Standardized monitoring of permafrost thaw: a user-friendly, multi-parameter protocol

Lead: Julia Boike[1,2]*, Sarah Chadburn[3]*, Julia Martin[1,4]* and Simon Zwieback[5]*

Contributors: Inge H.J. Althuizen[6], Norbert Anselm[1], Lei Cai[6,14], Stéphanie Coulombe [7], Hanna Lee[6], Anna K. Liljedahl[8], Martin Schneebeli[4], Ylva Sjöberg[9], Noah Smith[3], Sharon L. Smith[10], Dmitry A. Streletskiy[11], Simone M. Stuenzi[1,2], Sebastian Westermann[12] and Evan J. Wilcox [13]

* first four authors are the coordinating lead authors

Corresponding author: Julia Boike (julia.boike@awi.de), https://orcid.org/0000-0002-5875-2112

[1] Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI), Telegrafenberg, 14473 Potsdam, Germany

[2] Humboldt University Berlin, Geography Department, Unter den Linden 6, 10099 Berlin, Germany

[3] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, UK

[4] WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, Switzerland

[5] Geophysical Institute, University of Alaska Fairbanks, Fairbanks 99775, Alaska, USA

[6] Bjerknes Centre for Climate Research, NORCE Norwegian Research Centre, Nygårdsgaten 112, 5008 Bergen, Norway

[7] Canadian High Arctic Research Station, Polar Knowledge Canada, Cambridge Bay, NU X0B 0C0, Canada

[8] Woodwell Climate Research Center, 149 Woods Hole Road, Falmouth, MA, 02540-1644, USA

[9] Department of Geosciences and Natural Resource Management, Centre for Permafrost (CENPERM), University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark

[10] Geological Survey of Canada, Natural Resources Canada, Ottawa, ON-K1A 0E8, Canada

[11] Department of Geography, The George Washington University, 2036 H St NW, Washington DC, 20052, USA

[12] Department of Geosciences, University of Oslo, Sem Sælands vei 1, 0371 Oslo, Oslo, Norway

[13] Cold Regions Research Centre, Wilfrid Laurier University, 75 University Ave W., Waterloo, N2L 3C5, Canada

[14] Department of Atmospheric Sciences, Yunnan University, North Cuihu Road 2, Kunming, 650000, China.

Abstract

Climate change is destabilizing permafrost landscapes, affecting infrastructure, ecosystems and human livelihood. Permafrost thaw is affected by surface and subsurface properties and processes, all of which are potentially linked with each other. Yet, no standardized protocol exists for measuring permafrost thaw and these processes and properties in a linked manner. The framework of the Terrestrial Multidisciplinary distributed Observatories for the Study of the Arctic Connections (T-MOSAiC) permafrost thaw action group has developed a protocol, for use by non-specialists, citizen scientists, government agencies and indigenous groups, to collect standardized metadata and data on permafrost thaw.

The protocol introduced here addresses the need to jointly measure permafrost thaw and the associated surface and subsurface environmental conditions such as snow and vegetation height, soil properties and water level along transects. The metadata collection includes data on timing of data collection, geographical coordinates, land surface characteristics (vegetation, ground surface, water conditions), as well as photographs. The comprehensive description and management of all data with metadata, central data storage and controlled data access is applied through the Observation to Archives (O2A) dataflow framework. Through this standardized procedure, devices, sensor descriptions and data streams can be monitored in near-real time and their spatial distribution visualized. A dedicated user-friendly application (app) for android facilitates the data entry of field measurements and provides user-friendly standardized data collection and documentation.

Our new T-MOSAIC permafrost thaw measurement protocol documents in a standardized and sustainable manner the impacts of climate change on permafrost. The openly available dataset will also be highly valuable for validation and

parameterization of numerical and conceptual models, thus to the broad community represented by the T-MOSAIC project.

Keywords

protocol, thaw depth, snow depth, vegetation height, soil characteristics, water level

Background and General introduction

Northern landscapes and infrastructure are affected by the destabilization of permafrost, which in areas underlain by ice-rich permafrost can lead to surface subsidence and slope instability. Permafrost thaw has profound implications for Arctic ecosystems and their inhabitants, through changes to surface drainage and water resources, vegetation and wildlife habitats, and through the positive feedback to global warming via the emission of greenhouse gases.

There is an urgent need for standardized monitoring of permafrost thaw, as well as for collecting baseline information; the impacts of permafrost thaw on ecosystems are expected to continue to accelerate with climate warming, changes in precipitation and increasing surface disturbance. For 2020, the Arctic Report Card highlights the highest recorded surface air temperatures, record lows of June snow cover, opposing trends of tundra greenness, and extreme wildfires (Arctic Program, 2020). Permafrost temperature trends and increasing active layer thaw depths, show a large variability in magnitudes and rates, due to local variation in snow, vegetation and soil characteristics (Romanovsky et al. 2020). These local variabilities are critical for the evaluation of permafrost thaw. Not only do the rate and nature of permafrost thaw depend on factors such as snow depth, the thickness of the organic layer and vegetation height, but also permafrost thaw will in turn influence these variables. For example, increases in the density and height of shrubs have been reported from tundra regions across the Arctic, and locally shrub expansion is driven by permafrost degradation. The shrub growth can in turn reduce (Blok et al., 2010) or promote (Wilcox et al., 2019) permafrost thaw, depending on how shrub height affects snow accumulation and snow melt. The hydrological conditions in ice-rich permafrost lowlands determine the thawing of permafrost; inundated and wetter areas favour degradation, while drainage and drier areas favour stabilization (Nitzbon et al. 2020).

