Requirements for Monitoring of Permafrost in Polar Regions

A community white paper in response to the WMO Polar Space Task Group (PSTG)

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Context

The Polar Space Task Group (PSTG) has been established as the coordinating body of space agencies, in particular the Space Task Group (STG), for space-based observations of Polar Regions after the International Polar Year (IPY). The PSTG has been established under the auspices of the World Meteorological Organization's (WMO) Executive Council Panel of Experts on Polar Observations Research and Services (EC-PORS). The group's mandate is to provide coordination across space agencies to facilitate acquisition and distribution of fundamental satellite datasets, and to contribute to or support development of specific derived products for cryospheric and polar scientific research and applications.

Requirements for space-based monitoring of permafrost observables had been defined within the IGOS Cryosphere Theme Report at the start of the IPY in 2007 (IGOS, 2007). However, during the PSTG-3 meeting in Paris May 2013, the PSTG identified the need to review the requirements for permafrost monitoring and to update these requirements as necessary. Recommendations and data requirements specified are requested to be verified within the community. Requirement surveys with focus on satellite data are available from the ESA DUE Permafrost User requirements survey (2009), the United States National Research Council (2014) and the ESA-CliC-IPA-GTN-P workshop in February 2014. These connect needs especially those listed in the IGOS Cryosphere Theme report (IGOS, 2007). In the present white paper, both monitoring site-specific and sensor-specific recommendations are made for polar regions in response to the PSTG request.
A draft has been discussed at the Third European Conference on Permafrost (EUCOP) meeting in June 2014. Its modified version will be presented at the 4th WMO-PSTG meeting in September 2014.

Amendments:			
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0.2	15.06.2014	Updated draft	AB, GG, AK, TSt
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1. Motivation and background

Permafrost is acknowledged by WMO and UNFCCC as Essential Climate Variable (ECV). Its monitoring as part of the cryosphere has been identified as grand challenge by the World Climate Research Programme (WCRP) Joint Science Committee and a draft white paper on this topic published in 2012 (Kattsov et al. 2012). A focused effort on improving the representation of permafrost and high latitude land surface, including wetlands, in climate models, with specific emphasis on their role in the global carbon cycle has been requested. This has been further discussed during the WRCP and CliC workshop in Tromsø, Norway, 16–18 October 2013 (Pope & Baseman 2014). In this context, plans for assessment of the magnitude, timing, and form of carbon- based greenhouse gas release to the atmosphere from thawing permafrost and how to better incorporate this information into Earth System and Global Climate Models have been discussed.

The global implementation of permafrost monitoring has been identified as feasible in 2004 (GCOS implementation plan) within the 10 years baseline and as having a high impact on UNFCCC requirements. Associated parameters include:

- **Permafrost extent**
- **Soil temperature profiles**
- **Active layer thickness**

Further related properties of interest are thickness of permafrost, spatial patchiness of permafrost and ground ice content (NRC 2014). The International Permafrost Association (IPA, *ipa.arcticportal.org*) initiated the Global Terrestrial Network for Permafrost (GTN-P) to build up and manage a global network of permafrost observatories. The global network, authorized under the GCOS and its associated organizations, consists of two observational components: the Circumpolar Active Layer Monitoring (CALM) and the Thermal State of Permafrost (TSP, *ipa.arcticportal.org/activities/gtn-p/14-gtn-p.html).* The CALM and TSP programmes have been overhauled during the International Polar Year (IPY 2007-2008) and their coverage extended to provide a true circum-polar network in the Arctic, Antarctica, Asia (central Asia, Mongolia, China, Japan), South America and the mountain permafrost regions. Although key actions focus on the extension, consolidation, data management and data publication of the GTN-P measurement network, the demand for filling of spatial gaps and extrapolation of point measurements requires the use of satellite data and modeling.

A multitude of different satellite data types and product levels are currently utilized for permafrost research. The particular requirements strongly depend on the actual research focus. Permafrost monitoring requirements on global scale have also been discussed in general within the context of understanding greenhouse gas emissions and carbon upscaling from high latitude terrestrial environments. Temperature and pressure conditions under thick permafrost layers are also favourable for the formation and existence of gas hydrates that may degas through the degraded permafrost zones (e.g., lake taliks) as greenhouse gas emissions. Process-based models that estimate methane fluxes rely on the correct spatial representation of moisture and thermal surface conditions as well as the subsurface state, the land surface properties and the correct spatial distribution of wetlands. This context demands mapping and monitoring of permafrost-associated carbon pools (indirectly from land surface properties) and fluxes as well as thermal and moisture-related states and utilization of EO data for climate model evaluation. Land surface changes resulting in modification of terrain are a further issue. Permafrost related terrain changes, including geohazards in lowlands and mountain areas, are surface subsidence, landslides (including active layer detachment slides, rock slides), thermo-erosion as well as coastal erosion. Implications for infrastructure, specifically related to exploitation of natural resources as well as indigenous societies need to be addressed in this context. Indigenous residents are affected as ecosystems and the hydrological systems are continuously modified by surface and subsurface disturbances, which have an impact on resources traditionally available for humans.

