Arctic permafrost thermal variability across an environmental gradient from continuous to sporadic permafrost in the Northern Hemisphere – A PAGE21 compilation

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ABSTRACT
Permafrost temperatures are recorded in dominant ice-rich periglacial landforms in five different sites of continuous and sporadic permafrost for improved understanding of physical permafrost processes, and for the comparison of these processes between the five sites. Additionally active layer thickness from the official CALM data from each of the same sites have been compared. The landscapes vary from high-relief mountainous terrain to deltaic and floodplain lowlands, and are thus characteristic of large parts of the permafrost landscapes in the Northern Hemisphere, representing the landscape variability. Significant variation is seen in terms of the sensitivity towards climate change between the five site, ranging from relatively cold -8˚C permafrost in Siberia, but with very large thermal conductivity, over warmer -4˚C permafrost in Svalbard with normal thermal conductivity, to permafrost warmer than -1˚C in Abisko. Thickest active layer is found in Svalbard, and thinnest in Kytalyk in Siberia, but with the peat of the sporadic permafrost in Abisko at an intermediate level.

RÉSUMÉ
Des températures du pergélisol ont été enregistrées dans des formes périglaciaires riches en glace sur cinq sites différents de pergélisol continu et sporadique afin de mieux comprendre les processus physiques du pergélisol et de comparer ces processus entre les sites. En outre, l'épaisseur de la couche active à partir des données officielles de CALM à chacun des sites a été comparée. Les paysages varient d'un haut-relief montagneux, aux basses terres deltaïques et de plaines inondables, caractéristiques d'une grande partie des paysages du pergélisol de l'hémisphère nord, ce qui reflète la variabilité du paysage. Une variation significative entre les cinq sites est perçue en termes de sensibilité aux changements climatiques, allant d'un pergélisol relativement froid (-8 °C) en Sibérie, mais avec une très grande conductivité thermique et d'un pergélisol plus chaud (-4 °C) à Svalbard avec une conductivité thermique normale, à un pergélisol plus chaud de près de -1 °C à Abisko. La couche active la plus épaisse se trouve à Svalbard et la plus mince à Kytalyk en Sibérie. Étant donné la présence de tourbe, le pergélisol sporadique à Abisko se trouve à un niveau intermédiaire.

1 INTRODUCTION

The EU 7th framework project PAGE21 has as one of its key objectives to study the thermal state of permafrost across the Arctic and identify the effects of meteorology, snow, vegetation cover and sediment/ice properties, based on continuously observed permafrost temperatures from the key field sites. The primary PAGE21 field sites

Samoylov, Kytalyk, Zackenberg, Svalbard and Abisko are selected so that they cover the existing environmental gradients from continuous cold permafrost to maritime warm sporadic permafrost environments in the Arctic, but also to cover the periglacial landscape variability occurring in Arctic permafrost areas from the very extensive sedimentary lowland landscapes of northern Eurasia to the mountainous highlands of northern Scandinavia, Svalbard and Greenland.

Here we present the first compilation of the permafrost thermal state and active layer thickness from the 2012-2014 PAGE21 data collection period, and include earlier data as well where they exist.

2 METHODOLOGY

All PAGE21 sites already had or got at least one borehole established for permafrost thermal monitoring during the first two year project period. Just as all PAGE21 sites had at least one Circumpolar Active Layer Monitoring network, CALM, grid established before the PAGE21 period. Both the borehole and the CALM grids were located in a dominant periglacial landform at each site, thus together representing larger parts of the Arctic landscape. All boreholes are drilled only into sediments. And all CALM sites are recorded in sediments using the probing method.

At each borehole a metal or plastic casing was installed into the borehole right after drilling. Either a GeoPrecision or other types of thermistor strings, or 4 channel Hobo loggers with 4 individual thermistors (Abisko and Kytalyk) were used for ground temperature recording. Recording intervals vary from 1 hour at Samoylov, Zackenberg and Svalbard, 2 hours at Kytalyk to 12 hours at Abisko.

