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**Permafrost Warming in a Subarctic Peatland – Which Meteorological Controls are Most Important?**

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**ABSTRACT**

Since climate change can affect the carbon balance and hydrology in permafrost peatlands, a better understanding of their sensitivity to changes in temperature and precipitation is needed. In Tavvavuoma, northernmost Sweden, meteorological parameters and ground thermal properties have been monitored in a peat plateau, 2006–2013. During this time period the air temperature record shows no warming trend, and the late-season thaw depth has been relatively stable around 55–60 cm. Meanwhile, the mean annual ground temperature at 1 m depth has increased by 0.06°C/yr and at 2–5 m depth the permafrost is currently warmer than -0.3°C. Statistical analyses suggest that inter-annual changes in thaw depth and ground temperatures are affected by different meteorological factors. Summer air temperatures and annual thawing degree-days control thaw depth (p ≤0.05), whereas winter precipitation/snow depth affects ground temperatures (p ≤0.1). The permafrost in this peat plateau is most likely relict and not in equilibrium with current climatic conditions. Since the early 20th century there has been a regional increase in air temperature and snow depth. If the ongoing permafrost warming in Tavvavuoma is a result of these long-term trends, short-term variability in meteorological parameters can have an impact on the rate of permafrost degradation, but unless pronounced climate cooling would take place overall thawing of the peat plateau is inevitable.

**INTRODUCTION**

High northern latitudes are predicted to experience the most extensive temperature increases in the future due to global warming (ACIA, 2005; Collins *et al*., 2013). Also, an increase in annual precipitation is expected in the Arctic by the end of this century, particularly as snow during autumn and winter months (Collins *et al*., 2013). As a result of these climatic changes, a reduction in permafrost distribution and an increase in thaw depth are expected for most permafrost regions (ACIA, 2005; Collins *et al*., 2013). Warming of circum-Arctic permafrost during recent decades has been reported by e.g. Brown and Romanovsky (2008) and Romanovsky *et al*. (2010).

Permafrost peatlands cover extensive areas in northern boreal and subarctic regions, particularly in Russia (e.g. West Siberia Lowlands, ~ 540 000 km²) and Canada (e.g. Hudson Bay Lowlands, ~ 325 000 km²) (Martini, 2006). Within the northern circumpolar permafrost region peatlands are important reservoirs of soil organic carbon, containing c. 277–302 Pg C (Tarnocai *et al*., 2009; Hugelius *et al*., 2014). In these environments peat plateaus are characteristic landscape features. Peat plateaus consist of thick peat deposits that are uplifted above the surrounding water table by frost heave (Zoltai, 1988). As long as the peat remains
frozen these peatlands act as net carbon sinks. However, under warmer conditions increased thaw depth, thermokarst formation and changes in surface hydrology (Schuur et al., 2008; Kuhry et al., 2010; McGuire et al., 2010, Grosse et al., 2011). During recent decades, permafrost degradation and extensive landscape changes have been reported from palsas and peat plateau landscapes in North America (Laberge and Payette, 1995; Beilman and Robinson, 2003; Payette et al., 2004; Camill, 2005) and Scandinavia (Sollid and Sørbel, 1998; Zuidhoff and Kolstrup, 2000; Sannel and Kuhry, 2011). A common type of landscape change in these ecosystems is ground subsidence, as a result of melting ground-ice, forming collapse scar bogs/fens or thermokarst lakes. From lakes and fens high emissions of methane (CH\textsubscript{4}) are expected (Christensen et al., 2004; Walter et al., 2006; Myers-Smith et al., 2007; Karlsson et al., 2010). Peatlands located near the permafrost margin, in the sporadic and discontinuous permafrost zones, are particularly vulnerable to thermokarst formation since they are already near thawing (Tarnocai, 2006).