As permafrost is a thermal subsurface phenomenon it cannot be directly observed from space using the electromagnetic spectrum. However, through the use of models permafrost parameters such as subsurface temperature and active layer depth and therefore the spatio-temporal state of permafrost (e.g., permafrost extent, permafrost degradation) can be estimated. To some extent, satellite data can be used as model input. So far, the most frequently used data sources for a particular variable in space have been products from reanalysis projects (most commonly that of the National Centers for Environmental Prediction (NCEP) or from the European Centre for Medium-Range Weather Forecasts (ECMWF). Global gridded format and high temporal resolution make the reanalysis data appropriate, however they are not true observations but rather a combination of observations and model data. The various reanalysis data available are not all of the same quality and, especially for the polar or mountain regions with sparse in-situ data, they contain contributions from the errors in the underlying model. So far, operational satellite-derived products are underexploited in terms of their potential for permafrost-related modeling and complementing *in situ* measurements as done within the network of GTN-P. In addition, meta-data (surface conditions such as temperature, soil moisture, vegetation cover, snow cover, geomorphological units) for the monitoring sites can be provided from satellite data. Ground deformation on slopes that are affected by freeze/thaw processes can also be measured directly using remote sensing.

This report reviews the recent discussions of satellite data requirements of permafrost research, with a focus on current sensors in operation. Requirements independent from current technical constraints are available from the NRC (2014). In this report to the WMO-PSTG recommendations are summarized for data acquisitions (areas to be covered and data specifications) with respect to selected target groups which directly investigate permafrost surface expressions and the actual target parameters of GTN-P/GCOS. Permafrost related issues are addressed by many other fields of research outside of core cryosphere research (e.g. climate modelling, greenhouse gases). The relevance of land surface parameters of globally available products are discussed in this context (including issues with current products).

2. Review of requirements discussions

General requirements for satellite observations of permafrost are specified by the WMO Space Programme as well as CEOS. Maintained by the WMO Space Programme, the Observing Systems Capabilities Analysis and Review tool (OSCAR) is a component of the Rolling Requirements Review process for recording observational requirements and observing capabilities (both space-based and surface-based), and conducting critical reviews of how well the capabilities address the requirements. Permafrost is included as variable of the **land surface** layer in the OSCAR. Identified target areas are hydrology and climate (Terrestrial Observing Panel for Climate - TOPC). Optimum spatial and temporal resolutions have been specified with 0.1km/6h and 0.25km/24h respectively. These specifications comply with regional modelling requirements. The actual parameters to characterize this subsurface phenomenon remain undefined.

Requirements defined for *Permafrost* (2)

This tables shows all related requirements. For more operations/filtering, please consult the full list of Requirements
Note: In reading the values, goal is marked blue, breakthrough green and threshold orange

Id	Variable	Layer	App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
401	Permafrost	Land surface	Hydrology	5 8.5 25		0.1 km 1 km 100 km		6 h 14 h 3 d	6 h 17 h 6 d	Global land	reasonable	2003-10-20	ET ODRRGOS
675	Permafrost	Land surface	Climate-TOPC	5 7 10		0.25 km 0.85 km 10 km		24 h 36 h 5 d	24 h 36 h 5 d	Global land	firm	2007-07-19	TOPC

Figure 1: Current WMO OSCAR data base requirements specifications (source: www.wmo-sat.info/oscar/variables/view/124)

Within the GCOS implementation plan, land surface temperature and soil moisture have been identified as satellite products relevant for permafrost (GCOS 2004, page 87). Originally, a complete lack of operational products was recognized for these variables. Soil moisture has been identified as an emerging Essential Climate Variable (ECV) and the development of a satellite product including its validation has been listed as part of the terrestrial domain scientific and technological challenges (Action T37, GCOS 2004, page 87). The ECV snow cover has been identified as a parameter affecting the permafrost thermal state. Related to the parameter permafrost, Action T17 calls for implementation of operational mapping of seasonal soil/freeze thaw (GCOS 2004, page 97).

