ESA DUE PERMAFROST: AN EARTH OBSERVATION (EO) PERMAFROST MONITORING SYSTEM

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ABSTRACT

The task of the ESA Data User Element (DUE) Permafrost project is to build up an Earth Observation service for permafrost applications with extensive involvement of the permafrost research community. The DUE Permafrost remote sensing products are ‘Land Surface Temperature’ (LST), ‘Surface Soil Moisture’ (SSM), ‘Frozen/ Thawed Surface Status’ (Freeze/Thaw), ‘Terrain’, ‘Land Cover’ (LC), and ‘Surface Waters’.

A major component is the evaluation of the DUE Permafrost products to test their scientific validity for high-latitude permafrost landscapes. There are no standard evaluation methods for this range of remote sensing products, specifically not for these latitudes. Evaluation experiments and intercomparison is done on a case-by-case basis, adding value and experience in validating products for these regions. A significant challenge in the evaluation of remote sensing products for high-latitude permafrost landscapes are the very sparse ground data. We rely on ground data provided by the Users and by international programmes. The primary international programme is the Global Terrestrial Network for Permafrost (GTN-P) initiated by the International Permafrost Association (IPA). Leading projects are the networks of the 'Circumpolar Active Layer Monitoring' (CALM) and the 'Thermal State of Permafrost' (TSP). Prime sites for testing methods and scaling are the long-term Russian-German Samoylov Station in the Lena River Delta (Arctic Siberia), and the tundra and taiga-tundra transition regions in Western Siberia (RU). The results of the first evaluations of LST, SSM and Freeze/ Thaw using GTN-P and User’s data show the usability of the DUE Permafrost products for high-latitude permafrost landscapes.

The DUE Permafrost remote sensing products will be adapted as drivers, validation data and as newly available external input data for permafrost and climate models.

INTRODUCTION

DUE Permafrost – an Earth Observation-Service for Permafrost

A major task of the ESA Data User Element DUE Permafrost project (2009-2011) is to build up a mid- to long-term scenario for an Earth Observation (EO) service for permafrost. From the beginning, the project actively involved scientific stakeholders and the International Association of Permafrost (IPA) in the elaboration of the science and implementation plan.

Permafrost is a subsurface phenomenon, i.e. frozen ground below 0°C for at least two consecutive years (International Permafrost Association, IPA). However, in summer months, an upper thawed layer develops, the active layer, with consequences on surface soil moisture, run off, surface waters, vegetation, and terrain changes. Therefore, DUE Permafrost uses a suite of indicative spaceborne-derived parameters: 'Land Surface Temperature' (LST), 'Surface Soil Moisture' (SSM), 'Surface Frozen/Thawed State' (Freeze/Thaw), 'Terrain' and 'Terrain Displacement', 'Land Cover' (LC), 'Surface Waters', and 'Snow' (Snow Extent and Snow Water Equivalent).