Permafrost can be affected by several environmental and geophysical parameters, including air temperature, snow cover, vegetation, topography, fire and soil characteristics (French, 2007). A number of studies have analyzed the impact of different environmental factors on the ground thermal regime in permafrost terrain. Some have focused on the active layer depth (e.g. Zhang and Stamnes, 1998; Hinkel and Nelson, 2003; Christiansen, 2004; Frauenfeld et al., 2004) and others on ground temperatures (e.g. Mackay and MacKay, 1974; Zhang et al., 1997; Stiegitz et al., 2003; Zhang, 2005; Chudinova et al., 2006; Hinkel and Hurd, 2006; Osterkamp, 2007; Leutschg et al., 2008; Morse et al., 2012). These studies have mainly focused on mineral soils with thin or absent surface organic layers or mountain terrain. However, peatlands have very different soil physical and thermal properties, and can therefore be expected to respond differently to changes in the climate. During the summer when air temperatures are relatively warm dry peat can act as a good insulator (with a thermal conductivity of 0.3–0.6 \text{ W/(m·K)}), reducing the heat loss from the frozen peat to the atmosphere (Zhang, 2005). In the autumn the peat becomes wetter due to rainfall and decreased evaporation and the thermal conductivity increases (e.g. Kujala et al., 2008). The thermal conductivity increases even further (to 1.1–1.6 \text{ W/(m·K)}) when the nearly saturated peat freezes (Zhang, 2005), potentially resulting in large heat losses from peatlands during cold winters if the snow cover is thin (Zhang, 2005; Seppälä 2011). Relatively few studies have explored the control and influence of meteorological parameters on the thermal regime in peatlands. In West Siberian tundra peatlands, Popova and Schmakin (2009) conclude that air temperatures examined at a seasonal time scale explain more of the active layer depth variability than mean annual air temperature (MAAT) and annual thawing degree-days (TDD – the cumulative sum of mean daily air temperatures for days when temperatures are above 0°C) or freezing degree-days (FDD – the cumulative sum of mean daily air temperatures for days when temperatures are below 0°C), and that summer air temperatures of the preceding 1–2 years have the greatest impact on active-layer depths. For palsas in northern Quebec, Jean and Payette (2014a) report that the active layer thickness is positively correlated with TDD. Similar results are recorded in northernmost Sweden, where Åkerman and Johansson (2008) found that increased active layer depth in permafrost peatlands during recent decades is best correlated with summer air temperature and TDD. The active layer depth is also affected by changes in winter precipitation. When the snow depth increases, so will the active layer depth (Åkerman and Johansson, 2008; Johansson et al., 2013). An increase in snow depth will also result in increased winter ground temperatures (Seppäälä, 1994; Johansson et al., 2013; Jean and Payette, 2014b), and increased mean annual ground temperatures at relatively shallow
depths, indicating that snow cover mainly is important for heat exchange in the upper parts of the soil (Popova and Schmakin, 2009).

The aim of this study is to increase our understanding of how climatic factors affect the ground temperature and thaw depth in permafrost peatlands. In this paper we present monitoring records and trends between 2006 and 2013 from a peat plateau in Tavvavuoma, located in the sporadic permafrost zone in northernmost Sweden. In addition, statistical analyses of correlations between permafrost temperatures, thaw depth and meteorological parameters are presented and discussed. An increased knowledge about present climate – ground temperature responses in peatlands on the margin of permafrost distribution is needed to better predict future dynamics in the more widespread permafrost peatlands located in regions that today experience colder conditions.

STUDY AREA

In Tavvavuoma, located in the sporadic permafrost zone in northern Sweden, the landscape is dominated by vast wetlands along the river Dávvaeatnu (~ 550 m a.s.l.) surrounded by low mountains with a gentle relief (up to 800 m a.s.l.). Since the mountains are lower than 850 m a.s.l., which has been identified as the lower limit for upland permafrost in the region (Ridefelt et al., 2008), permafrost is only present in peatlands. The study site (68°28'N, 20°54'E, 550–560 m a.s.l.) is located in a broad, flat valley in a ~ 2 km² large peat plateau complex consisting of both relatively flat peat plateau surfaces and more dome-shaped palsas (Figures 1 and 2). Other characteristic features in this landscape are numerous small thermokarst lakes which have formed as a result of ground collapse following thawing of the ice-rich soil. Fens are also common, and are found in drained thermokarst lake basins and along drainage channels.

Figure 1. Map showing the location of Tavvavuoma in northernmost Sweden. Inset map with circum-Arctic permafrost zonation, from continuous permafrost at high northern latitudes, via discontinuous to sporadic and isolated permafrost at lower latitudes (adapted from Brown et al., 1997).
The peat plateau complex is surrounded by low hills with mountain birch (*Betula pubescens* ssp. *czerepanovii*) in the north and west, and a larger lake in the east (Lake Dávvajávri). On the dry peat plateau surfaces the vegetation mainly consists of dwarf shrubs (*Empetrum nigrum* ssp. *hermaphroditum*, *Betula nana*, *Andromeda polifolia*, *Vaccinium uliginosum* ssp. *uli*, *V. microcarpum* and *V. vitis-idaea* ssp. *vitis-idaea*), *Rubus chamaemorus*, mosses and lichens. The fens are dominated by *Sphagna* and sedges (mainly *Eriophorum* spp. and *Carex* spp.). Fen vegetation is also common along thermokarst lake shorelines.