The ground temperature data are included into the Global Terrestrial Network for Permafrost, GTN-P, which has been further developed in the PAGE21 project as the database for permafrost data (Biskaborn et al., 2015).

2.1 Site characteristics

All PAGE21 sites represent areas with long-term observations of the key permafrost research relevant parameters, such as surface energy balance including meteorology, some hydrology and snow dynamics, in addition to the thermal state of permafrost and active layer thickness.

Samoylov Island is part of the Lena Delta 72.4°N, 126.5°E, 20 m asl. in Russia with continuous permafrost (Boike et al., 2013). The landscape consists of low centred polygons on former river terraces. A 27 m deep borehole was drilled and instrumented in 2007. Active layer thaw progression has been recorded in a CALM grid with 80 points since 2002.

The Kytalyk site is located at 70.8˚N, 147.5˚E, 55 m asl. in Russia with continuous permafrost (van Huissteden et al, 2005). The overall landscape is dominated by a river floodplain, with drained thaw lake basins, remnants of Pleistocene 'yedoma' and actively expanding thaw lakes. A 7 m deep borehole was drilled and instrumented in 2010. Annual active layer thaw depths are recorded in a CALM grid of 121 points once as late in summer as fieldwork allows, from mid July to end of August.

The Zackenberg site is located in NE Greenland at 74.3˚N, 20.3˚E, in a large sediment infilled 2-3 km wide valley dominated by a large delta and glacial and periglacial sediments and landforms with continuous permafrost (Christiansen et al., 2008). An 18 m deep borehole was drilled in late summer 2012 and instrumented. Active layer thaw progression has been recorded since 1996 in two CALM grids.

Adventdalen in central Svalbard at 78.2˚N, 15.8˚E is also a sediment infilled large valley, which contains ice-wedge polygons and several other periglacial landforms with continuous permafrost (Christiansen et al., 2010). A borehole was drilled to 10 m in spring 2008 and instrumented in summer 2008. Active layer thaw progression has been recorded since 2000 in a CALM grid with 121 points.

Abisko is located at 68.2˚N, 18.5˚E, 385 m asl. in the lowlands of the mountain with sporadic permafrost in the palsa mires (Akerman & Johansson, 2008). A borehole was drilled and instrumented in 2008. Active layer measurements were initiated in 1978 in CALM grids with 40 point and from 1987 with 121 points.

2.2 Meteorology

The climate types vary from continuous polar to maritime polar for continuous permafrost sites. During the PAGE21 period the mean annual air temperatures for the 2012-2013 period varied between -0.3˚C in Abisko, -3.3˚C in Svalbard, -9.3˚C in Zackenberg, -12.3˚C in Samoylov and -13.5˚C in Kytalyk.

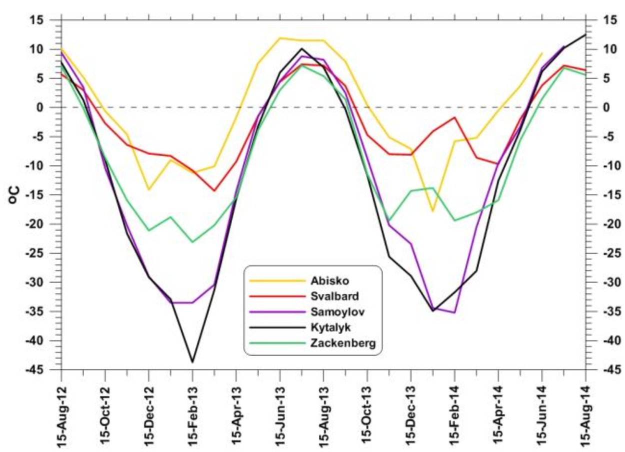

Figure 1. Monthly air temperatures recorded at 2 m at the key PAGE21 sites, August 2012-August 2014.

