Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016–2019 (PermaSval)

Hanne H. Christiansen[1], Graham L Gilbert[1,2], Ullrich Neumann[3], Nikita Demidov[4], Mauro Guglielmin[5], Ketil Isaksen[6], Marzena Osuch[7], and Julia Boike[8]

[1] University Centre in Svalbard, UNIS, Arctic Geology Department, Longyearbyen, Norway.
[2] Norwegian Geotechnical Institute, Natural Hazards Division, Oslo, Norway.
[3] Kolibri Geo Services, Risør, Norway
[4] Arctic and Antarctic Research Institute, AARI, Ministry of Natural Resources and Environment, Russia.
[5] Insubria University, Department of Theoretical and Applied Science, Varese Italy.
[6] Norwegian Meteorological Institute, Research and Development Department, Oslo, Norway.
[7] Institute of Geophysics, Polish Academy of Sciences, Poland.
[8] Alfred Wegener Institute for Polar and Marine Sciences, Potsdam, & Geography Department, Humboldt-Universität Berlin, Germany

Corresponding author: Hanne H. Christiansen, hanne.christiansen@unis.no
ORCID number 0000-0002-6218-3493

Keywords: Permafrost, ground temperature, active layer, ground ice content, drilling methods, Svalbard

DOI: https://doi.org/10.5281/zenodo.4294095

1. Introduction and objectives

Permafrost plays an important role in the Earth system, underlying 25% of the terrestrial parts of Planet Earth. In Svalbard, permafrost underlies almost all land areas not covered by glaciers. Permafrost is often near its freezing point and thus is sensitive to climatic changes. The thermal state of permafrost and active layer thickness are the two essential climate variables (ECVs) monitored to quantify the effects of climate change on permafrost conditions. We presented the observations of these ECVs in Svalbard in the first SESS report (Christiansen et al. 2019), focusing on their meteorological controls and provided an update in our SESS report card (Christiansen et al. 2020). The response of permafrost landscapes to thawing can be largely affected by the amount of ground ice in the stratigraphy, as was identified as a recommendation for future permafrost studies in both earlier SESS reports. When ice-rich permafrost thaws, melting ground ice often results in ground subsidence and instability. Therefore, the amount of ground ice provides a good indication of the sensitivity of permafrost landscapes to climate-induced changes. Additionally, thawing permafrost impacts infrastructure, nutrient and sediment transport into rivers and fjords, and landslide regimes, resulting in important links to large parts of the SIOS observation system.

A variety of drilling methods and monitoring equipment have been used to establish boreholes for permafrost thermal observation in different landforms and types of sediment, soil, and bedrock in Svalbard. In some cases, core samples were extracted during drilling these boreholes, allowing for ground ice determination and classification of stratigraphy. Permafrost drilling is typically conducted during winter, as rig transport must be done on frozen and snow-covered ground. Weather conditions during drilling operations are often demanding for both personnel and machines. Additionally, drilling and sampling in Arctic permafrost are logistically and technically challenging, requiring specialized techniques, custom drilling equipment, knowledge and experience from the drillers and project coordinators.

In this SESS report, we, therefore, focus on how to obtain samples and determine the ground ice content by presenting the research and drilling infrastructure currently available in Svalbard. We also present and discuss the ground ice content from the observation sites as a key factor for assessing the response of the Svalbard permafrost landscape to changes in climate. The objectives of this chapter are: (1) to provide a technical overview of the methods and drilling equipment used in permafrost in Svalbard and an overview of the available equipment for permafrost coring, (2) to summarise the currently available data on ground ice content and stratigraphy from the permafrost ECV observation sites, and (3) to summarise the observational time series of the Svalbard permafrost ECVs from the hydrological years starting in summer 2016 to summer 2019.

2. Connections and synergies with other SESS report chapters

In the introduction, we have made reference to our earlier SESS chapters and explained how this chapter advances our two earlier permafrost SESS contributions. As this contribution shows, assessing the permafrost changes needs access to meteorological observations as an important controlling factor. These have unfortunately not yet been analysed in large separate detail in SESS reports; but many chapters use different meteorological data available and, in this report, there is a chapter on meteorological modelling (Gjermundsen et al. 2021). Permafrost changes are relevant for the hydrological observations presented in a review in this report (Nowak et al. 2021). Permafrost observations are influenced by snow dynamics as is described by Killie et al. (2021). Clearly, surface hydrology, groundwater, and snow cover dynamics are related to permafrost; e.g. insulation effects of snow cover, convective and advective heat transfers of water in the active layer and frozen soils.

3. Overview of drilling equipment

A drill rig is typically needed to establish boreholes down to DZAA in permafrost (Gilbert et al. 2015). To also record the amount of ground ice in the permafrost, the drill rig needs to be able to collect cores during drilling. Here, we provide a first overview of the drilling methods and equipment used for permafrost drilling in Svalbard.

3.1. Drilling methods

Rotary drilling is used for all sites. The drill engine is mounted on a mast or tower that allows for vertical movement. It inserts rotation, thrust, torque and flushes fluid (water or air) through the drill rods to the drill bit. However, drill bit design differs for the five systems used in Svalbard and can be categorised into rotary percussion drilling and rotary core drilling. While rotary percussion drilling is developed for advancing into the ground efficiently, the latter is intended for retrieving core samples of the best possible quality.

3.1.1. Rotary percussion drilling

Down-the-hole hammer drilling (DTH) is most commonly used for boreholes in Svalbard. The percussion introducing unit is located right behind the drill bit in the borehole. It is powered by compressed air that flows through the drill rods. Combined with the rotation drill engine, small fragments are broken loose by carbide tungsten inserts in the drill bit front (Figure 1D). Cuttings are flushed up and out above the ground surface by the excess air of the hammer, allowing for the collection of bulk, bag samples. Besides the drill rig, the air compressor is the vital machinery providing enough energy to drive the hammer and remove the cuttings/the loose material being blown out of the borehole. This method was used for the following boreholes: Old Aurora Station, Endalen, Janssonhaugen, UNIS east, DBNyÅlesund, Kapp Linné 1, Kapp Linné 2, and Hornsund (Table 1). At Bayelva, a top hammer was used. In this set-up, the percussion introducing unit is situated above the borehole, in or near the drill motor. During rotation, percussion is applied to the drill bit through the drill rods.

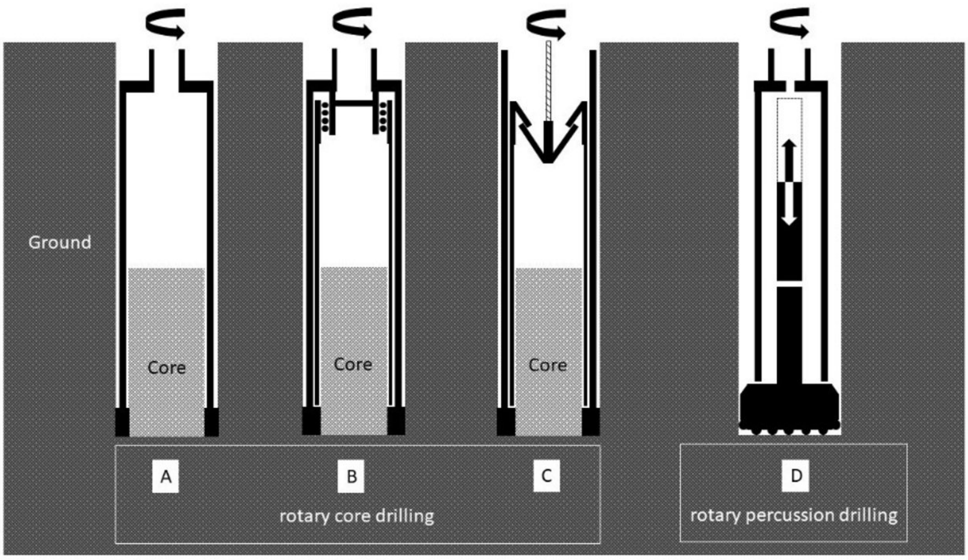

Figure 1: Schematic view of the drill bit and core assembly for rotary drilling: A – single core barrel. B – double core barrel. C – wire-line. D – Down-the-hole (DTH) hammer.