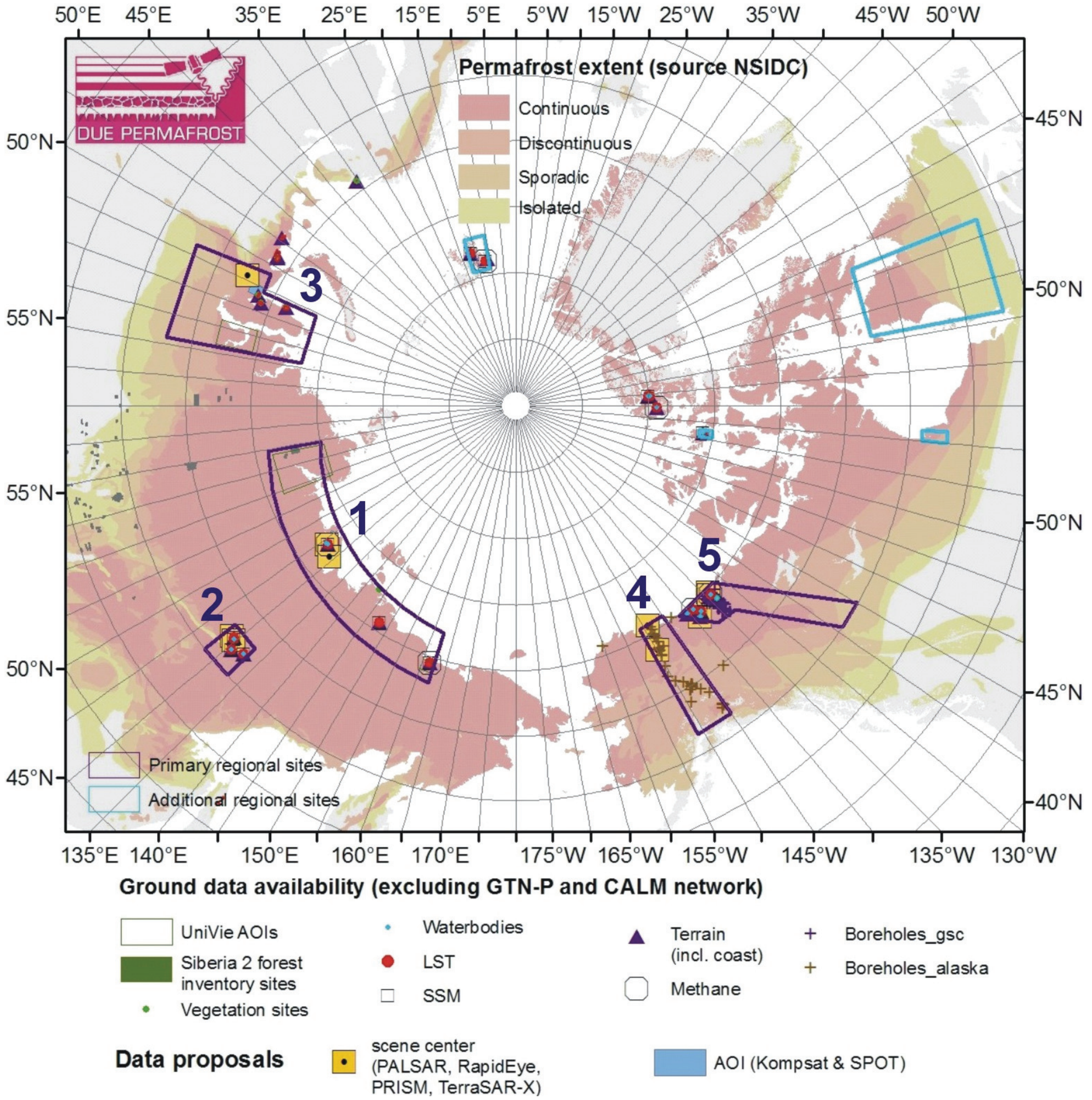

Figure 1: Key regions of the DUE Permafrost project. 1=Laptev Sea and Eastern Siberian Sea Region (RU), 2=Yakutsk Region (RU), 3=Western Siberia (RU), 4=Alaska Highway Transect (US), 5=Mackenzie River Delta and Valley (CA).

The DUE Permafrost consortium is led by the Vienna University of Technology, Austria (TU Vienna) and supported by four partners: University of Waterloo (UW, Department of Geography and Environmental Management, Canada); Friedrich Schiller University (FSU, Department of Remote Sensing, Jena, Germany); Gamma Remote Sensing (GAMMA, Switzerland); Alfred Wegener Institute for Polar and Marine Research (AWI, Potsdam, Germany). TU Vienna is responsible for all parameters based on microwave remote-sensing technology (active and passive microwave sensors): Surface Soil Moisture (SSM) with weekly to monthly averages from 2007 to 2010, Freeze/Thaw and Surface Waters. The UW provides merged products for the Land Surface Temperature Services (LST) from MODIS and ENVISAT-AATSR with weekly to monthly averages from

2007 to 2010. The FSU is responsible for the circum-Arctic/ boreal LC products. GAMMA has evaluated the newly released (2009) Global ASTER GDEM for high-latitudes and found frequent data voids and noises due to cloud coverage. Therefore, GAMMA has assembled national DEM data-sets and build up the first circum-arctic DEM dataset with a 100 m pixel resolution north of 55° N. AWI organizes the exchange between the scientific stakeholders of the Permafrost community and the project consortium, including the managing of the ground data and the adaptation of remote sensing products into the modelling. An operational monitoring service for Snow Extent and Snow Water Equivalent is currently being set up within the ESA DUE project GlobSnow[a].

The DUE Permafrost products are provided for the circum-Arctic/ boreal permafrost area. In addition, in order to set up the required validation tasks and information services, a target area approach with five case study regions with higher spatial resolution of the products is used (see Figure 1). These tests regions are (1) the Laptev Sea and Eastern Siberian Sea Region (RU; continuous very cold permafrost/ tundra), (2) the Yakutsk Region (RU; continuous cold permafrost/ taiga), (3) the Western Siberian transect (RU; continuous to discontinuous/ taiga-tundra) including Yamal Peninsula and Ob Region, (4) the Alaska Highway Transect (US; continuous to discontinuous/ taiga-tundra), and (5) the Mackenzie Delta and Valley Transect (CA; continuous to discontinuous/ taiga-tundra).