A number of protocols have already been created by specialized research communities (Table 1), yet no common protocol exists that simultaneously quantifies both permafrost thaw and all the associated environmental variables which affect permafrost thaw. The focus of our study was to design such a protocol.

Directly measuring permafrost thaw through changes in surface elevation or thermal monitoring (including below the permafrost table) requires expertise and equipment for drilling and (geodetic) surveys, thus it is often difficult to implement. Instead we focused on developing a protocol that can be implemented by any operator in the field using simple, universally available and inexpensive instruments. The urgent need for a standardized protocol for monitoring Arctic freshwater was recently pointed out by Heino et al. (2020).

If we simply measure permafrost thaw alone, we are missing information on the key factors that control it. This lack of data limits our ability to attribute the changes, and therefore to upscale or to make future projections of permafrost thaw. Thus, we also based our parameter selection on inputs required for numerical and conceptual models (including Earth system models and specialized models, such as CryoGrid; Nitzbon et al. 2020).

Here we developed simple protocols and an associated phone app that will enable a wide range of Arctic citizens and scientists to make high-quality, standardized and accessible measurements. Our protocols address the need for consistent collection and integration of data from around the permafrost region to: i) better monitor and understand permafrost thaw; ii) establish a baseline against which future change can be measured; and iii) support the integration of field measurements within pan-Arctic geospatial datasets developed through remote sensing analyses or modelling. The app guides the user through the observation process; ensures that the observations are consistent and well documented; and transfers the observations to an accessible database.

We developed the protocol in the Terrestrial Multidisciplinary distributed Observatories for the Study of the Arctic Connections (T-MOSAiC) action group on permafrost thaw. T-MOSAiC is an International Arctic Science Committee (IASC) pan-Arctic, land-based programme that extends the activities of the sea-based programme Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC; https://mosaic-expedition.org/). Originally T-MOSAiC was planned to run concomitantly with MOSAiC to achieve simultaneous measurements of biogenic, hydrological and atmospheric fluxes by extending the work to the lands surrounding the Arctic Ocean. Due to the COVID pandemic limiting travel to field sites, T-MOSAiC was extended to the end of 2021. We suggest using this year (2021) for intense monitoring to kick-start a longer term set of measurements monitoring the progression of permafrost thaw (and other associated changes) over many years.

In the following, we detail the rationale behind the protocol and choice of measurements, while the detailed protocol is available in the supplement.

The supplement gives further details of the app for data collection, as well as an instructional video. This was recorded at a permafrost site in northern Norway in autumn 2020. The video crew were students, not permafrost experts.

Table 1. Summary of existing protocols for the parameters for which we provide protocols. These parameters are grouped into the five following spheres: snow, permafrost, vegetation, hydrology, soil.

Sphere	*Existing protocols, Organization*	*Citation*
Snow	1. ECV Products and Requirements for Snow, The Global Climate Observing System (GCOS) 2. Estimating the snow water equivalent from snow depth data, International Commission for Snow and Ice Hydrology (ICSH) 3. The international classification for seasonal snow on the ground, International Association of Cryospheric Sciences (IACS) 4. European Snow Booklet, WSL Institute for Snow and Avalanche Research SLF 5. Chapter 5: Snow and Ice, International Tundra Experiment (ITEX) Manual, Danish Polar Center	1. The Global Climate Observing System (2016a) 2. Jonas and Marks (2016) 3. Fierz et al. (2009) 4. Haberkorn (2019) 5. Molau (1996)

Permafrost	6. Global Terrestrial Network for Permafrost, International Permafrost Association (IPA)	6. Streletskiy et al. (2017)
	7. Methods for Measuring Active-Layer Thickness, A Handbook on Periglacial Field Methods, IPA, Circumpolar Active Layer Monitoring Network (CALM)	7. Nelson and Hinkel (2003) in Humlum and Matsuoka (2004)
	8. Essential Climate Variables (ECVs) Products and Requirements for Permafrost, GCOS	8. The Global Climate Observing System (2016b)
	9. Active Layer Monitoring standard protocol, Arctic Development and Adaptation to Permafrost in Transition (ADAPT)	9. Arctic Development and Adaptation to Permafrost in Transition
	10. Chapter 6: Active Layer Protocol, (ITEX) Manual	10. Nelson et al. (1996)
	11. Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables, Permafrost	11. Smith and Brown (2009)
Vegetation	12. Chapter 8: Plant response variables, ITEX Manual	12. Molau and Edlund (1996)
	13. Vegetation standard description protocol, ADAPT	13. Grogan et al.
	14. New handbook for standardised measurement of plant functional traits worldwide	14. Pérez-Harguindeguy et al. (2016)
Hydrology	15. Guide to Hydrological Parameters – Volume 1, World Meteorological Organization	15. World Meteorological Organization (2008)
	16. Soil moisture content, CALM	16. Circumpolar Active Layer Monitoring Network

Soil	17. Sampling protocols for permafrost-affected soils	17. Ping et al. (2013)
	18. Soil Survey Fields and Laboratory Methods, U.S. Department of Agriculture, Natural Resources Conservation Service	18. Soil Survey Staff (2014)
	19. Active Layer Sampling standard protocol for C/H/N determination, ADAPT	19. Arctic Development and Adaptation to Permafrost in Transition
	20.Planning and making a soil survey, Food and Agriculture Organization of the United Nations	20. Food and Agriculture Organization of the United Nations
	21.Terrestrial Instrument System (TIS) Soil Pit Sampling Protocol, The National Ecological Observatory Network (NEON)	21. The National Ecological Observatory Network (2021)
	22. The United Nations Terminology Database, United Nations	22. United Nations (2012)

Protocol overview- Choice of parameters and scale issue

Protocols for everyone

The protocol's target group is the "non permafrost expert". The users range from citizen scientists to experts from related fields, such as ecologists and hydrologists, as well as field technicians, station managers and students.