The peat is underlain by silty ice-lake sediments (Wramner, 1973). Peat formation at the study site began soon after deglaciation of the Weichselian Ice Sheet, ~ 10.100 cal yr BP (calibrated years before 1950), with fen conditions prevailing throughout most of the Holocene (Hempel, 2009; Kessler, 2013; Prėskienis, 2013). The transition to bog peat and permafrost aggradation was probably recent, occurring around 250–100 cal yr BP (Hempel, 2009), suggesting that the peat plateau is of young age. The peat depth varies from ~ 0.5 m to >2 m, and in the frozen peat the volumetric ice content is >75% (unpublished data). Today, the permafrost temperature in the peat plateau is just below 0°C (Christiansen *et al.*, 2010).

The closest meteorological station is located in Naimakka (68°41’N, 21°32’E, 402 m a.s.l.) ~ 35 km north-east of the study area (Figure 1). According to climate normals for this station
(1961–1990) the MAAT is -3.0°C, the mean summer temperature from June to September is 8.4°C and the mean winter temperature from November to March is -13.1°C. The mean annual precipitation is 391 mm, and the mean summer (June–September) precipitation is 229 mm (Swedish Meteorological and Hydrological Institute, http://opendata-catalog.smhi.se/explore/).

**Borehole sites**

The vegetation around borehole T2 (within a 20 cm radius circle) is mainly comprised of mosses (covering ~40%), low growing *Betula nana* (~30%) and *Empetrum nigrum* ssp. *hermaphroditum* (~10%). Lichens (~10%) are also found, along with small patches of bare peat (~10%). Also around borehole T10 mosses cover most of the ground (~60%), and the remaining vegetation consists of *Betula nana* (~10%), *Rubus chamaemorus* (~10%), *Empetrum nigrum* ssp. *hermaphroditum* (~3%), *Vaccinium uliginosum* ssp. *uliginosum* (~2%) and lichens (~10%). Bare peat covers ~5% (Figure 3).

The stratigraphy at borehole T2 is characterized by a 2.1 m thick peat layer, dominated by fen peat and topped by a thin layer of rootlet peat (Hempel, 2009). The peat is underlain by fine sand. At T10 the peat layer is 1.0 m thick and comprised of slightly decomposed, dark-brown peat. The organic layer is underlain by coarse-grained sand (1.0 – 2.4 m), fine-grained sand (2.4 – 5.5 m) and loam (5.5 – 6.5 m) (Rivkin, 2009).

![Figure 3. Borehole sites on the Tavvavuoma peat plateau. a) T2. b) T10 (see Figure 2b–c for locations).](image)
METHODS

Meteorological parameters

Meteorological parameters - air temperature, summer precipitation, relative humidity, wind speed and direction, and snow depth - have been monitored on the peat plateau in Tavvavuoma since September 2005. The instrumentation consists of a Rotronic HygroClip S3 for air temperature and relative humidity, a Young Tipping Bucket Rain Gauge (model 52202/52203) for precipitation and a Young Wind Monitor (model 05103-5) for wind speed and direction. These sensors are placed ~ 2 m above the ground surface. All parameters, except snow depth, are measured every 60 seconds, recorded hourly and the data are stored in a Campbell Scientific CR1000 datalogger. Snow depth is monitored by a stationary digital camera (time-lapse package from Harbortronics with a Pentax K200D) overlooking the peat plateau complex that registers one image per day at 12:30 CET. Snow depth stakes (38 mm diameter steel pipes with 10 cm wide red and white stripes, allowing a measurement accuracy of ±2.5 cm when analyzing the images) have been installed in different landscape units; on the central part of the peat plateau, adjacent to the thermokarst lake shoreline and in the thermokarst lake. Due to technical problems with two previous stationary digital cameras, of a different kind, robust and consistent snow depth data is only available from 2010. However, field observations are available throughout the monitoring period for the month of April (when the site was visited for data downloading). To facilitate analyses of correlations between thaw depth/ground temperature and snow depth since 2006 a snow depth index was constructed, based on field notes and photos and/or photos from the stationary camera in mid-April. The index represents the average snow depth at four snow depth stakes located in different landscape units; on the peat plateau (n=2), at the lake shoreline (n=1) and in the lake (n=1). Also, based on field notes and photos and/or photos from the stationary camera, snow depth in the central part of the peat plateau adjacent to thermistor string T2 (Figure 2b-c) in mid-April has been used as an alternative, very local snow depth indicator for the regression analyses.

