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Past and Present Permafrost Temperatures in the Abisko Area: Redrilling of Boreholes

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Abstract Monitoring of permafrost has been ongoing since 1978 in the Abisko area, northernmost Sweden, when measurements of active layer thickness started. In 1980, boreholes were drilled in three mires in the area to record permafrost temperatures. Recordings were made twice per year, and the last data were obtained in 2002. During the International Polar Year (2007–2008), new boreholes were drilled within the 'Back to the Future' (BTF) and 'Thermal State of Permafrost' (TSP) projects that enabled year-round temperature monitoring. Mean annual ground temperatures (MAGT) in the mires are close to 0°C, ranging from −0.16 to −0.47°C at 5 m depth. Data from the boreholes show increasing ground temperatures in the upper and lower part by 0.4 to 1°C between 1980 and 2002. At one mire, permafrost thickness has decreased from 15 m in 1980 to ca. 9 m in 2009, with an accelerating thawing trend during the last decade.

Keywords Ground temperatures · Boreholes · Permafrost · Abisko · Sub-arctic Sweden

INTRODUCTION

Increasing ground temperatures are reported from around the Arctic (Romanovsky et al. 2007, 2010a, b; Brown and Romanovsky 2008; Christiansen et al. 2010; Smith et al. 2010), and permafrost (ground temperature at or below 0°C for two or more consecutive years) has started to thaw in the southern margins of the permafrost zone (e.g. Beilman and Robinson 2003; Payette et al. 2004; Akerman and Johansson 2008). Thawing permafrost affects populations both locally and globally because of its influence on landscape hydrology, geomorphology and biological processes as well as physical properties of soils. To monitor the status of permafrost, two parameters are generally measured; active layer thickness (the layer on top of permafrost that thaws and refreezes on an annual basis) and ground temperatures. In the Abisko area, northernmost Sweden, located at the southern margin of lowland permafrost, active layer thickness monitoring has been ongoing since 1978 in nine mires along a 100 km transect (Akerman and Johansson 2008). Monitoring of ground temperatures in lowland permafrost started down to 15 m in 1980 (Johansson et al. 2008) in three of the nine mires (Fig. 1). Owing to the instrumentation available when monitoring of ground temperatures started, the ground temperatures were only recorded during 1 week in May and 1 week in September. The last recordings from these boreholes were made in 2002. Data collected twice per year gave an indication on the state of permafrost but year-round measurements are needed to ensure that any trends seen are due to inter-annual variability rather than intra-annual variability.

During the International Polar Year, the Back to the Future (BTF IPY project no: 214) and the Thermal State of Permafrost (TSP IPY project no: 50) projects promoted the revisiting of old sites and the establishment of new recordings to investigate the development of e.g. ground temperatures over time. Under the auspices of these two IPY projects, five new boreholes were drilled in April 2008 at two of the three original ground temperature monitoring sites in the Abisko area. The third original site (Katterjokk 35 km West of Abisko) was not redrilled as permafrost has disappeared completely during the last decade (Akerman and Johansson 2008). The new boreholes and instrumentation used enable monitoring of ground temperatures to a depth of 13 m throughout the year. In this article, we present data on permafrost temperature trends from the old boreholes and snapshots from the new boreholes in the Abisko area.

