Permafrost thermal snapshot and active-layer thickness in Svalbard 2016–2017

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Introduction and objectives

This report is the product of international collaboration of several permafrost researchers working in Svalbard. The report aims to provide an overview of ground thermal conditions and active-layer thickness as they are recorded at five sites during the 2016/2017 hydrological year from 1 September 2016 to 31 August 2017 in Svalbard. We report on this period, as this is when observation variables are available from all sites. This provides the basis for comparison of spatial variations in permafrost thermal conditions and active layer thickness in Svalbard. For earlier summaries of permafrost conditions on Svalbard see Humlum *et al.* (2003) and Christiansen *et al.* (2010).

The specific objectives of this report are to: (1) introduce the study area and permafrost in Svalbard; (2) describe instrumentation and operation at each of the five sites; (3) characterize the ground thermal regime and present the active-layer thickness from the last 2016-2017 hydrological year; (4) provide an overall analysis of the ground-thermal observations with a focus on the implications of changing permafrost on other parts of the cryosphere relevant for the SIOS network; (5) ensure access to the reported data through the Global Terrestrial Network on Permafrost (GTN-P) adhering to the SIOS Data policy and (6) point to potential avenues and geographic locations for future permafrost observation needs in Svalbard.

This report builds on the IPY 2007-2008 snapshot of the permafrost thermal state and active layer thickness in Svalbard (Christiansen *et al.*, 2010), but now provides ground temperatures from more areas in Svalbard thanks to the international collaboration. The report may serve as a baseline for future regional observation programs and collaborative activities within the SIOS network.

Permafrost background

Permafrost plays an important role in the Earth System as it underlies 25% of the terrestrial parts of Planet Earth. It is a ground thermal condition occurring in cold regions, and is defined as ground (soil, sediment, or rock) that remains at or below 0°C for two or more consecutive years. Svalbard has the warmest permafrost this far north (Romanovsky et al., 2010). The thickness of permafrost on Svalbard is believed to range from a few meters in coastal areas to several hundred meters in mountain peaks (Liestøl, 1977; Humlum, 2005). Permafrost regions are further characterized by the presence of an active layer – the layer above the permafrost which thaws during summer and refreezes during winter. The active layer is of significance as it is the main zone through which water moves in permafrost landscapes, and in which chemical and biological processes are most active (French, 2013).

Due to the nature of permafrost being a negative thermal state of the ground that is often close to the freezing point, it can be affected by climatic changes. However, the relationship between air temperature and ground temperatures is mediated by conditions at or near the ground surface (Smith & Riseborough, 2002). Snow cover impacts ground temperatures, through its insulating effect, by reducing heat loss from the ground during the winter season. In addition, variations in the thermal properties of the active layer, between frozen and unfrozen states, reduce the heat flow into the ground. The thermal conductivity (the readiness with which a material conducts heat) is approximately four-times higher for ice than for liquid water. This means that the ground cools more readily when frozen. Finally, the amount of time it takes for the active-layer to freeze-back during the late autumn and early winter has a significant impact on the underlying permafrost. During active-layer freeze-back, temperatures in the active layer are isothermal above the phase-equilibrium temperature, and the permafrost is less directly influenced by the atmosphere (Osterkamp & Romanovsky, 1997). Following the freeze-back of the active layer, the temperatures at the permafrost surface is permitted to decline (c.f. Burn & Zhang, 2009). The duration of active-layer freeze-back is an important variable as it is a derivative of several factors including: active-layer moisture content, snow cover timing and thickness, and autumn air temperatures. Longer freeze-back durations reduce the amount of time available for ground cooling, resulting in increased ground temperatures in the permafrost.

Essential climate variables on permafrost in Svalbard

The monitoring of essential climate variables, ECVs, for permafrost is delegated to the Global Terrestrial Network on Permafrost (GTN-P) by the World Meteorological Organization (WMO). GTN-P established permafrost temperature and active-layer thickness (ALT) as ECVs related to two specific monitoring programs: 1) TSP (Thermal State of Permafrost) and 2) CALM (Circumpolar Active Layer Monitoring) (Romanovsky *et al.*, 2010; Shiklomanov *et al.*, 2012). GTN-P was developed in 1999 by the International Permafrost Association (IPA) with active support by the Canadian Geological Survey (Burgess *et al.*, 2000) under the Global Climate Observing System (GCOS) and the Global Terrestrial Observing Network (GTOS). The purpose of GTN-P is to establish an open access early warning system for the consequences of climate change in permafrost regions. The first overview of GTN-P observations and their key results include data from Svalbard (Biskaborn *et al.*, 2015).

Ground temperature monitoring sites consist of three elements: a borehole, an encased thermistor string and an automated data logger. As sites were established independently, there are differences in the instrumentation used and the depths at which ground temperature sensors (thermistors) are positioned. The density of temperature sensors generally decreases with depth as the temperature signal at the ground surface is rapidly attenuated moving with depth into the ground. The automatic data loggers in all boreholes are programed to record the borehole temperature at regular intervals (varying from 1 to 6 hours). The instrumentation used at each site is included in Table 1. Boreholes vary in length from a few meters to upwards of 100 meters. For this report, ground temperatures from within 20 m of the ground surface are included to characterize the upper part of the permafrost profile, the part that is most directly affected by climatic variations. We are aware that for some boreholes the casing might affect the ground temperatures recorded closer to the ground surface. To study the active layer dynamics we have also used data from all parts of the boreholes.