The protocol is geared to non-experts in three important ways. First, no specialized knowledge is needed. The measurements are simple, and the sampling guidelines were chosen so as not to be overly time consuming or burdensome. Second, no specialized equipment is needed. All protocols only require simple tools such as a ruler, camera, tape measure, and steel rod. Third, we developed an app that guides the user through the measurement process, thus facilitating data collection. By enforcing the compilation of required metadata and homogenizing data transmission, and storage, the app also plays a critical role in establishing data quality and usability.

Parameters

We group the parameters for which we provide protocols into five spheres:

1. Snow: snow depth
2. Permafrost: thaw depth
3. Vegetation: vegetation height
4. Hydrology: water level
5. Soil: organic layer depth, texture, ground ice

We chose the specific measurement parameters (Fig. 1) to cover the major controls of permafrost thaw with simple measurements that are accessible to non-experts, and in doing so we inevitably cannot include some commonly used parameters, such as soil temperature, due to their need for specialist equipment.

Figure 1 gives a broad overview of the spheres, as well as an overview of their seasonality, and measurements as described in this protocol. Measurements start during the wintertime on snow, and are continued at the same transect points through the seasons of snowmelt, vegetation growth, deepening of the thawed layer and water level development. Measurements of soil properties, such as organic layer thickness and soil texture are only done once along the transect – ideally during the later part of the season when the thawed layer has reached its maximum.

Not only do all of these spheres interact with each other but they also vary dramatically across the landscape. For example, snow depth on palsas is around 2x smaller than on an adjacent mire (Martin et al., 2019). This landscape variability is sometimes driven by dynamic feedbacks between these parameters that can amplify small variations into major sources of heterogeneity. For example, a small variation in surface elevation can lead to a positive feedback in which snow and water pool in the depression, warming the ground and leading to ground subsidence (if the ground is ice-rich), resulting in further accumulation of snow and water, and ultimately accelerated permafrost thawing in this location (Kokelj and Jorgenson, 2013; Nitzbon et al. 2020). Some features will vary on scales of metres, including microtopography such as hummocks and vegetation. Others will vary on the scale of hundreds of metres, such as differences between valley bottoms and hillslopes. In designing our protocol we considered these issues, with measurements of multiple parameters in different spheres being co-located on one transect (see next Section).

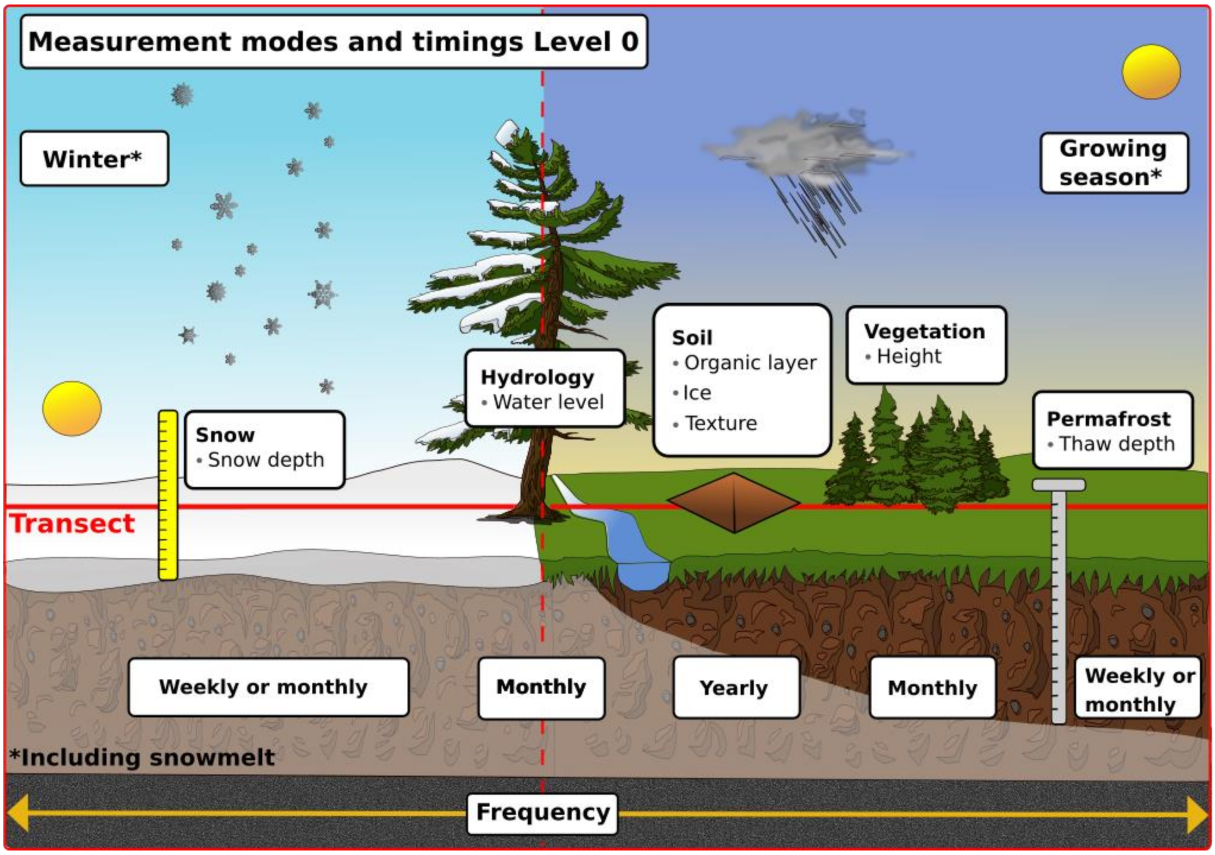

Fig. 1: Spheres with the associated parameters, measurement modes and observation timings.

