Final Report v2

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2012 March
This document was compiled for the DUE Permafrost project (ESRIN Contract No. 22185/09/I-OL), a project of the Data User Element initiative of the European Space Agency.

TU Wien project number: D1224209010

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If further corrections are required please contact Annett Bartsch. (ab@ipf.tuwien.ac.at).
The PERMAFROST project is funded by the European Space Agency (ESA) Data User Element (DUE) program, which is a component of the Earth Observation Envelope Program (EOEP). Permafrost is an Essential Climate Variable (ECV). The objective of this project is to establish a monitoring system based on satellite data.

The final report documents all demonstration datasets, algorithms, products and final services. It summarizes the requirements baseline, design justification, definition and validation.

This document has been updated after the final user workshop. The assessment of the service, an updated observation strategy and an executive summary has been added.

The first part reviews the project objectives, history, organization and observation strategy framework (section 1). The user requirements reflect the diversity of the interested organizations. This has been taken into consideration for the definition of service cases and development of the observation strategy. The pan-arctic service case area addresses mostly climate modeling groups. The local and regional service cases have been defined based on focus areas for ground observations and studies (section 3). The methodology for product adaption and development is presented by product type in section 4. This ties into the information system (section 5) which comprises the Permafrost Information System – Earth Observation (PEO) and the data portal. The data portal allows access to all datasets and visualization (WebGIS) (section 5.2). The service is eventually assessed by the user community (section 6).
Executive summary

The PERMAFROST project is funded by the European Space Agency (ESA) Data User Element (DUE) program, which is a component of the Earth Observation Envelope Program (EOEP). Permafrost is an Essential Climate Variable (ECV). The objective of this project was to establish a monitoring system based on satellite data.

The goal of the Permafrost project was to demonstrate Earth Observation (EO) integrated services in the field of permafrost monitoring of the boreal zone with active participation of user organisations, mainly from the scientific world. The project acted as a platform to users and service providers in order to harmonise information needs and develop a set of key tools to address them.

The international permafrost research community requires easy access to end-products which provide information on the current status of permafrost and add value to existing networks. Data interchange ability with respect to existing data platforms such as the Arctic Portal (Inter-map) and the NSIDC archiving system is a basic requirement. This has been addressed within DUE Permafrost and should be continued by future services.

The user community comprises institutions, organizations and scientists from a wide range of subjects and interests. Climate modelers as well as field investigators have expressed an interest to be an associated user with the project before its start (initially 10 user institutions including the International Permafrost Association).

The consortium was led by the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology (TU Wien) and was supported by four partners (University of Waterloo, Friedrich Schiller University Jena, Alfred Wegener Institute for Polar and Marine Research, Potsdam and Gamma Remote Sensing.

Observation strategy

Permafrost is a subsurface phenomenon and cannot be directly observed with satellite data. Yet, monitoring can be done based on indicators and via permafrost models. Indicators are especially thermokarst lake dynamics and surface elevation changes. Those phenomena need to be observed on a local scale. Regional to circumpolar monitoring requires the use of permafrost models. Relevant satellite-observable parameters are land surface temperature (LST), snow extent, snow water equivalent (SWE), vegetation, and soil moisture. Existing services have been integrated into the Permafrost processing system – Earth Observation (PEO) and adapted to the needs of permafrost modelling at high latitudes. All satellite datasets are made available via a data portal (incl. WebGIS) which will tie into the permafrost information system of the International Permafrost Association (IPA).

<table>
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<th>Service scales</th>
<th>Potential field of application</th>
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<td>Pan-arctic/boreal</td>
<td>As input for permafrost and climate modelling</td>
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<td>Regional</td>
<td>Regional modelling, Scaling</td>
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<td>Local</td>
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Service scales and potential field of application
The implemented service is based on a comprehensive user requirements survey and follows a multi-scale concept. Pan-boreal arctic products cover all permafrost affected areas north of 55°N. Five regional service cases have been identified based on ground data availability: Alaska North Slope/Borehole transect, Mackenzie delta and borehole transect, Ob-Esturay including Yamal peninsula, Laptev sea regions including East Taymir, Lena-Delta and Cherskii, and central Yakutia. Temporal coverage varies from product to product. The overlapping period for all products is 2007 – 2009.

User involvement

As part of the user requirement engineering in phase I, a comprehensive user survey has been carried out. It included not only the collection of requirements but also ground data availability. The location and extent of service case areas has been defined based on this user feedback.

As a concept within the ESA DUE programs, user workshops are an important tool for the interaction between the scientific user’s community and the remote sensing experts. The first DUE Permafrost User Workshop was held in May 2010 in Vienna as an official side-event of the EGU. The observation strategy for all products and regions was presented by the project team and reviewed with the participants.

The second DUE Permafrost User Workshop has been hosted and financially supported by the International Arctic Research Centre, IARC, University of Alaska Fairbanks (US) and took place from 2nd to 4th of March 2011. More than 40 scientists from scientific and governmental institutions participated. The workshop offered assessments of the DUE Permafrost products via tutorials (using the freely available software packages ESA BEAM-VISAT and Quantum-GIS). During in-depth sessions the participants discussed remote sensing products in context to modelling and permafrost monitoring.

Second user workshop at the International Arctic Research Centre, University of Alaska, Fairbanks, March 2011

The third and final DUE Permafrost User Workshop took place at AWI Potsdam (DE) from the 15th to 17th February 2012 back-to-back with the final ESA ALANIS User Workshop with more than 60 participants. The Workshop focused on discussion sessions on remote sensing products as drivers and boundary parameters for permafrost and climate modelling and remote-sensing applications for permafrost monitoring.

Third user workshop at AWI, Potsdam, February 2012
The service

The Permafrost Processing System (PEO) follows a modular approach. This approach was selected to take into account the different data sources and product contributors and to have an easy to adapt solution. Automated processing chains for database update have been implemented for land surface dynamic products available at a sufficiently mature level: land surface temperature, relative surface soil moisture, surface status and open water. Static components (no regular updates, although time series partly available) are land cover and terrain parameters.

Land Surface Temperature

The rate at which permafrost evolves can be determined by studying its thermal regime, which is dependent on surface temperature. Surface temperature is a key parameter as it governs the surface energy budget and the thickness of the permafrost active layer. The LST processing subsystem integrates the LST level 2 products from MODIS and AATSR distributed by NASA and ESA, respectively. Post-processing functions supply UW level-3 weekly and monthly LST products for regional and pan-Arctic scales.

The main components of the processing subsystem are: Interpolation to regular grid, Spatial averaging, Temporal averaging and weekly LST. The weekly LSTs are calculated from all satellite overpasses within a seven-day period based on aggregation of daily products. It is available for each day based on a 7-day sliding time window giving most recent observations highest priority following the GlobSnow convention. The monthly LSTs are calculated from all satellite overpasses within a calendar month period. It was noticed that the UW level 3 AATSR product was not consistent over the entire year. The product reached the largest deviation from air temperature and MODIS LST around the month of July at both sites, but performed well for other times of the year.

Land Surface Hydrology

Variations in parameters which impact heat conductivity play a role in the reaction of the subsurface frozen ground to changes in the atmosphere. Soil moisture information is one of the key parameter for modelling of permafrost extent. The moisture regime is important for active layer development. Soil moisture together with temperature is also a limiting factor for heterotrophic soil respiration. Water bodies or thaw lakes are an important mechanism of landscape modification in the arctic. Water is a class in all available global and regional land cover maps. The spatial resolution of those existing products ranges between 300 m and 1 km. The majority of lakes within the tundra environment is however much smaller than the spatial resolution of those maps.

The ASCAT Level 2 product including soil moisture data are produced by EUMETSAT in near-real time following the method developed and prototyped for EUMETSAT by the Institute for Photogrammetry and Remote Sensing of the Vienna University of Technology.
The Surface Soil Moisture parameter represents a relative measure of the soil moisture in the top layer of the soil, scaled between 0 and 100%. The ASCAT SSM DUE Permafrost product is the result of an improved SSM retrieval algorithm. The SSM Product is delivered with a weekly temporal resolution and 25km spatial resolution.

For integration into the Permafrost Information System (PEO) ASCAT data are resampled to a Discrete Global Grid (DGG). The soil moisture product also includes a quality flag which contains the number of used measurements. Data are masked for frozen ground conditions also based on MetOp ASCAT. The product is provided as weekly averaged images north of 50°N in GeoTIFF/NetCDF format and EASE Grid projection. The initial freeze/thaw status flag has been implemented initially for the weekly averaged surface soil moisture service. It has been improved in cooperation with the ESA STSE ALANIS-Methane project in order to reflect daily status and also snowmelt conditions.

Regional service for surface soil moisture (1km), open water summer extent (150m) and surface status (1km) has been implemented based on ENVISAT ASAR. The processing has been implemented with the TU Wien SGRT. For application at high latitudes the following adjustments to the algorithm have been implemented: (1) Processing (with NEST) in polar stereographic projection and storage of data. An entirely new gridding system has been set up in order to avoid oversampling and to reduce data storage; (2) A dry reference (representing wilting point) correction algorithm has been implemented in order to account for permanently wet areas; (3) Implementation of a post processing function for the production of weekly composites of surface soil moisture and enhanced masking with respect to signal-to-noise ratio and water fraction. Availability of ASAR Global Mode and Wide Swath data is highly variable in the high latitudes and needs to be accounted for. Auxiliary maps with numbers of measurements have been therefore derived as quality indicator.

**Terrain**

Information on surface topography and on change in surface topography is fundamental over permafrost regions. According to the characteristics and possibilities of Earth-Observation (EO) technologies we distinguish within our project between Digital Elevation Models (DEM), on one side, and surface subsidence, on the other side. Ice-rich layers are usually close to the surface and are the first to be melted by increases in downward heat energy flux due to changes in the surface energy balance. The immediate result is subsidence. The DEM is compiled at pan-arctic scale from available data sources and derived at local scale from optical stereoscopic pairs and SAR interferometry (InSAR).

The Circum-Arctic DEM was compiled with a 3 arcsec spatial resolution. SAR interferometry turned out to be a reliable tool to detect seasonal surface subsidence due to permafrost thaw on many regions thanks to the short repeat interval of 11 days of TerraSAR-X. The time-series of displacement highlighted that subsidence is occurring within a relatively short time period. In our investigations we found coherent annual interferograms only using the low frequency ALOS PALSAR data, but these interferograms were largely contaminated by ionospheric artifacts.
Land cover

Vegetation is commonly incorporated into spatial models predicting permafrost distribution. The land cover and the surface texture are affected by the seasonal thawing dynamics of the uppermost permafrost layer (active layer).

The yearly MODIS land cover product with a spatial resolution of 500 m, the GlobCover land cover map, SYNMAP and MODIS VCF (vegetation continuous field) have been combined into one land cover dataset. The datasets consist of four layers, describing the percentage information for each class, with a spatial resolution of 1 km. By summarizing all four layers each pixel ends up with a value of 100%. The harmonized land cover map was improved by using the Circumpolar Arctic Vegetation Map.

To represent the seasonal vegetation dynamics on pan-arctic scale the LAI product from GlobCarbon with a spatial resolution of 1 km was utilized. Pan-arctic fire information is presented by using different burned area and active fire products (MODIS, GlobCarbon, Terra Norte, ATSR World Fire Atlas).

Subject of the local land cover analysis were three different test sites: Central Yakutsk and Lena river delta (Siberia) as well as North Slope (Alaska). The land cover classification was done by utilizing an object based classification approach. Object characteristics (shape, spectral properties and information within different hierarchical object levels) are used to analyze vegetation class properties and to assign each image object to a thematic class. Land cover was analyzed using RapidEye data.

Service assessment and added value demonstration

Ground measurements in arctic permafrost regions 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 climatic change. A major part of the DUE Permafrost core user group is contributing to GTN-P. Ground data from the Global Terrestrial Network of Permafrost that was used for the evaluation of DUE Permafrost products MODIS LST (land surface temperature) and ASCAT SSF (Surface State Flag for the surface frozen and thawed ground). For both products, temperature was the evaluating parameter.

The accuracy of the ASCAT surface state flag has been assessed with air and near surface temperature measurements at permafrost boreholes in Western Siberia and Alaska. The agreement was in general > 90%, and >80% at grid points in proximity to coasts.

The correlation between air and soil temperature and MODIS LST has been investigated at various sites in Alaska and Canada. The correlation coefficient for the period of almost four years is high ($R^2 = 0.98$). This demonstrates that it is also possible to use time series of daily average air temperatures, which are available for much more sites than data with hourly resolution, for the evaluation of the LST products.
The added value of satellite products for permafrost monitoring has been discussed in the framework of the final user workshop. An abstract volume has been compiled and made available online. A range of applications of the DUE service have been proposed and tested e.g.:

- pan-arctic products application for climate and permafrost modeling,
- regional product service for global and regional datasets (from other sources such as altimeter, passive microwave) evaluation,
- application in ecology such as soil moisture data for calibration of tree-ring delta^{13}C and
- geomorphological applications such as pingo, thermokarst lake change, coastal erosion and weathering studies.

The use of DUE Permafrost products has been additionally discussed within the framework of ongoing FP7 Projects with high latitude focus: MONARCH-A, PAGE21 and EuRuCas.

**Data portal**

A dedicated server has been setup for data dissemination. GeoServer extensions which have specifically been developed in this project are the (1) support of temporal rasters, (2) pole centered coordinate systems and (3) user defined map styling. The implemented system facilitates data catalog query and download. It is interoperable with many GIS tools since all data are available through services based on international standards (OGC, ISO).

All datasets including product guides are available through the website. Users need to register and obtain a login first. Personalized logins are required for features such as the interactive style editor and storage of further settings for future sessions.

Data are accessed via drop-down menus. Optionally, a date range can be selected to narrow the search. Search results can be manually edited (select and deselect of single files). All selected files are be compressed into a zip-file. The size is estimated before and displayed as part of the search results. Relevant product guides are automatically included into the zip-file.

The full dataset will be additionally made available via the information system PANGAEA, an Open Access library aimed at archiving, publishing and distributing georeferenced data from earth system research. The system guarantees long-term availability of its content through a commitment of the operating institutions.

The DUE Permafrost dataset DOI is [doi:10.1594/PANGAEA.780111](http://doi.org/10.1594/PANGAEA.780111)

**Dissemination**

A project website has been set up at the beginning of phase 1 and will be maintained for at least two more years after project termination. Beside the data dissemination the website has a publicly accessible part. The web site provides the user community with updated information on the project including announcements, workshop material, publication activities and project status. The DUE permafrost project has been represented at relevant scientific conferences and international meetings (>30 presentations at >20 events). Three project newsletters have been issued. A forth newsletter will be send out at the end of the project with a report on the final workshop and description of the service.

**Future Observation Strategy Recommendations**

The present service relies only partly on operational services. Only acquisitions from Metop ASCAT (soil moisture and surface status) are ensured in the future. Land surface temperature monitoring is based on MODIS and is complemented by ENVISAT AATSR. Regional services for land surface hydrology rely on ENVISAT ASAR. Mid-term continuation is thus limited to ENVISAT lifetime. TerraSAR–X dataset could be potentially used for continuation of subsidence records although not on an operational basis and for selected sites only.

Regional to pan-arctic services can be continued on the long term based on the GMES Sentinel program and ESA CCI initiatives. A potential CCI Permafrost needs to focus on active layer depth and permafrost extent in agreement with GCOS requirements. This requires accurate information on terrain (DEM and vertical changes), land surface temperature, snow depth, snow water equivalent, soil moisture and land cover. These datasets can then serve as input for permafrost modeling.

The CoReH2O Earth Explorer candidate satellite mission will provide SWE, snow extent and snow depth at medium resolution (200-500 m) required by the permafrost community for global to regional scale applications.

**Sentinels**

The availability of data to be acquired by the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3 satellite (to be launched in 2013) could alleviate the current problem encountered with AATSR (i.e. frequency of acquisitions). Sentinel-3, will be the source for the continuation of a sustainable monitoring of the land surface (land cover, vegetation activity and fire affected areas).

Sentinel-1 could provide the necessary data coverage for soil moisture, freeze/thaw and open water dynamics. Similar results for seasonal subsidence mapping as with TerraSAR-X are expected in future using the Sentinel-1 SAR sensor which has a similar repeat interval (12 days).

**CCI activities**

Various sources of global coarse resolution land cover information are available and will be produced in the future. For upcoming investigation it is suggested to integrate state of the art global land cover information (e.g. CCI Land Cover Product).

Surface soil moisture and relevant applications are currently within focus of the ESA Climate Change Initiative Soil Moisture. Services should be linked to future high latitude permafrost monitoring services.

**High resolution optical**

Cloud coverage and a very short vegetation period very much limited the acquisition window for multispectral data acquisitions within the DUE Permafrost. It is therefore suggested to use sensor concepts that utilize a constellation approach (with 5-7 platforms) with spatial resolution of 1-5 m and the potential for daily revisits.
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## Acronyms

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<td>Advanced Along-Track Scanning Radiometer</td>
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<td>ALOS</td>
<td>Advanced Land Observing Satellite</td>
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<td>Advanced Microwave Scanning Radiometer - Earth Observing System</td>
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<td>LCCS</td>
<td>Land Cover Classification System</td>
</tr>
<tr>
<td>LCPC</td>
<td>Center Point Correction Procedure</td>
</tr>
<tr>
<td>LST</td>
<td>Land Surface Temperature</td>
</tr>
<tr>
<td>MERIS</td>
<td>Medium Resolution Imaging Spectrometer</td>
</tr>
<tr>
<td>MLCCA</td>
<td>MODIS Land Cover Classification Algorithm</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MOD</td>
<td>MODIS on Terra</td>
</tr>
<tr>
<td>MYD</td>
<td>MODIS on Aqua</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
</tr>
<tr>
<td>NEST</td>
<td>Next ESA SAR Toolbox</td>
</tr>
<tr>
<td>NSF</td>
<td>National Science Foundation</td>
</tr>
<tr>
<td>NSIDC</td>
<td>National Snow and Ice Data Center</td>
</tr>
<tr>
<td>NSR</td>
<td>Noise Signal Ratio</td>
</tr>
<tr>
<td>PALSAR</td>
<td>Phased Array type L-band Synthetic Aperture Radar</td>
</tr>
<tr>
<td>PEO</td>
<td>Permafrost Information System - Earth Observation</td>
</tr>
<tr>
<td>PRISM</td>
<td>Panchromatic Remote-sensing Instrument for Stereo Mapping</td>
</tr>
<tr>
<td>RE</td>
<td>RapidEye</td>
</tr>
<tr>
<td>RESA</td>
<td>RapidEye Science Achieve</td>
</tr>
<tr>
<td>RPC</td>
<td>Rapid Positioning Capability</td>
</tr>
<tr>
<td>SAON</td>
<td>Sustaining Arctic Observing Networks</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic aperture radar</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>Scanning Imaging Absorption Spectrometer for Atmospheric Cartography</td>
</tr>
<tr>
<td>SDS</td>
<td>Scientific Datasets</td>
</tr>
<tr>
<td>SE</td>
<td>Snow Extent</td>
</tr>
<tr>
<td>SMOS</td>
<td>Soil moisture and Ocean Salinity Mission</td>
</tr>
<tr>
<td>SPARC</td>
<td>Sensitivity of Permafrost in the ARCTic</td>
</tr>
<tr>
<td>SPOT</td>
<td>Satellite Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>SSM</td>
<td>Surface Soil Moisture</td>
</tr>
<tr>
<td>SSMI</td>
<td>Special Sensor Microwave Imager</td>
</tr>
<tr>
<td>SWE</td>
<td>Snow Water Equivalent</td>
</tr>
<tr>
<td>TSP</td>
<td>Thermal State of Permafrost</td>
</tr>
<tr>
<td>UAF</td>
<td>University of Fairbanks Alaska (US)</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>UW</td>
<td>University of Waterloo (CA)</td>
</tr>
<tr>
<td>VCF</td>
<td>Vegetation continuous field</td>
</tr>
<tr>
<td>WB</td>
<td>Water Bodies</td>
</tr>
<tr>
<td>WDC</td>
<td>World Data Centre</td>
</tr>
<tr>
<td>WFA</td>
<td>World Fire Atlas</td>
</tr>
<tr>
<td>WFM-DOAS</td>
<td>Weighting Function Modified Differential Optical Absorption Spectroscopy</td>
</tr>
<tr>
<td>WS</td>
<td>Wide Swath</td>
</tr>
</tbody>
</table>
Applicable documents

[AD-1] EOEP-DUEP-EOPG-SW-08-0009 Statement of Work – DUE permafrost
[AD-3] Requirements baseline (RB). Permafrost Team 2009
[AD-6] Prototype Validation and Assessment Report (PVAR). Permafrost Team 2010
[AD-14] GCOS Observation Requirements in WMO/CEOS Database (incl ECVs) July 2007
1 Project overview

1.1 Background and objectives

The PERMAFROST project is funded by the European Space Agency (ESA) Data User Element (DUE) program, which is a component of the Earth Observation Envelope Program (EOEP). Permafrost is an Essential Climate Variable (ECV). The objective of this project was to establish a monitoring system based on satellite data.

The main purpose of the ESA DUE Permafrost project is to define, demonstrate and validate, permafrost monitoring information service from local to large scale, mainly towards climate change studies and addressing the panboreal/arctic zone. The service is supposed to support the GCOS implementation plan with systematic satellite-based Earth Observations of global permafrost extent, change and related products. It should further support permafrost monitoring activities of national and intergovernmental bodies and scientific groups involved in climate change research.

The goal of the Permafrost project was to demonstrate Earth Observation (EO) integrated services in the field of permafrost monitoring of the boreal zone with active participation of user organisations, mainly from the scientific world. The project acts as a platform to users and service providers in order to harmonise information needs and develop a set of key tools to address them.

The Permafrost project objectives are to [AD-1]:

- Define EO based services for permafrost monitoring based on user requirements
- Integrate the latest EO technology with state of the art ground-based measurements
- Demonstrate and validate the services with the user organisations
- Develop mid- to long-term scenarios for boreal and arctic permafrost monitoring
- Contribute to new scientific results in the domain of climate change detection, climate modelling and hydrological modelling.

The project had two phases. Phase 1 (June 2009 – May 2010) comprised all tasks for the development of the service design and concluded with the first user workshop. Implementation and validation were covered in phase 2 (June 2010 – March 2012) after successful completion of phase 1.

1.2 The project team

The consortium is led by IPF of the Vienna University of Technology (TU Wien) and is supported by four partners (University of Waterloo, Jena University, Alfred Wegener Institute for Polar and Marine Research, and Gamma Remote Sensing).

- IPF at TU Wien is responsible for coordination of the project, for Data portal/WebGIS, and is involved in integrating soil moisture, thaw/refreeze, and regional scale water bodies into the information system.
The Department of Geography and Environmental Management of the University of Waterloo, Canada is involved in integrating land surface temperature into the processing system.

The Department of Remote Sensing of the Friedrich Schiller University Jena, Germany is involved in integration of land cover and disturbances, local scale water bodies, and methane.

The Alfred Wegener Institute of Polar and Marine Research in Potsdam, Germany, is responsible for user coordination and involved in validation, especially for land surface temperature.

Gamma Remote Sensing (Switzerland) has been responsible for setting up the processing system and integrating DEMs (from mapping agencies and SAR data) and subsidence analyses.

1.3 Earth observation for permafrost monitoring

Permafrost is a subsurface phenomenon and cannot be directly observed with satellite data. Yet, monitoring can be done based on indicators and via permafrost models. Indicators are especially thermokarst lake dynamics and surface elevation changes. Those phenomena need to be observed on a local scale. Regional to circumpolar monitoring requires the use of permafrost models. Relevant satellite-observable parameters are land surface temperature (LST), snow extent, snow water equivalent (SWE), vegetation, and soil moisture. Existing services have been integrated into the Permafrost processing system – Earth Observation (PEO) and adapted to the needs of permafrost modelling. All satellite datasets are made available via a dataportal (incl. WebGIS) which will tie into the permafrost information system of the International Permafrost Association (IPA).

The implemented service follows a multi-scale concept (Figure 1):

- Pan-boreal/arctic (> 50° N): 25 km. It is based entirely on existing remote sensing products. Product improvement through sensor fusion and adaptation to high latitude requirements
- Regional: 150m - 1 km. Regional service adjusted existing products and new products based on existing algorithms
- Local: as available. Local service in cooperation with users and for coarse level products assessment

![Figure 1: Service scales and potential field of application](image-url)
1.4 Associated users

The potential user community comprises institutions, organizations and scientists from a wide range of subjects and interests. Climate modelers as well as field investigators have expressed an interest to be an associated user with the project before its start:

- International Permafrost Association
- Alfred Wegener Institute of Polar and Marine Research, Potsdam, Germany
- International Arctic Research Center, University of Alaska, Fairbanks
- Hokkaido University, Graduate School of Environmental Science
- Geophysical Institute: Permafrost Laboratory, University of Alaska, Fairbanks
- Faculty of Geography, Lomonosov Moscow State University
- Melnikov Permafrost Institute, Siberian Branch Academy of Sciences
- Biogeochemical Model Data Integration Group, Max Planck Institute for Biogeochemistry, Jena, Germany
- State Hydrological Institute St. Petersburg, Russia
- Geological Survey of Canada, Natural Resources Canada, Earth Sciences Sector

User representatives have been invited to participate in project workshops to present the products and validation, discuss the results and collect feedback in annual intervals. The workshops have been open to a wider public of permafrost and climate change community. Training sessions on the use of the products and system have been organized in relation to the workshops. The presentations, contributions and outcomes of the workshops have been made available publicly on the Permafrost website. Funding has been provided from the project budget to cover the travel and subsistence expenses of involved users to attend at least one of these workshops.

As a concept within the ESA DUE programs, user workshops are an important tool for the interaction between the scientific user’s community and the remote sensing experts. The first DUE Permafrost User Workshop was held in May 2010 in Vienna as an official side-event of the EGU. The observation strategy for all products and regions was presented by the project team and reviewed with the participants.

The second DUE Permafrost User Workshop has been hosted and financially supported by the International Arctic Research Centre, IARC, University of Alaska Fairbanks (US) and took place from 2nd to 4th March 2011. More than 40 scientists from scientific and governmental institutions participated. The workshop offered assessments of the DUE Permafrost products via tutorials (using the freely available software packages ESA BEAM-VISAT and Quantum-GIS). During in-depth sessions the participants discussed remote sensing products in context to modelling and permafrost monitoring.

The third and final Permafrost User Workshop took place at AWI Potsdam (DE) from the 15th to 17th February 2012 together with the final ESA ALANIS User Workshop. The Workshop focused on discussion sessions on remote sensing products as drivers and boundary parameters for permafrost and climate modelling and remote-sensing applications for permafrost monitoring. Participants presented their applications in talks and on posters.
1.5 Dissemination

A project website has been set up at the beginning of phase 1 and will be maintained for at least two more years after project termination. Beside the data dissemination the website has a publicly accessible part. The web site provides the user community with updated information on the project including workshop announcements, publication activities and project status.

The DUE permafrost project has been represented at relevant scientific conferences and international meetings (>30 presentations at >20 events) including EGU, AGU, IGARSS, European Conference on Permafrost and the ESA Living Planet Symposium.

Three project newsletters have been issued:

1. Project overview and announcement of first user workshop
2. First user workshop summary, Phase II Kick-off, second user workshop announcement
3. Second user workshop report, test data description, announcement of final user workshop

A forth newsletter will be send out at the end of the project with a report on the final workshop and description of the service.