The thickness of the active layer is either recorded directly through probing or estimated by interpolating the depth of the 0°C isotherm using borehole thermal measurements (Burn, 1998). Probing is suitable only in fine-grained soils, without gravel and boulders. In addition to point measurements, made at each borehole, two Circumpolar Active Layer Monitoring (CALM) sites are established in Svalbard, one in Adventdalen (UNISCALM) and one near Barentsburg (Fig. 1; Christiansen & Humlum, 2008; Shiklomanov *et al.*, 2012). These CALM sites consist of a grid, measuring 100 m x 100 m or 50 x 50 m with 10 or 5 m grid size, and probe measurements are made at the 121 regularly spaced grid points. Measurements are repeated throughout the thawing season to monitor the thaw progression in the UNISCALM site.

In Svalbard, systematic measurements of active-layer thickness and ground-temperature profiles are presently limited to sites in the western and central parts in Spitsbergen (Fig. 1). Data from Ny-Ålesund, Adventdalen, Barentsburg, Kapp Linné, and Hornsund are examined. These areas are all located near major settlements and research stations in Svalbard, and have been established independently by scientists based in Norway, Svalbard, Germany, Italy, Russia, and Poland. The results of this report will therefore be of significance to those working in these areas, and form the foundation for a collaborative international long-term permafrost monitoring network in Svalbard as part of SIOS.

Table 1: Site information and metadata for permafrost boreholes used in this report.

Location	Borehole name/ ID	Operator	Longitude	Latitude
Adventdalen	Old Auroral Station 2	The University Centre in Svalbard	15°50’05”E	78°12’05”N
	Endalen	The University Centre in Svalbard	15°46’54”E	78°11’26”N
	Breinosa	The University Centre in Svalbard	16°04’01”E	78°08’35”N
	Janssonhaugen/ P10	Norwegian Meteorological Institute	16°28’01”E	78°10’46”N
	Janssonhaugen/ P11	Norwegian Meteorological Institute	16°28’01”E	78°10’46”N
Ny Ålesund	Bayelva	SPARC, Alfred Wegner Institute (AWI)	11°50’03”E	78°55’15”N
	DBNyÅlesund	Insubria University	11°52’00”E	78°55’14”N
Kapp Linné	Kapp Linné 1	University Centre in Svalbard	13°38’05”E	78°03’21”N
	Kapp Linné 2	University Centre in Svalbard	13°38’13”E	78°03’15”N
Barentsburg	Borehole 12	Arctic and Antarctic Research Institute (St. Petersburg)	14°14’27”E	78°05’42”N
Hornsund	Meteo	Polish Polar Station, Hornsund	15°31’59”E	76°59’58”N

*New borehole established in summer 2017, but not reported on here as not yet a full year data series.

Elevation (m a.s.l.)	Borehole depth (m)	Landform	Instrument manufacturer	Sensor depths (m)
9	9.85	Loess on terrace	Geoprecision	0, 0.25, 0.5, 0.75, 1, 2, 3, 5, 7, 9.85
53	19	Solifluction sheet	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 19
677	10	Blockfield	Geoprecision	0, 0.25., 0.5, 1, 2, 3, 4, 5, 7, 10
254	102	Hilltop (bedrock)	Campbell	0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5, 4, 5, 7, 9, 10, 11, 13, 15, 20, 25, 30, 40, 50, 60, 70, 80, 85, 90, 95, 97.5, 100
254	15	Hilltop (bedrock)	Campbell	0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5, 4, 5, 7, 10, 13, 15
25	9.3	Ground moraine	Geoprecision	0, 0.5, 1, 1.5, 2.5, 3.5, 5.5, 7.5, 9
55	48.5	Ground moraine	Campbell	0.3, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5.5, 8, 10, 13, 16, 20, 23.5, 30.3, 35.3, 40.3, 45, 48.5
20	29	Strandflat bedrock outcrop	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 29
20	38	Strandflat with beach deposits over bedrock	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 30, 35, 38
95	20	Marine terrace (gravels)	Geoprecision	0, 0.75, 1.5, 2.25, 3, 3.75, 4.5, 5.25, 6, 6.75, 7.5, 8.25, 9, 9.75, 10, 11.25, 12, 12.75, 13.5, 14.25, 15
10	1, 12*	Raised beach deposits (gravels)	Vaisala QMT107	0.05, 0.1, 0.2, 0.5 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 8.0, 10.0, 12.0*