The monthly air temperatures recorded during the PAGE21 period (Fig. 1) clearly show the continental climate of both the Russian sites in Siberia, and the maritime influence on both the Svalbard and Abisko site. The Zackenberg site is in an intermediate position in NE Greenland, where the East Greenland current reduces the maritime influence, despite the location close to the sea. Typically the longer winter periods have very varying cooling, most pronounced in the two Russian sites, with decreasing intensity in NE Greenland, and with slightly more cooling in Svalbard with somewhat longer winters than in Abisko. The short summers are relatively equal in terms of air temperature, only with somewhat warmer conditions in Abisko and a longer summer there. But also with somewhat warmer conditions in Kytalyk and Samoyloy at least in the 2014 summer (Fig. 1).

3 RESULTS

3.1 Permafrost temperature

The recorded permafrost temperatures from the deepest level in common to all sites at 7 and 8 m at the overall scale reflect the difference in meteorology (Fig. 2). With the two Russian sites as coldest, but not very much colder than NE Greenland, while Svalbard is somewhat warmer and Abisko as warmest below 0˚C. However, there are large differences between the sites with respect to annual variation, which is much larger (> 3˚C) in Russia than in both Zackenberg and Svalbard, which has annual variations in the order of 1˚C, whereas Abisko does not show a consistent seasonal pattern.

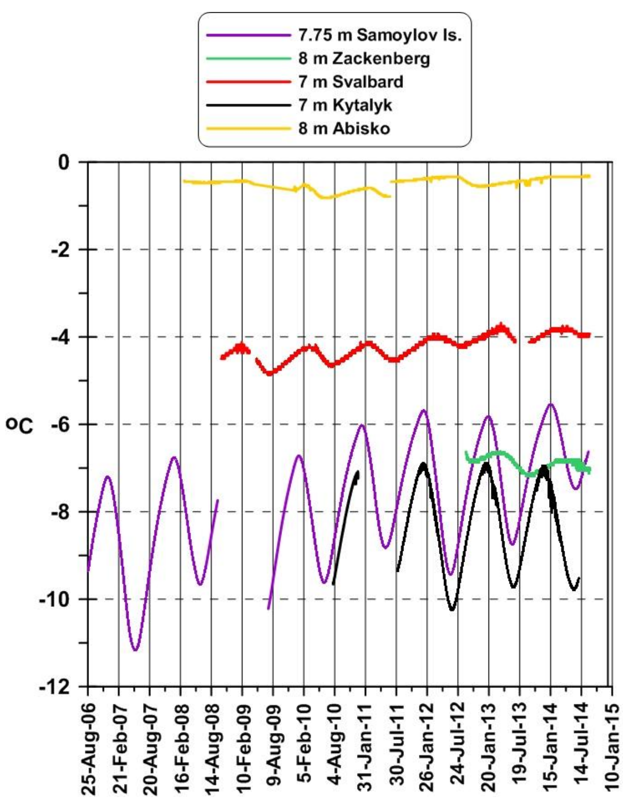

Figure 2. Continuous permafrost temperatures from all the PAGE21 sites extending back to the start of observations. In the Abisko site the thermistor string was stolen in 2011 and the sensor depth was changed to 7 m, when new hole was drilled next to the old one. At Kytalyk the installation was destroyed by foxes in 2010 and reestablished in 2013.

The PAGE21 period maximum, mean and minimum ground thermal values down to the end of the boreholes, often referred to as the trumpet curves (Fig. 3), also highlights the differences in the permafrost ground thermal regime between the different parts of the Arctic.

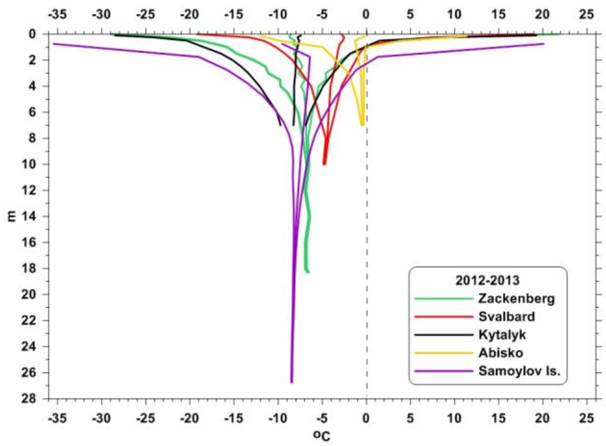

Figure 3. Maximum, mean and minimum ground temperatures in the hydrological year from 1 September 2012 to 31 August 2013 for all PAGE21 sites.