Table 1: Drill equipment information for permafrost boreholes presented in this report.

Drill equipment							Borehole			
Rig category	type	Operator	weight (ton)	Available drill methods	Location	rental	Location	Borehole name/ ID	Borehole depth (m)	Drill method used
Construction	Atlas-Roc 701	Store Norske Spitsbergen Kulkompani AS	10	DTH	Drill rig no longer available	No	Adventdalen	Jansonhaugen P10	102	DTH
							Adventdalen	Jansonhaugen P11	15	DTH
	Nemek 510	Anleggsdrift AS	10	DTH	Longyearbyen	Yes	Adventdalen	NGTS Adventdalen	30	DTH
							Adventdalen	NGTS UNIS east	30	DTH
	Nemtek 300 TS	Kings Bay AS	10	DTH	Ny-Ålesund	Yes	Ny-Ålesund	Bayelva		DTH
Geotechnical	Geotech 504	SINTEF	2.5	Core drilling, auger, sounding, DTH	Longyearbyen	Yes	Adventdalen	Old Aurora Station2	9,85	DTH
							Adventdalen	Endalen	19	DTH
							Kapp Linné	Kapp Linné 1	29	DTH
							Kapp Linné	Kapp Linné 2	38	DTH
	GM 50 GT Combi	Polish Polar Station, Hornsund	2.0	Core drilling, auger, sounding, DTH	Hornsund	Yes	Hornsund	Meteo	12	DTH
								Brzuchorzęska	5	DTH
								Lisek	10	DTH
								Brzydal Lola Renifer	10 20 20	DTH DTH DTH
Purpose build	UKB 12/25	Arctic and Antarctic Research Institute (St. Petersburg)	0.1	Core drilling	Barentsburg	Collaboration only	Barentsburg	Borehole 2	7.5 m	Single core barrel
	UNIS permafrost rig LB 1200 (modified)	University Centre in Svalbard, Kolibri Geo Services	0.6	Core drilling, DTH	Longyearbyen	Yes	Ny-Ålesund	DBNyÅlesund	48,5	DTH /double core barrel
							Verlegenhuken	Verlegenhuken	31	DTH / double core barrel
Exploration	Onram 1500	Store Norske Spitsbergen Kulkompani AS	3	Core drilling (Wireline)	unknown	yes	Adventdalen	Breinosa	335	Wireline

3.1.2. Rotary core drilling

A steel cylinder that accommodates the core is equipped with a barrel head to connect to drill rods and a drill bit that drills directly into the ground. The simplest coring equipment used is the single core barrel. It can consist of one piece or be made of several interchangeable elements (Figures 1A and 2A). The single core barrel is used "dry", where no flushing medium (water, air, mud, foam) is used. The borehole in Barentsburg was drilled this way. There the core barrel was fitted with tungsten carbide bit inserts.

To retrieve samples from the borehole at DBNyÅlesund, a double core barrel was used with impregnated diamond drill bits. The inner core barrel, held by ball bearings, does not allow contact of the core with the rotating outer core barrel (Figure 1B). An air compressor was used to cool the drill bit and flush cuttings to the surfaces. This method was used only to drill the upper part of the borehole.

Drilled as an exploration borehole, Breinosa was drilled using a wire line system (Figure 1C). As a "lazy" modification of the double core barrel, here the inner core barrel can be retracted by means of a steel wire. The outer rotating casing including the core barrel supports the borehole walls during operation. Cooling of the drill bit and removal of cuttings are carried out by water with salt as an additive to hinder freezing.

Figure 2: Location of relevant permafrost observation sites in Svalbard.

Figure 3: A) Single core barrel. Squared tungsten carbide inserts form the crown of the drill bit. (Photo: Ullrich Neumann), B) Borehole being drilled in Janssonhaugen. Drill rig, air compressor and accessories are placed onto one large sledge (Photo: Johan Ludvig Sollid). C) Rotary percussion drilling at Endalen borehole with the Geotech 504 geotechnical drill rig. (Photo: Håvard Juliussen). D) The Hornsund GM 50 GT Combi drill rig. (Photo: Tomasz Wawrzyniak). E) Russian drill rig in operation near Barentsburg. (Photo: Ullrich Neumann) F) UNIS permafrost drill rig drilling the DBNyÅlesund borehole. Kings Bay AS supplied the air compressor (Photo: Ullrich Neumann).

3.2. Equipment categories

3.2.1. Construction drill rigs

Designed for construction and mining purposes, construction drill rigs are very efficient drilling tools. Both machinery and methods are well established utilizing rotary percussion drilling methods. However, the rather high mass of around 10 tons makes them ineffective for boreholes far away from general infrastructure. Including the compulsory air compressor, the total weight is often over 20 tons. Generally, the rig can reach a depth of 300 m with a diameter of up to 300 mm. While the UNIS East borehole could be accessed by road, Janssonhaugen (Figure 2) was reached by a caterpillar towing the rig and accessories on a sledge in winter. Examples of such rigs and the boreholes they have drilled are as follows: Atlas-Roc 701 (Janssonhaugen; Figure 3B), Nemek 501 (UNIS east) and Nemek 300 TS (Bayelva).

3.2.2. Exploration drill rig

The Breinosa 335 m deep borehole was established using an exploration drill rig, prospecting for coal. The rig has a capability of 1000 m and more with a wireline system. A large logistical effort is necessary to supply supercooled water as a drill fluid on-site, and all necessary equipment must be airlifted in place. Today, this rig is no longer located in Svalbard.

3.2.3. Geotechnical drill rigs

Geotechnical drill rigs offer a broad spectrum of drilling and sampling methods for ground investigations. These rigs are self-propelled by tracks, have a weight of around 2 tons, and are operated by a crew of two. Geotechnical rigs offer rotary core drilling, auger, sounding, and DTH. Borehole diameters of up to 160 mm are possible. Both rigs, the Geotech 504 stationed at UNIS (Figure 3C) in Longyearbyen and the GM 50 GT Combi in Hornsund (Figure 3D) used DTH drilling methods to establish boreholes.

3.2.4. Purpose built permafrost drill rigs

The DBNyÅlesund and the new SIOS InfraNOR boreholes around Longyearbyen and Adventdalen were drilled by the UNIS permafrost drill rig, jointly developed by Lutz Kurth Drill systems, Kolibri Geo Services, and UNIS scientific staff, for drilling in remote locations in Svalbard and Greenland, mainly during winter (Figure 3F). The hydraulic rig, powered by a gasoline engine, has a weight of 600 kg and uses coring and percussion drilling methods. A total depth of 50 m can be reached with borehole diameters of up to 116 mm. Without propulsion, the rig is towed on a sledge by a snowmobile, pushed on wheels, or airlifted in place. It has been sent by the medium-sized Dornier airplane from Svalbard to N and NE Greenland for drilling permafrost monitoring boreholes there as well. This drill rig is presently being further developed to improve drilling into as many types of sediments in permafrost landscapes as possible, as part of the SIOS InfraNOR project.