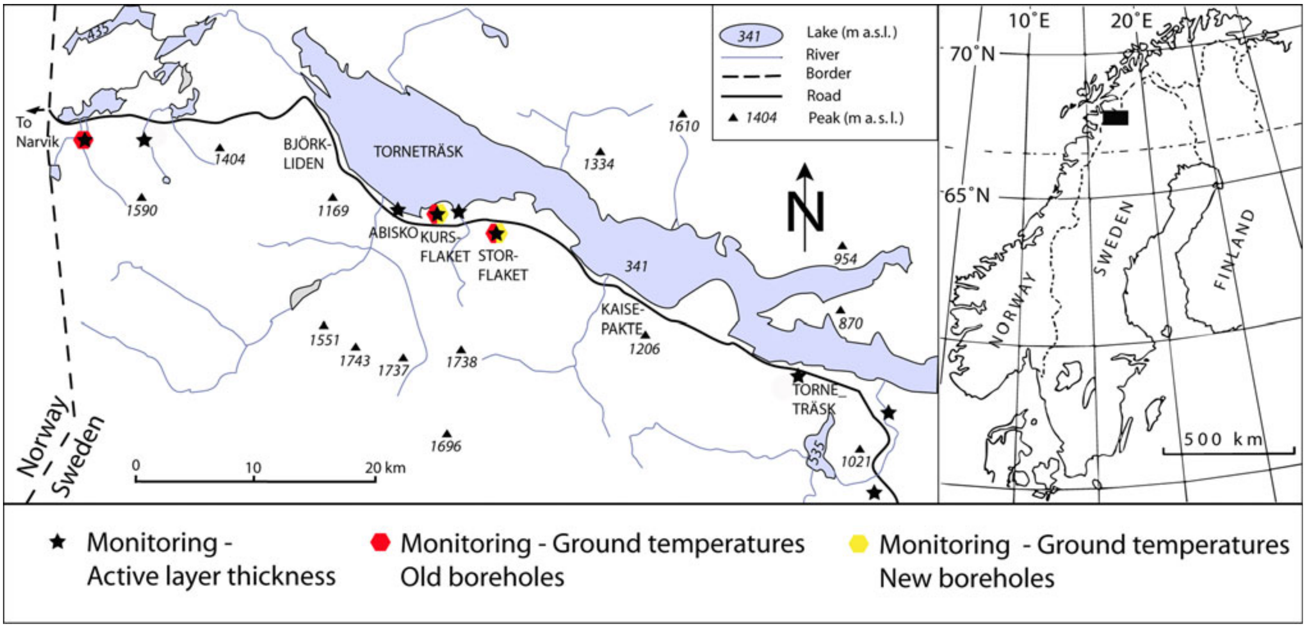

Fig. 1 Lowland permafrost monitoring sites in the Abisko area

General Characteristics of the Study Area

Abisko is located in sub-arctic Sweden and lies within the zone of discontinuous/sporadic permafrost (Brown et al. 1997). Mountain permafrost determined mainly by air temperatures is found approximately above 880 m above sea level (Jeckel 1988), whereas at lower elevations permafrost is only likely to exist in peat mires (due to the peat's insulating effect) (Johansson et al. 2006a). Abisko is located in a rain shadow, with a total annual precipitation of 303 mm per year (1913–2006). However, precipitation has increased during the last decade, especially during the summer (Callaghan et al. 2010). The mean annual air temperature is −0.6°C (1913–2006) and has increased by 2.5°C during the period of measurements. This has resulted in mean annual air temperatures above 0°C during the last decade (Callaghan et al. 2010). Snow depth in winter has increased by 0.02 m per decade during the last century (Kohler et al. 2006). However, in the past decade, snow depth has decreased markedly and hence diverges from the century-long increasing trend (Callaghan et al. 2010). No statistically significant trend was detected in the start and end date of the snow season (Kohler et al. 2006) which is also important parameters for ground temperatures.

Site Description

Two of the three original sites used for ground temperature monitoring were redrilled in April 2008 (Storflaket and Kursflaket; Figs. 1, 2). These sites are peat plateaus (a flat-topped expanse of peat, elevated above the surrounding area that contains segregated ice that extend downward into the underlying mineral soil, hereafter referred to as mires) situated 3 and 6 km East of Abisko (Fig. 1).

In 2008, when the new boreholes were drilled, the mean annual air temperatures at Storflaket and Kursflaket were 0.8 and 1.0°C, respectively (measurements at the latter site are from the Abisko Scientific Research Station; see Abisko in Fig. 1).The thickness of permafrost at Storflaket and Kursflaket was approximately 15 m when drilled through in 1980 (Akerman and Johansson 2008) but more recent results from geophysical surveys at Storflaket indicate that permafrost may be even thicker (Dobinski 2010) in other areas of the mire than was drilled through in 1980. Active layer monitoring has been ongoing on the two mires since 1978 and more recently according to the CALM protocol (Shiklomanov et al. 2008). Active layer thickness has increased during the last three decades at a rate of 0.007 m/year at Storflaket and 0.01 m/year at Kursflaket (Akerman and Johansson 2008). In 2008, when the new boreholes were installed, the average active layer thickness at Storflaket was 0.66 m and at Kursflaket 0.69 m. The thickness of peat is similar at the two mires, ranging from 0.6 to 0.9 m and is underlain by silt (Akerman and Johansson 2008; Klaminder et al. 2008). The ice content throughout the permafrost body at both Storflaket and Kursflaket is around 7–8% (mean value for the period 1980–2000). In the uppermost part of the permafrost, the ice content is approximately 35% at Storflaket and 30% at Kursflaket. High ice content (>20%) exists at the very bottom of the

Fig. 2 The old and new boreholes at the Kursflaket mire 3 km east of Abisko (Photo: J. Åkerman)

frozen silt. At Kursflaket, the highest ice content exists between 2.75 and 4.25 m depth and even exceeds 50% (Akerman and Johansson 2008).