The depth of zero annual amplitude (recorded over two years so far), ZAA, as less than 0.1˚C is only reached in the 27 m deep borehole in Samoylov, where the amplitude is 0.08˚C. Zackenberg reach the 0.18 ˚C at 18 m, while Svalbard reaches 0.19 at 10 m depth. Abisko reach 0.25 at only 7 m depth. However at 7-8 m depths both Russian sites have annual amplitudes of 2.8˚C Kytalyk and 2.9 ˚C Samoylov. This is a very large variation at this depth, which corresponds to sites with quartzite bedrock in continental climates in Canada with 2.5˚C at 10 m depth (Romanovsky et al., 2010).

3.2 Active layer thickness

Active layer thickness (ALT) data has been collected since before the PAGE21 period at all sites (Fig. 4). Deepest thaw is recorded in Svalbard, with from 75 to 110 cm. While Kytalyk only has 30-40 cm thaw depth.

Svalbard also has recorded the largest interannual variation in ALT, with a slight increase since 2009 to 2014, but with the deepest thaw recorded 110 cm in summer 2008.

In Samoylov ALT recording vary from mid July in 2004, but is for all other years recorded in the period from mid August to end of September. This variation in recording explains the largest interannual variability for this site. However, there is a clear increasing ALT through the period, largest from 2002 to 2008 and much less from 2008 to 2014.

In Kytalyk the timing of recordings also varies from 14 July in 2014 to 31 August in 2013, but this does not only explain the interannual variability. Overall ALT seems to have decreased in Kytalyk but clearly with the 2014 minimum being due to rather early measurements, whereas this is not the case for 2013.

In Zackenberg ALT have been increasing mainly from 62 cm in 1997 to 79 cm in 2005. From then only a smaller increase to a maximum of 82 cm in 2011 and 2012 has taken place.

ALT in Abisko is shallower than in Svalbard, thicker than the two Russian sites and generally close to the Zackenberg thickness except for the period from 2004 to 2012, where Abisko is around 10 cm thinner than Zackenberg. Generally ALT has increased from around 50 cm in the late 1980s to 75 cm in 2014.

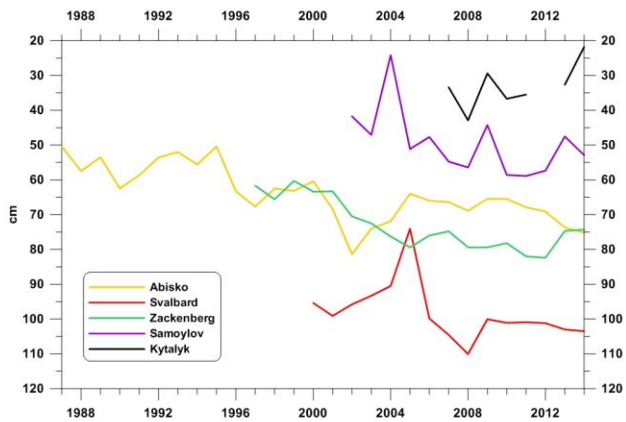

Figure 4. Active layer thickness recorded as averages of all the measuring points in the CALM grids of each PAGE21 sites. For Abisko, Svalbard and Zackenberg the reported numbers are all averages of the standard 121 CALM grid recording points.

