafrost. Summer conditions mainly determine the active layer thickness while permafrost temperatures reflect changes in mean annual conditions (Serreze *et al*., 2000). The mean annual air temperature at Abisko from 1913 to 2006 was -0.6 ºC (Appendix II). During the last Century there have been two warm periods, in the 1930s and 1940s and at the end of the Century. Air temperatures in the second warming period has just recently exceeded those in the earlier 20th Century warm period (Callaghan *et al*., *in prep*). The measured warming during the last Century is projected to continue into the future. Using B2 emission scenarios (used by the Arctic Climate Impact Assessment (ACIA, 2005)), the projected increase in mean annual air temperature for the Torneträsk area is 3.5ºC by the year 2080 (Saelthun & Barkved, 2003).

During the last 1000 years, the Torneträsk catchment has experienced two major climatic events, the Medieval Warm Period around AD1000 to AD1100 that was then followed by a shift to a colder climate that could be regarded as the starting point of the Little Ice Age that peaked in the 17th Century and lasted until the first decade of the 20th Century (Grudd *et al*., 2002). Recent findings from tree-rings in the Torneträsk region suggest that the summers (April- August) during the Medieval Warm Period in northern Fennoscandia were much warmer than previously recognized, even exceeding the late twentieth Century warming period (Grudd, 2008).

During winter the largest single factor accounting for local differences in ground temperatures is the spatial variability of snow (Desrochers and Granberg, 1988). Both the thickness and the duration of the snow affect the ground temperatures. At Abisko, an increase of snow depth of 4-5% per decade was measured between 1913 and 2004 (Kohler *et al*., 2006) but no trend could be detected in the start and end of the snow season. The trend of increasing snow depth is expected to continue throughout the 21st Century and it is predicted to increase by 18% in the year 2080 (Saelthun & Barkved, 2003). Overall, annual precipitation was higher throughout the Holocene than today according to tentative pollen analyses from the Torneträsk area (Bigler *et al.*, 2002). However, it is likely that precipitation has been lower during periods of colder temperatures (e.g. the Little Ice Age) as cold air can keep less moisture. No direct correlation between air temperatures and snow depth could be found.

Vegetation, another important driver of lowland permafrost, has its effects through insulation, its albedo and through trapping of snow. In the mires, vegetation changes have been observed during the second warming period (Malmer *et al.*, 2005). The wet sites dominated by graminoids expanded while areas of hummock sites dominated by dwarf shrubs decreased. Although there have been recent changes in vegetation, the mires have remained mires for thousands of years (Sonesson in Berglund *et al.*, 1996). The interface with surrounding forest might however have changed as forest growth decreased or densified according to climate (Emanuelsson, 1987).

Soil structure and especially the thickness of the organic layer affect the soil temperatures. In the Torneträsk catchment the thickness of the organic layer is in general thin whereas in the mires the organic layer consists of a thick layer of peat. Yi *et al.* (2007) concluded that such a layer of peat can preserve permafrost against past or projected climate change. The start of peatland formation has been dated to 6000 (Sonesson, 1972) and 4700 cal BP (Kokfelt *et al.*, *submitted*) in the Torneträsk area.

4.2 A long term perspective of permafrost dynamics and their implications: past, present and future

Possible lowland permafrost development during the last 1000 years was modelled at two sites, one currently with and one without permafrost. During the last 1000 years, modelled ground temperatures (based on proxy air temperature data (Moberg *et al.*, 2005) and different snow levels (+20, ambient, -20% and -50% relative to the 1961-90 mean in the study area)) at one site currently with permafrost indicate permafrost existence throughout the last 1000 years. However, this contradicts proxy data from the area (Kokfelt *et al. submitted*; Zuidhoff & Kolstrup, 2000) that suggests that permafrost formation occurred during the Little Ice Age. Consequently, the results for the 11th Century are quite uncertain. In a nearby site currently not underlain by permafrost, the modelled mean annual ground temperatures indicate values above 0 ºC, with a few years exception in the 16th Century. According to these results, it is not likely that lowland permafrost was widespread in the Torneträsk catchment during the last 1000 years, but was restricted to particularly favourable sites as today (Appendix IV).

During the 20th Century, modelled ground temperatures show two periods of lowland permafrost degradation that coincide with the two warm periods for which measurements exist. The degradation during the second warming period was greater than in the first according to model output. This is most likely due to the combined effects of increases in snow depth and air temperatures that did not occur during the first warm period in the 20th Century (Appendix IV). Monitoring of permafrost temperatures and active layer thickness in the area shows that the permafrost is currently degrading in the Torneträsk area. Borehole recording showed increasing ground temperatures of 0.04 to 0.05 ºC per year in the upper 1 m and 0.03 to 0.04 ºC per year in the lower 12-15 m between 1980 and 2002. However, no trend was detected in the middle of the profile. The changes in ground temperatures were correlated with increasing air temperature and increasing summer precipitation, but surprisingly not with snow depth. At lower depths, the increases may be due to possible increased heating from a slightly warmer or more freely flowing ground water (Appendix II).

Active layer thickness has increased, ranging from 0.69 to 1.26 cm per year during the last three decades in nine peat mires in the Torneträsk catchment. In addition, the permafrost has disappeared completely at one site and at another 81% of the sampling points in the westernmost site during the same time period. The increased active layer thicknesses are correlated with increases in mean summer air temperature, Degree-Days of Thawing (DDT) and in five of the nine sites also with increases in snow depth (Appendix III).

Future climate scenarios for the Torneträsk region project increased air temperatures and increased winter precipitation, hence an increased snow depth. The manipulation experiment that simulated projected increases in snow depth resulted in increased ground temperatures in winter and increased active layer thickness compared to the control plots. Lowland permafrost that today exists underneath the peat mires is sensitive to changes in snow depth as shown in the snow manipulation experiment. The manipulation experiment only altered the snow depth and not the air temperatures and the combined effect is expected to be even greater than that obtained (Appendix V). This agrees with Fronzek *et al*. (2006) who modelled the future distribution of palsa mires in Scandinavia and found that even small increases in mean annual air temperatures (1ºC) and total annual precipitation (10%) resulted in a considerable loss of areas suitable for palsa development. By the end of the 21st Century all but one scenario resulted in total disappearance of suitable regions for palsa development in Scandinavia.

4.3 Applicability and weaknesses of the approaches

Monitoring Monitoring of active layer thickness does not require any expensive equipment and hence can be carried out by anyone and due to standard measurement protocols provided by the CALM project, measurements from different permafrost areas around the world can be compared. A problem that the protocol faces in the 21st Century associated with the projected permafrost thawing is how to report on active layer thickness from a site that is thawing. Two of the sites monitored in this study Katterjokk and Låkta Hpl (Appendix III) has experienced rapid permafrost thawing during the last decade and currently only 19% of the original CALM grid is underlain by permafrost at the Katterjokk site and none in Låkta Hpl site. At the Katterjokk site, the mean active layer thickness was based on 121 points (CALM standard) in 1996, but in 2006 the mean active layer thickness was based on 23 points as the rest of the grid was no longer underlain by permafrost. Are these two numbers then comparable?

The monitored ground temperatures in this study have an excellent spatial resolution but a very coarse temporal resolution as the equipment used required staff present to manually record ground temperatures. The new borehole that was drilled in 2008 will enable year round monitoring of the permafrost temperatures but with coarser spatial resolution than those made in the past.

Modelling As the model used in this project only requires climate data for air temperature, snow depth and also a description of the soil, the model can be applied to many areas. The model version used here did not simulate any accumulation of peat that would alter the thermal properties of the soils throughout the period of modelling. In addition, this version did not take into account different vegetation types that would affect the ground temperatures through their insulation, albedo and snow trapping effects. The structure of the snow, for example ice layers at the bottom of the snow pack, that could potentially affect the runoff pattern and hence the soil moisture in the ground is also not taken into account in the current version of the model.

Manipulation The manipulation experiment is set up to require as little personnel as possible and many of the parameters are only measured once per year or data downloaded once per year from loggers. However, replicated snow depth recordings from all 12 sites require year round personnel or more snow cameras (that will be expensive). The applicability of the manipulation hence depends on funding available. Soil moisture that plays an important role on ground temperatures in peat mires was only measured at two of the plots in the manipulation experiment (one plot with a snow fence and one control plot without). Two impacts of the increased active layer thickness that could have been monitored, but were not, are surface subsidence and greenhouse gases. A major advantage of the manipulation experiment is that individual drivers of permafrost dynamics that co-vary under natural conditions can be varied independently in the experiment to examine their relative effects. On the other hand, these experiments use time and space intensively and the number of treatments and treatment interactions most be limited.

4.4 Recommendations to reduce uncertainties of current measurements, hindcast and future projections

Monitoring To get around the arising problem how to monitor active layer thickness in areas where permafrost is thawing, one additional part could potentially be added to the CALM protocol to report on how many percent of the grid are underlain by permafrost.

Modelling As the permafrost in the peat mires is a complex geo-ecological system with both positive and negative feedbacks related to vegetation change, future modelling could potentially include changes of peat accumulation, different vegetation types and associated changes in those. The snow profile structures including ice layers formed affecting the runoff could also potentially be important to include in the model, particularly as little is known about the interactions between snow profile structure and heat transfer to permafrost. Apart from the permafrost model, better projections of snow depths are required from GCMs that focus on snow water equivalent while proxies of past snow depths would reduce uncertainty in the hindcasting of permafrost dynamics.

Manipulation Replicates of soil moisture measurements are needed for the experiment and measurements of ground subsidence should be initiated. In addition, measurements of greenhouse gases should be initiated to increase the possibilities to predict the wider impacts of projected thawing permafrost in the Torneträsk area.

Concepts While the permafrost definition adequately reflects different permafrost types in space (continuous, discontinuous, sporadic and isolated patches (Brown *et al*., 1998)), there is no definition or concept of permafrost in time (other than that of below 0ºC for two or more consecutive years) and hence there is no differentiating from a two year frozen state and a million year frozen state. A more varied temporal dimension should be conceptualised in the term "permafrost" and this could lead to a finer temporal resolution understanding of permafrost dynamics at the margins of permafrost distribution that now experience rapid change.

5. CONCLUSIONS

This study has improved our understanding of current and past dynamics of lowland sub-arctic permafrost in northernmost Sweden. While it has demonstrated current rapid and accelerating thawing of discontinuous permafrost in nine mires, it has shown dynamics over the past 1000 years that differ considerably between two neighboring sites separated by only 6 km and located at similar altitudes. An initial and widely perceived concept at the outset was that permafrost dynamics would be strongly controlled by snow depth. A major conclusion of the monitoring, manipulation and modeling components of the study is that the strength of the relationship between snow depth and permafrost dynamics varies considerably. In addition, the manipulation study indicated that the structure of the vertical snow profile, for example an occurrence of a bottom ice layer, could potentially affect the thermal regime of the soil via lateral runoff of melt water. Another phenomenon, reported here in the study of ground temperatures is that temperature can increase more at depth (15 m) than in shallower soil layers (6m). This is perhaps caused by slightly warmer or more freely flowing ground water around and below the frozen body and opens the possibility for permafrost degradation at the top and bottom surfaces, thereby leading to particularly rapid loss.

The overall results and conclusions of this study emphasise the need to monitor the rapidly disappearing permafrost and to record its characteristics and associated ecology before they are lost. The results and conclusions also emphasize the need to better represent snow (both depth and profile structure) in models that can be used to both hindcast and predict future permafrost dynamics. Only then can adaptive measures be taken to reduce the impacts of thawing permafrost on infrastructure, human activities and natural, sensitive ecosystems associated with permafrost.

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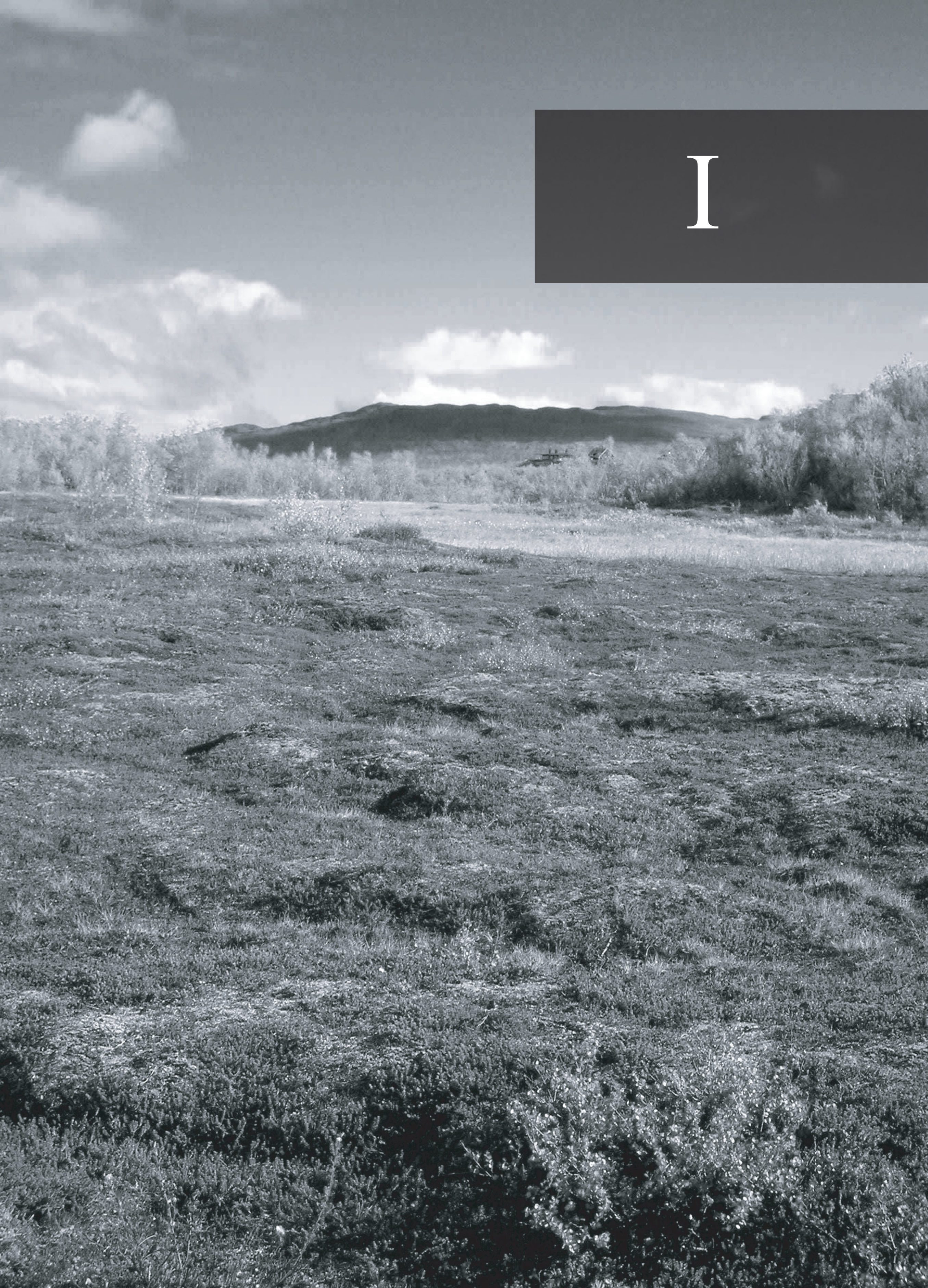

Margareta Johansson, Torben R. Christensen, H. Jonas Akerman and Terry V. Callaghan

What Determines the Current Presence or Absence of Permafrost in the Torneträsk Region, a Sub-arctic Landscape in Northern Sweden?

In a warming climate, permafrost is likely to be significantly reduced and eventually disappear from the sub-Arctic region. This will affect people at a range of scales, from locally by slumping of buildings and roads, to globally as melting of permafrost will most likely increase the emissions of the powerful greenhouse gas methane, which will further enhance global warming. In order to predict future changes in permafrost, it is crucial to understand what determines the presence or absence of permafrost under current climate conditions, to assess where permafrost is particularly vulnerable to climate change, and to identify where changes are already occurring. The Torneträsk region of northern sub-Arctic Sweden is one area where changes in permafrost have been recorded and where permafrost could be particularly vulnerable to any future climate changes. This paper therefore reviews the various physical, biological, and anthropogenic parameters that determine the presence or absence of permafrost in the Torneträsk region under current climate conditions, so that we can gain an understanding of its current vulnerability and potential future responses to climate change. A patchy permafrost distribution as found in the Torneträsk region is not random, but a consequence of site-specific factors that control the microclimate and hence the surface and subsurface temperature. It is also a product of past as well as current processes. In sub-Arctic areas such as northern Sweden, it is mainly the physical parameters, e.g., topography, soil type, and climate (in particular snow depth), that determine permafrost distribution. Even though humans have been present in the study area for centuries, their impacts on permafrost distribution can more or less be neglected at the catchment level. Because ongoing climate warming is projected to continue and lead to an increased snow cover, the permafrost in the region will most likely disappear within decades, at least at lower elevations.

INTRODUCTION

Permafrost is perennially frozen ground. It underlays 20%–25% of the terrestrial surface of the Northern Hemisphere (1, 2). The distribution of permafrost is usually defined in three zones based on the percentage of land surface underlain by permafrost: continuous permafrost (90%–100%); discontinuous permafrost (50%–90%); and sporadic permafrost (10%–50%) (3, 1). Permafrost can occur in soils or other surficial materials (from peat or clay to boulders) and in bedrock. The thickness of permafrost varies from a few decimeters up to several hundred meters (4). Permafrost is an integral part of many northern landscapes and has profound implications on infrastructures and economies in the north (5). It interacts with many ecosystems and contributes to periglacial processes. On top of the permafrost is an active layer that melts and refreezes on a seasonal basis. Its thickness varies depending on climate, vegetation cover, and soil type, from a few decimeters in peat to more than several meters in areas with well-drained materials (6). The active layer is the upper subsurface layer in which current biological activity, i.e., microbial decomposition and plant root function, are currently focused. However, the permafrost below often contains records of biological activity, particularly in the form of carbon from former periods when permafrost was absent or deeper in the ground profile. Permafrost characteristics we see today in terms of depths, land surface cover, and active layer depth, result from long-term dynamics that we observe at one point in time. These dynamics are controlled by many factors, particularly climate, that are in themselves dynamic.

The aim of this study is to review the various physical, biological, and anthropogenic parameters that determine the presence or absence of permafrost in the Torneträsk region, northern Sweden, under current climate conditions. We focus on this region in particular because it is situated in the sub-Arctic with a mean annual air temperature near 0°C, where permafrost is particularly vulnerable (7, 8). A slight shift in temperature can alter the status of the ground from frozen to unfrozen and some observations suggest this has already occurred in the Torneträsk region (9).

The Torneträsk region in sub-Arctic Sweden (Fig. 1) is located in the northernmost part of Sweden. According to Brown et al. (1) and Washburn (10), the area is located in the zone of discontinuous permafrost. A patchy permafrost distribution is not random, but a consequence of the site-specific factors that control the microclimate and hence the surface and subsurface temperature, together with past historical factors.

A second aim of the paper is to provide a baseline understanding from which possible future changes can be predicted. In the Arctic, including Scandinavia, the mean annual air temperature isotherms have shifted a greater distance north since the Little Ice Age than the permafrost distribution has. This means that permafrost in such areas, at least at marginal sites, persists as relict permafrost and will eventually disappear under the present climate (12, 13). In a warming climate, permafrost is likely to disappear first from areas with a mean annual air temperature around 0°C. It is important to know what determines the presence or absence of permafrost under current climate conditions in the Torneträsk region, northernmost Sweden, to be able to identify current areas of permafrost that are being lost and also to predict future changes in permafrost distribution.

PARAMETERS THAT DETERMINE PERMAFROST DISTRIBUTION

Even though it is difficult to distinguish the effect on permafrost of one parameter from another, we try to present the effects of

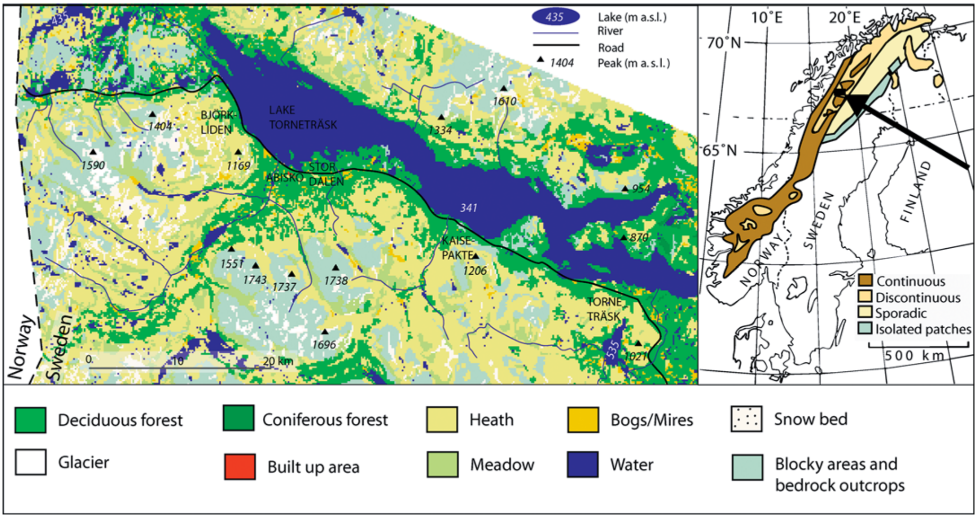

Figure 1. Location of the Torneträsk region in the discontinuous permafrost zone (1), northernmost Sweden, and the vegetation coverage in the area [derived from (11)].

most of these often interacting parameters separately to build a process-based understanding of permafrost dynamics. This is particularly important to add to the understanding of the current models of permafrost dynamics that focus on relatively few drivers of change (14, 15). Figure 2 gives a simplified overview of the various parameters and their effects on ground temperature and permafrost in the Torneträsk region.

The predominant driver of permafrost dynamics is ground temperature. Current ground temperatures are affected by a change in one or many of the parameters presented in Figure 2 at different time and depth scales. An increase in ground surface temperature, for example, affects the permafrost at three time and depth scales (16, 17): *i)* over a short time period (one to several years), a warming and thickening of the active layer is likely to occur (18); *ii)* development of a nonlinear temperature profile at depths of several tens to hundreds of meters will occur over periods of many decades (19); and *iii)* over decades, centuries or thousands of years, permafrost thinning will occur as a result of thawing at the base. The time required for melting depends primarily on the temperature of the permafrost, the ground ice content, and the initial permafrost thickness.

The following sections describe the various controls on ground temperatures.

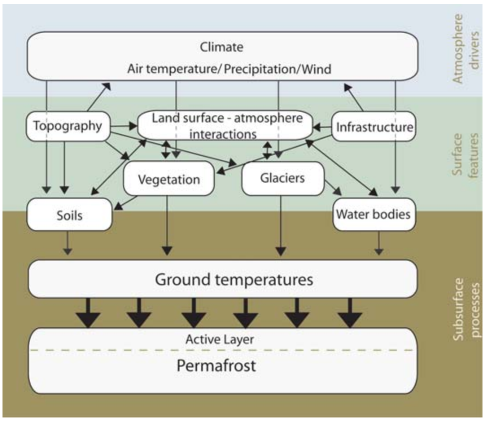

Figure 2. Parameters that affect ground temperatures and hence presence or absence of permafrost in Torneträsk region.