Originally developed for ground investigations in remote areas of Siberia, the Russian drill rig has a total weight of approximately 100 kg (Figure 3E). Both thrust and lifting are done by a manually operated winch, while a one-cylinder, two-stroke engine rotates the drill. The drill operation in Barentsburg used dry coring with a single core barrel with a 50–120 mm diameter range. A maximum depth of 50 m has been reached in peat deposits in northern Russia.

For climate change-related investigations, often a hand drill can provide important information about the ground ice content in the upper meters of the permafrost depending on the sediment type. At UNIS, a STIHL^{tm} BT 121 Earth Auger with drilling extensions and an unflighted (smooth-walled) core barrel with diamond cutting teeth is used for hand drilling to obtain shallow cores (Gilbert et al. 2015).

4. Ground ice and stratigraphy

A great deal of information about stratigraphy and ground ice content was collected during the drilling and installation of the boreholes included in this and earlier SESS reports on permafrost. Even for sites where cores and samples were not recovered, driller observations can provide valuable insight into the stratigraphy and ground ice content. Here, we provide the first overview of the stratigraphy and ground ice conditions at all the observation permafrost boreholes included in this report.

Drill records from the DBNyÅlesund site (Figure 2 and Table 1) indicate approx. 3.5 m of overburden sediment, likely moraine material, overlying bedrock. Observations indicate that the transition to bedrock is likely gradational and extends over a few vertical meters. During drilling, cores were retrieved in the upper 3 m of the borehole. Disturbed cutting samples were collected in the bedrock interval. The gravimetric ground ice content varies significantly, from between 5% and up to 40% in the upper 3 m (Figure 4A). No excess or visible ground ice was documented. A few samples from the bedrock interval were also analysed, but should be interpreted with caution, as they are disturbed samples. They show rather low ground ice contents of around 10%. Unfortunately, no drilling log is available from the Bayelva site in Ny-Ålesund.

The Old Aurora Station 2 in central Adventdalen has a sediment cover that is approx. 60 m thick and is comprised of a complex stratigraphy recording both marine (deltaic and fluvial) and terrestrial (aeolian loess) sedimentary infilling and development of a fjord-valley system following deglaciation (Gilbert

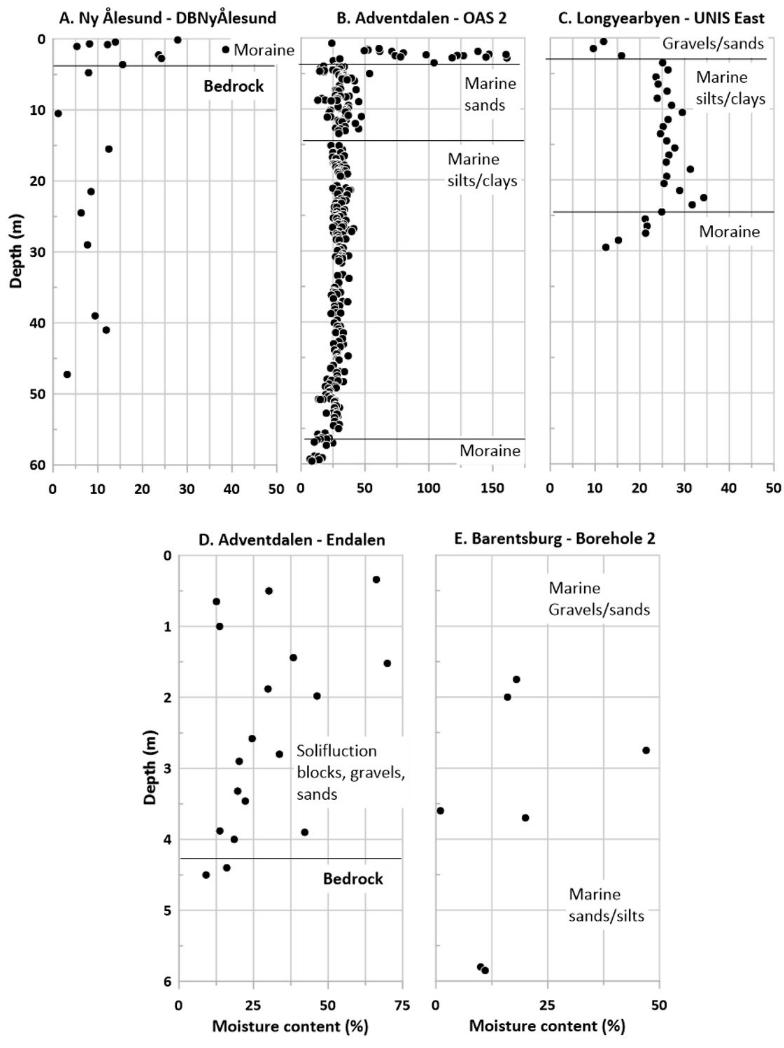

Figure 4: Permafrost gravimetric ice content in percent from the permafrost observations sites. Note that vertical scale is very different for A to C compared with D and E, as these boreholes are comparably shallow. The horizontal ice content scale is also adapted to each plot to illustrate the observed range in values in most detail. The depth where bedrock was encountered is indicated by a black horizontal line.

et al. 2018). The ground ice content has been quantified in 350 samples from a borehole located within approx. 100 m radius of the Old Aurora Station 2 site (Gilbert et al. 2018, 2019). These show rather large variability in the top 1.5–3.5 m of terrestrial sediments, from 50% to 160% ground ice content (Figures 4B and 5). The upper 3 m consists of sands and silts deposited as loess and enriched with ice. Below 3 m in fluvial and marine sand, silt, and clay sediments, the ground ice content varies much less and is generally only around 20–40% (Gilbert et al. 2018).

The UNIS East site consists of 4 m of sands and gravels overlying 21 m of marine clays overlying 5 m of moraine material. The amount of ground ice is rather low for this fine-grained site with a maximum of around 30% at 20 m depth, whereas the top permafrost has only around 10% ground ice (Figures 4C). Bedrock was not encountered during drilling of the borehole included in this report but is known to lay between 25 m and 35 m below the terrain surface in this area.

