Permafrost temperatures and active layer thickness in Svalbard during 2017/2018 (PermaSval)

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1. Introduction

Permafrost is ground (soil or rock) that remains at or below 0 °C for two or more consecutive years. In Svalbard, changes in permafrost conditions have the potential to impact infrastructure, ecosystems and slope stability. This is because the strength and stability of frozen soil are closely related to its temperature. Globally permafrost is significant due to its role in preserving ancient organic matter and entrapping greenhouse gases. Monitoring permafrost essential climate variables (ECVs) is important for the assessment of local landscape stability and in quantifying the impacts of climate change on cold-region landscapes and their ecosystems. Permafrost data are globally archived in the Global Terrestrial Network on Permafrost (GTN-P).

This report follows up on the report published in the SESS Report 2018 (Christiansen et al. 2019). Since 2018, the Norwegian Environment Agency has released the *Climate in Svalbard 2100* report summarizing observed trends in permafrost conditions over the period of field measurements and a forecast for the future, based on recent climate and permafrost modelling (Hanssen-Bauer et al. 2019). It is well established that the terrestrial cryosphere in Svalbard has changed since modern permafrost monitoring efforts began in the late 1990s. In central Svalbard in the Adventdalen area, ground temperatures have risen by as much as 0.15°C per year (10 m depth) and the thickness of the seasonally-unfrozen active layer increased by 0.6 cm per year since 2000 in sediments and 1.6 cm/year in bedrock (Hanssen-Bauer et al. 2019), while in Ny-Ålesund ground temperatures increased by 0.18°C/year and the thickness of active layer increased by 5 cm/year (Boike et al. 2018). Modern monitoring techniques mean that it is relatively easy to quantify permafrost change in terms of temperature. The visible effects of warming permafrost are, however, more ambiguous. A prolonged thaw season is anticipated to result in a thicker active layer, and increased rainfall intensity can result in more frequent landslides. The strength of frozen soil decreases when warming and permafrost change may expectedly result in infrastructure problems in cases where climate change was not considered during the initial design.

The aims of this part of the State of Environmental Science in Svalbard reporting are to: (1) provide an overview of permafrost data collected during the 2017-2018 hydrological year (1 September 2017 – 31 August 2018), (2) contrast these results with the 2016-2017 hydrological year as presented in Christiansen et al. (2019), (3) summarise developments in permafrost monitoring in Svalbard, and (4) provide recommendations for future permafrost investigations. Understanding the spatial distribution of permafrost conditions is critical to predicting geomorphological change and understanding the variability in climate impacts.

2. The thermal state of permafrost

A summary of air temperature, precipitation, permafrost temperature, and active layer thickness for the 2017-2018 hydrological year, extending from 1 September 2017 and 31 August 2018 is provided in this section. Background information concerning these climate variables and permafrost conditions in Svalbard can be found in Christiansen et al. (2019). Site specific details can be found in Isaksen et al. (2001), Christiansen et al. (2010), Demidov et al. (2016), Boike et al. (2018), Christiansen et al. (2019), and Gilbert et al. (2019). The borehole locations are presented in Figure 1.

