—Plenary Paper—

Recent Warming of European Permafrost: Evidence from Borehole Monitoring

Charles Harris
School of Earth, Ocean and Planetary Sciences, Cardiff University, Cardiff, CF10 3YE UK
Ketil Isaksen
Norwegian Meteorological Institute, P.O.Box 43 Blindern, NO-0313 Oslo, Norway

Abstract

Here we present a review of recent ground thermal data derived largely from the continent-scale network of instrumented boreholes within mountain permafrost established between 1998 and 2001 by the European Union PACE project. More recently, networks of intermediate and shallow boreholes in Switzerland, Norway, and Iceland have been added. A large number of complex variables determine permafrost temperatures, including altitude, topography, net radiation, and snow distribution. Thus, modeling the above-ground climate signal from observations of permafrost temperatures and coupling downscaled climate models to assess future permafrost thermal responses to climate forcing remain major research goals. Boreholes drilled in areas of steep mountain topography may penetrate complex three-dimensional thermal fields, making interpretation of thermal profiles in terms of changes in the upper thermal boundary extremely challenging. However, in the lower relief settings of the Scandinavian and Svalbard PACE boreholes, observed warm-side deviation in thermal profiles strongly suggests a period of sustained surface warming in the latter half of the 20th century and in the early 21st century. The significance of short-term extreme thermal events is illustrated with reference to the record-breaking summer of 2003 in the Alps and the anomalously warm winter-spring-summer period in 2005–2006 in Svalbard. It is concluded that such events may initially be more significant than the longer-term underlying trends in climate. Permafrost thermal responses to climate change occur at markedly different time scales, with changes in active layer thickness being more or less immediate, modification of thermal profiles below the depth of zero amplitude taking decades or centuries, and basal melting associated with progressive permafrost thinning requiring millennial time scales. However, as illustrated here by the example of Icelandic permafrost, where the frozen ground layer is thin and warm and the geothermal heat flux rates are high, permafrost decay and disappearance may be much more rapid.

Keywords: borehole monitoring; climate change; Europe; permafrost temperatures.

Introduction

In the present paper we review current evidence for permafrost warming within the European sector. In the mid-latitude high relief setting of the Alps, ground temperatures are only a few degrees below zero and permafrost may be thin near the lower permafrost boundary. Permafrost warming in alpine mountain slopes increases the risk of landslides, debris flows, and rockfalls (Noetzli at al. 2003, Gruber & Haeberli 2006). However, predicting the thermal response of mountain permafrost to climate change is challenging because of spatially complex topography and substrate properties (e.g. Hoezle et al. 2001). In contrast to the Alps, permafrost is continuous in the Arctic archipelago of Svalbard, outside the glaciated areas. Ocean-atmosphere coupling results in the climate being particularly sensitive to variations in sea-ice cover (Benestad et al. 2002, Isaksen et al. 2007b). Observed and predicted reductions in sea-ice (Stroeve et al. 2007, Serreze et al. 2007) suggest the onset of a rapid climate transition, with increasing frequency of anomalously high temperatures (Christensen et al. 2007, Isaksen et al. 2007b). The thermal response of permafrost may therefore exceed recent historical experience. Finally, the maritime setting of Iceland results in permafrost being restricted to higher elevations, and here geothermal heat flux increases the sensitivity of permafrost to changes in the upper boundary condition (Farbrot et al. 2007). This diversity of permafrost settings within Europe provides a background for this paper.

European Borehole Monitoring

A major stimulus to European permafrost research was provided by the PACE project (Permafrost and Climate in Europe), which commenced in 1997 (see Harris et al. 2001), and much of the more recent research reported here is a legacy of this program (Harris et al. submitted). Primary data have been collected through instrumented permafrost boreholes; the main borehole network of six instrumented bedrock boreholes drilled 100 m or more in depth was established between 1998 and 2001 through the PACE project (Fig. 1). The longest continuous European permafrost temperature time series is from the 32 m deep Murtèl Corvatsch borehole in Switzerland (Fig. 1) which was drilled in 1987, in an ice-rich rock glacier (Vonder Mühll and Haeberli 1990, Hoelzle et al. 2002). This borehole has been incorporated into the PACE network.