The first DUE Permafrost user workshop was held in May 2010 in Vienna as an official side-event of the EGU 2010. The observation strategy for all products and regions was presented by the project team and reviewed with the participants. The second user workshop has been supported by the International Arctic Research Centre, IARC, Fairbanks (US) and took place in March 2-4, 2011 in Fairbanks, Alaska. The workshop offered assessments of the DUE Permafrost products and in-depth discussion sessions on remote sensing products as drivers and boundary parameters for permafrost and climate modelling as well as remote-sensing applications for permafrost monitoring.

METHODS

Concept of the evaluation of the DUE Permafrost Products

Most of the foreseen DUE Permafrost remote-sensing applications are well established and can optimally become operational. However, are remote sensing products that have been developed and tested in agricultural, semi-arid or steppe to forest landscapes of low-to mid latitudes also valid for high-latitude permafrost landscapes? Permafrost landscapes are a challenge for qualitative and quantitative remote sensing. The land surface is characterized by high heterogeneity, patterned ground, disturbances, abundance of small-sized water bodies, and sharp moisture gradients. Therefore, a major component of the project is the evaluation of the DUE Permafrost products to lend confidence in their scientific utility for high-latitude permafrost landscapes.

Ground measurements in high-latitude landscapes involve challenging logistics and are networked on multidisciplinary and circum-arctic level by the Permafrost community. The International Permafrost Association (IPA) initiated the foundation of the Global Terrestrial Network for Permafrost (GTN-P) to organize and manage a global network of Permafrost observatories for detecting, monitoring, and predicting climate change. The network, authorized under the Global Climate Observing System (GCOS) and its associated organizations, consists of two observational components: the Circumpolar Active Layer Monitoring (CALM)[b] and the Thermal State of Permafrost (TSP)[c]. A major part of the DUE Permafrost core user group is contributing to GTN-P. The CALM and TSP programmes have been thoroughly overhauled during the International Polar Year (IPY 2007-2008) and extended their coverage to provide a true circum-polar network.

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[a] http://www.globsnow.info/

[b] http://www.udel.edu/Geography/calm

[c] http://www.gi.alaska.edu/snowice/Permafrost-lab/projects/projects_active/proj_tsp.html

In addition to using GTN-P data, user groups are also directly involved in providing ground data and evaluating the products [e.g., Helmholtz University Young Investigators Group HGF-Sensitivity of Permafrost in the ARCtic: SPARC at AWI, and the Land Use Land Cover Change programme LCLUC Yamal (NASA)]. There are only a limited number of well-described and multi-instrumented field sites in the Arctic. The long-term and multi-instrumented Russian-German Samoylov Station in the Lena River Delta (Arctic Siberia) is one of the prime sites of the SPARC research programme. Land surface classification is obtained through high-spatial resolution spectral imaging (VIS, NIR) using unmanned vehicles, kites and zeppelins (1). Therefore, the Samoylov Island in the Lena River Delta has become a test site for evaluation DUE Permafrost products for the landscape type 'wet polygonal tundra'.

The blended evaluation using ground data

DUE Permafrost follows the strategy of the Blended Evaluation – a mixture of strategies and methods using quantitative and qualitative metrics. There exist no standard evaluation methods for the broad range of remote sensing products within DUE Permafrost, specifically not for high-latitude Permafrost landscapes. Evaluation experiments and intercomparison is done on a case-by-case basis, adding value and experience in validating products for the High Northern Latitudes. The evaluation is conducted using absolute and descriptive methods as well as thematic and regional knowledge to assess the temporal, regional, and scaling variability.

Figure 2: The DUE Permafrost key region of Western Siberia (Ob Estuary and Yamal Peninsula). Yellow squares indicate the location of Western Siberian GTN-P sites. The blue colours show the extent of different Permafrost zones (dark blue = continuous, bright blue = discontinuous and greyish blue = isolated).

The ground data are: temperature (t_{air}, $t_{surface}$, t_{soil}, $t_{borehole}$), soil moisture, terrain (GPS, dGPS), land cover (aerial maps), and surface water (water level, aerial maps). Match-up data sets of ground data coincident in time and location with satellite observations are being built up for the evaluation of DUE Permafrost data sets. 'Descriptive truth' provides the qualitative evaluation using field description, field photos and expert information.