The following project related papers have been published/are in press in peer reviewed journals/proceedings:

- Annett Bartsch, Thomas Melzer, Kirsten Elger and Birgit Heim: Soil moisture from Metop ASCAT data at high latitudes. Proceedings of the Tenth International Conference on Permafrost, in press.
1.6 Project time line

ESA held an expert consultation workshop at the Alfred Wegener Institute of Polar and Marine Research, Potsdam, Germany in February 2008 in order to

- define permafrost indicators which are observable from space,
- describe opportunities for trend analyses from data archives (Earth observation and in situ),
- generate a strategy for present Earth observation capabilities, and
- develop recommendations for a future permafrost monitoring programme

In the following potential users have been asked for letters of commitment by summer 2008 and the call with the statement of work [AD-1] has been released in the following autumn. The project itself started in June 2009 and was completed March 2012. The first phase lasted 1 year. It comprised:

- User requirements engineering
- Definition of a monitoring strategy
- The service design engineering and system development

The service has been demonstrated and validated within the second phase. Already at the end of phase 1, a sample dataset has been made available to the user community. The first version of the full dataset has been released in the beginning of 2011. One year later, all updates and improvements have been completed. All data are available via a data portal which will be maintained for two more years after the completion of the project.
1.7 Observation strategy framework

The international permafrost research community requires easy access to end-products which provide information on the current status of permafrost and add value to existing networks. This shall be achieved in synergy with other current international activities such as the Global Cryosphere Watch and the Sustained Arctic Observing Network (SAON). The joint activities shall support regular updates of permafrost extent (e.g. monthly). This can be supported by the permafrost modelling community and through the IPA [AD-13] based on a long-term sustained management strategy.

The strategy which is followed within the DUE Permafrost project needs to consider the definition of suitable end-products and aim to fulfill expectations in terms of user-friendliness of the end-user interface. Data interchange ability with respect to existing data platforms such as the Arctic Portal (Inter-map) and the NSIDC archiving system is a basic requirement.

The ESA SoW [AD-1] which defines the framework for the information system setup throughout the project period foresees the development of a web-portal as end-user interface. Although its maintenance is currently limited until end of 2013 it may serve as a tool which has the capability for continuation of the service by integration of additional new or improved satellite data products in the future as well as continuous and new permafrost modelling results.

The service case scenario according to the SoW [AD-1] considers multi-scale monitoring of for permafrost relevant parameters based on mostly existing remotely sensed datasets and methods. The following parameters have been identified as sufficiently mature (although not ideal) to be included into the Permafrost Information System – Earth Observation (PEO): Land surface temperature, land cover (incl. vegetation and water bodies), snow (snow extent and snow water equivalent), soil moisture, elevation and methane. All existing datasets need to be first adapted to the needs of high latitude monitoring and assessed at local, regional and pan-arctic scale. Especially the regional and pan products need to be provided on a unified spatial and temporal grid. Regular updating of the datasets is envisaged on regional to pan-boreal scale where possible. The observation strategy [AD-9] was developed based on the requirements defined by the user core group [AD-2, AD-13], the ground data availability [AD-15] and the capabilities of remotely sensed datasets [AD-5].

Satellite datasets which are available for integration into PEO at regular intervals allowing for annual to weekly updates on regional to pan-boreal scale are land surface temperature, snow, soil moisture (incl. freeze/thaw), land cover, methane and lake dynamics [AD-10]. Elevation and all local products will be static components of the PEO. All PEO parameters except for methane and local components are used as either model forcing or validation [AD-5]. The web-portal may also provide tools for visualization of temporal variability of single parameters on the PEO.

A challenge for the setup of a long-term monitoring system as suggested by the IPA [AD-13] is the provision of regular updates of permafrost extents from the permafrost modelling community based on the PEO datasets. Additionally these outputs need to be integrated into existing international monitoring programs in the future.

Permafrost models such as GIPL also allow for active layer depth estimation. This might be considered as an additional monitoring parameter of a satellite data based monitoring system.

The currently feasible update intervals range between annual and weekly on regional to pan-boreal scale. The spatial scale of pan-boreal services is limited to 25km. Precise monitoring does, however, require daily time steps at minimum 1km. This agrees with the GCOS observation requirements for permafrost itself but not the ECVs which are model input parameters [AD-14, AD-3].


2 User requirements review

2.1 Global Climate Observing System GCOS - Requirements

Permafrost has been addressed as one of the Essential Climate Variables (ECV’s) of the terrestrial domain in the GCOS implementation plan 2004 for the global observing system for climate in support of the UNFCCC. Its global implementation has thus been identified as feasible within the 10 year baseline and as having a high impact on UNFCCC requirements. Associated parameters include permafrost extent, temperature profiles and active layer thickness. Although that key actions focus on extension of the Global Terrestrial Network of Permafrost, the demand for filling gaps requires the use of satellite data.

Within the implementation plan, land surface temperature and soil moisture have been identified as relevant satellite products (AD-14, page 87). A complete lack of operational products has been originally identified for those variables. Soil moisture has been identified as an emerging Essential Climate Variable 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). 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 (ref, page 97).

Within the progress report which covers the first 5 years (August 2009, AD-14) 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 and snow depth may provide input for the simulation of the soil thermal regime. Good progress has been made regarding the associated product ‘soil moisture’ within Action T37. ‘The most significant operational development is the availability of a global soil moisture product derived from ASCAT data at EUMETSAT.’ (AD-14, page 81).

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

2.2 User Requirements in DUE Permafrost

In the ITT, the Preliminary User requirements that do not state that products shall have the highest spatial resolution available can be attributed to modelling applications, similar results for modelling requirements have been collected in the RBD. Users involved in permafrost monitoring are in fact interested in the highest possible spatial and temporal resolution of physical parameters such as LST, SSM, freeze/thaw and vegetation. The high spatial and temporal resolution requirements for permafrost monitoring -as stated in the ITT- conflict with the current operational space missions limitations.

As part of the user requirement engineering in phase I, a comprehensive user survey has been carried out [AD-3]. It included not only the collection of
requirements but also ground data availability. The location and extent of service case areas has been defined based on this user feedback.

High spatial resolution of geomorphologic information has been explicitly claimed by a wide range of Users and by the International Permafrost Association IPA as a must for Permafrost Observations. Remotely sensed data shall provide information on relief, and vertical and horizontal change detection where the disturbances are mainly due to subsidence and erosion processes. The rate of subsidence phenomena in permafrost regions is on the order of centimetres per year (or less) and can exhibit a great spatial variability and therefore high vertical and horizontal accuracy and resolution is required.

Users informed that numerous types of permafrost landscapes are covered by small to medium-sized water bodies: ponds and lakes. The area percentage of water bodies in the coarser-scale remote sensing pixel needs to be known to understand the physical and bio-physical properties of products.

High-spatial resolution data is needed for the upscaling and evaluation/validation processes.

Researchers from modelling groups provided feedback to a survey based on questionnaires in 2009 [AD-3]. The models

- **Geophysical Institute Permafrost Lab Model GIPL** (Fairbanks, USA)
- **Lund-Potsdam-Jena Dynamic Global Vegetation Model LPJ** (Jena, Germany)
- **Minimal Advanced Treatments of Surface Interaction and Runoff Model MATSIRO** (Fairbanks, USA)

require near-surface air temperature that is the forcing parameter in all models. Partly, a very high temporal resolution is needed. E.g., to calculate the land only case, MATSIRO needs hourly data. 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.

The DUE Permafrost preliminary service case scenario using GlobCover for upgrading of CAVM classes has been accepted as adequate with its wide range of land cover classes. e.g., required Land Cover for MATSIRO are the Revised Simple Biosphere SiB2 Model classes (ice, mixed coniferous & deciduous forest, coniferous forest, high-latitude deciduous forest, wooded C4 grassland, shrub & bare ground, tundra, cultivated, bare ground). The LPJ uses the International Geosphere Biosphere Program IGBP LC classes that provide seasonal land cover and phenological information (onset, peak, and seasonal duration of greenness).

The users have been informed about the technical possibilities of current space missions for the physical parameters LST and SSM, and freeze/thaw, i.e. about the spatial resolution of 1 km to 25 km per pixel. The users proposed temporal averages (weekly, monthly) and tested the coarse spatial scales for their applications. Applications will be presented on the 3rd DUE Permafrost User Workshop at AWI Potsdam (DE) in early 2012.
**Table 1: Model requirements summary**

<table>
<thead>
<tr>
<th>spatial coverage</th>
<th>largest possible coverage: <strong>pan-arctic</strong></th>
</tr>
</thead>
</table>
| classes of required spatial resolution | < 1 km information for upscaling  
10 km  
25 km  
0.1° |
| required driving forces | required, highest priority:  
**near-surface air temperature**  
seasonal range of air temperature variations  
(amplitude)  
monthly near-surface air temperature  
mean annual air temperature |
| | required for initialisation and validation:  
**soil moisture**  
moisture content at different depths  
freeze/thaw-degree days  
solid-liquid ratio |
| | and  
**snow water equivalent, snow coverage** |
| classes of boundary parameters | [fixed] **land cover**:  
vegetation physiognomy / bare soils / water body/  
sand / peatland / moss  
area percentage of water body  
area percentage of vegetation physiognomy  
area percentage of bare soil |
| | [fixed] **elevation and topography** (variance and aspect) |
| | [variable] **albedo** (i.e. no snow, no leaf condition) |
| | [variable, e.g. monthly] **leaf area index LAI** or another volumetric index of total vegetation or an index of height of vegetation cover |
3 Service cases and products overview

3.1 Pan-boreal/arctic

Pan-boreal arctic products cover all permafrost affected areas north of 55°N.

Table 2: Pan boreal/arctic products overview

<table>
<thead>
<tr>
<th>Product</th>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
<th>Years/comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST MODIS</td>
<td>weekly</td>
<td>25 km</td>
<td>2007 – 2009</td>
</tr>
<tr>
<td></td>
<td>monthly</td>
<td>25 km</td>
<td>2000 – 2010</td>
</tr>
<tr>
<td>LST AATSR</td>
<td>weekly</td>
<td>25 km</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>monthly</td>
<td>25 km</td>
<td>2005 – 2009</td>
</tr>
<tr>
<td>ASCAT SSM with FT masking</td>
<td>weekly</td>
<td>25 km</td>
<td>2007 – Sept. 2010</td>
</tr>
<tr>
<td>DEM</td>
<td>once</td>
<td>3 arcsec</td>
<td></td>
</tr>
<tr>
<td>Harmonized land cover</td>
<td>once</td>
<td>1 km</td>
<td></td>
</tr>
<tr>
<td>Combined burned areas</td>
<td>monthly</td>
<td>1 km</td>
<td>1996 – 2009</td>
</tr>
<tr>
<td>External dataset:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GlobCarbon LAI</td>
<td>monthly</td>
<td>1 km</td>
<td>1998 – 2007</td>
</tr>
</tbody>
</table>

3.2 Regional and local

Five regional service cases have been identified based on ground data availability: Alaska North Slope/Borehole transect, Mackenzie delta and borehole transect, Ob-Estuary including Yamal-peninsula, Laptev sea regions including East Taymir, Lena-Delta and Cherskii and central Yakutia (Table 4 -
The total area covered by the five primary sites is 1.5 Mio km². A product overview is given in Table 3.

**Table 3:** Product overview and regional and local scale, for specification of service case areas #1 - #6 please see tables below.

<table>
<thead>
<tr>
<th>Product</th>
<th>Temp. resol.</th>
<th>Spatial resol.</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST MODIS</td>
<td>Weekly/monthly</td>
<td>1 km</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2007 – Sept. 2010</td>
</tr>
<tr>
<td>ASAR SSM</td>
<td>Weekly</td>
<td>1 km</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2005 – 2010</td>
</tr>
<tr>
<td>ASAR FT</td>
<td>Annually</td>
<td>1 km</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2005 – 2010</td>
</tr>
<tr>
<td>ASAR WB</td>
<td>Annually</td>
<td>150 m</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2007 – 2010</td>
</tr>
<tr>
<td>Local WB</td>
<td>Once</td>
<td>5 m</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Local Land-cover</td>
<td>Once</td>
<td>5 m</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Local DEM</td>
<td>Once</td>
<td>10 m</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>2007 – 2010</td>
</tr>
<tr>
<td>Local Subsidence</td>
<td>varying</td>
<td>20 m</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>2007 - 2011</td>
</tr>
</tbody>
</table>

**Table 4:** Service case region 1: Alaska North Slope & borehole transect

<table>
<thead>
<tr>
<th>Regional Service Case Area #1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Size and location of AOI</strong></td>
</tr>
<tr>
<td>151 - 145W, 61.5-71N</td>
</tr>
<tr>
<td><strong>Brief description</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>User organization</strong></td>
</tr>
<tr>
<td><strong>Associated users</strong></td>
</tr>
<tr>
<td><strong>Available data</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Other ongoing research</strong></td>
</tr>
</tbody>
</table>
Figure 2: Northwest American ground data availability (SCA #1 and #2)), boundaries of regional service case and locations of currently included sites in satellite data proposals for local scale analyses (source of permafrost extent: NSIDC)

Table 5: Regional Service Case Area 2 – Mackenzie

<table>
<thead>
<tr>
<th>Name</th>
<th>Mackenzie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Transect</td>
</tr>
<tr>
<td>Size and location of AOI</td>
<td>300,000 km²</td>
</tr>
<tr>
<td></td>
<td>124W, 60N; 137.5W, 70; W132, 70; 120W, 60; 124W, 60; with extension to 142W in the north</td>
</tr>
<tr>
<td>Brief description</td>
<td>- Mackenzie area has experienced the greatest increase in mean annual air temperature in Canada in the last century. - Large bodies of ground ice are common in the Mackenzie Delta, including ice wedges and pingos - transect covers continuous to sporadic permafrost</td>
</tr>
<tr>
<td>User organization</td>
<td>GTN-P GSC borehole data</td>
</tr>
<tr>
<td></td>
<td>GTN-P CALM</td>
</tr>
<tr>
<td></td>
<td>LST, SSM, Subsidence, lakes, methane</td>
</tr>
<tr>
<td>Associated users</td>
<td>ACCONET</td>
</tr>
<tr>
<td>Available data</td>
<td>Vegetation, LST, SSM, Subsidence, lakes</td>
</tr>
<tr>
<td>Other ongoing research</td>
<td>Over the last 25-30 years, the Geological Survey of Canada (GSC) has focused an important component of its permafrost research programme on the Mackenzie River Valley and Delta in response to knowledge needs required for hydrocarbon exploration, development and transportation, and more recently on the impact of climate change on permafrost.</td>
</tr>
</tbody>
</table>
**Table 6: Regional Service Case Area 3 – Laptev Sea Coast**

<table>
<thead>
<tr>
<th>Regional Service Case Area #3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Size and location of AOI</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Brief description</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>User organization</strong></td>
</tr>
<tr>
<td><strong>Associated users</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Available data</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Other ongoing</strong></td>
</tr>
</tbody>
</table>

**Figure 3:** Siberian ground data availability, boundaries of regional service cases (#3 and 4) and locations of currently included sites in satellite data proposals for local scale analyses (source of permafrost extent: NSIDC)
### Table 7: Service case region 4: Central Yakutia

<table>
<thead>
<tr>
<th><strong>Regional Service Case Area #4</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Size and location of AOI</strong></td>
</tr>
<tr>
<td>128-133 E, 60-63N</td>
</tr>
<tr>
<td><strong>Brief description</strong></td>
</tr>
<tr>
<td>- significant lake surface changes</td>
</tr>
<tr>
<td>- a large part of the Russian-Japanese scientific permafrost programs focus on the Yaktusk region</td>
</tr>
<tr>
<td>- continuous permafrost</td>
</tr>
<tr>
<td><strong>User organization</strong></td>
</tr>
<tr>
<td><strong>Available data</strong></td>
</tr>
</tbody>
</table>

### Table 8: Service case region 5: Ob - Estuary

<table>
<thead>
<tr>
<th><strong>Regional Service Case Area #5</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Size and location of AOI</strong></td>
</tr>
<tr>
<td>66-79E, 63-73.5N, includes Yamal Peninsula</td>
</tr>
<tr>
<td><strong>Brief description</strong></td>
</tr>
<tr>
<td>- dense borehole network and cryospheric long-term monitoring programs</td>
</tr>
<tr>
<td>- Clusters of economic development and infrastructure (gas fields, railway tracks)</td>
</tr>
<tr>
<td>- SCA covers continuous to sporadic permafrost</td>
</tr>
<tr>
<td><strong>User organization</strong></td>
</tr>
<tr>
<td><strong>Associated users</strong></td>
</tr>
<tr>
<td><strong>Available data</strong></td>
</tr>
<tr>
<td>Vegetation, LST, lakes</td>
</tr>
<tr>
<td><strong>Other ongoing research</strong></td>
</tr>
<tr>
<td>- Islands in the Ob Estuary are a Nature Reserve and a RAMSAR site since 1994.</td>
</tr>
<tr>
<td>- MIREKÖ long-term permafrost observatory (20-25 years)</td>
</tr>
<tr>
<td>- UCLA lake change studies</td>
</tr>
</tbody>
</table>
Figure 4: Westsiberian ground data availability, boundaries of regional service case (9 5) and locations of currently included sites in satellite data proposals for local scale analyses (source of permafrost extent: NSIDC)

Table 9: Secondary Local Service Case Area Polar Bear Pass, Canada

<table>
<thead>
<tr>
<th>Name</th>
<th>Polar Bear Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>High Arctic Island</td>
</tr>
<tr>
<td>Size and location of AOI</td>
<td>Bathurst Island, Nunavut, Canada (75°40’N, 98°30’W), 20 x 5 km²</td>
</tr>
<tr>
<td>Brief description</td>
<td>The second largest wetland in the Canadian Arctic Archipelago. The wetland is bordered in the North and South by debris-covered hills up to 300 m (arctic desert).</td>
</tr>
<tr>
<td>User organization</td>
<td>AWI</td>
</tr>
<tr>
<td>Associated users</td>
<td>York University, Toronto, Ontario, Canada</td>
</tr>
<tr>
<td>Research</td>
<td>e.g. local scale remote sensing, energy and water fluxes, hydrological modelling</td>
</tr>
</tbody>
</table>
4 EO Products

This chapter summarizes all algorithms, validation and the product (service) description.

4.1 Land surface temperature

The land surface temperature (LST) products and services identified by users in the requirements baseline document for the regional (1 km resolution) and pan-Arctic (25 km resolution) scales include weekly and monthly averages from which annual averages can also be calculated. Details regarding the LST processing subsystem (algorithms and processing chain) developed to derive these products, as well as the evaluation of the pan-Arctic and regional products are provided below.

4.1.1 LST processing subsystem and products

The LST processing subsystem integrates the LST level 2 products (L2) from MODIS and AATSR distributed by NASA and ESA, respectively. Post-processing functions supply UW level-3 (UWL3) weekly and monthly LST products for regional and pan-Arctic scales.

MOD11_L2 and MYD11_L2 LST (Version 5 from NASA Terra and Aqua satellites) and ATS_NR_2P (from ESA Envisat satellite) products at 1 km resolution are used as input data to generate pan-Arctic and regional products. The merging of MODIS and AATSR L2 into a new blended level 3 product was also investigated, but it was decided for reasons explained later to keep the MODIS/AATSR products separate at this stage.

The main components of the processing subsystem

- Interpolation to regular grid

L2 of both sensors AATSR and MODIS are characterized by an irregular distribution of observations based on the satellite orbits. The Northern Hemisphere EASE-Grid Lambert Equal Area Azimuthal projection with a sphere datum (with a radius of 6371.228 km) was selected as the standard projection for the operational pan-Arctic and regional products. The EASE-Grid projection was chosen since this is the system adopted by the GlobSnow project and for most snow and ice products distributed by NSIDC. L2 were projected using the EASE-Grid coordinate system and interpolated to an EASE-Grid with 1 km spacing using a triangulation algorithm. The interpolated L2 is stored temporary in the computer memory and used as input for spatiotemporal aggregation for regional and Pan-Arctic LST products.

Local time of L2 observations is calculated using UTC acquisition time and longitude. UTC is extracted from ADS information of L2 AATSR data and from the file name of L2 MODIS (Terra and Aqua), yielding a temporal accuracy of ± 15 minutes, which is found to be sufficient for weekly and monthly LST products.
Spatial averaging

The UWL3 pan-Arctic product, with a spatial resolution of 25 km, is produced by spatial averaging of interpolated L2. Valid 25 km pixels must have a minimum of at least 5% of the total 1 km observations falling within the 25 km pixel available (i.e. 5% x 625 = minimum of 31 observations). Spatial LST average is calculated using an arithmetic mean of all L2 LST observations within 25 km pixels.

In the case of AATSR data, an error was identified in a few original (L2) files. The erroneous L2 files contained a strip of similar LST values. Therefore, images were filtered and, if an image has over 5% of pixels has identical LST, it was flagged corrupted to avoid using it in subsequent calculations.

Temporal averaging

Temporal aggregation is applied to both regional and Pan-Arctic data to produce weekly and monthly LST averages.

Weekly Average Products

The weekly LSTs are calculated from L2 images acquired over all satellite overpasses within a seven-day period. It is available for each day based on a 7-day sliding time window giving most recent observations highest priority following the GlobSnow convention.

Monthly Average Products

The monthly LSTs are calculated from L2 images acquired over all satellite overpasses within a calendar month period.

Regional products (1 km) and Pan-Arctic products (25 km) are aggregated into two bins; a day-time bin (from 6 a.m. to 6 p.m. local time) and a night-time bin (6 p.m. to 6 a.m. of the next day) within the aggregation period (week or month). The processing steps and resulting (LST and supplementary) files are described in Figure 5. The definition of day and night does not take into account the notion of polar darkness and does not consider the seasonal changes of day length. It was defined to force final products to have an equal number of observations around the day. A mid-range average is calculated by taking the day-time and night-time average to avoid daily diurnal fluctuations during the week or month of interest. Day, night and mid-range LST are stored in separate files. The description of these files is as follow:
Figure 5: Flowchart of the processing steps and files generated

**LST files of the UW level 3 (UWL3) for both regional and Pan-Arctic products**

Three UWL3 LST files are generated:

001 – Weekly or monthly aggregated average LST based on equal weight of average day-time (003) and night-time (005) LST values.

003- Average day-time weekly or monthly LST based on all cloud free observations falling during 6 a.m. to 6 p.m. local time.

005- Average night-time weekly or monthly LST based on all cloud free observations falling into each pixel cell during 6 p.m. to 6 a.m. local time.

**Supplementary information data files**

002 - Number of interpolated L2 cloud free LST observations falling into each pixel for the aggregation (weekly or monthly) period. Associated with LST file 001.

004 - Number of interpolated L2 cloud free LST observations during day-time (6 a.m. to 6 p.m. local time) falling into each pixel. Associated with LST file 003.
006- Number of LST cloud free observations during night-time (6 p.m. to 6 a.m. local time) falling into each pixel. Associated with LST file 005.

**Nomenclature Name**

OOO="organisation", **UW**: University of Waterloo.

SSSSS="sensor and mode", **MOD, ATS, BLE** the three first letters correspond to: MOD for MODIS, ATS for AATSR and BLE for blend (derived from an average of both MODIS and AATSR with equal weights to both sensors), **AV** is added for average. Note that BLE is not currently produced.

PPP="product", **LST**: Land Surface Temperature.

VVV="product/software version" **1.1.4**: Version of the code written in IDL language used for calculations.

YYYYMMDD_HHMMSS="start date and time" (for period for which the data represents), i.e.: 20070409_000000.

YYYYMMDD_HHMMSS="end date and time" (same as above if data represents snapshot), i.e.: 20070415_235959.

RRR="region of interest", e.g. 001 (we have defined indicators for the regional sites)

<100> for pan-Arctic

<001> for North Slope of Alaska

<002> for Mackenzie River Basin

<003> for Laptev Sea

<004> for Lena River Delta

<005> for Ob Estuary

DDD="file content", from oo1 to oo6 and correspond to codes given for LST and supplementary data files described earlier.

EEE="file extension", e.g. tif or netcdf

Name example:

- Pan-Arctic LST January 2008 data from MODIS: **UW_MODAV_LST_1.1.4_20080101_000000-20080131_235959_000_001.tif**

- Ob Estuary number of observations for the first week of January 2008 data from AATSR: **UW_ATSAV_LST_1.1.4_20080101_000000-20080107_235959_005_002.tif**

### 4.1.2 Pan-Arctic

**Product descriptive statistics**

Weekly and monthly UWL3 pan-Arctic 25 km products show consistent patterns that follow the solar irradiance latitudinal distribution (cloud cover presence/absence) and land cover patterns. UWL3 derived from MODIS L2 observations are found to be more spatially and temporally complete than those generated from AATSR (Figure 6).
Figure 6: Examples of UWL3 pan-Arctic LST products. Monthly LST mid range average of (a) December 2005 of AATSR UW_ATSAV_LST_1.1.4_001_2005121_000-20051231_235959_100_001 and (b) December 2005 of MODIS UW_MODAV_LST_1.1.4_001_2005121_000-20051231_235959_100_001; weekly mid range average of one week (DOY 358 to 364 of year 2008) of (c) AATSR UW_ATSAV_LST_1.1.4_001_2008.12.23_0.0.0_2008.12.29_23.59.59_100_001 and (d) MODIS UW_ATSAV_LST_1.1.4_001_2008.7.26_0.0.0_2008.8.1_23.59.59_100_001.

The average number of L2 observations was found to vary with a yearly cycle. For example, MODIS L2 observation counts were found to decrease significantly during the snow-cover (winter) period suggesting that many L2 observations are rejected as they are labelled as top of cloud temperature. UWL3 of MODIS had equal contribution for both day-time and night-time observations as indicated by the close to one count ratio (Figure 6 and Figure 7).
Figure 7: Monthly UWL3 LST product from both MODIS and AATSR over the pan-Arctic above 50 degrees north during period 2005-2009. a) LST mean; b) count of valid day-time and night-time observations within each month and c) ratio between number of valid observations during day-time and night-time. A value of 1 is indicative of months when there were more valid day-time than night-time observations.

Figure 8: Weekly UWL3 LST product from both MODIS and AATSR over the pan-Arctic above 50 degrees north during year 2008. a) LST mean; b) number of valid day-time and night-time observations within each week and c) ratio between number of valid observation during day-time and night-time. A value of 1 is indicative of months when there were more valid day-time than night-time L2 observations.
Validation of the UWL3 25 km pan-Arctic product

Validating UWL3 pan-Arctic product is challenging. There are no available ground measurements that can match the coarse grid dimension of this product. An alternate approach is an evaluation based on a comparison between independent LST or near-surface air temperature (Ta) products at the same spatio-temporal aggregation scale. It is important to note that all products contain a certain level of uncertainty (error). This must be kept in mind when looking at the statistical difference between products.

a. Statistical comparison between UWL3 of MODIS and AATSR

UWL3 LST products of AATSR and MODIS target the same physical quantity. The difference LST (MODIS) - LST (AATSR) was found to have a root-mean-square-error (RMSE) of 3.76 K and mean error (ME) of -1.1 K for the period 2005-2009. This difference can be attributed to different sources inherent to the two sensor products (e.g. algorithm used, cloud mask efficiency, assignment of land cover type/emissivity, and density of observations). The general trend showed an increase of the difference during the snow-free period with the exception of year 2006. The difference of UWL3 weekly products of MODIS and AATSR for year 2008 has similar magnitude to the monthly difference (RMSE of 4.05 K and ME of -1.8 K) (Figure 8).