Within the progress report which covers the first 5 years (GCOS 2009), advances are reported for satellite based snow-cover mapping and terrestrial permafrost observations. Low progress has been made on the development of regular soil-surface freeze and thaw monitoring. Satellite based monitoring on regional to global scale is encouraged.

It is stated that especially product combinations with land surface temperature, snow depth, and snow water equivalent may provide critical input for the simulation of the soil thermal regime. Good progress has been reported regarding the associated product ‘soil moisture’ within Action T37 (GCOS 2009, page 81).

Although not listed as an associated parameter in the GCOS implementation plan, the availability and recent moderate/good progress in the development of regular land cover products (Action T26), vegetation parameters (T28), and disturbances (fires, T33) is of interest for permafrost monitoring.

The requirements from Earth Observation perspective have been addressed in 2009 as part of the ESA DUE Permafrost project and reviewed during the joint ESA-CliC-IPA-GTN-P workshop in February 2014.

In the recent years funded international and national activities on permafrost monitoring which specifically utilize remotely sensed data include

- ESA DUE Permafrost (2009-2012), including requirements review and, for the first time, service implementation for a range of applications as well as in situ monitoring (GTN-P). Land surface temperature and surface moisture time series have been provided as meta-data records for high latitude boreholes.
- PAGE21 (2011-2015, www.page21.eu), .This project focuses on carbon cycle changes associated with permafrost changes. Remotely sensed data are assessed and utilized for land surface hydrology and thermal characterization as input for upscaling of carbon pools and fluxes as well as in land surface modelling.
- NASA ABoVE (Arctic-Boreal Vulnerability Experiment, 2013-ongoing) Field Campaign (above.nasa.gov): This Terrestrial Ecology Field Campaign is conducted in Alaska and Western Canada. It will link to specifically remotely sensed data for scaling.

3. Monitoring sites and regions – recommendations

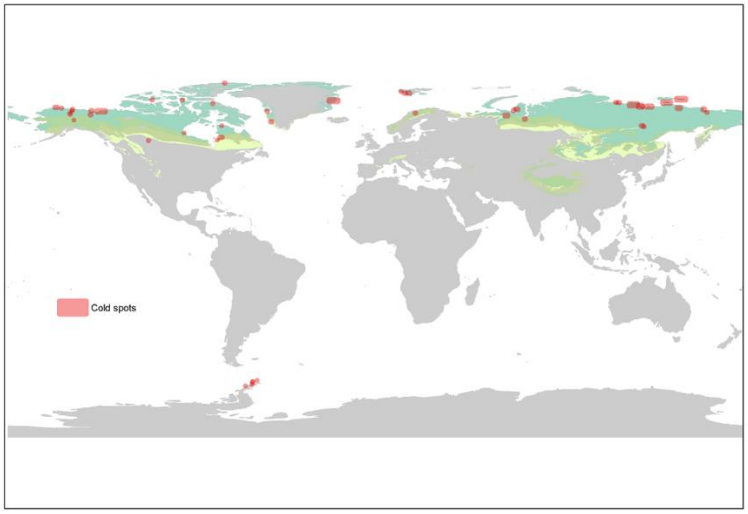
Monitoring of permafrost is required in all regions currently characterized by this phenomenon (Figure 2a). Current monitoring sites do in general represent locations that are easily accessible but in some case are not necessarily regions where significant changes occur. Satellite data should be utilized to

- **identify hot spots of surface change and thus advice on extension of *in-situ* monitoring networks;**
- **support modelling of sub-surface conditions;**
- **provide higher resolution (spatial and temporal) measurements in the proximity of long-term in-situ monitoring sites; and**
- **place the *in-situ* measurements into a wider spatial and temporal context.**

The implementation of a comprehensive cryosphere observing network of reference "CryoNet" sites has been identified as Action Item as part of the WIGOS Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP, 2013). Currently four out of the global list of CryoNet-defined supersites are located in polar permafrost environment. Three of these (Zackenberg, Barrow, Tiksi) are the focus of long term environmental research (*in situ*). However, **many sites which are not included in CryoNet are regularly monitored as part of GTN-P and CALM** (Circumpolar Active Layer Monitoring). There are at least 23 remote flux stations continuously operating in permafrost regions, measuring releases of CH_4 and CO_2 directly.