MATERIALS AND METHODS

Ground Temperature Monitoring in the Old Boreholes

The old boreholes were drilled in 1980 using a handheld cobra drill. Copper-Constantan thermocouples were installed in the boreholes at depths described in Table 1, and the borehole was then filled with the original material. Between 1980 and 2002, ground temperatures were recorded hourly during the third week of May and September using Campbell loggers (Table 1). No electricity was available at the two sites, and so, it was only when people visited the sites (twice per year) and brought car batteries that monitoring was possible.

Ground Temperature Monitoring in the New Boreholes

The new boreholes were made using the drill shown in Fig. 2. The boreholes were cased with plastic tubes and instrumented with Hobo loggers U12 (Industry, 4 channels) together with Hobo soil temperature sensors in accordance with the recommendations from the TSP project. Ground temperatures have been recorded two times per day since the 25 April 2008 (Table 1). However, problems with moisture in the loggers have resulted in a gap of data for three loggers between 2 June 2009 and 18 December 2009.

Data Analysis—Determining Trends

Trends were calculated in ground temperatures for September and May data from 1980 to 2002 at 1, 3, 5, 8 and 12 m depth at Storflaket and at 1, 3, 5, 8 and 15 m depth at Kursflaket using a robust linear regression, implemented in the software package MATLAB 7.1. Trends were assumed to be significant for p levels ≤ 0.05. No trend was calculated for the new data as only little more than 1 year of data was available so far.

RESULTS

Ground Temperatures

Data from the old boreholes showed a statistically significant trend for the period 1980–2002 towards recent warmer September ground temperatures at Storflaket at 1 and 3 m depth as well as in the lower part of the borehole at 12 m of

Table 1 The location, depth of measurements and observation period for the old and the new boreholes at Storflaket and Kursflaket

Site name	Latitude (WGS84)	Longitude (WGS84)	Elevation (m)	Monitored at depth (m)[a]	Observation period	Frequency of monitoring
Storflaket mire (old)	68°20′51″N	18°57′55″E	387	0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 12	1980–1982, 1984–1989, 1994–1997, 2000–2002	Hourly 1 week in May and 1 week in September
Storflaket 1 mire (new)	68°20′53″N	18°58′38″E	386	1, 3, 5, 7	2008–	Twice per day (8 AM and 8 PM)
Storflaket 2 mire (new)	68°20′50″N	18°58′26″E	385	1, 3, 5, 6.20	2008–	Twice per day (8 AM and 8 PM)
Storflaket 3 mire (new)	68°20′48″N	18°58′29″E	385	1, 3, 5, 8	2008–	Twice per day (8 AM and 8 PM)
Kursflaket mire (old)	68°21′03″N	18°52′24″E	355	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	Hourly 1 week in May and 1 week in September
Kursflaket 1 mire (new)	68°21′03″N	18°52′24″E	355	1, 3, 5, 8	2008–	Twice per day (8 AM and 8 PM)
Kursflaket 2 mire (new)	68°21′03″N	18°52′24″E	355	3, 5, 10, 13	2008–	Twice per day (8 AM and 8 PM)

[a] Note that all the monitoring depths were used during all observation periods for each borehole. The largest monitoring depth denotes the depth of the boreholes

