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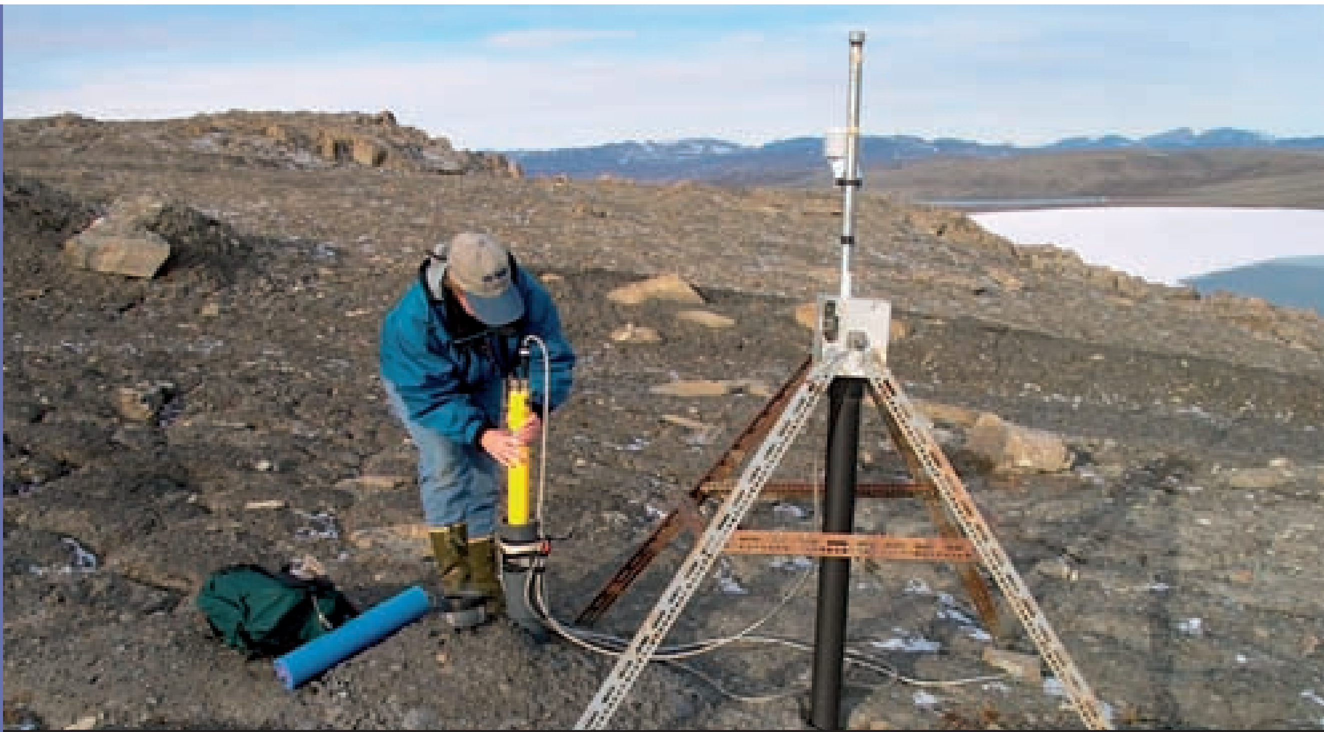
Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

GTOS 62



PERMAFROST

Permafrost and seasonally frozen ground

WMO UNESCO UNEP ICSU FAO

Photo taken CFS Alert, Nunavut Canada (August 2001) and is of courtesy of Geological Survey of Canada.

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Permafrost and seasonally frozen ground

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List of Acronyms

ALT	Active Layer Thickness
CALM	Circumpolar Active Layer Monitoring
CAPS	Circumpolar Active-Layer System
ECVs	Essential Climate Variables
GCOS	Global Climate Observing System
GPR	Ground Penetrating Radar
GTN-P	Global Terrestrial Network for Permafrost
IGOS	Integrated Global Observing Strategy
INPO	International Network of Permafrost Observatories
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
NDVI	Normalized Difference Vegetation Index
NSIDC	National Snow and Ice Data Center
PYRN	Permafrost Young Researchers Network
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCAR	Scientific Committee for Antarctic Research
TSP	Thermal State of Permafrost
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

Executive Summary

Decadal changes in permafrost temperatures and depth of seasonal freezing/thawing are indicators of changes in climate. Warming may result in an increase in active layer thickness, melting of ground ice and subsequent reduction in permafrost thickness and the lateral extent of permafrost. These changes can have an impact on terrain stability leading to ground subsidence or erosion, vegetation, ecosystem function and soil moisture and gas fluxes. Permafrost and seasonally frozen ground also influence surface and subsurface hydrology. Standardized *in situ* measurements are essential to understanding how permafrost conditions are changing, to improve predictions of future changes, and to calibrate and to verify regional and global climate change models. Long-term monitoring sites are contributing to the Global Terrestrial Network for Permafrost (GTN-P). These sites exist throughout the permafrost regions and have provided data that have facilitated the characterization of trends in permafrost conditions over the last two to three decades and in a few cases over much longer periods. Under the leadership of the International Permafrost Association a coordinated field campaign is under way during the International Polar Year to obtain a snapshot of global permafrost temperatures and active layer measurements.

The main parameters and measurement methods are:

Permafrost: sub-surface earth materials that remain continuously at or below 0°C for two or more consecutive years. Parameter is ground temperature (°C) at specified depths. Permafrost temperature measurements are obtained by lowering a calibrated temperature sensor into a borehole, or recording temperature from multi-sensor cables permanently or temporarily installed in the borehole. Measurements may be recorded manually or by data loggers. The depth of boreholes varies from less than 10m to greater than 100m. Data loggers may be utilized for daily measurements of shallow temperatures to reduce the frequency of site visits and provide a continuous record of ground temperatures. Ideally (although not always feasible at all sites), temperatures at shallow depths (upper 10 m to 20 m) should be collected at monthly or more frequent intervals as this allows the annual temperature envelope (i.e. range in temperatures at depth) and mean annual temperatures to be determined.

Active layer: the surface layer of ground, subject to annual thawing and freezing in areas underlain by permafrost. Parameters are thickness (cm) and temperatures (°C). Several traditional methods are used to determine the seasonal and long - term changes in thickness of the active layer: mechanical probing annually, frost tubes, and interpolation of soil temperatures. The minimum observation required under the Circumpolar Active Layer Monitoring (CALM) protocol is a late season mechanical probing of the thickness of the active layer on a gridded plot or transect. Interpolation of soil temperature measurements from a vertical array of sensors can be used to determine active-layer thickness at a point location (see www.udel.edu/Geography/calm/)

Seasonally frozen ground: refers to soils without permafrost that are subjected to seasonal freezing and thawing. Parameters are depth (cm) and temperature (°C). Winter frost penetration in regions of seasonal ground freezing is determined by measuring soil temperatures or by use of frost tubes; similar to methods used for active layer measurements.