Western Siberia was chosen as the first key-site for the DUE Permafrost project. The test region covers Novaya Zemlya in the west, the Yamal Peninsula and the western half of the Gydan Peninsula in the east and reaches ~150 km southward (see Figure 2). The eight West Siberian GTN-P sites are located in different permafrost zones (continuous to discontinuous permafrost, coastal to continental (Figure 2). The GTN-P temperature data (air, surface, ground), surface moisture data and the vegetation data serve as direct validators for the remote sensing products LST, Freeze/ Thaw, SSM, and Land Cover (see Figure 3). Investigations are ongoing as to how to optimally use data, such as the active layer depths, the detailed landform and topography description and site pictures, for the evaluation of Land Cover and Terrain products (Figure 3).

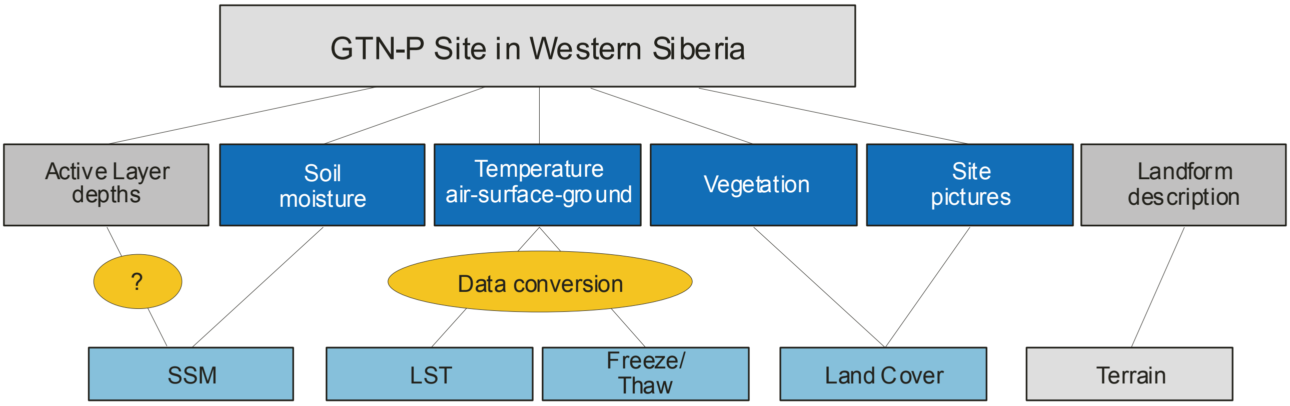


Figure 3: Overview of available ground data of the Western-Siberian GTN-P sites (Figure 2) and their use for the evaluation of the DUE Permafrost remote sensing products. Blue boxes indicate the type of data that can directly be used as validation parameters. Investigations are ongoing about the potential use of indirect parameters (grey boxes) as validators.

RESULTS

Land surface temperature

To investigate the thermal upscaling, an automated Thermal InfraRed (TIR) camera (7.5 to 14 µm) was mounted on high masts in Spitsbergen and on Samoylov Island in the Lena River Delta during summer months 2008 and 2009 (2,3). Langer et al. (2) describe their successful experimental upscaling in Samoylov for the permafrost landscape-type wet-poylongal tundra (for the snow-free period, see Figure 4). Westermann et al. (3) also have been successful in thermal-upscaling experiments at the Spitsbergen Permafrost site Ny-Alesund (barren-moss and -lichen cover-water). Both authors matched the thermal camera measurements against MODIS *LST* L2 concluding that: The spatial surface temperature variations at both highly heterogeneous sites are greatly reduced for averaging periods longer than the diurnal cycle. This has strong implications for satellite-based Permafrost monitoring schemes, since the validity of surface temperature averages is not affected by unresolved landscape heterogeneities, except for the free water bodies.

Water bodies show sustained differences in surface temperature from the remaining surface. Hence, high-resolution land water masks are essential for the interpretation of satellite LST products, since unresolved water bodies can bias the satellite observations if a high fraction occurs in the satellite footprint area. The success rate of MODIS *LST* data acquisition is limited due to a frequent cloud cover, which is typical for arctic regions. Reliable surface temperature averages therefore require the development of gap-filling procedures. Furthermore, the satellite data are biased by occasional erroneous measurements that are not masked out by the operational cloud-cover masking (see symbols of crosses in Figure 4).