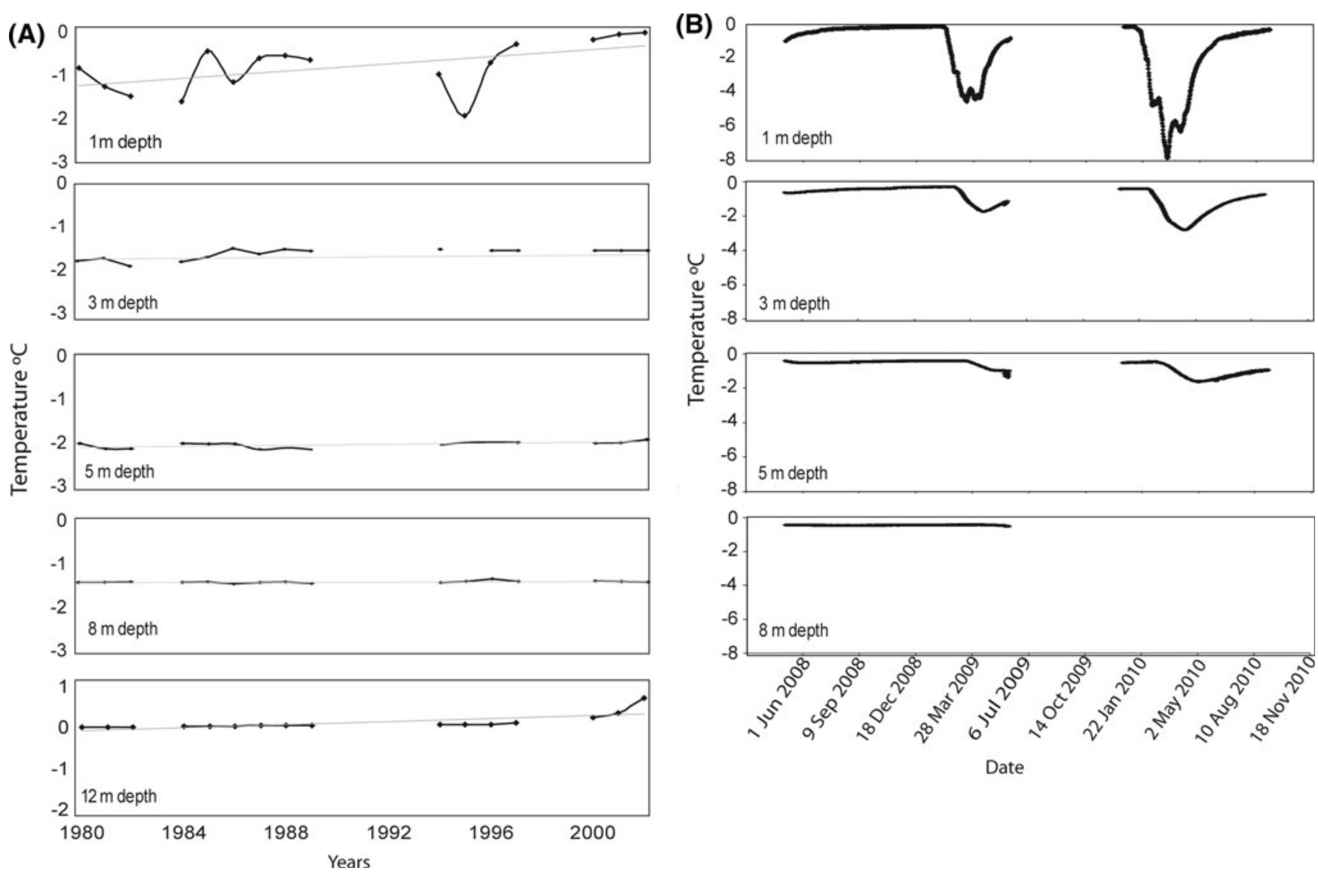

Fig. 3 Ground temperatures from Storflaket **a** old borehole recorded the third week in September (data partly presented in Johansson et al. 2008) and **b** a snapshot from the new borehole (Storflaket 3) recorded year round

ca. 1°C ($R^2 = 0.61$, $p = 0.004$), 0.5°C ($R^2 = 0.77$, $p = 0.02$) and ca. 0.4°C ($R^2 = 0.53$, $p = 0.001$), respectively. No statistically significant trend could be detected in the middle of the borehole at 5 and 8 m depth (Fig. 3). The data for May over the same period showed no statistically significant trends.