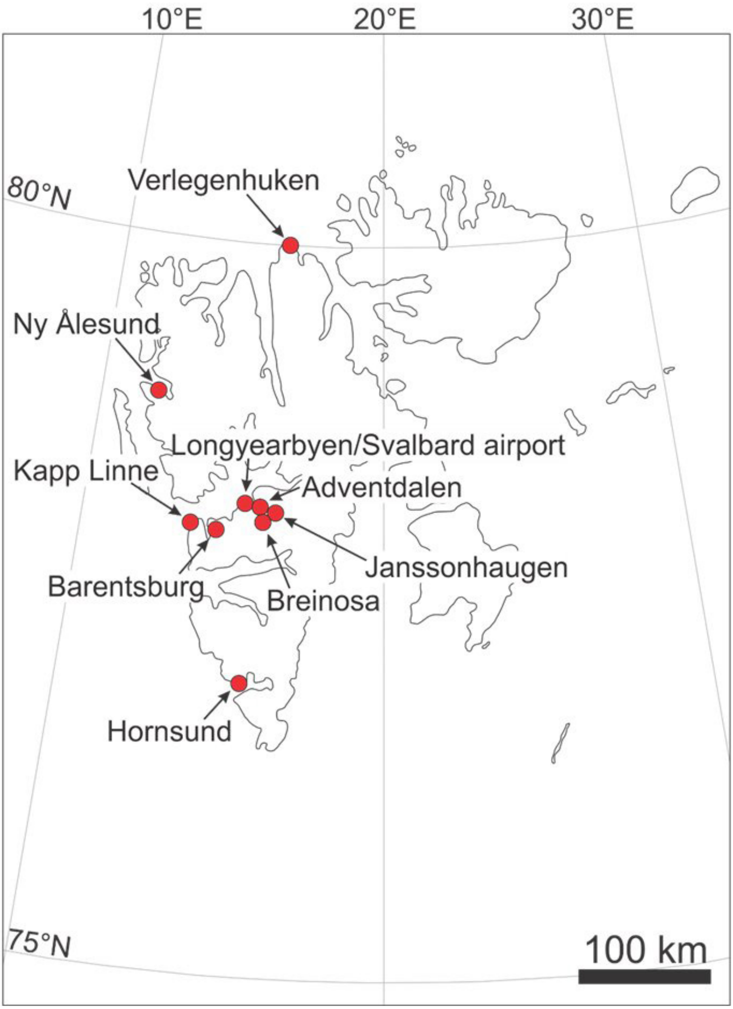

Figure 1: Location of permafrost boreholes and key observation sites mentioned in the text.

2.1 Air temperature, degree days, precipitation, and snow

Average air temperatures near the permafrost borehole locations during the 2017-2018 hydrological year ranged from -0.7°C at Kapp Linné to -3.0°C at Janssonhaugen. For most sites, average air temperatures were near to -1.5°C. In comparison with 2016-2017, conditions during the 2017-2018 hydrological year were markedly warmer (Table 1). Mean air temperatures were higher at all locations, by between 0.9°C (Ny-Ålesund) and 0.1°C (Hornsund).

The magnitude of freezing and thawing conditions is quantified and compared between the two hydrological years by using the thawing-degree days (TDD) and freezing-degree days (FDD) indices (Table 1). In the 2016-2017 hydrological year the thawing season extended relatively late until November 2016 (c.f. Christiansen et al. 2019), however, TDD calculated for both periods are comparable, within ca. 30 of each other (Table 1). This indicates that the total magnitude of the thawing season was relatively similar during the two periods. In contrast, the 2016-2017 hydrological year was significantly colder than the 2017-2018 hydrological year. FDD indices were greater in the 2016-2017 hydrological year (ranging from 1198 at Kapp Linné to 1955 at Janssonhaugen) than in the 2017-2018 hydrological year (ranging from 976 at Kapp Linné to 1678 at Janssonhaugen), indicating that, despite the shorter freezing season, the magnitude of cold temperatures was greater during the former period.

Total annual precipitation ranged from 801 mm (Hornsund) to 239 mm (Svalbard airport). The highest precipitation values were recorded near the west coast and decreased with distance inland. Generally, the total precipitation amounts were much lower than the rather wet hydrological year 2016-2017, with the largest reduction of 307 mm in Barentsburg, while Ny-Ålesund only had a 1 mm increase from the 2016-2017 hydrological year (Table 1).

Maximum snow depths at the monitoring sites varied from ca. 20 cm in Longyearbyen to ca. 140 cm in Barentsburg. In general, these spatial patterns are comparable to those described in Christiansen et al. (2019) and illustrate the effect of continentality moving towards the centre of Svalbard, and with elevation. Snow accumulation started in the end of October (e.g. 25/10/17 in Barentsburg). This is earlier than in 2016 when snow accumulation began in late-November. The timing and thickness of seasonal snow cover are significant for permafrost conditions as snow mediates the exchange of energy between the ground surface and the atmosphere. In general, a thicker snow cover which arrives earlier in the season will contribute to warmer ground conditions.

Table 1: Temperature summary at the permafrost borehole sites for the 2016-2017 and 2017-2018 hydrological years.