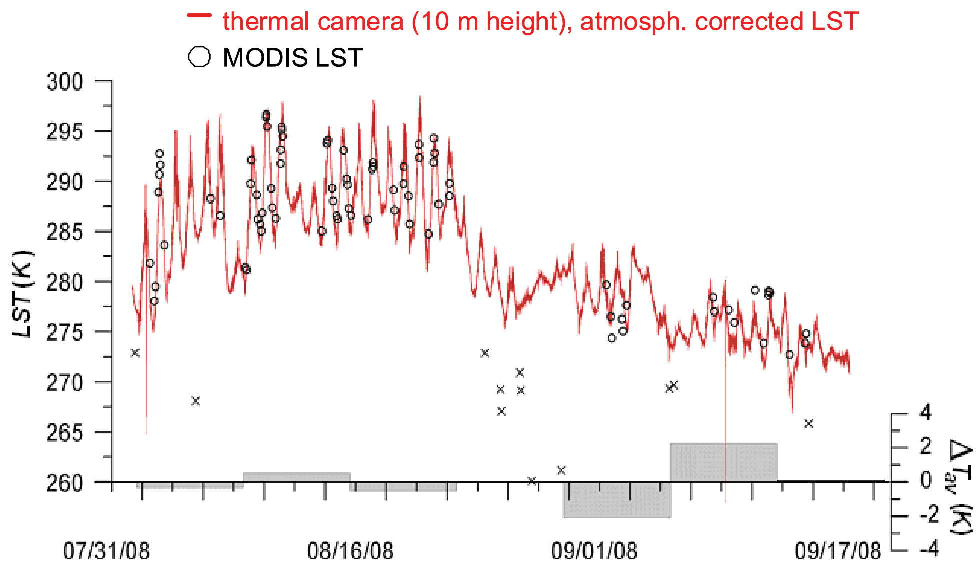
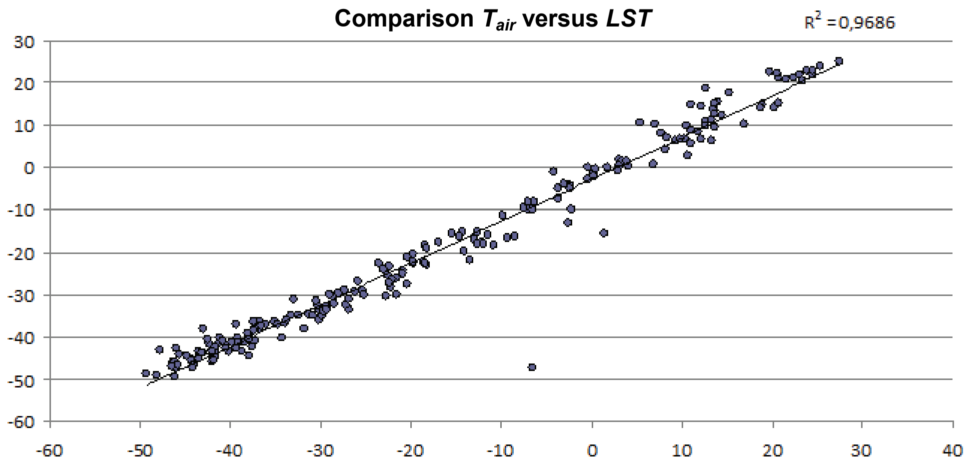


Figure 4: Continuous measurements of surface temperature (red line) using a thermal camera installed on a 10-m tower in summer 2008 (Samoylov Island, Siberia). The graph shows the match-ups with MODIS L2 LST (Circles and Crosses = errors due to imperfect cloud masking, in (2)).