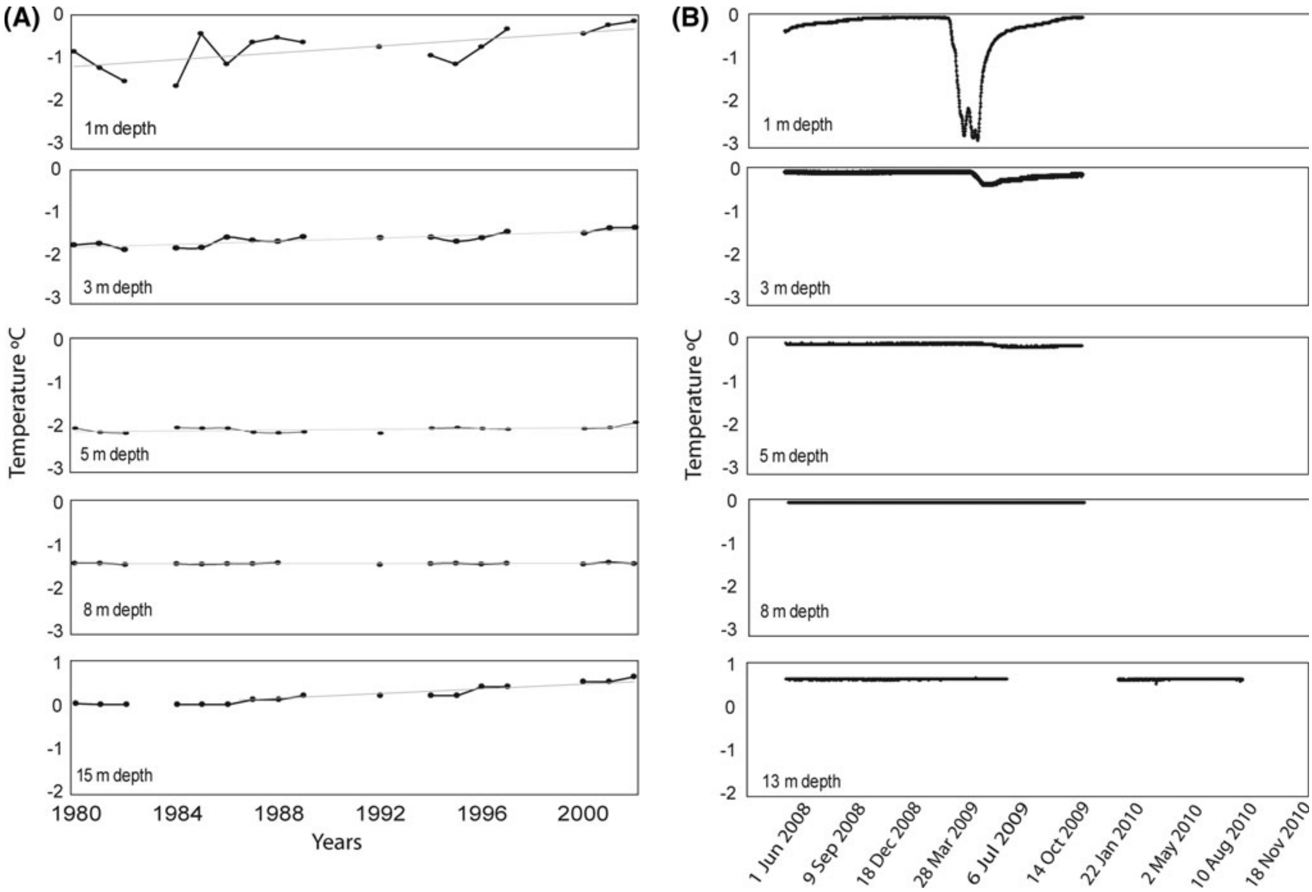

Fig. 4 Ground temperatures from Kursflaket **a** old borehole recorded the third week in September (data partly presented in Johansson et al. 2008) and **b** a snapshot from the new borehole (Kursflaket 1 (1, 3, 5, 8 m) and 2 (13 m)) recorded year round

Similar September trends could be detected at the Kursflaket mire with increasing ground temperatures in the upper and lower parts of the borehole. Ground temperatures in September increased at 1, 3 and 15 m by 0.9°C ($R^2 = 0.46$, $p = 0.003$), 0.4°C ($R^2 = 0.75$, $p = 0.02$) and 0.7°C ($R^2 = 0.90$, $p = <0.001$), respectively, while there was no significant trend at the intermediate depths of 5 and 8 m (Fig. 4). The data for May over the same period showed no statistically significant trends except at 15 m depth where an increasing trend of 0.6°C ($R^2 = 0.91$, $p = 0.03$) could be detected over the period 1980–2002.