Over the past decade, the number of intermediate and shallow (less than 25 m) depth monitoring boreholes has increased steadily, particularly in Switzerland, where permafrost monitoring is coordinated by the PERMOS programme (Vonder Mühll et al. 2004, 2007). In Norway and Svalbard the IPY project “Thermal State of Permafrost” (TSP) (Christiansen this volume) has also instigated a

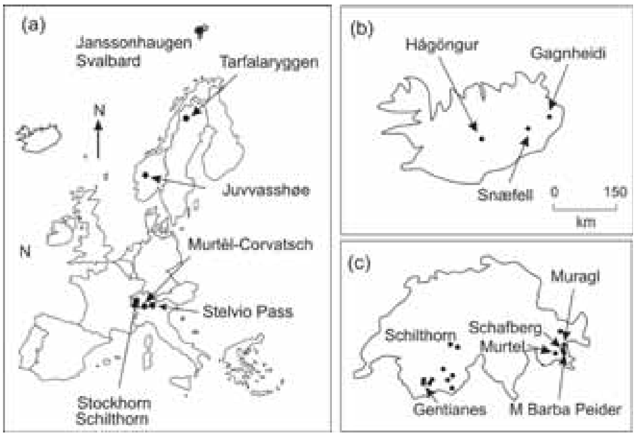

Figure 1. Distribution of boreholes mentioned in text. (a) PACE borehole network, (b) Icelandic boreholes, (c) Swiss boreholes.

program of permafrost monitoring through shallow boreholes. A total of 66 boreholes are listed from the European sector in the GTNP database (http://www.gtnp.org/); 31 of these are in Switzerland, 18 in Norway and Svalbard, and between 3 and 6 in Iceland, Italy, Spain, and Sweden. Not all are continuously monitored, and many have only short time series.

Instrumentation generally utilizes automatic logging of thermistor strings within cased boreholes. Recommendations on instrument specification, spacing, and logging frequencies may be found in the PACE Manual (see Appendix B, Vonder Mühll 2004), but all thermistors should be retrievable to allow periodic recalibration. In most PACE boreholes a second 15–20 m deep borehole was drilled adjacent to the deeper hole to allow more detailed higher frequency monitoring of the near surface (Isaksen et al. 2001, 2007a, Gruber et al. 2004c). In other borehole monitoring programs, a multimeter may be used to record thermistor temperatures periodically, or the borehole may be equipped with single-channel miniloggers, which are retrieved annually for downloading. Alternative approaches to monitoring the thermal status of permafrost include active layer thickness (e.g., the Circumpolar Active Layer Monitoring (CALM) program), and measurement of the Bottom Temperature of Snow (BTS) (e.g., Vonder Mühll et al. 2004, 2007).

Permafrost Geothermal Profiles

Since heat advection by ground water or air circulation is often negligible, permafrost geothermal profiles are primarily a function of heat conduction from the Earth's interior and heat fluxes at the ground surface. The annual ground surface thermal cycle penetrates to 15–20 m (the depth of zero amplitude), but larger perturbations of longer periodicity may penetrate much deeper and take much longer to do so (e.g., Lachenbruch & Marshall 1986). Perturbation of the thermal gradient below the depth of zero annual amplitude may provide direct evidence of thermal trends at the permafrost table during preceding decades or centuries (e.g., Cermak et al. 2000, Osterkamp & Romanovsky 1999).

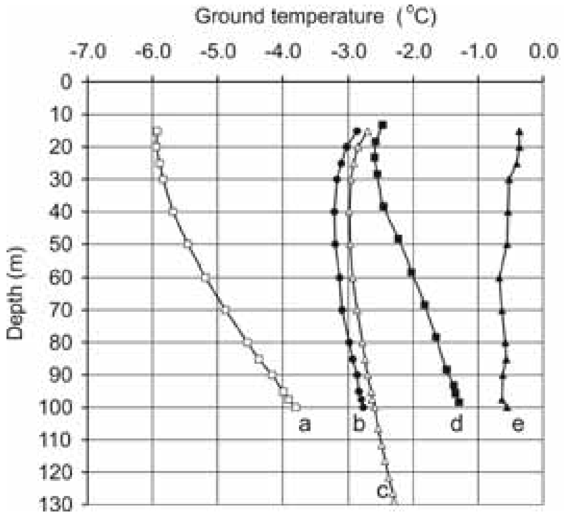

Figure 2. Ground temperature profiles in permafrost below 15 m at (a) Janssonhaugen, (b) Tarfalaryggen, (c) Juvvasshøe, (d) Stockhorn, (e) Schilthorn, and (f) Murtèl-Corvatsch. Data recorded 22 April 2005 (temperature profile at Juvvasshøe below 100 m depth recorded manually 1 October 2000).