About 50 locations ('cold spots') where permafrost (Arctic and Antarctic) *in situ* monitoring has been taking place for many years or where field stations are currently established (through, for example the Canadian ADAPT program) have been identified (Figure 2a). These sites have been proposed to WMO PSTG as focus areas for future monitoring by satellite data their specifications are available as supplement to this document.

a)



b)

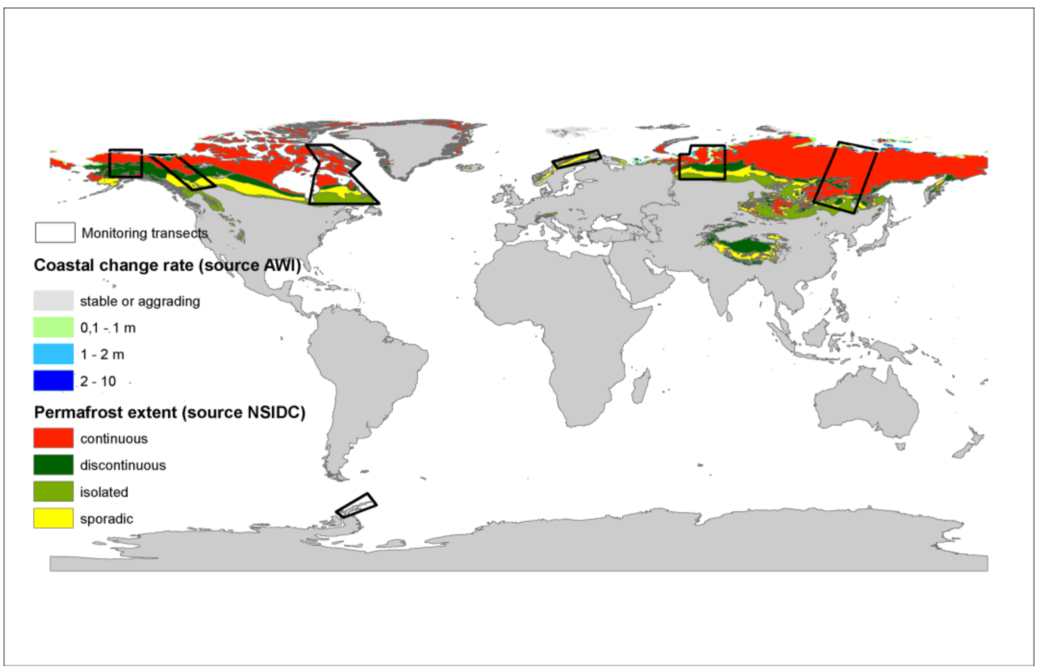


Figure 2: Monitoring sites and regions: a) Permafrost extent (General observation requirement) and 'cold spots' (science mission requirement); b) Transects for hot spot identification (reduced observation requirements)

Figure 3: Arctic coastal erosion rates (source Lantuit et al. 2012)

As a tie between monitoring sites and the global observation of permafrost underlain land area, monitoring **transects across permafrost zones** in representative regions (where changes are predicted) may be established. Some transects have been recommended within the ESA DUE Permafrost project based on a user survey. A refined version (including the Antarctic Peninsula) is provided as supplementary material to this document (Figure 2b). Furthermore, **arctic coastal areas impacted by active erosion** should be monitored regularly (Figure 3).

General observation requirements: All regions underlain by permafrost

Reduced [spatial extent] observation requirements: Transects across permafrost zones as well as arctic coasts

Science mission requirements: acquisitions with higher resolution modes over long term *in situ* monitoring sites ('cold' spots).

4. Observational requirements for permafrost modelling, mapping and monitoring and meta-data for GTN-P sites

While climatic factors are the main cause for the presence of permafrost, spatio-temporal modification occurs due to variations in snow, hydrology, topography and vegetation. Degrading/warming permafrost often results in wetter conditions. Wetter conditions in peatland-permafrost (organic) result in larger heat-transport down to the thawfront (increasing ground temperatures). In the seasons without snow coverage, shade from vegetation and wetness available for evapotranspiration may reduce the surface and the ground temperatures. These phenomena are observed at the circum-polar scale, as significant changes in permafrost temperatures occur for example across the tree line. At regional scales, permafrost distribution and degradation (thermokarst and thermo-erosion) modifies topography and is to some extent also controlled by topography through geomorphic and climatic processes (i.e. fluvial processes). Various bio-and geophysical, and topographic satellite products could potentially support the GTN-P programme and deliver meta-data (section 4.4) and the geo-spatial context of the measurements. Local indicators for permafrost and its state include rock glaciers in mountain permafrost and lake dynamics and thermo-erosional events in lowland permafrost landscapes with tundra and boreal ecosystems. Potential geohazards such as landslides, frost heave and subsidence as well as coastal erosion express themselves in the local topography and need to be observed on a local scale at high spatial and temporal resolutions.