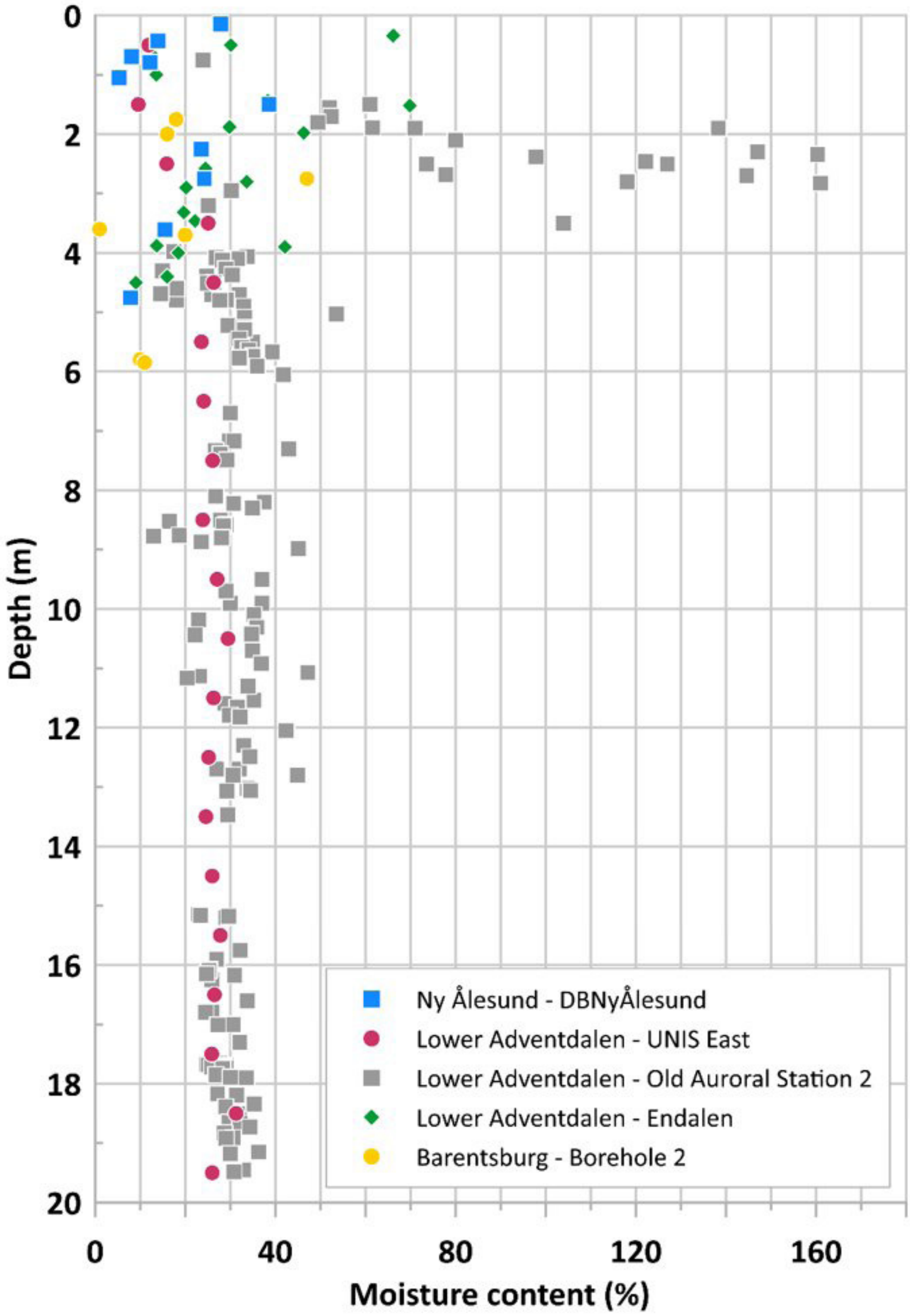

Figure 5: Permafrost gravimetric ice content in percent for all permafrost observation sites in Svalbard, allowing for direct comparison for the top 20 m.

The Endalen solifluction site is characterized by approx. 4–5 m of diamict material overlying bedrock. The transition to bedrock is gradational and extends over approx. 4 m. Core sample analyses of the top 4.5 m indicate that the ice content within the sediment varies quite a lot but ranges up to 70% (Figure 4D). Segregated ground ice is observed at this site (Figure 6E).

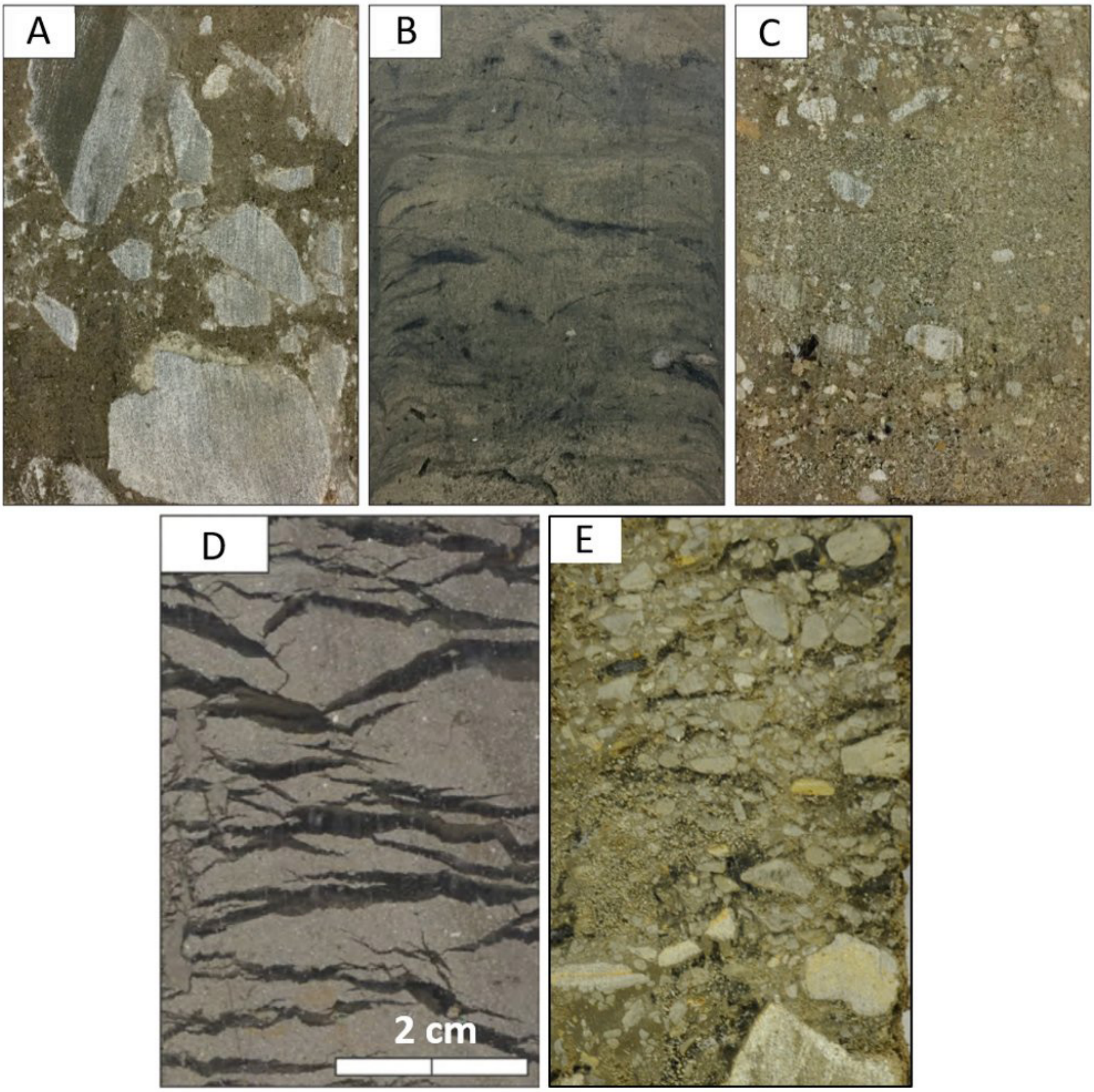

Figure 6: Example images of core samples. A) moraine sediment (UNIS East). B) marine clays (UNIS East). C) ice-poor sands and gravels (UNIS East). D) segregated ice lenses (Old Aurora Station2). E) Segregated ice (black) and gravels (Endalen). A–C reproduced from Gilbert et al. (2019). D reproduced from Gilbert et al. (2018). E Ullrich Neumann.

Stratigraphy at the Breinosa blockfield borehole consists of several meters of weathered bedrock overlying bedrock (Christiansen et al. 2010). Since the borehole was drilled as part of coal prospecting using exploration drilling, no permafrost samples were collected. However, direct field observations in the Breinosa area show high ice contents between individual blocks in the lower active layer in late summer.

The site at Janssonhaugen is drilled using the DTH technique into bedrock. Ground ice content data does not exist. However, XRD analyses of well cuttings from the drilling collected at 3–7 m intervals, show high quartz content interpreted as sandstone (Isaksen et al. 2000). Ice lenses were identified down to 6–7 m depth, just as clean ice chips were blown up during drilling from the most fractured parts (Isaksen et al. 2000).