Where permafrost is thin (<100m), such thermal perturbation may extend to the base, causing basal melting, but in thicker permafrost, deeper penetration of climatically forced thermal cycles is likely to require millennial time scales.

In mountain permafrost, the thermal field is often strongly three-dimensional (Noetzli et al. 2007) and the thermal offset between mean ground surface temperature and mean permafrost table temperature reflects spatial heterogeneity in active layer composition and snow distribution, the latter also being subject to large inter-annual variations (Gruber et al. 2004c). Thus, modeling the above-ground climate signal from observations of permafrost temperatures, and coupling downscaled climate models to assess future permafrost thermal responses to climate forcing, remain major research goals (Harris et al. submitted). The greater altitudinal range and more complex topography in the Alps lead to greater variability in permafrost temperatures recorded by Swiss boreholes than those in Scandinavia and Svalbard. Figure 2 shows ground temperature profiles from PACE boreholes recorded in April 2005.

Ground temperatures in the Alpine boreholes Stockhorn and Schilthorn are highly disturbed by topography. Gruber et al. (2004c) have shown that for Stockhorn, marked differences in thermal gradient occur over short distances in response to a strongly three-dimensional temperature field. At Schilthorn, permafrost temperatures are very close to 0ºC and are influenced by latent heat effects and convective heat transfers by water as well as topographic effects. In contrast, the three Nordic boreholes have low relief within 100–200 m of the monitoring sites, relatively uniform bedrock and thin snow cover, suggesting that the climate signal dominates the observed geothermal gradients (Isaksen et al. 2007b). At greater depths than the boreholes, the effect of larger-scale relief may be significant and may in part explain

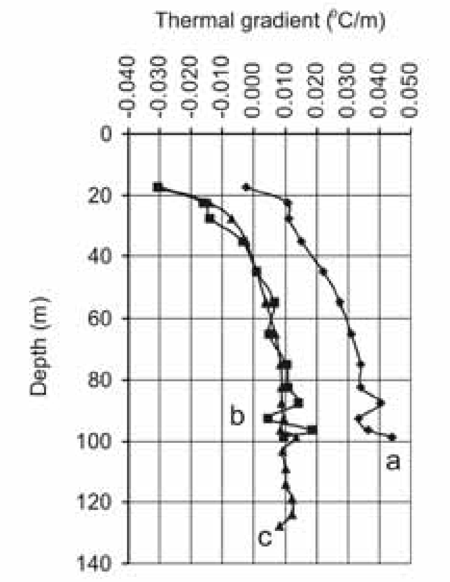

Figure 3. Thermal gradients at (a) Janssonhaugen, (b) Tarfalaryggen, (c) Juvvasshøe, calculated from profiles presented in Figure 2.

the low thermal gradients observed at Tarfalaryggen and Juvvasshøe (Fig. 3). All three boreholes show a significant warm-side deviation in their thermal profiles to 70 m depth, with marked increases in thermal gradient with depth. Just below the depth of zero amplitude, gradients are negative (Fig. 3). These characteristics probably reflect surface warming since the mid 20th century (Harris et al. 2003, Isaksen et al. 2001, 2007a) and extrapolation to the surface of temperature gradients between 30–20 m depths and 70–100 m suggests surface warming of ~1.4°C, ~1.1°C and ~1.0°C for Janssonhaugen, Tarfalaryggen, and Juvvasshøe respectively.

Recent Trends in Permafrost Temperatures

Permafrost temperatures at depths of around 10 m in Swiss and Norwegian boreholes are illustrated in Figure 4(a) and (b). At Murtèl-Corvatsch in Switzerland, marked warming was recorded between 1987 and 1995 (Vonder Mühll & Haeberli 1990, Vonder Mühll et al. 1998, 2002, 2007, Hoelzle et al. 2002), but this was reversed in the winter of 1995–96 and more markedly so in 1996–97. Since then, at Murtèl and other Swiss boreholes, no marked overall warming trend is apparent, with periods of rising ground temperatures being cancelled out by marked winter cooling in 2002–03 and 2006–07. Harris et al. (2003) showed that snow-poor early winter periods rather than markedly lower atmospheric temperatures were largely responsible for these ground cooling events.