![Figure 9: a) Difference between monthly UWL3 LST products derived from MODIS and AATSR (2005-2009). b) Difference between weekly UWL3 LST products derived from MODIS and AATSR during year 2008](image)

b. Statistical comparison with reanalysis data over North America

Methods

The “North American Regional Reanalysis (NARR) is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain”¹, which is developed

by the National Centers for Environmental Prediction (NCEP). Processed monthly averages of LST named '0 height air temperature' at 32 km resolution and stored in standard NETCDF format was obtained from Physical Science Division (PSD), National Oceanic & Atmospheric Administration, (NOAA) archive. LST (NARR) was interpolated to 25 km resolution EASE grid projection, and MAST images were generated by calculating an arithmetic average of the 12 calendar months. Interpolation of NARR data resulted in contaminated pixels at the shoreline with sea surface temperature. A binary mask was applied to remove all pixels within 25 km of shoreline as suggested by Royer and Poirier (2010). Differences between monthly and annually UWL3 LST (MODIS / AATSR) and LST (NARR) were expressed as ME and RMSE.

Results

UWL3 MODIS LST was found to be systematically colder than NARR LST as the bias is consistently negative, while UWL3 of AATSR is relatively warmer than LST of NARR during the summer and colder during the winter, with an exception to year 2006. We found through comparison with LST of NARR products that ME was between 1-6 K with the ME being lowest (2 K) during the months of July and August of every year, and highest (2-6 K) during the snow-cover period (Figure 10 and Figure 11). Given the current efficiency of cloud mask used to produce L2 of MODIS and AATSR sensors and the possibility of cloud contamination (indicated by station and LST images comparison) it is likely that any thermal infrared product (including our products) will underestimate the true surface temperature; for example, it was found that UWL3 of MODIS ME is always negative compared to LST of reanalysis (NARR) and the true surface temperature is most likely to be warmer (although NARR is not a perfect either). This uncertainty needs to be known by the science community if UWL3 LST products are to be integrated into permafrost models.

Figure 10: Difference monthly UWL3 LST (MODIS) - LST (NARR) and b) UWL3 LST (AATSR) - LST (NARR) over North America and Greenland between years (2005-2009), outliers are not plotted for clarity purpose. Envelops in blue represent ± 1 standard deviation (STDV). The yearly UWL3 averages, mean annual surface temperature, used for validation are not distributed as a product but it can be calculated.
Figure 11: Mean annual LST calculated from NARR, MODIS and AATSR, and differences of MODIS and AATSR with NARR. Monthly LST average of the twelve calendar months was required to start annual LST calculations. A number of locations in LST (AATSR) did not have all twelve months due to low frequency of observations, which resulted in numerous locations with missing data.

c. Statistical comparison between UWL3 of MODIS and near-surface air temperature derived from passive microwave AMSR-E data

Methods

Jones et al (2010) derived 2-m height air temperature (AMSR-E-Ta) from 18.7, and 23.8 GHz H and V polarized brightness temperature from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) during the snow-free season at 25 km resolution. The AMSR-E passive microwave sensor has the advantage of imaging in both clear sky and cloudy conditions. A comparison was conducted with UWL3 MODIS LST during months of May to September of 2007 and 2008. Air temperature product at 25 km resolution was obtained from online archive (NTSG, 2011) and it was projected to EASE grid projection. Daily averages were calculated from ascending and descending images and were used to produce monthly averages. RMSE, ME was calculated between UWL3 LST (MODIS / AATSR) and AMSR-E-Ta.

---

Results

The ME (UWL3 LST (MODIS) – Ta (AMSR-E)) was found to decrease during the snow-free period to a minimum of -0.5 K (°C), Ta being warmer during the month of July. The RMSE was found to be 2.6 K (°C) during the period June to August (2007 and 2008), while it increased during the months of May and September to a range of 4 to 6 K (°C) (Table 10).

Table 10: ME and RMSE between monthly UWL3 LST MODIS and Ta derived from AMSR-E

<table>
<thead>
<tr>
<th>Month</th>
<th>RMSE</th>
<th>ME</th>
<th>STDV</th>
</tr>
</thead>
<tbody>
<tr>
<td>May-07</td>
<td>6.24</td>
<td>-4.38</td>
<td>4.45</td>
</tr>
<tr>
<td>Jun-07</td>
<td>2.93</td>
<td>-0.97</td>
<td>2.77</td>
</tr>
<tr>
<td>Jul-07</td>
<td>2.54</td>
<td>-0.49</td>
<td>2.49</td>
</tr>
<tr>
<td>Aug-07</td>
<td>2.34</td>
<td>-1.23</td>
<td>1.99</td>
</tr>
<tr>
<td>Sep-07</td>
<td>3.68</td>
<td>-2.95</td>
<td>2.2</td>
</tr>
<tr>
<td>May-08</td>
<td>6.13</td>
<td>-4.67</td>
<td>3.97</td>
</tr>
<tr>
<td>Jun-08</td>
<td>2.71</td>
<td>-1.09</td>
<td>2.47</td>
</tr>
<tr>
<td>Jul-08</td>
<td>2.48</td>
<td>-0.49</td>
<td>2.43</td>
</tr>
<tr>
<td>Aug-08</td>
<td>2.62</td>
<td>-1.55</td>
<td>2.11</td>
</tr>
<tr>
<td>Sep-08</td>
<td>4.56</td>
<td>-3.69</td>
<td>2.69</td>
</tr>
</tbody>
</table>

4.1.3 Regional

Product evaluation methodology – 1 km L2 LST

Air temperatures (Tair) from meteorological stations were used for evaluation of the 1 km L2. Unfortunately, most of the meteorological stations of the regional areas approved for the DUE permafrost in Siberia and Alaska did not have either air temperature or long enough time series of measurements to be used in this comparison. Differences were thus examined for 46 stations over Canada, including those in the Mackenzie River Basin of the DUE permafrost project (Figure 11).

Evaluation of level 2 LST products with air temperature from meteorological stations

Method

In addition to evaluating the UWL3 products (described later in the text), the L2 (i.e. within the hour of overpass of the satellites), which are hourly distributed, are used for comparison with Tair from meteorological stations as follows:

- Retrieve LST values from L2 (MODIS and AATSR original datasets) for pixels corresponding to the station location at each satellite overpass.
- Retrieve hourly near-surface air temperature (Tair) from meteorological stations within the overpass times of the satellites. The stations were chosen to represent locations with different cover types found above 50°N including cloudy or clear sky information. They were obtained from the National Climate Data and Information Archive of Environment Canada (Figure 11).
- Compare the number of measurements of MODIS and AATSR at each station and per year in Table 11.
- Compare the L2 LST and Tair differences (mean error (ME): AATSR L2 LST-Tair, MODIS L2 LST- Tair) over a large range of surfaces from North to South and the Standard Deviation of Mean Error (SD). Compare MODIS and AATSR L2 LSTs to allow verification of their
correspondence and correlation with the purpose of using both for producing monthly and weekly UWL3 products. For this comparison, only the data measured at the same hour of overpass were used, and only stations which had more than 15 common values were used.

- Evaluate MODIS L2 LST cloud contamination with cloud information of meteorological stations. The cloud information is given hourly. Three sets of data were arranged to evaluate differences between cloudy and clear sky hours, days, weeks and months. The first dataset is the complete one, data are not separated: measurements under cloudy sky are evaluated with measurements under clear sky. Nevertheless a counting of number of clear and cloudy measurements per hour is set (i.e.: January 2nd at Baker Lake: 3 LST values were measured, 2 were done under clear sky, 1 under cloudy sky. The counting is added per week then first week of January, there were 2 measurements during clear sky conditions and 8 during cloudy skies and for the total month of January there were 13 measurements during clear skies and 44 during cloudy skies). The second and the third datasets represent respectively the clear and the cloudy conditions (i.e.: daily, weekly and monthly averages are made with these only measurements taken under the specific conditions). Then in Table 13, percent of clouds represents the percent of measurements (hourly values) taken in a month in the complete dataset. This show the months with the highest number of undetected clouds. The cloudy conditions represent LST measurements under undetected clouds. When the sensors do not detect a cloud presence, LST is measured. From the station information we know that these days were cloudy. Then the LSTs measured are measurements under undetected clouds by MODIS.

- Compare MODIS L2 LST and Tair database for each month to evaluate differences between cold and warm LSTs retrieving.

---

**Figure 12:** Environment Canada Meteorological Stations used for L2 LST evaluation
**Table 11**: Number of hourly measurements from 46 stations used for evaluation of LST level 2 data (2004-2009)

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>Min</td>
<td>85</td>
<td>74</td>
<td>91</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>193</td>
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<td>224</td>
<td>172</td>
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</table>

**a. Comparison between MODIS L2, AATSR L2 and Tair**

The hourly comparisons with Tair show that the three datasets MODIS and AATSR LSTs and Tair follow a similar distribution year round (warm in summer, cold in winter) reflected by values of the coefficient of determination ($R^2 > 0.96$). Standard deviations (SD) of ME are of the same order of magnitude (from 1 to 10°C). When all stations are considered the SD is smaller for MODIS (3.8 in 2005, 5.0 in 2006 and 3.6 in 2007) than for AATSR (4.8 in 2005, 6.1 in 2006 and 4.5 in 2007) against Tair. The two datasets give a similar relation with Tair when looking at an average of all stations and for the three common years (mean number of values n= 24), the mean difference (ME) between AATSR and MODIS is 1.7°C and SD is 2.4°C.

From this comparison we can conclude that AATSR could potentially be used as a complement to MODIS data in particular for hours of AATSR measurements when MODIS does not have any measurements. It could improve the number of measurements during a day to calculate a daily average.

However, taking into account the very low number of AATSR measurements, the AATSR dataset cannot be used alone. Averaging of MODIS and AATSR (blending) should be further evaluated to figure out if the use of AATSR data could make a difference in the calculation of the weekly and monthly average products. The small number of observations possible with AATSR in contrast to MODIS (Aqua and Terra) suggests that the creation of a blend product will mostly be similar to the MODIS product alone.

**b. Comparison between MODIS L2 and Tair with cloud contamination overall years (2004 to 2009) and all stations**

Table 12, which represents the average of all the values available on 6 years for all the stations, shows that the ME hourly is very low. It is better for clear value dataset than cloudy values. ME is also very small (0.4°C) for the complete data (including both clear and cloudy values). However the variability (SD) is higher than 5°C (LST fluctuates from -4.6°C to 5.4°C for any hours of any year). The MEs of daily, weekly and monthly averages are low and similar around 1.4°C. These MEs are higher than hourly MEs because of the low amount of LST measurements (2 values per day) when the daily Tair average is calculating with 24 measurements per day.

The SDs of ME are decreasing with the increasing of number of values used for averaging i.e.: daily to weekly to monthly averages. Then the weekly and monthly LST averages are closer to the Tair averages than the hourly and the daily averages.
Table 12: Average statistics of all the data available on 6 years and 46 stations for complete days, only clear days and only cloudy days

<table>
<thead>
<tr>
<th></th>
<th>Complete Dataset</th>
<th>Clear Dataset</th>
<th>Cloudy Dataset</th>
</tr>
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<tr>
<td>ME Hourly</td>
<td>0.4</td>
<td>-0.1</td>
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<tr>
<td>SD Hourly</td>
<td>5.3</td>
<td>5.1</td>
<td>5.5</td>
</tr>
<tr>
<td>Total Nb values</td>
<td>504</td>
<td>323</td>
<td>152</td>
</tr>
<tr>
<td>ME Daily</td>
<td>1.3</td>
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</tr>
<tr>
<td>SD Daily</td>
<td>4.1</td>
<td>3.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Nb values / day</td>
<td>2.3</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>ME Weekly</td>
<td>1.4</td>
<td>0.7</td>
<td>1.7</td>
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<tr>
<td>SD Weekly</td>
<td>3.1</td>
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<td>4.3</td>
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<tr>
<td>Nb values / week</td>
<td>9.7</td>
<td>6.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Nb days / week</td>
<td>4.0</td>
<td>3.0</td>
<td>2.3</td>
</tr>
<tr>
<td>ME Monthly</td>
<td>1.4</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>SD Monthly</td>
<td>2.4</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Nb values / month</td>
<td>42.0</td>
<td>27.0</td>
<td>12.7</td>
</tr>
<tr>
<td>Nb days / month</td>
<td>16.7</td>
<td>11.5</td>
<td>8.4</td>
</tr>
</tbody>
</table>

The low MEs and quite low SD for the weekly and monthly averages let us think that the MODIS L2 LST is a very useful tool to calculate weekly and monthly products despite the discontinuity and the small presence of undetected clouds.


The small amount of data available for each week does not allow the comparison by week; nevertheless the exercise was feasible monthly.

Table 13 shows the results of ME, SD, nDays (a Day is taking into account if at least one LST value was measured during 24 hours), and percent of cloudy values for each month and each year in station averaging. It appears that the months with the smallest MEs (< 2°C) are from June to September. The months for which the LST and Tair are closer each year, are June, July and August (ME < 1). It is also in June and July that the SD of MEs are the highest (2 < SD < 3°C). These differences between months are not related to the number of values available per month as they are all similar each year (15 < nDays per month < 20). MEs are positive for all other months with the maximum ME (>3.5°C). Months with lower cloud contamination are April, May and June (Cloud<30%) which does not influence the LST values. During the coldest months the cloud contamination is higher (40 to 50%), which most of the time should not influence the LST values, because the top cloud temperature is similar to snow cover temperature, except for hours of Tair > -15°C. The hours with Tair >-15°C and cloudy sky should be the one with higher LST errors.

To summarize the relation between LST and Tair by month, the year can be divided in three parts:

- The coldest period: January, February, March, April, November and December: 4 > ME > 3°C, and SD = 1.5°C, the maximal
range is: $4.5 + \text{LST} > \text{Tair} > 1.5 + \text{LST}$. LST is higher than Tair during the coldest months.

- The transition period: May and October: $3 > \text{ME} > 2^\circ\text{C}$, and $1.5 < \text{SD} < 2^\circ\text{C}$, the maximal range is $5 + \text{LST} > \text{Tair} > 1 + \text{LST}$. LST is closer to Tair during the transitional months.
- The warm season: June, July, August and September: $1.5 > \text{ME} > 0^\circ\text{C}$, and $1.5 < \text{SD} < 2.5^\circ\text{C}$, the maximal range is: $4 + \text{LST} > \text{Tair} > -1 + \text{LST}$. LST is closer to Tair during the warmest months.
Table 13: Average statistics for all stations by month and year. Legend: Purple values = ME < or = 2°C; blue values = SD > 2°C; pink values = month with the smallest number of day; green values = <30% of cloudy values.

<table>
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<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
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</table>
Evaluation of UW level 3 product against air temperature measurements at meteorological stations

Method

Evaluation of weekly and monthly UWL3 involved the retrieval of pixels corresponding to the station location.

A preliminary comparison was conducted to evaluate the general quality of the UWL3 LST (AATSR and MODIS) weekly product for stations of the Kuparuk watershed, North Slope, Alaska (year 2008).

Result

The results presented in Figure 12 and Figure 13 show that the UWL3 weekly LST-AATSR correlate well with the UWL3 LST-MODIS and air temperature measurements. The MODIS LSTs correlate slightly better with UWL3 LST-AATSR than the air temperature as both represent the same physical quantity.

![Figure 13: UW level 3 LST (AATSR and MODIS) comparison with air temperatures at the Betty Pingo (wetland) site (year 2008)](image)

It was noticed that the UW level 3 AATSR product was not consistent over the entire year. The product reached the largest deviation from air temperature and MODIS LST around the month of July at both sites, but performed well for other times of the year.
Figure 14: UW level 3 LST (AATSR and MODIS) comparison with air temperatures at the Eastern Kuparuk (Sagwon) site (year 2008)

The following map is a monthly example of UWL3 product.

Figure 15: Mackenzie River Basin, July 2008, LST from MODIS average UW_MODAV_LST_1.1.4_20080701_000000-20080731_235959_002_001.tif
4.1.4 Known issues and suggested improvements

The LST data are all measured during clear-sky conditions. The influence of clouds on surface temperature (e.g. temperature warmer under clouds in winter) is not reflected in the LSTs. This makes the LST colder than in reality due to the isolative effect of clouds.

The limit of the number of LST values due to cloud cover particularly affects the creation of the 1 km level 3 product since less observations are available than when aggregating to a 25 km pixel. To circumvent this problem and have the best representative value of LST for the different time periods, a simple algorithm able to redraw the sinusoidal function of temperature over a year from LST values, as described in Hachem et al. (2009) should be tested over several sites of the Arctic.

4.1.5 Local

Local Upscaling and Evaluation Experiments (HGF-SPARC, AWI) have been carried out on Samoylov Island (Siberia, RU) and in Alesund (Svalbard).

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 (Langer et al. 2010, Westermann et al. 2011, Westermann et al. 2012. Langer et al. (2010) describe their successful experimental upscaling in Samoylov for the permafrost landscape-type wet-polyglonal tundra (for the snow-free period, see Figure 14). Westermann et al. (2011) also have been successful in thermal-upscaling experiments at the Spitsbergen Permafrost site Ny-Alesund (barren–moss and -lichen cover-water) for the summer months. 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.

For winter conditions, Westermann et al. (2012) investigated seven winter seasons at a high-arctic permafrost site on Svalbard. find a significant cold bias of on average 3 K for the MODIS LST wintertime averages, with values ranging from 1.5 and 6 K for single seasons. The authors explain that the bias is partly caused by the lack of satellite measurements during prolonged periods with cloud-covered skies, where the surface temperature is on average considerably higher than during cloud-free periods. Temperature computed from different MODIS LST products to averages of in-situ measurements. The authors also state that strongly cold-biased MODIS LST measurements almost exclusively occur during cloudy periods, the cold-bias can be attributed to admixing of colder cloud top temperatures due to erroneous cloud detection.

In summary, Langer et al. (2010), Westermann et al. (2011), Westermann et al. (2012) conclude that the success rate of MODIS LST data acquisition is limited in the case to a frequent cloud cover. The MODIS LST measurements are biased by occasional erroneous measurements that are not masked out by the operational cloud-cover masking (see symbols of crosses in Figure 14). The authors show that the problematic time periods are the late summer season for the Samoylov site in the Lena River Delta, Arctic Siberia, and for Northern Svalbard, and for the wintertime period at Svalbard. Reliable surface temperature averages therefore require the development of gap-filling procedures.
Soil moisture and surface status

4.2 Pan-boreal/arctic

MetOp ASCAT data have been used for both the near surface soil moisture (SSM) product and determination of freeze/thaw status at pan-boreal/arctic scale. Metop-A, launched in October 2006 by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), is the first of three satellites within EUMETSAT’s Polar System (EPS) (Klaes and Holmlund 2007). Alternative global products exist from passive microwave sensors. In case of surface soil moisture, these datasets have been recently combined with ERS and ASCAT records within the ESA WACMOS project for a 30-year historic record (Liu et al. 2011). The DUE Permafrost service aims on regular updates and has been adjusted to high latitudes. This included the review of processing parameters and improved masking for frozen ground conditions. The initial freeze/thaw status flag has been implemented for the weekly averaged surface soil moisture service. It has been improved in cooperation with the ESA STSE ALANIS-Methane project in order to reflect daily conditions and also snowmelt conditions. It will be referred to as the enhanced freeze/thaw detection method or surface state flag (SSF) in the following.

Input and data preparation

The ASCAT Level 2 product including soil moisture data are produced by EUMETSAT in near-real time following the method developed and prototyped for EUMETSAT by the Institute for Photogrammetry and Remote Sensing of the Vienna University of Technology. ASCAT data are available via the EUMETCast system and are also accessible through the Unified Meteorological Archive and Retrieval Facility (UMARF) at EUMETSAT. A detailed technical description of the ASCAT level 2 data structure is given in the EUMETSAT ASCAT Product Guide (EAPG): http://oiswww.eumetsat.org/WEBOPS/eps-pg/ASCAT/ASCAT-PG-0TOC.htm
The ASCAT Level 2 data are delivered in orbit geometry at two different grid spacings: 25 km and 12.5 km. The two products are derived directly and on the same grid as the equivalent ASCAT Level 1b product (normalized backscatter), hence the resolution of the soil moisture values is approximately 50 km/25-35 km respectively. For Permafrost project the high resolution product with 12.5 km grid spacing is used.

For further processing, ASCAT data are resampled to a Discrete Global Grid (DGG). The DGG is an adapted sinusoidal grid using an ellipsoid based on the GEM6 model (Kidd 2005). The grid is defined such that the spacing is approximately 12.5 km. The underlying satellite data are oversampled to the DGG grid. For resampling a weighting function using a Hamming window based on the distance between the grid point and the location of the measurement is implemented. A description of the procedure is given by Bartalis (2005).

Product adjustment methodology – surface soil moisture

The Surface Soil Moisture parameter represents a relative measure of the soil moisture in the top layer of the soil, scaled between wilting level (0%) and field capacity (100%) (Wagner et al. 1999).

The ASCAT SSM DUE Permafrost product is the result of an improved SSM retrieval algorithm developed at the Institute for Photogrammetry and Remote Sensing (IPF) of the Vienna University of Technology (Naeimi et al., 2009). The SSM Product is delivered with a weekly temporal resolution and 25km spatial resolution.

For integration into the Permafrost Information System (PEO) ASCAT data are resampled to a Discrete Global Grid (DGG). The DGG is an adapted sinusoidal grid using an ellipsoid based on the GEM6 model (Kidd 2005). The soil moisture product also includes a quality flag which contains the number of used measurements. Data are masked for frozen ground conditions also based on MetOp ASCAT. The product is provided as weekly averaged images north of 50°N in GeoTIFF/NetCDF format and EASE Grid projection.

Figure 17: Examples of 25 km SAR Surface Soil Moisture mosaic product > 50°N
The backscatter data set used for this service is also from the ASCAT onboard the Metop-A satellite. The enhanced freeze/thaw detection method consists of stepwise threshold analysis and anomaly detection modules and identifies the state of the surface. The determination of surface state is accomplished via an evaluation chain processing backscatter observations through two decision trees. The backscatter evaluation begins with a simple and more general form but sequentially more specific situations are considered in decision process. The result of the evaluation chain is a so called surface state flag (SSF) indicating that the local surface is in one of four possible conditions: Unfrozen, Frozen, Snowmelt/water on the surface, and Unknown (Naeimi et al., in press).

The soil temperature variable of the surface layer 187 (0–7 cm) from the ECMWF ReAnalysis (ERA-Interim) data has been applied for evaluation of the backscatter measurements in order to extract model parameters.

In the surface state flagging process, decisions are made based on the time of year. A year is divided to four seasonal time zones: winter, transition from winter to summer (TWS1, TWS2), summer, and transition from summer to winter (TSW1, TSW2). It is assumed that seasonal transition does not take longer than two months. Hence, the transition zones are defined as 30 days period before and after the transition points between winter and summer seasons. In order to determine the seasonal transition points, a least square fitting of step function (as developed for SAR processing, Park et al. 2011) is applied on backscatter time series for each individual grid point. The transition points indicate the date of backscatter level change due to the seasonal transition between cold-warm and/or dry-wet seasons. The determination of the surface state is carried out by using stepwise threshold checks and sequential anomaly detection through two distinct decision trees. The first decision tree is used under “normal” circumstances where backscatter in winter is much lower than in summer, and the second decision tree is used for the regions where backscatter in winter is higher than in summer. Permafrost areas can be almost entirely characterized by the first case. The algorithm considers the noise of normalized backscatter, the deviation of the normalized backscatter from the mean, the standard deviation of normalized backscatter during the frozen period and a deep snow indicator (Naeimi et al. in press).

Validation – pan-arctic surface soil moisture

In-situ soil moisture measurements have been available and investigated for Alaska (Bartsch et al. 2012), Lena-delta (Heim et al. 2011) and Central Yakutia (section 4.2.2).

Data from Alaska have been obtained from the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS). Seven sites have been investigated, several have been investigated in many permafrost studies in the past (Hinkel & Nelson 2003). Barrow is close to the sea but the lowest probe depth (5 cm) is available from this site. This location has also been the focus of several soil moisture and permafrost related studies in the past, e.g. Hinkel et al. (1996), Engstrom et al. (2008) and Shiklomanov et al. (2010). Figure 16 shows the comparison at Barrow.
Figure 18: Comparison of Metop ASCAT surface wetness and USDA soil moisture measurements (5 cm depth) at site Barrow 1 (subsites: 1 – black, 2 – purple, 3 – red, 4 – green): left – time series plot of weekly averages for ASCAT relative soil moisture scaled between 0 and 1 (diamonds), Volumetric soil moisture values at USDA subsites (lines).

The spring peak always occurs earlier in the satellite data than is visible in the field probe measurements because the satellite data characterize the near surface. The timing difference is however small for Barrow 1 in 2007 and 2008 as the probe is at comparably shallow depth. Variations are well reflected in magnitude and timing.

The ASCAT product has been also compared to the regional soil moisture dataset – see section 4.2.2.

Validation and product cross comparison – freeze-thaw status

No global or pan-arctic in-situ measurements of the actual surface state are available. Instead, temperature measurements have to be used which do not necessarily represent the surface state and introduce comparison uncertainties and sometimes systematic biases. In the validation process we used a 0° C threshold for the temperature data to distinguish between frozen and unfrozen conditions. In similar studies (e.g. Kim et al.) a 3° C threshold is used to improve the likelihood of the temperature representing actual frozen/unfrozen conditions whereas this approach is most critical during the seasonal transition periods of the year when temperature is around 0° C. Temperature data are first interpolated to the ASCAT observation times using linear interpolation, then the SSF is compared with the temperature applying 0° C threshold where thawing conditions are flagged only if they occur during positive temperatures. The results are presented in percentage of the agreement with respect to all ASCAT measurements considered in the validation period.

The SSF product is compared with the air temperature data from the nearest WMO stations to the SSF grid points as well as two modeled soil temperature datasets, ERA-Interim and GLDAS-Noah. The GLDAS-Noah dataset is the output of the Global Land Data Assimilation System (GLDAS), a software package that can simulate several land surface models, simulating the Noah land surface model. GLDAS surface temperature dataset is available from February 2000 onwards in three hours temporal resolution on a 0.25° regular global grid (Rodell et al. 2004).

The comparisons between the SSF product and three different datasets are illustrated in Figure 17. The results of comparison are summarized in Table 12. All three global datasets compare rather well with the SSF. The accuracy of the freeze/thaw flagging is highest in summer and winter and lowest during transitional periods. The agreement between SSF and WMO air temperature data in winter is considerably lower compared to modeled data. This behavior is most likely due to the distribution of the stations which favor Europe and the United States whereas SSF in winter is more stable in Siberia and Canada with longest winter periods. All three comparison maps show relatively the same spatial patterns of agreement.
Table 14: Agreement between SSF and different temperature datasets indicated in percentage (source: Naeimi et al. (in press)).

<table>
<thead>
<tr>
<th></th>
<th>WMO-Meteo</th>
<th>ERA-Interim</th>
<th>GLDAS-Noah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>78</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Transition W-S</td>
<td>72</td>
<td>68</td>
<td>69</td>
</tr>
<tr>
<td>Summer</td>
<td>92</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>Transition S-W</td>
<td>73</td>
<td>71</td>
<td>75</td>
</tr>
<tr>
<td>Overall</td>
<td>82</td>
<td>83</td>
<td>84</td>
</tr>
</tbody>
</table>

Figure 19: Comparison of SSF with a) Air temperature from WMO meteorological stations, b) GLDAS surface temperature, c) ERA-Interim surface soil temperature (source: Naeimi et al. (in press)).