4.1 Observational requirements and recommendations for landsurface changes including geohazards assessment

4.1.1 Subsidence and thermokarst

SAR interferometry is evolving as an excellent tool for permafrost-related research, in particular to detect long-term surface subsidence due to permafrost thaw, annual frost heave/thaw settlement of the active layer, or rapid mass wasting due to thermoerosion (gullies) and thermo-abrasion (coasts, streams). However, the use of this method for permafrost applications is limited by several factors and still in development. Even at L-band, although the coherence is generally high, tundra land cover affects SAR penetration depth on the same spatial scale as elevation changes, primarily depending on soil moisture content and vegetation type. Temporal variations of snow cover, atmosphere and vegetation can also disturb the signal of interest.

Investigations within the framework of the ESA DUE Permafrost project showed that SAR interferometry is a reliable tool to detect seasonal surface subsidence due to permafrost thaw in many regions with short repeat intervals, specifically the 11 days of TerraSAR-X. The timeseries of displacement highlighted that subsidence is occurring within a relatively short time period. Similar results are expected in the future using the Sentinel-1 SAR sensor which has a similar repeat interval (12 days). Coherent annual interferograms are mainly found using the low frequency ALOS PALSAR (L-Band) data, but these interferograms can be contaminated considerably by ionospheric artifacts.

A major constrain is the availability of good quality DEM data for the removal of the topographic phase from the interferograms, but this situation is going to improve with TanDEM-X derived global high-resolution elevation data.

Very high resolution (< 10 m) SAR data are more suitable for mapping localized surface motion at thermokarst features. X-band TerraSAR-X data, however, suffer from significant loss of coherence over active thermokarst landforms.

Requirements summary: high-resolution (10-20 m), single (HH or VV) or dual polarization SAR data (X,C, L); less than two weeks intervals for seasonal subsidence analyses in case of X- and C-Band; interannual analyses possible with L-band (but constrained by ionospheric effects); DEM for removal of topographic phase and geocoding (30 m posting, 2 m relative height accuracy for flat terrain). Very high resolution (< 10 m) SAR (C-band and L-band) and DEM data (5 m posting, 0.5 m relative height accuracy for rough terrain) for thermokarst deformation.

4.1.2 Rock glacier and landslides

Ice-rich permafrost slopes may coherently deform under gravity and this deformation can be measured using SAR interferometry and offset tracking using high-resolution repeat optical images. These techniques are well established in cold mountain regions, mostly in the European Alps and in the Sierra Nevada of California. SAR interferometry based on all bands available from space (X, C, L) has been successfully applied for that purpose. The choice of bands depends thereby mostly on the time-scale that should be covered in relation to the movement rate. Sufficient detection and quantification of small movement rates (order of mm-cm/year), for instance, requires longer temporal baselines and L-band data might thus be necessary to minimize effects from phase coherence loss. On the other hand, faster movement rates (order of dm-m/year) require shorter temporal baselines before geometric coherence loss takes over. For the latter case, 11-day repeat TerraSAR-X data are well suited.

Whereas successful single interferograms are suited for inventorying rock glaciers and landslides, time series of interferograms with seasonal, annual or pluriannual repeat rates could reveal changes in movement rates, which can be related to climatic changes (e.g. through changes in ground ice temperature or water percolation), and reveal slower rates of movements (on the order of magnitude of mm/year).

Requirements summary: Very high-resolution (3-10 m), single polarization (HH or VV) SAR data; repeat X-, C-, or L-band data with temporal baseline of a few weeks in maximum during summer and autumn; repeat of acquisition pattern on an annual base; good quality DEM for removal of topographic phase (<5 m posting, 0.5 m relative height accuracy for rough terrain).

4.1.3 Coastal erosion

Permafrost along arctic coasts as well as lake shores degrades due to thermal erosion. The retreat can be identified over long time intervals using high to medium (Landsat type) resolution optical and very-high resolution SAR satellite data (TerraSAR-X spotlight type). Apart from the displacement of the land/water boundary, on an intermediate level thaw slumps occur locally. Along large parts of the arctic coasts erosion rates range between 1 - 10 m per year (Figure 3). Their monitoring is of relevance with respect to material export (carbon etc) to the Arctic Ocean.

Requirements summary: Annual coverage during ice-free period of all active arctic coastal areas and selected lake-rich areas with high (1m) to medium resolution (10-20m) satellite optical data and single-polarization, very-high resolution SAR data (HH or VV). For highly active areas, coverage is required at a less than two weeks interval with optical and SAR data. Exposition of slopes and looking direction need to be taken into consideration.