Location	Borehole name/ ID	MAT (°C) TDD (°C) FDD (°C)		MGST (°C)		MPST (°C)	
		2017	2018	2017	2018	2017	2018
Ny Ålesund	Bayelva	-2.3 701 1486	-1.4 729 1232	-3.6	-2.9	-2.7	-2.9
	DBNyÅlesund			-3.7 (0.3 m)	-3.1 (0.3 m)	-2.7	-3.1
Lower Adventdalen	UNIS East	-1.9 833 1514	-1.3 822 1279	n/a	-1.3	n/a	-2.2
	Old Auroral Station 2			-1.3	-1.1	-3.2	-3.3
	Endalen			n/a	-0.1	-0.5	-1.1
Inner Adventdalen	Breinosa	-3.8 569 1955	-3.0 591 1678	-4.1	-4.1	-4.0	-4.2
	Janssonhaugen/ P10			n/a	n/a	n/a	n/a
	Janssonhaugen/ P11			-3.7 (0.2 m)	-3.3 (0.2 m)	-3.7	-3.5
Kapp Linné	Kapp Linné 1	-1.2 746 1198	-0.7 732 976	-1.6	-1.5	-1.8	-1.8
	Kapp Linné 2			-1.6	-1.4	-1.5	-1.3
Barentsburg	Borehole 12	-2.2 707 1506	-1.7 680 1292	-0.8	-1.5	-1.3	-1.8
Hornsund	Meteo	-1.3 726 1210	-1.2 607 1049	-1.0	-0.7 (0.2 m)	n/a	-0.9

MAT: Mean annual air temperature
TDD: Thawing degree days
FDD: Freezing degree days
MGST: Mean ground surface temperature
MPST: Mean permafrost surface temperature

	MGT (°C) (depth)		Precipitation (mm)		Maximum snow depth (cm)	Active layer thickness (cm)* *Interpolated values* **CALM grid (± std. dev.)**		Duration of active-layer freeze-back (days)	
	2017	2018	2017	2018		2017	2018	2017	2018
	-2.8 (9 m)	-2.6 (9 m)	656	657	>100	*200*	*179*	*49*	*62*
	-3.1 (20 m)	-3.1 (20 m)			50	*148*	*142* **166±20**	*35*	*56*
	n/a	-3.0 (8 m)	305	239	<20	*n/a*	*96*	*n/a*	*63*
	-5.2 (10 m)	-5.1 (10 m)			20	*94* **105±6**	*93* **103±5**	*22*	*53*
	-2.7 (19 m)	-2.6 (19 m)			50	*190*	*204*	*140*	*151*
	-5.1 (10 m)	-5.1 (10 m)	n/a	n/a	<50	*49*	*64*	*18*	*2*
	-5.0 (20 m)	-4.8 (20 m)			<20	n/a	n/a	n/a	n/a
	n/a	n/a			<20	*185*	*187*	*41*	*36*
	-2.6 (20 m)	-2.5 (20 m)	711	427	<10	*300*	*297*	*44*	*72*
	-2.8 (20 m)	-2.7 (20 m)			<10	*190*	*195*	*49*	*72*
	-2.3 (15 m)	-2.3 (15 m)	849	542	ca. 20	*175* **138±10**	*147* **145±10**	*59*	*59*
	-1.1* (12 m)	-1.2 (12 m)	754	801	46	*n/a*	*463*	*n/a*	*113*

2.2 The ground thermal regime

Ground thermal conditions are presented for the five main permafrost observation sites in Svalbard: Ny-Ålesund, Adventdalen, Kapp Linné, Barentsburg, and Hornsund. Borehole locations and instrumentation at each site is detailed in Christiansen et al. (2019) and Gilbert et al. (2019). A summary of the ground thermal regime during the 2017-2018 hydrological year at each site is presented in Figure 2 . A time-series of selected depths in the top active layer and at around 10 m depth as close as possible to the depth of zero annual amplitude, is plotted together with air temperatures in Figure 3 to indicate the seasonal temporal fluctuations in temperatures. Mean hydrological year temperatures at key depths are summarised in Table 1, since 2016.