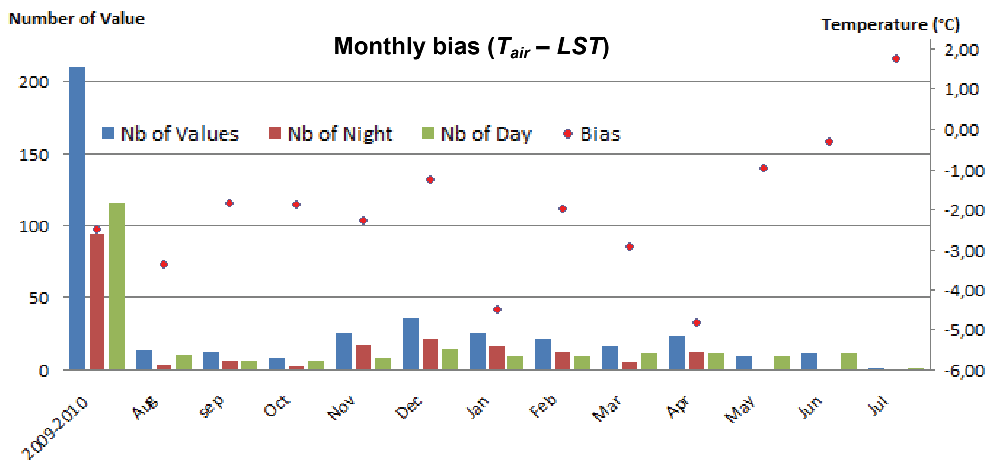


Figure 5: GTN-P Western Siberia comparison of the weekly LST product. The upper graph shows air temperature versus MODIS L2 LST at the GTN-P site Nadym (Western Siberia) from Aug 2009 to Aug 2010. Nadym is an alluvial plain dissected by lakes, ravines and frost mounds. Large areas are moss-lichen peatlands. The selected set of air temperature data is within one hour of MODIS LST (n=210). The lowert graph shows the yearly/monthly bias of air temperature versus MODIS L2 LST.

The DUE Permafrost *LST* product will be composed from merged MODIS *LST* and AATSR *LST* in weekly and monthly averages. The first quality assessments are done by matching the LST sets (AATSR, MODIS) separately against T_{air} sets (hourly) including the comparison with Land Cover maps and *NDVI* maps. Comparison between MODIS and AATSR *LST* products will allow the verification their correspondence and correlation with the aim of using both in producing monthly and weekly products.

Surface soil moisture

Samoylov in the Lena River Delta is a small island surrounded by the Lena River. Contamination from variations in water-surface extent and roughness within the footprint is therefore expected. Micro-topography adds to further small-scale differences. Low-centred polygons are typical in this environment. Ground data represent different micro-topographical units of such a polygon: polygonal rim, polygonal slope and centre. All these micro-units have been considered in the comparison of remote sensing products versus soil moisture ground measurements. Direct comparisons of the datasets reveal variations of the relationship between the years and micro-units (rim, slope, centre).

EUMETSAT ASCAT-derived relative surface soil moisture (4,5) can be used to distinguish between wet and dry conditions at the slopes of polygons which have a variation of more than 35 % Volumetric Water Content (VWC).

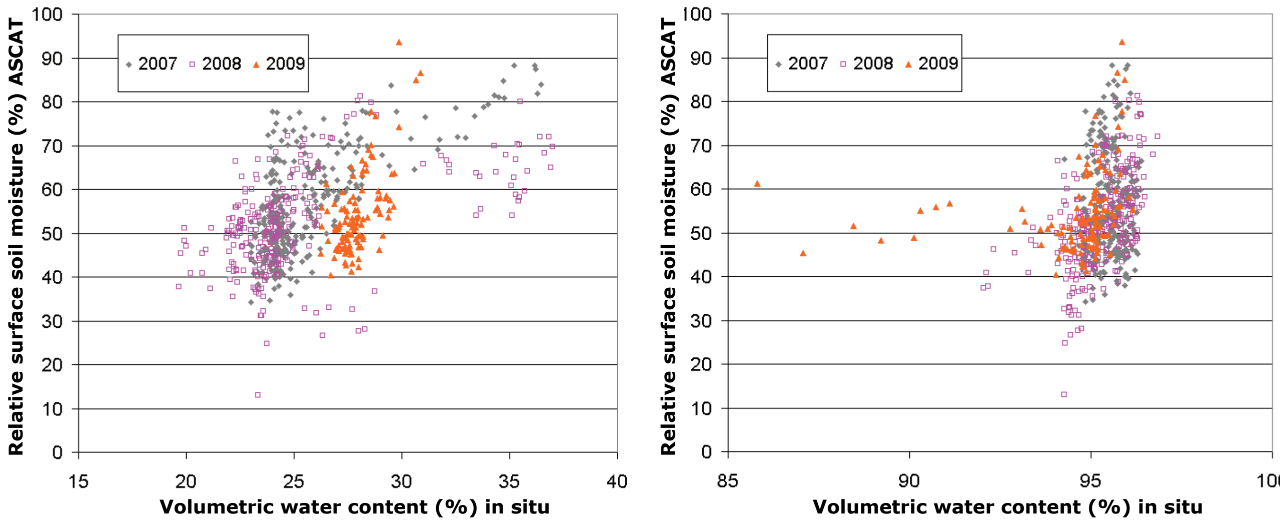


Figure 6: Volumetric water content (in %) from in-situ measurements of Samoylov Island (Lena River Delta, RU) and relative surface-wetness from Metop ASCAT (in %, 25 km resolution) for summers 2007, 2008 and 2009: left: slope of polygon, right: centre of polygon.

Variations integrated within the 25 km footprint in this very heterogeneous landscape represent polygon slopes more than the ground measurements within the polygon centres (Figure 6). The general drying trend after snow melt is captured as well as an increase in soil moisture which is probably due to precipitation events (Figure 6).