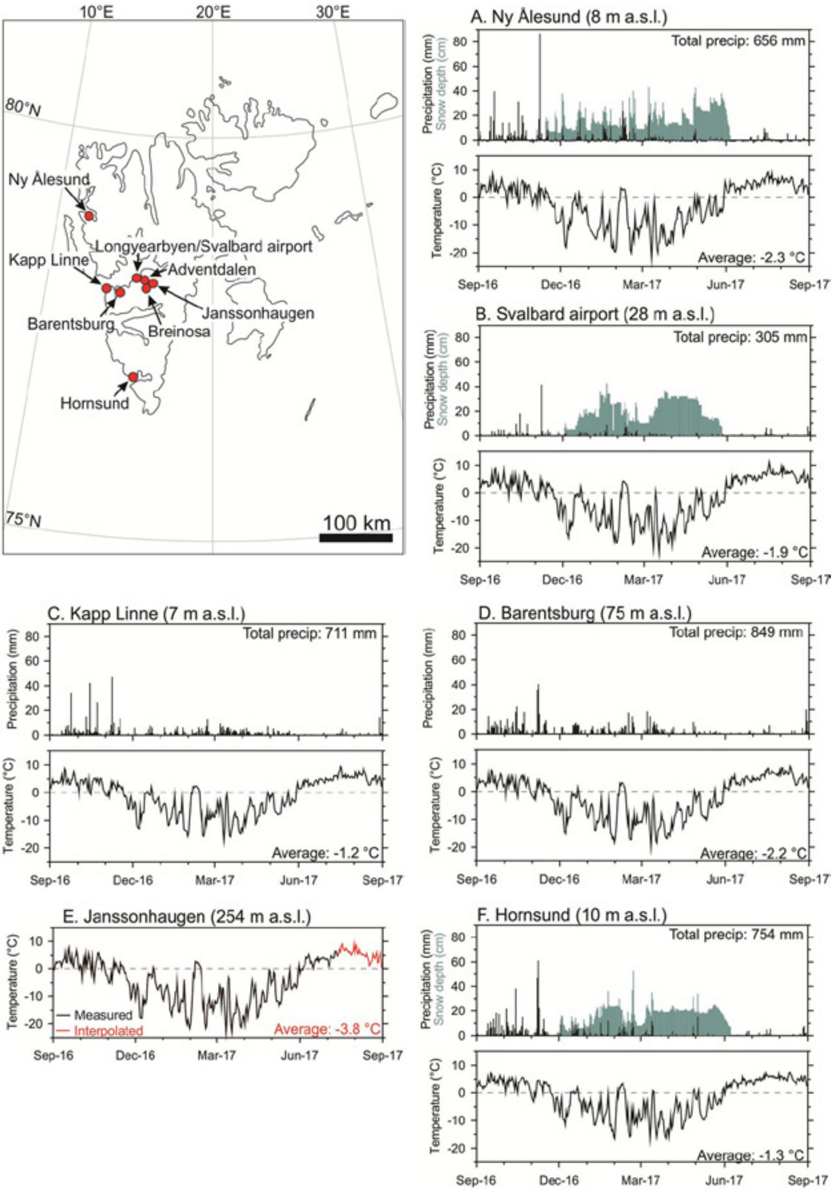

Figure 1: Location of the reported permafrost observations in Svalbard, and meteorological parameters recorded close by. Included in the A-F meteorological plots are the average air temperatures for the hydrological year 2016-2017. The interpolated data series in E is based on regional meteorological stations and included to complete the time series.

Meteorology 2016-2017 and long-term permafrost observations in Svalbard

The climate of western and central Spitsbergen is strongly influenced by the warm Norwegian current, flowing along the western coast (Førland *et al.*, 2011). In addition, Svalbard is located within the North Atlantic cyclone track (Hanssen-Bauer *et al.*, 1990). Cyclones lead to relatively high air temperatures, especially during the winter period. The net effect of these geographic phenomena is that western and central Spitsbergen is markedly warmer than other locations at comparable latitudes. While other sites throughout the high Arctic recorded mean annual air temperatures (MAAT) ranging from -9°C to -15°C in 2009 (Eckerstorfer & Christiansen, 2011), MAAT during 1981-2010 in western and central Svalbard ranged from -3.8°C at the most maritime site at Isfjord Radio (close to the permafrost site at Kapp Linné) to -5.2°C at the northernmost site in Ny-Ålesund (Førland *et al*. 2011; Gjelten *et al*. 2016). Ny-Ålesund and Svalbard Airport were coldest in winter, spring and autumn, whereas in summer Hornsund in the south is coldest, probably due to more lingering sea ice than at the other stations (Gjelten *et al*. 2016).

The hydrological year 2016-2017 had a particularly warm, wet and long-lasting autumn in Svalbard (Fig. 1). Several all-time high air temperature and precipitation extremes were registered on Svalbard, and in the Arctic in general (AMAP 2017). Mean air temperature (MAT) at e.g. Svalbard Airport during autumn (SON) 2016 was 2.2°C, which is 6.2°C above the 1981-2010 average, and 2.3°C higher than the previous maximum in 2000 (Nordli et al. 2014). Ground freezing generally begins towards the end of September in Svalbard. However, air temperatures in September and October, 2016, remained above freezing, and the freezing season was delayed into mid-November. Thus, air temperatures during the study period were significantly higher than normal, affecting the permafrost thermal regime, as the time available for the ground cooling was shorter than in other years. Within the study sites, the average air temperature during the 2016-2017 hydrological year ranged from -1.2°C at Kapp Linné (Isfjord Radio), to -3.8°C at Janssonhaugen (Fig. 1). In general, air temperatures decreased with distance from the coast, in a northerly direction and with altitude. These trends illustrate the increasing degree of continentality moving east (cf. Gjelten *et al*. 2016) and cooling with elevation. Precipitation amounts were additionally greatest at the coastal sites, 656 mm in Ny-Ålesund, 711 mm in Kapp Linné (Isfjord Radio), 849 mm in Barentsburg, and 754 mm in Hornsund, and lowest at the more continental site in Longyearbyen (Svalbard Airport) with 305 mm.