Where to measure?

Our protocol design attempts to ensure that measurements represent the variability within a landscape. Since our overarching goal is to understand permafrost thaw on a pan-Arctic scale, we must consider the issues in scaling between a measurement at a single point to regional models / satellite data pixels (10s to a few 100s of m to kms) and global models (10s – 100s km).

To ensure representation of variability within a landscape, we considered the target audience and the time constraints that a citizen scientist may have: we therefore chose the scale of the measurements as a 10–30 m long transect to allow *typical microtopographic features* to be resolved by sampling every 1 m. This means that the minimum effort (one 10-m long transect) can resolve a key aspect of variability and requires very little investment of time.

Time permitting, larger-scale variability will be captured with further transects in the local area, taking account of the landscape features that are present. For example, at the Iskoras site (Fig. 2), a transect would ideally take place in the palsa mire, in the forest and on the nearby upland tundra. In the protocol we urge the users to consider the landscape variability in and around their site, and to select ‘representative’ locations for their transect (see protocol section 0).

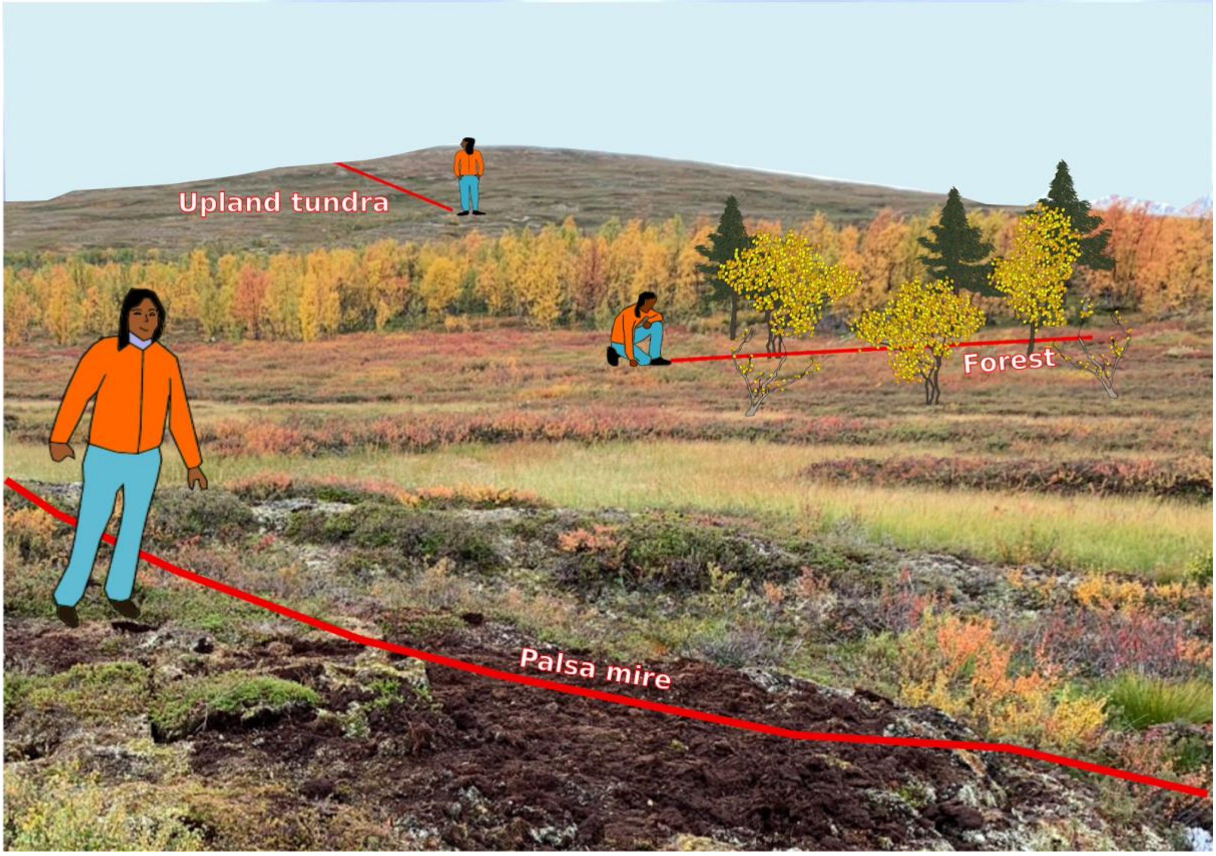

Fig. 2: Example of landscape variability covering palsa mire, forest and upland tundra (Iskoras; Finnmark, northern Norway). Typically, one 10-m long transect cannot cover all the characteristic features as shown in this figure. If timing and capacities allow, several transects can be established. If there is already a transect set up at your site you can use it.