To evaluate the ASCAT Surface State Flag (SSF) it is also compared to land surface temperature (LST) data from MODIS and AATSR which have been part of the project phase 1 test dataset. MODIS data was available in 2 test regions: Ob Estuary 2008 and North Siberia 2007/2008 (8 day composite – 28 km resolution). AATSR data was available in the following test region: Kuparuk River (North Slope, Alaska) – 2008 (8 day composite – 1km resolution).

Because the SSF is based on the ASCAT sigma 40 time series it does not have a fixed temporal resolution. In order to compare the 8 day composite data with the SSF the temporal resolution of the latter had to be changed to an 8 day, exponentially weighted, average.

For comparison the same algorithm was used for all datasets. An overview of the process can be found in Figure 19 The output was classified into 3 classes, the classes and the conditions for each class are explained in Table 13.

Figure 20: Overview of the comparison between LST and SSF
Table 15: Conditions for classification of LST for SSF validation

<table>
<thead>
<tr>
<th>Class</th>
<th>Correct</th>
<th>Around zero</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>LST &lt; 0°C and SSF 2/4</td>
<td>LST &gt; 0°C and SSF 1/3</td>
<td>LST in ± 2 °C range</td>
</tr>
<tr>
<td></td>
<td>LST &lt; 0°C and SSF 1/3</td>
<td>LST &gt; 0°C and SSF 2/4</td>
<td>LST &gt; 0°C and SSF 2/4</td>
</tr>
</tbody>
</table>

Figure 21: Examples for the comparison between LST and SSF

The ‘Around zero’ class was introduced to account for the accuracy of the LST data.

In Figure 19 the percentages of the 3 classes are shown for several sites and years. In winter and summer the SSF is nearly one hundred percent in agreement with the LST data, the problematic times are in spring and autumn. In spring the SSF flag indicates unfrozen soil too soon. Most of the incorrect values are because the SSF indicates temporary water surface/melting conditions. If the 8 day composite LST has a value below -2°C and the SSF flag shows
temporary water surface/melting conditions then this is not necessarily contradictory, if it happens in a thawing period. In autumn only very few measurements are classified as incorrect until week 38 where the SSF shows unfrozen in 40% of the test area without any rise in LST.

The common disagreements between the SSF and LST from MODIS and AATSR are that unfrozen surface conditions are flagged to soon in spring and too long in autumn. It also happens in some parts of Siberia and in the Ob Estuary that the SSF jumps from frozen to unfrozen and back about 8 day period 38 (see the red spikes in Figure 19) without any apparent change in LST. The second problem is how to interpret the SSF when it shows "temporary melting conditions" because that mainly happens in areas where the 8 day composite LST is still negative. Another problem is that the LST temperature is not accurate if clouds obscured the view to the ground.

Additionally, an assessment by use of GTN-P data has been carried out for Western Siberia and Alaska. Details are provided in section 6.1.3.

4.2.2 Regional

Product adjustment methodology – surface soil moisture

The parameter represents a relative measure of the soil moisture in the top layer of the soil, scaled between wilting level (0%) and field capacity (100%) similarly to the ASCAT pan-arctic product (section 4.2.1). The product is provided as weekly composites, when data availability allows. It is based on the algorithm introduced by Wagner et al. (1999) for scatterometer data. The approach had been demonstrated valid under conditions without seasonally frozen and snow covered conditions (e.g. Bartsch et al 2008, Pathe et al. 2009).

The processing has been implemented with the TU Wien SGRT (Sabel et al. in press). It makes use of ENVISAT ASAR Global Monitoring level 1b data, a Digital Elevation Model (SRTM30 version 2.1”) and probabilities for wet and dry soil, derived from ERS Scatterometer time series. For geocoding of the ASAR GM data also DORIS orbit files are used in order to optimise geolocation accuracy (Sabel et al. in press).

For application at high latitudes the following adjustments to the algorithm have been implemented:

- Processing (with NEST) in polar stereographic projection and storage of data. An entirely new gridding system has been setup in order to avoid oversampling and to reduce data storage (Bartsch et al. in press). This feature has already benefitted further high latitude research especially in the framework of the ESA STSE ALANIS methane project.
- A dry reference (representing wilting point) correction algorithm has been implemented in order to account for permanently wet areas (Bartsch et al. 2011b).
- Implementation of a post processing function for the production of weekly composites
- Enhanced masking with respect to signal-to-noise ratio and water fraction

The SSM retrievals for each 7-day period were averaged in order to obtain the weekly SSM product, producing 0.5x0.5 degree tiles. Pixels in the tiles expected to contain unreliable SSM estimates were masked. The masking was based on thresholds of local sensitivity to soil moisture changes and amount of open water bodies within the pixel, whereby pixels with sensitivity below 5.5 dB or a water body fraction above 4.4% were masked (i.e. set to the no-data value). The water body fraction was computed for each pixel from the maximum water body extent for the months of July and August for the years 2007, 2008 and 2009 (for Central Yakutia only 2007 and 2008) derived from the Permafrost project’s 150 m Water Body product. In case coverage of the Wa-
ter Body product was not available, only the SSM sensitivity was used for masking.

**Product development methodology – surface status**

The algorithms are detailed in Park et al. (2011). In most previous studies, methods to determine the onset of thaw from the scatterometer have relied on a temporal change detection approach with threshold values which have been calibrated by surface weather stations.

Distinctive seasonal differences in backscatter can be used to determine the onset of spring transition. However, seasonal threshold approaches can be hardly applicable to the ASAR GM data because of the noisy backscatter time-series and complex seasonal response to different land cover types and climate conditions.

An alternative approach without threshold values, named temporal edge detection technique, has been developed (McDonald et al., 2004). According to the temporal edge detection method, the timing of a freeze/thaw transition can be determined by maximizing the convolution of backscatter time-series and first derivative of a Gaussian distribution such as:

\[
\max \int_{-\infty}^{\infty} \phi'(x) \sigma^0(t-x) \, dx, \quad (1)
\]

where \(\phi(x)\) is the Gaussian distribution function and \(\sigma^0(t)\) is a time-series of radar backscatter. Although this technique has been successfully applied to the passive microwave data from the Special Sensor Microwave/Imager (SSM/I) (McDonald et al., 2004), it can be easily applied to the active microwave time-series data.

Similarly to the regional soil moisture retrieval, the processing has been implemented with the TU Wien SGRT (Sabel et al. in press). It makes use of ENVISAT ASAR Global Monitoring level 1b data.

**Validation and Product cross comparison – surface soil moisture**

Validation of both the ASCAT and the regional SAR based soil moisture product with in-situ measurements has been carried out over sites in Central Yakutia with records from several years. The datasets have been provided by the user institution ‘Hokkaido University’. Detail regarding the variation between the years 2006 – 2009 is presented in Figure 21. They demonstrate the ability of Metop ASCAT to capture general trends, rain events and short term dry up (Neleger site) and trends over several years near the surface (Spaskaya Pad).

ENVISAT ASAR GM variability varies between the years and is in general lower after 2006, when ASCAT data became available. This impedes detailed comparison of the two sensors in this region, but similar patterns can be observed. Time series from 2006 for both sites Neleger and Spaskaya Pad show that the satellite measurements could capture the wetting trend towards the end of the summer.
Figure 22: Time series of Volumetric water content from in-situ measurements for Neleger and Spaskaya Pad (Central Yakutia, depth 5cm, Data source: University of Hokkaido) and relative surface wetness from Metop ASCAT and ENVISAT ASAR GM for summers 2006 - 2008

Re-analyses data such as ERA-Interim contain modeled spatially continuous data. The differences of correlation between the satellite derived datasets are due to the impact of open water surfaces, limited data availability in case of ASAR (Figure 22). Low correlation can be also observed in areas with bare ground/rock out crops, where no soil layer exists. This can be e.g. observed in the centre of the Laptev Sea coast region.

Results between Metop ASCAT and ENVISAT ASAR GM derived surface soil moisture differ due to temporal and spatial resolution. Largest differences occur in tundra regions which are characterized by an abundance of small ponds (Figure 23). The correlation is therefore lower along the Laptev Sea Coast, around the Ob-Estuary and Yamal Peninsula. The datasets agree largely for central Yakutia.
Figure 23: Correlation between Surface Soil Moisture from ERA.Interim and ENVISAT ASAR GM (hamming window 40km) over a) the Laptev Sea Region, b) Ob-Estuary and c) Central Yakutia.
Figure 24: Correlation between Metop ASCAT and ENVISAT ASAR GM derived soil moisture for a) the Laptev Sea Region, b) Ob-Estuary and c) Central Yakutia.

Validation and product cross comparison – freeze-thaw status

In-situ surface status measurements are rarely available. One alternative is the use of re-analyses data. Breakup and freezeup periods estimated from air temperature derived from ERA-Interim (ECMWF) data points have been used for the assessment of the accuracy over central Yakutia. The agreement in spring and autumn are 90.6% and 87.5%, respectively (Park et al. 2011).

The snowmelt time product derived from SeaWinds scatterometer (Bartsch et al., 2007) allows to evaluate GM based spring transition for entire study area. According to the snow melt period of the SeaWinds product, 85% of the spring transition of the study region derived from GM time-series occurs between start and end of snowmelts, which supports the validity of the proposed method in the detection of thawing events. Park et al. also showed that the spring transition date derived from GM time-series corresponds to the end of snowmelt in sparsely vegetated tundra areas while it becomes correlated with the beginning of snowmelt in boreal forests. However, the proposed method is limited to the case when there is a distinct thaw and freezeup period and no multiple short term thaw and freezeup. A limitation in data availability can deteriorate the qualities and details of spatial structures of the estimation of seasonal transition dates from radar time-series. Therefore all locations with less then on average weekly acquisitions are masked in the final product.

The ASCAT surface state flag at 25 km resolution has been extracted for the freeze-up and thaw dates of the ASAR product for the Mackenzie and Alaska regional service case areas. Records agree in case of clear single melt and freeze-up periods. The method applied for ASCAT can capture multiple events. This especially can occur in spring. Figure 26 exemplifies this for Alaska.
Figure 25: ASCAT – ASAR spring thaw timing - Mackenzie

Figure 26: ASCAT – ASAR freeze up timing - Mackenzie

Figure 27: ASCAT – ASAR spring thaw timing – Alaska
Figure 28: ASCAT – ASAR freeze-up timing Alaska

Figure 28 shows an example of an overlay of the surface status at a specific spring and autumn day for both datasets. Similar patterns are clearly visible.

Figure 29: ASCAT SSF overlayed with ASAR thaw and freezeup timing information – Laptev Sea coast 2010
Known problems

Significant geometric shifts (up to 13 km) have been observed in the ASAR GM geocoding results. Tests suggest that the geometric shifts are in most cases a result of inconsistencies in the ASAR products as georeferencing between NEST and SARscape usually correspond well. The impact on the final products has been assessed by case studies over the Ob Estuary and Mackenzie regions. The SSM model parameters were affected and in particular the SSM dry reference. A fraction of the region suffer from differences of larger than +/- 2dB in the dry reference model parameter. Distinctive features (shaped like contour lines) in difference maps were experienced. The Pearson correlation between soil moisture retrievals were consistently close to unity for both test sites.

SSM

The RMSE values for Ob Estuary test site were below 1% for 96.4% of the site and below 3% RMSE for 99.5% of the data. Maximum RMSE was 8%. The bias for Ob Estuary was between -1% and +1% in 97.6% of the data, while more than 99.9% of the bias values were confined within +-3%.

For the Mackenzie test site the RMSE values were below 1% for 93.7% of the site and below 3% for 98.7% of the site. Maximum RMSE was 8%. The bias values were within +-1% in 95% of the site and within +-3% for 99.8% of the site.

It should be noted that the date of acquisition of shifted datasets has great importance for the impact on the SSM product quality, as only data acquired during the summer months (mid June through mid September) and December is used for SSM model parameter retrieval. In the case of Ob Estuary, even though in total 7 ASAR datasets were identified, only 1 of them was acquired within this period. For Mackenzie all three datasets were acquired within the above specified period. The result for the Mackenzie test site is therefore assumed to represent a more severe case than the result for Ob Estuary. Obviously, the impact for other sites may be more severe.

FT product

For the Ob Estuary test site, the estimated day of year (DOY) of freezing was clearly influenced with 6.4% of the data showing differences of more than 5 days. 78.5% of the test region was unaffected (zero days difference). The estimated DOY of thawing was less influenced with 94.9% unaffected and 2.2% with more than 5 days difference.

For the Mackenzie test site, the estimated DOY of freezing showed no difference in 74.4% of the site but as much as 15.6% with more than 5 days difference. For the DOY of thawing, 99.1% of the test site was unaffected.

4.3 Surface water

4.3.1 Regional

Product adjustment methodology

Water is a class in all available global and regional land cover maps. The spatial resolution of those existing products ranges between 300m to 1km. The majority of lakes within tundra environment is however much smaller than the spatial resolution of those maps. ENVISAT ASAR Wide Swath data with 150 m resolution can identify 50% more open water surface areas than land over maps based on MODIS (Bartsch et al. 2008) and allows regular (annual) updates on regional scale.
The DUE Permafrost SAR processing subsystem for the Water Bodies (WB) product is similar to the SAR soil moisture processing but uses ENVISAT ASAR Wide Swath level 1b data, a Digital Elevation Model and orbit state vector information (e.g. DORIS files). Due to the comparably high spatial resolution of the WS data, the setup of a database which is suitable for storage and processing in polar stereographic projection has been the focus of the methodology adjustment. Availability of WS data is highly variable in the high latitudes (Bartsch et al. 2012) and needs to be accounted for. Auxiliary maps with numbers of measurements are therefore derived as quality indicators.

The Water Bodies maps represent the extent of water bodies for the summer months and are produced on an annual basis. The unit is a binary indicator with the pixel value 1 representing water and 0 representing non-water. In addition to the water body indicator the number of measurements used to derive the water bodies product are also provided.

Validation and product cross comparison

A comparison with GlobCover 2005/6 and 2009 has been made for three of the regional sites which cover tundra environments. Watersurface area varies between the GlobCover products. Globcover 2006 contains more water surfaces than 2009. However, upto 50% less open water is detected compared to ASAR WS.

Table 16: GlobCover water class (300 m) and ENVISAT ASAR WS (75m) threshold classification for open water: water extent in km²

<table>
<thead>
<tr>
<th>Regional Site</th>
<th>ASAR WS</th>
<th>GlobCover 2009</th>
<th>GlobCover 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mackenzie</td>
<td>34819</td>
<td>21349</td>
<td>26816</td>
</tr>
<tr>
<td>Alaska</td>
<td>20893</td>
<td>3728</td>
<td>10458</td>
</tr>
<tr>
<td>Ob Estuary</td>
<td>38821</td>
<td>20093</td>
<td>34240</td>
</tr>
</tbody>
</table>

A verified Landsat-based landcover classification has been developed by AWI for the entire Lena Delta previously (Schneider et al. 2009). A subset from the central part with an extent of approximately 50 by 70 km has been selected for the assessment of the ENVISAT ASAR WS water surface product. Altogether 915 km² of water have been determined with the 30 x 30 m resolution of Landsat. The total water extent from the 150 x 150 m ASAR WS (2009) product is 881 km², about 96% of what can be detected with Landsat (2000).
4.3.2 Local

The natural ecosystem of arctic permafrost regions underlies changes caused by climate driven variations in freeze/thaw processes. As a result in many locations degradation of permafrost has been observed during the last decades, which lead to the transformation of existing landforms like changes in terrain (thermokarst effects), hydrology and vegetation. In this context, the variance of thermokarst water bodies is quantified for different study areas using multitemporal high resolution satellite data.

The local water body product is generated with an object based classification approach using historical panchromatic Corona data as well as recent RapidEye imagery with 5 m pixel size each. Additionally, Landsat MSS data (79 m spatial resolution) is used to obtain historical near-infrared information in order to derive former lake objects more precisely. The following tables summarize the technical specifications for both sensors.

Table 17: Specification of KH-4B Corona Mission (Grosse et al. 2005, modified)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of operation</td>
<td>15.09.1967 to 25.05.1972</td>
</tr>
<tr>
<td>Camera type</td>
<td>J-3, panchromatic</td>
</tr>
<tr>
<td>Flight altitude</td>
<td>150 km</td>
</tr>
<tr>
<td>Focal length</td>
<td>61 cm</td>
</tr>
<tr>
<td>Frame format</td>
<td>5.5 cm x 75.7 cm</td>
</tr>
<tr>
<td>Film resolution</td>
<td>160 lines/mm</td>
</tr>
<tr>
<td>Photo scale of the film</td>
<td>1:247,300</td>
</tr>
<tr>
<td>Ground coverage</td>
<td>13.8 km x 188 km</td>
</tr>
<tr>
<td>Best ground resolution</td>
<td>1.8 m</td>
</tr>
</tbody>
</table>

Table 18: Specification of the RapidEye sensor (RapidEye 2009, modified)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Satellites</td>
<td>5</td>
</tr>
<tr>
<td>Spacecraft Lifetime</td>
<td>7 years</td>
</tr>
<tr>
<td>Orbit Altitude</td>
<td>630 km in sun-synchronous orbit</td>
</tr>
<tr>
<td>Equator Crossing Time</td>
<td>11:00 am (approximately)</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>multi-spectral push broom imager</td>
</tr>
<tr>
<td>Spectral Bands</td>
<td>Name</td>
</tr>
<tr>
<td>Blue</td>
<td>Blue</td>
</tr>
<tr>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Red</td>
<td>Red</td>
</tr>
<tr>
<td>Red Edge</td>
<td>Red</td>
</tr>
<tr>
<td>NIR</td>
<td>NIR</td>
</tr>
<tr>
<td>Ground sampling distance (nadir)</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Pixel size (orthorectified)</td>
<td>5 m</td>
</tr>
<tr>
<td>Swath Width</td>
<td>77 km</td>
</tr>
<tr>
<td>Revisit time</td>
<td>daily (off-nadir) / 5.5 days (at nadir)</td>
</tr>
<tr>
<td>Image capture capacity</td>
<td>4 million sq km/day</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>up to 12 bit</td>
</tr>
</tbody>
</table>

Two different study areas in Siberia are investigated: Central Yakutsk and Lena river delta (see Table 15). These regions are covered by various vegetation types and exhibit a vast occurrence of thermokarst lakes under continuous permafrost conditions. Almost 30% of the Lena river delta (within an ob-
served area of 26500 km²) are covered by water bodies, in Central Yakutsk large areas of thermokarst lakes occur east of the Lena river.

Figure 31: Location of local landcover analyses sites

An essential part of Earth observation data analysis is the preprocessing of the recorded satellite data. RapidEye data from 2009 to 2011 was provided by DLR/RESA (RapidEye Science Archive) in NITF format (National Imagery Transmission Format) including RPCs (Rapid Positioning Capability) and are corrected for atmospheric effects using the ATCOR2 correction algorithm (Richter 1996). Georeferencing is done applying the provided RPC information with reprojection to UTM WGS84 with a spatial resolution of 5 m. Processed RapidEye data is used as a spatial reference (master) dataset for the relative co-registration and georeferencing of Key-Hole data (declassified Corona data) from the 1960s. The co-registration follows a lake center point correction algorithm (LCPC) (Hese 2008, Sheng et al. 2008) in order to obtain a spatially accurate image matching for the lake change analysis. Afterwards, all relevant images of the test sites are joined to one large mosaic file. For the Lena river delta, seven single Corona stripes and eight RapidEye scenes are used for land cover classification and water change analysis (Table 16: A and C; see also section 6.2.3). A histogram matching routine is applied for radiometric normalization (Richards and Jia 2006). Due to different acquisition dates and atmospheric conditions, adjustments are necessary to produce reasonable corrected mosaics (Table 16: B and D).
Figure 32: Large scale mosaics for RapidEye (on top) and Corona Key-Hole data (below) before (A, C) and after histogram matching (B, D) for the study area Lena river delta.

4.4 Landcover and disturbances

4.4.1 Pan-arctic scale - synthesizing earth observation information from multiple information sources

The land cover and the surface texture are affected by the seasonal thawing dynamics of the uppermost permafrost layer (active layer). This layer varies in depth from several centimeters in high northern latitudes to a few meters in the sporadic permafrost zones. Within the different permafrost zones the land cover types vary from lower vegetation species to shrublands and large boreal forest areas as result of seasonal dynamics of the active layer (Anisimov & Reneva, 2006).

There is clear evidence that changes in vegetation cover and composition need to be monitored at different spatial and temporal scales, thus ranging from local increases in shrub/tree cover or water bodies to increases in above-ground production, phenology and disturbances of arctic tundra and boreal forest vegetation across large regions (i.e. see Myneni et al., 1997; Neigh et al., 2008; ACIA, 2004; Walker et al., 2011). As an important indicator land
cover is commonly incorporated into models predicting permafrost distribution (Gruber & Hoelzle, 2001).

Land cover is one of the parameters measured with remote sensing systems. For operational land cover observations and continuous permafrost monitoring the different spatio-temporal scales have to be considered (Townshend et al., 2008; Neigh et al., 2008). For observation of large areas of land cover integrated approaches with coarse resolution (e.g. MODIS), fine-scale satellite data (e.g. SPOT) and in-situ observations are most suitable (Herold et al., 2008).

Analysing the vegetation structure and dynamics on pan boreal scale, global land cover, fire and phenological products will be utilized (Table 17). The aim is to use existing global products to regionalize patterns and processes through integrating and synthesizing earth observation in-formation from multiple information sources.

The user feedback has shown the need of area percentage information for different land cover types (trees, shrubs, herbaceous and barren areas) and disturbances (fire information). The user requirements have also shown the need of the seasonal dynamics of vegetation development (LAI). The methodology and processing chain on pan-arctic scale are strongly connected to the user’s needs.

Table 19: Data products overview

<table>
<thead>
<tr>
<th>data products</th>
<th>spatial resolution</th>
<th>temporal resolution</th>
<th>time series</th>
</tr>
</thead>
<tbody>
<tr>
<td>land cover</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODIS Land Cover</td>
<td>500 m</td>
<td>yearly</td>
<td>2001 – 2007</td>
</tr>
<tr>
<td>GLOBCOVER</td>
<td>300 m</td>
<td>-</td>
<td>2005/2006</td>
</tr>
<tr>
<td>SYNMAP</td>
<td>1 km</td>
<td>-</td>
<td>1991 and 2000</td>
</tr>
<tr>
<td>MODIS VCF</td>
<td>500 m</td>
<td>yearly</td>
<td>2000 – 2005</td>
</tr>
<tr>
<td>vegetation dynamics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLOBCARBON (LAI)</td>
<td>1 km</td>
<td>monthly</td>
<td>1998 – 2007</td>
</tr>
<tr>
<td>fire affected area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODIS BA</td>
<td>500 m</td>
<td>monthly</td>
<td>since 2000</td>
</tr>
<tr>
<td>GlobCarbon BA</td>
<td>1 km</td>
<td>monthly</td>
<td>1998 - 2007</td>
</tr>
<tr>
<td>Terra Norte BA</td>
<td>1 km</td>
<td>monthly</td>
<td>2000 - 2006</td>
</tr>
<tr>
<td>ATSR World Fire Atlas</td>
<td>1 km</td>
<td>monthly</td>
<td>since 1995</td>
</tr>
</tbody>
</table>

The yearly MODIS land cover product with a spatial resolution of 500 m (Friedl et al., 2002) and the GlobCover land cover map (Arino et al., 2007a) are the most established global land cover products made by remote sensing data. Land cover products which use input-data from various remote sensing platforms like the SYNMAP showing a synergetic combination of the land cover products as a best estimate classification (Jung et al., 2006). Also the MODIS VCF (vegetation continuous field) provides information about the cover percentage of trees, herbs and barren within a 500 m pixel as utilizable land cover information (Defries et al., 2000; Hansen et al., 2002). There are future prospects to map forest cover and biomass via multi-temporal data from SENTINEL-1 (Attema, 2005; Attema et al., 2008).

Vegetation dynamics could be represented by phenological products like the MODIS phenology product which analyzes and detects changes from the EVI by a moving window approach (Zhang et al. 2003).

The influence of fire on land cover could be designated by various fire products. GlobCarbon provides a fire product based on ATSR-2, AATSR and SPOT-Vegetation satellite data (Roy & Boschetti, 2008; Simon et al., 2004). By using the World Fire Atlas (WFA) it is possible to identify fire hotspots since 1995 (Arino et al., 2007b). With a spatial resolution of 500 m the MODIS fire product is mapping burned areas via changes in reflectance of the spectral bands (Roy et al., 2002; Roy et al., 2005).

One of the key issues was the harmonization of different land cover products. A harmonization is a process whereby the similarities between existing
datasets are emphasized and inconsistencies are reduced (Herold et al. 2006). To extract the cover percentage information for different land cover classes the detailed legend description of the products were used to define cover information for trees, shrubs, herbaceous and barren areas. This information was then linked to the MODIS VCF product, which already provides information about the cover percentage of trees, herbaceous and barren land. Finally the Version 1 datasets consist of four layers, describing the percentage information for each class, with a spatial resolution of 1 km (Figure 31- on top). By summarizing all four layers each pixel ends up with a value of 100%. More information about the version 1 land cover product can be found in Urban et al., 2010. The land cover product version 2 was improved by using the Circumpolar Arctic Vegetation Map from Walker et al. (2002). The aim was to exclude cover percentage misclassification from trees in the arctic tundra regions to improve the representation of cover information within the taiga tundra transition zone (Figure 31- below). This is mandatory since the modelling group needs an exact definition of land cover types by distinguishing between forest and non-forest information in the high latitudes regions.

To represent the seasonal vegetation dynamics on pan-arctic scale the LAI product from GlobCarbon with a spatial resolution of 1 km was utilized. This product is generated by using ATSR-2, AATSR and MERIS data from the ENVISAT satellite. More information can be found in Plummer et al., 2007a-c.

Pan-arctic fire information is presented by using different burned area and active fire products. Due to different temporal and spatial resolutions it is useful to combine different products to build a fire affected area database. This database provides information about the fire affected areas including quality/confidence values. In detail, a pixel with a value of 1 indicates that only one of the four fire datasets has detected a burn scar or fire hotspot. However, a pixel value of 4 indicates that three of the used datasets had detected a burn scar and the active fire product also classified this pixel as fire hot spot.
Figure 33: Pan-Arctic land cover product (Version 1 – on top and Version 2 - below) providing percentage cover information for vegetation physiognomy and barren areas (Legend: R (%-herb); G (%-shrub); B (%-tree), non-vegetated areas are displayed in black).
4.4.2 Validation of the pan-arctic products

Landcover

All pan-arctic products have been validated using medium-resolution Landsat imagery. To assess the accuracy of the pan-arctic land cover product the Landsat scenes were classified into the four land cover classes used in the pan-arctic land cover product (Urban et al., 2010) (trees, shrubs, herbaceous and barren areas). For the validation of the burned areas, a burn scar detection classification was applied on the Landsat reference. To validate the GlobCarbon LAI product, LAI values were extracted from the Landsat bands.

By using a fishnet method the accuracy of the coarse resolution products were assessed (Figure 32). In detail, the Landsat imagery with a spatial resolution of 30°m where overlaid by the 1 km fishnet grid cells which are based on the spatial resolution of the pan-arctic product. The 1 km fishnet grid was the basis for the extraction of sampling points. In average 200 sampling cells were used for each Landsat scene in the accuracy assessment.

![Figure 34: Fishnet over Landsat reference and land cover product](image)

The accuracy of the land cover information has been assessed for three zones (tundra – taiga-tundra transition area – taiga) (Table 18). The burned area products, which were integrated into the fire affected area dataset, were validated for the test region around the town Yakutsk. The GlobCarbon LAI product was validated for a north – south transect in the oblast Yakutia.