Compared to the Arctic regions in Russia and North America, the ground thermal records in Svalbard are of short duration (Romanovsky *et al.*, 2010). Fragmentary ground temperature data were first obtained at Kap Thordsen, in central Svalbard from 1882 to 1883 during the first IPY (Ekholm, 1890; Wood and Streletskiy, 2008). Since then, however, systematic permafrost temperature measurements extend back to 1998 (Isaksen et al. 2001; Christiansen *et al.*, 2010; Boike et al. 2018). Ground temperatures have been reported to increase over the duration of this period of time at both the Adventdalen (Janssonhaugen), Kapp Linne and Ny Ålesund sites, whereas such long records do not exist from the other two sites (AMAP, 2017; Romanovsky et al., 2017; Boike *et al.*, 2018). These changes conform to observations from throughout the circum-Arctic (IPCC, 2013; AMAP, 2017). It should therefore be recognized that ground temperatures from the 2016/2017 hydrological year are likely to be among the highest during the period of the instrumental record, when also air temperatures peaked.

Svalbard permafrost observations

Ground thermal conditions studied from boreholes in Svalbard all come from the five field sites: Ny-Ålesund, Adventdalen, Barentsburg, Kapp Linné, and Hornsund (Fig. 1). Borehole locations and metadata is provided in Table 1. Sites and instrumentation are discussed in detail below.

Ny-Ålesund

Meteorological data from Ny-Ålesund records a MAAT of -2.3°C and 656 mm of precipitation for the 2016-2017 hydrological year. There are two boreholes at this location: DBNyÅlesund (48.5 m deep) and Bayelva (9.3 m deep). The DBNyÅlesund borehole is located at 55 m a.s.l. on *Kolhaugen*, between the coast and the Austre Broggerbreen forefield. The borehole stratigraphy consists of ca. 14 m of diamicton, possibly a glacial till, with bedrock from ca. 14 m depth. The gravimetric ice content of the permafrost ranges from ca. 10% to 40%, and no excess ice was observed. Several inactive sorted circles occur in the area as well as some soli-gelifluction lobes and terracettes. The Bayelva borehole is located between two mountains (Zeppelinfjellet and Scheteligfjellet), ca. 3 km from Ny-Ålesund. This borehole is located on top of the Leirhaugen hill, which consists mainly of rock, but is partly covered by till, together with fine-grained glaciofluvial sediments and clays. The vegetation cover is approximately 50–60%, with the remainder being bare soil with a small proportion of stones (cobbles and gravel; Lloyd *et al.*, 2001). The site is described by Boike *et al.* (2018).

There is a grid for recording active layer thickness in Ny-Ålesund next to the DB/Meteo borehole. Due to the blocky substrate, it is only possible to report the active layer depth as an average of 10 grid points, where thermistors are installed in combination with the borehole data. This is because probing in not possible.

Adventdalen

The Adventdalen study area is located in central Svalbard near the town of Longyearbyen. Average air temperature during the study period, as measured at the Svalbard Airport, was -1.9°C and approximately 305 mm of precipitation was reported. Five boreholes (Table 1) encompass the range in landform and local topographical locations which cause different ground thermal conditions, have been selected for this study: Endalen, Old Auroral Station 2, Breinosa, and Janssonhaugen. These sites have previously been described by Christiansen *et al.* (2010). Active-layer measurements are made in the UNISCALM site (Christiansen & Humlum, 2008) with 121 points in a 100 x 100 m site, monitored with 10 m grid size.

The 19 m deep Endalen borehole is located at 53 m a.s.l. and is drilled within a solifluction sheet. The stratigraphy at Endalen has 6 m of solifluction material overlying sedimentary bedrock. The 10 m deep Old Auroral Station 2 site is located at 9 m a.s.l and installed in an aggrading loess terrace. The borehole stratigraphy consists of sands and the gravimetric moisture content varies between ca. 30% and 150%. The 10 m deep Breinosa borehole is located at 677 m a.s.l in a blockfield consisting of *in situ* weathered bedrock. The Janssonhaugen boreholes –102 m and 15 m deep are located at 254 m a.s.l. and are drilled into fine-grained porous sandstones and siltstones. The vegetation cover on Janssonhaugen is sparse and surficial deposits are made up of *in situ* weathered bedrock (Isaksen *et al*. 2001).

Barentsburg

The Barentsburg study area is located at the mouth of Grønfjorden, in the vicinity of the Barentsburg mining settlement (Fig. 1). The average air temperature was -2.2°C and 849 mm of precipitation was reported during the study period. Long-term permafrost observations began at the permafrost site of the Russian Scientific Center in Svalbard in summer 2016 (Demidov *et al*., 2016). Permafrost temperature observation sites are established in a sequence of Holocene marine terraces. Automated thermistor cables were installed in three boreholes, each 7 m to 15 m deep, to monitor the temperature close to the depth of zero annual amplitude and seasonal distribution of the zero-degree isotherm. Data from the 2016/2017 hydrological year is only available from borehole 12, which is 15 m deep. Permafrost temperatures from two additional boreholes (borehole 2, 7.5 m deep and borehole 8, 15 m deep) will be available in the coming years.