To examine how robust the meteorological datasets retrieved in Tavvavuoma are, the air temperature and precipitation records have been compared with data recorded at the meteorological station in Naimakka, expected to have ~ 0.9°C warmer MAAT because of the altitudinal lapse rate. For summer and winter precipitation, where the data from Tavvauoma are partly unreliable or missing, meteorological data from Naimakka have also been used in the statistical analyses examining the correlation with thaw depth and ground temperatures.

Thaw depth

The thaw depth adjacent to each borehole was measured by probing a 1 m long graduated steel rod (10 mm diameter) into the ground, until it reached the permafrost table. The refusal encountered by the rod closely corresponds to the 0°C isotherm (Mackay, 1995). Because of a high heterogeneity in particularly vegetation but also microrelief on the peat plateau it was important to make the probings relatively close to the borehole, where vegetation and surface conditions are similar. At each borehole three probings were made within ~ 20–25 cm radius from the borehole centre, and a mean value was calculated. The thaw depth measurements have been made when the seasonal thaw depth can be expected to be close to its maximum; in the beginning of September 2006–2011, in late August 2012 and in mid-September 2013. According to other studies from the region the maximum thaw depth is reached during the third week of September (Åkerman and Johansson, 2008), or as late as mid-October when freezing has started from the surface (Seppälä, 1982). But, the deepening between mid-August and mid-October is likely small (only a few cm) (Seppälä, 1982). Since we cannot assure that
our measurements correspond to the maximum thaw depth (active layer), we have chosen to use the term late-season thaw depth throughout this paper.

**Ground temperatures**

Ground temperatures have been monitored in Tavvavuoma since September 2005, when the first thermistor strings were installed in the peat plateau. In 2006, 2007 and 2008 additional strings were installed, and today ground temperatures are monitored in a 6 m deep borehole on the peat plateau and in eight shallow (1-2 m deep) boreholes in different landscape units within the peat plateau complex. For this study, only data from two boreholes located in the central part of the peat plateau have been used; T2 installed in 2005 with thermistors at 100 and 200 cm depth (thermistors also at 2, 10, 25, 50 and 150 cm depth – not used in this study) and the deeper borehole T10 installed in 2008 with thermistors at 210, 309, 410, 509 and 608 cm depth (thermistors also at 10 and 112 cm – not used in this study). The thermistors are of Fenwal UNI curve type (192-502LET-A01) and have a curve tolerance of ±0.2°C. Before installation the thermistor strings were calibrated at 0°C in an ice-water bath, improving the accuracy of the thermistors to ±0.05°C (Pettersson et al., 2003). The 2 m deep borehole (T2) was made by hammering steel pipes (38 mm outer diameter) into the ground with a sledge hammer, ~ 5–10 cm at a time before they were pulled back up (Figure 3). The 6 m deep borehole (T10) was made using conventional drilling equipment, and had a diameter of ~ 50 mm (Figure 3). The thermistor strings were affixed to plastic rods with 30 mm diameter. When inserted into the ground the rod with attached cable nearly filled the hole and close to the surface peat and moss was packed around the rod to avoid air circulation. The strings were logged by a Campbell Scientific CR1000 datalogger using a Campbell Scientific Multiplexer AM16/32. Ground temperatures were stored every 3 hours (starting at 00:00 CET).

**Statistical analyses**

To determine how late-season thaw depth and mean annual ground temperatures (MAGT) at 1 m and 2 m depth are affected by meteorological factors, simple linear regression analyses were performed. The investigated parameters include MAAT, mean summer temperature, mean winter temperature, annual TDD and winter season FDD, summer precipitation and snow depth/winter precipitation. For all parameters the regression analyses were performed not only for the same year but also for the preceding year, since Popova and Schmakin (2009) found the best correlation with active layer depths in tundra peatlands with summer air temperatures of the preceding 1–2 years. The regressions were considered statistically significant if \( p \leq 0.05 \).