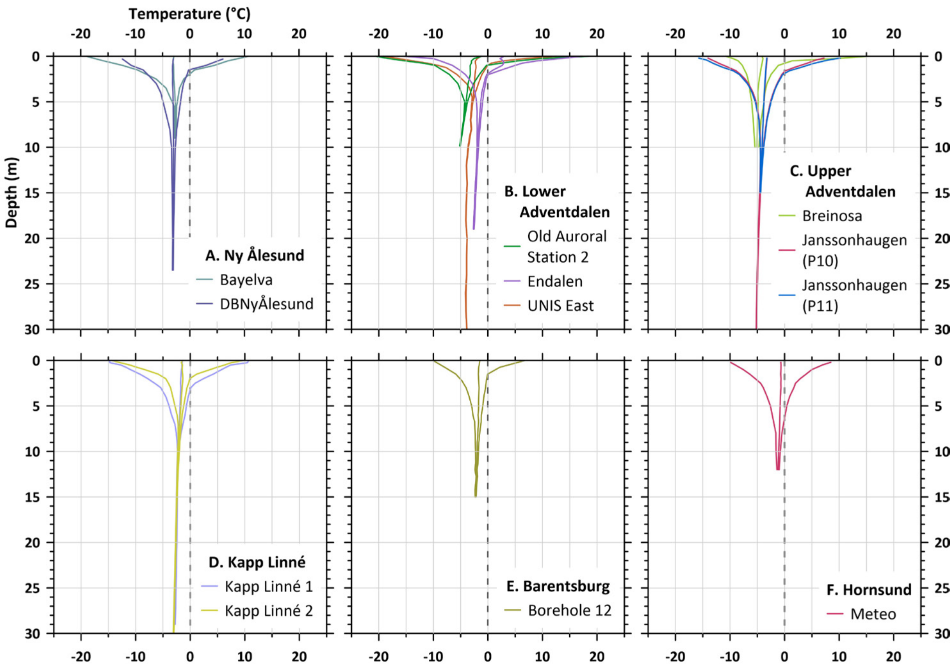

Figure 2: Ground thermal snapshot (minimum, mean, and maximum temperatures) measured in the upper 10 – 30 m of the permafrost observation boreholes in Svalbard during the 2017-2018 hydrological year.

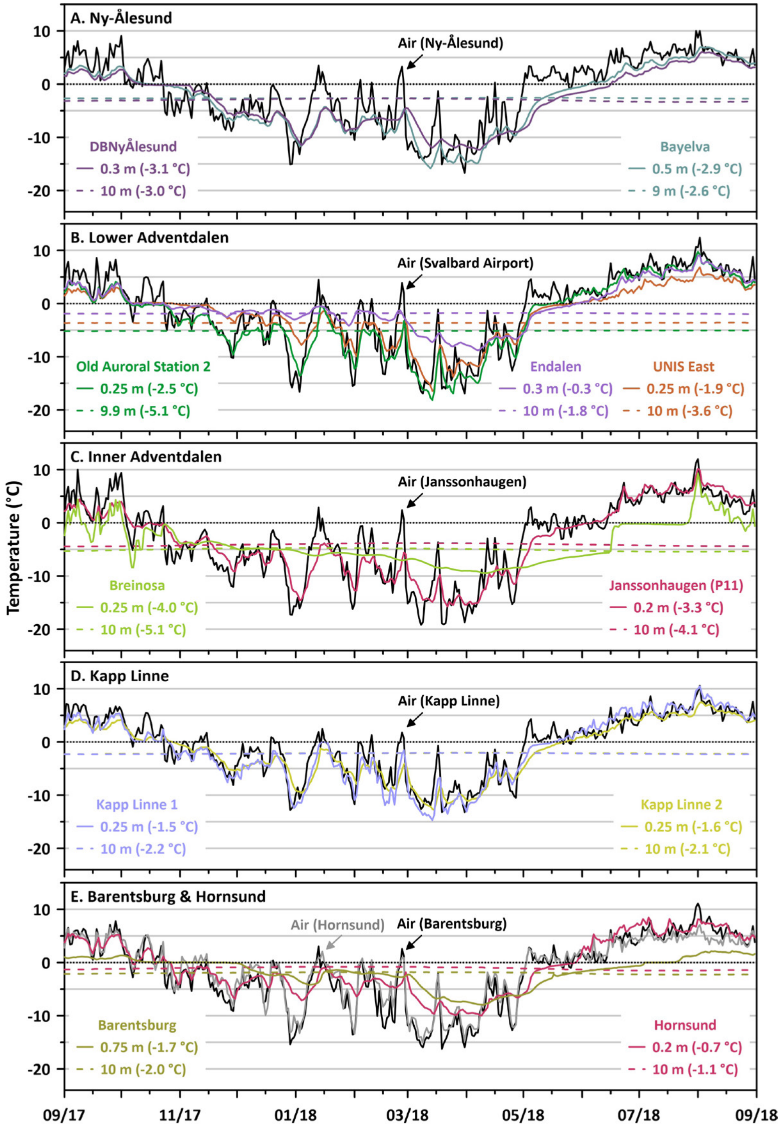

Figure 3: Air and ground temperatures during the 2017-2018 period for the five permafrost observations areas in Svalbard. The presented selected sensors are located near to the ground surface (ca. 0.2 – 0.75 m) and at 10 m depth (where possible). The mean ground temperature, calculated at each depth, is presented in brackets.