4.1.4 Thaw lakes and wetlands

Wetlands in permafrost regions include peatlands, tundra wetlands (composed of small lakes according to the RAMSAR classification), fens and seasonally inundated river floodplains whereas the latter are often interconnected with small lakes. High spatial resolution as well as high temporal resolution observations are required to capture the seasonality which needs to be considered for long-term change studies related to subground permafrost change. Short term changes (change of land cover type to wetlands) are associated with wild fires (section 4.3.2). Current global land cover datasets cannot capture tundra lakes since a significant proportion of lakes and ponds in tundra regions have an extent below 200 m, many even below 30m. SAR data for all wavelengths have been shown to be applicable for regular monitoring. For open water HH polarisation is required. In case of fens and emerging vegetation, combinations of H and V information (including co-polarized (HH/VV) or quad-polarized) information is needed. Soils with conditions close to saturation can be captured with C and L-band (e.g. from SAR soil moisture products). Such a description of wetlands including open water, inundation patterns and moisture regimes is a crucial component of Arctic eco-tone specific assignments of land cover classes (4.3.2). A critical parameter for understanding thermokarst lake dynamics is the assessment of lake ice. As many of these lakes are shallow, lake ice may freeze to the bottom of such lakes and prevent the formation of thawed zones under lakes, whereas lakes that do not freeze to the bottom will develop perennially thawed zones. C-band and X-band SAR have been shown to efficiently differentiate grounded versus floating ice lakes and changes in the proportion of these lake types in the landscape, which are critical for thermokarst dynamics and detecting changes therein. For this, SAR time series data are necessary covering the entire winter season in bi-monthly intervals. Furthermore, thermokarst lake ice has been demonstrated to capture methane ebullition from thawing permafrost under lakes. Various studies demonstrated that C- and L-band SAR signal components correlated with the amount of methane ebullition bubbles trapped in lake ice, allowing an indirect quantification of methane emissions from Arctic lakes with SAR. For this, early winter (right after freeze-up) ice monitoring with high-resolution (<30m) SAR is required.

Apart from the description of fraction and extent of lakes, their summer and winter properties provide valuable information for landscape development. This includes sediment influx and redistribution (water colour) and ice structure and depth. The first requires multispectral optical measurements; the latter can be assessed with SAR. Requirements for lake ice are addressed in a separate white paper.

Optical high resolution data (<1m, e.g. Pleiades, WorldView, GeoEye and other satellites) allows detection and measurements of lateral erosion along thermokarst lake shores. Annual time series are required in combination with historical aerial data.

Requirements summary: SAR data (HH and combination of H and V) with better than 30m resolution and weekly intervals. High-spatial resolution multispectral satellite data (min. 5 (for thermokarst lakes) - 20 m; optimum 1 m, weekly resolution) are needed to monitor turbidity events and changes in lake colour. High spatial resolution imagery (panchromatic) (<1m) in annual intervals to quantify thermokarst lake expansion.

4.2 Comments on models (various spheres): forcing, constraining and evaluation

Remote sensing has the potential to provide model-analogous observations in terms of variables temporal/spatial frequency for forcing, constraining and validation in different application areas (hydrological models, climate models, permafrost models, coupled land-atmosphere models for greenhouse gas emissions, ecological models).

4.2.1 Land surface modelling

The following recommendations have been extracted from the ESA DUE Permafrost user survey (Bartsch et al., 2012):

- Land surface models require near-surface air temperature as forcing parameter. Partly, a very high temporal resolution is needed. E.g., to simulate the atmospherically decoupled land only case in climate models, the input of hourly data is needed. However, the pseudo intra-monthly variations can be calculated. For atmosphere-coupled calculations monthly averages are required. The required parameter accuracy of the temperature product is high around the freezing point: ~0,1°C, and 1°C when far from the freezing point.
- Soil moisture, the snow water equivalent, and optionally the water body ratio within a grid point are used for initialization and validation. Since soil moisture is a prognostic value in the model, moisture related values are important in terms of model

performance validations. Parameter accuracy for 'soil moisture' should be 5 to 10 % of the volumetric water content.
- Land Cover, LAI (or an equivalent measure for biovolumina or height of vegetation cover), topography and snow coverage provide the boundary conditions.

4.2.2 Permafrost modelling

Permafrost models are developed specifically to spatio-temporally map permafrost states and to assess the effect of a changing climate on permafrost. In general, permafrost models are quasi-transitional and spatially distributed, using an equilibrium model for calculating the active layer thickness and mean annual ground temperature (MAT). Satellite derived land surface temperature has been shown to be applicable for permafrost modelling. Static satellite products on Arctic eco-tone specific land cover (surficial material, section 4.3.2) topography and can provide the boundary conditions as well as potential products on subsurface ice content indirectly inferred from ground subsidence (section 4.1.1). Thermal sensor based land surface temperature products are characterized by the clear sky bias and the transition below or above 0° C is often not well captured due to prevailing cloud cover during these periods. Microwave sensors can complement these measurements (freeze/thaw state from SAR at the similar spatial resolution, emissivities from passive microwave sensors at coarse resolution).