The Meteo borehole in Hornsund is drilled in crystalline quartz bedrock. Unfortunately, ground ice data are also not available from this site, which was also drilled using the DTH technique. Kapp Linné 1 was drilled into an outcrop of silicified carbonate and clastic sedimentary bedrock, and Kapp Linné 2 was drilled through 6.2 m of beach ridge gravels overlying the same type of bedrock (Christiansen et al. 2010). Ground ice data are not available from these two sites either as drilling was done using DTH (Figure 4C) before the UNIS drill rig was developed.

The stratigraphy at borehole 2 in Barentsburg is 1.3 m of sands and gravels overlain by an intermediate soil loam containing different ground ice structures. A gradual transition to bedrock is encountered at approx. 7 m depth. Some ground ice content measurements exist from the top 6 m. These show a large variation even over a short depth from only a few percent to close to fifty percent (Figure 4E). Borehole 12 in Barentsburg was drilled during coal exploration in the early 1930s, and unfortunately, no detailed description of the stratigraphy for this borehole drilled into sediments is available.

The ground ice content in the Svalbard permafrost observation boreholes is generally largest in the permafrost in valley bottom sediments up to 160%. This is clearly much more ice than in the bedrock sites, which typically have below 15% (Figure 6). In Adventdalen, the permafrost has a much higher content of ground ice, reaching 150% in the top 1–3 m, where terrestrial sediments such as loess and solifluction sediment dominate. Ground ice content is typically lower (approx. 25–35%) in the underlying fluvial sands and gravels and marine sediments (silts and clays) (Figure 6).

5. Meteorology 2016–2019

Air temperatures in Svalbard have increased by 1°C per decade since 1971, while total liquid and solid precipitation has increased by 4% per year (Figure 7 upper), with the most increase occurring in the autumn (NCCS 2019). Mean annual air temperatures at both Hornsund and Ny-Ålesund were reduced by around 2.5°C from 2016 to 2019 (Figure 7 upper). The total amount of precipitation recorded was from around 100 mm (Longyearbyen area) to around 500 mm (Hornsund) less during the 2018–2019 period (compared with 2016–2017 (Figure 7).

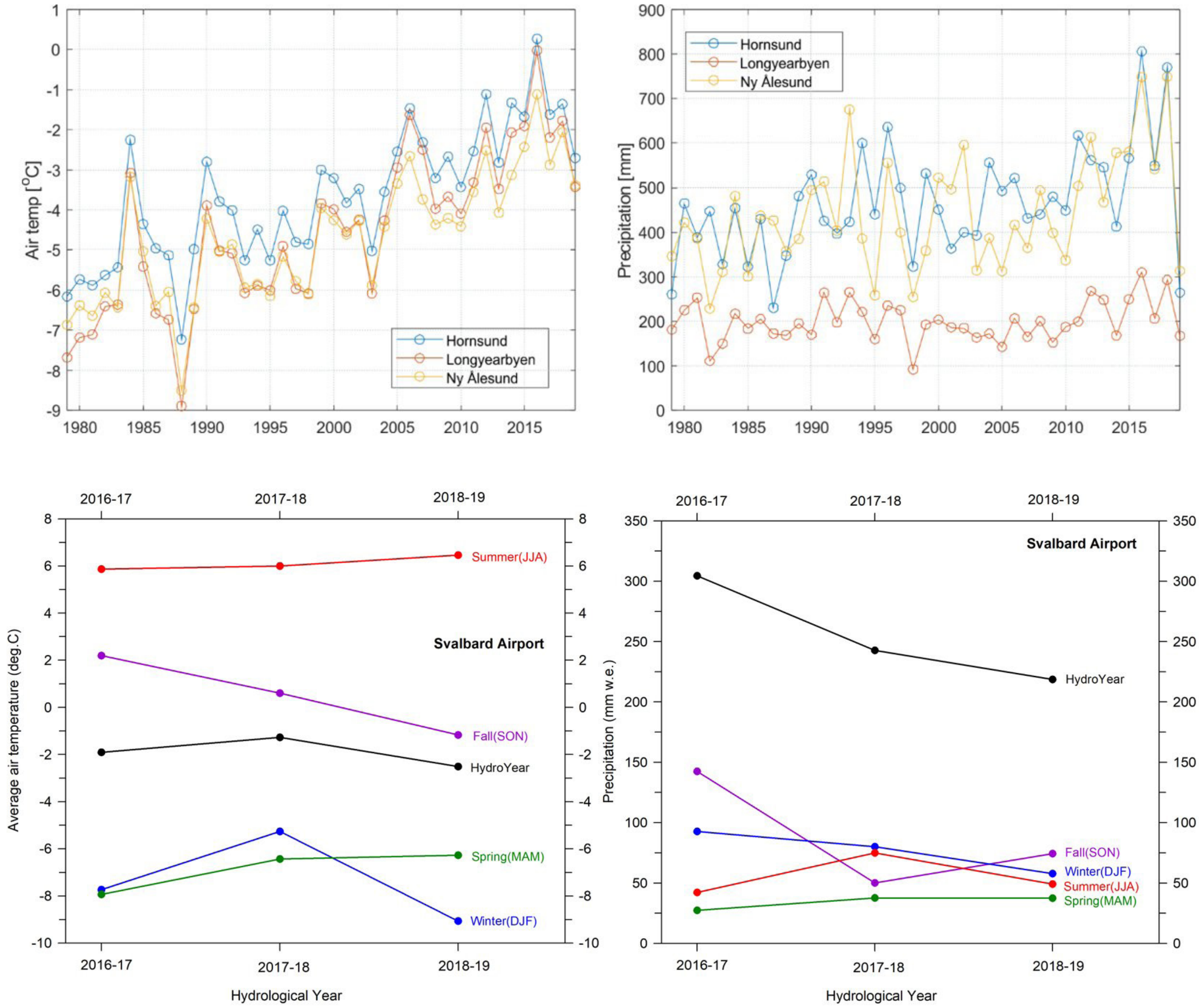

Figure 7: Upper: Meteorological records of mean annual (calendar year) air temperature and precipitation from 1979 to 2019 of 3 stations in Hornsund, Longyearbyen, and Ny-Ålesund, covering the variation in our permafrost observation areas in Svalbard. Lower: Mean annual and seasonal air temperature and precipitation for the hydrological years from 2016–2017 to 2018–2019 at the Svalbard Airport in the Longyearbyen area. Hydrological years run from 1 September to 31 August the year after.

Air temperatures in the calendar year 2016 reached a record high mean annual value of -0.1°C recorded at Svalbard Airport (Figure 7 upper), characterised by a particularly warm and wet autumn (Christiansen et al. 2019) (Figure 7 lower). During the 2016–2017 hydrological year (from 1 September to 31 August), mean annual air temperature was -1.9°C, and 305 mm of precipitation was recorded, an above-average amount. During the observation period we report on in this PermaSval contribution mean hydrological annual air temperatures have varied from -1.3°C in 2017–2018 to -2.5°C in 2018–2019 at the Svalbard Airport. Seasonally, at Svalbard Airport, the largest changes are a 1°C cooling in the autumns, but only to a value of -1.2°C in the 2018 autumn. Summers and springs have remained relatively stable with only small increases in the summer of 2019, and from spring 2017 to spring 2018. The largest seasonal variability was observed in the winter air temperatures, which ranged from -5.3°C in 2017–2018 to -9.1°C in 2018–2019. Precipitation has generally been low in all seasons, reflecting the overall dry climate, particularly in central Svalbard. The reduction in precipitation of approx. 100 mm is attributed to drier autumns after the record wet autumn 2016 value of 142 mm (September–November 2016). Autumn 2016 had 47% of the annual precipitation of that hydrological year, with a value clearly much higher than any other season that hydrological year.