Climate

Air Temperature. Past air temperatures have been important for the formation of permafrost. Current air temperature is now an influential parameter for permafrost existence, since low air temperatures are required to keep the ground from thawing. Mean annual air temperatures can be used as a very general indicator of presence of permafrost at a continental scale (13), but other factors are involved in determining its thickness and other characteristics (as discussed below). Based on many investigations in Fennoscandia, King (4) concluded that the boundary between continuous/discontinuous permafrost corresponds approximately with the –6°C isotherm and the limit between discontinuous/sporadic permafrost zones corresponds approximately with the –1.5°C isotherm of the mean annual air temperature. At Abisko Scientific Research Station (located in the Torneträsk region at 385 m above sea level (a.s.l.); Fig. 1) the mean annual air temperature for 1913 to 2004 was –0.6°C (20). The active layer thickness is determined primarily by summer conditions while permafrost temperatures reflect changes in mean annual conditions (2). The depth in penetration of the seasonal air temperature signal is around 20 m in permafrost at six sites along a latitudinal transect from the Alps, through Scandinavia to Svalbard (21).

Precipitation/Snow. For a given air temperature the largest single factor accounting for variations in the ground surface temperatures during the winter months is the local and regional

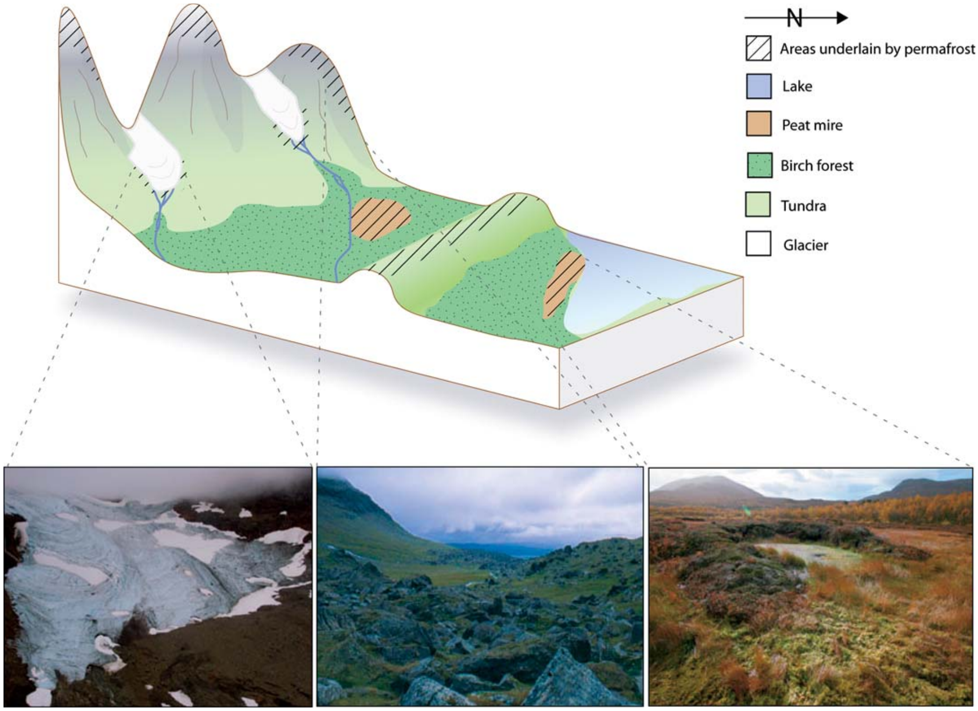

Figure 3. Overview of where permafrost is likely to occur in the Torneträsk region as a result of site-specific characteristics, such as topography (altitude and aspect), hydrology, soil type, and vegetation.

spatial variability in snow cover (22). The thickness and duration of snow cover is hence a critical parameter for the presence or absence of permafrost in the sub-Arctic. The snow acts as an insulator and protects the ground from heat loss and prevents the cold winter air temperatures from penetrating into the ground. In areas with mean annual air temperatures close to 0°C, snow cover can be responsible for the absence of permafrost in certain locations (8). Data from Inuvik, Alaska, showed that snow cover during winter was the primary responsible factor for maintaining mean annual surface temperature at 5–10°C above mean annual air temperature (8). More recent studies from the Torneträsk region showed an increase in soil temperature of up to 2.2°C when the snow depth was experimentally increased two- to threefold during October–April (23). Local differences in permafrost occurrence, depending on the thickness of the snow cover, are typical for areas of discontinuous permafrost (7). This relationship is also clearly illustrated in the development and distribution of palsas in Scandinavia and elsewhere (24, 25).

The timing of the start and end of the snow season also affects ground temperatures and hence permafrost existence. Favorable conditions for permafrost exist when snow falls late in the autumn, allowing cool autumn air to penetrate and when snow falls late in the spring, resulting in high albedo that reflects the sun's energy (26).

The Torneträsk region covers a strong climatic gradient and the mean annual precipitation ranges from 1000 mm/y in the westernmost part to 300 mm/y at Abisko as a result of a rain shadow effect of the mountains towards the west. The resulting different snow cover depths correlate well with the permafrost depths found in mires along an east-west transect in the Torneträsk region. The deepest permafrost occurs around Abisko (9) where the shallowest snow depth is found. At Abisko (Fig. 1) the snow depth has increased by 4%–5% per decade between 1913–2004 (20). This trend has most likely caused an increase in ground temperatures in the area and has contributed to the thawing of permafrost.

Wind. Wind speed and direction have indirectly the potential to change the state of frozen ground, i.e., the distribution of permafrost. Wind is important because it determines where insulating snow cover will accumulate, and where the surface will be snow free (27). The drift pattern is related to the prevailing wind, wind speed, wind direction, and the topography and is therefore generally reproduced in a specific pattern every year.

Topography

In areas with a discontinuous permafrost distribution, the number of permafrost locations increases with increasing altitude (assuming sites have similar ecological conditions). The thickness of the permafrost also increases with increasing altitude from one or a few meters to many tens of meters (4). Permafrost is found at lower altitudes on north-facing slopes, since these areas are rarely exposed to direct solar radiation (Fig. 3). The elevation in the Torneträsk region ranges from 340 to 1750 m a.s.l. (Fig. 1). Permafrost is common above the treeline in the tundra zone. Åkerman and Malmström (28) concluded that permafrost was mainly restricted to mounds at levels above 850 m a.s.l. and Jeckel (29) concluded from ground temperature measurements, that the lowest limit of permafrost occurrence was 880 m a.s.l. in the Torneträsk region. However, the distribution pattern of permafrost is much more complex than that and permafrost does exist as low as 350 m a.s.l. in the Torneträsk region for other reasons. Many locations—for example, wind-swept slopes and exposed plateau areas—lack an insulating snow cover during winter and are therefore favorable sites for permafrost at all altitudes (Fig. 3).

Glaciers

Permafrost can occur underneath glaciers depending on their basal temperature. The glaciers in the Torneträsk region are polythermal (30), i.e., both cold based (where the basal layers of ice are below pressure melting point and so frozen to the glacier bed) and warm based (where the basal layers of ice are above pressure melting point and not frozen to the glacier bed) and it may therefore be possible to find permafrost underneath parts of them (i.e., the cold-based part). During the 20th century, the glaciers in the Torneträsk region have retreated, thinned, and some have even disappeared (31). At present approximately 38 km^2 of the Torneträsk region are covered by glaciers (equals less than 1% of the total area of the Torneträsk catchment area) (11). Counterintuitively, a thinning of a glacier may favor permafrost evolution because a thin ice layer prevents the ground temperature from exceeding 0°C during summer (due to the albedo effect), and in winter the cold air can penetrate the thin surface ice layer, which leads to a cooling of the ground (due to lack of insulation) and hence favorable conditions for permafrost formation (32).

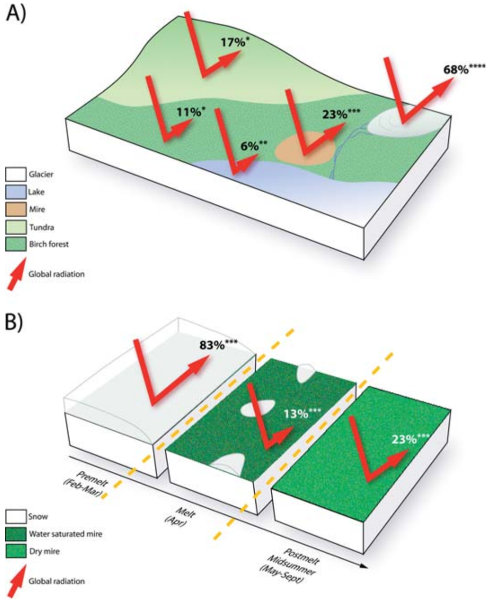

Figure 4. Albedo differs not only (A) spatially in a region, but also (B) temporally. Temporal measurements are from Stordalen in Torneträsk region (see Fig. 1 for location) (45–48).

Water Bodies

Williams and Smith (33) stated that the thermal effects of water bodies constitute the greatest local departures of ground temperatures from any systematic geographical patterns determined by climate. Water bodies like lakes that do not freeze to the bottom in winter, act as a heat source and have a marked effect on ground temperatures and the local distribution of permafrost. As a consequence, it is common to find taliks (unfrozen soil layers) underneath water bodies in areas of discontinuous permafrost. The heating effect is largest immediately after freeze-up and during cooling of the active layer. It is less important during warming and thawing of the active layer and during freezing and thawing of seasonally frozen ground (34). In the Torneträsk region, Lake Torneträsk is the main water body. It covers an area of 330 km^2, has a maximum depth of 182 m, and has a mean depth of 52 m (35). Even though the air temperatures are often quite low during winter in the area (down to –40°C), the lower part of the lake remains unfrozen throughout the winter as a result of the depth of the lake and it hence acts as a heat source. Water bodies in the Torneträsk region cover a total area of 606 km^2, which is approximately 10% of the total area of the Torneträsk catchment area (11). It is highly unlikely that permafrost exists underneath Lake Torneträsk and the other larger water bodies in the area (Fig. 3).

In a warming climate as observed in the Arctic during the last decades (36), observations from continuous permafrost areas in Siberia have shown that the total lake area has increased. In areas of discontinuous and sporadic permafrost the total lake area has on the contrary decreased in both Siberia and Alaska. The discrepancy between the different permafrost zones can be explained by the fact that initial permafrost warming leads to development of thermokarst and lake expansion, followed by lake drainage as permafrost continues to degrade (37). In contrast to the findings from the discontinuous permafrost zones in Siberia and Alaska, an increase in surface ponding has been observed from the Torneträsk region, probably driven by slumping and collapsed terrain features that are then filled with water (thermokarst) (38).

Vegetation

The vegetation cover in the Torneträsk region ranges from remnants of boreal pine forest through the subalpine zone dominated by mountain birch forest (*Betula pubescens* spp. *czerepanovii*), through the low alpine belt that extends from the treeline up to where *Vaccinium myrtillus* no longer persist, to the high alpine belt with nonvegetated surfaces (39). The mountain birch forest covers an area of 1200 km^2, which is ~25% of the total area of the Torneträsk catchment area (Fig. 1) (11). The vegetation cover affects the thermal properties of the soil/ground mainly in two ways: first, by forming a snow trap in winter that increases the snow accumulation and persistence of snow cover; and second, through reducing the amount of solar radiation reaching the ground surface in summer (40). A stand of trees therefore creates its own microclimate and as vegetation develops it affects the heat and moisture exchange at the ground surface (8). An increase in snow depth occurs as the vegetation reduces the velocity of blowing snow and reduces the sublimation rates. Models suggest that in northern Alaska the snow accumulation can increase as much as 20% as a result of the reduction in sublimation associated with vegetation. Shrub canopies can increase winter soil temperature by 2°C relative to adjacent shrub-free tundra (41). In Arctic North America where spruce forest is common, permafrost often occurs underneath the vegetation as a result of the cooling effect the canopy creates in summer, thereby reducing the mean annual ground temperature. Smith (8) reported a difference in mean annual surface temperature of 3°C (ranging from −4 to −1°C) when comparing spruce forest and bare ground. In a warming climate it is likely that the canopy effect (which can also be expressed by the Leaf Area Index) increases (42) and then more radiation is absorbed by the canopy and less penetrates to the surface and as a consequence ground surface temperature decreases (43). An example of the LAI effect is the different trends in air and soil temperatures from high Arctic Svalbard to sub-Arctic Abisko. Summer air temperatures increase from the polar desert in Svalbard to the sub-Arctic birch forest in Abisko, but soil temperatures are higher at Svalbard (44).

In the Abisko area, the birch forests do not have a dense canopy and therefore do not create the cooling effect in summer, which is favorable for permafrost occurrence. In contrast, the dominant effect of vegetation in the Torneträsk region is the effect of the trees acting as a snow trap, which increases the snow depth resulting in better insulation with associated increase in the surface temperature and absence of permafrost (Fig. 3). Treeline dynamics are therefore important in the Torneträsk region as a result of the trapping of snow. The treeline is usually 100–200 m lower on north-facing slopes than on south-facing slopes (39). As described above permafrost is also usually found at lower altitudes on north-facing slopes as a result of less direct solar radiation. The fact that the treeline is located further down probably also affects the permafrost distribution on the slopes as the reduced vegetation might lead to less snow on the north-facing slopes and hence less protecting snow cover in winter. Snow manipulation experiments are required to test this hypothesis.

Land Surface–Atmosphere Interactions

The heat exchange at the atmosphere/ground boundary is mainly controlled by the net exchange of radiation, which depends on the fluxes of global short-wave radiation and terrestrial long-wave radiation, but depends also on local conditions such as topography and vegetation. Part of the global radiation that reaches the surface is reflected, the degree is determined by the surface albedo (the reflectivity of a surface). The amount of global radiation reflected in a certain area varies spatially since different surfaces have different albedo, but it also varies temporally (Fig. 4). Typical albedo values for the different surfaces found in the Torneträsk region in the summer are likely to range from 68% at glaciers with a snow cover (45), to 17% for tundra vegetation, 11% in birch forest (46) to 6% for lakes (47). Rydén (48) concluded that the global radiation reflected from a mire in Stordalen (see Fig. 1 for location) where *Sphagnum* mosses were dominant, varied temporally from 83% in March and April during premelt conditions to 13% during snow melt in May to 23% during postmelt and midsummer. The amount of heat transported from the surface down in the ground therefore varied greatly for the same location over a few months.

Soil Type

Apart from the surface characteristics (described above), the soil type and amount of organic material are also of great importance for the heat flow from the surface to the ground and hence for ground temperatures. The depth of thaw generally increases as the organic layer thickness decreases. This increase is associated with the fact that heat penetrates much less rapidly in organic soils than in mineral soils (49) as a result of the soil texture and the water content. Permafrost is generally absent in mineral soils with a mean annual air temperature above −2°C (13). Unfrozen water content, which increases the soil's conductivity (i.e., its capacity for transferring heat), shows

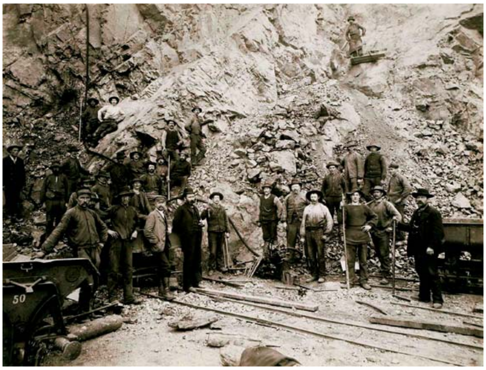

Figure 5. The construction of O-foten railway at the end of the 19th and beginning of the 20th century is the major impact on the environment in the Torneträsk region made by humans. Courtesy of the Photo Museum in Sundsvall (http://www.fotomuseet.sundsvall.se). Photo: B. Mesch.

a significant site-to-site variation and is small in peat layers and larger in silts (34). Sandy soils, such as found in the forests in the Torneträsk region, have lower thermal conductivity than soils found in the heath because of the lower water content and looser packing of the soil grains. The heath soils, which are rich in silt, are capable of holding large quantities of water and have a high thermal conductivity and hence a good capacity for transferring heat to the ground during the summer (50). Permafrost is therefore unlikely to occur in these areas in the Torneträsk region and observations verify this general picture. In contrast, the conductivity of peat in summer is usually very low since the peat is usually dry, and as a result the peat layer acts as an insulating cover preventing the warm summer air from penetrating the ground. The peat's conductivity varies seasonally with its moisture conditions. In the autumn and the beginning of winter the peat usually has higher water content than in summer, which increases its conductivity and allows the cool autumn/winter air to penetrate through its surface and affect ground temperature. Peat is therefore a very favorable soil type for permafrost existence (Fig. 3), and permafrost is very likely to occur where peat exists in the Torneträsk region. Permafrost can be found in peat lands as far south as the current +1°C air isotherm and beyond (13) and peat lands or palsa mires are often found as hosts to the southernmost occurrences of sub-Arctic permafrost.

Humans

Even though many of the areas that are underlain by permafrost are sparsely populated, the pressure from humans in some areas is still large. In Siberia, the industrial impacts have increased since the beginning of the 20th century, first mainly because of the development of forestry and then by the processing of mineral and fuel resources (51). Roads, pipelines, and transmission lines associated with oil and gas exploration and development, have caused fragmentation of large intact areas in both North America and Siberia. In Russia, 15% of the tundra territory has been destroyed by transport activities like Caterpillar transport vehicles, which results in permafrost melting, erosion, and thermokarst development (51). Exploitation of the Arctic by humans affects permafrost on a site-specific scale as well—for example, by construction of infrastructures. A structure built on or in permafrost will change the geocryological conditions by altering the heat exchange between the atmosphere and the ground and by altering the hydrology. The removal of the vegetation and a decrease or removal of organic layer in association with engineering activities makes the active layer thicker and degradation of permafrost may occur (6, 5). In most cases, an infrastructure will increase the heat flow from the atmosphere to the surface and hence increase the ground temperature. An increased snow accumulation around, under, and adjacent to the structure will also enhance the increase of ground temperature (27). Permafrost in the vicinity of infrastructures may therefore also be affected, particularly where engineering is inadequate and building insulation is poor.

Not only big industrial exploitation has a marked effect on the status of the permafrost in high Arctic. In addition, everyday activity by inhabitants in isolated northern settlements can result in a change of the state of permafrost. For example, dust that originates from burning of coal, fuel oil, and firewood for heating, covers the soils near settlements, and can cause the development of thermokarst by altering the surface energy balance (52).

The major influence of humans on the environment in the Torneträsk region has been through the construction of the Ofoten Railroad in the beginning of the last century (Fig. 5) and also through the construction of the highway in the late 1970s and early 1980s. Following the development of the infrastructure, small villages and cabins have been built along the railroad and road. Reindeer herding in the area probably began sometime during the 18th century (53). In an alpine environment, herbivory plays an important role for the structure and composition of the vegetation (39). In areas with high reindeer population density, grazing affects the vegetation cover, alters the albedo, alters the amount of radiation that reaches the ground and results in a warming of the ground temperature. As outlined above, the overarching vegetation cover has important effects on the permafrost distribution. However, in the Torneträsk region, the reindeer herding is not likely to have had any major impact on permafrost distribution at the catchment scale. At a very local scale the grazing and resting of reindeer on top of palsas where snow cover is thin and food is more available, could contribute to an increased speed in the degradation of palsas. The impact of tourism in the Torneträsk area is mainly by intensively used footpaths and snowmobile tracks, which have locally degraded the vegetation and have most likely resulted in higher ground temperatures along, for example, the major hiking track, "Kungsleden." The overall impact of humans in the Torneträsk area is, however, small.

CONSERVATION

Areas underlain by permafrost are sensitive to disturbances and changes in climate and it is usually difficult to stop a degrading process once it has started. In the Arctic, there are actions to protect the great areas of land underlain by permafrost that are exploited by man. For example, actions are taken when construction is undertaken to prevent thawing of ice-rich permafrost in order to avoid slumping of buildings, pipelines, and roads. Another example to prevent severe damage on the sensitive environment on the Alaskan North Slope by off-road vehicles is to restrict the time period when travel by off-road vehicle is allowed to times when the active layer is completely frozen and the vegetation is adequately protected by snow. The length of the time period when off-road vehicles are allowed has been reduced by almost 3 mo from the early 1970s to today as a result of a warming climate (54). Climate change is likely to have a significant impact on existing Arctic infrastructures and on all future development in the region. In most cases, however, engineering solutions are available to address climate change impacts and it is today more an economical than technological issue (5).

Unlike the great areas underlain by permafrost in North America and Siberia, the areas underlain by permafrost in northern Scandinavia are restricted to relatively small areas and those are usually not very exploited by man. As a consequence there are few conservation actions taken in this region. One example is wooden boards that are placed on mires underlain by permafrost in order to protect and prevent disturbance on the sensitive vegetation from tourists hiking in the Torneträsk region.

PROGNOSIS

During the 20th century, the mean annual air temperature increased globally, but the increase was specifically pronounced in the Arctic (55). Even though northern Scandinavia has experienced a more moderate warming compared to, for example, parts of Siberia, Alaska, and northwest Canada, its mean annual air temperature has still risen by approximately 1°C from the 1950s to today (56). The mean annual air temperature in the Arctic is expected to continue to increase. When using the B2 carbon emission scenarios [used by the Intergovernmental Panel of Climate Change (IPCC) and the Arctic Climate Impact Assessment (ACIA)], the projected panarctic increase is approximately 1°C by 2020, 2–3°C by 2050, and 4 to 5°C by 2080 (57). Using downscaled climate change scenarios for the Torneträsk region, the projected increase in mean annual air temperature for the area is 1°C for 2020, 2.5°C by 2050, and 3.5°C by 2080 (58). Even climate downscaling, however, is inadequate to allow permafrost dynamics to be predicted because of the frequent mismatch between air and ground temperatures (59). Snow depth in the Torneträsk region that plays a major role in determining where permafrost is present and absent, is predicted to increase by 6% in 2020, 12% in 2050, and 18% in 2080 (58). The precipitation increase is expected to be twice as high in winter/autumn as in summer (60). Increasing air temperatures interacting with an increasing snow cover in winter will most likely result in an overall thinning of the permafrost in the Torneträsk region at a faster rate than predicted from temperature increase alone. If the trend continues, permafrost is likely to eventually disappear in the area.

RECOMMENDATIONS TO REDUCE UNCERTAINTIES

Extended Monitoring

In the Torneträsk region, environmental monitoring had started already at the end of the 19th century and it has continued since then. This has resulted in long-term data series of, for example, climate that extend almost 100 y in time. Permafrost monitoring began in 1978 and the active layer measurements are now part of the International Permafrost Association's Circumpolar Active Layer Monitoring (CALM) network. It is important to continue the ongoing long-term monitoring series and to complement them with new continuous records that address the uncertainties described in this paper. In particular, more detailed information is needed on ground temperatures and soil profiles in different vegetation types. Although ground temperature measurements have been ongoing sporadically during the last three decades, permanent monitoring of temperature at different depths in boreholes would provide information that would help to better understand the dynamics of the permafrost in the area.

Campaigns to Obtain Baseline Information

The International Polar Year 2007/2008 is providing possibilities to carry out coordinated campaigns at many sites to compile existing information and to gather new baseline information. Initiatives like the Thermal State of Permafrost (TSP) and Back to the Future (BTF) are examples of projects that will revisit old nonactive sites and remeasure some of the parameters monitored decades ago. The boreholes that have been used to measure ground temperatures in the Torneträsk region will most likely be revisited within those programs and IPY could be the start of long-term monitoring of the thermal state of the ground in the region.