Borehole 12 was drilled during coal exploration in the early 1930s. The borehole was cased and instrumented for ground-thermal monitoring in August 2016. It is situated on a gently inclined surface, sloping 2° to the NW, at the top of a set of marine terraces near the Barentsburg aerodrome. The soil is 80 % plant-covered and 20 % covered by rocks. Geologically, the borehole site has fractured sandstone and mudstone overlain by 2 m of gravelly loam with rocks. The terrace surface around the borehole has a poorly defined pattern structure. A 15 m thermistor cable is installed in this borehole.

A CALM site was established in September 2016 including 121 point with a 10 m grid size. In September 2017, the CALM site was reduced to a 5 m grid size to observe in a more homogeneous setting. Stratigraphically the CALM site has interlayering sand, loam and clay with rare boulders. The surface has a distinct pattern structure with sorted circles.

Kapp Linné

The Kapp Linné region in western Spitsbergen (Fig. 1) has a maritime and relatively warm local climate. Mean air temperature and precipitation sum at the nearby meteorological station at Isfjord Radio during the study period was -1.2°C and 711 mm respectively. Two boreholes are located at this site: Kapp Linné 1 (KL-B-1) and Kapp Linné 2 (KL-B-2). Kapp Linné 1 is 29 m deep and drilled into an outcrop of silicified carbonate and clastic sedimentary bedrock. Kapp Linné 2 is 38 m deep and drilled through ~6.2 m of gravels overlying the same type of bedrock. Both boreholes are located on a strandflat, with extensive coarse-grained raised marine beach ridge at ca. 30 m a.s.l. (Christiansen *et al.*, 2010). The sites were established to test the variability between sedimentary and bedrock boreholes, as they are only 200 m apart on the strandflat.

Hornsund

The Polish Polar Station Hornsund is located on the northern shore of the Hornsundfjord on Wedel Jarlsberg Land in SW Spitsbergen (Fig. 1). The mean annual air temperature at the metrological station was -1.3°C and 754 mm of precipitation was reported during the study period. Since July 1978 shallow year round ground temperature observations were established. Variations of ground thermal conditions for the entire study period were measured within the top one meter of the ground surface only near the meteorological station. In spring 2017, three additional boreholes (10 m to 20 m deep) were established. The first deeper full-year permafrost time-series will be available from summer 2018. The ground temperature data included in this report consist of the near-surface ground temperatures together with the ground temperature measured at 12 m depth, which is only recorded in July and August 2017, near the meteorological station. The temperature at 12 m depth, has measured in a new deep borehole at the meteorological station, and has been included as a preliminary estimate of ground temperature near the depth of zero annual amplitude.

Ground thermal regime & active-layer thickness 2016-2017

Permafrost thermal state

Mean ground temperature measured at the depth of zero annual amplitude (ZAA) (Table 2), or the depth at which there is no annual fluctuation in the ground temperature, provide the point to monitor the response of permafrost to climate change. Ground thermal profiles recorded throughout the period are summarized in Fig. 2 and Fig. 3. The highest mean ground temperature was observed as -1.1°C in Hornsund, but only measured during 2 months (so not yet a full year). The highest full-year permafrost temperature measurement at -2.3°C was recorded at Barentsburg, which was then higher than the -2.6°C and -2.8°C recorded further out at the west coast at Kapp Linne. Adventdalen had the lowest permafrost temperatures at -5.2°C, but with a rather large variation with up to -2.7°C for the Endalen site. The permafrost in the Ny-Ålesund area is almost as warm as the other west coast sites with respectively -2.8°C and -3.1°C. The -3.1°C value measured in the deep borehole show somewhat colder conditions in this northern most part.

The mean ground surface temperatures and mean temperature at the permafrost surface were highest closest to sea level (Fig. 3; Table 2). Comparing all sites, the air temperature range was 2.6°C, whereas there was 4.5°C of variation in mean temperature at the ground surface. In addition, a large degree of local variation in temperatures at the ground surface and permafrost surface are identified, particularly in Adventdalen, where more boreholes exist. The range and local variation in mean ground surface temperature is attributed to the effect of snow, which is unevenly distributed throughout the landscape due to variations in topography and wind-exposure. Sites such as Endalen, which experience thick and long-lasting snow cover, have a higher mean ground surface temperature of 0.4°C. Sites where relatively little snow accumulates however, are comparatively cooler even with a distance of only 500 m apart, such as the Old Auroral Station 2 which measures temperatures of -1.3°C.

Generally both the permafrost surface temperatures and the permafrost temperature at ZAA were lower than the air temperatures. This and the shape of the ground thermal profiles (Fig. 2) show warming permafrost conditions.

Table 2: 2016-2017 hydrological year thermal characteristics, snow conditions, and active-layer thickness at the permafrost borehole sites. Reported active-layer thickness determined by interpolation.