The methods described above are presented in a combined draft manual developed for the International Polar Year Thermal State of Permafrost (IPY/TSP) which is available on the International Permafrost Association (IPA) Web site (www.ipa-permafrost.org/). Deriving ISO standards from this manual should encourage the adoption of these standard methodologies and promote the expansion

of the observational networks. Unlike ice and snow covers, properties of permafrost terrain are currently not directly detected from remote sensing platforms. However, many surface features of permafrost terrains and periglacial landforms are observable with a variety of sensors ranging from conventional aerial photography to high-resolution satellite imagery in various wavelengths.

Recommendations

- Finalize the IPY-TSP manual and ensure its endorsement by the international and national communities as the standard manual of methodologies to be followed.
- As appropriate, develop ISO standards from the IPY-TSP manual.
- Develop a permanent status for the existing GTN-P borehole and active layer networks under a spatially comprehensive "International Network of Permafrost Observatories (INPO)". National observing agencies should collect and report these observations at existing stations.
- Upgrade existing sites with automated data loggers, remote data acquisition (reduce cost associated with site visitation) and instrumentation for collection of ancillary climate and other environmental data.
- Further develop the GTN-P by creating partnerships with those monitoring other cryospheric components (e.g. snow) to co-locate monitoring sites and expand existing networks at reduced cost. Partnerships with industry can help to establish monitoring sites in key resource development areas.
- An international network for monitoring seasonally frozen ground in non-permafrost regions should be formed. Soil temperature and frost depth measurements should be recommended as standard parameters to all WMO and national cold regions meteorological stations. As part of the new network, remote sensing algorithms should be developed and validated to detect soil freeze/thaw cycles (microwave passive and active sensors).
- New upscaling techniques for research sites and permafrost networks are required to extend point measurements to a broader spatial domain, to support permafrost distribution modeling and mapping techniques within a GIS framework, and to complement active layer and thermal observing networks with monitoring of active geological processes (e.g. slope processes, thermokarst development on land and under lakes, coastal dynamics, and surface terrain stability). This approach requires high resolution DEMs of permafrost regions.
- Data rescue and management activities must be sustained. National and international funding for permafrost data management is an explicit priority. The IPY activities provide an ideal opportunity to recover and analyse permafrost-related and soil temperature data and to encourage long-term commitments to shared data practices and distributed products.
- Methods and standards for active layer and thermal measurements are available on the CALM, TSP and IPA Web sites.

Recommendations modified from Chapter 9, IGOS Cryosphere Theme Report, 2007

1. Introduction

Decadal changes in permafrost temperatures and depth of seasonal freezing/thawing are indicators of changes of climate in high latitude and mountain regions. Warming may result in an increase in active layer thickness, melting of ground ice and related ground subsidence or erosion, and subsequent reduction in permafrost thickness and the lateral extent of permafrost. These changes can have an impact on terrain stability, vegetation, ecosystem function and soil moisture and gas fluxes. Permafrost and seasonally frozen ground also influence surface and subsurface hydrology. Standardized *in situ* measurements are essential to understanding how permafrost conditions are changing, to improve predictions of future changes, and to calibrate and to verify regional and global climate change. Long-term monitoring sites are contributing to the Global Terrestrial Network for Permafrost (GTN-P). These sites exist throughout the permafrost regions and have provided data that has facilitated the characterization of trends in permafrost conditions over the last two to three decades and in a few cases over much longer periods. Under the leadership of the International Permafrost Association a coordinated field campaign is under way during the International Polar Year (IPY) to obtain a snapshot of global permafrost temperatures and active layer measurements.

In the Northern Hemisphere, permafrost regions occupy approximately 23 million km^2, or 24% of the ice-free land surface. Permafrost regions include large areas of Canada, China, Mongolia, Russia and Alaska, Antarctica and areas at higher elevations in mountain chains of many other countries in both the Northern and Southern Hemispheres. Unlike snow and ice covers, permafrost and the overlying seasonal thaw zone (active layer) is not easily observed remotely, and requires *in situ* observations to define its extent and properties. Permafrost temperature is used to detect the terrestrial climate signal since it provides an integration of changes at the ground surface, that in turn may reflect changes in climate. Seasonally frozen ground occupies well over 50% of the landmass of Earth and includes both permafrost and non-permafrost regions.

The active layer undergoes seasonal freezing and thawing. Across this layer energy and water are exchanged between the atmosphere and underlying permafrost. Because most biological, physical, chemical, and pedogenic processes take place in the active layer, its dynamics are of interest in a wide variety of scientific and engineering problems.

Both the active layer and permafrost are defined entirely on thermal criteria, without regard to material composition or properties. The volume and properties of the active layer are highly variable in time and over space. Variations in vegetation, surface organic layer, substrate properties, and water content can result in very large differences in ALT, even over small distances (Nelson *et al.* 1999; Burgess *et al.* 2000; Walker *et al.* 2004). Temporal changes, particularly surface temperature and moisture conditions, can also lead to substantial year-to-year differences in ALT, even at fixed locations. For these reasons, it is necessary to monitor ALT using well-defined measurement and sampling techniques.

The Global Terrestrial Network for Permafrost (GTN-P) is the primary international programme concerned with monitoring permafrost parameters. GTN-P was developed in the 1990s with the long-term goal of obtaining a comprehensive view of the spatial structure, trends, and variability of changes in the active layer and permafrost temperature (Brown *et al.*, 2000; Burgess *et al.*, 2000). The programme's two international monitoring components are: (a) long-term monitoring of the thermal state of permafrost in an extensive borehole network (Thermal State of Permafrost-TSP); and (b) monitoring of active-layer thickness and processes at representative locations