Environmental Manipulation Experiments

In order to construct scenarios to project future permafrost distribution, long-term environmental manipulation experiments are required to complement monitoring. Environmental experimental manipulations allow system sensitivity to individual parameters to be assessed. During autumn 2005, a manipulation experiment was set up on a mire in the Torneträsk region to explore the projected increase in snow cover effects on ground temperatures, the active layer depth, the vegetation cover, etc. The increased understanding of how the system reacts to a change in snow depth and snow duration gained from environmental manipulation experiments can be used to refine and validate models.

Modeling

Modeling is essential to integrate information from the monitoring approach and from environmental manipulations and as a tool to scale up in space from the spot measurement and the experimental plot to the landscape scale. It is also essential to scale in time by providing predictions of impacts of future climate on permafrost distribution.

SUMMARY

This paper has reviewed various parameters that determine the presence or absence of permafrost in the Torneträsk region under current climate conditions. In an area with discontinuous permafrost the current permafrost distribution is determined by a range of site-specific parameters and is a product of both past and current processes in the area. In the Torneträsk region physical parameters like topography (aspect and altitude), soil type, and hydrology have a great influence on the surface and subsurface temperatures and hence the distribution of permafrost. Climatic parameters—especially snow cover, which acts as an insulating layer in wintertime—are one of the single most important parameters for the ground temperature regime. Some parameters—for example, wind—are unlikely to have a major direct impact on the ground temperature but may affect the distribution of snow and hence the ground temperature. The vegetation in the Torneträsk region, which is dominated by birch forest, does not have a dense canopy and therefore does not have a major cooling effect on the ground temperatures in summer. However, the vegetation acts as a snow trap in wintertime, which results in an increase in ground temperatures. Human activities in the Torneträsk region have not affected the distribution of permafrost at a catchment scale. At a local scale, humans have affected areas underlain by permafrost, for example by developing infrastructure. The impact of tourism in the area has mainly been from intensively used footpaths and snowmobile tracks that have locally most likely resulted in higher ground temperatures, but conservation measures have reduced damage to sensitive areas. In the Torneträsk region, the mean annual air temperature is just below 0°C, which makes the area very sensitive to future changes because a slight change in temperature can alter the state of the ground from frozen to unfrozen. Climate change scenarios for the region project an increase in air temperature and in precipitation (especially in wintertime), and this will most likely result in an overall thinning of the permafrost in the Torneträsk region at a faster rate than predicted from air temperature increase alone. This paper has identified the major areas where research is needed to reduce the uncertainties and has suggested approaches to make us better capable of predicting future changes (61).

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II

Photo:F. Keuper

Increasing Permafrost Temperatures in Subarctic Sweden

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Abstract

This paper reports permafrost temperatures from three peat mires in subarctic Sweden. There were trends of increasing ground temperatures in the boreholes between 1980 and 2002 of 0.04°C a^{-1} to 0.05°C a^{-1} in the upper 1 m and 0.03°C a^{-1} to 0.04°C a^{-1} in the lower 12–15 m. However, no trend was detected in the middle of the profile. To verify the trends from the mires (with scarce temporal resolution), we use ground temperatures from Abisko Scientific Research Station recorded in an area currently nearby permafrost. Here, ground temperatures have increased on an annual basis and at all seasons apart from the summers, where decreasing temperatures were detected. The changes in ground temperatures could be correlated to increasing air temperature and increasing summer precipitation, but surprisingly not with snow depth. At lower depths the increases may be due to possible increased heating from slightly warmer or more freely flowing ground water.

Keywords: Abisko; ground temperatures; subarctic Sweden.

Introduction

Increases in air temperatures in the Arctic region have been almost twice as high as for the rest of the world during the last decades. This arctic amplification is expected to continue (ACIA 2005). These increases have had and will have profound effects on ground temperatures and, hence, on permafrost distribution (Anisimov et al. 2007). Even though it is widely known that there is a mismatch between air and ground temperatures, as there are other parameters of importance to ground temperatures, increasing air temperature in general increases ground temperatures (e.g., Thorn et al. 1999). For time scales up to a decade, the climatic changes of primary importance for ground temperatures are the changes in air temperatures and snow cover (Osterkamp & Romanovsky 1999). Increasing snow depth increases the insulation of ground from prevailing low winter temperatures and, hence, increases the ground temperatures. In contrast, late snowfall decreases soil temperatures due to the high albedo and the consumption of latent heat during snowmelt (Zhang et al. 2001a). In areas of discontinuous permafrost where air temperatures are close to 0°C, shallow permafrost is especially sensitive to climate warming. In such areas, snow depth and duration are particularly important and, together with air temperature, determine the presence or absence of permafrost.

Increasing ground temperatures have been reported from around the Arctic (e.g., Walsh et al. 2005, Romanovsky et al. 2007, Isaksen et al. 2007, Osterkamp & Romanovsky 1999), but information is underrepresented for the lowland discontinuous permafrost area of northern Fennoscandia. This paper reports permafrost temperatures from three peat mires in subarctic Sweden. Here, important changes in permafrost distribution and active layer depth have been recorded in lowland mires (Akerman & Johansson, submitted). We use the relationships between air temperatures, precipitation, and snow depth to explain the recorded changes in ground temperatures found during the last decades.

Research area

Abisko is located in subarctic Sweden and lies within the zone of discontinuous permafrost (Brown et al. 1998). Mountain permafrost determined mainly by air temperatures is found approximately above 880 m a.s.l. (Jeckel 1988), whereas at lower elevations permafrost is only likely to exist in peat mires (due to the peat's insulating effect) and underneath wind-exposed ridges (due to lack of snow) (Johansson et al. 2006). Ground temperatures have been recorded in peat mires around Abisko (Storflaket and Kursflaket, Table 1), which is located in an area of rain shadow, with a mean annual precipitation of 303 mm a^{-1} (1913–2006) and a mean annual air temperature of -0.6°C (1913–2006). In similar climatic conditions 6 km west of the mires at the Abisko Scientific Research Station, ground temperatures have been recorded in an area currently without permafrost (Abisko AWS, Table 1).

Table 1. The location, depth of measurements and observation periods for the four sites.

Site name	Coordinates (Lat/Long)	Measured at depth (m)	Observation period
Storflaket mire	68º20′51″N 18º57′55″E	0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 12	1980-1982, 1984-1989, 1994-1997, 2000-2002
Katterjokk mire	68º25′31″N 18º10′29″E	0, 0.5, 1, 1.5, 2, 3, 4, 5	1980-1982, 1984-1989, 1994-1998, 2000-2002
Kursflaket mire	68º21′05″N 18º52′42″E	0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 12, 15	1980-1982, 1984-1989, 1992, 1994-1997, 2000-2002
Abisko AWS (Automatic Weather Station)	68°21′20″N 18°49′14″E	0.05, 0.2, 0.5, 1	1985 until present

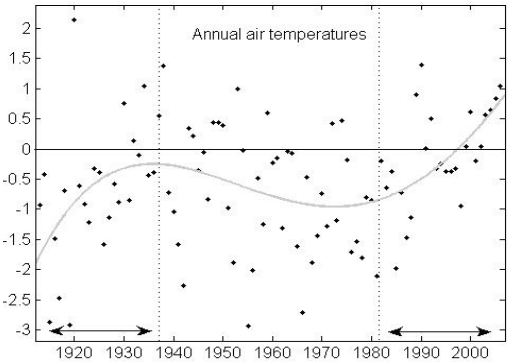

Figure 1. Annual air temperatures and a 4th degree polynomial fit from the Abisko Station, 1913 to 2006. The vertical dotted lines depict the two warming periods for which independent regression analysis was performed.

In addition, ground temperatures have been recorded at a mire located 35 km west of Abisko (Katterjokk, Table 1). Due to a very strong climatic gradient that occurs in the area, this site experiences a maritime climate with a mean annual precipitation of 848 mm a^{-1} and a mean annual air temperature of –1.7°C (1960–1990: Alexandersson et al. 1991). The depth of the peat is similar at all mires ~90 cm and is underlain by silt.

Snow depth in winter has increased by 2 cm/decade from 1913 until present in the area, but no statistically significant trend was detected in the start and end date of the snow season (Kohler et al. 2006).

The depth of permafrost ranges from a few meters in the mire located west of Abisko down to 16 m in the other mires close to Abisko (Akerman & Johansson submitted).

Methods

Air temperature monitoring

Air temperatures have been recorded manually at the Abisko Scientific Research Station from 1913 until present (at the outset, every third hour using the same method as used at the Swedish Meteorological and Hydrological Institute, 2 m screen air temperature). In 1984 an automatic weather station was installed and air temperatures have been recorded automatically every 10 minutes since then.

Ground temperature monitoring

At the mires, Copper-Constantan thermocouples were installed in boreholes at depths described in Table 1 and ground temperatures were recorded hourly, the third week of May and September using Campbell loggers.

At Abisko AWS, ground temperatures were recorded using a resistance temperature sensor Pt100 that was connected to an Automatic Weather Station. Data was recorded automatically every 10 minutes.

Data analysis – determining trends and attributing causes of the observed changes

Trends were calculated for the ground temperatures from the three mires and from the Abisko Station by using a robust linear regression, as implemented in the software package MATLAB R2006a. Trends were assumed to be significant for p levels ≤0.05. For air temperatures a 4th degree polynomial curve fit was used. To attribute the causes of the observed changes in the ground temperatures, correlation between ground temperatures, air temperatures, snow depth, and precipitation were calculated using multiple regressions (REGRESS) also within the software package MATLAB. All data were normalized and standardized prior to analysis.

Results

Air temperatures from Abisko

The mean annual air temperature at Abisko was -0.6°C between 1913 and 2006. The annual air temperatures at Abisko have during the 20th century experienced an increase in the beginning of the century that lasted until the late 1930s, which was then followed by a slight cooling trend until the mid 1970s and then again followed by an increase that is still ongoing. The regressed mean annual air temperature has been below zero degrees more or less throughout the 20th century, but in the last seven years the regressed annual air temperature has increased above the critical 0°C boundary (Fig. 1). There is an increase in air temperatures during the period of observation of 0.03°C a^{-1} (regression estimate of temperatures). Due to the distinct warming and cooling periods that have occurred throughout the last century, the overall increase in air temperature was not statistically significant (R^2 0.20 *p-value* 0.07). However, when analyzing the two warming periods that correspond roughly with the first 26 years of the record and the last 26 years, statistically significant increases were found (0.09°C a^{-1} for 1913–1938

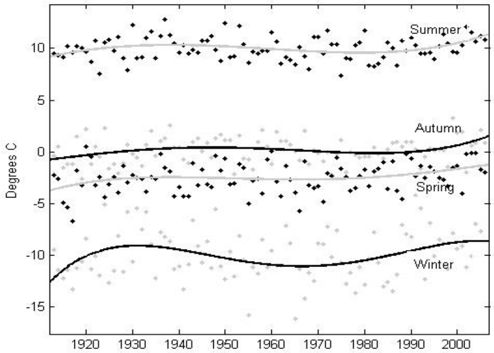

Figure 2. Seasonal air temperatures and a 4th degree polynomial fit from the Abisko Scientific Research Station, 1913-2006.

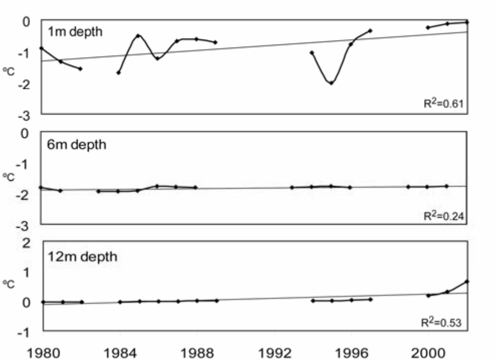

Figure 3. Ground temperatures at 1, 6 and 12 meters depth and linear trends at Storflaket mire measured in September from 1980 to 2002.

(R^2 0.28 *p-value* 0.005) and 0.10ºC a^{-1} for 1981-2006 (R^2 0.43 *p-value* 0.001).

For the whole period of observations there has been an increase in air temperatures in all four seasons that follows the same trend as the annual air temperatures (Figure 2). The largest increases in temperatures are found in winter (December, January and February) 0.04ºC a^{-1} (regression estimates), in autumn (September, October and November) and summer (June, July and August) an increase of 0.02ºC a^{-1} was found. Spring (March, April and May) experienced the lowest increase of 0.01ºC a^{-1}. As the seasonal trends follow the annual trends with increases in the beginning of the Century, followed by a cooling period and then again a warming period, the trends in increasing air temperatures are not statistically significant for the whole period of observation at all seasons (MAM R^2 0.06 *p-value* 0.02; JJA R^2 0.003 *p-value* 0.6; SON R^2 0.02 *p-value* 0.19; DJF R^2 0.005 *p-value* 0.48). However, over shorter periods of the temperature records, statistically significant trends, like the increases in the beginning and end of the Century can be found. In general it is the lower temperatures that have increased.

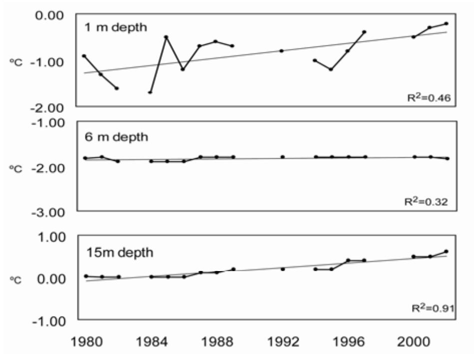

Figure 4. Ground temperatures at 1, 6 and 15 meters depth and linear trends at Kursflaket mire measured in September from 1980 to 2002.

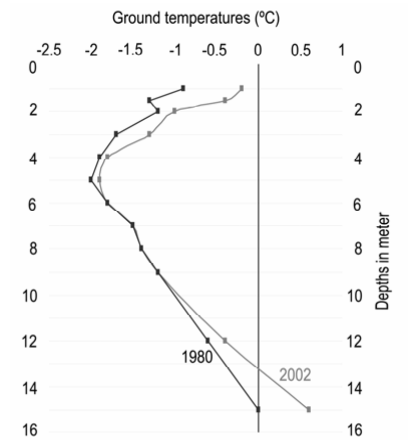

Figure 5. Ground temperatures in September 1980 and 2002 from Kursflaket mire (note: there was no subsidence of the ground surface where the temperatures were measured).

Ground temperatures from the mires

At Storflaket mire, the ground temperature monitoring has been conducted down to 12 meters. There is a statistically significant trend towards warmer September ground temperatures in the upper 1 (0.05ºC a^{-1}; R^2 0.61 *p-value* 0.004) and the lower 12 m (0.04ºC a^{-1}; R^2 0.53 *p-value* 0.001) depths. In the middle of the borehole no statistically significant trend could be detected (Figure 3).

In May, statistically significant increasing trends were found at one (0.09ºC a^{-1}; R^2 0.38 *p-value* 0.01) and 12 m

Table 2. Regression statistics of ground temperatures between 1985 and 2006 for Abisko AWS including estimates from the regressions of initial and final temperatures and the differences between them.

Time	Depth (cm)	R^2	*p-value*	Regression estimate of temp °C in 1985	Regression estimate of temp °C in 2006	Difference estimated from the regression °C a^{-1}
Annual	5	0.06	0.253	1.86	2.26	0.02
	20	0.20	0.039	1.46	2.10	0.03
	50	0.29	0.009	1.44	2.23	0.04
	100	0.38	0.002	1.38	2.30	0.04
Spring (March, April, May)	5	0.01	0.744	-0.56	-0.40	0.007
	20	0.11	0.127	-1.22	-0.58	0.03
	50	0.34	0.004	-1.30	-0.14	0.05
	100	0.49	0.000	-0.84	0.28	0.05
Summer (June, July, August)	5	0.52	0.000	9.90	7.73	-0.1
	20	0.40	0.002	8.23	6.45	-0.08
	50	0.19	0.043	5.93	4.84	-0.05
	100	0.00	0.856	3.48	3.58	0.005
Autumn (September, October, November)	5	0.37	0.003	1.81	3.01	0.05
	20	0.48	0.000	2.07	3.41	0.06
	50	0.58	0.000	2.73	4.08	0.06
	100	0.57	0.000	3.07	4.48	0.06
Winter (December, January, February)	5	0.24	0.022	-3.72	-1.29	0.11
	20	0.29	0.009	-3.24	-0.89	0.11
	50	0.34	0.004	-1.59	0.14	0.08
	100	0.45	0.001	-0.20	0.87	0.05

(0.004°C a^{-1}; R^2 0.89 *p-value* 0) depth, but again not for the depths in between.

At Kursflaket mire, ground temperature monitoring has been conducted down to 15 m. The ground temperatures in September have increased in the upper 1 m (0.04°C a^{-1}; R^2 0.46 *p-value* 0.003) and in the lower part of the borehole at 12 m and 15 m (0.03°C a^{-1}; R^2 0.91 *p-value* 0), while there is no significant trend at depths in between (Figs. 4, 5). In spring no trends were detected at 1 m and 6 m depths. At 15 m there was a statistically significant increasing trend (0.03°C a^{-1}; R^2 0.91 *p-value* 0).

At Katterjokk mire the permafrost is very shallow ranging from 2 m to 5 m; hence, no deeper temperature recordings have been made. The same trend as found in the other two mires was detected, with statistically significant increasing ground temperatures in September in the upper 1 m (0.04°C a^{-1}; R^2 0.53 *p-value* 0.001); but below no significant trend was detected (Fig. 6). In May, statistically significant trends were detected at both 1 m and 5 m depths, and increases of 0.07°C a^{-1} (R^2 0.66 *p-value* 0.0001) and 0.01°C a^{-1} (R^2 0.71 *p-value* 0), respectively, were recorded.

Ground temperatures from the Abisko Scientific Research Station

At the Abisko AWS, the ground temperatures have on an annual basis, increased at all depths (Table 2), but only at 50 cm and 100 cm depth is there a statistically significant trend. In spring, increasing statistically significant trends occur for the same depths, but not in the upper 50 cm. In summer, a decreasing trend in ground temperatures is detected, and down to 50 cm it is statistically significant. In autumn, again we see an increasing trend in ground temperatures, and it is statistically significant for all depths. In winter, there is also an increasing trend that is statistically significant for all depths.

Correlations of air temperatures and ground temperatures, snow depth and precipitation

On an annual basis, we could detect a statistically significant correlation between air temperature and ground temperature at Abisko. The highest correlation is found at the 20 cm depth (R^2 0.66) and the lowest, at the 1 m depth (R^2 0.42). The same pattern is detected for the spring. For summer, no correlation could be found between air temperature and soil temperatures. In autumn, statistically significant correlations could be detected at 5 cm (R^2 0.45) and 20 cm (R^2 0.36) depths, but not at lower depths. In winter, statistically significant correlations between air temperature and ground temperature were found at all depths, 5 cm = R^2 0.64, 20 cm = R^2 0.62, 50 cm = R^2 0.55, and 100 cm = R^2 0.45.

No statistically significant correlations were detected between snow depth and the ground temperature in any of the seasons or on an annual basis at the Abisko AWS.

On an annual basis, a weak statistically significant trend could be detected between precipitation and soil temperature at the 20 cm depth, but not at any other depths. In spring, autumn, and winter no correlations between precipitation and ground temperatures were found, but in summer, a statistically significant trend could be detected at 5 cm and 20 cm depths (R^2 0.30 and R^2 0.23).

Discussion

Mean annual air temperatures at Abisko (Fig. 1) follow the same trend as shown for the Northern Hemisphere (Houghton et al. 2001, IPCC 2007), with a warming period in the beginning of the 20th century continuing until about 1940, followed by slight cooling until the 1970s, and then a second warming period that is still ongoing. Although interannual variation is so large during the last century that the overall increase is not statistically significant, temperature increases are statistically significant in the two warming periods when they are analyzed separately. Similarly, Kohler et al. (2006) did not detect a trend for the whole period (apart from the spring record) but also found statistically significant increases over a shorter time period (1956–2000). The recent increase at the end of the century, mainly due to increases in lower air temperatures, has resulted in a current temperature that is possibly higher than those since at least the Medieval Warm Period (Grudd et al. 2002).

The temporal pattern of mean annual air temperature is repeated in each of the seasons (Fig. 2). For example, Holmgren & Tjus (1996) reported an increase in summer air temperatures from the beginning of the century to about 1940, which was as high as 1.5°C. In addition to the increases in seasonal and mean annual air temperatures, increases in snow depth (Kohler et al. 2006) and active layer depth (Akerman & Johansson Submitted) have occurred in the area.

Increasing ground temperatures could be detected from all four sites, but in the mires, increases in ground temperatures only occurred in the upper and lower parts of the permafrost (Figs. 3, 4). This is accompanied by an increase in active layer depth (Åkerman & Johansson submitted). In the middle, no significant trend was found. Isaksen et al. (2007) also found increases in ground temperatures in mountain permafrost in northern Scandinavia. They detected significant warming down to at least 60 m in depth. Statistically significant correlations were found between the seasonal ground and air temperatures (Isaksen et al. 2007).

We hypothesized that ground temperatures would have been determined by snow depth in addition to air temperatures. This hypothesis was based on studies such as that by Thorn et al. (1999), who worked in a valley close to the Katterjokk mire and concluded that air temperatures could explain as much as 95% of the variance in ground temperatures at shallow depths at some sites. However, at other sites with differing microclimate determined by variation in elevation, aspect, and vegetation cover, air temperatures could only explain as little as 20%. This was suggested to be due to a role of seasonal snow cover (although this was not measured) (Thorn et al. 1999). In addition, Josefsson (1990) found a relationship between ground temperatures and climatic parameters, especially snow cover at four sites near Abisko. Both Thorn et al. (1999) and Josefsson (1991) have interpreted snow cover

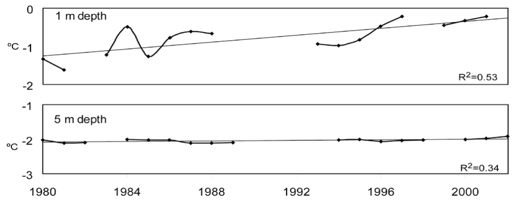

Figure 6. Ground temperatures at 1 and 5 m depth and linear trends at Katterjokk mire measured in September from 1980 to 2002.

as one of the most important parameters that determine ground temperatures in our study area.

We also found correlations between air and ground temperatures. Surprisingly we could not detect any correlation between snow depth and ground temperature even though we used two unique snow datasets from Abisko. Changes in starting and ending dates of snow cover could affect the ground temperatures at Abisko, but no such changes were detected at Abisko (Kohler et al. 2006); hence these cannot explain increases in ground temperatures.

As we found a decrease in summer ground temperatures (Table 2) that could not be correlated to snow depth and air temperature, and the correlations that were found between air temperature and ground temperature explained little of the variance, it can be concluded that other factors also determine the ground temperatures in the Abisko region. The decrease in summer ground temperatures could be caused by a change in vegetation which alters the albedo, shading, and soil moisture. Vegetation has not shifted at the Abisko AWS and, hence, cannot explain the decreasing trend in summer ground temperatures. The decrease in ground temperature was correlated, however, with increases in summer precipitation that have occurred during the last decades. An increase in precipitation increases evaporation which in turn increases the energy consumption resulting in cooler ground temperatures. Similar trends with decreasing summer ground temperatures have been reported from Irkutsk in southcentral Siberia, where they were also attributed to increases in summer precipitation (Zhang et al. 2001b).