Location	Borehole name/ ID	MAT (°C)	MGST (°C)
Adventdalen	Old Auroral Station 2	-1.9	-1.3
	Endalen	-1.9	n/a
	Breinosa	-3.8	-4.1
	Janssonhaugen/ P10	-3.8	n/a
	Janssonhaugen/ P11	-3.8	-3.7(0.2 m)
Ny Ålesund	Bayelva	-2.3	-3.6
	DBNyÅlesund	-2.3	-2.8 (0.3 m)
Kapp Linné	Kapp Linné 1	-1.2	-1.6
	Kapp Linné	-1.2	-1.6
Barentsburg	Borehole 12	-2.2	-0.8
Hornsund	Meteo	-1.3	-1.0

MAT = mean air temperature (at nearest meteorological station)

MGST = mean ground surface temperature

MPST = mean temperature at the permafrost surface

MGT = mean ground temperature (at depth of zero annual amplitude if different from total borehole depth or at lower most sensor)

ALT = active-layer thickness (as estimated from interpolating the depth of the 0 °C isotherm)

**Only recorded during July and August 2017*

	MPST (°C)	MGT (°C)	Duration of AL freeze-back (days)	Maximum snow depth (cm)	ALT (cm)
	-3.2	-5.2 (9.9 m)	22	ca. 20	94
	-0.5	-2.7 (19 m)	140	ca. 50	190
	-4.0	-5.1 (10 m)	18	<50	49
	n/a	-5.0 (20 m)	n/a	<20	n/a
	-3.7	n/a	41	<20	185
	-2.7	-2.8 (9 m)	49	< 30	200
	-2.7	-3.1 (20 m)	35	<30	192
	-1.8	-2.6 (20 m)	44	<10	300
	-1.5	-2.8 (20 m)	49	<10	190
	-1.3	-2.3 (15 m)	59	ca. 20	175
	n/a	-1.1* (12 m)	n/a	46	n/a

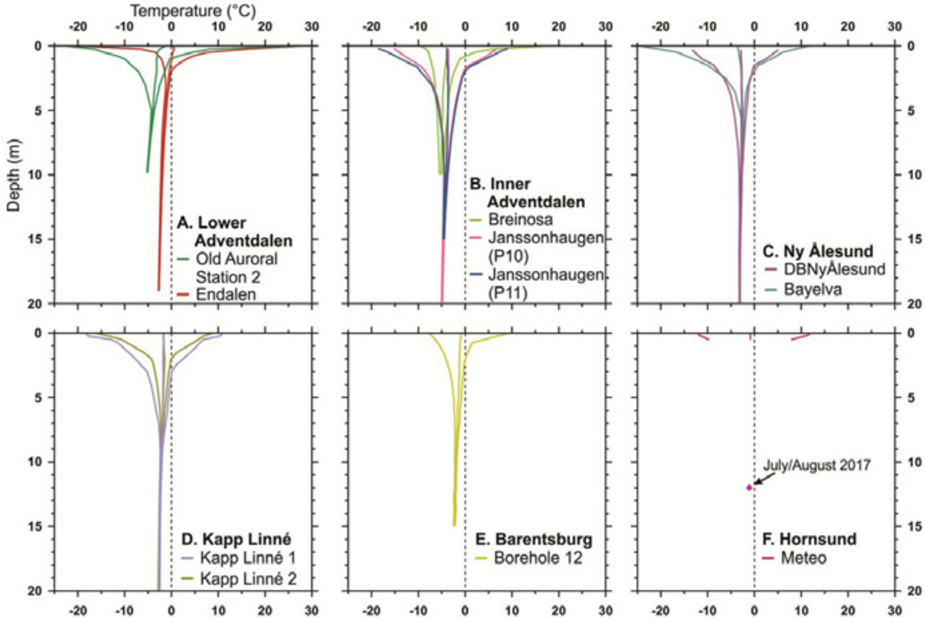

Figure 2: Ground thermal snapshot (minimum, mean, and maximum temperatures) as measured in the upper 10 to 20 m of the permafrost observation boreholes in Svalbard during the 2016/2017 hydrological year.