6. Permafrost thermal state and active-layer thickness 2016–2019

The permafrost thermal state is presented for the five main permafrost observation sites in Svalbard: Ny-Ålesund, Adventdalen, Kapp Linné, Barentsburg, and Hornsund (Figure 2). Borehole locations and instrumentation at each site were previously described in detail in Christiansen et al. (2019), Gilbert et al. (2019), Boike et al. (2018), Demidov et al. (2016), and Isaksen et al. (2001). We present hydrological year data, calculated from 1 September to 31 August the year after.

Permafrost temperature at the depth of zero annual amplitude (DZAA) is typically found between 10 to 20 m and reflects climate and ground conditions over a longer duration. Temperature at the DZAA is commonly used to interpret the response of permafrost to climate changes. The top permafrost temperatures respond to annual and even seasonal variations and are thus more directly sensitive to short-term meteorological fluctuations.

Interpolation is used at the end of the thawing season to calculate active-layer thickness from the borehole temperature data. For the three CALM grids in Svalbard, located in Adventdalen (UNISCALM), near Barentsburg, and in Ny-Ålesund (Christiansen & Humlum 2008; Shiklomanov et al. 2012; Christiansen et al. 2019), the active layer thickness is determined by manual probing at 121 points, spaced evenly in a 100 m x 100 m grid, reporting the mean for the entire grid.

6.1. Permafrost thermal state

The permafrost surface temperatures, determined from the upper-most temperature sensor within the permafrost, typically varied less between the observation sites in Svalbard than the deeper permafrost temperatures during this observation period, with a range only from around -1°C to -4.5°C (Figure 8a). There is a general decline observed in all sites ranging from 0.3°C to 1.2°C, in response to decreasing mean annual air temperatures and precipitation during the three-year period.

The lowest permafrost temperatures at DZAA are observed in boreholes at inland mountain sites at higher elevations, such as Breinosa (677 m a.s.l.) and Janssonhaugen (254 m a.s.l.), and in sites with thin winter snow cover and winter cold air drainage such as in Adventdalen Old Aurora Station 2 (Figure 8). In these sites, observed permafrost temperatures are around -5°C, with a slightly positive trend over the observation period only for Janssonhaugen. Sites where winter snow cover (e.g. UNIS East) is thicker and/or with a thick, moisture-rich active layer (e.g.

Endalen), have characteristically higher permafrost temperature from -4° to -2.5°C, also with a slightly positive trend. Permafrost temperatures at DZAA are higher in the more coastal lowland sites in Ny-Ålesund (25 m and 55 m a.s.l.), Barentsburg (95 m a.s.l.), and Kapp Linné (20 m a.s.l.), ranging from -2.2 C to -3.1°C. These coastal sites also had a smaller increase in permafrost temperatures. The highest permafrost temperature observations at DZAA are from Hornsund, where temperatures are only -1.2°C at 12 m depth. This value has been rather stable over the two-year observation period (Figure 8B). Clearly, most of the deeper permafrost temperatures still increase slightly, responding to the overall decadal warming that has been going on in Svalbard.

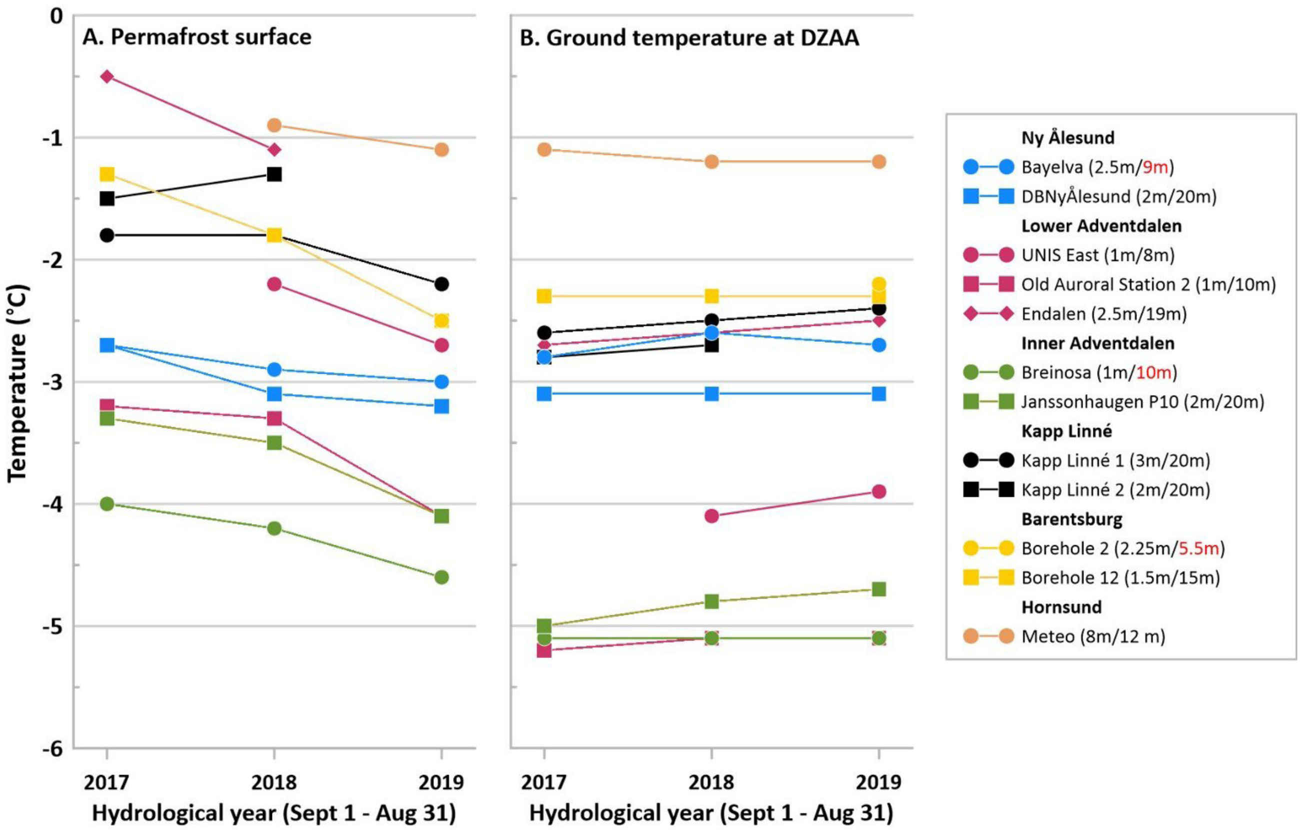

Figure 8: Mean annual ground temperature development as recorded at (A) the permafrost surface (represented by the upper-most temperature sensor in the permafrost) and (B) the depth of zero annual amplitude (DZAA) or deepest sensor for the hydrological years 2016–2017 to 2018–2019. DZAA (black text) or location of the deepest sensor (red text) is given in brackets beside each borehole in the legend. Borehole location areas are shown in Figure 5.