The ground is warmest near to the coasts (e.g. Kapp Linne & Hornsund) and in areas with thicker snow cover during winter (e.g. Endalen & Bayelva). Mean annual temperatures at the ground surface (MGST) ranged from - 0.1°C (Endalen) to - 4.1°C (Breinosa). Mean annual temperature near the permafrost surface (MPST) varied from - 0.9°C (Hornsund) to - 4.2°C (Breinosa), see Table 1. Mean annual ground temperatures (MGT), as measured at the depth of zero annual amplitude or lowermost sensor, varied from - 1.2°C (Hornsund at 12 m depth) to - 5.1°C (Breinosa and Old Auroral Station 2 at ca. 10 m depth) Table 1.

The duration of active layer freeze back is a significant parameter which, as an integral of air temperatures, snow conditions (onset and total thickness), soil moisture, and surficial geology, influences permafrost conditions by restricting heat exchange to the atmosphere for its duration. During the 2017-2018 hydrological year, the duration of active layer freeze back varied from 2 days at Breinosa to 151 days at Endalen (Table 1). Breinosa is a mountain top dry block-field site with coarse blocky material (Christiansen et al. 2019). Estimating active layer freeze back at this site is problematic due to convection within the blocky material. In most cases, the active layer freeze back duration was longer during the 2017-2018 hydrological year than in the 2016-2017 hydrological year. The difference is likely due to the smaller number of FDD during the 2017/2018 hydrological year providing less cooling following the transition to freezing air temperatures in autumn.

Aside from proximity to the coast, the temporal distribution of snow and soil moisture appear to be the most significant factors controlling permafrost conditions locally in Svalbard. Temperature presented in this report, including the first full year of ground temperature data from the Hornsund area, indicate that the north-south gradient present in air temperatures is also present in ground temperatures in Svalbard with the warmest permafrost temperatures in Hornsund in the South, intermediate in Barentsburg and Kapp Linne in the central part, and lowest in the Ny-Ålesund area in the northern part. The Endalen site, located on a hillslope in central Spitsbergen exhibits the warmest permafrost conditions in Svalbard. This is likely because of snow conditions coupled with drainage conditions on the slope, which impact permafrost through advective heat transfer and saturation of the active layer – prolonging active layer freeze back and delaying cooling. It appears permafrost is most susceptible to degradation at such locations.

2.3 Active layer thickness

The thickness of the active layer is either recorded directly through probing in CALM sites or calculated by interpolating the depth of the 0°C isotherm using borehole thermal measurements (Burn, 1998). Interpolation is used towards the end of the thawing season to calculate active layer thickness in the borehole temperature data. From the three Circumpolar Active Layer Monitoring (CALM) sites in Svalbard, in Adventdalen (UNISCALM), near Barentsburg, and in Ny Ålesund (Christiansen & Humlum 2008; Shiklomanov et al. 2012; Christiansen et al. 2019) thaw progression measured by probing is provided as a value recorded towards the end of the thawing season (Table 1).

Active layer thickness varied in summer 2018 between 64 cm (Breinosa) and 463 cm (Hornsund). The thinnest active layer is reported from a block field. Sites with sediment typically report active layer thicknesses of between 90 cm and ca. 180 cm. At bedrock sites, active layer thickness exceeded 185 cm. Comparing the results from this period with the 2016-2017 hydrological year (Christiansen et al. 2019), there is no clear pattern in change. Based on borehole interpolation, active layer thickness appears to have decreased in Ny-Ålesund and at selected sites in Adventdalen, Kapp Linné, and Barentsburg, while increasing at Janssonhaugen and a few other sites. Data measured in the CALM grids indicate a reduction in mean active layer thickness in Adventdalen and an increase in Barentsburg (Table 1). Interpolated data indicate an active layer thickness of ca. 463 cm at Hornsund. This is tentatively attributed to a combination of local meteorological conditions with higher air temperatures, ground water flow and the advection of heat to the thawing front. Analysis of extended data series will help to better understand the relation of active layer thickness and environmental variables in Svalbard.