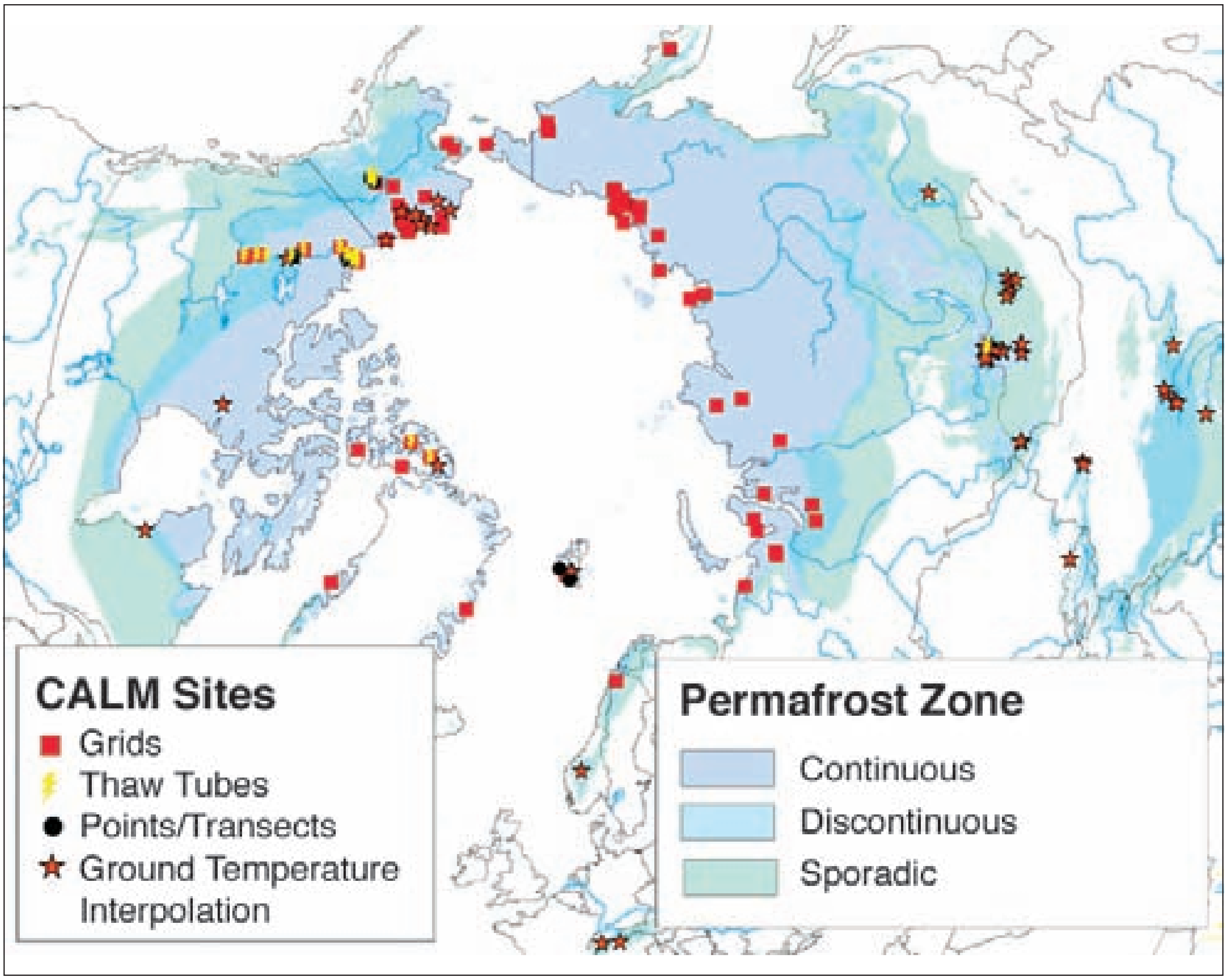

Figure 1. GTN-P monitoring sites (a. CALM sites)

(Circumpolar Active Layer Monitoring-CALM). Figure 1 shows the location of monitoring sites. Both TSP and CALM have regional components for the Antarctic in cooperation with the International Permafrost Association and the Scientific Committee for Antarctic Research (SCAR). Summary papers were published for the Ninth International Conference on Permafrost that was held in Fairbanks, Alaska, in summer 2008 (Brown and Romanovsky, 2008; Nelson *et al.* 2008; Romanovsky *et al.* 2008; Shiklomanov *et al.* 2008).

The data generated from these observation sites can be utilized to develop and validate models which can be used to provide regional information on permafrost conditions. Such spatially distributed models can be utilized to produce maps at regional to circumpolar scales of current permafrost conditions and also to predict future permafrost conditions (see for example Anisimov and Reneva, 2006; Riseborough *et al.*, 2008; Romanovsky *et al.*, 2007; Sazanova and Romanovsky, 2003; Sazanova *et al.*, 2004). The ongoing operation of the permafrost monitoring network is critical to provision of information that can be utilized to improve these models and thereby reduce uncertainty in prediction of future permafrost conditions.