6.2. Active layer thickness

Most of the active layer thickness observations fall in a range from 100 to 200 cm (Figure 9). However, in the highest located borehole at Breinosa, the active layer has been as shallow as 49 cm, and we observe much thicker active layers in the bedrock coastal site at Kapp Linné around 3 m and at Hornsund around 5 m. The active layer is generally thinnest at sites with well-drained sediments in the Adventdalen area such as Breinosa, UNIS East, and the Old Aurora Station 2, ranging from 50 to 100 cm. Observations from boreholes in sediment and moraine, e.g. Ny-Ålesund and Barentsburg, suggest an active-layer thickness of approx. 150 cm. Thicker active layers in slopes e.g. Endalen and in bedrock boreholes e.g. Kapp Linné and Janssonhaugen, are observed all around 175 to 200 cm. The deepest thaw depth is recorded at the Meteo borehole in Hornsund – approx. 500 cm. The observations at Hornsund are quite exceptional and might reflect a more complicated situation at the site than simple heat conduction. The very thick active layer may be influenced by groundwater flow during summer, but it is also possible that the quartzite bedrock with its high thermal conductivity causes this.

The active-layer thickness has doubled at the blockfield bedrock site at Breinosa to 98 cm and has increased by 75 cm at the Meteo raised beach bedrock site in Hornsund over only 1 year (Figure 9). At the Barentsburg Borehole 12, the active layer thickness decreased by 37 cm over the observation period. At the Janssonhaugen and the Kapp Linne bedrock borehole sites active-layer thickness increased slightly over the three-year observation period, while a slight decrease was observed at all other sites.

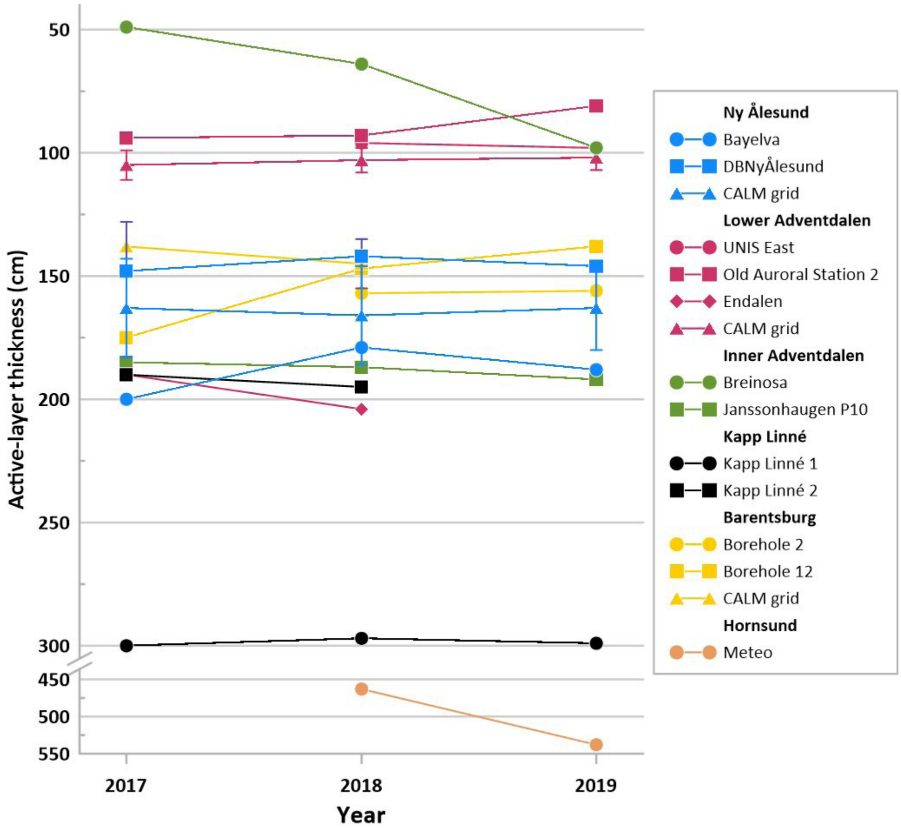

Figure 9: Active-layer thickness through the 2017–2019 period. Values are reported in autumn of each year. The active-layer thickness is determined by interpolating the temperature profiles at the end of the thawing season. CALM grid means also show one standard deviation. Note the break and change in the vertical axis and spacing to accommodate observations from Hornsund.

7. Conclusion

Being able to combine the information on the ground ice content with the permafrost ECVs allows for an improved understanding of the permafrost ECV dynamics during the observation period 2016–2019 in Svalbard. The presented permafrost ECV data range from either no warming (Breinosa at 10 m depth; DBNyÅlesund at 20 m depth; Borehole 12 Barentsburg at 15 m depth) up to 0.15°C/y warming (Janssonhaugen at 20m depth) at 10–20 m depths. This shows that there is still a response to the general warming that Svalbard has seen over the last decades. On the rather short time scale of our three-year observation period in which mean annual air temperature declined and there was reduction in the annual amount of precipitation, the temperature in the top permafrost decreased in all observation sites ranging from 0.2°C/y (Kapp Linne 1) to 0.6°C/y (Borehole 12 Barentsburg) as a response to this small-scale variability.

The active layer has generally decreased slightly in thickness, ranging from 1 cm/y (DBNy-Ålesund) to 6.5cm/y (Old Aurora Station Adventdalen), but two sites had small increases from 1 cm/y (Kapp

Linne 1) to 3.5 cm/y (Janssonhaugen). However, two other sites experienced larger changes. In the blockfield at Breinosa, the active layer increased by 24.5 cm/y, while in the raised marine sediments at Borehole 12 in Barentsburg, the active layer thinned by 18.5 cm/y in the two-year observation period from summer 2017 to summer 2019.

Less than half of the observation boreholes have detailed ground ice information, but the ones that have this information represent both bedrock and sediments and thus allow us to extrapolate this information and use it at a general level to interpret the results from all the permafrost observation sites. Most of the permafrost observation sites have warmed only slightly at 10–20 m depth but at the same time show consistent cooling in the top permafrost and small-scale thinning of the active layer in response to the cooling over the observation period 2016–2019. However, two sites have not seen warming at 10–20 m depth and had cooling of the top permafrost and decreasing active layer thicknesses (DBNyÅlesund and Borehole12 Barentsburg). Both had relatively high ground ice contents in the top permafrost, which is sedimentary. Bedrock underlies the Ny-Ålesund site, while the entire borehole is in sediment in Borehole 12 in Barentsburg. This shows how high ground ice contents protect and preserve the permafrost.

The blockfield observation site at Breinosa had no warming at 10 m, exhibited permafrost top cooling, and at the same time experienced an active layer doubling. Clearly, more air circulation must be the main reason why the active layer doubled in this landform, with no other landforms having this response. This, clearly, was not directly air temperature driven, but was probably also caused by less precipitation. The only other site which had a small-scale active layer increase (3.5 cm/y) was the hilltop Janssonhaugen borehole site, which had permafrost warming at 20 m, while the permafrost top cooled. This presumably reflects the influence of the slight summer warming in combination with the exposed nature of the hilltop, which prevents snow accumulation at this site and allows quick heat conduction into the bedrock which probably has low ground ice content.

Additionally, the overview of the drilling equipment clearly demonstrates how well-equipped Svalbard now is for drilling boreholes with both methods and a range of equipment, allowing for both deep and shallow boreholes. The review of the drilling methods used for the present observation boreholes also shows that most drilling operations, even though made for permafrost observation, did not collect cores, and some did not even have any stratigraphical record.

8. Unanswered questions and recommendations for the future

- *Always collect ground ice and stratigraphy information from long-term permafrost observation sites* – This reporting shows how important data on stratigraphy and ground ice content are to best understand the detailed responses of permafrost to climatic changes. Therefore, it is a clear recommendation to invest in obtaining and analysing the ground ice content of cores collected through drilling of all new boreholes being established for permafrost ECV observation. This is more costly but clearly provides important data for interpreting the observed permafrost ECV data in larger detail and thus allows us to better predict future responses to climatic changes. Also, the present drilling equipment in Svalbard will be/is now offering a very good variety of methods which suit most needs from shallow to deep boreholes.