The increases in ground temperatures in the lower part of the permafrost might be due to a slight "heat wave" as a result of the warming period at the end of the century. More likely though, there is a possible heating affect from slightly warmer or more freely flowing ground water around and below the frozen bodies of silt and turf. Although, there are no direct measurements of surface and ground water temperatures, temperatures at 12 m and 15 m of just above 0°C indicate that liquid water is flowing at the bottom of the permafrost. However, observations of seasonal variations in ground temperatures at the base of the permafrost are needed to confirm this. If the relatively high temperatures at the base of the permafrost in the mires reflect the movement of liquid water, then the permafrost is even more vulnerable than we first expected because of the influences of warming from above and below.

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III
Photo:J.Åkerman

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Thawing Permafrost and Thicker Active Layers in Sub-arctic Sweden

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ABSTRACT

Observations of active-layer thickness from nine sites with up to 29 years of gridded measurements located in the Torneträsk region, northernmost Sweden, were examined in relation to climatic trends. Mean annual air temperatures in this area have warmed and recently rose above 0°C. Active layers at all sites have become thicker, at rates ranging from 0.7 to 1.3 cm per year. This trend has accelerated in the past decade, especially in the westernmost site where rates have reached 2 cm per year and permafrost has disappeared at 81 per cent of the sampling points. Increased active-layer thicknesses are correlated with increases in mean summer air temperature, thawing degree-days and, in five of the nine sites, with increases in snow depth. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: active-layer thickness; thawing permafrost; Abisko; subarctic Sweden

INTRODUCTION

There is a general trend in the northern hemisphere towards permafrost warming, although a small number of sites have experienced less warming or even cooling (Lemke *et al*., 2007). In addition, land areas underlain by permafrost in the Arctic have been reduced in extent during recent decades (Anisimov *et al*., 2007). Mean annual air temperatures in regions north of 65°N have increased by about 2–3°C since the 1950s, which is almost twice the rate of the rest of the world (Serreze *et al*., 2000; ACIA, 2005). Global circulation models project pronounced future warming in areas where discontinuous and continuous permafrost is currently present (Kattsov *et al*., 2005) and despite the many uncertainties associated with climate predictions there is a general agreement that this climatic warming will have serious impacts on high-latitude permafrost.

Future increases in regional temperatures are expected to lead to widespread degradation of permafrost and thaw depths are expected to increase, especially in the discontinuous and sporadic permafrost zones (Anisimov *et al*., 2007). The active layer plays an important role in cold regions since most ecological, hydrological and biogeochemical activities take place there (Kane *et al*., 1991; Hinzman *et al*., 2003). Widespread increases in active-layer thickness can lead to considerable changes in biogeochemical cycling (Christensen *et al*., 2004; Johansson T. *et al*., 2006), biological, geomorphological, and hydrological processes (Anisimov and Nelson, 1996) and can also affect the infrastructure and economy of northern communities (Instanes *et al*., 2005; Anisimov *et al*., 2007). The degradation of permafrost may lead to the release of carbon pools that are currently stored in the permafrost, releasing additional greenhouse gases to the atmosphere and thereby potentially affecting climate at a global scale. As there are uncertainties in estimates of the magnitude of these feedbacks, there is an increasing urgency for researchers to resolve questions about the fate of permafrost (Walker, 2007).

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The greatest changes in permafrost are likely to occur in areas where the mean annual air temperatures are close to 0°C and where this temperature has recently been exceeded. This paper describes the recent dynamics of permafrost in nine peat mires along a west-east transect in the Torneträsk catchment, northern Sweden over the last three decades. This area has experienced recent temperature increases and the mean annual air temperature has passed 0°C during the last decade (Johansson *et al*., 2008). Active-layer thickness has been monitored annually since 1978 and from the mid-1980s onwards, largely conforming to protocols developed through the CALM (Circumpolar Active Layer Monitoring) programme (Brown *et al*., 2000). Here we present records from nine sites which show increasing active-layer thicknesses throughout the whole time series but with an accelerating trend during the last decade. In addition, we examine the causes of the changes and discuss their consequences.

STUDY AREA

The Torneträsk region is situated in the northernmost part of Sweden and lies within the zone of discontinuous permafrost (Brown *et al*., 1998). Permafrost is widespread above approximately 880 m a.s.l. (Jeckel, 1988), while at lower elevations it is likely present only in peat mires and beneath wind-exposed ridges (Johansson, Christensen *et al*., 2006). The CALM sites are located in peat mires along a west-east oriented transect, with similar local topographic conditions (Figures 1 and 2). Elevations range from 500 m above sea level (a.s.l.) in the easternmost and westernmost sites to 350 m a.s.l. around Abisko. Five of the nine sites are situated within 1.5 km of Lake Torneträsk, the main water body in the area (Figure 1).

The study area extends across a strong climatic gradient, ranging from a maritime climate in the west to a more continental climate in the east. In general, regional precipitation decreases and annual temperature amplitudes increase eastwards. The highest precipitation (~900 mm/yr) occurs near the Norwegian border, while the lowest is in a rain shadow area around Abisko (~300 mm/yr). The mean annual air temperature for 1913–2006 at Abisko was −0.6°C (Abisko Scientific Research Station) and it remained <0°C throughout most of the 20th century. In the last few years, however, it has risen above 0°C (Johansson *et al*., 2008). Climate parameters relevant to active-layer thickness are presented in Figure 3 (data from the Abisko Scientific Research Station and updated from Kohler *et al*., 2006).

The vegetation in the Torneträsk region ranges from boreal forest, through birch forests to areas with very sparse vegetation. Although all the mires in the transect are fully covered by vegetation, the dominant type varies. At the westernmost and easternmost sites, vegetation is dominated by graminoids in wet minerotrophic conditions. The vegetation in the mires around Abisko is characterised by dwarf shrubs in dry ombrotrophic conditions. Many periglacial features are found in the mires, including palsas, pounus, peat plateaus and polygonal cracks (Table 1).

The thickness of permafrost in the mires, obtained by drilling until the frozen bodies were penetrated, ranged from a few metres to 16 m in the 1980s (Figure 1B). The thickness presented in Knutsson (1980) was used for Narkervare. The thickness reflects snowfall trends resulting in relatively thick permafrost around Abisko due to small amounts of snow, and very thin permafrost in the westernmost mires which receive substantially more winter precipitation. The thickness of the peat layer is ~90 cm at all the sites. The permafrost in the study area is only a few degrees below zero (Johansson *et al*., 2008). Visible ice contents at Kursflaket and Storflaket averaged around 7–8 per cent (mean value for the period 1980–2000) but were approximately 30 per cent and 35 per cent, respectively, in the upper part of the permafrost body. At the base of the frozen silt, high visible ice contents (>20%) were also found. At Kursflaket, the highest visible ice content was between 2.75 and 4.25 m depth where it exceeded 50 per cent.

METHODS

Active-layer Thickness

Active-layer thicknesses were measured annually during the third week of September which is the time of maximum thaw. Eight of the nine sites are part of the CALM programme (Brown *et al*., 2000). Sample points at each location are spaced 10 m apart and arranged in a grid. The number of points in each grid varied from 40–121 (the latter is the CALM standard; Brown *et al*., 2000; see Table 1) depending on the size of the mire, local drainage and limitations imposed by stones in the ground. Thaw depths were determined by mechanical probing using a 1-cm diameter graduated steel rod (1 m or 2.2 m long) inserted into the soil to refusal. Resistance due to permafrost could be differentiated from that due to rocks or stones. At each grid point, the ground was probed three or four times.

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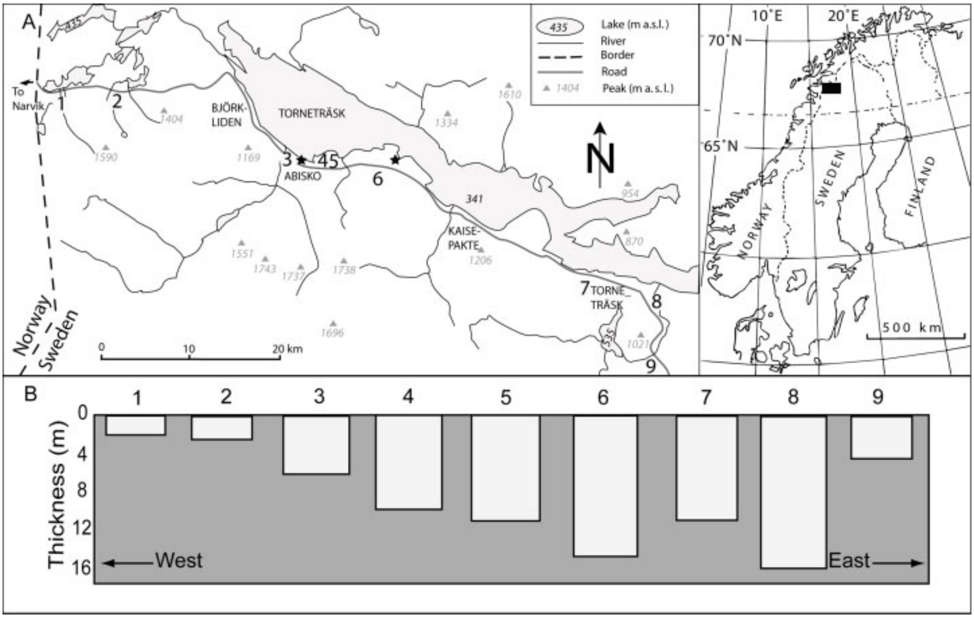

Figure 1 (A) Location of the nine mires: (1) Katterjokk; (2) Låkta Hpl; (3) Heliport; (4) Kursflaket; (5) Mellanflaket; (6) Storflaket; (7) Torneträsk; (8) Narkervare; and (9) Bergfors. The black star to the left denotes location of the Abisko Scientific Research Station, and the one to the right, Stordalen. (B) Thickness of the permafrost measured in boreholes at each location in 1984, except for site 8 (from Knutsson, 1980).

Data Analysis

Trends were calculated for active-layer thickness from the nine mires using a robust linear regression, as implemented in the software package MATLAB (REGRESS function). Trends are assumed to be significant for p-values ≤ 0.05. To determine what caused the observed changes in active-layer thickness, relationships between it and the following parameters were examined: mean summer (June, July and August) air temperature, thawing degree-days (TDD) (June to August and May to September), summer precipitation, snow depth and air temperatures over the preceding winter. The last is justified by results from Smith (1975) who concluded that the insulating effect of snow increases until a snow depth of 50–60 cm has been reached and then additional increases in snow cover have a reduced insulating capacity. As the snow depth rarely exceeds a few decimetres at most of the mires investigated, the air temperature from winter may affect soil temperatures and hence active-layer thickness. Meteorological data for the area were obtained from the Abisko Scientific Research Station for 1978 to present. All data were standardised prior to analysis to assure a unitless analysis for multiple regression (Zar, 1996).

Contour maps of active-layer thickness were prepared by generating thaw-depth fields using a low-order inverse distance weighting interpolation algorithm available in the commercial software package Golden Software (1999; Surfer version 7). This produced a smooth surface for visual inspection of the spatial variation in active-layer thickness in accordance with CALM recommendations (Brown *et al*., 2000).

RESULTS

Active-layer Thickness

Active-layer thickness varied spatially within the grids and temporally over the period of observation at all nine sites (Figure 4). The thickest active layers on average developed in the westernmost and easternmost sites and the thinnest were in the area around Abisko. The data show that average thaw depths

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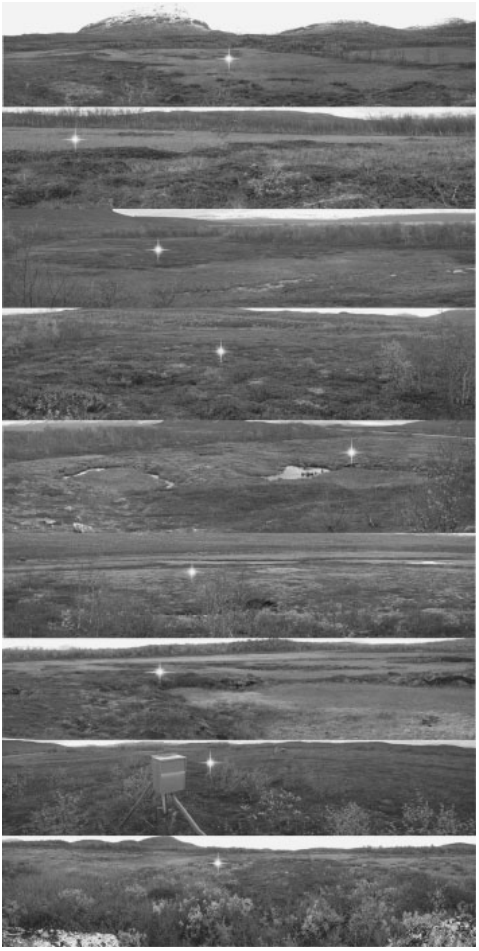

Figure 2 Photographs of the mires shown from west to east (upper to lower): (1) Katterjokk; (2) Låkta Hpl; (3) Heliport; (4) Kursflaket; (5) Mellanflaket; (6) Storflaket; (7) Torneträsk; (8) Narkervare; and (9) Bergfors. The white mark denotes the centre point of each Circumpolar Active Layer Monitoring grid.

increased at all of the sites from 1978–2006 by 0.7 to 1.3 cm per year (Table 2).

The increase in active-layer thickness was not uniform throughout the period of observation but accelerated, especially from 1997 onwards. The rate of increase in active-layer thickness for the last decade was statistically significant only at the westernmost and easternmost sites. The maximum statistically significant rate of increase was 2.0 cm per year at Katterjokk (Table 2).

Permafrost Disappearance

The effects of a thicker active layer were most dramatic in the westernmost sites that initially had thin permafrost (approximately 2 m thick). The number of points in the grid underlain by permafrost at Katterjokk (the westernmost site) decreased from 121 to 23 from 1999 to 2006. Only 19 per cent of the grid is now underlain by permafrost and the rest thawed quickly (over less than a decade; Figure 5). Figure 6 shows the spatial distribution of active-layer thickness in Katterjokk from 1996 to 2006; red indicates areas where the permafrost disappeared. At present, there is only permafrost in the northernmost parts of the grid. The Låkta Hpl site has a similar climatic setting and experienced comparable change but since it had only 40 sampling points and very few exhibited permafrost by 2004, the site was abandoned in that year.

Causes of Change in Active-layer Thickness

Active-layer thicknesses correlate with mean summer (June, July and August) air temperatures represented by R^2-values from 0.27 to 0.68, which are statistically significant at all nine sites (Table 3). As an example of the linkage, the highest mean summer air temperature and the thickest active layer were both recorded in 2002. Correlations were still higher for TDD when calculated for May to September, ranging from 0.44 to 0.69 (Table 3, Figure 7). A statistically significant correlation between average snow depth in the preceding winter and active-layer thickness was found for five of the nine sites (Katterjokk, Heliport, Kursflaket, Torneträsk, Narkervare). Correlations between active-layer thickness and winter air temperatures (October to May) or summer precipitation were not statistically significant at any of the sites.

DISCUSSION

Active-layer Thickness

Active-layer thicknesses vary among and within the mire sites as a result of the interaction of numerous factors. Even though the mires have different climatic settings in terms of annual precipitation,

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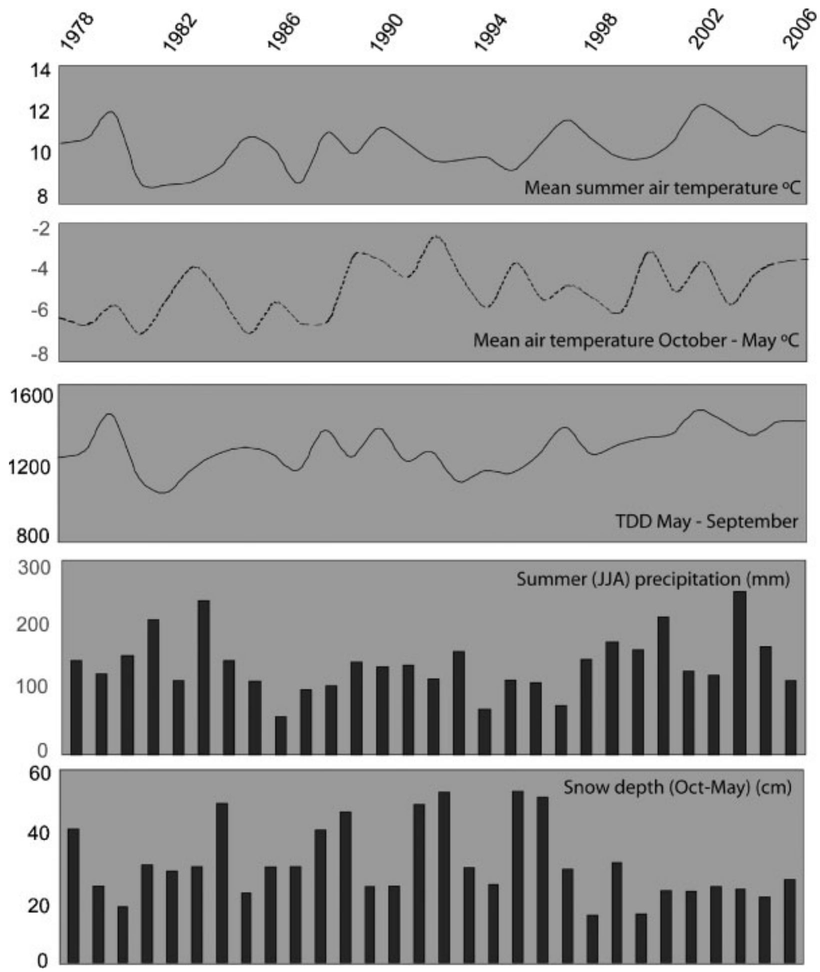

Figure 3 Climate characteristics for the region (data from the Abisko Scientific Research Station; Johansson M. *et al*., 2008; updated from Kohler *et al*., 2006).

the trend of increasing active-layer thickness was detected at all of them. These results agree with previous observations from the area. For example, active-layer thickness at the Stordalen mire (a site within the International Biological Programme) located in the middle of the transect (Figure 1) increased in dry areas from 48 cm at the beginning of the 1970s to 63 cm at the beginning of the 2000s. In wet areas, however, active-layer thickness was more or less unchanged, ranging from 87 cm to 86 cm for the same period of time (Rydén and Kostov, 1980; Johansson T. *et al*., 2006).

A mire located between Heliport in our transect and the Abisko Scientific Research Station (Figure 1) has a similar active-layer thickness today as Heliport. Ekman (1957) indicated that its active-layer thickness was 68 cm and 52 cm in September 1936 and 1938, respectively. Although we are unsure about the measurement method used and if this is a single sample or the mean of many measurements, it seems

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Table 1 Detailed description of the 9 sites along the transect

Site	Lat/Long	Elevation (m a.s.l.)	Available record (years)	Number of sampling points	Mean annual air temperature and total annual precipitation 1961–90*	Site characteristics
1 Katterjokk	68°25′31″N 18°10′29″E	470	1978–2006	121	−1.7°C 848 mm	Small isolated bog with low palsas and pounus. Within birch forest
2 Låkta Hpl	68°25′35″N 18°20′00″E	490	1978–2003	40	−1.7°C 848 mm	Small isolated bog with pounus. Within birch forest
3 Heliport	68°21′52″N 18°47′44″E	378	1978–2006	121	−0.8°C 304 mm	Peat plateau. Dissected into mounds or small plateaus. Pounus
4 Kursflaket	68°21′05″N 18°52′42″E	353	1978–2006	55	−0.8°C 304 mm	Peat plateau. Polygonal cracks. Pounus
5 Mellanflaket	68°20′53″N 18°57′51″E	390	1978–2004	40	−0.8°C 304 mm	Peat plateau. Polygonal cracks
6 Storflaket	68°20′51″N 18°57′55″E	383	1978–2006	121	−0.8°C 304 mm	Peat plateau. No isolated palsas. Polygonal cracks
7 Torneträsk	68°13′32″N 19°43′24″E	347	1978–2006	40	−1°C 476 mm	Numerous isolated dome-shaped palsas. Pounus
8 Narkervare	68°11′52″N 19°45′57″E	385	1984–2006	75	−1°C 476 mm	Peat plateau. Partly dissected. Polygonal cracks
9 Bergfors	68°08′44″N 19°45′46″E	507	1988–2002 2004–2006	121	−1°C 424 mm	Small isolated bog with low palsas and pounus. Within birch forest

*Data from Alexandersson *et al*. (1991).

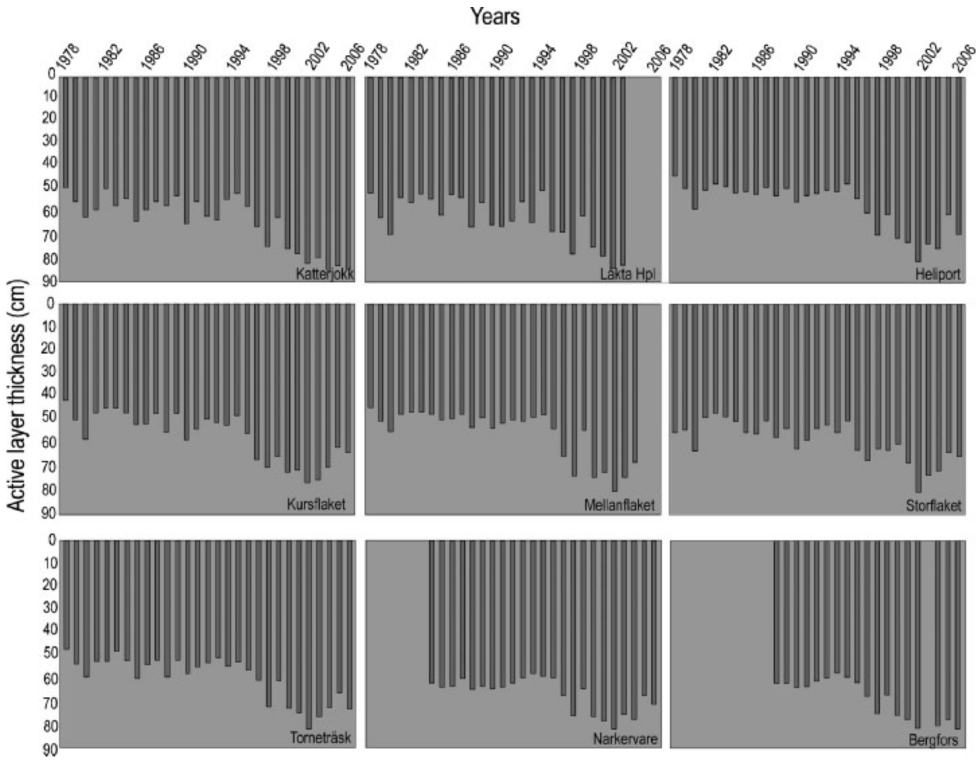

Figure 4 Active-layer thickness from 1978 to 2006 at the nine sites. The active layer has become thicker over the monitoring period, especially during the last decade.

possible that active-layer thickness in the study area was actually thicker during the 1930s warm period compared to the 1970s when our monitoring began and active-layer thicknesses were ~45 cm.