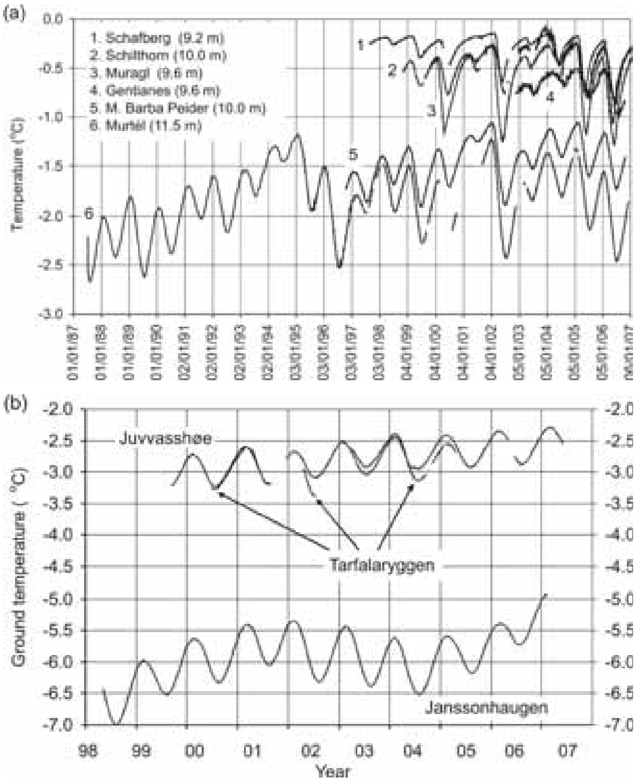

Figure 4. Permafrost temperature time series from around 10 m depth. (a) selected Swiss PERMOS boreholes. (b) Nordic PACE boreholes. For locations of boreholes, see Figure 1.

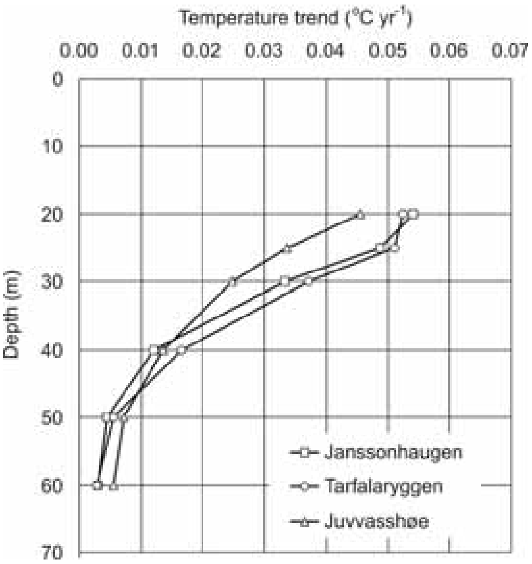

Figure 5. Observed linear trends in ground temperature as a function of depth. Time series at start in 1999 at Janssonhaugen, 2001 at Tarfalaryggen, and 2000 at Juvvasshøe, and they last for 6, 4, and 5 years, respectively.

In the three Nordic boreholes, deflation maintains relatively thin snow cover in winter, so that ground temperatures are strongly coupled to atmospheric temperatures (Isaksen et al. 2007a). At Janssonhaugen especially, temperature records at 10 m depth show pronounced fluctuations and large inter-annual variability, making identification of longer-term trends more difficult. However, recorded ground temperature changes below the zero annual amplitude provide direct evidence of thermal trends at the ground surface during recent decades. At all three sites a clear trend towards warming ground temperatures is detected (Fig. 5). For instance, at 30 m depth, present warming rates are in the order of 0.025 - 0.035°C yr^{-1}. Isaksen et al (2007a) demonstrated that statistically significant ground warming may be detected to 60 m depth, the rate of warming being greatest at Tarfalaryggen and Janssonhaugen (Fig. 5).

The Significance of Extreme Events

Climate warming in the 20th and 21st centuries is likely to increase active layer thicknesses. However, an associated increase in frequency of high-temperature anomalies with sustained higher than normal temperatures may well dominate active layer evolution. Two examples of such extreme periods are discussed below: summer 2003 in the Alps, when temperatures during June, July, and August were approximately 3°C higher than the 1961–1990 average (Gruber et al. 2004c) and Svalbard in 2005–6 when anomalously high winter spring and summer temperatures caused significant permafrost warming (Isaksen et al. 2007b).