For the validation of the tundra regions (zone 1) the accuracies for the cover percentage information of shrubs, herbaceous and barren areas were assessed. The validation was carried out for three test areas – North Slope, Alaska, Taymir and Chokurdakh, Russia. The result for the North Slope region has shown a great agreement between the Landsat. The overall accuracy for this test region is 91 % for shrub, 78 % for herbaceous and 85 % for barren areas. The test site Chokurdakh results accuracies of 87 % for shrub, 66 % for herbaceous and 74 % for barren. The validation of the test area at the Taymir peninsula has shown an overall accuracy of 90 % for shrub, 72 % for herbaceous and 80 % bare soil.

The validation for the transition zone between taiga and tundra (zone 2) is done for three selected test sites in Canada, the northern part of Yakutsk in Russia and Alaska (Figure 33).
The accuracy of the pan-arctic land cover product within the taiga-tundra transition area is ranging from 44.7% to 87.9%, where the classifier tree is showing the lowest overall accuracy and barren the highest overall accuracy. The herbaceous layer shows also low accuracies with an overall accuracy of 55%. The validation of the percentage cover information from shrubs and barren areas are showing an accuracy of 67.5% and 97.9%. A detailed overview of the matrices can be found in the Production and Validation Report [AD-12] on page 51 – table 14.

Since the validation of zone 2 only focused on the transition zones between taiga and tundra, low accuracies, especially for trees, shrubs and herbaceous vegetation are expected. These transition zones represent a mixture of different vegetation classes and are frequently classified as mosaic classes in global land cover products. Bicheron et al., (2008) pointed out, that “...the Globcover land cover map contains a significant amount of mosaic classes, which may limit the thematic sharpness of the Globcover product and its relevancy to derive very specific products.” This assumption is likely the cause of the resulting low accuracies. Additionally, it can be highlighted, that a validation of a global land cover product is always a challenging issue, which is influenced by mixed pixel, the spatial resolution and precise geolocation of the reference data (Herold et al., 2006).

The validation of the tree cover information from zone 3 (boreal region) was carried out for two test sites in Canada and two test sites in Russia. The results have shown the highest accuracies for the tree cover information for the test sites in Russia (87% - 97%). The test sites in British Columbia and Quebec has shown an agreement between the reference and the pan-arctic land cover product from 83% to 86%.

An overview of the calculated accuracies for all test areas and validation zones can be found in Table 18.
Table 20: Results from validation of the pan-arctic land cover product

<table>
<thead>
<tr>
<th>Validation Zone</th>
<th>Description</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Arctic Coastline (Tundra)</td>
<td>Shrubs: 87 - 91 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Herbaceous: 66 - 78 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barren: 74 - 85 %</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Taiga-Tundra Transition</td>
<td>Trees: 44.7 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Herbaceous: 55 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shrubs: 67.5 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barren: 87.9 %</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Boreal Region (Taiga)</td>
<td>Trees: 83 – 97 %</td>
</tr>
</tbody>
</table>

In Figure 34 the agreement between the Landsat reference, the pan-arctic land cover product and GlobCover 2009 is visualized. The Landsat classification shows similar structures like the pan-arctic land cover product, especially for the forested and shrub land areas. Some differences could be caused by the different spatial resolution. For this specific case there is almost no agreement between the Landsat reference and the pan-arctic land cover product in comparison with the GlobCover 2009 classification.

Figure 36: Comparison of Landsat, DUE Land Cover Product and Globcover 2009.

GlobCarbon LAI

The validation for the GlobCarbon LAI product was done for three selected test regions along a transect ranging from the Lena River Delta system in the north to the town of Yakutsk in the south. In total 24 Landsat images were taken. The temporal coverage of the reference data is 2000 to 2006. For the accuracy assessment only images from the summer season were taken. Since the GlobCarbon LAI values are monthly means, it was the goal to use Landsat reference information from the same month to assure that the GlobCarbon LAI is comparable to the reference information. One of the main focus was to
choose a LAI equation which seems to be the most comparable to the GlobCarbon algorithm.

For the year 2000 the comparison of the GlobCarbon LAI and the Landsat reference for the northern validation area results in accuracies ranging from 25 % to 62 % (R). An example of the correlation can be found in Figure 35.

![Figure 35: Comparison of Landsat LAI and GlobCarbon LAI for the northern parts of Yakutia.](image)

The comparison of the GlobCarbon LAI and the Landsat reference for the northern validation area for the year 2002 results in accuracies ranging from very low correlation of 7 % to fair correlation of 53 % (R). Nevertheless, much higher correlation between the Landsat reference and the GlobCarbon LAI product can be found for the middle part of Yakutia with values ranging from 33 % to 73 % for the year 2000. The same results can be found for southernmost area around the town Yakutsk. Here accuracies between 37 % and 56 % are reached. In all cases, the result of the accuracy assessment has shown an underestimation of the GlobCarbon LAI when compared to the Landsat reference.

One of the most challenging tasks in the comparison of the LAI values from Landsat and GlobCarbon is the definition of the algorithms which is used to extract the LAI information. Even if the same algorithm was taken here (Chen et al., 2002) different implementations can be a reason for a reduced
comparability. Additionally, the amount of reflected solar radiation, which varies between different sensors, can be highlighted as error source. To solve this problem, a radiometric correction of both Landsat and ENVISAT data, which were used to calculate the LAI, need to be done prior to the calculation. In this case, this was not possible, since the GlobCarbon product only provides the final LAI values and no raw data. Another source of error can be the different spatial resolutions of the reference and the LAI product. In situ LAI information would be a useful source to quantify the differences/errors of the Landsat and GlobCarbon LAI values.

**Figure 38**: Comparison of three coarse resolution burned area datasets with the Landsat reference
The validation of the three burned area products, which were used to create the fire affected area dataset, was done using eight Landsat 7 ETM+ scenes for the years 2001 and 2002 covering the area around the town of Yakutsk. To extract the burn scar information from the reference data, a difference Normalized Burn Ratio (dNBR) (Lutes et al. 2006) was applied.

The validation was done for two global datasets; MODIS burned area (MCD45A1) and GlobCarbon; and one regional burn scar product; the Terra Norte burned area.

The results have shown that the regional burned area product from Terra Norte has shown the highest accuracies ranging from 60 % to 97 % in comparison to all reference scenes. Moreover, the burn scar product from Terra Norte tends to under-represent the burn scars in comparison to the Landsat reference.

The MODIS burned area product has shown similar accuracies like the product from Terra Norte with correlation values ranging from 48 % to 84 %.

The burned area estimates from the GlobCarbon dataset has shown the lowest accuracies in comparison with the reference. The highest correlation between the product and the Landsat reference data was 62 %. It was found, that the GlobCarbon burned area dataset shows the highest amount of over-classification in comparison the reference data. For each dataset two examples are given in the Figure 36.

### 4.4.3 Local scale analyses

Varying characteristics of permafrost are influenced by climate, precipitation (rain/snow), presence or absence of water bodies, vegetation, soil characteristics and topography. Vegetation structure and land cover information are important indicators of permafrost and therefore commonly incorporated into models predicting permafrost distribution (Gruber and Hoelzle 2001).

The land cover classification is done by utilizing an object based classification approach. Object characteristics (shape, spectral properties and information within different hierarchical object levels) are used to analyze vegetation class properties and to assign each image object to a thematic class. Land cover is analyzed using RapidEye data, the technical specifications of the RapidEye sensor can be found in section 4.3.2.

Subject of the land cover analysis are three different test sites: Central Yakutsk and Lena river delta (Siberia) as well as North Slope (Alaska). These regions are covered by different vegetation types consisting of meadow, grass and shrub-dominated areas up to large areas of coniferous forest. Each test site exhibits high numbers of water bodies. The satellite scenes of all regions are affected by cloud coverage.

Preprocessing is done as described in section 4.3.2, main constituents are orthorectification, atmospheric correction and mosaicing (a mosaic is created only for the Lena delta test region).

For the land cover classification several thematic layers are initially generated pixel-based for supporting the segmentation and classification algorithms such as a brightness layer (reflects the intensity of the gray values), NDVI layer (used to determine vegetation conditions) and the filtered standard deviation of the brightness (to distinguish between spectral homogeneous and heterogeneous areas).

The segmentation approach follows a multiscale segmentation method. After an initial segmentation the objects are reshaped using different segmentation methods at an either higher or lower scale. Afterwards, different land cover classes (depending on the quality of the reference data for each test site) are processed by interpreting several object features (NDVI, brightness, proximity to other classes, homogeneity). Maps and statistics of the classification results are exported (Figure 37). In order to increase processing speed, a tiling and stitching routine is used to derive land cover information of large areas. An overlap of 10 % of the generated tiles guarantees the creation of meaningful objects and avoids border effects.
The resulting datasets provide information of the derived land cover class for each object, stored as attributes in the vector dataset. As an example, the results of the land cover classification for the Lena river delta are described hereinafter. A total area of 27600 km² was classified analyzing the RapidEye mosaic with 5 m spatial resolution. Almost 30% of the classified area belong to rivers or lakes, most of the greater lakes are situated in the north-west. Four different vegetation types are classified: dry and wet mosses and sedges appear to be the main vegetation types, representing approximately 50% of the land cover, while the mixed class moist to dry dwarf shrub-dominated tundra represents 8.2% of the study area. Non-vegetated areas primarily occur at the riverbank, along with grassland they are the rarer land cover types in the Lena river delta as it is shown in Figure 38.
To assess the accuracy of the land cover classification, a stratified sampling design was chosen. An expert vegetation classification provided by partner AWI, based on work from Schneider, Grosse and Wagner (2009) serves as reference data and is used to validate the classification results based on stratified random sampling points (50 points per class). A confusion matrix is generated in order to enable statements about the user and producer accuracy of each class.

In comparison to the reference data, the classification shows an overall accuracy of 76.33 %. With regard to the spectrally different input data of the mosaic this classification represents a reasonable result. Figure 39 outlines the accuracies of the single land cover classes in respect of commission and omission errors. Water bodies and wet sedges/mosses turn out to be the most accurately classified land cover objects. The user accuracies of the different vegetation types vary from 0.62 for moist to dry dwarf shrubs (the class with the lowest accuracies) to 0.88 for wet sedges and mosses. Mainly non-vegetated areas exhibit a distinct difference between omission and commission error. False classifications are caused by alterations of the Lena river (sedimentary deposition) within the interval between reference and classified data as well as by vegetation growth, cloud and ice coverage. Cloud shadow induces difficulties delineating water bodies accurately.

The accuracy assessment of the Lena delta land cover classification is complicated by the fact that the reference data itself is derived partly by a supervised earth observation data classification through partner AWI Potsdam and ground reference data was limited to very few regions. Also the comparison of pixel based and object oriented classification methods as well as the different resolutions of the datasets (Landsat and RapidEye) causes some errors. Furthermore, the quality of the data mosaic and the positional accuracy between reference data and classification are crucial when validating the classification results.

Validation of classification results for the study areas Central Yakutsk and North Slope was impossible due to missing spatial high resolution reference data coverage.
4.4.4 Evaluation of Land Cover by the User Communities

Global Land Cover derived from optical satellite data serve as external input data into permafrost and climate models: the Land Cover2000 (LC2000, http://bioval.jrc.ec.europa.eu/products/glc2000/products.php), Ecoclimap (http://www.cnrm.meteo.fr/gmme/PROJETS/ECOCCLIMAP/frame_text_ecoclimap.html), GlobCover2009 (http://ionia1.esrin.esa.int/) and potentially the DUE Permafrost vegetation product with the percentages of vegetation structure (tree layer, shrub layer, grass layer, barren) derived from GlobCover2009 and merged with the Circum-Arctic Vegetation Map CAVM. How valid are these land cover products for the high-latitude 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. The high-spatial resolution mapping provides a correct parameterization for coarser-spatial resolution LC products. Muster et al. (submitted 2011, accepted) 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. Muster et al. (submitted 2011, accepted) investigated how to link plot measurements of evaporation with aerial data and scale up to medium-scale land cover (Landsat 30 m resolution). The authors state that a large portion of the total wet tundra (80 %) and water body area (30 %) appeared in form of patches less than 0.1 ha in size which could not be resolved by Landsat satellite data. Wet tundra and small water bodies represented about half of the total evapotranspiration in summer. Morgenstern et al. (2008) calculated that Landsat derived water surface area for all the lakes (thermokarst and floodplain lakes) excluding the the Lena river and all the river side arms (including the rivers accounts for ~ 30 % surface water area) accounts for 13 % total lake area in the Lena River delta. Muster et al. (submitted 2011, accepted) extracted from the Landsat reflectances the subpixel-scale of the water body ratio and added 7 % water surface area from water ponds for the wet-polygonal tundra of the Lena River Delta.
Figure 42: Landsat mosaic (2001), Lena river delta (Siberia). Percentage of sub-pixel-scale open water for each of the nine k-means classes. White areas were not included in the classification as they are not spectrally representative of the ice-wedge polygonal tundra on Samoylov Island. Orange boundaries indicate the second terrace, red boundaries the third terrace of the Delta. The remaining area is the first stratigraphic-topographic terrace that is characterized by ice-wedge polygonal tundra. (in: Muster, Langer, Heim, Boike, Subpixel heterogeneity of ice-wedge polygonal tundra: A multi-scale analysis of land cover and evapotranspiration in the Lena River Delta, Siberia; submitted 2011, accepted)

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 41) in exchange with other Arctic programmes.

Figure 43: 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.

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.

Another outcome of the ESA-DUE Permafrost–NASA Land-Cover and Land-Use Change LCUCL Yamal Workshop (January 2011) has been the joint YAMAL2011-expedition of the teams of the Earth Cryosphere Institute (ECI), Siberian Branch of the Russian Academie of Science, RU; the University Virginia, US; the University of Alaska Fairbanks, US; and the Alfred Wegener Institute for Polar and Marine Research (AWI), DE that took place as part of the NASA Yamal Land Cover/Land Use Change (NASA Yamal-LCLUC) program during the period from 11th July to 9th September 2011. The AWI-project 'hyperspectral Arctic VEGetation Indices’ (hy-Arc-VEG) is funded by the national preparation program for the Environmental Mapping and Analysis Program, EnMAP (German hyperspectral space mission) under the contract number DLR/BMWi 50 EE 1013.

The main research goals addressed were to measure the spectro-radiometrical characteristics of tundra biomes to investigate vegetation variables such as Normalized Differenced Vegetation Indices (NDVI), Leaf Area Index (LAI), fraction of Absorbed Photosynthetically Active Radiation (fAPAR) for tundra. The Bidirectional Reflectance Distribution Function (BRDF) characteristics of low-growing tundra biomes have not been investigated in depth so far (Vierling et al., 1997). The anisotropy measurements were carried out using an the AWI developed field spectro-goniometer Eyesight (patented in 2011). First results show for tundra réleve plots with 10 to 15 % vascular plant cover on 100% moss cover the mirror asymmetry with respect to the principal plane. The BRDF calculations also show the maximum scattering displaced in the backward direction, but no minimal forward scattering as it is the theory for the BRDF characteristics of vegetation. Instead, the forward scattering from the moss-dominated tundra type is characterised by similar to higher reflectance values in the forward scattering direction The calculated NDVI shows the BRDF effect with different band width and center positions (MODIS, MERIS, EnMAP).

![Figure 44: NDVI comparison (AVHRR, MODIS, EnMAP) at the NASA- Greening of the Arctic (GOA) site Vaskiny Dachi-1, Yamal (Siberia), AWI-Eyesight BRDF measurements, GOA releve25 (2012-08-29).](image-url)
4.5 Terrain

Information on surface topography and on change in surface topography is fundamental over permafrost regions. According to the characteristics and possibilities of Earth-Observation (EO) technologies we distinguish within our project between Digital Elevation Models (DEM), on one side, and surface subsidence, on the other side. The former is compiled at global scale from available data sources and derived at local scale from optical stereoscopic pairs and SAR interferometry (InSAR). The latter is considered at local scale with use of differential InSAR. Various sites with different conditions were considered in our project, see Figure 45 for an overview.

![Figure 45: Overview of sites considered for terrain. Background is the Circum-Arctic DEM.](image)

DEM are essential for identifying permafrost-related landforms, for modeling periglacial geomorphology, hydrology, surface energy budget, and matter fluxes resulting from permafrost degradation, and for satellite images orthorectification. On the circum-arctic scale a minimum requirement for a DEM is 100 m grid cell resolution and a vertical accuracy of 0.5 m to be produced on a decadal scale. Such a DEM would complement the SRTM DEM at the northern latitudes >60º. On local scales, much higher resolutions (0.5 m to 10 m), accuracies (5 cm) and temporal sampling (annual scale) are necessary to detect, classify and quantify permafrost related surface features and related processes.

Permafrost regions are distinguished by the ubiquitous although variable presence of ice below the surface. Ice-rich layers are usually close to the surface and are the first to be melted by increases in downward heat energy flux due to changes in the surface energy balance. The immediate result is subsidence. The position of the Earth surface is thus the only direct measure of permafrost change, in particular of its disappearance due to warming. Change detection relies on repeat acquisitions of snow-free elevation or relative elevation in late summer to early fall, when the annual freeze-thaw cycle reaches maximum thaw. Changes in elevation can reach decimeters per year. Annual to decadal time scales yield interannual and decadal variability in subsidence. Local coverage at a spatial resolution of 10 m would allow the identification of key sites for monitoring and adequately indicate regional scale climate changes. Required vertical accuracy is 1 cm at the end of the summer over several years [AD-3].
4.5.1 Circum arctic DEM

As a primary source for terrain elevations a global DEM is very convenient. DEMs covering circum-Arctic landscapes at a spatial grid-cell resolutions of 1 km (e.g. GETASSE, ACE, GLOBE30) are inadequate for identifying permafrost-related landforms. The global ASTER GDEM was created by stereo-correlating the 1.3 million archived ASTER VNIR scenes, covering the Earth’s land surface between latitudes 83º north and 83º south. Version 1 was released in the Summer of 2009 with a spatial grid-cell resolutions of 30 m (http://asterweb.jpl.nasa.gov/gdem.asp). However, due to its dependency on the availability of suitable cloud-free optical ASTER stereo images, the quality and accuracy of GDEM varies significantly globally. In addition, artifacts and voids are largely present and let us conclude not to consider the current release of the ASTER GDEM within our project.

Complete topographic data is also freely available from various other sources:

- SRTM-3 DEM (Shuttle Radar Topography Mission) up to 60º latitude;
- RTM (Russian Topographic Maps) for much of Western Europe and Asia;
- CDED (Canada Digital Elevation Data);
- U.S. Geological Survey DEM (for Alaska);

These DEMs were commonly digitized from contour lines that were derived from aerial photogrammetry. The detailed procedures for DEM derivation, however, might vary significantly and are not in all cases well documented. There are different releases of the DEMs provided at different spatial grid-cell resolutions. For the purposes of our project a regional scale DEM at 3” resolution, similar to that of SRTM, is well suited and was therefore created by homogenizing the above mentioned data sets (Figure 42).

The SRTM DEM is an elevation dataset available for all land masses between 60 degrees N and South. For the DUE Permafrost project the 3-arcsec version 4.1 provided by the Consultative Group on International Agricultural Research / Joint Research Centre (http://srtm.csi.cgiar.org) is used. This is a void-filled version of the version 2.0 dataset provided by NASA JPL. The data is available in tiles of 5×5 degrees, in equiangular projection, at 3 arcsec spatial resolution. Quality reports are provided in (Rabus et al., 2003) and on the CGIAR website.

The dataset of Russian Topographic Maps stems from digitized maps at 1:200,000 scale, available at http://www.viewfinderpanoramas.org. The dataset covers all land masses above 60 deg N, with the exception of North America. The DEMs are provided as SRTM-like tiles (version 2), i.e. covering 1×1 deg, with 3-arcsec posting. There are no official reports on data quality and accuracy, however the data producer ensures the highest possible quality and provides examples on the quality of the dataset on the website. A comparison with the National Land Survey (NLS) elevation dataset of Sweden (Santoro & Cartus, Deliverable 3 of the STSE-BIOMASAR Project, 2009) indicated an average elevation difference of 1.4 m and a standard deviation of 16.6 m. Only very local mismatches in form of shifts of the order of a couple of hundred meters were noticed.

The Canadian DEM dataset consists of maps at 1:250,000 extracted from the hypsographic and hydrographic elements of the National Topographic Data Base (NTDB) or various scaled positional data acquired from the provinces and territories. The time period covers the years 1945-2010. The horizontal accuracy is related to the data source(s) used to generate the CDED. A comparison with SRTM-3 data has been carried out when preparing the Global DEM database for latitudes where both elevation datasets are available. The agreement was high in the horizontal and the vertical direction. This however does not imply that the accuracies are similar for the entire

The USGS elevation dataset provides coverage in 1×1 degree blocks with 3 arcsec resolution for all of the contiguous United States, Hawaii, and most of Alaska. The basic elevation model is produced by or for the Defense Mapping Agency (DMA), but is distributed by the USGS, EROS Data Center, in the DEM data record format. In reformatting the product the USGS does not change the basic elevation information. 1-degree DEM’s are also referred to as "3-arc second" or "1:250,000 scale" DEM data. The topographic features (e.g., contours, drain lines, ridge lines, lakes, and spot elevations) are first digitized and then processed into the required matrix form and interval spacing. The quality check of the USGS dataset revealed data gaps in the data Lat: 68/69 N / Long: 149/147 W and Lat: 64/65 N / Long: 164/163.5 W. In addition, the tile covering Lat: 61/62 N, Long: 163/162 W looks as stretched along the N-S direction.

The database of elevation provided to the DUE Permafrost project consists of tiles with following specification (SRTM standard tiling system):

- Latitude coverage: > 55 deg N
- Longitude coverage: full
- Elevation: as in original datasets
- Projection: equiangular, i.e. latitude/longitude
- Ellipsoid/datum: WGS-84
- Tile coverage: 1×1 deg
- Posting: 3 arcsec = 0.0008333333 deg (i.e., approximately 90 m at Equator)
- File name coding: NyyWxxx.hgt (western hemisphere), NyyExxx.hgt (eastern hemisphere)
- File format: Plain binary Short integer
- Byte order: big endian
- Width: 1201 pixels
- Length: 1201 pixels

### 4.5.2 Local scale DEMs

At local scale DEMs from high resolution satellite optical data and space-borne SAR interferometry were created to complement and enhance the circum-arctic DEM. Availability of optical data is constrained by the short snow free period and high data costs, but Ikonos and Quickbird can provide vertical accuracies of < 1 m and horizontal accuracies of 5-10 m, i.e. what is required on an annual basis on local scale. Given the large baseline and short time interval, ERS-ENVISAT cross-interferometry has the best potential for the generation of precise DEMs in relatively flat areas, e.g. wetlands. DEMs from mapping agency, high resolution DEMs compiled by the users, ground levelling data, and GCPs served as a validation for the local DEMs.

Local scale photogrammetric processing of ALOS-Prism Triplets (ground sampling distance 2.5m) has been carried out within three service case regions. The analysis has been made for central Yakutia (Russia), Polar Bear Pass (Canada) and a site at the Yamal peninsula (Russia, Ob service case region). ERDAS LPS 2010 has been used for orientation of the images and surface point extraction (correlation threshold 50). OPALS was used for surface interpolation. An additional DEM with the same methodology was created over Austria for assessment with Laser scanner data.

---

In accordance with users, the following geographic locations for local scale DEMs were selected:

1. Polar Bear Pass, Bathurst Island, Nunavut, Canada (75°40'N, 98°30'W);
2. Mackenzie River Delta, Northwest Territories, Canada (65°-70° N, 136.5°-132° W)
3. Central Yakutsk, Sibiria, Russia (61°-63° N, 129°-133° E)
4. Yamal Peninsula, Sibiria, Russia (68°-71° N, 68°-71° E)

**Polar Bear Pass**

The Polar Bear Pass wetland area on Bathurst Island is the second largest wetland in the Canadian Arctic Archipelago with a coverage of 20 x 5 km². The wetland is bordered in the North and South by hills up to 300 m. Runoff from the adjoining hills is effective in moving both water and matter into the wetland zone. Surface topography is important in determining the characteristics of water fluxes that can vary significantly over comparatively small distances and have control over transport and delivery of nutrients and carbon in the wetland. For example, surface runoff during snowmelt period is the main water and carbon source in northern wetlands. A high resolution DEM allows the identification of possible surface inputs and differences in rate and direction of water movement when considered together with other water balance components (e.g. seasonal precipitation). Also, variability in local topography available from the high resolution DEM helps to show the extent of water storage and spatial connectivity between wetland units.

![Figure 46: (A) InSAR DEM and (B) ALOS DEM with lakes and rivers over Polar Bear Pass.](image)

DEMs were derived using two InSAR pairs of ERS2-ASAR from 2009.02.16 and 2009.03.23 and an ALOS PRISM triplet. The relative accuracies of the DEMs were evaluated by comparing them to tachymeter surveys conducted in the field in summer 2008. Survey area encompasses hill slope and low lying wetland. A total of 1341 survey points were available.
covering an area of about 0.5 km². The mean relative height difference between field surveys and the InSAR DEM is -0.1 m ± 0.7 m. The ALOS DEM features a higher elevation than the InSAR DEM with a mean deviation of 14.5 m ± 3.6 m. Differences are highest in areas with steep slopes over short distances. An assessment of the absolute accuracies of the DEMs is not possible as no DGPS measurements have been conducted in the field.

The InSAR DEM presents a unique high-resolution data set of topographic information in the Canadian High Arctic (Figure 43). Height sensitivity is high: the DEM shows the elevated position of the old flood plain within the valley and features the main drainage pathways from North and West to East towards the ocean. Although the ALOS DEM has about the same spatial resolution (10m), it does not resolve the wetland topography as clearly. Also, ALOS DEM features several artefacts.

**Mackenzie River Delta**

An ERS-2 – ENVISAT Tandem (EET) pair acquired on 2009.03.10 over the Mackenzie River in Northern Canada was also analyzed. The interferogram showed high coherence over many parts of the scene, but we failed in generating a DEM over this area because of high spatial phase gradients which prevented us from finding a reliable unwrapping solution. In spite of this the interferometric phase and coherence, as shown in Figure 44, contain interesting information over this area.

**Figure 47:** EET InSAR differential phase relative to CDED (left, a color cycle corresponds to a phase cycle) and RGB composite of the coherence (red) backscattering (green) and backscatter change (blue, right) of Mackenzie River Delta. Yellow boxes indicate Sections 1 to 4 which are discussed in Wegmüller et al. (2009). The size of this area is approximately 100km x 300km.

**ALOS PRISM DEMs: Central Yakutsk and Yamal Peninsula**

From the images only points on the surface can be extracted where the image contrast is large enough, therefore the distribution of the extracted surface points depends on the image content and will vary over the area. Thus the quality of the surface description (its resolution) is not homogenous over the area.

The grid width used for the DEM is 10m (which is 4 times the ground sampling distance of the original ALOS images of 2.5m). In order to docu-
ment the quality of the surface description a so-called chamfer image was created also which is co-registered to the DEM. The chamfer image stores in each cell the distance to the closest cell which contains extracted surface points. From this one can clearly see that no points were e.g. extracted in the river regions, most points are extracted in the city areas.