Principal component analysis (PCA) was used to evaluate inter-relationships between monitored permafrost response variables (MAGT and thaw depth) as well as their relation to meteorological parameters (all parameters from years 2006–2013). Meteorological parameters were included as environmental variables that do not directly affect the ordination. The PCA scaling is focused on inter-variable relationships. The gradient length of the permafrost response variable dataset was calculated in Detrended Correspondence Analysis (DCA) to 0.04 standard deviations, confirming that the data set shows linear responses suitable for analyses in PCA (Jongman et al., 1995). Data processing and statistical analyses were performed in MS Excel and Canoco 4.5 (Ter Braak and Smilauer, 2002).
RESULTS

Meteorological parameter, thaw depth and ground temperature records

Tavvavuoma and Naimakka show very similar air temperature trends (MAAT, mean summer temperature and mean winter temperature) from 2006 to 2013 ($R^2 > 0.94$) (Figure 4a–c). The small bias in the annual and summer temperature records, with 0.3–1.1°C warmer temperatures in Naimakka, is most likely caused by the altitude difference. The air temperature records are variable, with a MAAT in Tavvauoma between -0.9°C and -3.6°C, mean summer temperature of 7.5–10.2°C and mean winter temperature between -9.3°C and -14.2°C. There is significant inter-annual variability but no linear warming trend during this time period. The annual TDD and winter season FDD closely follow the mean summer and winter temperatures (Figure 4d).

For summer precipitation, the recorded data in Tavvavuoma and Naimakka are not consistent ($R^2 = 0.23$) (Figure 4e). In general, precipitation is characterized by higher regional scale spatial variability compared to air temperature (e.g. Popova and Schmakin, 2009), so some local variability in the data from Tavvavuoma can be expected. However, the very low summer precipitation in 2011 is potentially a result of measurement errors since the recorded value is much lower compared to all other years during the monitoring period, and is more than 200 mm lower compared to Naimakka. To avoid an impact of this potential error on the regression analyses, an alternative estimated value for the summer precipitation in Tavvavuoma based on the average deviation in precipitation between Tavvavuoma and Naimakka during the remaining seven monitoring years was used. Using this estimated value for 2011, the variability in summer precipitation in Tavvavuoma ranges from around 180–320 mm, with a relatively high inter-annual variability and a slight decreasing linear trend (2006–2013).

The snow depth index in mid-April shows a slight increasing linear trend from 2006 to 2013, but is very variable between years (20–80 cm) with a distinct peak in 2008 (Figure 4f). At T2 the snow depth has been very shallow in mid-April and has varied between 0–25 cm, with a small increasing linear trend throughout the monitoring period. To cover the complete seasonal pattern rather than just a snap-shot in mid-April, winter precipitation in Naimakka is presented in Figure 4g.

Between 2006–2013 the late-season thaw depth has been relatively stable around 55–60 cm (Figure 4h). The MAGT at 1 m and 2 m depth has varied from -1.0°C to -0.3°C (Figure 4i). Cooling of the permafrost temperature (upper 2 m) took place between 2008 and 2009, but has since then been followed by a warming trend. Over the entire monitoring period (2006–2013) the ground temperature at 1 m depth has increased by 0.06°C/yr. At 2 m depth the increase has been 0.05°C/yr (Figure 5a). Also in the 6 m deep borehole there has been a continuous warming trend since 2009 (Figure 5b). Here, the permafrost is currently very close to thawing, with a MAGT of -0.02°C at 2 m depth (2013). The depth of zero annual amplitude in the peat plateau is approximately 2–4 m.
Figure 4. Meteorological parameter, thaw depth and MAGT records in Tavvvouma from 2006 until 2013. a) MAAT. b) Mean summer temperature (June–September). c) Mean winter temperature (November–March). d) Annual TDD and winter season FDD. e) Summer precipitation (June–September). f) Snow depth in mid-April. g) Winter precipitation in Naimakka (November–March). h) Late-season thaw depth at T2. i) MAGT at T2 (2006–2013) and T10 (2009–2013). The lack of data points at 608 cm depth from 2011–2013 (T10) is due to thermistor failure.
Figure 5. MAGT in the Tavvavuoma peat plateau. a) At 1–2 m depth, 2006–2013 (T2). b) At 2–6 m depth, 2009–2013 (T10). The lack of data points at 608 cm depth from 2011–2013 is caused by thermistor failure.