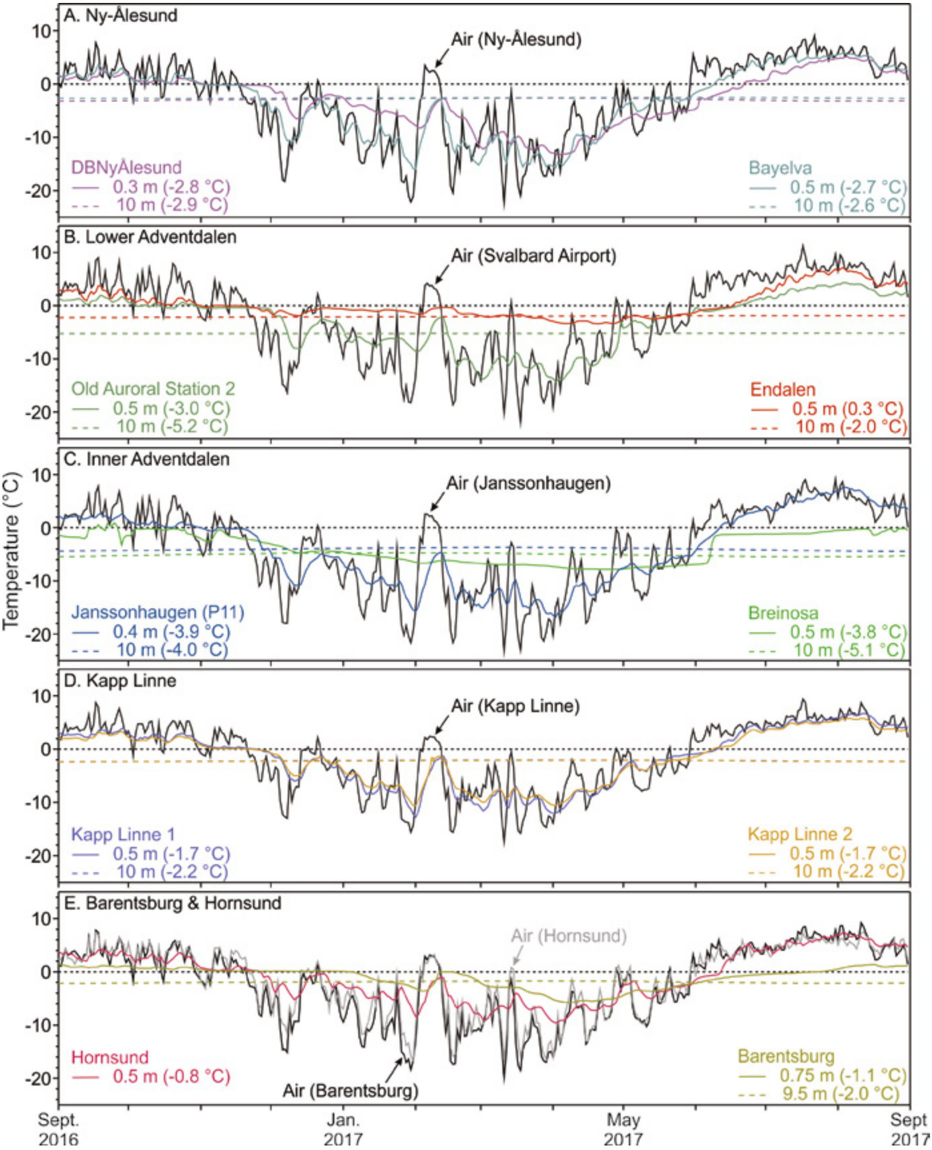

Figure 3: Continuous air and ground temperatures during the 2016-2017 year for the five permafrost observations sites in Svalbard. The presented selected sensors are located approximately in the middle of the active layer at 0.5 m depth (or as close to as possible) and at 10 m depth (where possible). The mean ground temperature, calculated at each depth, is presented in brackets.

Active-layer thickness

The active-layer thickness, as measured in autumn 2017, is presented in Fig. 4 and Table 2. Except for the CALM sites in Barentsburg and Adventdalen, active-layer thickness was estimated by interpolation of the zero-degree isotherm. Active-layer thickness in the study area ranges between ca. 49 cm (Breinosa) and ca. 300 cm (Kapp Linné 1), with most sites falling in the range of 100 cm to 200 cm. Spatial trends in active-layer thickness are difficult to discern due to the range in factors which influence ground thawing. However, boreholes in bedrock (Janssonhaugen & Kapp Linné 1) generally have a thicker active-layer than those in soil or sediment, due to lower ice content and a higher thermal conductivity. The thinnest active layers are in the more continental parts of the archipelago in a high-lying coarse-grained blockfield and in sediments with higher ice content.

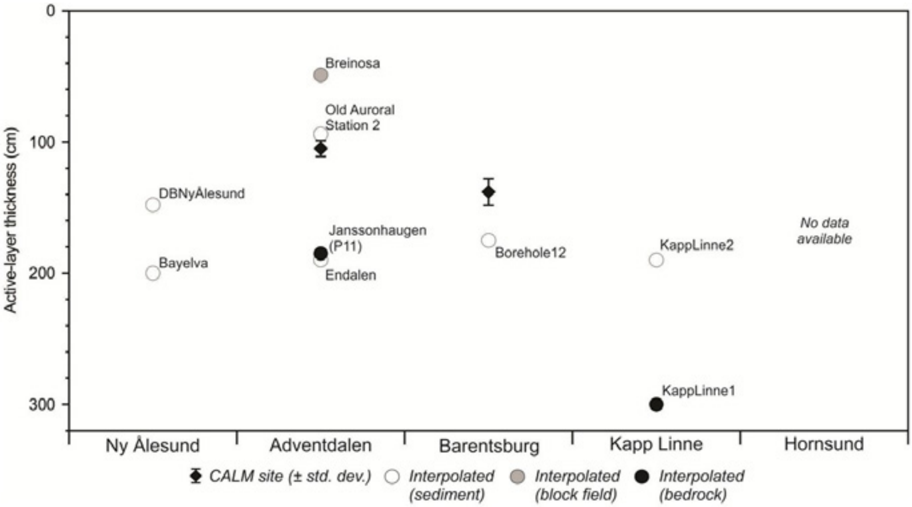

Figure 4: Active-layer thicknesses recorded at the end of August, 2017 from CALM grids and interpolated from the reported boreholes. The active-layer at the Bayelva site in Ny Ålesund was estimated using the Stephan equation. Note shading denotes substrate type.