Figure 48: ALOS PRISM DEM of Central Yakutia (bottom right)

For Yamal two triple images from 2007.07.09 plus the nadir image from 2010.07.05 (too many clouds in the whole triple) have been used. Using the software Leica Photogrammetry Suite 2011 (LPS) we improved the orientation of the images using ca. 100 tie points and 26 ground control points (GCPs). The GCPs were obtained in Google Earth (longitude, latitude) – thus their quality is not very good. The GCP’s heights were then interpolated from an ASTER DEM of that area. Afterwards using only the forward and backward images surface points were matched using LPS. Then a DEM with raster size 10m was interpolated from these points using the software Opals. The gap areas in between were filled using a TIN. Finally using this DEM ortho-images were computed for the six images. The following Figure 46 shows the DEM as shading, the distribution of the originally matched surface points and two nadir ortho-images.

Figure 49: DEM of ALOS scene “Yamal”: left) shading, middle) distribution of originally matched surface points, right) ortho photo. Note that surface points can only be matched at locations of good image texture (e.g. grey edges). Therefore the point distribution is very inhomogeneous. (Covered area: 39 x 66 km²)
Only very limited in-situ observations have been available for the three sites. A user assessment is available for Polar Bear Pass [AD-12]. In order to determine the accuracy which can be achieved with the chosen data and methods we applied exactly the same workflow on ALOS PRISM scenes from Austria “North Burgenland” (including GCP provision using Google Earth and ASTER DEM). Afterwards the DEM with a raster width of 10 m derived from LPS and Opals was compared with a reference DEM derived by airborne laser scanning (accuracy 1 dm), which was kindly provided by the federal government of Burgenland ("Amt der Burgenländischen Landesregierung, Landesamtshauptamt, Stabstelle Raumordnung – Referat GIS-Koordination").

The comparison was done by computing a spatial similarity transformation from the ALOS DEM onto the ALS DEM using least squares matching so that the height differences between both DEMs are minimized. The transformation obtained this way for the ALOS DEM results in median shifts for (X/Y/Z) of (-6/-5/48) [m]. This quantifies the quality of the absolute positioning based on Google Earth and ASTER DEM. The standard deviation of the height differences between both DEMs results to 2.0 m, which corresponds to 0.8 pixels in an ALOS image. This quantifies the geometric quality of the surface representation based on the LPS image matching. However, one must keep in mind that the surface points are very inhomogeneously distributed, and the DEM quality naturally depends on the density of the original points. The found value of 2 m is an overall representative for areas where points were matched. In areas without points the DEM quality will be worse. Additionally we can see from the colour coding of the difference between both DEMs (see Figure 47) that the distribution of the differences is not random but a systematic pattern remains. In the middle area parallel to the satellite’s flight direction mainly negative differences occur and mainly positive differences can be seen close to the border. This may be attributed to residual errors in the interior orientation of the ALOS images; e.g. the registration of the sub images.

Figure 50: Colour coding of height differences in the North-Burgenland area between ALOS DEM and reference ALS DEM (superimposed on the shading of the ALOS DEM). The standard deviation of the height differences is 2m. (Covered area: 39 x 33 km²)
4.5.3 Local scale subsidence

Differential SAR interferometry is a powerful technique for mapping from satellite land surface deformation with cm to mm accuracy at fine spatial resolution over large areas (Bamler Hartl, 1998, Rosen et al., 2000). Since many years differential SAR interferometry has developed into a robust technique for subsidence monitoring in urban and arid areas as a result of ground-water pumping, mining, gas extraction, subsurface tunneling, and natural compaction of sediments. InSAR analyses using long series of SAR data permitted to extend the application from urban areas to regions characterized by a limited number of anthropogenic structures, e.g. mountainous areas. In particular over alpine regions permafrost related instabilities (e.g. rock glaciers) have been widely detected (Delaloye et al., 2007). However, the presence of vegetation and snow-cover remains a strong limitation to SAR interferometry.

The development of SAR interferometry 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) appears to be an excellent opportunity for permafrost-related research. However, the use of this data for permafrost applications is still being developed. Even at L-band, although the coherence is generally high, tundra land cover affects SAR penetration depth on the same spatial scale as elevation differences, primarily depending on soil moisture content and vegetation type. Also snow cover, atmosphere and vegetation can mask the signal of interest.

Local scale studies related to subsidence monitoring with InSAR were conducted in three regions with a total extend of about 300 km²:

1. North Slope, Alaska, USA (70°06' N, 148°42' W);
2. Polar Bear Pass, Bathurst Island, Nunavut, Canada (75°40'N, 98°30'W);
3. Tuktoyaktuk, Northwest Territories, Canada (69°43' N, 134°05' W).

In-situ observations for validation are sparse in all sites, although boreholes are available on North Slope.

Multiple interferograms from different sensors (ERS-1/2, ENVISAT, ALOS, TerraSAR-X) were considered in every case. Multi-temporal short-baseline InSAR analysis (Berardino et al., 2002) was employed in consideration of data availability, land and snow cover and topography. The main results of the SAR interferometric analysis are maps of the averaged displacement rates on coherent targets in the satellite line-of-sight direction and temporal series of displacements on points of particular relevance.

North Slope

On the North Slope of Alaska Liu et al. (2010) applied InSAR with ERS-1/2 data to measure surface deformation over permafrost during the 1992–2000 thawing seasons. They found significantly systematic differences in surface deformation between floodplain areas and the tundra-covered areas away from the rivers. Using floodplain areas as the reference for InSAR’s relative deformation measurements, they found seasonally varying vertical displacements of 1 – 4 cm with subsidence occurring during the thawing season and a secular subsidence of 1 – 4 cm/decade. They hypothesize that the seasonal subsidence is caused by thaw settlement of the active layer and that the secular subsidence is probably due to thawing of ice-rich permafrost near the permafrost table about phenomena.

We considered multiple interferograms from the ENVISAT, ALOS and TerraSAR-X SAR sensors. The dates of the images are indicated in Table 19. Data availability for ENVISAT ASAR data was very limited and interferograms were mainly decorrelated. A large number of ALOS PALSAR data was acquired over North Slope and interferograms showed good coherence values also for time intervals larger than one year and baselines larger than 1000 m. However, the interferograms are largely contaminated by ionospheric artifacts. An attempt to correct the ionospheric contributions based on azimuth
offsets maps, as proposed by Raucoules and de Michele (2010), is still under development in order to possibly retrieve yearly subsidence signals.

TerraSAR-X interferograms with 11 days time interval showed a very good coherence under snow-free conditions and permitted to compute two maps of the averaged displacement rates on coherent targets in the satellite line-of-sight direction for the summer seasons of 2010 and 2011 (Figure 48). As suggested by Liu et al. (2010) floodplain areas were chosen as reference. Temporal series of displacements on selected areas (Figure 49) indicates that subsidence during the thawing season is occurring rather suddenly with maximum displacements on the order of 4 cm. Yearly TerraSAR-X interferograms were largely decorrelated.

Table 21: Dates of SAR data considered for North Slope (YYYYMMDD)

<table>
<thead>
<tr>
<th>ENVISAT ASAR</th>
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<tr>
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</table>

**Figure 51:** Subsidence maps over North Slope from TerraSAR-X InSAR from (left) 13 June to 29 August 2010 and (right) 11 June to 29 September 2011. The stars indicate the reference position, the dot the area where the profiles of Image 5 were extracted. Displacement is in the satellite line-of-sight direction with an incidence angle of ~40°.
Tuktoyaktuk

Tuktoyaktuk is a community in the western Arctic that faces a variety of pressures, as climatic change related permafrost thaw, sea level rise, coastal erosion, and potential subsidence due to resource extraction (Short, 2011). Also for Tuktoyaktuk multiple ERS-1/2, ENVISAT, ALOS and TerraSAR-X SAR data were considered, see Table 20. The ERS and ENVISAT data set was rather limited and interferometric coherence was generally low. Use of these sensors was not possible for this site.

Also the ALOS PALSAR data set was rather limited, but the interferograms showed good coherence values also over years. A short baseline InSAR analysis was thus conducted. As an example, the subsidence map from June 30 2007 to August 4 2009 is shown in Figure 50.

The analysis of the TerraSAR-X data showed a generally good coherence of the interferograms. Major difficulties were found in the removal of the topographic related phase from the interferograms because the quality of the Canada Digital Elevation Data considered for this purpose. Nevertheless, temporal series of subsidence maps were derived for both summer seasons (Figure 50), showing important differences between the two years. The subsidence over the 2009 summer season was smoother, while over the 2010 season we observed for certain areas movements in both upwards and downwards directions. Again, yearly TerraSAR-X interferograms were largely decorrelated.

Table 22: Dates of SAR data considered for Tuktoyaktuk (YYYYMMDD)

<table>
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<td>19950417, 19950522, 19950626, 19950731, 19950904, 19951113, 19951114, 19960122, 19960123, 19960401, 19960402, 19960506, 19960507, 19960820, 19980127, 19990216, 19990323, 19990601, 19990706, 19990810, 19990914, 19991123, 19991228</td>
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</table>
Figure 53: Subsidence maps over Tuktoyaktuk from TerraSAR-X and ALOS PALSAR InSAR. The stars indicate the reference position. Displacement is in the satellite line-of-sight direction with an incidence angle of ~40° for TerraSAR-X and of ~35° for ALOS.

Polar Bear Pass

Over Polar Bear Pass only TerraSAR-X data were considered, see Table 21. The 11 days interferograms showed in many cases decorrelated areas due either to the presence of snow-cover or water or comparatively large incoherent movements. Only in a few cases complete subsidence maps could be derived (Figure 51), showing movements up to 1 cm in the line-of-sight direction. No temporal series of movement could be derived in this case.

Table 23: Dates of SAR data considered for Polar Bear Pass (YYYYMMDD)

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</tbody>
</table>
Figure 54: Subsidence maps over Polar Bear Pass from TerraSAR-X InSAR from (left) 11 to 22 July 2009 and (right) 20 to 31 July 2010. The stars indicate the reference position. Displacement is in the satellite line-of-sight direction with an incidence angle of ~30°.

4.5.4 Conclusions and outlook

A Circum-Arctic DEM was compiled with a 3 arcsec spatial resolution and is available on the DUE PERMAFROST information system for all interested users. In the Autumn of 2011 Version 2 of the global ASTER GDEM was released but its quality for permafrost-related studies was not investigated in the current project. In future, the German Tandem-X will provide a global DEM with an unprecedented vertical resolution of 2m on 12m by 12m grids.

Local scale DEMs were produced from optical stereoscopic pairs for three sites, two in Russia and one in the Canadian Arctic. Lack of ground data limits the possibilities for validation. A similar setup and processing has however been carried out over an Austrian site for which high precision DEM information has been available from LIDAR. The standard deviation for the difference of the elevation sources which could be achieved is approximately 2m.

ERS2-ENVISAT InSAR was investigated for DEM generation at latitudes above 60°N over rather flat areas, i.e. a delta region and a wetland. Well suited InSAR pairs could be identified but the differential interferometric phase showed for most of the areas such strong spatial variations that reliable unwrapping of the phase failed. We conclude that ERS2-ENVISAT InSAR DEM generation over high northern latitudes is not straightforward but indeed very difficult to achieve. On the other hand, over very flat areas (e.g. the wetland over Polar Bear Pass) there clearly exists a good potential to achieve sub-meter precision.

SAR interferometry turned out to be a reliable tool to detect seasonal surface subsidence due to permafrost thaw on many regions thanks to the short repeat interval of 11 days of TerraSAR-X. The time-series of displacement highlighted that subsidence is occurring within a relatively short time period. Similar results are expected in future using the Sentinel-1 SAR sensor which has a similar repeat interval (12 days). In our investigations we found coherent annual interferograms only using the low frequency ALOS PALSAR data, but these interferograms were largely contaminated by ionospheric artifacts and a correction based on the azimuth shift map is still under development in order to possibly detect yearly subsidence signals.

As a side investigation, ERS-1/2 and ALOS PALSAR InSAR data over Brooks Range (Alaska) were analysed. Despite the fact that the external DEM used to remove the topographic phase component was not of very good quality, promising signatures on rock glaciers could be identified (Figure 52). An inventory of slope movements in this periglacial mountain environment, simi-
lar to that produced in Switzerland by Delaloye et al. (2007), is under compilation.

Figure 55: ALOS PALSAR interferogram of July 22 to September 6 2007 with a 241 m perpendicular baseline of active rockglaciers in Brooks Range (black outlines).
The information system consists of two components:

- the Permafrost Processing System – EO (PEO)
- the data portal which facilitates access to the data:
  - Visualization via WebGIS
  - Data download functionality

## 5.1 Processing System

### 5.1.1 General description of the overall processing system

The Permafrost Processing System (PEO) follows a modular approach. This approach was selected to take into account the different data sources and product contributors and to have an easy to adapt solution. As indicated in Figure 53 the PEO consists of the kernel part (red) that contains the database, input and output data interfaces to external, and some data processing functionality.
Figure 56: Data flow diagram of the PEO. Potential derived product generation can be plugged in internally or run externally.

Data processing covers on the one hand general functionality such as re-projection, mosaicking etc, but also the homogenization of some of the products.

5.1.2 Database

The database organizes all the data that are stored permanently on the PEO and that are made available externally. The information consists always of the product, the accompanying meta information and the corresponding log file. The database is organized per product.

The data format depends on the product and is presented in more detail in the corresponding sections below. Meta information and processing log information is in ascii format. Maps are in GeoTiff format (WebGIS interface).

Filenames contain the product date (or period if appropriate), the release version, the processing date, and the software version.
5.1.3 Processing system

The processing system provides the following tasks

1 Retrieval of external products (pull)
2 Upload functionality for external products (push)
3 Data conversion
4 Reprojection
5 Mosaicking
6 Derived Product Generation (potential)
7 Database access
8 WebGIS interface
9 Task Scheduler
10 System Access

These functionalities is implemented as much as possible using Free and Open Source Software (FOSS).

Table 24: Processing System functionalities

<table>
<thead>
<tr>
<th>Task</th>
<th>Solution</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrieval of external products (pull)</td>
<td>Shell scripts based on curl and operated from cron</td>
<td></td>
</tr>
<tr>
<td>Upload functionality for external products (push)</td>
<td>sftp</td>
<td></td>
</tr>
<tr>
<td>Data conversion</td>
<td>Processing chains by partners</td>
<td>Plugin Modules</td>
</tr>
<tr>
<td>Reprojection</td>
<td>Processing chains by partners, Gdal</td>
<td>Plugin Modules, WebGIS Modules</td>
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<tr>
<td>Mosaicking</td>
<td>Processing chains by partners, Gdal</td>
<td>Plugin Modules, WebGIS</td>
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<tr>
<td>Product Generation</td>
<td>Processing chains by partners</td>
<td>Plugin Modules</td>
</tr>
<tr>
<td>Derived product generation</td>
<td>e.g. C program</td>
<td>None implemented, can be plugged in like the Product generation</td>
</tr>
<tr>
<td>Database access</td>
<td>Web, sftp</td>
<td></td>
</tr>
<tr>
<td>WebGis Interface</td>
<td>WMS</td>
<td></td>
</tr>
<tr>
<td>Task Scheduler</td>
<td>Cron</td>
<td></td>
</tr>
<tr>
<td>System Access</td>
<td>ssh</td>
<td></td>
</tr>
<tr>
<td>Operating System</td>
<td>Ubuntu Linux LTS</td>
<td></td>
</tr>
</tbody>
</table>

5.1.4 Interface Definitions

In the following we will discuss the different interfaces (in terms of data format and exchange protocol) between the PEO and the outside world (data providers, users) and the internal interfaces between the different modules.
**Data provider – PEO**

Depending on the data provider and data volume the data is either accessed over the net or read from an attached storage. The data format is given by the data provider. Most data formats are hdf/netcdf based and/or GeoTiff. The WebGIS interface requires GeoTIFF.

**PEO – Users**

The data format is following the User Requirements as specified in the DJF [AD-5]. The data access is through the data portal (section 5.2).

**Internal interfaces**

The internal data formats are whenever possible in the projection of the final product. Intermediate data are stored in raster binary format. Meta and log information as ASCII text.

---

**5.1.5 Product generation Modules**

*Scatterometer Surface Soil Moisture and Surface status*

The ASCAT SSM processing is initiated by a shell script that checks if another task is already running and the initiating the IPF IDL routine ipf_dailynindl_to_ease_runtime.sav in the IDL virtual machine. Input is read from a defined input directory and results are written to a predefined output directory.

The processing is based on ASCAT SSM (Surface Soil Moisture) ascending and descending data preprocessed by the IPF Eumetsat processing chain (Warp 5.2).

*SAR Surface Soil Moisture*

The SAR SSM processing is initiated by a shell script that checks if another task is already running and initiating the IPF JAVA program mosaic-1.2.one-jar.jar. Input and output directories are given on the commandline. The processing is based on ASAR GM data products preprocessed by IPFs SGRT (SAR Geophysical retrieval Toolbox). The resulting ENVI data files are mosaicked, reprojected and converted to GeoTIFF format. The core processing is implemented in Java.

*SAR Water Body (SAR WBO)*

The SAR WBO processing is initiated by a shell script that checks if another task is already running and initiating the IPF JAVA program mosaic-1.2.one-jar.jar. Input and output directories are given on the commandline. The processing is based on ASAR WS data products preprocessed by IPFs Eumetsat processing chain. The resulting ENVI data files are mosaicked, reprojected and converted to GeoTIFF format. The core processing is implemented in Java.

*SAR Freeze Thaw*

The SAR FT processing is initiated by a shell script that checks if another task is already running and initiating the IPF JAVA program mosaic-1.2.one-jar.jar. Input and output directories are given on the commandline. The processing is based on ASAR GM data products preprocessed by IPFs SGRT. The resulting ENVI data files are mosaicked, reprojected and converted to GeoTIFF format. The processing is implemented in Java.
Land Surface Temperature (LST)

The LST processing is initiated by a shell script that checks if another task is already running and is initiating the UW IDL routine run_recurring_ma_products2.sav in the IDL virtual machine. Input is read from a defined input directory and results are written to a predefined output directory given in the config file recurring_ma_products2.cfg. The processing is based on MODIS Level 2 products as well as on Level 2 AATSR data.

5.2 Data portal

5.2.1 Technical background

One dedicated server has been setup with 8 Cores, 2x Opteron 2382 2.6 GHz, 32 GB memory and 8 TB RAID.

Server software description:
- Apache Tomcat
- GeoServer
  - OSGeo project
  - Extensions (developed in this project)
    - Temporal rasters
    - Support for pole centered coordinate systems
    - User defined map styling
- PostGIS
  - Spatial extension for PostgreSQL database

Client:
- OpenLayers
- Dojo Javascript Toolkit

The Architecture is visualized Figure 54

Figure 57: Architecture of the WebGIS
5.2.2 Features

The implemented system facilitates data catalog query and download. The visualization of the Web Mapping Service (WMS) allows

- The overlay of map layers
- Customizing of map styling via a web form, and
- Map query

It is interoperable with many GIS tools since all data are available through services based on international standards (OGC, ISO). The web services are managed through the Geoserver:

- Requests
  - HTTP GET parameters
  - XML/HTTP POST
- Response
  - Metadata: XML
  - Actual data: Various formats

The web mapping service (WMS) supports human consumption, e.g., visual interpretation (8-bit RGB only, relation to original values through legend). It supports all common web image formats (GIS, PNG8, PNG24, and JPEG).

Specifications of the Styled Layer descriptor (SLD) are:

- OGC Standard
- XML File
- Can be created using OS Tools (e.g., uDig)
- Vector Map Styles
  - Line, Area, Point, Symbol Styles
  - Labels
  - ...
- Raster Map Styles
  - Band Selection
  - Color Palettes
  - No Data Values
  - Transparency

An interactive editor for map styles has been implemented. It generates internally user-specific SLD files. Figure 19 shows an example for the visualization of the terrain model.

![Interactive Map Style Editor](image)

Figure 58: Example of the interactive map style editor
The Web Feature Service (WFS) handles vector data. Typically all attributes are available. The format is GML (Geography Markup Language; XML, OGC + ISO Standard) It is intended for consumption by GIS Software.

The web coverage service (WCS) handles raster data. The datasets contains original values. Many bands are possible and any type of data including floating point. Formats include GeoTIFF. It is also intended for consumption by GIS Software.

5.2.3 Data access

All datasets including product guides are available through the website. Users need to register and obtain a login first. Personalized logins a required for features such as the interactive style editor and storage of further settings for future sessions.

Data are accessed via drop-down menus. The levels are:

- Region (pan-arctic, Alaska etc) – regional site boundaries are made available as kml file
  - Product category (parameter e.g. LST, SSM)
    - Product (e.g. AATSR or MODIS LST)
    - Type (e.g. number of observations or actual data)

Optionally, a date range can be selected to narrow the search. Search results can be manually edited (select and deselect of single files). All selected files will be compressed into a zip-file. The size is estimated before and displayed as part of the search results. Relevant product guides are automatically included into the zip-file.
5.3 Publication of DUE Permafrost Products: PANGAEA

The information system PANGAEA is operated as an Open Access library aimed at archiving, publishing and distributing georeferenced data from earth system research. The system guarantees long-term availability of its content through a commitment of the operating institutions.

Most of the data are freely available and can be used under the terms of the license mentioned on the data set description. Authors submitting data to the Pangaea data library for archiving agree that all data are provided under a creative commons license. PANGAEA is a designated archive for the journal Earth System Science Data (ESSD). The description of each data set is always visible and includes the principle investigator (PI) who may be asked for access.

Each dataset can be identified, shared, published and cited by using a Digital Object Identifier (DOI). Data are archived as supplements to publications or as citable data collections. Citations are available through the portal of the German National Library of Science and Technology (GetInfo). Archiving follows the Recommendations of the Commission on Professional Self Regulation in Science for safeguarding good scientific practice. The system is operated in the sense of the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities which is a follow up to the Budapest Open Access Initiative. The policy of data management and archiving follows the Principles and Responsibilities of ICSU World Data Centers and the OECD Principles and Guidelines for Access to Research Data from Public Funding.

The system is hosted by AWI and MARUM, Germany. System concepts and development: Dr. Michael Diepenbroek (MARUM, SD DataSolutions GmbH); data librarian and organisation: Dr. Hannes Grobe (AWI); User service, tools and data products: Dr. Rainer Sieger (AWI). PANGAEA is supported with funding by The European Commission, Research, Federal Ministry of Education and Research (BMBF), Deutsche Forschungsgemeinschaft (DFG), International Ocean Drilling Program (IODP).

The ESA DUE Permafrost data set is published within a hierarchical structure in which the parent DOI for the ESA DUE Permafrost complete data set was installed under DOI doi:10.1594/PANGAEA.780111 (Figure 60). The search in PANGAEA can be undertaken using key words (Figure 59). It will be possible to publish project-related additional data sets under the parent DOI for DUE Permafrost. Each DUE Permafrost product data set is permanently published under a child-DOI of the parent DOI. Child-DOIs are attributed to the product data sets of Land Surface Temperature (Figure 61), Surface Soil Moisture & Freeze & Thaw, Surface Waters, Land Cover, Digital Elevation Model and Subsidence.

Figure 59: The PANGAEA search for the ESA DUE Permafrost data set.
Figure 60: The parent for the ESA DUE Permafrost complete data set, doi:10.1594/PANGAEA.780111.

Figure 61: The DOI for the ESA DUE Permafrost LST child-data set, doi:10.1594/PANGAEA.780111.
6 Service assessment

The achieved service is discussed in this chapter. The following sections cover realized and potential use, evaluation through user organizations, added value demonstration. An updated monitoring strategy to a mid and long term scenario and the content of the Service Assessment Report (SAR) has been added in version 2 of this report.

6.1 Realized products and potential use

Table 25: Parameter: Elevation

| DUE Permafrost product | 1) first circum-artic DEM N° of 60° with a 100 m spatial resolution; absolute elevation.  
2) local INSAR and ALOS-PRISM DEMs Polar Bear Pass, Bathurst Island, Canada; Yamal, Western Siberia, Russia; Yakutsk region, Central Siberia, Russia.  
3) relative terrain changes North Slope, Alaska, USA; Polar Bear Pass, Bathurst Island, Canada; Tuktoyaktuk, Northwest Territories, Canada. |
|---|---|
| potentials, field of use, ground parameters | 1) substitutes global DEMs (USGS, GETASSE) with 1 km spatial resolution.  
the SRTM global DEM data with high spatial resolution (90 m) has no complete global coverage. There are no data N° of 60° N.  
2) surface topography |
<table>
<thead>
<tr>
<th>3) subsidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>classes of temporal parameters</td>
</tr>
<tr>
<td>1) static DEM</td>
</tr>
<tr>
<td>2) static DEMs</td>
</tr>
<tr>
<td>2) multi-temporal short-baseline InSAR analysis</td>
</tr>
<tr>
<td>classes of spatial resolution (m)</td>
</tr>
<tr>
<td>1) 100 m, circum-arctic</td>
</tr>
<tr>
<td>2) 10 m</td>
</tr>
</tbody>
</table>

**Table 26: Parameter Temperature**

<table>
<thead>
<tr>
<th>DUE Permafrost product</th>
<th>brightness surface temperature corrected towards Skin Surface temperature between soil/air</th>
</tr>
</thead>
<tbody>
<tr>
<td>potentials, field of use, ground parameters</td>
<td>ground parameter: air temperature from stations modeled parameter: surface temperature</td>
</tr>
<tr>
<td>classes of temporal parameters</td>
<td>weekly averages monthly averages annually average metadata: n, n night, n day, n cloudy</td>
</tr>
<tr>
<td>classes of spatial resolution (km)</td>
<td>1 km regional, 25 km circum-arctic</td>
</tr>
</tbody>
</table>

**Table 27: Parameters surface soil moisture and surface status**

<table>
<thead>
<tr>
<th>DUE Permafrost product</th>
<th>1) surface soil moisture 2) thaw/freeze status (circumpolar) / DOY (regional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>potentials, field of use, ground parameters</td>
<td>1) Ground parameter: volumetric moisture content (m³/m³) in upper soil layer (ca 5 cm) model parameter: liquid_water_equivalent_thickness_of_moisture_content_of_soil_layer 2) ground parameter: air temp, soil temp, borehole temp model parameter Freeze/thaw?</td>
</tr>
<tr>
<td>classes of temporal parameters</td>
<td>weekly averages monthly averages status: frozen, unfrozen, melting snow metadata: n</td>
</tr>
<tr>
<td>classes of spatial resolution (km)</td>
<td>1 km regional, 25 km circum-arctic</td>
</tr>
</tbody>
</table>
Table 28: Parameter Land Cover

| DUE Permafrost product | 1) classes of vegetation structure  
|                        | 2) disturbance regime ‘fire’: burned area  
|                        | 3) Leaf Area Index MODIS LAI  
| potentials, field of use, ground parameters | boundary conditions and drivers for modelling  
| classes of temporal parameters | 1) static (based on GlobCover2009)  
| | 2) burned area (1996-2009): monthly  
| classes of spatial resolution (m) | 1) 0.009° circum-arctic  
| | 2) 1 km  
| | 3) 1 km  
| | local: 5 m to 30 m for upscaling and evaluation

Table 29: Parameter Surface Waters

| DUE Permafrost product | 1) regional: surface water status, late summer  
|                        | 2) local: lake status, lake change  
| potentials, field of use, ground parameters | density, density/mean area ratio of water bodies -> limnicity  
| | area variance -> change detection  
| classes of temporal parameters | 1) annual late summer status, metadata: n  
| | 2) local – time of acquisitions  
| classes of spatial resolution (m) | 150

Table 30: Parameter Methane

| DUE Permafrost product | Methane content in atmospheric column – Ob Estuary region test dataset only  
| potentials, field of use, ground parameters | Methane concentration near surface surface-atmosphere fluxes of green house gases  
| classes of temporal parameters | monthly averages  
| classes of spatial resolution | 0.5°
6.1 Products evaluation through user organizations

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 for 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-latitudeal permafrost landscapes.