Increasing active-layer thicknesses over the past few decades have been reported from elsewhere in the Arctic, including Russia (Pavlov, 1996, in Lemke *et al*., 2007; Mazhitova *et al*., 2004), Iceland (Kneisel *et al*., 2007) and Svalbard (Åkerman, 2005). Christiansen (2004) reported active-layer thickness in Greenland, from two CALM sites, from 1996 to 2002. At one of them, the active layer had become thicker, but at the other it had remained more or less constant. In the Mackenzie Valley, Canada, the depth of thaw penetration increased at most sites along a 1200-km transect, but this increase was however not always related to a proportional increase in active-layer thickness due to variable thaw settlement (Tarnocai *et al*., 2004). In contrast, no general trend in active-layer thickness was reported from Alaska from seven CALM sites that have been monitored since 1995 (Hinkel and Nelson, 2003). In Finland, Seppälä (2003) reported that no unusual development in the active layer on palsas had been detected and that actually new permafrost was found in small peat hummocks (pounus). Despite these regional variations, the Torneträsk results form part of what appears to be a general trend towards increasing active-layer thicknesses around the Arctic.

Permafrost Disappearance

Palsa mires in northern Scandinavia are degrading more frequently than new palsa mires are forming (Sollid and Sørbel, 1998; Zuidhoff and Kolstrup, 2000). The disappearance of permafrost (i.e. degradation of the palsa mire) in the westernmost site at Katterjokk is mainly because permafrost initially was

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Table 2 Trend in active-layer thickness at the nine sites for the whole monitoring period and for the last decade (in italics)

Site	Year	Regression estimate of rate (per year)	R^2	*p*-value*
Katterjokk	1978–2006	1.1 cm	0.65	**0.000**
	1997–2006	*2.0 cm*	*0.72*	***0.002***
Låkta Hpl	1978–2003	0.9 cm	0.48	**0.000**
	1997–2003	*2.3 cm*	*0.48*	*0.083*
Heliport	1978–2006	0.9 cm	0.61	**0.000**
	1997–2006	*0.6 cm*	*0.09*	*0.411*
Kursflaket	1978–2006	1.0 cm	0.64	**0.000**
	1997–2006	*−0.3 cm*	*0.04*	*0.595*
Mellanflaket	1978–2004	1.0 cm	0.60	**0.000**
	1997–2004	*1.0 cm*	*0.13*	*0.390*
Storflaket	1978–2006	0.7 cm	0.51	**0.000**
	1997–2006	*0.6 cm*	*0.07*	*0.454*
Torneträsk	1978–2006	0.9 cm	0.61	**0.000**
	1997–2006	*0.8 cm*	*0.16*	*0.252*
Narkervare	1984–2006	0.7 cm	0.45	**0.001**
	1997–2006	*0.2 cm*	*0.02*	*0.718*
Bergfors	1988–2006	1.3 cm	0.75	**0.000**
	1997–2006	*1.3 cm*	*0.62*	***0.011***

*Statistically significant trends if *p*-value ≤ 0.05 (denoted in bold).

very thin, which made it particularly vulnerable to changes in temperatures and snow depth. Similar observations were made in the Torneträsk catchment by Johansson T. *et al.* (2006) who reported that permafrost was now absent under a large area (1.0 ha) of Stordalen where it was present in the 1970s. Sollid and Sørbel (1998) reported that palsa plateaus in Dovrefjell (Norway) that were almost intact in the 1960s had almost completely disappeared by the end of the 1990s.

Causes of Changes in Active-layer Thickness

Active-layer thickness responded mainly to forcing by air temperatures represented by mean summer air temperature and TDD and to a lesser extent snow depth. The deepest thaw depths were recorded during hot summers, and active-layer thickness was thinner during cooler summers. This is in agreement with many other observations from around the Arctic (e.g. Brown *et al.*, 2000; Mazhitova *et al.*, 2004; Hinkel and Nelson, 2003; Christiansen, 2004) that have shown a strong correlation between end-of-season thaw depth and TDD. In the Torneträsk region, Christensen *et al.* (2004) and Johansson T. *et al.* (2006) reported from Stordalen that changes in active-layer thickness were most likely caused by increased air temperatures and increased snow depths.

Rydén and Kostov (1980) concluded from Stordalen that the relationship between precipitation and thaw rate was especially strong. Precipitation effectively promotes thawing by increasing the thermal conductivity through increased soil moisture, particularly in peat, thereby increasing summer heat transfer downwards. Despite this, we could not find any statistically significant relationship between summer precipitation and active-layer thickness in the study area.

The observation that it is mainly air temperature that determines the thickness of the active layer also explains the deeper thaw depths found in the 1930s by Ekman (1957) in the mire near Heliport. The Torneträsk catchment area experienced a warming period from 1916 to 1939 (when the measurements were conducted), which was then followed by a cooling period 1940–87 (during which active-layer thickness was most likely thinner), which was then again followed by a warming period (Holmgren and Tjus, 1996; Nyberg and Rapp, 1998).

Consequences of Increased Active-layer Thickness and Disappearance of Permafrost

The increased active-layer thickness found in the study area has led to surface subsidence and in some cases to the formation of thermokarst. Changes in groundwater and surface conditions affect surface stability by altering the albedo and energy budget at the surface

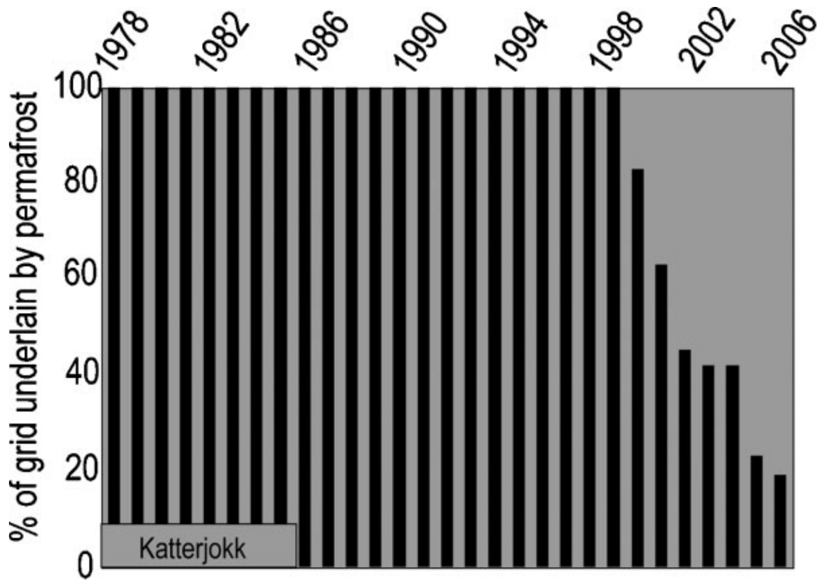

Figure 5 Number of sampling points underlain by permafrost at Katterjokk Circumpolar Active Layer Monitoring grid.

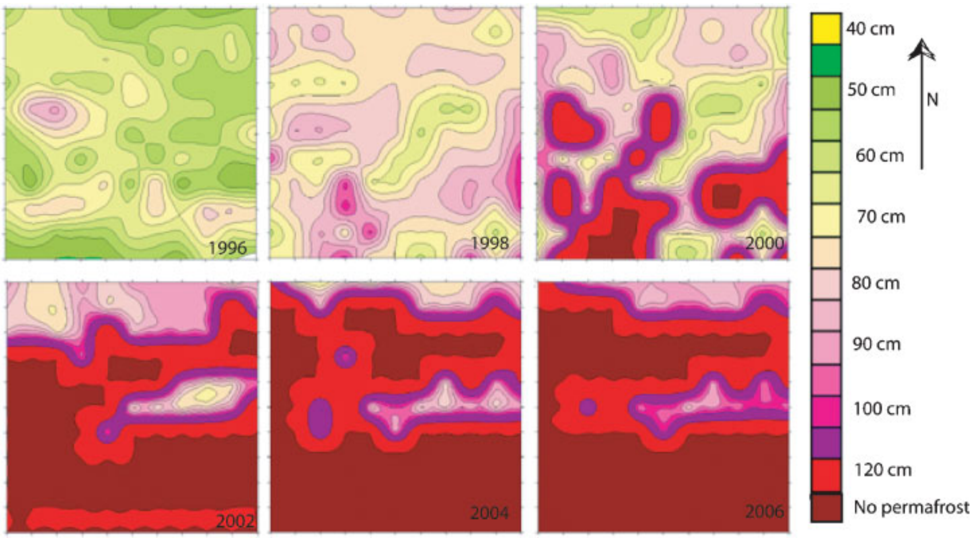

Figure 6 Spatial and temporal variation in active-layer thickness at the westernmost site (Katterjokk) from 1996–2006.

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Table 3 Statistical influence of climatic variables on active-layer depth

Site		Summer mean air temperature (June to August)	Winter mean air temperature (October to May)	Thawing degree-days (May to September)	Total summer precipitation (June to August)	Mean snow depth (October to May)
Katterjokk	R^2-value	**0.33**	0.13	**0.49**	0.10	**0.16**
	p-value	***0.001***	*0.059*	***0.000***	*0.103*	***0.033***
Låkta Hpl	R^2-value	**0.50**	0.02	**0.53**	0.00	0.08
	p-value	***0.000***	*0.459*	***0.000***	*0.969*	*0.152*
Heliport	R^2-value	**0.34**	0.09	**0.49**	0.07	**0.17**
	p-value	***0.001***	*0.118*	***0.000***	*0.152*	***0.028***
Kursflaket	R^2-value	**0.42**	0.06	**0.53**	0.03	**0.15**
	p-value	***0.000***	*0.214*	***0.000***	*0.413*	***0.041***
Mellanflaket	R^2-value	**0.34**	0.07	**0.44**	0.04	0.08
	p-value	***0.001***	*0.199*	***0.000***	*0.341*	*0.161*
Storflaket	R^2-value	**0.68**	0.04	**0.69**	0.01	0.11
	p-value	***0.000***	*0.270*	***0.000***	*0.657*	*0.078*
Torneträsk	R^2-value	**0.38**	0.05	**0.52**	0.03	**0.21**
	p-value	***0.000***	*0.232*	***0.000***	*0.367*	***0.011***
Narkervare	R^2-value	**0.37**	0.04	**0.50**	**0.25**	**0.21**
	p-value	***0.002***	*0.340*	***0.000***	***0.015***	***0.029***
Bergfors	R^2-value	**0.28**	0.01	**0.46**	0.25	0.21
	p-value	***0.043***	*0.800*	***0.006***	*0.058*	*0.085*

Note: Trends are considered statistically significant if *p*-value ≤ 0.05 (denoted in bold). For years of record, see Table 1.

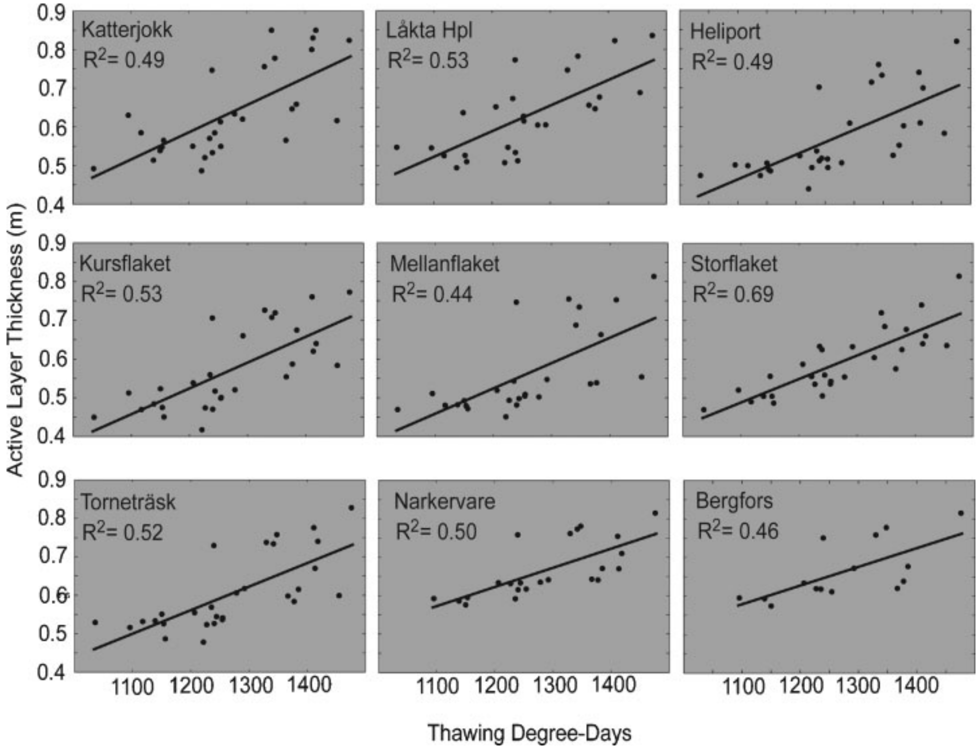

Figure 7 Relationship between active-layer thickness and thawing degree-days (May–September) at the nine sites.

and by contributing to heat flow in the subsurface (Woo, 1992). Surface subsidence was monitored at Kursflaket using a theodolite and measuring from a fixed point in bedrock and subsidence followed the same trend as active-layer thickness. Changes in active-layer thickness affect hydrology and nutrient availability and can pose serious threats to existing ecosystems through either drying or oversaturation (Hinzman *et al.*, 2005; Walsh *et al.*, 2005). At some sites, hydrological conditions have become much wetter (Christensen *et al.*, 2004) so that over the last few decades the vegetation has changed from dry shrub-dominated ombrotrophic conditions to wet graminoid-dominated more nutrient-rich conditions (Johansson T. *et al.*, 2006).

The presence or absence of permafrost and the thickness of the active layer have significant impacts on local hydrology. They therefore influence the exchange of greenhouse gases between ecosystems and the atmosphere. At Stordalen (Figure 1), changes in microtopography and hydrology indicated by vegetation change have caused an increase in the landscape-scale methane (CH_4) emissions from 1970 to 2000 of 22 to 66 per cent (Christensen *et al.*, 2004). Johansson T. *et al.* (2006) showed an increased radiative forcing from this ecosystem due to the relative importance of increased CH_4 emissions compared with carbon dioxide (CO_2) uptake. Ström and Christensen (2007) concluded that changes in vegetation composition will further increase emissions of CH_4 as the species that are expanding stimulate the production and transport of CH_4 to the atmosphere.

Projected Changes

Climate scenarios project increased temperatures and increased precipitation for the Torneträsk region (Saelthun and Barkved, 2003). Increased temperatures will lead to further permafrost degradation and thicker active layers, and increased precipitation will accelerate this process. The future distribution of palsa

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mires in Scandinavia was modelled by Fronzek *et al.* (2006) and they found that even small increases in mean annual air temperatures (1°C) and total annual precipitation (10%) resulted in a considerable loss of areas climatically suitable for palsa development. By the end of the 21st century all but one scenario resulted in total disappearance of suitable regions for palsa development in Scandinavia.

CONCLUSIONS

The active layer has become thicker at all nine mires studied in the Torneträsk region over the past three decades. The average rate of increase in thickness was between 0.7 and 1.3 cm per year but rates accelerated, especially during the last decade, to as high as 2 cm per year. Over the same time period, permafrost disappeared completely at 81 per cent of the CALM grid points in the westernmost mire (with initially thin permafrost). Increased active-layer thicknesses were correlated with increases in summer air temperature, TDD and at five of the nine sites also with increases in snow depth. If air temperature and precipitation continue to increase as predicted for the Torneträsk region (Sælthun and Barkved, 2003), trends in permafrost degradation and increasing active-layer thickness are expected to continue.

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IV

Modelled, sub-arctic lowland permafrost development during the 20th Century and scenarios for the last 1000 yrs

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ABSTRACT

Increasing ground temperatures, permafrost thawing and active layer thickening have been reported from the Torneträsk area, sub-arctic Sweden. This region has experienced two warm periods during the last Century. To form a basis for improved predictions of how ground temperatures at two sites (one currently with and one without permafrost) will respond to projected future climate change, lowland permafrost development in the Torneträsk catchment is modelled for the 20th Century. To explore if the dynamics of permafrost in the 20th Century have, or have not been unique in the past 1000 yrs, likely ground temperature scenarios for the two sites are modelled for the last 1000 yrs, using different snow depth levels. The modelled annual ground temperatures reflect the known climatic periods that have occurred during the last 1000 years in the Torneträsk catchment. Permafrost degradation has occurred during the two warm periods in the 20th Century and at the site currently without permafrost, conditions for permafrost occurred in the upper soil layers around 1915. The model results from the site currently underlain by permafrost indicate annual ground temperatures down below 0 ºC to 10 m for the last 1000 yrs. This contradicts the proxy data from the area that suggests that permafrost formation occurred during the Little Ice Age. Consequently, the results for the 11th Century are quite uncertain. The modelled annual ground temperatures for the nearby site currently without permafrost indicate annual ground temperatures above 0 ºC, with a few years exception in the 16th Century. According to these results, it is hence not likely that lowland permafrost was widespread during the last 1000 yrs, but was restricted to particularly favourable sites as today. The contrast in ground temperature trends between the two sites is mainly due to thickness of organic layer and also different snow conditions. A good understanding of the roles of peat, vegetation and snow depth in modelling past ground temperatures provide a better basis for new studies that seek to project future rapid changes in permafrost distribution.

INTRODUCTION

Increasing ground temperatures have been reported since the 1980s from many areas around the Arctic (Brown and Romanovsky, 2008) resulting from the recent warming period (Serreze *et al.*, 2000). Thawing of permafrost is currently observed at the southern limits of the permafrost zone (Brown and Romanovsky, 2008). The Torneträsk catchment, northern Sweden is located at the southern limit of discontinuous permafrost in Fennoscandia (Brown *et al.*, 1998). Currently, lowland permafrost only exists in areas especially favourable for permafrost, for example in peat mires where the peat insulates the ground in areas with little precipitation. Lowland permafrost can also exist underneath ridges that are windswept of snow in the winter (Johansson *et al.*, 2006a). The permafrost in the mires is called "ecosystem-protected permafrost" (Shur & Jorgensen, 2007) and was developed when the climate was colder and today only exists due to the protecting peat layer. Once the permafrost starts to thaw, the process is non-reversible under the present climate.

In the Torneträsk catchment, permafrost temperatures are increasing (Johansson *et al.*, 2008), permafrost is thawing and the active layer has become thicker during the last decades (Åkerman & Johansson, 2008, Christensen *et al.*, 2004, Johansson *et al.*, 2006b, Ström & Christensen, 2007). The observed changes in permafrost in the Torneträsk area are correlated with increasing air temperatures and snow depth (Åkerman & Johansson, 2008) associated with a current warming period. The Torneträsk region has however, experienced two warm periods during the 20th Century, one in the early 1920s to 1940s and one that started around 1980 and is still ongoing. It is only since about 2000 that the air temperatures during the second warming period have exceeded those during the earlier warm period (Callaghan *et al.*, *in prep*; Johansson *et al.*, 2008). We hypothesise that current permafrost degradation started already during the first warm period in the 20th Century, was then on hold during the colder period, and has continued as observed (Åkerman & Johansson, 2008) during the second warming period of the 20th Century. This paper addresses the apparently Century long processes of permafrost degradation. If the thawing of permafrost started in the beginning of the 20th Century, then the remaining permafrost in the second warming period would be potentially more vulnerable to warming and this could at least partially explain why we currently experience major, rapid changes in lowland permafrost in the Torneträsk area.

Lowland permafrost in the peat mires is relatively thin (~15m; Åkerman & Johansson, 2008). In other parts of the Arctic within the present-day sporadic and discontinuous permafrost zones, shallow permafrost (15 to 25 m), is assumed to have been formed during the Little Ice Age (Romanovsky *et al.*, 1992). During the last 1000 years, the Torneträsk catchment has experienced two major climatic events, the Medieval Warm Period around AD1000 to AD 1100 that was then followed by a shift to a colder climate that could be regarded as the starting point of the Little Ice Age that peaked in the 17th Century and lasted until the first decade of the 20th Century (Grudd *et al.*, 2002). We hypothesise that lowland permafrost in the Torneträsk region originate from the cold period during the Little Ice Age and that it might be possible that also other lowland sites currently not underlain by permafrost were underlain by permafrost during this period.

The Abisko Scientific Research Station is located in the Torneträsk catchment and climate has been monitored since 1913. By using these climate records, it is possible to model lowland permafrost

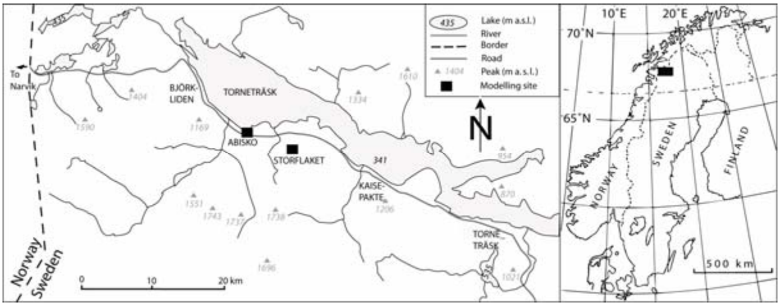

Figure 1 The two modelling sites in the Torneträsk catchment, northern Sweden

development in the Torneträsk catchment during the 20th Century and to investigate whether the permafrost degradation in the area started already during the early warm period. This aim of the study is addressed by modelling permafrost development for the 20th Century for two lowland sites (one currently with and one without permafrost). A second aim is to explore if the dynamics of permafrost in the 20th Century have, or have not been unique in the past 1000 yrs, i.e. before the instrumental period. To address this aim, we model likely ground temperature scenarios for the two sites for the last 1000 yrs, using different snow depth levels, assuming that snow depth is a major driver of permafrost dynamics (e.g. Desrochers and Granberg, 1988). These results will form a basis for improved predictions of how these sites will respond to projections of future climate change for the study area, that include an increase in mean annual air temperatures of up to 4.5ºC and total annual precipitation by 18% by 2080 (Sælthun & Barkved, 2003).

STUDY SITES

The model runs were based on two locations in the Torneträsk catchment, northern Sweden (Figure 1). The study area covers a strong climatic gradient, ranging from a maritime climate in the West to a more continental climate in the East. In general, seasonal temperature differences increase and regional precipitation decreases towards the East. The lowest precipitation is found around Abisko (~300 mm/yr; mean 1961-90) due to a rain shadow and the highest is found near the Norwegian border (~900 mm/yr; mean 1961-90) (Alexandersson *et al*., 1991). Both modelled sites lie within a rain shadow. The mean annual air temperature at Abisko between 1913 and 2006 was -0.6ºC (Johansson *et al*., 2008).

One of the sites "Storflaket" is a peat plateau (68º20'47''N 18º58'12''E, elevation 383 m a s l), and is currently underlain by permafrost. The dominant plant species at the mire are *Rubus chamaemorus*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Eriophorum vaginatum*, *Sphagnum spp.* and *Betula nana*. This site has a thick organic layer consisting of peat (~40 cm) underlain by a mixture of silt and organic material down to ~70 cm, underneath which is glacial silt (Klaminder *et al*., 2009). The underlying bedrock is quartzite and slate (Kulling, 1963). Permafrost exists in the mire due to the thick organic layer that protects the soil from warm air in the summer. In autumn, the peat is usually wet and this increases the thermal conductivity allowing cold autumn air to penetrate. During winter, very little snow accumulates on the mire due to its exposure to wind. This relative lack of snow also contributes to preserving the low soil temperatures. The other site "Abisko" is located in the birch forest (68º21'06''N, 18º48'57''E, elevation 365 m a s l) 6 km west of Storflaket, very close to the Abisko Scientific Research Station and is currently not underlain by permafrost. The dominant plant species at the site are *Betula pubescens*, *Vaccinium vitis-idaea* and *Empetrum nigrum*. This site has a shallow organic layer of approximately 5 cm underlain by moraine. The bedrock is banded sericite-quartzite and schist (Kulling, 1963).