Data from the new boreholes showed that the permafrost temperatures in the two mires are close to 0°C. Mean annual ground temperatures (MAGT) at 5 m depth for the period 2008–2009 were −0.38°C at Storflaket 1, −0.31°C at Storflaket 2, −0.47°C at Storflaket 3 (Table 2) and −0.16°C at Kursflaket 1 and Kursflaket 2 (Table 3). The largest intra-annual differences are found in the upper part of the boreholes while in the lower part of the boreholes, very small intra-annual differences can be detected (Figs. 3, 4).

Permafrost Thickness

No changes in permafrost thickness could be detected at the Storflaket mire as the new boreholes were only 8 m deep and did not completely penetrate the permafrost. At Kursflaket, it was possible to redrill at the same site that was drilled in 1980 (Fig. 2) and also to drill through the permafrost in this mire. The permafrost thickness has decreased from 15 m in 1980 to 13 m in 2002 and then to ca. 9 m in 2009 (Fig. 5).

DISCUSSION

Ground Temperatures

Data from the old boreholes show increasing ground temperatures from both sites from 1980 to 2002 in the upper and lower parts of the boreholes. This gives a good indication that permafrost temperatures have increased in accordance with the general trend reported from the Arctic

Table 2 Maximum, minimum and MAGT (°C) at the new boreholes at Storflaket for the period 1 May 2008–30 April 2009

Depth (m)	Min	Max	MAGT
Storflaket 1			
1	−3.81	−0.12	−0.76
3	−1.56	−0.23	−0.46
5	−0.73	−0.28	−0.38
7	−0.42	−0.40	−0.40
Storflaket 2			
1	−3.39	−0.06	−0.60
3	−1.18	−0.23	−0.34
5	−0.51	−0.26	−0.31
6.2	−0.40	−0.31	−0.36
Storflaket 3			
1	−4.50	−0.12	−0.92
3	−1.73	−0.28	−0.55
5	−0.93	−0.40	−0.47
8	−0.48	−0.42	−0.46

Table 3 Maximum, minimum and MAGT (°C) at the new boreholes at Kursflaket for the period 1 May 2008–30 April 2009

Depth (m)	Min	Max	MAGT
Kursflaket 1			
1	−2.83	−0.09	−0.49
3	−0.40	−0.12	−0.14
5	−0.17	−0.14	−0.16
8	−0.06	−0.06	−0.06
Kursflaket 2			
3	−0.45	−0.06	−0.19
5	−0.17	−0.14	−0.16
10	0.25	0.27	0.26*
13	0.61	0.66	0.63*

* No permafrost

from the IPY TSP project (Romanovsky et al. 2010a, b; Christiansen et al. 2010; Smith et al. 2010).

Ground temperatures, especially near surface, are mainly determined by snow depth and air temperatures in the study area (Johansson et al. 2006a). The trend found in the dataset from the old boreholes with increasing ground temperatures correlates well with increasing air temperatures recorded in the area (Callaghan et al. 2010). Snow depth has increased during the last century in the area (Kohler et al. 2006) but during the last decade this trend has shifted and decreasing snow depths have been recorded (Callaghan et al. 2010). No correlations could be found between the snow depth and ground temperatures (even though we used two separate snow datasets from Abisko Scientific Research Station), which was most likely due to the wind drift resulting in very little snow on the mires. The snow onset date and melt date can affect the ground temperatures but no changes have been recorded in either of these parameters from 1913 to 2004 (Kohler et al. 2006), and hence, these cannot explain increases in ground temperatures. The lack of trend in the middle of the borehole profile is most likely due to the thick peat that exists at both mires, which creates a lag effect due to its insulating effect, i.e. it will take longer for the trend in increasing ground temperature that can be seen in the upper part of the borehole to be recorded in this middle part of the borehole.