Synthetic-Aperture Radar (SAR) data can provide data for surface soil moisture (SSM) similar to scatterometer data but with much higher spatial resolution if sufficient measurements are available (6). ScanSAR data from ENVISAT ASAR operation in Global Monitoring Mode (1x1km, after exclusions of measurements under frozen ground conditions) have been compared with in-situ measurements on the island during summer 2005 and 2006. At this scale, low-centre polygon measurements show high correlations (>0.7) (7). ASCAT data are only available after this time period since 2007. This highlights the need for multi-scale investigations for the parameter soil moisture.

Freeze/thaw surface state

GTN-P borehole-temperature time-series at 0 m and 0.5 m depth serves as validation data for the frozen/ unfrozen surface status. Figure 7 shows a comparison between borehole temperature time-series (0 m and 0.5 m depth) in 2007 for Yubileynoe (RU) and the ASCAT 'Freeze/Thaw' Surface Status.

First unfrozen surface and melting snow conditions in April 2007 are detected when the surface temperature is around 0°C. Refreeze during spring (in May) is correctly captured with the ASCAT surface state flag. In June 2007 with rising temperature (0 m borehole above 0°C) the surface is correctly determined as 'unfrozen'. The separation between unfrozen ground without snow and melting snowcover cannot be clearly determined in all cases both are indicative for the temperature rise.

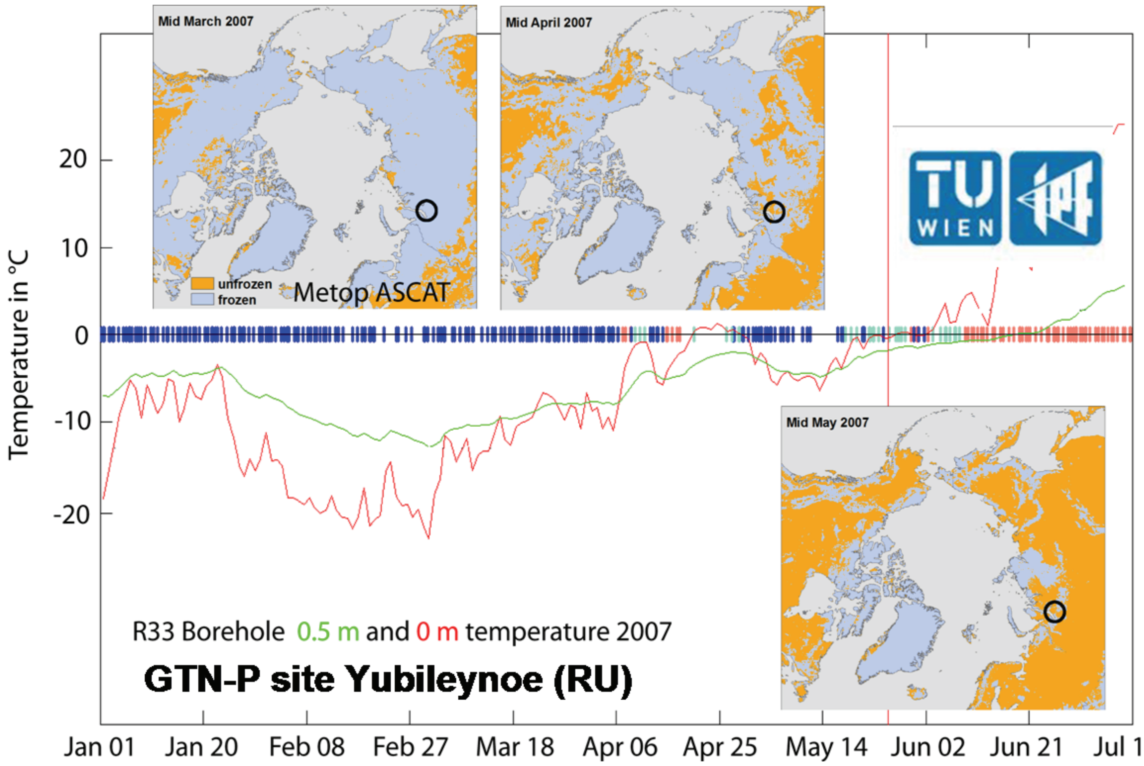


Figure 7: Comparison of Metop ASCAT-derived surface status (SSF: unfrozen, frozen, melting or ice) and borehole temperature measurements at 0 (red) and 0.5 m (green) depth (GTN-P CALM site Yubileynoe, borehole 2, Western Siberia, RU) in 2007.