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-latitudinal 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. First, the Product Set (LST, SSM, LC, Freeze/Thaw, surface water, terrain) is examined for its overall coherency, in terms of the general structures and possible artificial features (e.g. sharp boundaries) and inconsistency (e.g. missing data, etc.). The second major step consists of evaluation experiments of all products using cross-validation with remote sensing products and ERA interim modelled data is described in detail in the DUE Permafrost PVR [AD-12].

The evaluation using field-based data was conducted by absolute and descriptive methods as well as thematic and regional knowledge to assess the temporal, regional, and scaling variability. The types of ground data are: temperature (tair, tsurface, tsoil, tborehole), 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.

6.1.1 Ground data from the Global Terrestrial Network of Permafrost (GTN-P) and associated networks used for the evaluation of DUE Permafrost products

Ground measurements in arctic permafrost regions 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 climatic 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, www.udel.edu/ Geography/calm) and the Thermal State of (underlying) Permafrost (http://ipa.arcticportal.org/activities/gtn-p/tsp/15-tsp.html).

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, which is the most important source of ground truth data for the DUE Permafrost products. All GTN-P data is freely accessible via the world wide web. Both, the CALM and the TSP programmes are decribed in more detail in the Product and Validation Report [AD-9].

Table 29 gives a list of Alaskan ground data from the Global Terrestrial Network of Permafrost that was used for the evaluation of DUE Permafrost products MODIS LST (land surface temperature) and ASCAT SSF (Surface State Flag for the surface frozen and thawed ground). For both products, tem-
perature was the evaluating parameter. Hachem et al. (2012) described the evaluation of MODIS LST for several sites in Alaska and Canada. Recent publications on the evaluation of DUE Permafrost Freeze/Thaw products can be found in Park et al. (2011) and Naeimi et al. (2012).

Table 31: Overview of GTN-P ground data from Alaska used for the evaluation of MODIS LST and ASCAT SST products. $T_{air}$ = air temperature, $T_{surface}$ = surface temperature, $T_{soil}$ = soil profile temperature, $T_{borehole}$ = borehole temperature; daily = time series with daily averaged values, hourly = more than six values daily and the information on the measuring hour.

<table>
<thead>
<tr>
<th>Site name</th>
<th>Longitude/Latitude</th>
<th>Elev [m]</th>
<th>Parameter</th>
<th>Vegetation cover</th>
<th>Soil characteristics</th>
<th>L S S T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrow</td>
<td>W 156.649305 N 71.320875</td>
<td>3</td>
<td>$T_{air}$ daily</td>
<td>Outer coastal plain, drained lake basin, graminoid-moss tundra (wet and moist acidic)</td>
<td>Tropic Histosol, Tropic Aquatoll</td>
<td>x</td>
</tr>
<tr>
<td>Betty Pingo upland</td>
<td>W 148°53' 445&quot; N 70°16' 46,3&quot;</td>
<td>12</td>
<td>$T_{surface}$ hourly, 2000-2008</td>
<td>marshy drier mor e tundra</td>
<td>Organic overlying layers of fine sand and silt</td>
<td>x</td>
</tr>
<tr>
<td>Betty Pingo wetland</td>
<td>W 148°53' 445&quot; N 70°16' 46,3&quot;</td>
<td>12</td>
<td>$T_{soil}$ hourly</td>
<td>wet sedge tundra and larch tundra (BPH),</td>
<td>Organic overlying layers of fine sand and silt</td>
<td>x</td>
</tr>
<tr>
<td>Council Forest</td>
<td>W 163.674483 N 64.9076</td>
<td>70</td>
<td>$T_{air}$ daily</td>
<td>Spruce forest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Franklin Bluffs</td>
<td>W 148°46' 44,8&quot; N 69°53' 31,8&quot;</td>
<td>78</td>
<td>$T_{air}$ hourly</td>
<td>Grasses and sedges rooted in mosses and lichens</td>
<td>Organic materials of variable thickness overly silt loam textured mineral soils poorly drained</td>
<td>x</td>
</tr>
<tr>
<td>Innuvik Basin</td>
<td>W 149°18' 13&quot; N 68°30' 58,6&quot;</td>
<td>937</td>
<td>$T_{air}$ daily</td>
<td>Tussock tundra, mosses and lichens shrubs</td>
<td>Soils cold wet poorly drained silt loams with a high organic content and include many glacial erratics</td>
<td>x</td>
</tr>
<tr>
<td>Ivtok Moss</td>
<td>W 155°44' 71&quot; N 68°29' 56,6&quot;</td>
<td>570</td>
<td>$T_{air}$ daily, $T_{surface}$</td>
<td>daily 2000-2001, 2007</td>
<td>Moss lichen tussock</td>
<td>x</td>
</tr>
<tr>
<td>Ivtok Shrub</td>
<td>W 155°44' 34&quot; N 68°29' 12&quot;</td>
<td>570</td>
<td>$T_{air}$ daily</td>
<td>daily 2000-2004, 2004-2007</td>
<td>Shrub lichen tussock</td>
<td>-</td>
</tr>
<tr>
<td>Sagwon</td>
<td>W 148°41' 45,1&quot; N 69°25' 27,5&quot;</td>
<td>299</td>
<td>$T_{surface}$ daily</td>
<td>daily 2003-2008</td>
<td>Tussock tundra</td>
<td>-</td>
</tr>
<tr>
<td>Upper Kuparuk</td>
<td>W 149°22' 23&quot; N 68°38' 24,5&quot;</td>
<td>774</td>
<td>$T_{surface}$ daily</td>
<td>daily 2000-2008</td>
<td>Tussock tundra</td>
<td>-</td>
</tr>
<tr>
<td>West Kuparuk</td>
<td>W 150°20' 26,3&quot; N 69°25' 34,3&quot;</td>
<td>158</td>
<td>$T_{surface}$ daily</td>
<td>daily 2000-2008</td>
<td>Moist acidic tundra, tussock tundra</td>
<td>Loumy with peaty surface layer poorly drained</td>
</tr>
<tr>
<td>West Dock</td>
<td>W 148°33' 39&quot; N 70°22' 50&quot;</td>
<td>6-7</td>
<td>$T_{air}$ daily</td>
<td>daily 2000-2008</td>
<td>Marshy drained lake basin tundra</td>
<td>Organic overlying layers of sand and silt</td>
</tr>
</tbody>
</table>

An overview on the Russian ground-truth data retrieved from the GTN-P network is given in Table 30. Table 29 and Table 30 list only those ground-truth datasets which were used for the evaluation. For many sites, daily-averaged air and soil temperature time series are available for more years than mentioned in the Table 29 and Table 30.

Associated with the GTN-P programme, soil moisture time series were obtained from the United States Department of Agriculture (USDA). Table 31 gives an overview on the available data sets. Measurements are made at 20-minute intervals and averaged and recorded every hour. Daily average values are available for download. For the evaluation of DUE Permafrost products, data for the period 2007-2009 was used. The first evaluation results for the DUE Permafrost ASCAT Surface Soil Moisture Product are described in Bartsch et al. (2012).
Table 32: Overview of field-based data from the GTN-P network in Russia. See used for the evaluation of DUE Permafrost MODIS LST and ASCAT SSF products. See description of Table 29 for the explanation of abbreviations

<table>
<thead>
<tr>
<th>Site name</th>
<th>Longitude/Latitude</th>
<th>Elev [m]</th>
<th>Parameter</th>
<th>frequency/period</th>
<th>Vegetation cover</th>
<th>Soil characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ayshe Yurta</td>
<td>E 64° 11' N 67° 35'</td>
<td>148</td>
<td>Tair</td>
<td>May-Nov</td>
<td>Mesic dwarf shrunb-</td>
<td>Turf herb (Gleiochlycoidae), Gray-Tobacco-Crosbly (Loamy)</td>
</tr>
<tr>
<td>Mare Sete</td>
<td>E 66° 51' N 69° 48'</td>
<td>18</td>
<td>Tair</td>
<td>2008-2009</td>
<td>Dry and mesic</td>
<td>Dystric-Gleiochlycoidae (sandy) and Fibrity-Crosbly (clayey)</td>
</tr>
<tr>
<td>Nadym</td>
<td>E 72° 36' N 65° 31'</td>
<td>28</td>
<td>Tair</td>
<td>May-Oct</td>
<td>Wet dwarf shrunb-lobb</td>
<td>Dystric-Gleiochlycoidae (sandy) and Sphagnum Crosbly</td>
</tr>
<tr>
<td>Vaskoyni</td>
<td>E 65° 54' N 70° 17' 10'</td>
<td>29</td>
<td>Tair</td>
<td>Daily</td>
<td>Mesic prostrate</td>
<td>Gley-Crosbly (sandy and clayey)</td>
</tr>
<tr>
<td>Yakutsko-ye</td>
<td>E 75° 46' 46.7' N 66° 00' 34.1'</td>
<td>74</td>
<td>Tmeasure</td>
<td>2006-2007</td>
<td>Wet drained lake</td>
<td>- s</td>
</tr>
<tr>
<td>Yakutsko-ye</td>
<td>E 75° 46' 48.8' N 66° 00' 36.2'</td>
<td>76</td>
<td>Tmeasure</td>
<td>2006-2007</td>
<td>Peatland, Betula nana,</td>
<td>- s</td>
</tr>
</tbody>
</table>

Table 33: Overview of available soil moisture and temperature datasets from USDA Soil Climate Research Stations in Alaska. * GTN-P data: different period than Tsoil and soil water content. Owners: 1 = University of Delaware, Dept. of Geography; 2 = University of Cincinnati; Dept. of Geography; 3 = University of Alaska Fairbanks, Geophysical Institute; 4 = University of Alaska Fairbanks, Palmer Research Center, 5 = USDA-NRCS, National Soil Survey Center

<table>
<thead>
<tr>
<th>Site name</th>
<th>Longitude/Latitude</th>
<th>Elev [m]</th>
<th>Measured data</th>
<th>period</th>
<th>owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alquistuk</td>
<td>157° 24' 42.4' W 70° 27' 08.7' N</td>
<td>22</td>
<td>Tair, Tsoil (0-120 cm), soil water content at 15, 25, 40, and 50 cm depths</td>
<td>1995-2009</td>
<td>1, 5</td>
</tr>
<tr>
<td>Barrow 1</td>
<td>156° 36' 39.3' W 71° 19' 20.7' N</td>
<td>9</td>
<td>Tsoil at various depths to a maximum of 120 cm, soil water content at 5, 20, and 35 cm depths</td>
<td>1996-2009</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Barrow 2</td>
<td>156° 35' 19.9' W 71° 18' 27.6' N</td>
<td>4</td>
<td>Tsoil (at 15, 25, 40, and 50 cm depths), soil water content (at 15, 25, 34, and 44 cm depths), Soil temperature and moisture content are measured in a frost boil at 10, 25, 40, and 55 cm depths</td>
<td>2005-2011</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Westlock low</td>
<td>148° 33' 56.2' W 70° 22' 13.7' N</td>
<td>1.5</td>
<td>Tair, solar and net radiation, wind speed and direction, and soil temperature at various depths to a maximum of 120 cm</td>
<td>2009-2009</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Westlock high</td>
<td>148° 34' 07.2' W 70° 22' 13.4' N</td>
<td>3</td>
<td>Tair, solar and net radiation, wind speed and direction, and soil temperature at various depths to a maximum of 120 cm</td>
<td>2009-2009</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Betty Pingo</td>
<td>148° 53' 36.5' W 70° 16' 57.3' N</td>
<td>12</td>
<td>Tair, Tsoil at various depths to a maximum of 120 cm, and soil water content at 15, 25, and 40 cm depths</td>
<td>1996-2009</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Sagwon 1</td>
<td>W 148° 40' 07.8' N 69° 26' 22.2'</td>
<td>244</td>
<td>Tair, Tsoil at various depths to a maximum of 70 cm, and soil water content at 10, 25, and 40 cm depths</td>
<td>2005-2009*</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Sagwon 2</td>
<td>W 148° 47' 52.9' N 69° 24' 08.9'</td>
<td>329</td>
<td>Tair, Tsoil at various depths to a maximum of 70 cm, and soil water content at 10, 25, and 40 cm depths</td>
<td>1996-2009</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>Toolik Soil Climate station</td>
<td>149° 36' 35.4' W 68° 57' 22.9' N</td>
<td>759</td>
<td>Tair, Tsoil at various depths to a maximum of 120 cm, precipitation, soil water content at 9, 12, 38, 39, and 68 cm depths</td>
<td>1998-2009</td>
<td>3, 4, 5</td>
</tr>
</tbody>
</table>

6.1.2 Ground data from user groups

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, the Land Use Land Cover Change programme LCLUC Yamal (NASA) under the guidance of Prof. D. A. Walker, UAF (US) and H. Epstein, University of Virginia (US), and the Hokkaido University (JA) for the long-term measurement fields in the Yaktusk and Chokurdakh regions. 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. 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'.

Evaluation studies and experiments have been described in detail in Langer et al. (2010), Westermann et al. (2011), Westermann et al. (2012), Heim et al. (2011), Bartsch et al. (2012), and Elger et al. (2012). The new evaluation experiments that have not been described in the PVR [AD-]) are described in the following sections.

6.1.3 Evaluation of MODIS LST and ASCAT SSF with GTN-P ground data in Alaska and Western Siberia

The evaluation of regional LST and SSF products with in-situ data from the GTN-P network was performed for sites in Alaska and Western Siberia. Figure 7-1 gives an overview of the location of all GTN-P sites (small circles) and those for which data is shown in this paper (larger circles).

The Alaskan north-south transect covers continuous to discontinuous permafrost zones of the tundra and taiga (Figure 56 left). Seventeen GTN-P sites have soil temperatures measured within the first meter below the ground. Available data are time series for daily averaged temperature data for 2006-2010. The Western Siberian test site stretches from Novaya Zemlya in the west, across the Yamal Peninsula, to the western half of the Gydan Peninsula in the east, and reaches ~150 km southward (Figure 56 right). The eight West Siberian GTN-P sites are also located in different permafrost zones.

Time series of daily averaged GTN-P temperature data (Tair, Tsurface) were used to validate the DUE Permafrost SSF product. For the evaluation of weekly LST we benefited from GTN-P air and surface temperature data with and daily hourly resolution (hourly means here more than six values daily and the information on the measuring hour). These time series are the ideal database for the evaluation of the LST products, because it allows the selection of temperature data measured only within a couple of hours to the satellite overflight.
The following subsections show results of the evaluation of remote sensing products with GTN-P ground truth data

**ASCAT Surface State Flag (SSF)**

For GTN-P sites Nadym and Mare Sale (Western Siberia, Figure 57) the comparison of ASCAT SSF for the period August 2007 to August 2008 shows a good agreement with temperature data provided by the GTN-P programme.

The SSF generally shows frozen surface during negative temperatures and unfrozen when temperatures are positive. Between September and beginning of November 2007, the fluctuations of temperature are in general fairly reflected in SSF time series. For Nadym, the agreement of the SSF with the parameter air temperature is 90.36 %, with surface temperature 91.79 %. For Mare Sale, soil temperatures at 0.02 m depth have 82.75 % and at 0.5 m have 80.13 % agreement with SSF.

**Figure 64:** Time series of SSF and temperature data (2007-2008) for GTN-P sites Nadym and Mare Sale in Western Siberia (Russia). Colour-coded in the middle of each plot is the satellite-derived Surface State Flag (SSF). Each vertical line represents one day. Blue indicates frozen surface, red unfrozen, and green temporary water on surface/snow melt. The graphs represent measured air and soil temperatures (at different depths) derived from GTN-P permafrost monitoring stations and WMO Climate stations. The quality of the correlation is given in [% agreement] for each graph.
Figure 65: Series of SSF and temperature data (2007-2008) for GTN-P sites in Alaska (Barrow 2, Council Forest, SagwonMNT). See description of Figure 57. for more information on the figure.

This good agreement between the SSF and in-situ GTN P temperature data, with mostly well over 80 % agreement, is also visible at GTN-P sites in Alaska (Figure 58). Generally, the accuracy is highest in summer and winter and lowest during transitional periods. The deeper a ground temperature was measured, the smaller is the agreement with the SSF since the microwaves emitted by ASCAT only penetrate uppermost centimetres of the surface. The fluctuation of air temperature agrees slightly more with SSF than surface or soil temperature. However, especially during the freezing period, surface or uppermost ground temperatures reflect the delayed change in the SSF better than air temperatures because the snow layer acts as a buffer (e.g. Barrow 2 and Council Forest in May 2007, see Figure 58). SagwonMNT shows the overall highest percental agreement between SSF and in-situ data.

Land Surface Temperature (LST)

Comparison of MODIS LST measurements with GTN-P temperatures (with hourly resolution) for two sites in Western Siberia (Nadym, Ayach-Yatha Vorkuta, Figure 7.5) shows a good correlation between ground and satellite data. The selected match-up set of air temperature data is within two hours of MODIS LST. Due to abundant cloud coverage, the total number of MODIS LST measurements is n = 209 at Nadym (from Aug 8th 2009 to Aug
and n = 150 at Ayach-Yatha Vorkuta (from Jan 3rd to Sep 24th 2007).

The right graphs of Figure 59 show that the agreement between air temperature and MODIS LST is very good for Nadym (R² = 0.9686). For Ayach-Yatha/ Vorkuta the correlation coefficient is smaller (R² = 0.6222) with largest errors during the summer months and there is more scatter in the data. We assume that this is caused by erroneous MODIS LST values due to incorrect cloud masking. Erroneous LST measurements due to undetected clouds have been also described by Langer et al. (2010) and Westermann et al. (2011) for the Lena River Delta (Siberia) and Spitsbergen.

For Alaska, Hachem et al. (2012) investigated the correlation between air and soil temperature and MODIS LST at various sites in Alaska and Canada. For the West Dock case study, which is described in detail in Hachem et al. (2012), the comparison was made for the mean daily LST (combined Day and Night data of both, Terra and Aqua satellites) and mean daily average air temperatures from May 2005 to November 2008 (Figure 60). The correlation coefficient for the period of almost four years is high (R² = 0.98), and there is no scatter in the data (Figure 60). This shows that it is also possible to use time series of daily average air temperatures, which are available for much more sites than data with hourly resolution, for the evaluation of the LST products.

**Figure 66:** Comparison between LST and air temperature at Western Siberian GTN-P Sites Nadym and Ayach-Yatha/ Vorkuta. To the left: LST overlayed on the air temperature graph. To the right: relation between air temperature and LST. Only air temperatures within two hours of satellite flyover were considered for calculation.

**Figure 67:** Comparison between the mean daily LST and mean daily air temperature at GTN-P site West Dock (Alaska). To the left: LST overlayed on in-situ air temperature (daily averages), and on the right: relation between the two sets of measurements (Hachem et al. 2012).
Conclusions and Outlook

The evaluation of remote sensing products requires ground data with high temporal resolution (time series of daily or hourly averages). For the described evaluation case studies, MODIS LST and ASCAT SSF, temperature was the validating ground parameter. Ground data from the GTN-P network, with more than 800 sites in the circum-arctic provide an extensive and very valuable database for the evaluation of remote sensing derived products. First results of the evaluation studies are promising and demonstrate the great benefit of freely available ground truth databases for the evaluation of remote sensing derived products.

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. Ongoing discussions and evaluation activities, interactive 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.

6.2 Service demonstration and assessment at the final user workshop

6.2.1 Overview

The final workshop of the ESA DUE Permafrost project was held between February 15-17 2012 at the Alfred-Wegener-Institute for Polar and Marine Research (AWI) in Potsdam. Dr. Birgit Heim (AWI) and Dr. Annett Bartsch (Technical University Vienna) jointly organized the workshop. It brought together a multidisciplinary permafrost community working on satellite-derived data and in-situ field validation. Overall 62 participants from Austria, Canada, Finland, France, Germany, Italy, Japan, Norway, Poland, Russia, Sweden Switzerland, UK, and USA gave 22 oral presentations and 20 poster presentations.

The workshop started with a welcome by Prof. Dr. Hans-Wolfgang Hubberten, appointed IPA-President, and Dr. Frank-Martin Seifert from the ESA centre for Earth observation in Frascati, Italy. After an "Introduction into Permafrost Remote Sensing" (Dr. Claude Duguay, University of Waterloo, Canada) the workshop focussed on presenting products such as the pan-Arctic elevation model, land cover products, the thermal state and the hydrology of the North. Detailed results were related to assess surface temperature, surface soil moisture, freeze/thaw detection, a surface water inventory and terrain changes from satellite-derived data. In another presentation it was shown how the ESA products will be disseminated e.g. through the TU Vienna web portal with downloadable products (http://www.ipf.tuwien.ac.at/permafrost/) or through the PANGAEA database (pangaea.de), which also provides the opportunity to publish data sets.

The presentation of recent international remote sensing programs included reports on "GlobSnow", “STSE Northern Hydrology”, "CoastColour", “STSE-Alanis”, “EuRuCAS” and “MONARCH-A” by various speakers representing these programs. Arctic climate modellers pointed out in their presentations that permafrost land surface conditions are more and more implemented to run regional models. The modelling community is interested in surface parameters that may be extracted from satellite-derived data including roughness criteria and vegetation patterns, snow properties (e.g. from microwaves sensors) and land surface temperatures (e.g. MODIS or AATSR) across the North validated by in-situ surface measurements.

Projects on remote sensing in permafrost areas on various scales were presented using data from e.g. Interferometry (e.g. rock glacier observation), gravimetry (GRACE) and satellite altimetry (catchment hydrology). In addition, northern vegetation patterns are monitored using hyperspectral optical systems
with refined data calibration based on in-situ surface measurements. Applications have been demonstrated for climate modelling and also ground investigations.

The workshop agenda was as follows (see below):

**Wednesday 15th of February 2012**

9.15 – 11.00 a.m
Welcome
- by Prof. H.-W. Hubberten, head of AWI Potsdam and current President of the International Permafrost Association
- by ESA Data User Element DUE Officer F.M. Seifert, ESA

Project Overview
- Annett Bartsch, Vienna University of Technology (AT)

Introduction to Remote Sensing of Permafrost
- Claude Duguay, University of Waterloo (CA)

11.00 – 11.20 a.m.  refreshment break
11.20 – 1.05 p.m
- ESA DUE Permafrost: elevation and land cover harmonization from multiple sources
  - Elevation (circum-Arctic product); GAMMA Remote Sensing (CH)
  - pan-Arctic digital elevation model (DEM)
- Land Cover (global and regional products); Friedrich Schiller University of Jena (DE)
  - land cover and vegetation parameters
  - land cover disturbance: the fire product
- Land Cover (local scale); Friedrich Schiller University of Jena (DE)
  - local-scale applications: land cover and lake change; Friedrich Schiller University of Jena (DE)
  - local-scale applications: land cover and lakes; Alfred Wegener Institute (DE)
- Elevation (local scale); GAMMA Remote Sensing (CH)
  - local-scale subsidence and INSAR DEMs

1.00 – 2.00 p.m.  lunch break
2.00 – 3.45 p.m.
ESA DUE Permafrost – thermal state and hydrology
- Land Surface Temperature (circum-Arctic and regional products); University of Waterloo (CA)
  - Land Surface Temperature
- Hydrology (circum-Arctic and regional products); Vienna University of Technology (AT)
  - Surface Soil Moisture
  - Freeze/Thaw
  - Surface Waters

3.45 – 4.15 p.m.  refreshment break
4.15 – 5.15 p.m
ESA DUE Permafrost – Data dissemination and User Interaction

- GTN-P data from the International Permafrost Association Community for the evaluation of Freeze/Thaw and LST; Alfred Wegener Institute (DE)
- Web GIS and data download demonstration; Vienna University of Technology (AT)
- PANGAEA publishing network for geoscientific and environmental data; Alfred Wegener Institute (DE)

Discussions

Thursday 16th of February 2012

9.15 – 10.50 a.m

- International remote sensing programmes (chair: A. Bartsch)
  - ESA DUE GlobSnow (Luojus K., Finnish Meteorological Institute FMI, FI)
  - ESA STSE Northern Hydrology (Duguay, C., Univ. Waterloo, CA)
  - ESA DUE CoastColour (Brockmann, C., Brockmann Consult, DE)

- Modelling - ALANIS (ESA), MONARCH-A (EU), EuRuCAS (EU) (chair: A. Bartsch)
  - Climate and hydrological modelling in EU EuRuCAS Project (Bobylev, L., NERSC, RU)
  - STSE-ALANIS (ESA)-Integrated Land-Ecosystem-Atmosphere Processes Study (iLEAPS) (Hayman, G., Centre for Ecology and Hydrology, UK)
  - Modelling of Permafrost and other Land Essential Climate Variables (ECV) in the MONARCH-A project (EU) (Kantzas, E., University Sheffield, UK)

10.50 – 11.20 a.m. refreshment break

11.20 – 1.00 p.m Modelling (permafrost, climate) (chair: C. Duguay)

- Sensitivity of Arctic climate change to changing land surface conditions (Matthes, H. & Rinke, A., AWI, DE)
- Ideas of benefits of remotely-sensed soil moisture data for the validation of a land-surface model (Gouttevin, I. & Krinner, G., Laboratoire de Glaciologie et Géophysique, Grenoble, F)
- Potential use of ESA DUE products-Applying a regional climate model for Siberia (Klehmert, K. & Rockel, B., HZG Geesthacht, DE)
- Applications of near-surface permafrost modelling at regional scales (Streletskii, D., CALM, University of Delaware, US)
- Snow Water Equivalent and Land-Surface Temperature across the Northern High-Latitudes of Earth in comparison with GIPL model and in-situ (Muskett, R., University of Fairbanks Alaska, UAF, Geophysical Institute Permafrost Lab., GIPL, US)
- Current permafrost distribution in Alaska from modelling using MODIS land-surface temperature and verification with in-situ surface measurements (Marchenko, S., UAF, GIPL, US)

1.00 – 2.00 p.m. lunch break

2.00 – 3.30 p.m. Multiscale observations (plot, aerial and spaceborne) and spatial applications in permafrost regions-I (chair: B. Heim)

- Monitoring of inter-annual water storage changes in the Lena basin, Siberia using GRACE and satellite altimetry (Vey, S., University of Hannover, DE)
- Data fusion of remote sensing products for operational permafrost monitoring (Westermann, S., Univ. of Oslo, NO & AWI, DE)
• Use of satellite-derived surface soil moisture data to compare with estimated soil moisture based on tree-ring delta13C and methane emission in eastern Siberia (Tei, S., Univ. of Hokkaido, JP)

• Debris flows in the Brooks Range, Alaska, observed with satellite SAR interferometry (Strozzi, T., GAMMA, CH & Grosse, G., UAF, GIPL, US)

• Satellite InSAR and Envisat Wide Swath backscatter time series for monitoring of periglacial landscape features on Svalbard (Lauknes, L., Northern Research Institute NORUT, NO & Christiansen, H., UNIS, NO)

• Thermodegradational Feature Distribution in the Brooks Range and foothills of Northern Alaska (Balser, A., Institute of Arctic Biology, UAF, US)

3.30 – 4.00 p.m. refreshment break

4.00 – 4.30 p.m. Multiscale observations (plot, aerial and spaceborne) and spatial applications in permafrost regions-II

• The remote sensing vegetation index and the bidirectional reflectance distribution function (BRDF) of tundra (EnMAP programme) (Buchhorn, M. & Heim, B., AWI, DE)

• Trace Gas Exchange in the Earth –Atmosphere System on Multiple Scales (Sachs, T., GeoForschungsZentrum GFZ, DE)

4.30 p.m. Short Oral Poster Presentation

5.00 – 7.30 p.m. Poster Presentation

Friday 17th of February 2012

9.30 – 10.30 a.m

• 1st Session, Open Discussion – Modelling and Remote Sensing [Permafrost]
  o This session will discuss issues on modelling and remote sensing data, for example, remote sensing data as input as external spatial data, forcing spatial data, boundary spatial data and evaluating spatial data for modelling of climate, permafrost and vegetation. In this session, case studies will be introduced to stimulate the discussion.

refreshment break

11.00 – 12.30 a.m

• 2nd Session, Open Discussion – Field monitoring and Remote Sensing [Permafrost]
  o This session will discuss issues on field monitoring and remote sensing data: for example the vice-versa effective use of field data needed for the evaluation of remote sensing data and remote sensing data as a tool for monitoring, extrapolation and scaling.