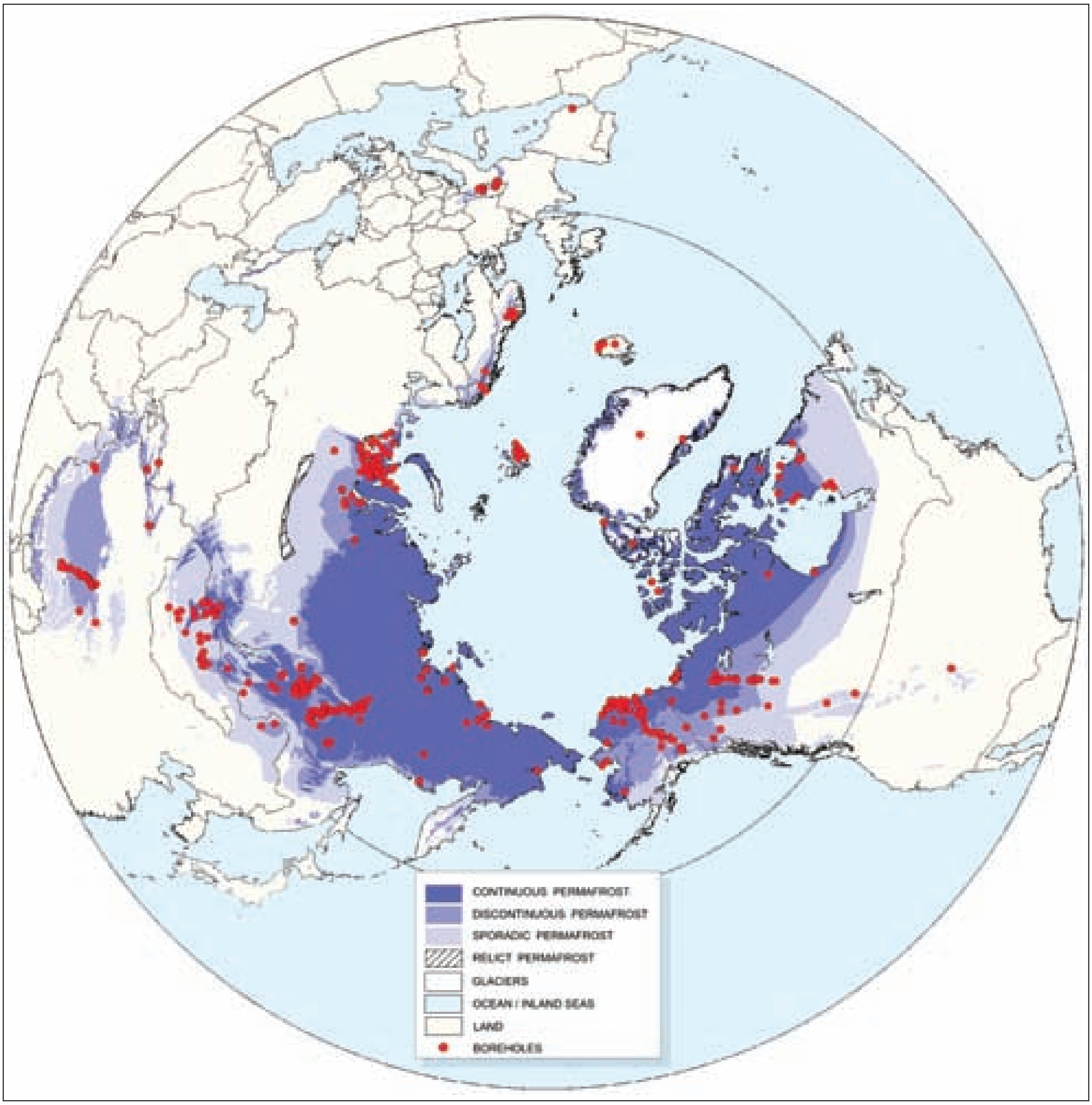

Figure 2. GTN-P monitoring sites (b. TSP sites)

2. Definition and units of measure

2.1 Permafrost

Sub-surface earth materials that remain continuously at or below 0°C for two or more consecutive years. Ground temperatures (°C) at specified depths.

2.2 Active-layer

The surface layer of ground, subject to annual thawing and freezing in areas underlain by permafrost.

2.3 Seasonally frozen ground

The term refers to soils without permafrost that are subjected to seasonal freezing and thawing.

2.4 Units of measure

- **Permafrost - Thermal state of permafrost (TSP)**: Ground temperatures measured at specified depths (°C).
- **Active-layer thickness (ALT)**: Thickness measured in (cm) and temperatures (°C)
- **Seasonally frozen ground**: Depth measured in (cm) and temperatures (°C)

3. Existing measurement methods, protocols and standards

3.1 *In situ* measurement

Current methods are presented in a combined draft manual developed for the IPY-TSP observations and are available on the International Permafrost Association (IPA) website (www.ipa-permafrost.org). Development of ISO standards will assist in expanding observational networks.

Permafrost temperatures

Permafrost temperatures define the thermal state of permafrost and are obtained by lowering a calibrated thermistor into a borehole, or recording temperature from multi-sensor cables permanently or temporarily installed in the borehole. Measurements may be recorded manually with a portable temperature logging system or by data loggers. Less frequent site visits are required if data loggers are utilized. The accuracy and resolution of the thermistors and measurement varies but it is desirable for accuracy to be ±0.1°C or better.

The depth of boreholes varies from less than 10 m to greater than 100 m. At shallower depths, generally less than 15 m, ground temperatures experience an annual temperature cycle and it is desirable to have several measurements throughout the year, at a minimum spring and fall but ideally monthly. Data loggers may be utilized for daily measurement of shallow temperatures to reduce the number of site visits and provide a continuous record of ground temperatures. At depths below the penetration of the annual temperature wave (depth of zero annual amplitude), and up to depths of about 50 m, annual temperature measurements are sufficient. At greater depths where temperatures change slowly, biennial or less frequent (5-10 years) measurements are required. Spacing of sensors on cables (or the spacing of measurements if single sensor used) generally increases with depth. For example, in the upper 5 to 10 m, sensor spacing of 0.5 to 1 m can adequately define the shallow thermal regime while spacing may increase to 5 to 10 m or more at depths greater than 20 m.

The maximum and minimum annual temperature at each depth above the level of zero amplitude defines the annual temperature envelope and can be utilized to characterize the ground thermal regime. The collection of data on a monthly or more frequent basis will facilitate the determination of the temperature envelope. Other derived parameters that are often determined are the mean ground temperature at each depth and the level of zero temperature annual amplitude. Where deeper temperatures are available, the base of the permafrost may also be determined. This may be done through interpolation between sensors if temperatures are measured below the base of permafrost or through extrapolation below the deepest sensor.

Monitoring of permafrost temperature is undertaken by some national programmes, but in general many observations are part of academic research projects. Current activities and recent results were reported at the Ninth International Conference on Permafrost. See the following references: Clow 2008a; Etzelmuller *et al.* 2008; Midttomme *et al.* 2008; Osterkamp 2008; Romanonvsky *et al.* 2008 a and b; Sharkhuu *et al.* 2008; Smith *et al.*, 2008a; Vonder Muehll *et al.*, 2008; Zhao *et al.* 2008. For a detailed discussion of high precision temperature measurements, the reader is directed to Clow (2008b).

Advantages: A data logger installed on a multi-sensor cable in a borehole permits year round measurements at regular time intervals without the need to revisit the site. This data acquisition allows for additional analyses of seasonal temperature variations. Low cost data logging systems now make it possible to deploy more cables and recorders. The periodic, annual logging of boreholes with a portable temperature logging system allows for more precise measurements with high spatial (depth) resolution that are required for climatic reconstructions.

Disadvanatges: Although acceptable techniques to measure permafrost temperatures are available, the location of measurements is limited by availability of shallow to deep boreholes. Drilling new boreholes is expensive. As a result many remote sites that are considered representative of regional conditions are not presently observed. The periodic logging of boreholes with a portable temperature logging system requires additional time at each site that may result in added logistical cost.

Active Layer Thickness (ALT)

At most active layer monitoring sites, the maximum thickness of the active layer is determined. However seasonal progression of the active layer, may also be monitored at sites of intensive investigations for process understanding.

Several traditional methods reviewed by Nelson and Hinkel (2003) are used to determine the seasonal and long-term changes in thickness of the active layer: mechanical probing once annually, frost (or thaw tubes) and interpolation of soil temperatures obtained by data loggers. See website for more details and measurement protocols (www.udel.edu/Geography/calm/).