4. DISCUSSION

4.1 Permafrost temperature

The difference in climate over the Arctic is clearly reflected in the ground thermal regimes at the PAGE21 sites during the 2012-2013 PAGE21 recording period. The permafrost temperatures are lowest in the two Russian sites in Yakutia with mean annual ground temperatures (MAGT) of -8.3 ˚C in Kytalyk and -7.1 ˚C in Samoylov at 7 and 8 m depths. This is slightly warmer than typical alas depression permafrost temperatures reported from the Yakutia region varying from -9˚C at 71˚41'N to -7 ˚C at 68˚50'N (Romanovsky et al., 2010a). Very large annual ground thermal variations occur in the top permafrost at both sites. The largest was at Samoylov, reflecting the large annual air temperature amplitudes in particular the large winter cooling, relatively thin snow covers, but also high ice contents in the sedimentary ground.

In NE Greenland the permafrost is almost as cold with MAGT of -6.8˚C at 8 m depth as in the two Russian sites, but with much less seasonal variation probably due to less winter cooling and only a thin snow cover.

Maritime Svalbard sees the same amount of annual variation in the permafrost temperature as NE Greenland, but is warmer with MAGT of -4.4˚C, clearly affected by the warm winters, but still with a relatively high ice content in the top permafrost (Cable et al submitted).

The MAGT at Abisko is only -0.4˚C, and there is clearly no influence of the long summer warming of the ground, as the maximum ground temperature is very stable below the active layer (Fig.3).

The presented ground temperatures might have some recording problems for some of the sites, which have not yet been completely identified, allowing some wriggles on the trumpet curve from Zackenberg, and not completely realistic values in the top of the Samoylov borehole. In Samoylov the top 2 m metal casing is known to be causing problems with correct ground temperature recording.

Generally the permafrost temperatures have increased during the period leading up to the PAGE21 recording period in Samoylov and Svalbard. In Samoylov the permafrost has warmed about 2˚C in the period from 2006-2007 to 2012-2013. However, from summer 2011 to summer 2013 no larger changes took place before a warming in summer 2014, which must therefore represent a winter warming. In Svalbard a warming of about 1˚C took place primarily from winter 2011 to late winter 2013, while the temperature has been more stable since then. In Kytalyk there is no distinct change. The only 2 year long time series from Zackenberg show a decrease of about 0.5˚C. Also Abisko recorded a very small decline in temperatures from 2008 to 2011, and since then no change.

Comparing the timing of the annual ground temperature variations both Russian sites have maximums in mid winter, while both the Svalbard and NE Greenland sites have maximums some months later in winter. This must reflect the larger annual temperature variations with an earlier and longer cooling period for the continental sites compared to the maritime site in particular Svalbard. The fact that Abisko does not have an obvious seasonal pattern shows that the peat deposits are more isolating than sediments, and potentially have a higher ice content.

4.2 Active layer thickness

The ALT values mainly reflect the meteorological differences between the sites as well, but also show that the active layer material has large influence. In particular the relatively thin ALT in Abisko is caused by the peat material rather than reflecting meteorological forcing. The very shallow ALT of Kytalyk partly reflects the timing of recording being too early in summer, due to limited fieldwork periods. However, with some years of recording in end of August, and thus the overall size of between only 30 to 40 cm should be correct.

The longest ALT data series from Abisko starting in 1987 with full CALM grid measurement show a general increase in ALT, with some 2-3 year long periods with quick increases of 15-20 cm, while in the longer periods in between ALT first decreases somewhat again followed by almost no change. The same increase in ALT is seen in Samoylov, Zackenberg and Svalbard, from the start of observations in 2002, 1997 and 2000 respectively. However, this increase ends around 2009 for these three sites. Since then, only a small increase in ALT has been recorded in Svalbard, whereas during the PAGE21 recording period ALT have thinned in Zackenberg, Samoylov and Kytalyk, but increased most at Abisko.

5. CONCLUSIONS

The presented PAGE21 permafrost thermal state and active layer thickness variability across the Arctic show the overall climatic control on the ground thermal dynamics. However, the data also indicate that site specific details such as vegetation, high ice content and landforms type can have large influence and needs to be understood to correctly evaluate future permafrost sensitivity at landscape scale. In order to understand this even further more detailed analyses needs to be included.

6. ACKNOWLEDGEMENTS

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