METHODS

GIPL-2.0 Model

The GIPL-2.0 model was developed at the Geophysical Institute, Permafrost Lab (GIPL) University of Alaska Fairbanks and simulates soil temperature dynamics and the depth of seasonal freezing and thawing by solving 1-D non-linear heat equation with phase change numerically (Marchenko *et al.*, 2008). The basic mathematical model is the Enthalpy formulation of the one-dimensional Stefan problem (Alexiades & Solomon 1993, Verdi 1994). This special Enthalpy formulation of the energy conservation law was used previously for the two dimensional problem (Sergueev *et al.*, 2003) and makes it possible to use a coarse vertical resolution without loss of latent heat effects in phase transition zone even in case of fast temporally and spatially varying temperature fields. In GIPL-2.0 model the process of soil freezing/thawing is occurring in accordance with the unfrozen water content curve and soil thermal properties, which are specific for each soil layer and for each geographical location. Input data required for the model is climate data (air temperature and snow depth, used for the upper boundary conditions), preferably with daily resolution and a description of the soil (number of layers, their thicknesses, thermal properties and moisture contents).

Input climate data for the 20th Century

The Abisko site Daily air temperature data is available from the Abisko Scientific Research Station back to 1913 (Callaghan *et al.*, *in prep;* Johansson *et al.*, 2008). Daily snow depth measurements are also available from the Abisko Station extending back to 1956 (called “single stake” in Kohler *et al.*, 2006). For the period 1913-1955, modelled snow depth data was used (with a 0 cm mean difference to the long term monthly snow record from Abisko and a standard

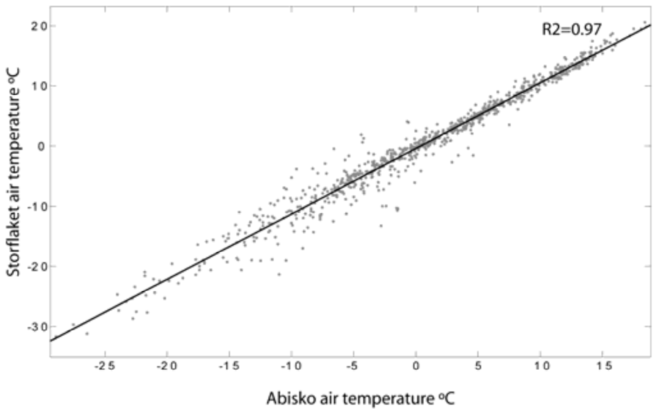

Figure 2 Relationship between Abisko and Storflaket air temperature.

deviation of 8.8 cm for the period 1913-2004)(Kohler *et al*., 2006).

The Storflaket site Daily air temperature data is available from 2005-2007. This daily data was compared to the Abisko record and a linear relationship between the two data series could be detected with a R^2 value of 0.97 (Figure 2). The temperatures were in general higher at Abisko (overall mean 0.5ºC) than at Storflaket (overall mean 0.16ºC). The Abisko data were entered into the linear polynomial fit *y=1.089x-0.398* to estimate air temperature at Storflaket back to 1913. At Storflaket, snow depth measurements are only available once per month for the two winters 2005-2006 and 2006-2007. The mean snow depth for these winters was 8 cm. The mean snow depth for the same time period at Abisko was 76% more (33 cm). The Abisko data (monitored (1956-2007) and modelled (1913-1955)) was modified by this constant to estimate the Storflaket data back to 1913.

Input climate data 1000 yrs back in time

A variety of records of climate reconstructions from pollen, chironomids, diatoms (e.g. Bigler *et al*., 2002) and tree-rings (Grudd *et al*., 2002; Grudd, 2008) exists from the Torneträsk area. The problem is that most reconstructions are limited to summer conditions, which is the main reason why we choose to use a different proxy data series for the Northern Hemisphere (Moberg *et al*., 2005a; 2005b) that also includes annual proxies.

The Abisko site The data from Moberg *et al.* (2005b) is presented as anomalies from 1961-1990 and hence to adjust the Moberg data to the Abisko data, the anomalies for Moberg and Abisko were compared for the period 1913-1979 (when the Moberg data ended). For this period the anomalies presented by Moberg were lower than those for Abisko (0.25ºC). The Moberg data was adjusted by this constant to estimate the Abisko temperatures back to AD 1000. As no reliable proxy data exists for snow depth, four different levels relative to the 1961-90 mean were used throughout the whole period 1)Ambient snow depth 2) -20% 3) -50% 4) +20%. These values do not represent formal GCM – derived scenarios but instead are used as a sensitivity analyses.

The Storflaket site The estimated Abisko data were used in the linear polynomial fit $y=1.089x-0.398$, that explained the relationship between Abisko and Storflaket data, to further estimate the Storflaket data back to AD1000. The proportional changes in snow depth used at the Abisko site were used for the Storflaket site relative to the 1961-90 mean at Storflaket.

Out of the four different snow depth levels used, the -50% is perhaps the most appropriate for the Little Ice Age, as there has been an increase in snow depth since then by 45% (Kohler *et al*., 2006). Pollen analyses from the Torneträsk area, however tentatively suggest that annual precipitation was higher throughout Holocene than today (Bigler *et al*., 2002) indicating that perhaps the +20% snow depth level reflects the longer term conditions better. Of course the precipitation has not been

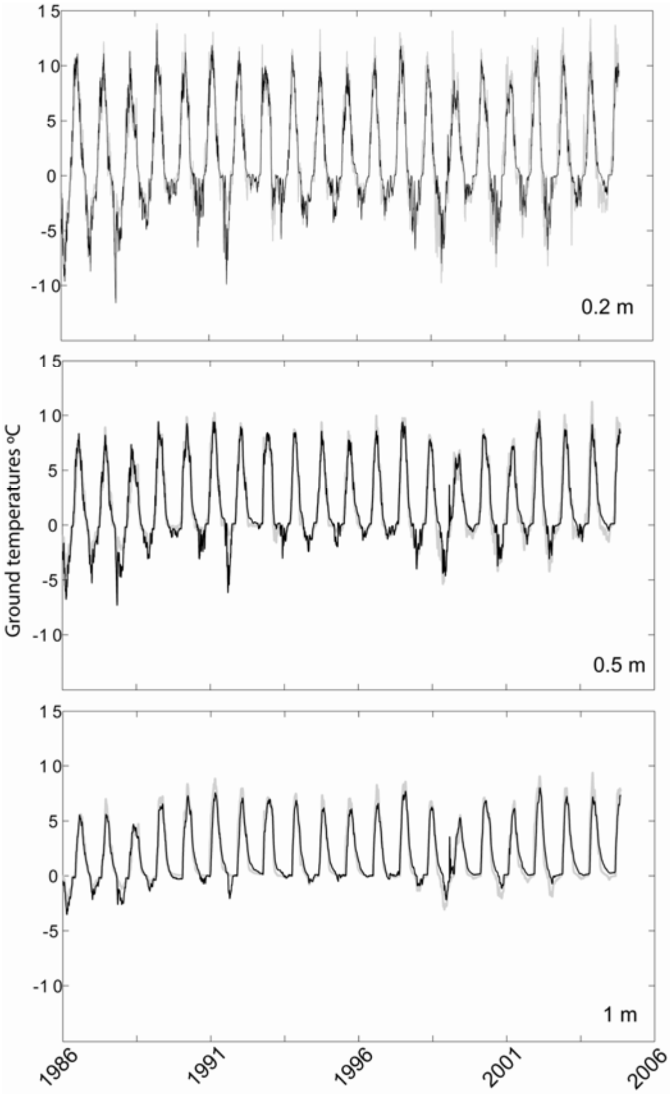

Figure 3 Modelled (black line) and measured (grey line) daily ground temperatures at different depths at the Abisko site 1986-2005.

constant throughout the last 1000 yrs, but since no correlation between air temperatures and snow depth could be found for the period of the instrumental record and no long term proxies apparently exists, we chose to use the constant levels.

Calibration of the model

With the temporal approach to the calibration of modelled permafrost temperatures against the observed data, the quality of the modelling series is assessed by time series regression against measured data. The quantitative relationship between simulated and measured data is then determined for a ‘‘calibration’’ period with some instrumental data withheld to assess the veracity of the relationship with independent data. In this method (Romanovsky *et al.*, 2002) that was developed at the Permafrost Lab of the Geophysical Institute, University of Alaska Fairbanks, variations in the air temperature and snow cover (thickness and properties) are the driving forces of the permafrost temperature dynamics. The model is calibrated for a specific site using measured permafrost and active layer temperatures (usually several years of available data are used) and data from the closest meteorological station for the same time interval. The calibrated model can then be applied to the entire period of meteorological records at this station, producing a time series of permafrost temperature changes. The same calibrated model can be applied for retrospective analysis. Using this modelling technique and available paleoclimatic reconstruction (Moberg *et al.*, 2005a; 2005b), we performed a retrospective analysis of the permafrost temperature variations at these two locations for the last 1,000 years.

Different earth’s materials have varying thermal properties. The soil thermal conductivity and heat capacity vary within the different soil layers as well as during the thawing/freezing cycles and depend on the unfrozen water content that is a certain function of temperature. The method of obtaining these properties is based on numerical solution for a coefficient inverse problem and on minimization locally the misfit between measured and modelled temperatures by changing thermal properties along the direction of the steepest descent. The method used and its limitations are described in more detail elsewhere (Nicolsky *et al.*, 2007).

At the Abisko site, daily ground temperatures are available from 1986 to present at 0.05, 0.2, 0.5, 1 m depth (Johansson *et al.*, 2008) and at Storflaket daily ground temperatures are available at 0.15 and 0.5 m depth from 2005 to 2007. In addition, data down to 12 m depth, are available with high spatial but sparse temporal resolution (one week in May and one week in September) (*Johansson et al.*, 2008) for Storflaket. The difference between modelled and observed ground temperatures for the period 1986-2005 at the Abisko site is 0.15ºC with a standard error of 0.49 (mean of the four depths mentioned above) (Figure 3). The difference between modelled and observed ground temperatures for the period 2005-2007 for the Storflaket site is 0.16ºC with a standard error of 0.89.

Visualising the ground temperatures

Contour maps of ground temperature profiles have been prepared by generating temperature fields using a kriging interpolation algorithm available in the commercial software package Surfer 8.0.

RESULTS

Permafrost development during the 20th Century

At the Storflaket site, modelled mean annual ground temperatures were below 0ºC at less than 1 meter depth throughout the 20th Century (Figure 4). The coldest ground temperatures were found between 1913 and 1920. The ground temperatures derived from the model then increased and even exceeded the threshold of 0ºC in the end of the 1930s. The ground then became colder until around 1990 when a second warming period started. The warmest modelled ground temperatures occurred at the end of the modelling period i.e. after 2005. In the lower

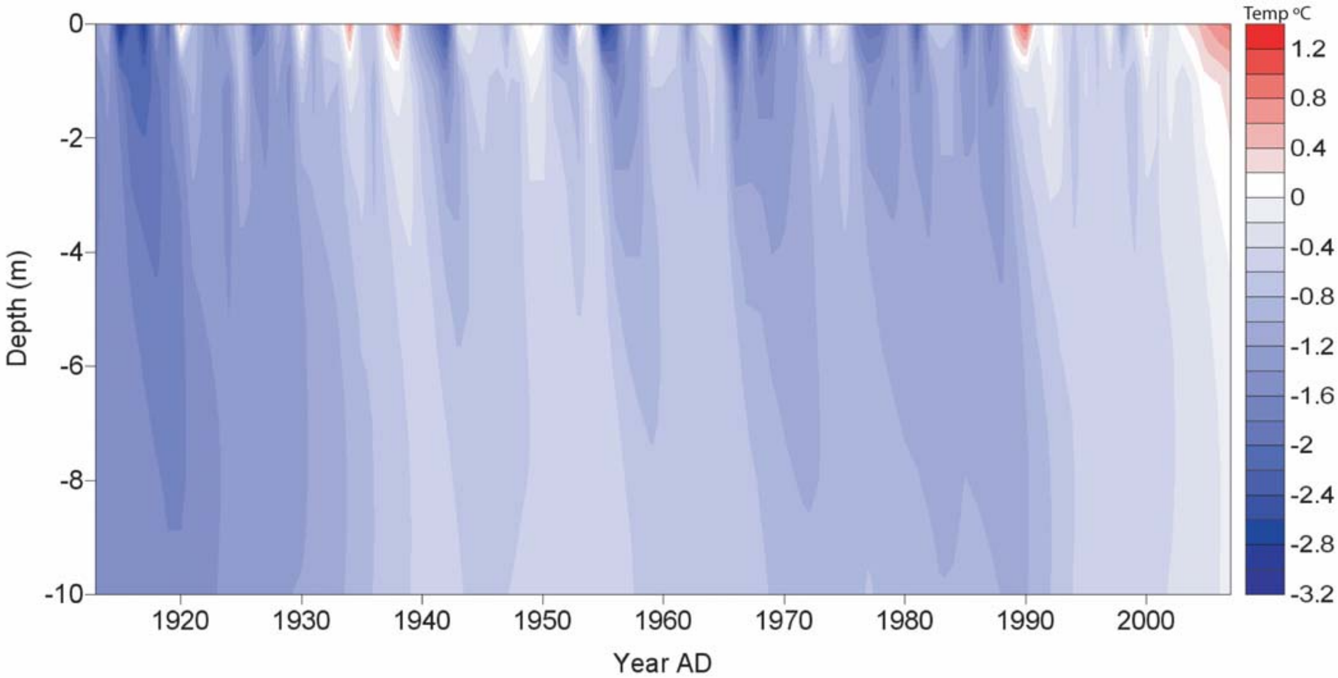

Figure 4 Modelled mean annual ground temperatures at the Storflaket mire from 1913-2007.

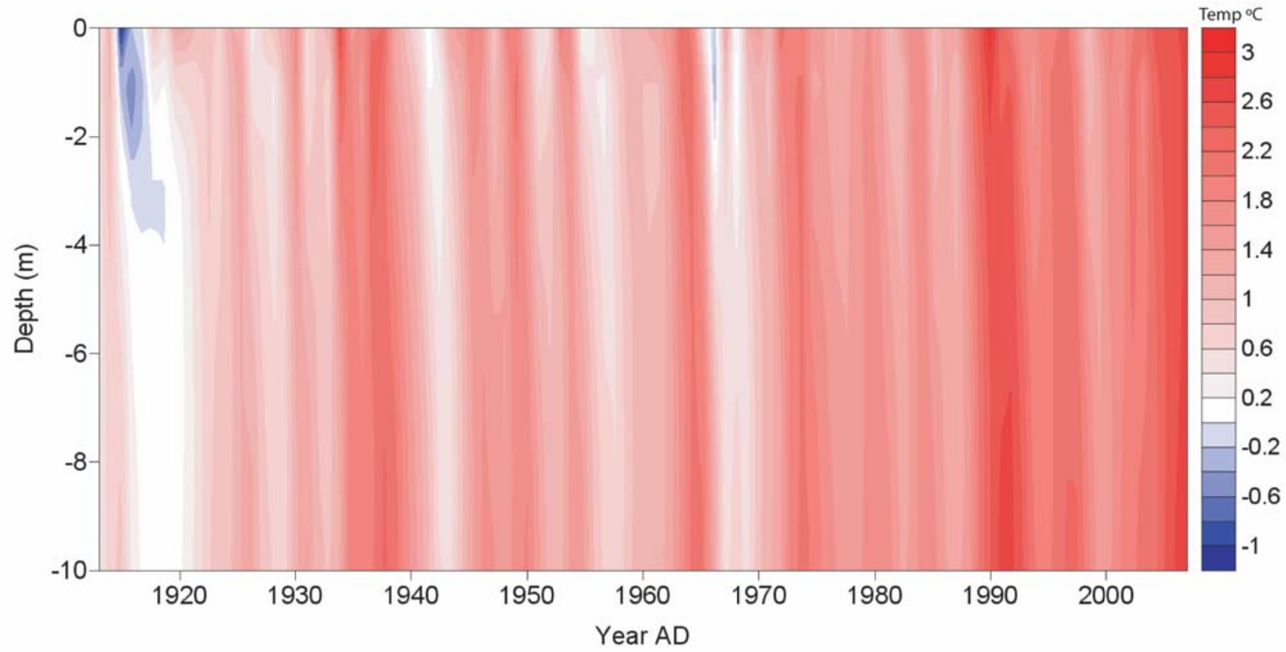

Figure 5 Modelled mean annual ground temperatures at the Abisko site from 1913-2007

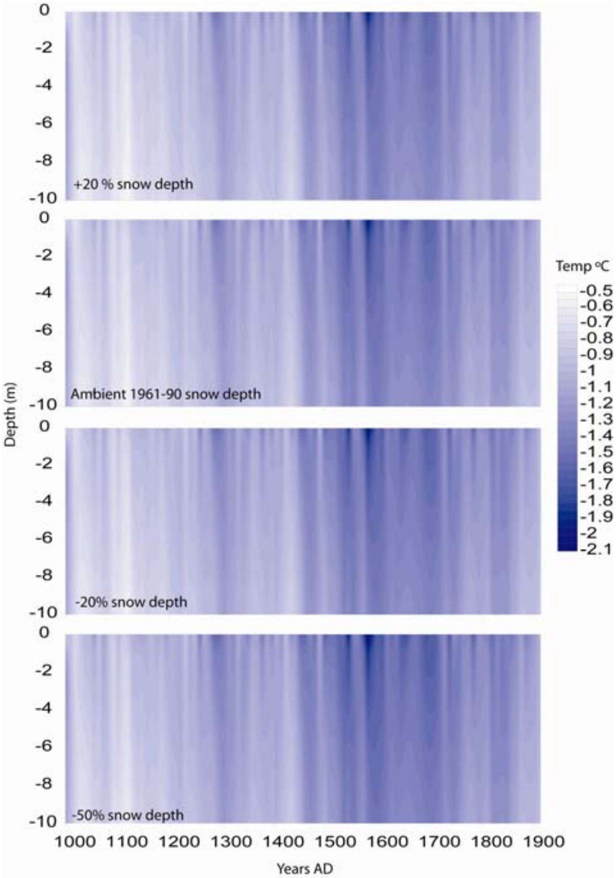

Figure 6 Modelled mean annual ground temperatures for the Storflaket site using different snow depth levels

soil layers, there is a small delay of about three years compared to the upper layers, in the onset of the two warm periods. Because ground temperatures have been below 0ºC for all except a few years in the 1930s, we assume that permafrost has been present at the site. However, permafrost thawing has occurred during the first and the second warm period at the Storflaket site according to the modelled output.

At the Abisko site, the modelled ground temperatures infer the absence of permafrost. The coldest modelled

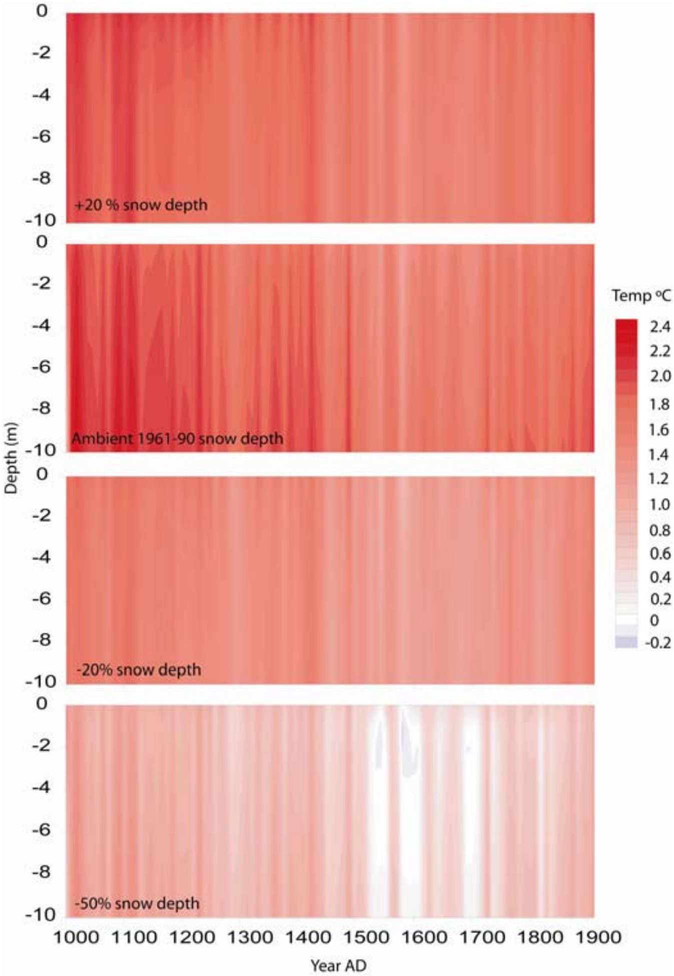

Figure 7 Modelled mean annual ground temperatures for the Abisko site using different snow depth levels.

temperatures were in the beginning of the modelled period when, for a few years, the mean annual modelled ground temperatures dropped below 0ºC in the upper layers (Figure 5). After this cool period in the beginning of the 20th Century, the temperatures increased and the mid 1930s-1940s were especially warm. This warm period was then followed by a cooling period where modelled mean annual ground temperatures dropped below 0 ºC again in the 1960s. The warmest periods were modelled in the beginning of the 1990s and the end of the modelled period i.e. after 2005.

Possible permafrost scenarios for the last 1000 years

Modelled mean annual ground temperatures at Storflaket stayed below 0ºC at all levels down to 10 m depth for the last 1000 yrs, for all four levels of different snow depths (Figure 6). Relatively warm ground temperatures were modelled until AD1200, when the ground temperatures started to drop. The coldest temperatures were modelled around AD1500-1700. There is very little difference in the ground temperatures for the four different snow depth levels.

At the Abisko site, the modelled mean annual ground temperatures, in contrast to those at the Storflaket site, stayed above 0ºC during the last 1000 years using the +20%, Ambient, -20% snow depth levels (Figure 7). Using the 50% reduction in snow depth levels, the annual temperatures were predicted to be below 0ºC for two short periods in the 16th Century. The warmest temperatures at this site were also modelled in the beginning of the period i.e. AD1000-1100. In all modelled outputs both at the Storflaket site and also at the Abisko site, a warm period in the beginning of the record could be detected as well as a cold period peaking in the 18th Century.

DISCUSSION

The modelled annual ground temperatures accurately reflect the known climatic periods during the last 1000 yrs in the Torneträsk area i.e. the Medieval Warm Period (AD1000-1100), the Little Ice Age (13th to the 20th Century) (Grudd *et al*., 2002) and also the two warm periods in the 20th Century (Callaghan *et al*., *in prep*.; Johansson *et al*., 2008).