Probing

The minimum observation required under the Circumpolar Active Layer Monitoring (CALM) protocol is a late season mechanical probing of the thickness of the active layer. Time of probing varies with location, ranging from mid-August to mid-September, when thaw depths are near their end-of-season maximum. Probing utilizes a graduated metal (e.g. stainless steel) rod, with a tapered point and handle, typically 1 cm in diameter and about 1 m long. Longer probes of greater diameter may be used where active layers are thicker (e.g. 1-3 m) although difficulties arise when probing to greater depth. The probe rod is inserted into the ground to the point of resistance which is associated with a distinctive sound and contact that is apparent when ice-rich, frozen ground is encountered. All measurements are made relative to the surface; in standing water, both thaw depth and water depth are recorded. Typically, two measurements are made at each location and the average reported. If a standard spacing is maintained between the two sampling points, probing is performed within one meter of each other.

A gridded sampling design or transect allows for analysis of intra- and inter-site spatial variability (Nelson *et al.*, 1998; Burgess *et al.*, 2000). The size of the plots or grid and length of the transects vary depending on site geometry and design; grids range between 10, 100, and 1000 m on a side, with nodes distributed evenly at 1, 10, or 100 m spacing, respectively.

Advantages: Probing has the advantage of being the most practical, low-cost method of nondestructive and areally extensive data collection. The primary advantages of probing are: (a) its suitability for collecting large numbers of measurements; (b) its ability to generate samples of data that are statistically representative of local areas; and (c) it can be used in conjunction with vegetation and soil information to estimate the volume of thawed soil over extensive regions (e.g. Nelson *et al.*, 1997; Shiklomanov and Nelson, 2002).

Disadvantages: Timing is one of the primary limitations with probing. Ideally, measurements should be collected at the time of maximum thaw depth. Field measurements are, however, often constrained by logistical or weather-related considerations. Experience can help the researcher decide when to collect end-of-season measurements, but the date usually varies from year to year at each site. It is therefore unlikely that measurement of thaw depth coincides perfectly with the actual active-layer thickness. However, because thaw progression is usually proportional to the square root of the time elapsed since snowmelt, late-season thaw-depth measurements generally correspond closely with the maximum thickness of the active layer.

In coarse and bouldery soils, and in deeper active layers (>1.5 m), probing becomes impractical and other methods should be considered. More intractable problems with probing arise when substrate properties prevent accurate determination of the frost table's position. In some cases, the top of the frozen (ice-bearing) zone does not coincide with the position of the frost table as defined by the 0°C criterion. The relation is dependent on soil salinity, particle size, and temperature. Well-drained sands and gravels may contain too little interstitial ice for adequate resistance to probing to develop. In saline or extremely fine-grained soils probing can yield inaccurate estimates owing to the presence of unfrozen water. Under such conditions it may be possible to calibrate mechanical probing using a thermal probe (Mackay, 1977; Brown *et al.*, 2000, p. 172). Probing cannot ascertain if thaw subsidence has occurred.

Frost/thaw tubes

When read periodically, frost tubes provide information about seasonal progression of thaw and maximum seasonal thaw. The exact vertical position of a single frost tube should be determined at the end of the first summer of active layer measurements by selecting a point representative of the mean active layer depth for the entire grid.

Thaw/frost tubes are devices extending from above the ground surface through the active layer into the underlying the permafrost. They are used extensively in Canada. Construction materials, design specifications, and installation instructions are available for several variants of the basic principle (Rickard and Brown, 1972; Mackay, 1973; Nixon, 2000). A rigid outer tube is anchored in permafrost, and serves as a vertically stable reference; an inner, flexible tube is filled with water or sand containing dye. The approximate position of the thawed active layer is indicated by the presence of ice in the tube, or by the boundary of the colorless sand that corresponds to the adjacent frozen soil. Each summer the thaw depth, surface level, and maximum heave or subsidence is measured relative to the immobile outer tube. These measurements are used to derive two values for the preceding summer: (1) the maximum thaw penetration, independent of the ground surface and corrected to a standard height above the ground established during installation; and (2) the active-layer thickness, assumed to coincide with maximum surface subsidence. With modifications, the accuracy of the measurements is about 2 cm.

Advantages: The primary advantage of frost/thaw tubes is that they provide an inexpensive annual record of both maximum thaw penetration and active-layer thickness, although it is not possible to determine the date. Because thaw tubes are durable (long lasting), a multi-year record is available for comparison. Thaw tubes may also be utilized to monitor heave and settlement (subsidence) of the ground surface.

Disadvantages: Thaw tubes have several limitations, ranging from single point measurements to difficulties in drilling. Annual site visits are required. Timing is important as the thaw tube must be visited after the previous year's maximum thaw depth has been reached but prior to the period of late season thaw in the following year. Frost jacking of the thaw tube can also be a problem if it is not adequately anchored in frozen ground. This can be a problem in warm fine-grained soils having high unfrozen water contents and when thaw depths approach the length of the outer thaw tube.

Soil temperature profiles

Soil and air temperature are recorded as basic information at many CALM sites, especially with the increasing availability of inexpensive, reliable temperature data loggers. Temperature sensors (usually thermistors) are inserted into the active layer and upper permafrost as a vertical array. Several CALM installations currently use an array of thermistors embedded in a small-diameter acrylic cylinder and connected to a high-capacity data logger. Soil temperature should be recorded at approximately one - to three-hour intervals, measured at a sensor interval of 15 cm, and on a seasonal basis to determine maximum thaw penetration or additionally on an annual basis to establish mean annual soil temperatures.

Temperature records from a vertical array of sensors can be used to determine active-layer thickness at a point location. The thickness of the active layer is estimated using the warmest temperatures recorded at the uppermost thermistor in the permafrost and the lowermost thermistor in the active layer. The temperature records from the two sensors are interpolated to estimate maximum thaw depth (0°C) during any given year. For this reason, the probe spacing, data collection interval, and interpolation method are crucial parameters in assessing the accuracy and precision of the estimate (Riseborough, 2008).

Advantages: The advantages of soil temperature profiles are similar to those for frost tubes. Further, it is possible to estimate the date of maximum thaw with a reasonable degree of accuracy. If data loggers are used data may be collected over periods of greater than one year (two or three years or longer) before the logger storage capacity is reached. This means that the timing of visits are not critical and that less frequent (e.g. every 2 years) site visits are possible reducing field travel costs. Depending on whether probes are in a fixed or floating (i.e. zero mark can be adjusted for changing ground surface position) configuration, it may be possible to determine if thaw subsidence has occurred at the location. Numerical methods can be used with high-frequency thermal observations to estimate the thermal properties of the substrate, such as effective thermal diffusivity (e.g. Hinkel, 1997). Thermal records can also be used to identify the operation of non-conductive heat-transfer processes in the active layer, and can be related to meteorological events at the surface (Hinkel *et al.*, 1997, 2001a; Kane *et al.*, 2001).