Data quality and metadata

The protocols are designed to ensure that the data and metadata meet scientific standards. The app collects and compiles additional information about the measurement process and location, including site characteristics such as location, field photos, and observation characteristics such as date and name. By complying with FAIR principles (Wilkinson et al., 2016), the app ensures that the observations can be used and interpreted routinely by people unfamiliar with the site. Upon transmission from the user’s device, the data are curated and stored.

Details of the spheres

The sections below describe each of the five measurement spheres. Here we give details on the scientific importance of each sphere and its interactions with permafrost thaw, as well as the rationale behind the choice of parameter to measure and the chosen measurement technique.

Snow

Background

Snow precipitation in Arctic regions is predicted to increase; whereas its duration is likely to decrease (Callaghan et al., 2011). The solid precipitation accumulates with the ongoing snow season forming a snow cover that interacts with all spheres. We focus here on snow depth, as the key variable for determining the effects of snow (Crumley et al., 2020).

The low thermal conductivity of snow creates an insulating layer exerting a strong influence on the permafrost-affected soil’s thermal regime (Zhang, 2005; Grünberg et al. 2020). The insulating power of snow can be greatly influenced by the type of vegetation cover (Domine et al., 2018). In spring, snow strongly reflects the solar radiation (i.e., a high albedo) (Striegler et al., 2016). The duration and extent of the snow cover in spring regulate the soil temperature and meltwater supply (Boike et al., 2003).

Snow depth shows a strong spatial variability, as a result of land cover characteristics (topography, vegetation) as well as wind-induced redistribution. For example, the snow cover on plains can experience drift, and therefore redistribution (Parr et al., 2020, Sturm et al., 2001a); whereas local depressions, or an abundance of shrubs, trap snow (Sturm et al., 2001b). This is why we measure along a transect. Critical observation times are the onset of snow accumulation at the beginning of the winter season, its maximum and the minimum height prior to spring melt. Continual observations are best, and a measuring frequency of at least one set per month is recommended (ideally measurements should be made once per week).

Measurement

Snow depth is the full height of a snowpack measured perpendicular to the underlying ground (Haberkorn, 2019). It allows the snow cover evolution to be captured over time with minimal effort but maximum information. It is measured mechanically using either a simple ruler to record the depth or if available a snow rod with the measuring units already on the probe. Those tools are easy to obtain, user friendly and no special knowledge is necessary. Snow depth measurements can be difficult if: the snowpack is very hard or if the soil below the snow is very soft. In the first case, the probe may not reach the ground (e.g., if there is a hard refrozen crust within the snowpack or in presence of a basal ice layer). In the second case, the probe may penetrate the ground (e.g. unfrozen peat, deep grass or moss hummock). In a very shallow snowpack these sources of error can be checked by digging a snowpit to confirm the snow depth. Additionally, we suggest making several measurements at the same spot. We recommend measuring every metre along the transect.

Permafrost

Background

Thaw depth is the only variable for characterizing permafrost conditions that is included in the T-MOSAiC protocol. It is defined as the distance between the surface and the frost table (Brown et al., 2000). Thaw depth progressively increases over the summer period, as the thaw front penetrates deeper into the ground. The most critical time for measuring thaw depth is at the end of the thaw period, when thaw depth is at or near its yearly maximum (Brown et al., 2000). The annual maximum is closely related to, but nevertheless distinct from, the thickness of the active layer (the layer that seasonally thaws and freezes) and the depth to permafrost.

Thaw depth is an important variable for characterizing changing permafrost conditions. The maximum annual thaw depth varies from year to year (Shiklomanov et al., 2010). Increasing air temperatures and ground warming are often associated with an increase in the maximum thaw depth, which makes it a valuable climate indicator (Brown et al., 2000). However, two additional factors have to be considered. First, the thermal regime and consequently thaw depth also depend on interrelated variables such as soil moisture, vegetation, and snow (e.g., Walker et al., 2003;

Shiklomanov et al., 2010; Grünberg et al., 2020). Second, the thawing of permafrost that contains a lot of ice primarily induces subsidence rather than increases in thaw depth (Osterkamp et al., 2009; O'Neill et al. 2019). A comprehensive quantification of permafrost thaw hence necessitates subsidence observations (Streletskiy et al., 2017). While direct observations of subsidence are not included in the protocol due to the lack of simple methods, the measurements of vegetation and inundation (wetness) can indicate subsidence induced by thaw of ice-rich permafrost.

Measurement

Multiple methods exist for determining thaw depth in the field (Smith and Brown, 2009). Mechanical probing is arguably the most popular method because it does not require sophisticated equipment (Brown et al., 2000). Mechanical probing is the method adopted for the T-MOSAiC protocol.

To measure thaw depth by mechanical probing, a metal rod (usually 1–1.5 m in length) is inserted into the soil until the point of resistance against the frost table at each point along the transect. The depth that the rod has gone into the ground can then be read off using a measuring tape or based on graduated marks on the rod itself.

The measurements need to account for the substantial small-scale spatial variability in thaw depth. To ensure unbiased sampling and to facilitate comparisons over time, the measurement should be made in immediate proximity to the marked transect point. If standing water should make it too difficult to measure at the point, the measurement should be marked as "Water".