At the bedrock borehole of Schilthorn, Switzerland, active layer thickness ranged from around 4.4 m to around 4.9 m in the five years prior to 2003, but increased to nearly 9 m (Fig. 6a) during the 2003 extreme summer. In subsequent years the thickness has been around 4.8 m. At Stockhorn the active layer increased from around 3 m in the previous few years to 4.27 m in 2003. Numerical modeling has shown that in 2003 Alpine active layers were thicker than in the previous 21 years and were probably the greatest for several centuries (Gruber at al. 2004b). Rapid warming and thawing of bedrock containing ice-bonded joint planes led to a marked increase in rockfall events (Keller 2003) particularly on north-facing slopes where the effects of elevated atmospheric temperatures are greatest, and permafrost most widely distributed (Gruber et al. 2004b, Noetzli et al. 2007). The sharply increased depth of thaw during the summer of 2003 far outweighed the direct effect of gradually rising temperatures on the stability of the uppermost few metres of rock in most Alpine rock walls (Gruber et al. 2004c, Gruber & Haeberli 2006).

In contrast, active layer thickness changed much less dramatically at the ice-rich rock glacier of Murtèl-Corvatsch (Fig. 6b) in Switzerland where latent heat demand during thaw at the permafrost table provides an effective heat sink, limiting the active layer thickening. The general trend since 1987 has been towards increasing active layer thickness and in 2003 it reached 3.51m, around 11 cm thicker than in the previous summer and the greatest value since monitoring began in 1987. However, once thawed, meltwater drains away, leaving a thicker active layer with much lower ice content and therefore latent heat demand than the underlying permafrost. Thus, despite a much cooler summer in 2004, the active layer reached the same thickness as in 2003, and in 2005, which was cooler again, thaw penetration was only a few cm less than in 2003 (Vonder Mühl et al. 2007).

The winter-spring-summer period in 2005–6 on Svalbard provides a remarkable example of extreme atmospheric temperatures. The mean air temperature between December and May 2005–2006 was as high as −4.8°C, which is 8.2°C above the 1961–1990 average and 2.8°C higher than the previous record from 1954, amounting to an offset of 3.7 standard deviations from the mean (Isaksen et al. 2007b). The anomaly coincided with a marked reduction in sea-ice cover and an unusually large extent of marine open water around Svalbard during winter, spring, and summer 2005–2006. The warm winter was followed by warmer than average summer temperatures, which were around 2°C above the 1969–1990 normal. For calendar year 2006, the cumulative negative ground temperature at the permafrost table in the Janssonhaugen borehole (2 m depth) showed a 40% reduction compared with the average of the previous six years.

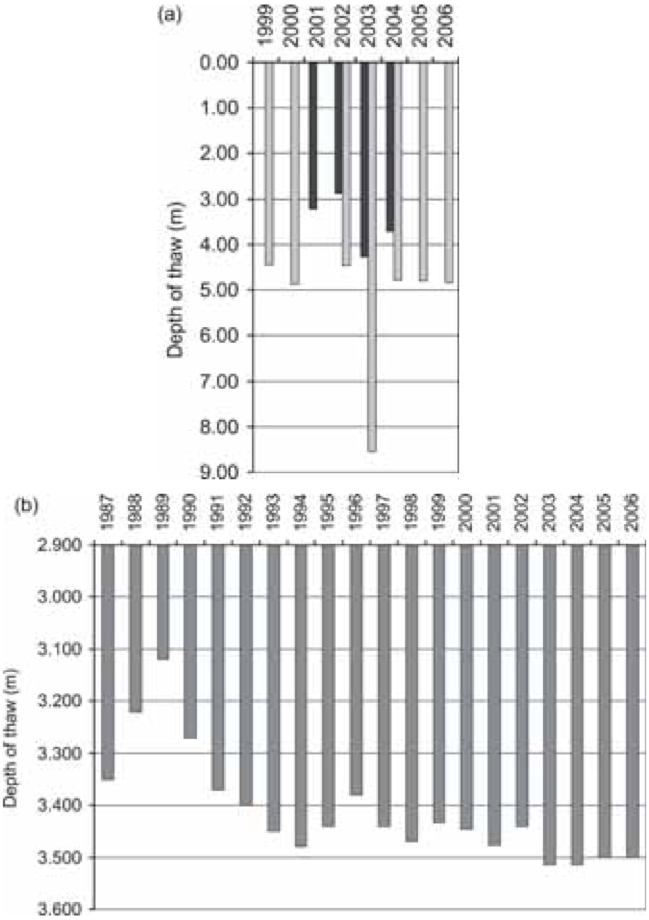

Figure 6. Active layer thickness: (a) Schilthorn (light bars) and Stockhorn (dark bars); (b) Murtèl-Corvatsch.