Disadvantages: Limitations are similar to those of frost tubes; thermistor strings effectively comprise only a single point measurement. They are relatively expensive. They are also subject to surface and installation disruptions, including vandalism and disturbance by animals. Malfunctions of equipment may also occur. The accuracy of the active-layer thickness estimate is fundamentally limited by the vertical spacing of the probes and the data-collection interval.

Ancillary Data

Other data may be collected at monitoring sites to aid in interpretation of active layer and permafrost temperature data and to characterize the relationship between permafrost conditions and climate or local factors. Air temperature and snow depth are often measured at monitoring sites as well as other climatic data in order to better characterize microclimate. Soil moisture content may also be measured as it is an important factor determining the thermal behaviour of the ground. With the exception of soil moisture, off-the-shelf instrumentation can be utilized to make these measurements automatically and relatively inexpensively. Presently, data are typically recorded on a data logger that can be downloaded during annual (or less frequent) visits to the site.

Seasonally frozen ground

Seasonal frozen ground (SFG) is determined by measuring soil temperatures or by use of frost tubes; similar to methods used for active layer (see above). To avoid confusion with soils underlain by permafrost, the use of the term is applied to soils without permafrost. However, since large areas in the discontinuous permafrost regions do not contain permafrost, by definition SFG also occurs in these regions. Traditionally, seasonal frost penetration has been measured at meteorological and agricultural stations and transportation facilities such as airfields. These observations can be obtained at sites that measure soil temperatures and moisture. No coordinated international program is in place to assess seasonal soil frost.

Advantages and Disadvantages: see above discussion for active layer.

3.2 Remote sensing methods

Satellite remote sensing has potential for broad-scale monitoring of the state of ground (U.S. Arctic Research Commission Permafrost Task Force, 2003). The most recent reviews and recommendations are available in the IGOS Cryosphere Theme Report (WMO 2007), Zhang and Armstrong (2001), Zhang *et al.* (2004) and Kääb (2008).

Although there is an urgent need and potential to use satellite-based sensors to supplement ground-based measurements and extend the point observations to the broader spatial domain, techniques are not well developed or validated. Sensors for satellite and airborne platforms do not adequately penetrate the frozen and unfrozen earth materials, and therefore, it is not possible to map the depths of soil freezing and thawing or properties of the upper permafrost. However, many surface features in permafrost terrains especially periglacial landforms are observable with a variety of sensors ranging from conventional aerial photography to high-resolution satellite imagery in various wavelengths. Utilization of remote sensing techniques including aerial photography can facilitate mapping of changes in the extent of permafrost and areas where degradation is occurring (e.g. Beilman and Robinson 2003).

Satellite imaging systems hold promise for monitoring thaw depth across large areas. In particular, synthetic aperture radar, carried at appropriate wavelengths, may have sufficient energy to penetrate the often-saturated active layer and return a signal to the satellite receiver (Kane *et al.* 1996). Interpretive, convergence-of-evidence approaches have been used by Peddle and Franklin (1993) and Leverington and Duguay (1996) with some success, although the derived classes of ALT were very broad. All aircraft- or satellite-based systems necessitate collection of training data on the ground for calibration and verification of the signal processing algorithms. The impetus for such a system may come from unmanned missions to Mars. A combined ground-based and remote sensing approach was developed by McMichael *et al.* (1997), who used the Normalized Difference Vegetation Index (NDVI) to exploit known relations between vegetation units and ALT across a toposequence in northern Alaska. A similar approach has been used to map, at a regional scale, the distribution of near surface permafrost in the dynamic environment of the Mackenzie Delta, NWT, Canada (Nguyen *et al.*, 2009)

Passive microwave remote sensing sensors, especially low frequency and high resolution sensors, can be further developed to detect the timing, frequency, duration, and areal extent of near surface soil freeze/thaw (e.g. Zhang and Armstrong, 2001; Zhang *et al.*, 2003, 2004). Combined with products from other sensors, including surface temperature and snow depth, a comprehensive frozen soil algorithm can be used to detect and simulate soil thermal regime and freeze/thaw depth at regional and global scales.

Ground penetrating radar (GPR) has been used with some success to map active-layer thickness along transects. Because water effectively absorbs electromagnetic pulses, profiling is most effective in winter, when the ground is frozen and covered with snow. The method relies on the principle that the active layer contains less ice than the permafrost immediately below, resulting in a reflecting horizon at the interface. With careful local calibration, usually accomplished through coring, estimates of thaw depth along a continuous profile can be made. The accuracy of the estimates is incompletely known, but appears to be within ± 15% in fine grained soils. The expense, however, is often prohibitive. It is likely that GPR methodologies will continue to develop. Further details on the use of GPR in permafrost and active-layer investigations are available in Doolittle *et al.* (1990), Hinkel *et al.* (2001b), Moorman *et al.* (2003), and Kneisel *et al.* (2008). Although standard methodologies/algorithms are not available there is a need for *in situ* validation and cross calibration between systems.

3.3 Summary of Requirements and Gaps

The discussion above in section 3.1 outlined the measurement methods for both permafrost thermal state and active layer thickness. For active layer monitoring the minimum measurement required is a single value representing the maximum (or late season) active layer thickness. The standards and protocols for reporting active layer measurements are developed and are described in greater detail on the CALM web sites.

Permafrost thermal state also utilizes standard methods but protocols have been difficult to develop given the variation in borehole depth and range in instrumentation that may be utilized which is to some extent influenced by available resources and the remoteness of monitoring locations. In addition many monitoring sites were established 2 to 3 or more decades ago for other purposes and characteristics of sensor spacing, borehole depth etc. can vary greatly. Also, limitations of borehole drilling equipment and characteristics of subsurface materials often result in boreholes not being completed to desired depths for pre-made thermistor cables to be installed with adjustments required in the field (especially in remote locations) which lead to modifications of sensor position. The discussion in section 3.1, does offer some guidelines for monitoring of permafrost thermal state which allow for some flexibility for the constraints imposed by field and other conditions. One standard, however for all monitoring sites is that temperature sensors (thermistors) must have a resolution and accuracy of ±0.1°C or better and this information should accompany the data. Sensor spacing of 0.5 to 1 m in the upper 5 m are recommended with increased spacing at greater depths. Measurement frequency required for shallow ground temperatures to 15 m depth is monthly or more frequent to allow definition of the annual range in temperatures. Minimal reporting requirements for shallow depths are the maximum, minimum and mean temperature for each sensor position (i.e. temperature envelope). For deeper temperatures (to depths of 50 m) the minimum reporting requirement is an annual measurement of ground temperatures at each sensor depth, including the temperature at the depth of zero temperature annual amplitude. For greater depths, reporting may be less frequent.