Mechanical probing works best in organic and gravel-poor mineral soils that are ice bonded when frozen (Brown et al., 2000). The app guides the user through challenges that may arise in measuring substrates that are less amenable to probing. The most commonly encountered limitations are:

- In bedrock or gravel, probing may be impossible altogether.
- It can be difficult to distinguish between subsurface stones and frozen substrate, for instance in soils that contain gravel.
- In locations of deep thaw or no permafrost, the thaw depth may exceed the length of the rod.
- In saline marine sediments or plastically frozen clays, the unusual mechanical properties present a challenge to frost probing

Vegetation

Background

Vegetation is an important component in shaping the surface energy balance and the thermal and hydrological regime of permafrost. At the same time it can also react to changes in the environment (Myers-Smith et al., 2011). Different vegetation types can have contrasting effects on permafrost ecosystems. Forests are usually considered to efficiently insulate the underlying permafrost (Chang, 2015) by altering the thermal regime, intercepting snow, and promoting the accumulation of an organic surface layer (Bonan, 2003). Low stature tundra vegetation can similarly affect permafrost thaw by altering thermal and hydrological conditions through differences in albedo between vegetation types (Juszak et al., 2016, Aartsma et al., 2020), as well as the effect of vegetation height on snow conditions, including snow depth and snowmelt (Wilcox et al., 2019). From a permafrost thaw perspective we consider the presence and the height of vegetation as the most important parameters for including vegetation in permafrost modelling. Commonly, vegetation height is measured from the soil surface to the highest point of the vegetation. This is unclear for the special case of tussock vegetation which hasn't been described in detail in previous protocols. Here, we suggest measuring the height of the entire tussock from the soil surface as well as the height from the inter-tussock space to the highest leaf. As multiple measurements are made within each quadrant this will then provide representative average vegetation heights along the transect (similarly with height measurements of multiple trees).

Measurement

The measurement of vegetation height can provide a good estimate of the type of vegetation regime present and requires little knowledge about actual plant species or plant functional types. Height measurements should be carried out in 1x1 m quadrats at each point along a 10–30 m transect. This transect should be established before taking any measurements at the site. Optionally, if the site is located in forest, a minimum of 10 individual trees in a 15x15 m plot should also be measured. Most measurements therefore require a ruler or tape measure only, but in tall forest it might be necessary to give training in height estimation beforehand.

Hydrology

Background

Because the fluxes of water and energy are so strongly linked in Arctic landscapes some understanding of hydrology is crucial when studying permafrost thaw (Riseborough et al., 2008; Woo, 2012). The water content of a soil is generally the most important factor determining its thermal conductivity, and thereby the transport of heat between the active layer and the permafrost. The latent heat associated with freezing/melting of water/ice in the ground further influences the freeze/thaw rate of the ground. This can be observed in ground temperature records which typically show a prolonged period of near-freezing temperatures in the spring and fall, commonly referred to as the zero-curtain effect (Outcalt et al., 1990). The water content of a saturated soil is equal to the soil's porosity. Considering that porosity of soils in the active layer commonly ranges from 40% for mineral soils to > 90% for peat, spatial and temporal variability in soil water content can be considerable in arctic landscapes (Hinzman et al., 1991, O'Connor et al., 2020). Seasonal variability in soil wetness is often high in permafrost regions, due to the large input of water during snowmelt. With changing climate and permafrost thaw, expected changes in soil wetness include increased and deeper infiltration of water in the ground, changed precipitation patterns and earlier timing of snowmelt, increased potential evapotranspiration, and thermokarst (Walvoord and Kurylyk, 2016; Liljedahl et al., 2020; Nitzbon et al., 2020).

Measurement

From a permafrost thaw perspective, we consider the spatial and temporal distribution of soil wetness indicated by the height of the water table the most important hydrological variable to record. Water table observations are most easily done in combination with measurement of thaw depth, as it can be carried out with the same equipment and along the same transect. Acquiring observations of both wetness and thaw depth at the same locations and times helps in later interpreting the relationship between water level and soil thaw. Following our protocol, the height of the water table relative to the ground surface level is noted as: “above the ground surface”, “within 10 cm below the ground surface”, or “more than 10 cm below the ground surface”. This very simple classification, carried out at points along transects, provides valuable information for characterizing soil wetness which can be used by permafrost modellers.

Soil

Background

By nature, permafrost-affected soil is a complex mixture of various media including organic matter, sand, silt, gravel, and ice. Understanding the overall characteristics of the soil structure and texture provides knowledge about the genesis of sediments and the history of accumulated materials (Rieger, 1983; French and Shur, 2010), but also the likely direction of future changes in the land surface under permafrost thawing (Jorgenson et al., 2010, Rasmussen et al. 2018). The nature of the soil can also play a significant role in controlling the mechanical properties of the sediments, as well as the shape and distribution of ice within the sediments. Soil properties play a crucial role in energy, water, and elemental transfer by affecting the exchange of heat between the atmosphere and the subsurface. For instance, soil texture affects pore spaces, which determines the maximum amount of water that can be contained in a soil layer. In addition, the ice content and the form of ice such as ice lenses or massive ice can affect energy transfer, as well as induce frost heave or subsidence of the ground surface in response to the formation or melting of the ice. Organic matter content and organic layer depth can exert an insulating effect on permafrost thawing. Soil structure and texture, ice content and structure, and gravel content are some of the key points of information that can be gained from our protocol.