Statistical analyses

Based on simple linear regression analyses, mean summer air temperature, annual TDD and MAAT provide the best correlations with late-season thaw depth ($R^2 = 0.39–0.58$) (Table 1). The MAGT in the central part of the peat plateau (T2, at 1 m depth) is best correlated with the winter precipitation in Naimakka and snow depth (both snow depth index and measured snow depth at T2) in Tavvavuoma in mid-April ($R^2 = 0.39–0.57$).

Table 1. Regressions between late-season thaw depth and MAGT at T2 and meteorological parameters based on simple linear regression analyses.

<table>
<thead>
<tr>
<th>Meteorological parameter</th>
<th>Thaw depth at T2</th>
<th>MAGT at T2 (1m)</th>
<th>MAGT at T2 (2m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>$p^*$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>MAAT</td>
<td>0.39</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>Summer temp (JJAS)</td>
<td></td>
<td></td>
<td>0.58</td>
</tr>
<tr>
<td>Winter temp (NDJFM)</td>
<td>-0.28</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Annual TDD</td>
<td>0.54</td>
<td>0.04</td>
<td>-0.09</td>
</tr>
<tr>
<td>Annual FDD (winter season)</td>
<td>-0.24</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>Summer precipitation (JJAS)**</td>
<td>0.06</td>
<td>0.54</td>
<td>-0.16</td>
</tr>
<tr>
<td>Summer precipitation in Naimakka (JJAS)</td>
<td>0.00</td>
<td>0.94</td>
<td>0.05</td>
</tr>
<tr>
<td>Snow depth index in mid-April</td>
<td>0.05</td>
<td>0.61</td>
<td>0.45</td>
</tr>
<tr>
<td>Snow depth at T2 in mid-April</td>
<td>0.09</td>
<td>0.47</td>
<td>0.39</td>
</tr>
<tr>
<td>Winter precipitation in Naimakka (NDJFM)</td>
<td>0.02</td>
<td>0.73</td>
<td>0.57</td>
</tr>
</tbody>
</table>

* statistically significant correlation if $p \leq 0.05$ (denoted in bold)
** using the estimated precipitation value for Tavvavuoma in 2011 (see methods section)
The first two principal components (PCs) of the PCA explain 98% of the total variability in the permafrost response variable dataset, confirming that there are two main gradients in the dataset. The ordination diagram (Figure 6), illustrates that MAGT is strongly associated with PC1 (65% of total variance) and uncorrelated to thaw depth which is strongly associated with PC2 (33% of total variance). The MAGT is strongly correlated with meteorological parameters reflecting winter precipitation. Thaw depth is strongly associated with high MAAT, summer air temperature and annual TDD. Summer precipitation at Naimakka and Tavvavuoma are only weakly associated with the response variables and negatively associated with each other. Winter air temperature and FDD are negatively correlated with thaw depth and weakly correlated to MAGT. The spread of monitoring years illustrate a large inter-annual variability with no apparent time-series trends.

**Figure 6.** Ordination diagram showing the first two principal components of a Principal Component Analysis of the permafrost response variables monitored 2006–2013 at T2 (ground temperature and thaw depth). The meteorological parameters for the same time period are included as environmental variables and do not directly affect the ordination. The direction and length of arrows reflect correlations between variables. Individual monitoring years are shown as point symbols. Summer records include data from June–September and winter records data from November–March. For information about the mid-April snow depth index – see methods section.