The effect on permafrost temperatures at Janssonhaugen is most clearly captured by considering the 12-month period from 1 December 2005 to 30 November 2006 (Isaksen 2007b). Plotting mean ground temperatures over this period, for instance the uppermost 3 meters, shows temperatures at the permafrost table 1.8°C above the 1999–2005 average, with the thermal anomaly traceable to a depth of at least 15 m. The start of active layer thawing was the earliest in the 8-year record and active layer thickness was 1.8 m, exceeding the mean of the previously recorded years by 0.18 m (an 11% increase).

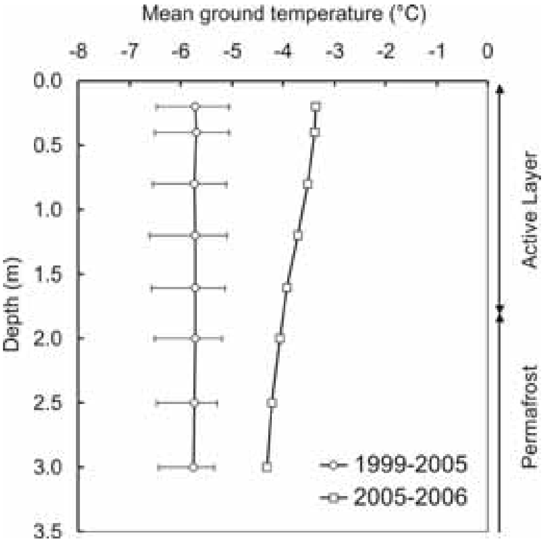

Figure 7. Mean ground temperature profile at Janssonhaugen for 2005–2006 compared with the mean for 1999–2005. Horizontal bars show the absolute variations of the previous years.

In order to place this anomaly into the context of climate change, Isaksen et al. (2007b) compared the accumulated degree day air temperature curve for 2006 at Svalbard airport with equivalent curves derived from empirical-statistical downscaling based on the multi-model World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP3) of the most recent Intergovernmental Panel on Climate Change (IPCC) assessment in which atmospheric CO_2 reaches 720 parts per million by 2100. The 2006 accumulated degree day curve lay well within the range of the predicted scenarios for 2071–2100. Since 1999, accelerated warming has been observed at Janssonhaugen, the calculated rate at the top of the permafrost being in the order of 0.6–0.7°C/decade (Isaksen et al. 2007a). Thus the extreme temperatures of 2005–2006 were superimposed on a significant warming trend. If the frequency of such high temperature anomalies increases, then near-surface permafrost warming will be irregular rather than gradual and punctuated by rapid warming events such as that in 2005–2006.

Sensitivity to Geothermal Heat Flux

In Iceland, maritime conditions give cool summers and mild winters. The MAAT for 1961–1990 is around 4°–5° C in the south, and 2°–3°C in the north in lowland areas (Farbrot et al. 2007). Extensive non-glaciated mountain areas have MAAT below -3°C, indicating a potential for permafrost where snow cover is thin or absent. A regional model, calibrated against borehole thermal data and rock glacier inventories, suggests the presence of permafrost above around 800m a.s.l. in the north and above 1000m in the south (Etzelmüller et al. 2007, Etzelmüller et al. 2008), with the thickness of snow strongly modulating permafrost distribution.

Four monitoring boreholes in central and northeastern Iceland were established in 2004 (Farbrot et al. 2007, Etzelmüller et al. 2007, Etzelmüller et al. this volume), at altitudes of between 890–930 m a.s.l. (Fig. 1b). All boreholes are shallow (12–22 m deep) and penetrate thin sediment into basaltic bedrock. Permafrost was absent at the Vopnafjörður site due to excess snow cover, but at Snæfell and Gagnheiði it was estimated to be 30–35 m thick (Fig. 8b, c), with active layers around 2 m and 4 m respectively. At the Hágöngur borehole, permafrost was thin and the active layer thick (around 6 m) and permafrost temperatures close to zero degrees C (Fig. 7a). Meteorological data indicate that mean annual ground surface temperatures for the past few years in Iceland have been 0.5–1°C higher than those for the 1961–90 period (Etzelmüller et al. 2007). At the Gagnheiði and Snæfell boreholes, temperature profiles show warm-side deviation from steady state, suggesting recent rises in the upper boundary temperature (Fabrot et al. 2007).