For the last Century, the modelled annual ground temperatures at the Abisko site stayed above 0ºC with few exceptions. These reflect the colder periods when the modelled annual ground temperatures went below 0ºC in the upper part of the ground indicating a few years of potential permafrost conditions. In contrast, the modelled ground temperatures at Storflaket were below 0ºC during most of the 20th Century. According to the model, permafrost degradation occurred during the first and the second warming period at the Storflaket site as we hypothesised, but at a greater rate during the second warming period. This is most likely due to the combined effects of both increases in air temperature and in snow depth that was not as pronounced in the beginning of the Century. Similar snow depth was observed for the first and second warming period in the autumn but in the winter and spring months, higher snow depths were recorded for the second warming period (Kohler *et al*., 2006). At the Abisko site there are especially warm ground temperatures in the early 1990s. This reflects high winter precipitation during these years that in addition to cause an increase in ground temperatures also resulted in positive mass balance for the glaciers in the region (Holmlund & Jansson, 1999).

The contrast in ground temperature trends between the two sites is mainly due to two factors. Firstly the thickness of the organic layer is approximately 5 cm at the Abisko site compared to about 40 cm of peat at the Storflaket site. Yi *et al*. (2007) concluded that such a layer of peat can preserve permafrost against past or projected climate change. The second factor that contrasts between the two sites is the snow conditions. Although both sites are within a rain shadow, the Abisko site has a 75% greater snow depth compared to the Storflaket site, despite the short distance between them and similar precipitation patterns. This is due to different vegetation. At the Abisko site, located in a birch forest, the birches trap the snow. At the Storflaket site the vegetation on the mire does not trap snow; the snow is instead blown off.

The thawing of permafrost modelled in the second warming period in the 20th Century is validated by measurements from 1978-2006 for nine mires in the Torneträsk region (Åkerman and Johansson, 2008). It is associated with a change in vegetation from dry shrub dominated ombrotrophic conditions to wet graminoid dominated more nutrient rich conditions, surface subsidence and thermokarst formation (Christensen *et al*., 2004; Johansson *et al*., 2006b; Malmer *et al*., 2005). Photos from the 1970s in the area show that the peat plateaus were relatively undisturbed and since the permafrost is "ecosystem-protected" permafrost (Shur and Jorgensen, 2007) and the process of degradation is non-reversible under the present climate, it is likely that impacts like surface subsidence, changes in hydrology and vegetation seen today did not occur during the first warm period, or at least not in the magnitude as today. The modelled warm mean annual ground temperatures during the first warm period most likely contributed to an increased speed of permafrost degradation during the second warming period.

During the last 1000 yrs at the Storflaket site, the modelled ground temperatures have been below 0ºC indicating permafrost extending further back than the Little Ice Age that contradicts our hypothesise. Modelled ground temperatures by Kukkonen *et al*. (2001) showed that mountain permafrost was formed already 5000 yrs ago in northern Fennoscandia. According to Moberg *et al* (2005a), current air temperatures are the highest during the last 2000 yrs and as permafrost exists today, it can be possible that permafrost also existed in the beginning of the 11th Century as our model suggests. However, Kokfelt *et al*. (*submitted*) concluded from peat and lake sediment records that permafrost had occurred in the Stordalen mire (approximately 4 km East of the studied mire) during two periods, approximately 2800-2100 cal BP and after approximately 700 cal BP, but not during the 11th Century. Also, Zuidhoff & Kolstrup (2000) dated the start of palsa growth in Laivadalen, northern Sweden (66ºN) to the Little Ice Age. In other parts of the Arctic within the present-day sporadic and discontinuous permafrost zones, shallow permafrost (15 to 25 m), is assumed to have been formed during the Little Ice Age (Romanovsky *et al*., 1992). Recent findings from tree-rings in the Torneträsk region suggests that the summers (April- August) during the Medieval Warm Period in northern Fennoscandia were much warmer than previously recognized, exceeding the late twentieth Century warming period (Grudd, 2008). If this is true also for winter air temperatures, then it is likely that the permafrost did not exist during this period at the Storflaket site even though the modelled results indicate its presence. Consequently, the results for the 11th Century are quite uncertain. The modelling result from the Abisko site shows that it is unlikely that permafrost was widely spread in lowland terrain throughout the last 1000 yrs even though a few years could have provided the right conditions for permafrost formation.

Kukkonen *et al*. (2001) concluded that the occurrence of permafrost in northern Fennoscandia cannot be simply forecasted using mean annual air temperatures as the heat transfer across the air-ground interface is controlled by many interrelated factors such as precipitation, snow depth, vegetation, soil type etc. The model used in this study does take into account air temperatures, snow depth and different soil types. However, it does not take into account different vegetation types that affect the ground temperatures both through their snow trapping effect and also through their insulating capacities and different albedo (Chapin *et al*., 2005; Sturm *et al*., 2005). The model takes into account differences in thickness of the organic layer, but the modelling performance in this research does not simulates any mechanism for any accumulation of peat that would alter the thermal properties of the soils throughout the period of modelling. However, air temperatures play an important role on ground temperatures at the two sites modelled here as they are in a rain shadow. At the Storflaket site there is very little difference in the modelled ground temperatures for the four different snow depth levels. This is due to the shallow initial snow layer that exists due to wind exposure and even when decreasing the snow depth by 50%, the actual decrease of snow depth was only ~4 cm. At the nearby Abisko site the effect of altered snow conditions were greater because of greater observed snow depths. When reducing the snow depth by 50%, the modelled ground temperatures dropped below 0 ºC during the 16th Century resulting in a short period of time with possible permafrost in the upper soil layers (down to ~4 m). Consequently, occurrence of at least one period of permafrost can not be ruled out depending on snow depth but there are no proxies for past snow depths for the region.

The model results indicate periods of permafrost, at both sites: the site currently underlain by permafrost on a scale of many centuries and at the site currently without permafrost on a scale of a few years. While the permafrost definition adequately reflects different permafrost types in space (continuous, discontinuous, sporadic and isolated patches (Brown *et al*., 1998)), there is apparently no definition or concept of permafrost in time (other than that of below 0ºC for two or more consecutive years). A more varied temporal dimension should be conceptualised in the term “permafrost” and this “transient permafrost” concept could lead to a finer temporal resolution understanding of permafrost dynamics at the margins of permafrost distribution that now experience rapid change. This concept, together with the understanding of the roles of peat, vegetation and snow depth in modelling past ground temperatures provide a better basis for new studies that seek to project future rapid changes in permafrost distribution.

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Photo: M. Jackowicz-Korczynski

Rapid response of active layer thickness and vegetation in sub-arctic Sweden to experimentally increased snow cover

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Abstract

Increased snow depth observed and predicted for the future in the subarctic region is of critical importance to lowland permafrost and vegetation. Snow acts as an insulator that protects vegetation but may lead to permafrost degradation. An experimental manipulation was set up at a lowland permafrost site in northernmost Sweden, to simulate projected future increases in winter precipitation and to study its effects on permafrost and vegetation. After three years of treatment, statistically significant differences in mean winter and minimum ground temperatures could be detected between the control and the manipulated plots. A statistically significant difference between active layer thicknesses in the control plots (decrease from 67 to 58 cm) and the manipulated plots (remained around 66 cm) could also be detected. No statistically significant difference could be detected in the abundance of species between the different treatments, however at the manipulated sites, the vegetation stayed greener longer. In August 2008, the vegetation was between 140-145% greener in manipulated plots compare to the control plots. It is likely that the type of changes in permafrost and vegetation that has been demonstrated by this experiment will occur in the future as winter precipitation is projected to increase and because the increase in active layer thickness, changes in vegetation and ultimately permafrost thawing will be a non-reversible process under current climate.

Keywords: snow manipulation, active layer thickness, vegetation change, Abisko, sub-arctic Sweden

Introduction

Snow covers vast land areas for long periods of the year and plays an important role in the Arctic cryosphere. Snow has been identified as the single most important mesoscale variable that controls biological systems in Arctic ecosystems (Walker *et al*., 1993; Chernov, 1985). The largest single factor accounting for variations in ground surface temperatures during the winter months is the local and regional spatial variability in snow cover (Desrochers and Granberg., 1988) and snow is hence also a critical factor for permafrost formation (e.g. King, 1986; Seppälä, 1994). Snow acts as an insulator and prevents cold winter air temperatures from penetrating into the ground and it reduces ground temperature variability (e.g. Walker *at al*, 1999). Such insulation protects vegetation but may lead to permafrost degradation. In addition, when melted, snow can add water and alter the thermal conductivity of the soil that is of importance for permafrost (e.g. Romanovsky and Osterkamp, 2000) and provides water and nutrients for vegetation (e.g. Aerts *et al*., 2006). Snow depth and duration of cover also exerts a significant control on fluxes of CO_2 in natural communities (Fahnestock *et al*., 1998; Groendahl *et al*., 2008). In some parts of the Arctic, snow depth (expressed as water equivalent) is expected to decrease during the 21st Century, but in some areas, e.g. the high Arctic, it is projected to increase (Barry *et al*., 2007).

In the Abisko area, in northernmost Sweden, there has been an increasing trend in snow depth during the last Century by about 2-3 cm per decade in December, January and February (Kohler *et al*., 2006). Downscaled climate scenarios for the Abisko region predict a further increase in precipitation by 1.5-2% per decade for the coming 80 years (Saelthun & Barkved, 2003). This precipitation increase is expected to be twice as high in winter/autumn than in summer. It is therefore very likely that the increasing trend in snow depth seen during the last Century will continue also throughout the 21st Century. The projected increases in winter precipitation is mainly expected to occur due to increasing surface temperatures of the northern Atlantic Ocean that is likely to cause higher evaporation and subsequently more snow fall in northern Fennoscandia (Seppälä, 2003).

The observed change in snow cover has affected peat mires in the area as thawing of permafrost, increases in active layer thickness and associated vegetation changes have been reported during the last decade (Åkerman & Johansson, 2008; Christensen *et al.*, 2004, Malmer *et al.*, 2005; Ström & Christensen, 2007, Johansson T *et al.*, 2006). A shallow snow layer is critical for the preservation of permafrost in these peat mires located at the mean annual isotherm of 0ºC and it is therefore likely that the process of permafrost degradation (Åkerman and Johansson, 2008) will continue or even accelerate due to the increasing snow cover predicted for the future in the area. As a consequence, the vegetation including the plant species composition will change at those sites of continuing permafrost degradation.

To be able to predict such future changes, it is necessary to study both vegetation and permafrost, as the impact of climate change on permafrost is indirect and associated with vegetation dynamics. Permafrost is a component of a complex geo-ecological system with both positive and negative feedbacks related to changes in vegetation and soil properties (Shur & Jorgensen, 2007). Vegetation affects permafrost through for example insulation, its albedo and through trapping of snow, whereas permafrost affect vegetation by limiting the depth of soil where seasonal biologically activity is possible, reducing rooting zones as well as soil temperatures and preventing drainage. Snow manipulation experiments have been set up in the Arctic to look at the effects of increasing snow on vegetation (e.g. Walker *et al.*, 1999; Dorrepaal *et al.*, 2003) and on permafrost (e.g. Nicholson, 1978; Seppälä, 2003, Hinkel & Hurd, 2006), but snow-permafrost-vegetation interaction that are essential to understand the system have not to our knowledge, been carried out before. We present a snow manipulation experiment where we simulate the future scenario of increased winter precipitation predicted for the Abisko area looking at the effects on both vegetation and permafrost in a peat mire.

Materials and methods

Study site

The snow manipulation experiment was set up in autumn 2005 on a peat mire (68º20’48’’N, 18º58’16’’E), approximately 6 km East of the Abisko Scientific Research Station in northernmost Sweden (Figure 1). The Abisko area is situated in a rain shadow and the total annual precipitation was for the period 1961-1990 304 mm (Alexandersson *et al*., 1991). However the total annual precipitation has increased since then and for the period 1997-2007 it was 362 mm (Abisko Station meteorological data). The mean annual air temperature was –0.6ºC for the period 1913-2006 (Johansson *et al*., 2008). The Abisko area lies within the zone of discontinuous permafrost (Brown *et al*., 1998). Permafrost is widespread above approximately 880 m a s l (Jeckel, 1988) and at lower elevations it only exist in peat mires and underneath wind-exposed ridges (Johansson, M. *et al*., 2006). The permafrost at the study site is so called “Ecosystem protected permafrost”. This type of permafrost has formed under colder climates but can persist as sporadic patches under a warmer climate due to the ecosystem properties (peat and vegetation). “Ecosystem protected permafrost” is typically found in climates where current mean annual air temperature is approximately 2ºC to –2ºC (Shur & Jorgensen, 2007). The thickness of permafrost in the study mire is approximately 14 metres (Åkerman and Johansson, 2008). The peat plateau is

900 m long and 400 m wide and is divided into a western and eastern part by a depression with standing water. The vegetation on the drier parts of the plateau is dominated by dwarf shrubs (*Andromeda polifolia, Vaccinium uliginosum, Empetrum nigrum* and *Betula nana*), mosses (*Dicranum scoparium*, *Sphagnum fuscum* and *Sphagnum balticum*) and lichens (*Cetraria cucullata*, *Cetraria nivalis* and *Cladonia* spp.). In addition, *Rubus chamaemorus* is widespread throughout the plateau. In the wetter areas on the plateau and surrounding the mire, graminoids like *Eriophorum vaginatum* are dominant. The mire borders a sparse birch (*Betula pubescens* ssp. *czerepanovii*) forest to the East and West, in the South it borders a railway and in the North the main road (E10) through the area.

Experimental set up

The experimental manipulation was set up on the western part of the plateau where 12 plots were established and active layer thickness, species composition, soil (at 15 and 50 cm depth) and air temperatures (2 m height), soil moisture and snow depth were recorded (Figure 1). Six of the sites were randomly chosen and at those, snow fences (10 m long and 1 m tall) were erected before the snow onset (mid October) and removed at the end of the snow season after the snowmelt (beginning of June). The snow fences were erected perpendicular to the dominant wind direction (westerly and easterly winds, hence in N-S direction). The snow fences were removed during summer to avoid damage to and by reindeers that frequently visit the plateau. The other 6 sites without snow fences were set up to be control plots. On the eastern part of the plateau, monitoring of the active layer thickness using the Circumpolar Active Layer Monitoring (CALM) protocols has been ongoing since 1978 (named Storflaket in Åkerman & Johansson, 2008). The active layer data from this part of the mire is used to compare with the trend seen in the control plots

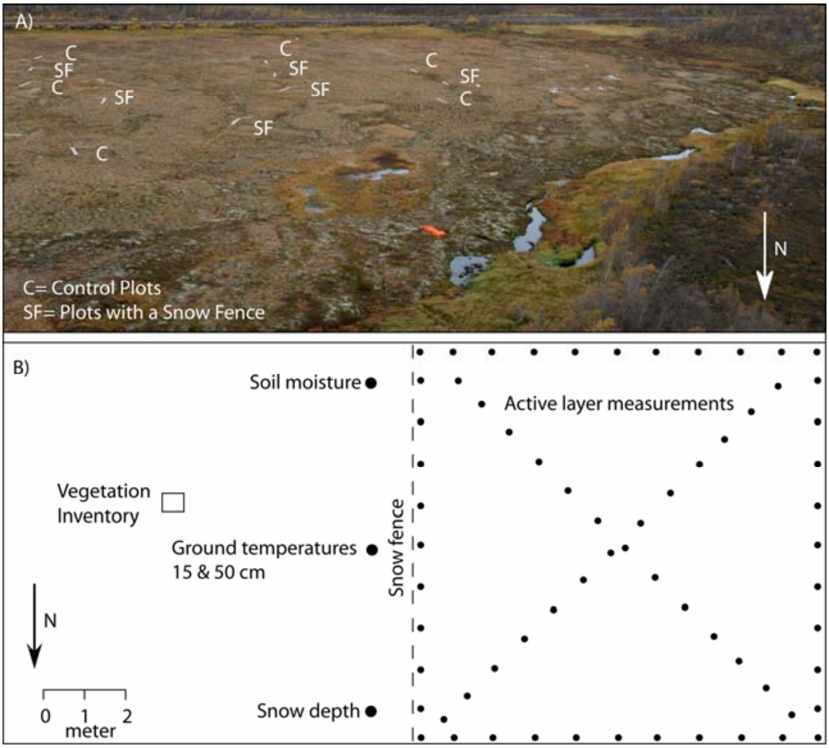

Figure 1 The experimental set up. A) the location of the 12 plots with and without snow fences on the mire B) the set up for each individual plot with and without a snow fence.

on the western part of the mire.

Parameters monitored

Snow depth was recorded manually once per month at all 12 plots and daily at one control and one plot with a snow fence using a remote digital camera, model RDC365 produced by Metsupport Aps, Denmark. At each site there was a 1 m stick where every 10 cm was marked to enable daily recording of snow depth at these sites. In addition the RDC recorded snow onset and snow melt. Manual snow recording was only carried out during the first two years of the experiment.

Soil temperatures were recorded at 15 cm depth at all

12 plots. At one control plot and one plot with snow fences they were also recorded at 50 cm. The temperature was recorded hourly, using TinyTag loggers (model: Tinytag Plus 12G). Air temperature was recorded using a TinyTag logger located in a small shelter, to avoid any disturbances due to direct sun radiation.

The active layer thickness measurements were conducted annually during the second week of September, to monitor the maximum thaw depth. At each of the plots, 66 sample points were recorded and the distance between two sampling points is one meter (see Figure 1). The thaw depth was determined by mechanical probing. A 1 cm diameter graduated steel rod was inserted into the soil to the depth of resistance to determine the active layer thickness.

Soil moisture was measured hourly at one control plot and one plot with a snow fence using Campbell CS615 water content reflectometer connected to a Campbell CR10X data logger.

Vegetation inventories were carried out at 50 points at each site using the point intercept method (Jonasson, 1988) in a 50 x 50 cm grid.

Statistical analyses and computing relative greenness

Data was analysed using the statistical software SPSS ver.16.0. Normal distribution of the data was tested using a nonparametric test (one sample Kolmogorov-Smirnov). To determine if there were any statistically significant differences between the control plots and the plots with snow fences in the monitored parameters the General Linear Model (Repeated Measures Test) was used.

To compute the relative greenness of the different plots in the end of the summer, photographs taken from a helicopter with an ordinary digital camera were used. As the camera used did not record the Near Infrared (NIR) wavelengths, we could not use NDVI ((NIR-

Table 1 Mean snow depth (cm) at the 6 plots with snow fences (SF) and the 6 control plots (C) for the seasons 2005-2006 (Year 1) and 2006-2007 (Year 2).

Yr	SF 1	SF 2	SF 3	SF 4	SF 5	SF 6	C 1	C 2	C 3	C 4	C 5	C 6	Mean SF (+/- std error)	Mean C (+/- std error)
1	15	19	21	31	22	18	9	9	6	7	8	13	21 (2.28)	9 (0.94)
2	17	14	14	19	19	15	8	8	6	6	7	10	16 (1.01)	7 (0.63)

RED)/(NIR+RED)) to describe the greenness of the vegetation. However, as greenness is strongly related to the amount of chlorophyll content in the vegetation present that can be depicted from the photos within the green wavelength, an index that is based on the visible part of the spectrum (Visible Atmospherically Resistant Index -VARI) ((GREEN-RED)/(GREEN+RED-BLUE)) utilized to compute relative greenness (RG) of vegetation was used (Schneider *et al.*, 2008; Gitelson *et al*., 2002). The colours in the photograph were separated in Adobe Photoshop Elements 2.0.

Results

The fences accumulated additional snow and the thickness was statistically significantly greater (*p=0.00*) at the fenced plots than the controls for both years of manual measurements (Table 1). The mean snow depth for 2005-2006 was 9 cm (std error 0.94) for the control plots and 21 cm (std error 2.28) for plots with snow fences. In 2006-2007, the mean snow depth was 7 cm (std error 0.63) for the control plots and 16 cm (std error 1.01) for plots with snow fences. There was also a difference in the date of snow melt between the plots with snow fences and the control plots. In 2007 snow had disappeared from the control plots by mid April but remained for another three weeks on the plots with snow fences before a heavy snowfall (10 May) covered the whole mire with snow again. Three days later, the snow had yet again

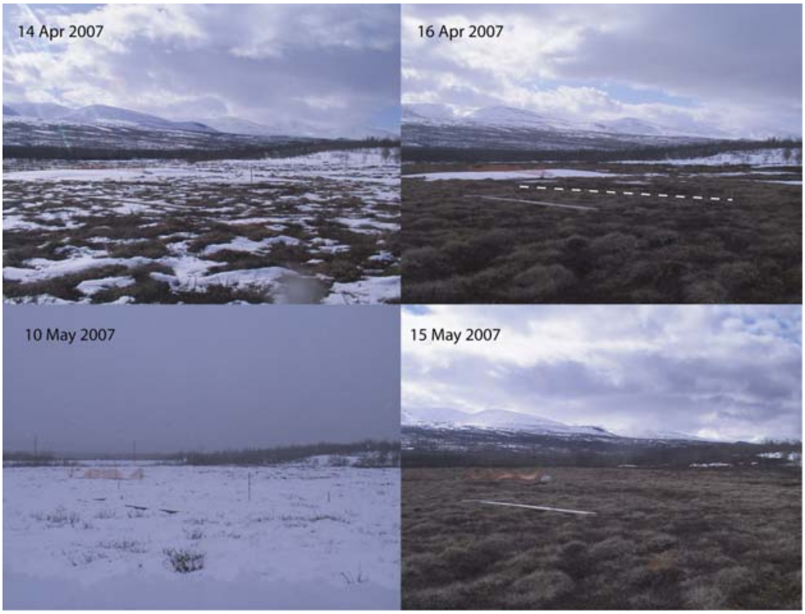

Figure 2 Snow duration at the plateau in 2007. The photos cover one plot with a snow fence and one control plot (dotted line in upper right picture denotes the middle part of the control plot).

disappeared from the control plots and after an additional two days later (15 May) the snow had also disappeared in the plots with snow fences (Figure 2). A similar development was found the following year, when the snow was gone from the control plots in mid April but stayed approximately 3 more weeks in the fenced plots.