**DISCUSSION**

**Short-term impacts on thaw depth**

Our results show that there is a strong relationship between late-season thaw depth and air temperature parameters (mean summer temperature and TDD). This corresponds well with other studies of active layer depth in permafrost peatlands, which suggest that mean summer air temperature and TDD are important factors (Akerman and Johansson, 2008; Popova and Schmakin, 2009; Jean and Payette, 2014a). Unlike Popova and Schmakin (2009), we do not find any positive correlation between the mean summer air temperature the preceding year and the late-season thaw depth.
Furthermore, our results do not show any relationship between snow depth and thaw depth. Snow can have both direct and indirect effects on the ground thermal regime. Since the snow layer is largely filled with air, its thermal conductivity is very low (Zhang, 2005). Therefore a thick snow cover provides better insulation from cold air temperatures and thereby less energy loss from the soil during the winter (Goodrich, 1982). A thick snow cover also produces more meltwater in the spring, increasing the soil moisture and thereby the thermal conductivity of the soil, potentially resulting in warmer ground temperatures (Romanovsky and Osterkamp, 2000). Unexpectedly, our results indicate that these processes are of limited importance for the thaw depth in the Tavvavuoma peat plateau. This is contrary to findings from peat plateaus near Abisko, ~ 85 km west of Tavvavuoma (Figure 1), where Johansson et al. (2013) performed a snow depth manipulation experiment and concluded that there is a statistically significant relationship between snow depth and active layer depth at five out of nine study sites. This snow depth manipulation experiment increased snow depth from on average 8 cm in the control plots to on average 21 cm in the manipulated plots. The results also showed a lag in the system where it took two consecutive years of manipulation before thaw depth increased in the manipulated plots. A delay in the ground thermal response to snow depth manipulations is also reported for palsa in Finnish Lapland where no significant changes were recorded after five years (Seppälä, 2003), but in 2013 the artificially snow covered palsa had disappeared (Matti Seppälä, personal communication, 2015). Our results show that the recorded inter-annual variability of snow depth measured at T2 is of the same magnitude as that produced by the snow manipulation experiment performed by Johansson et al., (2013). However, the time series from Tavvavuoma is variable and the only occurrence of several consecutive years with deep snow is in 2012 and 2013 (thaw depth also increases in 2013).

We hypothesize that a longer time series with the occurrence of several consecutive years of deep snow cover on the Tavvavuoma plateau would affect thaw depth.

The impact of snow depth on thaw depth has also been demonstrated for sites located mainly in mineral soils (Frauenfeld et al., 2004). However, many other studies performed largely in mineral soils suggest that end-of-season thaw depth primarily is controlled by temperature and has the strongest correlation with TDD (e.g. Brown et al., 2000; Hinkel and Nelson, 2003; Christiansen et al., 2004), which correspond to our findings from Tavvavuoma.

Since wet peat has higher thermal conductivity compared to dry peat (Zhang, 2005; Kujala et al., 2008) a correlation between summer precipitation and thaw depth might have been expected, but this was not found in our data (Table 1). This result is consistent with the findings presented by Åkerman and Johansson (2008) from Abisko, with no statistically significant correlations between active layer thickness and summer precipitation.

**Short-term impacts on ground temperatures**

Our study shows that snow depth parameters (snow depth index in mid-April, snow depth at T2 and winter precipitation in Naimakküla from November to March) have a near significant positive correlation with ground temperatures at 1 m depth ($p \leq 0.1$). As expected the correlations for all winter precipitation/snow depth parameters are a little stronger for ground temperatures at 1 m depth compared to 2 m depth. However, the ground temperature at 2 m depth is still affected by the snow depth, indicated by a relatively strong, near significant linear correlation with the mid-April snow depth index ($p \leq 0.1$). These results correspond well with other studies from permafrost peatlands, which suggest that snow depth is a significantly important factor affecting the ground thermal regime (Seppälä, 2011; Johansson et al., 2013; Jean and Payette, 2014b), particularly at shallow depths (Popova and Schmakin, 2009). A strong positive correlation between snow depth and permafrost temperatures has also been
found in mineral soils (Zhang, 2005; Hinkel and Hurd, 2006; Morse et al., 2012), but here it seems that also air temperature parameters play an important role (Stieglitz et al., 2003; Chudinova et al., 2006).

In Tavvavouma no correlations were found between air temperature parameters and permafrost temperatures. A possible explanation for why the snow depth is far more important than the air temperature record for ground temperatures could be the characteristic landforms in permafrost peatlands. Peat plateaus and palsas are uplifted above the surrounding wetland surface, and the snowfall is normally quickly redistributed by wind into depressions in the landscape (fens and lakes). As a result, the snow cover on the open peat plateau surface remains very shallow throughout most of the winter season. Where the snow cover is thin, the ground thermal regime is most sensitive to variations and changes in snow depth (Mackay and MacKay, 1974; Zhang, 2005; Osterkamp, 2007).