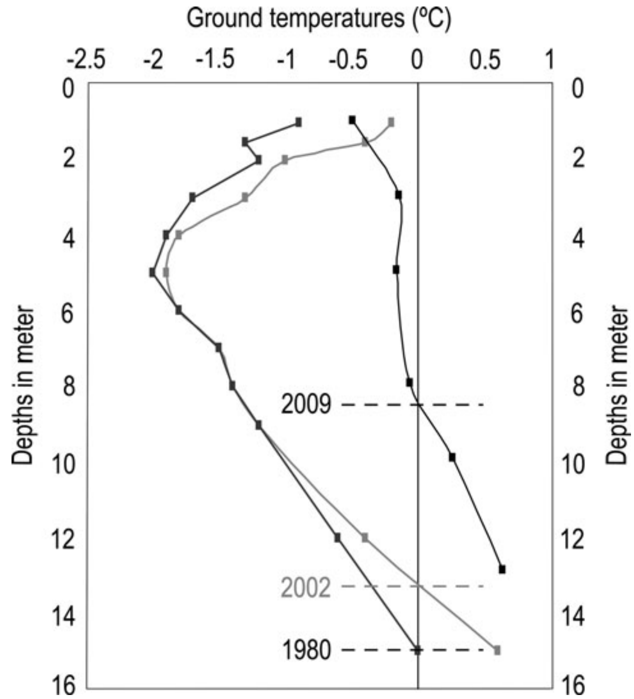

Fig. 5 Kursflaket vertical temperature profile for 1980, 2002 (September data) and 2009 (annual mean). The *dashed lines* indicate approximate permafrost thickness (data updated from Johansson et al. 2008)

Similar trends in increasing ground temperatures as to those observed here have also been reported from the region in mountain permafrost by Isaksen et al. (2007). They detected significant warming down to at least 60 m depth. Statistically significant correlations were found between the seasonal ground and air temperatures (Isaksen et al. 2007).

Data from the new boreholes show that the MAGT in the mires are close to 0°C. The permafrost at the study site is likely to be so called ‘Ecosystem protected permafrost’. This type of permafrost was formed under climates colder than present but can persist as sporadic patches under a warmer climate due to the peat mire ecosystem’s properties (in this case the peat’s insulating capacity). ‘Ecosystem protected permafrost’ is typically found in climates where current mean annual air temperature is approximately from

2 to −2°C (Shur and Jorgenson 2007). During the last decade, the air temperatures in the Abisko area have increased and have now exceeded 0°C in mean annual air temperature (Callaghan et al. 2010). Downscaled climate scenarios for the Abisko region predict an increase in air temperature by 3°C (in 2050) and 4.5°C (by 2080) and an increase in precipitation by 18% by 2080 (Sælthun and Barkved 2003). It is not likely that lowland permafrost in the mires will 'survive' an increase in air temperature of 3°C as the mean annual air temperature will then be well above the 2°C that Shur and Jorgenson (2007) identified as the limit for 'Ecosystem protected permafrost'. Data from the new boreholes will provide year-round data that can be used to reveal more about the future of the permafrost in the two mires.

The increasing ground temperatures and thawing of permafrost are associated with several impacts such as an increase in active layer thickness (Akerman and Johansson 2008), surface subsidence and changes in hydrology towards wetter conditions (Christensen et al. 2004). During the last decades, the vegetation has changed from dry shrub-dominated ombrotrophic conditions to wet, graminoids-dominated and more nutrient rich conditions (Malmer et al. 2005; Johansson et al. 2006b).

Permafrost Thickness

The increases in ground temperatures in the upper and lower part of the old boreholes have also affected the permafrost thickness at the mires. At Storflaket, it was not possible to redrill at the same location, and hence, it is not possible to compare present permafrost thickness in this mire with the recordings from 1980 published in Akerman and Johansson (2008). The old borehole was located near the edge of the mire, while the new boreholes are located towards its centre. New geophysical surveys (Dobinski 2010) close to the new boreholes indicate that permafrost could be thicker than the 15 m recorded in 1980 (Akerman and Johansson 2008). However, the recent observation by Dobinski (2010) cannot be compared with the ones of 1980 to describe the development of permafrost thickness at Storflaket, since permafrost is likely to be thinner near the edge of the mire than in the middle of it.

At Kursflaket, the permafrost thickness has decreased, particularly during the last decade. Johansson et al. (2008) concluded that the thawing from below was likely due to a heating effect from slightly warmer or more freely flowing ground water around and below the frozen bodies of silt and peat. The boreholes at Kursflaket are located at the edge of the mire, and there is liquid water flowing very close to the bottom of the permafrost in the boreholes. Further investigations on ground water are needed to confirm this hypothesis.

CONCLUSION

During the last decades there has been increasing ground temperatures in the upper and lower part of the permafrost in peat mires near Abisko in northernmost Sweden. This has also lead to a decrease in permafrost thickness in one of the mires from 15 m in 1980 to ca. 9 m in 2009. MAGT are close to 0°C in the area, which makes the permafrost very vulnerable to predicted future climate warming in the area.

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