Impacts on ground temperatures

The increase in snow depth at the plots with snow fences affected ground temperatures. The temperature varied among the plots with and without snow fences but also within plots with the same treatment. An example of two individual plots (one with snow fence and one without) is presented in Figure 3, where the control plot

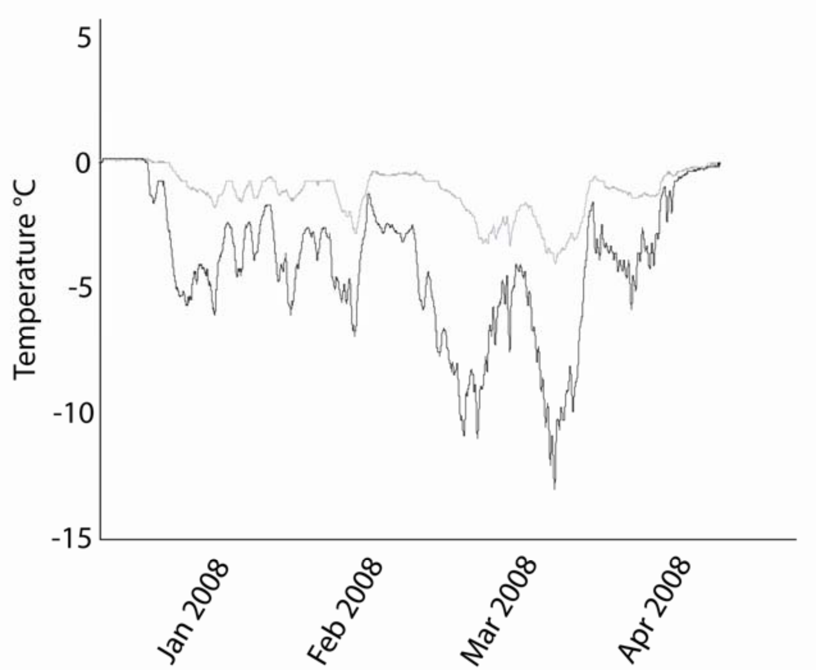

Figure 3 Ground temperatures at 15 cm depth at two individual plots, one control site (black line) and one plot with a snow fence (grey line) in spring 2008.

experienced a minimum temperature of -13°C in 2008, while a plot with a snow fence experienced a minimum temperature of only -4°C for the same year. When comparing all the plots with snow fences with the control plots, there was a statistically significant difference (*p=0.02*) between the ground temperatures at 15 cm depth during winter (October to May in 2nd and 3rd year of treatment, November to May for the first year of treatment as monitoring started in late October). The control plots were colder than the plots with snow fences and the mean winter temperature difference was between 0.5 and 1°C higher at the plots with snow fences (Figure 4). There is also a statistically significant difference (*p=0.00*) in minimum soil temperatures with a difference between treated

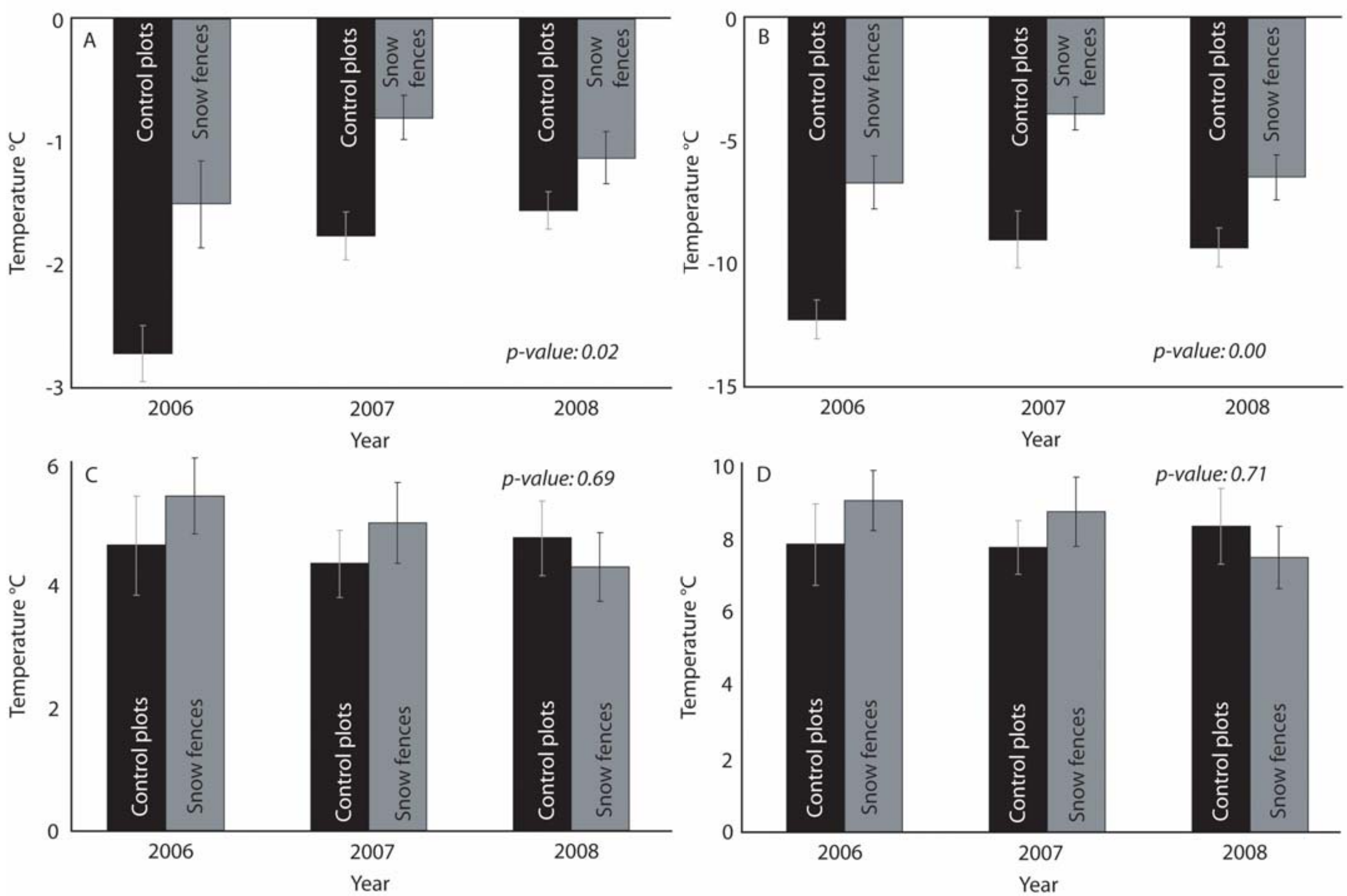

Figure 4 Mean ground temperatures and standard error at 15 cm depth A) Winter mean temperature B) Minimum mean temperature C) Summer mean temperature D) Maximum mean temperatures.

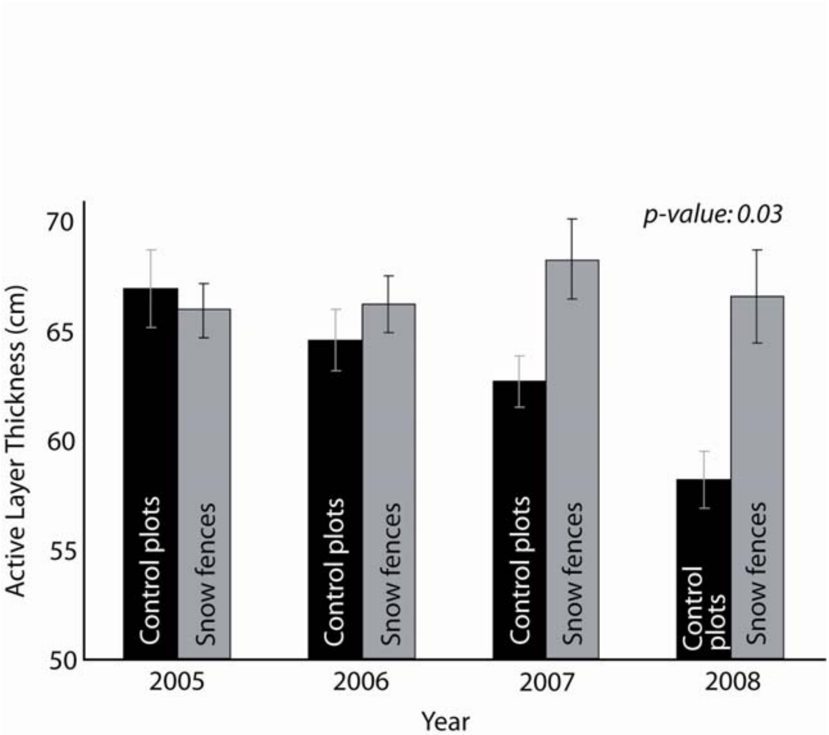

Figure 5 Mean Active Layer Thickness measured at the experimental and the control plots and the standard error. (Note that measurements from 2005 are made at the outset of the experiment).

and untreated plots ranging from 3 to more than 5°C in the winter. No statistically significant differences were found in the summer (June, July and August) soil temperature (*p=0.69*) and the maximum soil temperature (*p=0.71*) during the three years of treatment.

Impacts on active layer thickness

At the outset of the experiment (2005) there was no statistically significant difference in active layer thickness between the control plots and the plots with snow fences. For the second and third years of treatment, there was a statistically significant

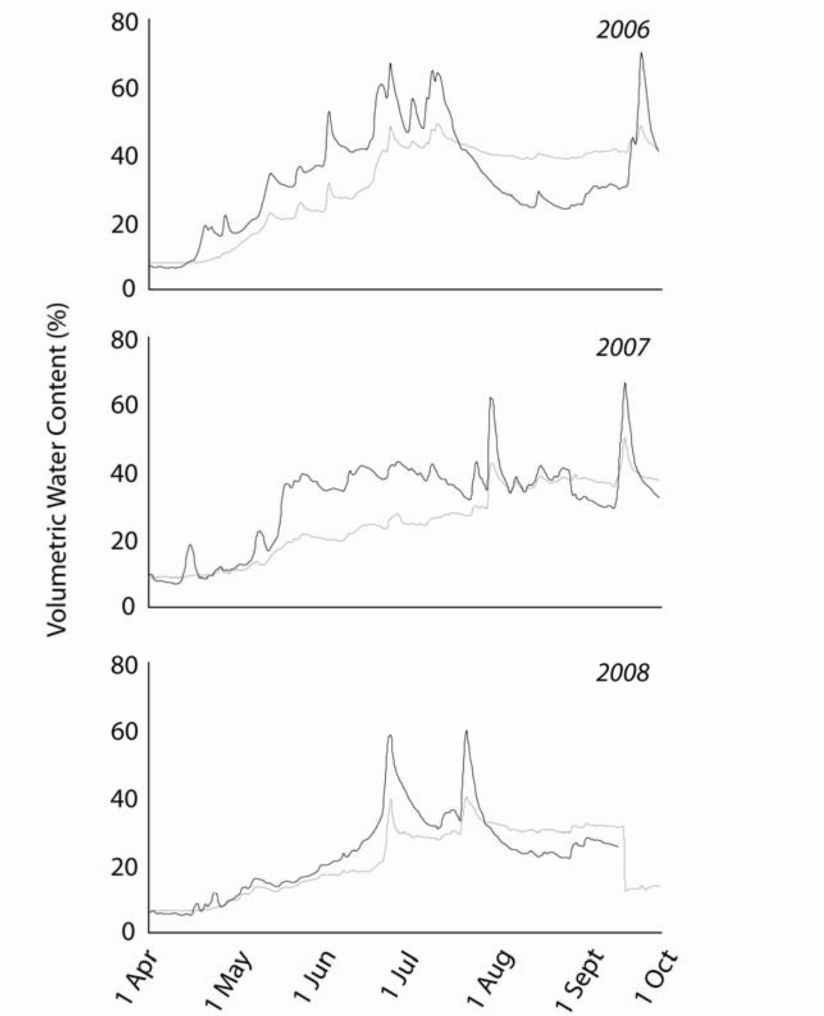

Figure 6 Volumetric Water Content (%) in one control plot (black line) and one plot with a snow fence (grey line) for April – September 2006, 2007, 2008.

difference between the active layer thicknesses in the control plots compared to the plots with snow fences (*p=0.03*). The active layer thickness decreased for all three years of measurements in the control plots (from 67 to 58 cm) but remained around 66 cm for all years apart from 2007 when it even increased to 68 cm in the plots with snow fences (Figure 5).

Impacts on soil moisture

A difference in soil moisture could be detected between the control plot and the plot with a snow fence. The actual values varied from year to year but it was in generally wetter at the control plot compared to the plot with a snow fence. Even though the actual values varied from year to year, the same seasonal pattern could be found during all three years. Soil moisture was higher in the control plot than at the plot with a snow fence from April (when snow melt starts) till the end of July/beginning of August when the opposite pattern could be found (Figure 6).

Impacts on vegetation

During the three years of treatment, no species invaded the experimental site and no species became "extinct". The abundance of species varied between the three broad functional types "dwarf shrubs", "graminoids", "mosses and lichens" and the litter component. However, no statistically significant changes could be detected between the plots with snow fences compared to the control plots for neither dwarf shrubs ($p=0.52$), graminoids ($p=0.64$), mosses and lichens ($p=0.64$) nor litter ($p=0.37$) (Figure 7). In the end of the summer (August and September), the vegetation was green in the plots with a snow fence compare to the rest of the mire that had turned into the brownish autumn colours. Using the VARI index, the plots with a snow fence showed an increase in greenness 140-145% compared to the control plots.

Discussion

The future scenarios for the area project an increase in precipitation of 18 % by the year 2080 and the precipitation increase in winter/autumn is expected to be twice as high as in summer (Saelthun & Barkved, 2003). The increase in snow depth that has been reported from the Abisko area during the last Century has not been accompanied by a long term trend in the start,

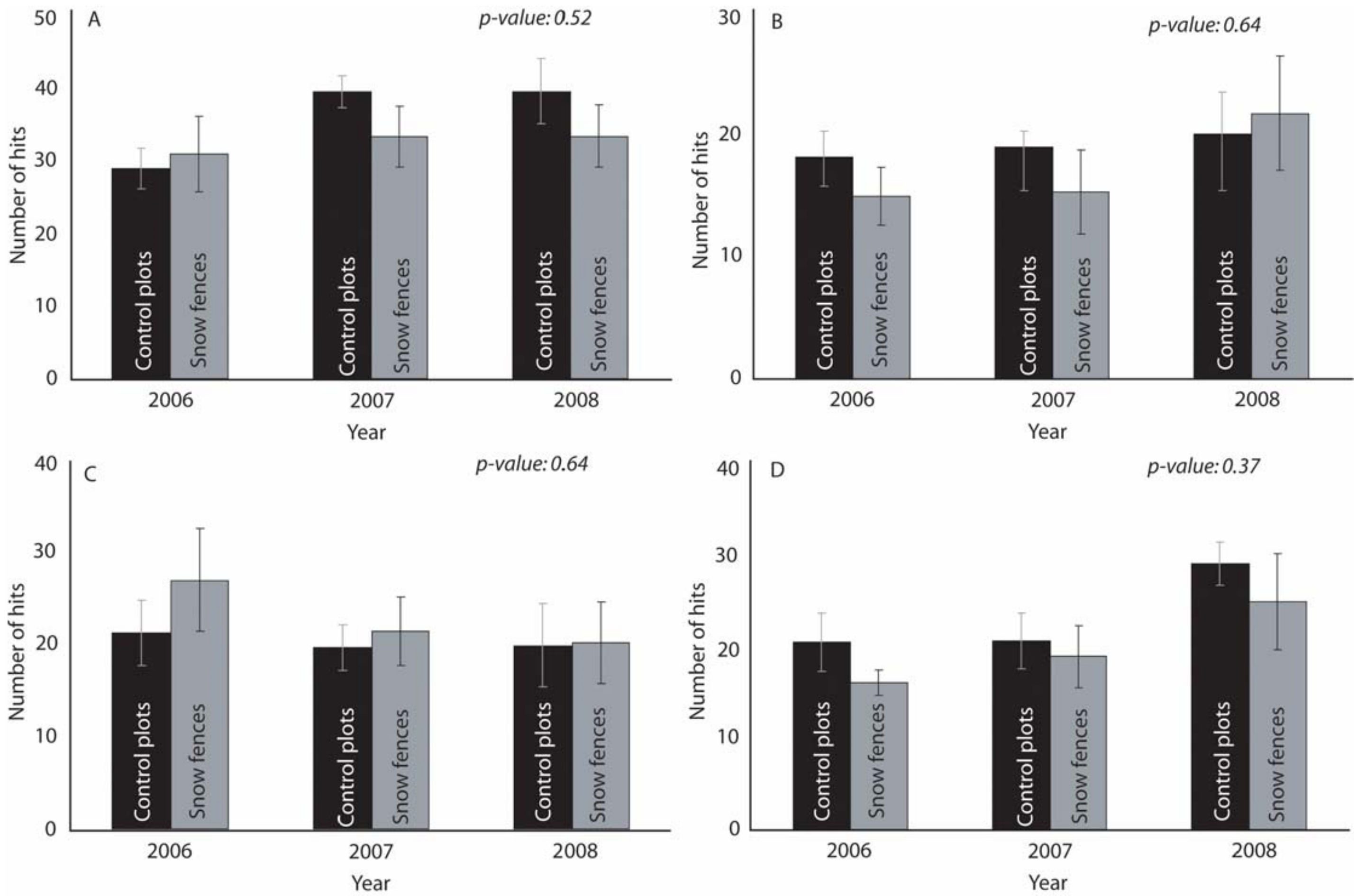

Figure 7 Vegetation inventories for control and snow fence plots and standard error. A) Dwarf shrubs B) Graminoids C) Mosses and lichens D) Litter.

end and length of snow season (Kohler *et al*., 2006).

Impacts on ground temperatures

The additional snow trapped by the snow fences resulted in increased ground temperatures during winter (October to May) with mean ground temperatures at 15 cm depth 0.5-1 ºC higher in plots with snow fences compared to the control plots. The greatest difference between a plot with a snow fence and one without was more than 9ºC. Similar increases in winter ground temperatures have been reported from earlier experiments. From the Abisko area, Dorrepaal *et al*. (2003) reported increases in soil temperature at 5 cm depth of up to 2.2 ºC when the snow depth was experimentally increased two to three-fold during October – April. From northern Finland, Seppälä (2003) reported temperature differences between 0.2ºC and 3.6ºC at 20 cm depth, between a palsa with snow fence and a control palsa, using a snow fence 1.5 m tall. From Barrow, Alaska, Hinkel & Hurd (2006) reported that ground temperatures at 50 cm depth increased between 6ºC and 14ºC compared to the control after eight years of treatment. In Toolik Lake, Alaska, ground temperatures were about 15ºC warmer on average than in the control plots (Walker *et al*., 1999). At both the sites in Alaska much taller snow fences (4 and 2.8 m tall) were used compared to this study (1 m), that resulted in much thicker deposits and hence higher temperature increases during winter compared to the temperature increases found in this study. The duration of the snow season also affect ground temperatures. In the plots with snow fences the snowmelt was delayed by approximately three weeks, and this should be favorable conditions for permafrost as the snow results in high albedo which reflects the sun’s energy instead of transport it down to the ground (Zhang *et al*., 2001). The extended snow season found in the experimental plots could in theory result in lower summer ground temperatures at the plots with snow fences. However, no statistically significant difference between the control plots and the plots with a snow fence could be detected for the summer ground temperatures. This is most likely due to the fact that snow disappeared so early in the season. This is in contrast to Seppälä (2003) who reported cooler mean summer soil temperatures in the experiment plot compare to the control plot due to a thick snow cover that persisted several weeks or months after the surrounding area was snow free.

Impacts on active layer thickness

During the most recent years, a decreasing trend of the active layer thickness has been observed at the CALM–grids in the Abisko area, which is probably due to relatively dry conditions in the mires enhancing the insulating capacity of peat. This follows three decades of increasing active layer thickness in the area (Åkerman and Johansson, 2008). The measurements from the control plots agree with the measurements from the CALM grid. In the experimental plots the active layer thickness has in contrast to the control plots remained more or less the same during the three years of treatment. Seppälä (2003) expected an increased rate of degradation of palsa and increased active layer thickness from his experimental treatment in northern Finland. However, the opposite scenario was found. A thick cover of snow persisted several weeks or months after the surrounding area was snow free resulting in reduced active layer thickness. The active layer thickness was greater in five out of the six years of measurements at the control plot compared to the experimental site. In Barrow, Alaska, no obvious correlation between the average thaw depth on the experimental plots and the control plots could be detected (Hinkel & Hurd, 2006). At the Storflaket study site a small surface subsidence could be detected in the plots with snow fences (personal observations), similar to what has been detected at other mires when there is a relative increase of active layer thickness (Åkerman & Johansson, 2008).

Impacts on soil moisture

The impacts on soil moisture are of importance to the active layer thickness as the soil moisture determines the conductivity of peat. If the peat is dry, it acts as an insulating cover preventing the summer heat from penetrating through the ground, whereas higher water content in the peat increases its conductivity and allows the heat to penetrate, thereby affecting ground temperature. The expected result of this study was that there would be an increase in soil moisture in the beginning of the summer due to additional water from melting snow. However, in the plot with a snow fence the soil moisture was lower in the beginning of the summer, but was higher in the end of the summer than the control plot. Seppälä (2003) also found a lack of increase of soil moisture in the beginning of the melt season and he concluded that most snow probably disappeared by sublimation in this continental area (Seppälä, 2003). It is likely that our lack of additional water to the plot with a snow fence in the beginning of the summer could also be a result of snow disappearing by sublimation. An alternative explanation may be the characteristics of the snow profile. If ice layers have been produced in the snow pack this would have prevented water from melting snow to penetrate the ground in situ (Riseth *et al*., *In prep*). Gardiner *et al.* (1998) reported from the Signy Island, that basal ice layer affected the drainage of meltwater and promoted rapid drainage to a stream (instead of penetration through the snow pack). Soil moisture is also of great importance to the vegetation.

Impacts on vegetation

No statistically significant changes could be detected in species composition during the three years of treatment in our study. This was expected as changes of species composition usually take longer and as Walker *et al*. (1999) concluded, it requires long term experiments to investigate changes in vegetation as tundra plant communities do not equilibrate quickly. After eight years of treatment with additional snow (3 m) in Alaska, Wahren *et al*. (2005) detected significant changes in the cover of shrubs, live vegetation, litter and canopy height that had all increased, while lichen cover and diversity had decreased. In a moist site, the graminoids, especially *Eriophorum vaginatum*, had increased (Wahren *et al*., 2005). The same graminoid species is common in the moist part of our study site, and it appears that *Eriophorum vaginatum* has become taller in the plots with snow fences.

An increase in greenness at our manipulation site was detected for the plots with a snow fence compared to the control plots. Similar results was also observed at the snow manipulation experiment in Barrow, Alaska (Hinkel & Hurd, 2006) whereas at Toolik Lake, Alaska no differences in greenness between plots with snow fences and the control plots was detected (Walker *et al*., 1999). The increase in greenness detected at our study site was probably due to the higher soil moisture content that could be detected in 2006 and 2008 in the end of the summer. The increased ground temperatures during winter could potentially have been favourable for microbial activity and hence made more nutrients available in the plots with a snow fence compared to the plots without (Aerts *et al*., 2006) and also contributed to the increased greenness. Another potential explanation of the increased greenness at the end of the summer could be a delay in the growing season. Using a threshold of 5 °C for the start of the growing season (Holmgren and Tjus, 1995), the growing season started for example in 26 May in 2007 and then the snow was already gone and hence the increased greenness in the end of the summer could not be related to a delayed growing season. A potential problem with the increased greenness in the end of the growing season is that the plants become more sensitive to frost (Robinson *et al*., 1998).

Expected effects on green-house gases

Snow is of great importance for fluxes of CO_2 in natural communities as snow depth strongly controls the ground temperatures and can insulate microbial populations from very cold temperatures, sustaining higher levels of activity throughout winter and hence increasing the winter CO_2 fluxes (Fahnestock *et al*., 1998). At Toolik Lake, the increases in snow depth increased the winter CO_2 fluxes on a scale similar to that found in natural snowdrifts (Walker *et al*., 1999). It is likely that this has also and will occur in our study area in the future due to the projected increased in winter precipitation. The date of snow-melt has been documented in several comparable boreal and arctic ecosystems to be a good predictor of the annual atmospheric carbon accumulation (Aurela *et al*., 2004; Groendahl *et al*. 2008). A possible change in dynamics associated with the snow melt date will therefore most likely also affect ecosystem atmosphere carbon exchange.

Future prospects of the permafrost and vegetation in the Abisko area

Shur & Jorgensen (2007) conclude that "Ecosystem protected permafrost" can persist as sporadic patches under warmer climates, but cannot be re-established after disturbance. It is therefore very likely that the changes in permafrost and vegetation that has been demonstrated by this experiment will continue in the future and will be a non-reversible process under current climate. It can be concluded, that permafrost degradation due to increasing snow depth may happen very quickly once the process has started.

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