Requirements summary: weekly to monthly averages of land surface temperature and snow water equivalent (resolution see TOPC requirements, Figure 1). Better than weekly surface status from SAR (C or L-band) at similar spatial resolution like thermal data (ca. 1km). Snow parameters are addressed in detail in a separate white paper.

4.2.3 Consistency of the satellite-derived and simulated variables

The spatial, temporal and bio-geophysical characteristics of the satellite products need to be consistent with the respective simulated variables. Yet, the land surface temperature, albedo and soil moisture satellite products are up to now not entirely consistent with the model output variables in terms of the time nodes (time steps) and the physical properties.

- The satellite-derived albedo products, normalized to mid-day clear-sky, are not consistent with the simulated model albedo at a respective time node that is calculated throughout the whole spatial domain with all sky conditions.
- Meta data on the number of feasible acquisitions / pixel are lacking in the available satellite products for LST and albedo to correctly simulate clear-sky LST and clear-sky albedo in the models.

- Also a rigorous assessment of the random and systematic errors of satellite products is needed for high-latitude permafrost landscapes.
- At the high latitudes north of 70°N, the spatial grid nodes are not consistent for satellite products in sinusoidal projection formats: the gridding processing for the sinusoidal projection that is inherent to all MODIS-derived products (e.g., albedo, LST, vegetation products and many more) causes a minimum of 10 % percent data loss.
- Even if there is < 15 % vascular plant cover, there is 100 % moss cover underneath/ not 75 % open soil as currently defined in global landcover datasets.

4.3 Comments on assessments of ecosystems, carbon pools and fluxes in permafrost regions

The organic sources and genetic conditions and the transport processes are the key to the carbon dynamics in northern ecosystems. Sediment and organic litter accumulation, poor organic matter decomposition under cold often anoxic conditions, as well as cryoturbation are key processes to incorporate large amounts of carbon into permafrost soils, resulting in accumulation and long-term storage of carbon. In lowland permafrost areas, many tundra and boreal ecosystems have anoxic soil conditions due to water logging. Permafrost peatlands are significant soil carbon stores.

Vascular aquatic plants may act as conduits for internal methane diffusion allowing the methane transfer to bypass the oxic soil zone potentially accounting for up to 90% of the methane emissions from northern wetlands. Also the rise of gas bubbles through water bodies (ebullition) is an important process of methane release from thawed zones underneath thermokarst lakes. Natural gas seeps, otherwise sealed off by impermeable ice-rich permafrost, may increasingly release thermogenic methane in disturbed and degraded permafrost zones.

Mapping, monitoring and upscaling of various components of carbon pools and fluxes (vertical and lateral) is applicable with satellite-derived variables. Land cover and wetlands can be upscaled to greenhouse gas emission regimes. The mapping of carbon sources and monitoring of hydrology in tundra and taiga permafrost landscapes is crucial for the estimation of methane methane and carbon dioxide emissions and lateral organic carbon fluxes.

The dynamics of methane emissions and organic carbon fluxes from regions with changing/degrading permafrost are particularly critical in terms of immediate and long-term global climate effects especially considering very substantial carbon storage pools locked in the present permafrost formations. The rapidly changing conditions for ecosystems and the state of these sensitive polar ecosystems of permafrost landscapes need to be mapped and monitored in the Arctic and Antarctica.

Land cover serves as information on upscaling of inherent ecosystem characteristics in permafrost regions, higher level products such as moisture regimes and carbon pools (incl. soil carbon). Several aspects need to be covered in higher level products aiming on land cover description: (1) the differentiation between mosses, shrubs, sedges and cryptogam crusts (as in the existing Circum Arctic Vegetation Map – CAVM, 1km) and (2) tundra and taiga applicable plant functional types. In the warming Arctic, the treeline and shrub growth advances northward, the high-Artic polar deserts start to green-up (Greening of the Arctic programme GOA, www.geobotany.uaf.edu/goa/). On the other hand, permafrost degradation in taiga zones results in land cover changes to fens, bogs and grassland. Fire events can severely affect the ecotones and leave behind a heavily degraded upper permafrost layer. Fire events can be monitored using thermal satellite sensors, fire scares can be mapped with optical sensors and shifts to fens and bogs complemented by SAR data (see section 4.1.4). Fire-induced surface subsidence can be quantified using SAR interferometry.