3. Future permafrost challenges in Svalbard

3.1 Permafrost conditions in other geographic areas in Svalbard

Recent efforts by Norwegian permafrost researchers have centred on expanding the ground temperature monitoring network in Svalbard as part of the SIOS-InfraNor project[1]. In summer 2019, a 30 m deep borehole was drilled and instrumented at Verlegenhuken on the northernmost part of the island Spitsbergen at 80°N, next to the existing meteorological station. Measurements, recorded one day after drilling, indicated ground temperatures at 30 m depth were -4.3 °C. However, temperatures might be out of equilibrium due to the energy introduced during drilling. Future measurements, when collected during 2020, will be very interesting to study to provide the first data on the permafrost thermal regime in northern Svalbard.

1 https://sios-svalbard.org/InfraNor

The Russian team drilled and equipped two temperature monitoring boreholes (15 m each) in the top of two pingos in Grøndalen and has already fed data into GTN-P. Hopefully, it will also be possible to expand the permafrost observation network to cover the Pyramiden settlement located centrally in Svalbard, where no permafrost observations are yet collected, but where meteorological observations take place. It will hopefully be possible to establish permafrost observations in Pyramiden as a result of our international cooperation.

3.2 Permafrost conditions at greater depth in the ground

As part of the SIOS-InfraNor project, a drilling campaign was conducted during spring 2019 to extend existing boreholes in central Svalbard to 20 m depth. This will provide additional information on ground temperatures below the depth of annual temperature fluctuations, further increasing our ability to analyse the impacts of permafrost thermal conditions on environmental change. In addition, analysis of permafrost cores taken during this drilling campaign will improve our understanding of the physical properties of permafrost, necessary to make better predictions of future changes. These investigations will aid in answering questions regarding permafrost thermal conditions at depth and in portions of Svalbard not previously instrumented.

4. Connections and synergies

Permafrost is the foundation for the built environment and many landforming processes in Svalbard. Changes in permafrost conditions impact many other research areas including ecology, glaciology, hydrology, greenhouse gas cycling and nutrient transport. The effects of permafrost change are likely to spill-over and impact other realms. The contents are relevant for other research themes addressed in the current SESS report including understanding spatial variations in plant productivity, ecological and seismic monitoring, and glacier change. Future versions of SESS reporting may seek to better integrate permafrost related research outcomes with other aspects of the terrestrial cryosphere and environmental monitoring initiatives.

5. Recommendations for the future

- *Maintain existing monitoring networks and instrumentation*. Long-term, field-based monitoring of the permafrost essential climate variables (ECV) is essential to develop knowledge of the impacts of climate change on polar landscapes. The monitoring network operated between the international partners contributing to this SESS report will be critical in evaluating permafrost conditions in Svalbard into the future.
- *Expand the permafrost ECV monitoring network and making the data available online*. Currently, there are large areas with little or no permafrost observations in northern, southern, and eastern Svalbard. Recent (e.g. instrumenting the borehole at Verlegenhuken) and planned future permafrost observation efforts through SIOS will contribute to improving our knowledge about permafrost conditions in these relatively unknown areas. New boreholes using modern technology should be able to provide online access to the permafrost data both for improved process understanding, but also for use during potential landslides preparedness situations and educational and outreach purposes.
- *Assessing the response of permafrost landscapes to changes in climate by obtaining more knowledge about the ground ice content*. Only a few of the permafrost observation borehole in Svalbard have full scale cryostratigraphical information, with the key parameter the ground ice content being very important for understanding potential consequences at landform scale for warming permafrost and thicker active layers.
- *Investigate avenues to increase the time-scale of permafrost observations*. Efforts should be made to rehabilitate sites where permafrost conditions may have been monitored in the recent past – either as part of mining exploration or scientific research in Svalbard.
- *Continue to develop remote sensing tools for monitoring permafrost conditions and landscape response*. Site-specific monitoring information can be upscaled using remote sensing tools that SIOS also provides.
- *Improve interdisciplinary networking on permafrost related issues*. Increase the dialogue between the research scientists and practitioners on engineering and other key cryospheric issues related to permafrost. Additionally, very little is known about conditions at the base of permafrost (total thickness, permeability, and pressures) – increasing dialogue between other branches of geosciences may allow for new breakthroughs and understanding of the role of permafrost in trapping hydrates and greenhouse gases.

6. Data availability

The data included in this report have been made available through the Global Terrestrial Network for Permafrost (GTN-P) database.

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