Land Cover

Global Land Cover derived from optical satellite data serve as external input data into permafrost and climate models: the Land Cover2000 (LC2000)[d], Ecoclimap[e] and potentially GlobCover2009[f]. How valid are these land cover products for the high-latitudinal permafrost landscapes? A major error source could be a too generalized land cover description and the high fraction of surface waters within the remote sensing pixels.

Within the SPARC programme, high spatial-resolution land-surface classification is obtained using VIS, NIR and TIR cameras on unmanned platforms (kites, zeppelins) for scaling experiments. Multi-temporal nadir airborne VIS-NIR imagery has been acquired in 2006, 2007, and 2008 on Samoylov Island (Siberia) to map seasonal dynamics of surface water, moisture, and vegetation.

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[d] http://bioval.jrc.ec.europa.eu/products/ glc2000/products.php

[e] http://www.cnrm.meteo.fr/gmme/PROJECTS/ECOCLIMAP/frame_text_ecoclimap.html

[f] http://ionia1.esrin.esa.int/

The high-spatial resolution mapping provides a correct parameterization for coarser-spatial resolution LC products. Muster et al. (1) extracted a water-body ratio of 0.25 from the aerial VIS-NIR data that they assign to the moist to wet polygonal tundra landscape. This is relevant as meta-data information for the DUE Permafrost products LST, SSM, and LC. The spatial high-resolution of this surface-water product and the moisture regime support the evaluation and the scaling experiments.

The DUE Permafrost project has started with a statistical evaluation on the global LC data sets for the northern high-latitude Permafrost area (see example in Figure 8) in exchange with other Arctic programmes. The ESA-DUE Permafrost–NASA Land-Cover and Land-Use Change LCUCL Yamal Workshop took part in January 2011 at AWI Potsdam (Germany) for scientific exchange between two large programmes focusing on Remote-Sensing Applications in Northern High-Latitudes. The first outcomes are that the classification of tundra landscapes as 'sparse, i.e., <15% vegetation cover' is erroneous and will in turn lead to wrong parameterization of external input parameters into models for albedo, thermal emissivity, thermal ground fluxes and others. DUE Permafrost in cooperation with the IPA is preparing a statistical report on the evaluation of Land Cover in Northern High Latitudes using the GTN-P data.

Figure 8: GTN-P site vegetation-descriptions are compared to global LC datasets (GlobeCover2009, LC2000). The figure shows GTN-P site photographs and descriptions in the left and the GlobeCover and LC2000 id's (at the coordinates of the GTN-P site) and landscape description.

SUMMARY AND OUTLOOK

The first version of the DUE Permafrost dataset was completed in early 2011 and its evaluation is ongoing. The first results for the Western Siberian Permafrost region and the Lena River Delta are promising: The blended evaluation of the various DUE Permafrost products shows that operational remote sensing products such as LST, Freeze/Thaw and the dynamics of SSM products are also valid for high-latitudinal applications and permafrost landscapes. Still, high cloud-coverage poses a problem for the thermal and optical remote sensing applications. A high fraction of surface water will always influence the values of geo- and bio-physical parameters in optical, thermal and microwave remote sensing products. Investigations are ongoing about the impact on the weekly and monthly-averaged products that will be used for Permafrost monitoring and modelling.

In summary, ongoing discussions and evaluation activities, inter-active user workshops and the strong involvement of scientific stakeholders and the International Permafrost Association (IPA) make the DUE Permafrost products trustworthy for the permafrost and the climate community. The final DUE Permafrost remote sensing products will soon be released (early 2012) and can then be used to extract the temporal dynamics, map the spatial patterns of indicators, and serve as drivers and external input data into models. A web interface will be implemented for data download and will be used to deliver the final version of the data set at the end of the project. The last step of the project will consist of the implementation of the Permafrost Earth Observation Information System, the PEO information system, with feeds to regional and global climate models (as a joint initiative of the ESA and the IPA in late 2011). The first, ready-to-use product now available is the circum-arctic DEM with a 100 m pixel resolution north of 55°N.

The second ESA DUE Permafrost user workshop (March 2011 in Fairbanks, Alaska) initiated how to adapt the DUE Permafrost products for modelling of permafrost and climate. In cooperation with the Helmholtz Climate Initiative REKLIM (Regional Climate Change) the remote sensing products will be adapted as drivers, validation data and as newly available external input data for permafrost and climate models. The outcome will be presented and discussed on the third user workshop that will be held at the Alfred Wegener Institute for Polar and Marine Research in Potsdam, Germany, in early 2012. Further information is available at http://www.ipf.tuwien.ac.at/ Permafrost.

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