- *Consider expanding the permafrost observation network* – Expand the network to make sure it contains not only all the different parts of Svalbard but also covers the landform variability. The presented results clearly show how different landforms can respond very differently to the same climatic forcing. Other types of site-specific forcing are also very important, such as grain size, lithology, ground ice content, aspect, and vegetation cover.

- *Perform ground ice studies from slopes* – Current knowledge about ground ice in Svalbard is focused on coastal lowlands, valley bottoms, and periglacial landforms such as pingos and solifluction sheets. Climate change is expected to impact landslide frequency in sloping terrain. However, knowledge about the amount and distribution of ground ice in slope deposits is sparse but could improve estimates of the future stability of slopes in Svalbard. New boreholes should be drilled in slopes with cores retrieved and laboratory studies carried out to quantify the ground-ice content and stratigraphy. Temperature and pore water pressure sensors should be installed in such boreholes to improve our understanding of their sensitivity to climate change and for preparedness situations in populated areas.

- *Get more permafrost ECV and SIOS SCD operational and online* – New boreholes, or old boreholes getting new instrumentation, should be using modern technology that provides online access to the permafrost data for improved direct scientific and societal use.

9. Data availability

The permafrost ECV data included is generally available through the Global Terrestrial Network for Permafrost (GTN-P) database. These two types of permafrost ECV data are both SIOS core data, and therefore, also available through the SIOS data access portal. An overview of the permafrost temperature data are included in Table 2 . Ground ice content data are available through the references included in this report or by contacting the authors. The information about the drilling equipment is all included in the text, figures, and Table 1.

Table 2. Permafrost temperature data in GTN-P and as appearing in the SIOS data access portal.

Dataset	Period	Location	Metadata/Data Access
GTN-P Barentsburg Borehole 12	2016–2017	Barentsburg	SIOS data access portal: https://bit.ly/346AVLN
GTN-P DBNyÅlesund	2016–2017	Ny-Ålesund	SIOS data access portal: https://bit.ly/2Wr2co5
GTN-P Breinosa (E-2009)	2009–2020	Breinosa	SIOS data access portal: https://bit.ly/2Kp3ygh
GTN-P Kapp Linne 1	2008–2020	Kapp Linne	SIOS data access portal: https://bit.ly/3oRhH4F
GTN-P Kapp Linne 2	2008–2018, 2019–2020	Kapp Linne	SIOS data access portal: https://bit.ly/3mizyzZ
GTN-P Endalen PYRN	2008–2020 (with some gaps)	Endalen	SIOS data access portal: https://bit.ly/3qYJan4
GTN-P Old Auroral Station PYRN	2008–2019	Adventdalen	SIOS data access portal: https://bit.ly/3oRHbyY

Acknowledgements

We are grateful to SIOS for supporting the development of this report. The permafrost data that this report is based on has been funded by our national research councils and the participating institutions where the authors are based. Financial support at Hornsund was provided by the Polish National Science Centre through grant No. 2016/21/B/ST10/02509. This work was supported by the Research Council of Norway, project number 291644, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre, operational phase. Thanks to Sarah Strand for checking the language and for uploading data into GTN-P.

References

Boike J, Juszak I, Lange S, Chadburn S, Burke E, Overduin PP, Roth K, Ippisch O, Bornemann N, Stern L (2018) A 20-year record (1998–2017) of permafrost, active layer and meteorological conditions at a high Arctic permafrost research site (Bayelva, Spitsbergen). ESSD 10:355

Christiansen HH, Etzelmüller B, Isaksen K, Juliussen H, Farbrot H, Humlum O, Johansson M, Ingeman-Nielsen T, Kristensen L, Hjort J, Holmlund P, Sannel ABK, Sigsgaard C, Åkerman HJ, Foged N, Blikra LH, Pernosky MA, Ødegård RS (2010) The thermal state of permafrost in the Nordic area during the international polar year 2007–2009. Permafr Periglac Process 21:156–181

Christiansen HH, Humlum O (2008) Interannual variations in active layer thickness in Svalbard. In: Kane, DL & Hinkel, KM (eds) 9th Int. Conf. on Permafrost Proceedings, Institute of Northern Engineering, University of Alaska, Fairbanks, USA, pp 257-262

Christiansen HH, Gilbert GL, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2019) Permafrost thermal snapshot and active-layer thickness in Svalbard 2016-2017. In Orr et al (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 26-47 https://sios-svalbard.org/SESS_Issue1

Christiansen HH, Gilbert GL, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2020) Permafrost temperatures and active layer thickness in Svalbard during 2017/2018, In: Van den Heuvel et al (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-249 https://sios-svalbard.org/SESS_Issue2

Demidov NE, Verkulich SR, Karaevskaya ES, Nikulina AL, Savatyugin LM (2016) First results of permafrost monitoring on the cryospheric site of Russian Scientific Center on Spitsbergen (RSCS). Problems of Arctic and Antarctic 110: 67-79

Gilbert GL, Christiansen HH, Neumann U (2015) Coring of unconsolidated permafrost deposits: Methodological successes and challenges. GeoQuebec 2015, 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference. In: Gilbert, GL (2018) Cryostratigraphy and sedimentology of high-Arctic fjord-valleys. Ph.D. thesis, University of Bergen & UNIS, paper II

Gilbert GL, O'Neill HB, Nemec W, Thiel C, Christiansen HH, Buylaert JP (2018) Late Quaternary sedimentation and permafrost development in a Svalbard fjord-valley, Norwegian high Arctic. Sedimentology 65: 2531-2558

Gilbert GL, Instanes A, Sinitsyn A, Aalberg A (2019) Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard. AIMS Geosciences. 5: 868–885

Gjermundsen A, Graff LS, Bentsen M, Breivik LA, Debernard JB, Makkonen R, Olivié DJL, Seland Ø, Zieger P, Schulz M (2021) How representative is Svalbard for future Arctic climate evolution? An Earth system modelling perspective. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 38-59 https://doi.org/10.5281/zenodo.4034104

Hanssen-Bauer I, Førland E, Hisdal H, Mayer S, Sandø A, Sorteberg A (red.) 2019. Climate in Svalbard 2100 – a knowledge base for climate adaptation. Norwegian Centre for Climate Services (NCCS)

Isaksen K, Mühll D, Gubler, H, Kohl T, Sollid, JL (2000). Ground surface temperature reconstruction based on data from a deep borehole in permafrost at Janssonhaugen, Svalbard. Ann Glaciol 31: 287-294

Isaksen K, Holmlund P, Sollid JL, Harris C (2001) Three deep Alpine-permafrost boreholes in Svalbard and Scandinavia. Permafr Periglac Process 12, 13-25

Killie MA, Aaboe S, Isaksen K, Van Pelt W, Pedersen ÅØ, Luks B (2021) Svalbard snow and sea-ice cover: comparing satellite data, on-site measurements, and modelling results. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 220-235 https://doi.org/10.5281/zenodo.4293804

Nowak A, Hodgkins R, Nikulina A, Osuch M, Wawrzyniak T, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I, Rachlewicz, G (2021) From land to fjords: The review of Svalbard hydrology from 1970 to 2019. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 176-201 https://doi.org/10.5281/zenodo.4294063

Shiklomanov NI, Streletskiy DA, Nelson FE (2012) Northern hemisphere component of the global circumpolar active layer monitoring (CALM) program. In: Proc. 10th Int. Conf. on Permafrost, 1, pp 377-382