Measurement

Soil measurements are taken as a one-time observation from a single measurement point on the transect (considering a “representative” location, see section X.Y above). A soil pit should be dug close to the other measurements but set to the side to avoid digging up the ground where the other measurements are taken. The pit should be approximately 1 metre wide and 1 metre deep, or until one cannot dig due to frozen ground. For this reason, the measurements should be taken at the end of the growing season when thaw depth is greatest. The scale of 1 metre is chosen to allow a clear soil profile to be revealed in the side of the pit (with a smaller pit, it is difficult to see a clear profile), as well as to give a reasonable estimate of the surface organic layer thickness, since this is extremely variable. If digging a pit is not allowed or possible, estimating the surface (organic) layer using a hand held soil auger/drill is recommended. After digging a pit, a photograph of the clear profile should be taken and a description of visible characteristics should be recorded, such as depth of organic layer, contents of ice and rocks, colour of the soil, and soil texture. For non-specialists, we provide a flow chart that helps identification of soil texture (i.e., clay, silt, sand, gravel) using a simple “hands-on” flow chart within the app adapting the protocol of the mySoil app (Natural Environment Research Council, 2016). Overall, the soil measurements are designed so that they do not require any specialist equipment or laboratory analysis; one only needs a shovel and a measuring tape. It is not absolutely necessary, but a small hand saw or a bread knife is very useful to cut through the organic layer. To restore the site, the pit has to be refilled and the organic mat reassembled.

Metadata

Metadata standards are important because metadata provide essential information about the quality, use and genesis of the information being collected. Our metadata protocol complies with the standards of the Open Geospatial Consortium (OGC) (Open Geospatial Consortium, 2021) and thus facilitates interoperability. The protocol requests basic information about the site location, including latitude, longitude, altitude, and the location of the nearest weather station. This information is crucial for both mapping and modelling, and therefore adds greatly to the usability of the data collected. Land surface models require various forcing data, which they will take either from the nearest weather station, or in some cases from gridded products where they will take the nearest grid cell to the site. We then request an overview of the site characteristics as seen by eye, including whether the site is rocky, what type of soils are there, and how wet it is. For example, it may be a very wet or dry site, or it may be mixed, and these overview assessments, while providing similar information to the spheres themselves, will give an overview of the site as a whole. They will also tell the user of the data about how representative the transect measurements are. While vegetation height is covered in its own sphere, the dominant type of vegetation merits inclusion as metadata because it is a key indicator of the type of site. Basic information about any water features, such as ponds and rivers, as well as natural and anthropogenic disturbances are recorded as these will also affect the site, impacting the hydrology and permafrost thaw. Photos are required in the four cardinal directions in a standardized manner that provides a sense of scale, to give an overview of the site and clarify descriptions. An additional photo shows the placement of the transect.

Data collection, transfer and storage

We aim to provide quality-assured and FAIR data management over the whole data life cycle. Data should be findable, accessible, interoperable, and reusable according to these FAIR principles (Wilkinson et al., 2016). Hence, measurement data and metadata need to be provided accurately and completely, have a persistent and unique identifier, and deposited in a trusted repository. It must follow the semantics of a standardized, controlled vocabulary to have broadly applicable language for maschine access and processing. We apply the Observation to Archives (O2A) dataflow framework which includes the comprehensive description and management of all data with metadata, central data storage and controlled data access (Koppe et al. 2015; Gerchow et al. 2015). Through a standardized procedure data uploads can be monitored in near-real time and their spatial distribution visualized. The data can be accessed instantly as is via the near-real time database (Alfred Wegener Institute, 2021) while quality controlled and thematically curated datasets will be published in the PANGAEA (Pangea, 2021) long-term repositories and thus giving credit to the data provider in a data publication (Schäfer et al. 2020). A map-based search and visualization of the data with download link for the data (example: thaw depth) is planned. Data will be collected using a mobile app directly in the field. Data uplink occurs on-the-fly or whenever the data collector can upload it to an AWI server and will be automatically ingested into the O2A process chain (Fig. 3).

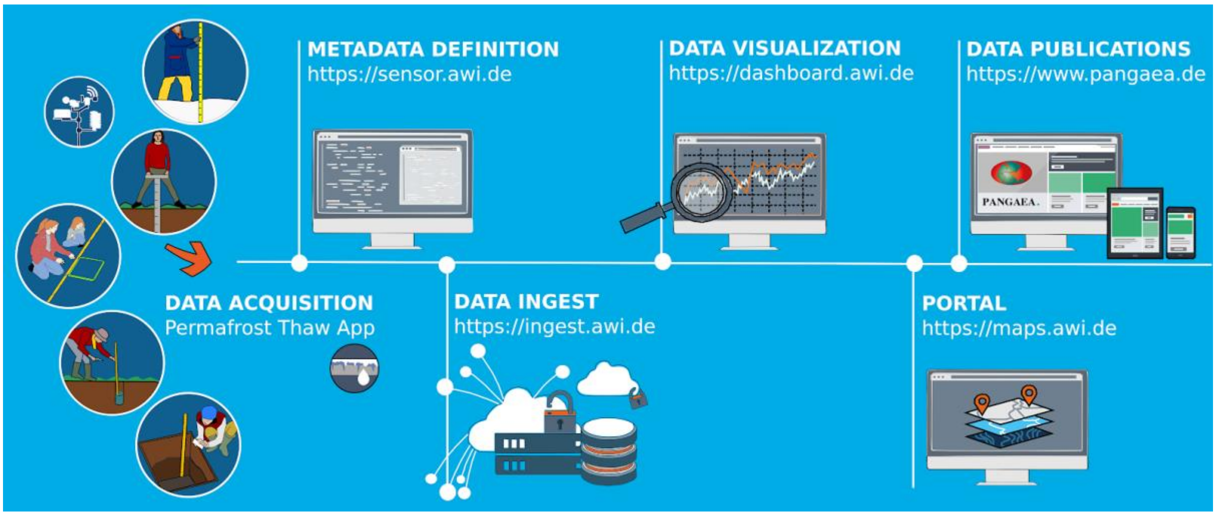

Fig. 3: Illustration showing the workflow of the data collection (App) and O2A (Alfred Wegener Institute, 2021) process chain towards archival into repository. Data are collected offline and ingested into O2A in delayed mode (as soon as internet access is available) using full metadata annotation. A dashboard is used for visualization of the data once they are uploaded. Data can be visualized spatially on the Portal. Final publications take place in the repositories. Figure adapted after Koppe et al. (2015).