4.4 Metadata for GTN-P

GTN-P metadata follow international standards for geographic information ISO TC211 and its extension 19115/2:2009 for describing imagery and gridded data. Following standardized data structures and methodologies in international research networks is an important requirement to maintain the quality and comparability of the measurement data.

With support of the NSIDC (NSF project: Science-Driven Cyberinfrastructure: Integrating permafrost data, services, and research applications), the interoperability between databases will be developed towards international integration and application of web services. A standard information model for the representation of permafrost observations data, with the intent of allowing the exchange of such data sets across information systems, is developed following the model of related research communities, e.g. geoscience (GeoML) and hydrology (WaterML). The GTN-P support group aims towards a new “PermafrostML”.

5. WMO PSTG SAR group – specific recommendations and comments

Current acquisition strategies for space borne SAR data only partially cover polar permafrost regions and some of the long-term *in-situ* measurement sites. Many stations are located in proximity to coastal areas and glaciers which to some extent may allow joint usage by different cryosphere applications but requirements may deviate. Table 1 reviews selected current SAR missions. Several SAR based applications have been highlighted in section 4. They are summarized in Table2.

Table 1: Current missions comments

Mission	Comments
Sentinel-1	Coastal regions which are covered due to the objective of sea ice monitoring are mostly located within continuous permafrost. It is however crucial to have discontinuous permafrost zones covered as well. Modes will be IW and EW, where IW would be preferred for permafrost applications. The foreseen HH-HV or HH polarization for the monitoring of polar environments would be also applicable for land surface hydrology monitoring over permafrost.
ALOS-2 Palsar	ALOS-2 PALSAR acquisitions are foreseen over two of the reduced observation requirement transects (Alaska, Western Siberia) where permafrost changes are reported. The defined areas cover all permafrost zones.
TerraSAR-X	Continuous acquisitions are available for selected ground monitoring sites (cold spots – science missions requirements) since 2013 The TanDEM-X lake mask which is produced as side product would be of value for regional analyses of permafrost regions, but does however not include repeated surveys. Polar region DEMs are mostly based on winter acquisitions, which introduces elevation offsets due to snow cover.
Radarsat-2	Continuous acquisitions are available for selected ground monitoring sites, mainly in Canada. Coastal regions which are covered due to the objective of sea ice monitoring are mostly located within continuous permafrost, but acquisitions are at lower spatial resolution.

Table 2: SAR requirements summary

Parameter	Spatial res.	Temporal res.	Band	Polarization	Comment
Subsidence	10-20 m	Bi-weekly during snow free season	L, C, X	Single (HH or VV)	InSAR
Rock glaciers	3-10 m	Bi-weekly during snow free season	L, C, X	Single (HH or VV)	InSAR
Surface status	< 30 m	Better than weekly, shoulder seasons	L, C, X	any	
Wetlands and lakes	< 30 m	Weekly, shoulder and snow free seasons	L, C, X	HH plus HV/VH, HH/VV or quad	
Coastal erosion	1 m	Annually during the ice and snow free season	L, C, X	Single (HH or VV)	Be-weekly for highly active areas (figure 3)
Lake depth and thawed zone characteristics	1-30 m	Weekly during winter	C, X	Single (HH or VV)	Detecting whether lakes have grounded or floating ice; indication of thermokarst activity under lakes
Methane emissions from lakes	1-20 m	Weekly during should seasons (freeze-up, ice-out)	L, C	Single (HH or VV), HH/VV, quadpol	Quantification of methane ebullition bubbles

6. Preliminary requirements summary with respect to current missions

Table 3: Preliminary request summary with respect to capabilities of current missions

Level	**Specifications**
Science	○ bi-weekly SAR acquisitions of all 'cold spots' for InSAR applications ○ annual high resolution optical (<1m) acquisitions of all 'cold spots' (July-August)
Reduced to General	○ bi-annual (early and late summer) high (<1m pan, <5m ms) to medium resolution (<30m ms) optical and SAR of all monitoring transects for landcover applications ○ once per year high resolution SAR and optical acquisitions of **arctic coast** line (high activity areas) in consistent polarization and frequency, and orbit (with differentiation between actual exposition of slope) ○ annual coverage of all **rock glacier-**characterized regions with high-resolution optical (1 good image) and SAR (2-3 cycles for interferometry) for general inventory and hot spot identification ○ annual circumpolar **lake** inventory (<30m) in thermokarst dominated lowland regions (with time stamp for each pixel in case of higher level product, consistent frequency and resolution) ○ annual lake ice status for monitoring transects (grounded versus floating ice, end of winter, before snowmelt)

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