Although gaps exist regarding standards and protocols for permafrost thermal state, accepted practices are used and information is provided in site metadata that gives details of instrumentation etc. at each site. A manual is also being finalized which will provide guidance for monitoring site establishment, operation, and reporting.

Regional gaps exist in the network with some areas being poorly represented. Efforts have been made during the International Polar Year periods by national organizations to fill in gaps and increase the coverage of the monitoring network (see for example, Isaksen *et al.* 2008; Smith *et al.* 2008b).

As mentioned above, no coordinated international programme is in place to monitor seasonal soil frost. Seasonally frozen ground, while it can exist within the permafrost region (where permafrost is discontinuous) it occurs over a much broader region. Development of standards and protocols for monitoring seasonally frozen ground as well as coordination of an international network should involve a much larger community than the permafrost community which under the leadership of the IPA has provided coordination for permafrost related monitoring. A diverse group of scientists including agricultural experts, soil scientists, hydrologists and engineers probably needs to be engaged in the overall development and coordination of a monitoring programme for seasonally frozen ground.

Mountain Permafrost

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Although general observation parameters and methods of lowland permafrost also apply for monitoring of permafrost in mountain ranges, several specific aspects need to be considered and require adaptation. These adaptations are tackled within European monitoring programs: on a continental scale through Permafrost and Climate in Europe (PACE, Harris *et al.* 2001b), and on a national level particularly in Switzerland through Permafrost Monitoring in Switzerland (PERMOS, Vonder Muehll *et al.* 2008) and TSP Norway (Isaksen *et al.* 2008). These mountain monitoring sites are all being integrated into GTN-P.

The characteristics, distribution, and changes of permafrost in high mountain areas are strongly influenced by topography. Steep and complex topography causes high vertical and lateral variability in local climate, snow cover, surface and subsurface properties, and hence, surface and subsurface temperatures. For this reason, distribution pattern of mountain permafrost are strongly heterogeneous. Because large parts of mountain permafrost have temperatures only a few degrees below the melting point and the subsurface warms significantly faster than in flat terrain as a result of multi-lateral warming (Noetzli and Gruber 2009), mountain permafrost is particularly sensitive to climate change. In addition, due to steep topography considerable mass movements occur (e.g., permafrost creep or rock fall) that are related to the presence and thermal state of permafrost (e.g., Gruber and Haeberli 2007, Haeberli *et al.* 2006, Harris *et al.* 2001a). Especially in the densely populated European Alps, where numerous smaller but also large rock fall events from periglacial areas (e.g., Gruber *et al.* 2004a, Noetzli et al. 2003) as well as a significant increase in the speed of most rock glaciers (e.g., Delaloye *et al.* 2008, Kääb *et al.* 2007) have been observed, monitoring increasingly focuses on their documentation (Vonder Muehll *et al.* 2008).

The interpretation of temperature measurements in boreholes requires separation of climate signals from 3-dimensional effects caused by topography (Gruber *et al.* 2004b). Likewise the extrapolation of such point measurements to assess permafrost thickness and extent is not straightforward and requires modeling techniques that account for the high spatial variability, 3-dimensional pattern, and transient effects. Corresponding approaches are being developed (Noetzli and Gruber 2009). In order to monitor the high variability of surface temperatures and snow cover at locations of varying topographic situations and surface covers in the area, a number (around 10–20) of small temperature logging devices complement the borehole measurements. Active layer thickness is typically estimated by interpolation between thermistors in boreholes. Other techniques such as probing or thaw tubes are not applied, since they are designed for fine-grained and ice-rich permafrost soils and not for bedrock or debris slopes. The seasonal as well as long-term variations of the ice and water content in the borehole areas are being monitored with fix-installed arrays for electrical resistivity tomography (Hilbich *et al.*, 2008).

Kinematics of creep processes and in relation with slope instabilities in permafrost areas have recently been integrated into monitoring programs (PERMOS 2009). Regularly flown air photos (in temporal intervals of 1–5 years, depending on the creep velocity) provide the basis for photogrammetric analyses (e.g., Kääb 2002). Terrestrial surveys and differential GPS are currently being tested for the monitoring of creep processes at a number of rock glacier sites that have recently shown increased speed. Standardized documentation of fast mass movements from permafrost areas (e.g. rock fall) Is in preparation. More information can be found on the PERMOS web site.

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4. Contributing networks and agencies

As stated previously the Global Terrestrial Network for Permafrost (GTN-P) is the primary international programme concerned with monitoring permafrost parameters. Efforts have been made over the past decade to re-establish a borehole temperature monitoring programme under the auspices of GTN-P to monitor, detect, and assess long-term changes in the active layer and the thermal state of permafrost, particularly on a regional basis. Currently the International Polar Year (2007-2009) is providing the motivation and in several cases the national funding to expand the GTN-P and to obtain a global snapshot of permafrost temperatures and active layer measurements. This comprehensive measurement campaign is under the coordination of the 26-member-nation International Permafrost Association. The IPA Standing Committee for Data, Information and Communications will be responsible for data compilation (Parsons *et al.* 2008). The IPY-IPA legacy includes a sustainable database and establishment of an international network of permafrost observatories (INPO).

The borehole network has approximately 500 candidate sites, many of which are instrumented with data loggers. These include approximately 150 new borehole and active layer sites needed to obtain representative coverage in the Europe/ Nordic region, Russian Federation and Central Asia (Mongolia, Kazakhstan, China), in the Southern Hemisphere (South America, Antarctica), and in the North American mountain ranges and lowlands.

Borehole metadata (provided on a standardized form) for the TSP component and summary data, for some sites, are available on the GTN-P web site (www.gtnp.org) hosted by the Geological Survey of Canada's permafrost web site. More detailed data sets are also transferred or linked periodically to a permanent archive at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. Data may also be archived and available through various national government organizations with metadata accessible through NSIDC and other data portals. Efforts are currently underway to update summary data dissemination through the web site and to encourage investigators to make their summary data available.

The CALM network (www.udel.edu/Geography/calm/) is currently coordinated through the University of Delaware who also host the web site that disseminates site metadata and active layer data. Metadata and ancillary information are available for CALM site, including climate, site photographs, and descriptions of terrain, soil type, and vegetation. This site description information is provided by investigators on a standardized form that is available on the web sites.