Active-layer freeze-back duration

The duration of the active-layer freeze-back, measured as the period extending from when sustained freezing temperatures are established at the ground surface to when the temperature at the permafrost surface begins to decline, record when a complete phase change has occurred. Freeze-back durations are listed in Table 2, and range from 18 days to 140 days. At sites in block fields (Breinosa) and relatively dry locations (Old Auroral Station 2), freeze-back occurs quickly (18-22 days). At sites with a thicker active-layer and higher soil moisture content (e.g. Endalen) the period of active-layer freeze-back occupies a significant fraction of the freezing season (140 days). The duration of freeze back is important in regulating when permafrost cooling can begin. Therefore, sites with long active layer freeze-back commonly have higher permafrost temperatures, as a smaller proportion of the freezing season is available for permafrost cooling (Table 2).

During the 2016/2017 hydrological year, ground freezing initiated in November. As a result active-layer freeze-back extended into December or January at most sites, and into April at the Endalen location. The net effect of this was relatively high temperatures in the near surface of the ground-temperature profile (Fig. 2). This effect is also observed when comparing temperatures at the permafrost surface and ground temperatures (Table 2). In all cases, temperatures at the permafrost surface are significantly higher than at depth.

Conclusion

The reported ground temperatures and active layer thicknesses illustrate the range in the observed permafrost conditions in Svalbard in 2016-2017. In general, westerly sites, close to the coast are warm, while sites at higher elevations or in the more continental central parts of Svalbard are cooler. Exceptions are sites which experience a thicker winter snow pack. The following points summarize the observed distribution of ground temperatures and active-layer depths in Svalbard:

- Mean annual air temperature and total precipitation during the study period ranged between -1.2°C and -3.8°C, and 305 mm and 849 mm, respectively at the five studied permafrost sites in western and central Svalbard. In general, maritime sites situated closer to the coast were wetter and warmer than those in more central areas or at higher altitudes. In this particularly warm hydrological year 2016-2017 ground freezing only started in November, with active layer freeze-back lasting from December to April for the studied sites. This causes relatively high permafrost temperatures in the top permafrost.
- Permafrost temperatures were highest at coastal sites or where a thicker snow cover during winter occured. Mean annual ground surface temperatures during the

2016-2017 hydrological year (1 September 2016 to 31 August 2017) observed in boreholes in the five permafrost study sites in Svalbard, ranged from -1.0°C to -4.1°C. Mean annual temperatures at the permafrost surface ranged between -0.5°C and -4.0°C, and permafrost temperatures at or close to the depth of zero-annual amplitude varied from (-1.1°C) -2.3°C to -5.2°C. Differences are attributed to variations in snow cover, landforms, the degree of continentality and ground ice contents. All the results clearly show that we have rather warm permafrost in extensive parts of particularly the lowland Svalbard landscape, which is especially sensitive to climatic warming and where the population is living. Along the west coast there is a clear gradient from the warmest permafrost in the south at Hornsund -1.1°C, over -2.3°C at Barentsburg, and to the coldest in the north at Ny-Ålesund with -3.1°C.

- The thickness of the active layer, as measured in autumn 2017, varied from 49 to 300 cm, but generally fell within the range of 100 cm to 200 cm. The thinnest active-layers are reported from blockfields at higher elevations and in sediments. Thicker active-layers are encountered in bedrock settings.

Future permafrost observations in Svalbard

Previous observations have focused on understanding permafrost conditions near to settlements and research stations in western and central Svalbard. However, ground thermal conditions are not likely to be representative of the northern and eastern reaches of the archipelago, where the climate is considerably cooler. Future observations efforts will therefore focus on characterizing permafrost environments in northern and eastern parts of Svalbard. Including such areas will most likely allow observations of the full diversity of permafrost conditions throughout the entire Svalbard landscape. New permafrost observations to be established in these areas will be co-located with automatic weather stations (AWSs) within the Norwegian project *SIOS – Infrastructure development of the Norwegian node* (*SIOS-InfraNor*) and potentially also by other SIOS partners in national or international collaborations. This will expand our existing understanding of permafrost conditions throughout Svalbard, and provide the baseline infrastructure required for observing responses of the Svalbard permafrost to climate changes.

In addition to the discussed ECVs for permafrost, ground-ice content is a key parameter for assessing the response of permafrost landscape to changes in climate. Where permafrost contains an abundance of ice, warming and thawing will lead to marked geomorphic change. In flat areas, ground-ice degradation can result in thermokarst and subsidence; excess water on slopes released during ground ice melting, particularly in the top permafrost, can initiate landslides. Degradation of permafrost through the increase in active-layer thickness is of significance for local ecosystems and hydrology. Nutrients, gasses and minerals frozen within the upper meters of the permafrost zone can be released into local eco- and hydrological systems during permafrost thaw. Continued research in these areas will further aid in coupling changes within permafrost to the remainder of the cryosphere, as is a goal for a better Earth System understanding.

Data accessibility

All reported data have been submitted into the GTN-P database (https://gtnp.arcticportal.org/). This includes both metadata and direct access to the data.

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