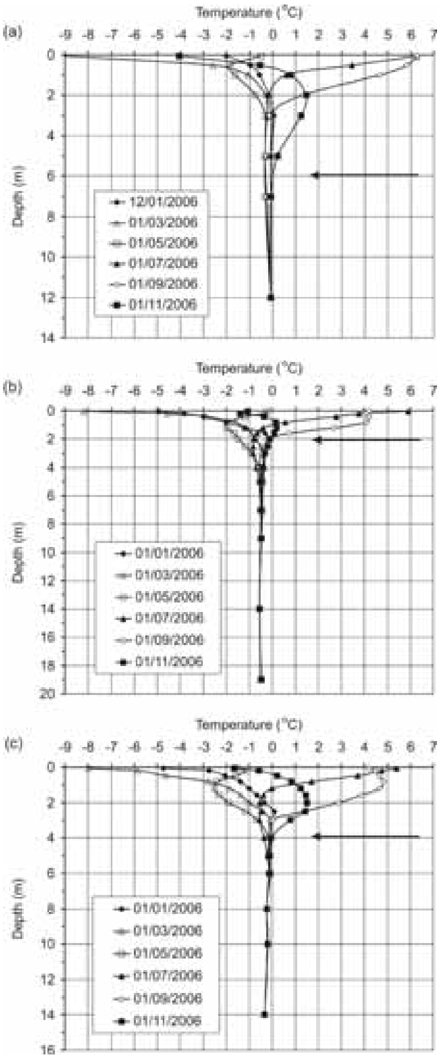

Figure 8. Temperature profiles in boreholes during 2006: (a) Hágöngur, (b) Snæfell, (c) Gagnheiði. Active layer thickness during the 2006 summer season indicated by arrows.

Using a one-dimensional thermal model, Farbrot et al. (2007) showed that increases in mean daily surface air temperatures of (a) 0.01°C a^{-1} and (b) 0.03°C a^{-1} would cause permafrost to disappear at Snæfell in 160 and 100 yr respectively and at Gagnheiði in 125 and 75 yr respectively, the slower thermal response at Snæfell reflecting higher ice contents. Modeled temperature evolution since 1955 suggested that the present-day permafrost thicknesses reflect cooling in the late 1960s/early 1970s. This rapid permafrost thermal response is in part a reflection of the shallowness of the permafrost layer, but it is also due to the influence of high geothermal heat fluxes, which at Snæfell are around 170 mW m^2, approximately five times the values at the Scandinavian PACE borehole sites.

Conclusions

The spatial complexity of European mountain permafrost makes the representativeness of data from the small number of monitored boreholes extremely difficult to assess. The time series of borehole temperatures are mainly less than 10 yr, apart from Murtél-Corvatsch.

The addition of new boreholes provides the opportunity to sample a wider diversity of terrain and substrate character. However, prediction of permafrost distribution and response to climate change in European mountains requires further progress in physically-based numerical modeling coupled with remotely sensed data on relief, ground cover, and substrate characteristics.

PACE boreholes in Norway, Sweden, and Svalbard provide firm evidence for significant and accelerating ground warming. In addition, the importance of short-term extreme thawing events is emphasized. These have included the three-month period of sustained high temperatures during summer 2003 in the Alps, when active layers thickened significantly in bedrock sites and, in Svalbard, the anomalously warm year of 2005–6 when marked warming of permafrost occurred. Comparison of 2006 air temperatures in Svalbard with downscaled model scenarios of warming associated with enhanced greenhouse gases in the 21st century indicates that 2005–6 was well within the range predicted for the period 2071–2100, suggesting that the Svalbard archipelago may be in a critical location, with potential for particularly rapid climate change.

Given the variability of climate in the past and evidence for continued and possibly accelerated change in the future, permafrost is clearly in a transient state. More or less immediate response to extreme annual temperature variations may be anticipated in active layer thickness, while thermal profiles extending to several decimeters below the depth of zero amplitude reflect changes over many decades or centuries. Permafrost warming and basal melting are, however, likely to take several millennia, except where permafrost is thin and — as is the case in Iceland — where geothermal heat flux is unusually high.

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