Active layer data are submitted to CALM annually utilizing a standardized reporting format and are disseminated through the web site. Data are transferred or linked periodically to a permanent archive at the NSIDC.

5. Available data and products

The need for consistent and comprehensive permafrost data management has long been recognized. A workshop was organized in 1988 that led to the establishment of a Data and Information Working Group within the IPA and establishment of an IPA data strategy. The Global Geocryological Database was established and the first compilation of permafrost related information was released in the CAPS CD in 1998. An updated compilation was released in 2003 as CAPS2 and the Frozen Ground Data Center (http://nsidc.org/fgdc) was established in 2002. For a further discussion on the establishment of database strategies and data management systems, see Barry (1988), Clark and Barry (1998) and Parsons *et al.* (2008). These efforts increased the available of information on both active layer and permafrost thermal state and facilitate understanding of both current permafrost conditions and recent changes as well as providing key information to improve predictions of future conditions. The next version of CAPS2 planned for release in 2012 will focus on presentation of the IPY snapshot database.

Permafrost-related products include digital maps, reports on analysis of permafrost temperature time series, documentation of spatial and temporal variation in permafrost temperature and the active layer, and information for the evaluation of hydroclimatic, land surface, and climate-change models.

Metadata and summary data appear on the Circumpolar Active-Layer System (CAPS) CD-ROM at approximately five-year intervals. These products are produced by NSIDC in cooperation with the International Permafrost Association.

The CALM web site contains gridded and point data by country, and a current bibliography of programme publications. The GTN-P maintains metadata for all boreholes and links to data for national programmes.

Several government publications and international assessment reports on current and future potential permafrost thermal conditions have recently become available, including the Working Group I contribution to the 4th Assessment of the IPCC (Lemke *et al.* 2007), and the UNEP Global Outlook on Snow and Ice (Romanovsky *et al.* 2007). Numerous scientific papers on TSP and CALM have also been published, including a large number published in the Proceedings of the Ninth International Conference on Permafrost. (e.g. Clow 2008a; Etzelmuller 2008; Harris *et al.* 2008; Midttomme *et al.*, 2008; Nelson *et al.* 2008,Osterkamp, 2008, Romanovsky *et al.* 2008a and b; Smith *et al.* (2005); Vonder Muehll *et al.* 2008; Wu and Zhang 2008; Zhao *et al.* 2008).

6. Other Issues

The GTN-P is built largely on voluntary regional and national networks and programmes. Many of these sites were not initially established for long-term monitoring and are often a component of specific research programmes. These sites are often maintained with the support of short-term project funds. Although funding was acquired through some national IPY funding programmes which facilitated both collection of data from existing sites and establishment of new sites to address gaps, long-term commitment and resources are still required to maintain the network.

Ancillary data such as air temperature, snow cover and other climatic parameters are collected at some sites. These ancillary data are required to facilitate improved understanding of permafrost-climate linkages and the attribution of observed changes in permafrost conditions. Many sites however lack the instrumentation for collection of these data. Further development of partnerships with those monitoring other cryospheric components (e.g. snow) and climatic parameters to co-locate monitoring sites would lead to enhancement of monitoring sites at a reduced cost and benefit both GTN-P and other cryospheric networks.

7. Conclusions

- The initial role of the IPA GTN-P permafrost networks is to organize the systematic collection and distribution of standardised data. The Geological Survey of Canada is providing the international data management for the GTN-P borehole temperature monitoring programme and maintains GTN-P Web site. Metadata will be accessible as well as regularly submitted summary data. The International Polar Year has provided the stimulus to expand the GTN-P network of sites in the polar regions.
- Several methods are used to measure active layer-thickness. Each method is associated with distinct advantages and disadvantages. Physical probing has the advantage of being the most practical, low-cost method of non-destructive and a really extensive data collection. However in coarse and bouldery soils and with deeper active layer (>1.5 m) probing becomes impractical and other methods should be considered.
- The CALM programme was developed to provide standards of measurements and a comprehensive database describing the history and geography of ALT and other selected parameter at a large number of sites representative of permafrost terrain. It represents the first widely implemented attempt to measure permafrost-related variables using a standard protocol. Other variables should also be measured combined with site-specific information about soils, landscape and vegetation. CALM data coordination and compilation is under a project at the University of Delaware, USA.
- Reliable instrumentation is currently available and being utilized to measure ground temperatures at depth and to characterize the thermal state of permafrost. National programmes are active in most countries or regions in which permafrost occurs, including the Antarctic.
- Available literature and expertise appear to provide sufficient basis to prepare guidance on standardised methodology.

8. Recommendations

- Finalize the IPY-TSP manual and ensure its endorsement by the international and national communities as the standard manual of methodologies to be followed.
- As appropriate, develop ISO standards from the IPY-TSP manual.
- Develop a permanent status for the existing GTN-P borehole and active layer networks under a spatially comprehensive "International Network of Permafrost Observatories (INPO)". National observing agencies should collect and report these observations at existing stations.
- Upgrade existing sites with automated data loggers, remote data acquisition (reduce cost associated with site visitation) and instrumentation for collection of ancillary climate and other environmental data.

- Further develop the GTN-P by creating partnerships with those monitoring other cryospheric components (e.g. snow) to co-locate monitoring sites and expand existing networks at reduced cost. Partnerships with industry can help to establish monitoring sites in key resource development areas.
- An international network for monitoring seasonally frozen ground in non-permafrost regions should be formed. Soil temperature and frost depth measurements should be recommended as standard parameters to all WMO and national cold regions meteorological stations. As part of the new network, remote sensing algorithms should be developed and validated to detect soil freeze/thaw cycles (microwave passive and active sensors).
- New upscaling techniques for research sites and permafrost networks are required to extend point measurements to a broader spatial domain, to support permafrost distribution modeling and mapping techniques within a GIS framework, and to complement active layer and thermal observing networks with monitoring of active geological processes (e.g. slope processes, thermokarst development on land and under lakes, coastal dynamics, and surface terrain stability). This approach requires high resolution DEMs of permafrost regions.
- Data rescue and management activities must be sustained. National and international funding for permafrost data management is an explicit priority. The IPY activities provide an ideal opportunity to recover and analyse permafrost-related and soil temperature data and to encourage long-term commitments to shared data practices and distributed products.
- Methods and standards for active layer and thermal measurements are available on the CALM, TSP and IPA Web sites.

Recommendations modified from Chapter 9, IGOS Cryosphere Theme Report, 2007.

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FGDC:
http://nsidc.org/fgdc/

GIPL:
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GTN-P:
www.gtnp.org

IPA:
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Permos:
www.permos.ch

TSP Norway:
www.tspnorway.com/

TSP:
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