Other parameters that could be important are the timing and duration of the annual snow cover. Chudinova et al. (2006) suggest that both snow depth and seasonal duration of the snow cover have an impact on ground temperatures in mainly mineral soils. According to Lafrenière et al. (2013) the timing of snow accumulation is more important than snow depth in determining winter soil temperatures in frost polygons. Also in sub-Arctic peatlands the timing of snow accumulation in the autumn is of great importance for winter soil temperatures (Johansson et al., 2013). Unfortunately, our dataset from Tavvavuoma does not include information about the onset of snow accumulation or the duration of the snow cover 2006/07–2009/10 due to technical problems with the two first stationary digital cameras, and these parameters have therefore not been evaluated.

**Long-term impacts on ground thermal conditions – and future projections**

If short-term variability in air temperature does not have a significant impact on ground temperatures in permafrost peatlands, what is then causing the warming of the permafrost? Snow depth is one parameter that seems to play an important role on shorter time scales, but inter-annual variability in snow depth cannot explain why the peat plateau is close to thawing. The permafrost in the Tavvavouma peat plateau most likely formed during the Little Ice Age (Hempel, 2009), when the climate in northernmost Sweden was colder than today with summer air temperatures and MAAT ~ 2°C lower than at present (Grudø et al., 2002; Klingbjer and Moberg, 2003). According to Halsey et al. (1995) permafrost in peatlands can be out of equilibrium with the regional climate for more than a century. Osterkamp and Romanovsky (1999) conclude that complete thawing of even relatively thin discontinuous permafrost can take hundreds to thousands of years. Therefore, it is likely that the permafrost degradation in Tavvavouma today also is a result of long-term regional climatic trends. In Abisko an increase in both MAAT and snow depth has been reported since the early 20th century (Kohler et al., 2006; Callaghan et al., 2010). For the MAAT the gradual increase has been particularly strong since the mid-20th century (Callaghan et al., 2010). The snow depth in December–February has increased continuously throughout the 20th century with 2–3 cm per decade (Kohler et al., 2006), up until the last 10-15 years when there has been a decreasing trend (Callaghan et al., 2010).

An increase in MAAT is predicted by General Circulation Models (GCM) for most of the Arctic. In northern Fennoscandia the temperature is projected to increase with up to 4°C until 2065 and up to 7°C until 2100 (Collins et al., 2013). Also, the winter precipitation (December–February) is projected to increase by 10–20% until 2065 (Collins et al., 2013). Similar scenarios are suggested by regional GCM’s for the annual precipitation, which is
expected to increase with 18% until 2080 with the highest rise predicted to take place during the winter and autumn seasons (Sælthun and Barkved, 2003).

If the projected increase in MAAT is accompanied by increased winter precipitation/snow depth continued permafrost degradation can be expected in the Tavvavuoma peat plateau. Even though general warming, deepening of the active layer and thawing may be a slow process (Osterkamp and Romanovsky, 1999), sudden and rapid landscape changes such as thermokarst formation and changing surface hydrological conditions can speed up the degradation, and result in increased greenhouse gas emissions from decomposition of previously frozen soil organic matter.

CONCLUSIONS

During the 8-year monitoring period, 2006–2013, there has been a relatively high inter-annual variability in the meteorological parameters (MAAT, summer temperature, winter temperature, TDD/FDD, summer precipitation and winter precipitation/snow depth), but no consistent warming trend. Despite this, the ground temperature at 1 m depth has increased by 0.06°C/yr and at greater depth (2–5 m) the MAGT is currently just below 0°C. The thaw depth has been relatively stable around 55–60 cm.

On short (annual) time scales simple linear regression and multivariate statistical analyses suggest that thaw depth and ground temperatures in subarctic permafrost peatlands largely are affected by different environmental factors.

- The late-season thaw depth is primarily affected by parameters related to air temperature (mean summer temperature and annual thawing degree-days) ($p \leq 0.05$).

- For the ground temperature at 1 m depth winter precipitation/snow depth parameters are most important (winter precipitation at the nearby meteorological station in Naimakka, snow-depth index and actual snow depth on the peat plateau in mid-April) ($p \leq 0.1$).

It is likely that the permafrost in this peat plateau is relict and not in equilibrium with current climatic conditions. Since the early 20th century an increase in both air temperature and snow depth has been reported from the region (Kohler et al., 2006; Callaghan et al., 2010). If the ongoing increase in ground temperature in Tavvavuoma is a result of these long-term trends, short-term variability in meteorological parameters can still have an impact on the rate of permafrost degradation, but unless pronounced climate cooling would take place, thawing of the peat plateau is inevitable.

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