Description of mobile app for data collection

An app for installation in mobile phones is currently under development and will be available freely to everybody (in supplement). The app allows the data collected to be exported to central data storage for data analysis and reporting. One of the advantages of apps is the possibility of gathering data offline or while on-the-go. The offline form allows researchers to collect and store data while in the field and upload it once an internet connection is available (for example, at the field station). As nearly all researchers and citizens today own a mobile phone, we see immense advantages in using a mobile over a field notebook or report-based archives. The app is designed for use in cold climates and is user friendly, with help /guidelines and "pop-up window" options when necessary. Since our protocol asks for measurements at multiple moments across time and spheres, at new and recurring locations (i.e., long term measurements at the same sites), the app is able to identify the recurring location, thus eliminating the need to re-enter the metadata.

The app will be available under CC BY licence. Further maintenance and development, such as security updates and, if necessary debugging, are planned for the future.

In summary, we provide a secure and collaborative data entry, resulting in a faster data analysis, visualization, access and storage.

Conclusions and outlook

We present a set of simple protocols for observing permafrost thaw and associated environmental conditions, namely: snow, vegetation, hydrology and soil. The protocols are unique in that they

- are for everyone: no knowledge or sophisticated equipment is needed;
- encompass multiple critical parameters, so that the drivers and controls of permafrost thaw can be quantified;
- come with an app that guides the user through the measurement process and guarantees data quality, consistency and accessibility.

The protocols address the urgent need for high-quality field observations of permafrost conditions. The observations will be critical for understanding and predicting permafrost thaw and for establishing a baseline for quantifying future change. The consistency and accessibility of the observations is crucial for data-driven analyses. The dataset will serve to enhance and validate Earth system models and remote sensing methods that are indispensable for monitoring and projecting permafrost thaw across the Arctic.

The current protocol has already been implemented by some INTERACT sites and data will be collected in 2021. The next steps include sharing it with a wider group of scientists and the public, for example to colleagues, the Permafrost Young Researchers Network, Cryolist server and sharing on social media. The protocol should be distributed to researchers and citizen scientists to obtain data on snow, vegetation, soil and thaw depth at locations around the Arctic. Future work will include a linked higher level protocol which includes measurements, for example of ground subsidence and soil temperatures for which more advanced instruments, techniques and expertise are required.

More widely, similar integrated protocols that address carbon and nutrient cycling would also be of great value in monitoring the permafrost landscape. Beyond these community-led initiatives, national infrastructure funding for permanent monitoring sites is also needed to understand long term permafrost thaw.

Acknowledgement/Financial Support

We acknowledge the following grants and funding for this work:

JB, JM: Helmholtz Association in the framework of MOSES (Modular Observation Solutions for Earth Systems); DS: NSF 1836377 and 2019691; IA: Norwegian Research Council, KLIMAFORSK programme, NFR project number 294948 (2019–

2022); SMS: ERC consolidator grant Glacial Legacy of Ulrike Herzschuh (grant no. 772852) and Federal Ministry of Education and Research (BMBF) of Germany grant to Moritz Langer (no. 01LN1709A); EJW: W. Garfield Weston Award for Northern Research (PhD), Ontario Graduate Scholarship; SEC: Natural Environment Research Council grant no. NE/R015791/1; SW: European Space Agency (ESA) Permafrost CCI; Nunataryuk (EU grant agreement no. 773421); SZ: NASA 80NSSC19K1494.

The authors declare there are no competing interests.

Valuable comments to the initial protocol were contributed by Annett Bartsch, Liane Benning, Bill Cable, Matthias Fuchs, Birgit Heim, Stefan Kruse, Susanne Liebner, Maribeth Murray, Jan Nitzbon, Peter, Pulsifer, Gabriela Schaepman-Strub, Warwick Vincent. The app was developed by Ole Eckermann. The video tutorial was recorded by E. Auunsdottier and S. Azanova and edited by S. Azanova.

Author contributions

JB, SC, SZ conceived the idea and conceptualization for the protocol and paper.

The original draft and outline of the paper and protocol were prepared by JB, SZ, SC, JM.

The individual sections with details of the spheres in the paper and protocol were contributed by the following: snow: JM, MS; permafrost: SZ, JB, EJW, DS, SS; vegetation: IA, SMS; hydrology: YS, AL; soil: JB, SC, HL; metadata: SC, LC, NS, SW; data collection, transfer and storage: JB, NA.

All other sections were written by JB, SC, SZ.

Figures were drawn by JM with inputs from JB, SC, SZ and NS.

JB, SC, SZ, JM organized the writing and contribution from the co-authors.

Review and editing of the various versions of the paper were provided by JB, SZ, SC, JB, JM, SB, IA, NS.

NA. set up the O2A data flow with inputs from JB.

The video tutorial was organized by IA and HL.

All co-authors approved the final version of the manuscript.

Appendix/Supplement

- Protocol
- App (link where to download)
- The video tutorial by art students from Iskoras, Norway, September 2020 is available here: https://youtu.be/pFVKnXULnA0. The link to this channel will be updated and made available through an official accessible channel.

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