• Final Discussion – Future Aspects and Closing
Figure 68: DUE Permafrost final workshop (Potsdam 15.-17. February 2012): Presentation of DUE Permafrost Products by members of the DUE Permafrost consortium. Photos from left to right and from top to bottom: A. Bartsch (TU Vienna, AT), H.-W. Hubberten (head of AWI Potsdam), T. Strozzi (Gamma, CH), F. M. Seifert (ESA), C. Duguay (Univ. Waterloo, CA), Ch. Schmulius (FSU Jena, DE), A. Soliman (Univ. Waterloo, CA), K. Elger (AWI Potsdam, DE), S. Hese (FSU Jena, DE), B. Heim (AWI Potsdam, DE).
Figure 69: DUE Permafost final workshop (Potsdam 15.-17. February 2012): Oral presentations of participants, followed by an evening poster session. Photos from left to right and from top to bottom: audience, H. Matthes (AWI Potsdam, DE), K. Luojus (Finnish Meteorological Institute, FI), C. Brockmann (Brockmann Consult, DE), G. Hayman (Centre for Ecology and Hydrology, UK), A. Urban (Melnikov Permafrost Institute SB RAS, RU), D. Streletsky (George Washington University, US), I. Gouttevin (Université Joseph Fourier, FR), G. Schwamborn (AWI Potsdam, DE), K. Wester and P. Wrammer (Brockmann Geomatics, SE), S. Westermann (Univ. of Oslo, NO), R. Muskett (UAF, Alaska, US), short oral presentation of posters, coffee break.
6.2.2 Open discussion

The discussion part pointed out the need to close the gap between satellite-derived parameters and those that can be commonly measured on the ground by field scientists. To better validate satellite-derived data for hemispheric modelling the field efforts must account for the pixel and sub-pixel scale. This includes the monitoring of permafrost properties such as the soil moisture, the land cover types, the snow, the frozen/unfrozen surface state, and the temperature and emissivity distribution. The discussion outcome is summarized in the following protocol:

Protocol of the open discussion on
“Modelling and Remote Sensing”, Potsdam, 2012-02-17, 9:30h
(chair: Claude Duguay, CD)
- Welcome by Birgit Heim (BH), thanks for actively participating at the workshop, also very active poster session.
- CD prepared questions: - (1) Can the remote sensing (RS) products we generated be used directly? - (2) Is it appropriate to replace air temperature by surface temperature? - (3) Is the skin temperature equivalent to the buffer layer? (We need to provide error bars.) – (4) Absolute accuracy of RS product needed? CD thinks for relative comparison is ok, but some people are interested in absolute values for evaluation, others only for spatial and temporal variability.
Reginald Muskett (RM) and others: climate models use air temperature, but for permafrost, surface temperature is more important. The annual amplitude is sufficient. There are lots of different types of models out, transient and equilibrant, and with different scales. Soil moisture is an interesting parameter, important and users are ready to use it.

CD: Daily temperature products have the problem of fusing day and night time measurements. Thus, a time stamp must be provided to allow the user for the interpretation of data.

Sebastian Westermann (SW): LST time series are interesting, because a one-day clear sky measurement does not help very much for permafrost applications. Averaged products would be a great dataset to have. MODIS dataset over the last 10 years is too short for transient permafrost models. There is a need of consistent datasets from the 80ies, maybe not a pure RS product, but this would be a step forward for permafrost modelling.

BH: Use of RS data for comparison of spatial patterns: DUE Permafrost LST monthly summer averages and modelled summer surface temperature derived from several models show - in general - cold mountain regions. However, RS LST show one exception: the skin temperature of the Central Yakutian mountain range (~1000 m height) along the Lena River is warm in summer months, not cold.

Marina Leibman (ML): This mountain range is a plateau and the top is warm in summer, there may be no permafrost at some places on top.

Dima Streletskii (DS): Also temperature inversions in mountain regions in winter in general do not show up in modelled surface temperature in climate models. ML: In Central Yakutia there are also temperature inversions in summer.

Soil moisture

The organic layer is now included in most models and can be parameterized. The organic layer changes the thermal conductivity, and the saturation of the upper layer is important.

For permafrost areas it is not simple to derive evapotranspiration and soil moisture for hydrological modelling.

What about the development of new sensors? CD: NASA develops a new sensor; an active microwave sensor with coarse resolution (>1 km) for daily measurements of soil moisture.

BH: Model outputs are usually water content per defined layer. DUE Permafrost RS products are relative moisture from wilting point to field capacity. How to compare relative moisture and modelled water content per defined layer? What is assumed in models for the upper soil, a thin organic layer, litter or barren? Is sub-information of sediment needed?

Annett Bartsch (AB): Soil maps usually do not show the upper litter/organic layer, which relates to the detected surface moisture.

Modellers: The conductivity of the organic layer is known. A daily record is very important.

ML: The moisture changes from hour to hour, from year to year. From RS we can get differences between sites; i.e. more wet – clay, less wet - sand (~25%). If one knows, this is a wet place, you can get thermal conductivity from the table. Map the differences, then the trends. Field experience from Yamal is that everything is drying. We need the parameter “moisture” first for mapping surfaces and then for deriving trends.

Land Cover

Every model uses different plant functional types (PFT), different land cover types, and different resolutions. Mosses are not defined or very different from model to model. It is difficult to generalize products, to get information on the procedures of parameterization; e.g. the parameterization of NDVI or the Leaf-Area-Index (LAI) values for the vegetation cover. Yet, there is no comparison of different PFTs from models.

Important statement: For present applications the land cover products are more detailed then needed. But what about archiving for future, when one wants to compare multi-temporal datasets?
BH: For most models tundra, which has a 100% vegetation cover in reality, is defined as sparse vegetation in further processing of the land cover data sets. This leads to a large soil contribution (>50%) in the parameters (a) fraction of vegetation, (b) albedo, and (c) emissivity, which is incorrect.

For models an annual record of land cover is too much. A good assumption is that it is stable. What about transient land cover datasets?

Abstracts and discussion results of the workshop will also be sent to ESA (Olivier Arino) and the GlobCover team.

User feedback: The Land Cover data sets should be provided in netcdf format.

Snow

DS: It is important to provide the period of snow cover, especially when it disappears, because of thermal insulation. Is snow coming earlier/later?

Frank-Martin Seifert (FMS): We will continue with GlobSnow and GlobCover. Improvements of classes relevant to permafrost will be done.

Users: More field studies are needed on how to parameterize the influence of snow cover (- actually not a task for remote sensing -).

Sergey Marchenko (SM) via email: Snow data derived from satellites need to be discussed. We have incorporated in the GIPL permafrost model the snow sub-model, which simulates the snow properties like snow depth or height, density, and thermal conductivity using as an input the snow water equivalent or precipitation from the Met Stations or GCMs (if it is a forecast). All of these snow parameters we need for the precise heat transfer process modelling through the snow cover. You know that the snow cover is a very good insulating layer and it is very important for the permafrost modelling. Sometimes we have the situation that the snow cover defines where there is permafrost or not.

RM: At the beginning and ending of the snow season there is uncertainty regarding the location of the snow-edge by satellite-based passive microwave detection methodologies/techniques. Recommendation of RM: Use GlobeSnow. For a thin snow cover the derivation using passive microwave data is difficult, also disturbance due to vegetation.

Surface state: frozen/ unfrozen

How do models incorporate this into models? ALANIS researchers compared it to snow pattern. Snow starts to melt, fluxes start. Carbon emissions go up. This is not considered in climate models. Processes in soils in relation to duration of snow cover. Frozen/unfrozen products are very valuable.

AB explained that originally the frozen / unfrozen RS product was developed for masking soil moisture in case of frozen surface conditions.

SW: Surface state frozen/unfrozen can be directly used, important for thermokarst processes.

Surface can thaw at 0°C.

ML: Lots of other applications; difference in snowmelt and ground thaw means how much water is available for erosion, how much goes in the discharge. In terms of climate change everyone thinks about disappearing permafrost, but it will not just because of rising temperature. Changes in precipitation are more important, also for thermokarst at the landscape level. Thermokarst is also a matter of accumulation of water. Thermal erosion starts under the snow.

For Permafrost modelling it is important: when surface thaws, ground is able to store water. You need to have timing, two time points for each cell.

SW: RS data sets are important, there are currently about 10 equipped monitoring sites in the Arctic, five of them are not in a good situation.

LST is not a problematic parameter for permafrost modelling; permafrost modelling can work with averages. More problematic are the snow parameters, coverage and thermal properties, and unknown soil properties.

SW and CD: But LST can become a problematic parameter in discontinuous permafrost.

Elevation
now 100 m DEM. Subgrid variability. So far only 1 km global DM data have been available >50° N. New DUE Permafrost DEM could be interesting for wetland mapping. Many modellers are not aware of the artefacts in the global DEMs in high latitudes that will result in incorrect topographic wetness index.

ML: Local scale DEM are needed for site validation and only then to be extended into larger regions and DEMs. In the new DEM the depressions come out and with almost no artefacts -> better to use. For Eurasia files were developed and uploaded in Scotland by Jonathan de Ferranti (http://www.viewfinderpanoramas.org/dem3.html).

**Protocol of the open discussion on**

“RS & field monitoring”, Potsdam, 2012-02-17, 11:15h  
(chair: Claude Duguay, CD)

CD: There is much more to be done, field data need to be used to reduce the error bars – e.g., temperature. CALM and TSP (GTN-P) measurement programs need to be maintained, to become spatially denser. Not enough temperatures at the surface available from the boreholes and soil profiles, sensors installed too deep for the evaluation of skin temperature. Big gap of measurement locations in central Siberia – despite there are a lot of changes happening there.

DS: 10 sites in Alaska, measurements every 2 hrs, provide long-wave real surface temperature.

AB: Moisture rarely or not measured at all.

ML: Snow is the weakest part in the permafrost modelling, most expeditions take part in summer, and few ground data on snow cover. Technological barrier to measure surface temperature at the ground, to transfer the data, animals take away everything above the ground.

Moritz Langer (MLa): Need for infrared measurements to measure and validate skin surface temperatures. Monitoring is also necessary for soil moisture. To select the monitoring areas, regions with different surfaces, different land covers are needed. Very few measurements, very few supersites in the Arctic, BSRN stations already as a network in the Arctic, long-wave radiation measurements available also from meteo-sites; where longwave radiation is available -> it is a starting point to collect data.

ML: Where to put the loggers?

CD: Already 2 cm in the ground starts to decouple.

FMS: ESA will start a global temperature-monitoring project; Simon Pinnoch will send out the mail to the participants of this workshop, the User Consultation meeting will be in June in Edinburgh. – What is needed? Invitation to the user community to develop a prototype of concept and sensors.

CD: Will funding be available to install monitoring stations?

FMS: There will be no funding available for a global LST ground monitoring network, ground data will come from users; high resolution thermal modelling is projected. Are there limits in the sensor technology or limit in the measurements/methodology? Which requirements to get better instruments in the future?

There is a need to determine error bars – the set of monitoring sites should be harmonized to end up with a harmonized product.

ML: Meteo-stations in Russia are standardized, CALM standards exist, have own additional measurements, now more awareness on how and what to measure with regard to RS.

FMS: There is a network of in-situ stations – no funding from ESA available for in-situ measurements.

ML: Wants precise recommendations on what and how to measure in the field.
SW: There is a problem when you measure ground temperatures, but for RS you have the influence of the canopy – many shortcomings in the technique.

CD: The long-wave radiation is measured at meteo-stations.

SW: Accuracy has to be determined.

ML: Better to have many cheap than one sophisticated sensor, e.g. e-buttons, you can cover several landscape types and install them also at top of canopy.

MLa: Problem for surface loggers in winter – covered with snow, not the skin temperature for RS LST evaluation.

SW: One validation sensor to determine the offset, which can be transferred to the rest of the many loggers/measurements.

MLa: You have to have at least one radiation measurement.

Aiman Soliman (AS): Problem to get the right emissivity of different surfaces.

SW assumes that the error due to the large mixed pixels bigger than unknown emissivity.

CD: Is there confidence in the products we generated for monitoring changes? Are the algorithms robust enough to be used for climate monitoring? 5 – 10 years, trends. If not, what needs to be done?

AB: For the soil moisture there is a data gap in 2000-2007, but there is also another ESA project (WACMOS), which also uses AMRE_E and SSMI that allows going 30 years back in time. The database becomes better the closer we get to today, because more sensors are available – more confidence for the recent years. Continuity expected for the future. Still needed: validation in the high latitudes, problems in heterogeneous landscapes (tundra with many water bodies) because of coarse resolution. More continuous near-surface measurements are needed in the different compartments.

BH: What ground truth do we need for evaluating subsidence?

Tazio Strozzi (TS): Most difficult is to set the reference ("everything is moving...").

BH: Surface waters; hard to get validation data.

AB: Surface waters; what do you as users use the information for?

ML: To plan the fieldwork.

SW: Sub-grid heterogeneity in modelling can be assessed, will be incorporated in the future, important information for modelling.

BH: How do models incorporate this information? Surface water is underestimated – what to do for a better parameterization of the models?

Modellers’ feedback: Percentage of open water in the grid will be integrated.

ML: In combination with DEMs areas can be divided into thermokarst-dominated and thermoerosional-dominated.

BH: High-spatial resolution RS is needed for upscaling, field planning, and DEMs. Does ESA plan to provide them in the future?

FMS: Some agreement with TPM to provide them; he will inform him and inform us – PRISM DEMs are not available anymore, ALOS is commercial now.

BH: There exist several good and interesting IKONOS acquisitions at high latitudes, but they are all not in the ESA IKONOS archive.

FMS: Commercial high-spatial resolution optical imagery problematic in the high latitudes, commercial providers are not eager to acquire data in the Arctic, because most of the optical acquisitions are not usable due to cloud cover, -> thus too expensive; reluctance to offer data for research.

BH: An approach of ground truthing for MODIS LST comes from SW and ML.
SW: But there is a difference from the point of validation; the approach becomes different and cheaper, if you go to a homogeneous landscape, this is more pressing than to investigate heterogeneity.

BH: LAI ground measurements different for tundra, only the vascular plant coverage can be properly defined with the LAI method, not the moss cover as discussed in the session before. Are there any other groups investigating this in the field; i.e. LAI for tundra?

Closing:

Outcome of the User Workshop at IARC, Fairbanks, Alaska: not only to use field data for the evaluation of RS, but also the other way around, to use the spatial information of RS data, not only high-spatial optical data, but also the coarse-scale parameters (LST, soil moisture, freeze/thaw) to plan the field and plan to set up new measurement stations/ measurement fields, e.g. within anomalies.

SW: In Norway they use RS to set up sites in the field.

CD: Need to provide some confidence for the users. Will it be the same product for LST? And for soil moisture and freeze/thaw?

AB: A lot of work has yet to be done in low to mid latitudes, still a lot needs to be done for evaluation at high latitudes. Landscapes are highly heterogeneous, lots of surface waters.


The attendees of the Final Workshop and their presentation types are listed below.
6.3 Added value demonstration

The added value of satellite product for permafrost monitoring has been discussed in the framework of the final user workshop. An abstract volume has been compiled and made available online. A range of applications of the DUE service have been proposed and tested, e.g.:

- ASAR WS water bodies for assessment of passive microwave wetland monitoring schemes (Dhomps et al.)
- ASCAT Soil moisture for land-surface model validation (Gouttevin et al.)
- ASCAT Soil moisture and surface status for land-surface model validation (Hayman et al.)
- Service application for Permafrost modeling (Heim et al.)
- Landsurface temperature and GlobSnow products application for regional model output evaluation (Khlemet et al.)
- ASCAT surface status information for tracing arctic frost weathering intensity (Schwamborn et al.)
- ASCAT soil moisture data for calibration of tree-ring delta $^{13}$C (Tei et al.)
- DUE Permafrost DEM assessment for topographic wetness index retrieval and potential use for wetland dynamics in climate models (Reschke et al.)
- ASAR surface soil moisture and freeze/thaw for pingo research (Urban)
- Landsurface temperature, moisture and freeze/thaw, GlobSnow products for permafrost monitoring by data fusion (Westermann et al.)
- Evaluation of radar altimetry and radiometry remote sensing with ASCAT freeze/thaw and ASAR water bodies (Zakharova et al.)

The use of DUE permafrost products has been additionally discussed within the framework of ongoing FP7 Projects with high latitude focus: PAGE21 (www.page21.eu), MONARCH-A (http://monarch-a.nersc.no/), and EuRuCas.

6.3.1 Land surface temperature

Surface temperature is a critical parameter to measure for understanding biological, hydrological and climatological systems, and their interactions. Arctic and sub-Arctic regions merit particular attention in this respect since they are very sensitive to climate change. In these regions, permafrost (i.e. soil that is frozen for more than two consecutive years) is subject to thaw which affects its stability. The rate at which permafrost evolves can be determined by studying its thermal regime, which is dependent on surface temperature. Surface temperature is a key parameter as it governs the surface energy budget and the thickness of the permafrost active layer. Given that the North covers a large area, and is remote and relatively unpopulated, the costs associated with the operation and maintenance of ground-based permafrost monitoring sta-

tions can be prohibitive. Satellite remote sensing sensors can provide air-soil interface (skin) temperature measurements at low cost over large areas.

Fitting a sinusoidal model over LST readings to reproduce seasonal thermal variations near the ground and calculations of mean annual surface temperatures and of thawing and freezing indices can be use to create maps which show the expected geographic distribution of near-surface temperatures and acceptably represent known permafrost boundaries (Hachem et al. 2009).

6.3.2 Surface soil moisture and status

**Final workshop presentation: The ALANIS Methane project (G Hayman, E Blyth, D Clark, A Bartsch, C Prigent, M Buchwitz, J Burrows, F O'Connor and N Gedney)**

‘ALANIS Methane is a research project to produce and use a suite of relevant earth observation (EO) derived information to validate and improve one of a state-of-the-art land-surface models and thus reduce current uncertainties in wetland-related CH4 emissions.

EO products have been used to improve and evaluate the Joint UK Land Environment Simulator (JULES, development led by the UK Centre for Ecology & Hydrology), a state-of-the-art land surface-atmosphere model capable of characterizing methane emissions from boreal lakes and wetlands. The JULES model, coupled with the HadGEM2 Earth-system model (i.e. Hadley Centre Global Environmental Model, developed by UK Met Office) and constrained by the retrievals of atmospheric CH4 amounts, is used to provide estimates and associated uncertainties of CH4 emissions from boreal lakes and wetlands.

A secondary objective of the ALANIS Methane project is to demonstrate and foster the use of ESA data within the iLEAPS community. Delivering new or improved EO-derived products and improving the JULES model will support iLEAPS efforts to improve the observation, understanding and prediction of land-atmosphere processes in boreal ecosystems.

![Figure 71: Offline JULES vs. Metop ASCAT Surface soil moisture product: area averages. Left: Western Siberia, right: Lena basin](image1)

![Figure 72: Offline JULES vs. Metop ASCAT Surface State product: area averages. Left: Western Siberia, right: Lena basin](image2)

The DUE Permafrost Metop ASCAT products (relative surface soil moisture) have been compared to model outputs (Figure 61 and Figure 62). Area averages for the years 2007 and 2008 have been extracted and gridded to 0.5° for Western Siberia (incl. Northern Ob basin) and the Lena Basin. The soil moisture variation amplitude of JULES agrees with the ASCAT weekly aver-
aged product. Differences in seasonality can be found for eastern Siberia. For the surface status there is generally good agreement between EO and model estimates, although snowmelt in JULES appears to start later than observed.’

Final workshop presentation and abstract: Use of satellite-derived surface soil moisture data to compare with estimated soil moisture based on tree-ring delta-13C and methane emission in eastern Siberia (S. Tei, Atsuko Sugimoto, R. Shingubara, S. Takano, H. Yonenobu, G. Iwahana, T. C. Maximov)

‘Ecosystems in eastern Siberia have experienced significant climate changes over the past few decades. Changes of soil moisture in this region are closely related to the variability of climate (e.g. precipitations) and permafrost conditions. Fluctuation of soil moisture affects not only the vegetation but also the stream flow characteristics when the runoff changes from the land system to a river. Therefore, it can be said that soil moisture in this region plays an important role in the hydrology of the ecosystem.

We estimated past 100 years soil moisture form tree-ring delta-13C in Yakutsk (62°N, 129°E), central eastern Siberia. The estimated soil moisture was compared with satellite-derived surface soil moisture (ESCAT) for the period from 1991 to 2000 and we found significant positive correlation ($r=0.69$, $p<0.05$). This result provides a validation for each dataset. Soil moisture conditions also have a large influence on methane emission, which is a strong greenhouse gas and which is controlled by changes of the vegetation pattern or the soil moisture conditions.

We compared the satellite-derived surface soil moisture (ASCAT) with the methane emission observed at the taiga-tundra boundary near Chokurdakh (70 N, 148 E) in summer from 2009 to 2011 in order to clarify the controlling factors of the interannual variation in methane emission.’

6.3.3 Surface water

The resulting datasets of the local scale water surface detection can be used to derive water body changes within an interval of about 45 years. Water bodies are classified in historical (Corona and Landsat MSS) and recent (RapidEye) satellite images by applying an object oriented classification approach. A hierarchical class description based on several levels and different topologically connected image object segmentation scales is generated. Lake object changes are analyzed using a spatial intersection of the classified water objects in the 1960s and 2009-2011. Additionally, simple lake area statistics and other elementary shape features are calculated (lake object border index, lake object elliptical fit, lake object density, lake direction and the roundness of water objects). Figure 61 outlines the strategy of the analysis.
Considerable changes are mapped for both study areas. The Yakutsk region is well known for its increasing lakes and most of the water body changes in this region are related to permafrost degradation and as discussed in Iijima et al. 2009 also to precipitation and temperature changes. Similar results are shown by the lake change analysis. Due to the cloud cover in the western part of the image for Central Yakutsk, the lake object change analysis is restricted to the area east of the Lena river. Lake objects mapped in Corona data and those mapped using RapidEye data are showing significant area changes. Especially in the eastern and northern parts of the study area a number of new small lakes appeared. Most of the water objects mapped in Corona and RapidEye data have an area lower than 0.2 km². The derived lake objects characteristics show only slight changes. Comparing the lakes which exist in both scenes, the lake area increase becomes explicit (Figure 62).

While the number of lakes in the Lena river delta decreases within the observed interval, the total lake area shows no significant changes. Additionally there is a growth of the mean lake area. Together with the reduction of lake objects this indicates possible fusions of small lakes to larger ones. Figure 63 illustrates the comparison of multi-temporal lake objects in a detailed view and for the overall classification results.

**Figure 73:** Example of lake object classification of historical and recent satellite data. Additional near-infrared information of Landsat MSS data helps to classify shallow water areas. Classification results of both time steps are compared and spatial lake properties are generated.
The resulting datasets provide information about the derived lake objects and additional structural lake features (area, border index, density, elliptic fit, main direction, roundness), stored as attributes in the vector dataset. The accuracy of the lake change analysis is influenced by cloud and ice coverage of some lakes as well as by the quality of the co-registration of the multi-temporal dataset. While multispectral high-resolution RapidEye data is suitable to derive lake objects very accurate, the different resolution of panchromatic Corona and Landsat MSS data makes it more complicated to classify former water bodies.
Morgenstern et al. (2008) used a mosaic of three Landsat-7 ETM+ scenes taken in the summers 2000 and 2001 covering 98% of the Lena delta (Schneider et al., 2010) as a basis for lake extraction to create a detailed inventory of the Lena Delta lakes. As the spatial resolution of the Landsat data is 30 m, the authors (Morgenstern et al. 2008) set the minimum lake size for analyses to 20 ha to ensure reasonable results. The results are that the total area of lakes ≥ 20 ha is 1861.8 km², which corresponds to 6.4% of the delta area. For all analyzed morphometric lake variables Morgenstern et al. (2008) found significant differences between the three geomorphological main terraces of the Lena Delta (Figure 64).

Morgenstern et al. (2008) conclude that the first main terrace, which represents the modern active delta, is characterized by small lakes of irregular shape, like abandoned lakes. Large oriented lakes with their major axes tending in NNE directions dominate on the second terrace, which consists of Late Pleistocene to Early Holocene homogeneous sands. On the third terrace, which is represented by relics of a Late Pleistocene accumulation plain with heterogeneous fine-grained and ice-rich deposits, typical thermokarst lakes with regular, circular shorelines prevail. Morgenstern et al. (2008) discuss that for comparing morphometric lake characteristics in the Lena Delta with other arctic deltas like the Colville or the Mackenzie River deltas, only the first geomorphological main terrace should be considered as it represents an actual deltaic environment.

For detailed investigations of lake change on the third terrace (Yedoma-type) of the Lena delta, Günther et al. (2010) calculated DEMs from a triplet set of ALOS PRISM (2006), and CORONA stereo pair (1968) and a DEM based on tacheometric field survey on the AWI-Lena2008 summer expedition. CORONA data were processed using camera and flight information for the minimization of wrong height parallax measurements and led to the generation of a 5 m DEM, representing the relief situation in 1968. The DEMs then were used for orthoimage generation of the CORONA and the ALOS PRISM data to allow accurate distance and area measurements. For 2D-change detection purposes another historical dataset (1964) consisting of two adjacent CORONA filmstrips was used. The 3D-change detection showed the expansion of the thermokarst depression with rates up to 9 cm/a. Over the period 1964-2006 a decrease in water area (2291 to 2216 ha) about minus 3.5% could be observed, caused mainly by 45 catastrophic lake drainage events while persistent lakes increased about 2%. These parallel processes of lake drainage and expansion well detectable with high resolution data reveal ongoing lake dynamics that are not reflected in the overall limnicity change (8.7 to 8.5%). The lake center monitoring shows an oriented shift of all large lakes in the northern direction.
6.3.4 Terrain

Final workshop abstract: Added value assessment of the DUE Permafrost DEM - Comparison of topographic wetness indices and wetland distribution (J. Reschke, A. Bartsch, G. Hayman, D. Clark).

‘The focus of the ESA STSE ALANIS Methane project (www.alanis-methane.info) on the remote sensing side is the development of new and/or improved wetland maps, and snowmelt and frozen ground information. The pan-arctic DEM product of DUE Permafrost project has been evaluated within the framework of the ALANIS methane project. The DEM was used to derive the topographic wetness index for Northern Eurasia using the same formula as used for calculation of the CTI (compound topographic (wetness) index (USGS 2011)). The CTI is derived of HYDROk1 (GTOP0 30) with a resolution of 1 km and frequently used for climate modeling. The additionally generated Wetness Index product (RTM WI derived from RTM DEM provided by DUE Permafrost with a resolution of 100 m) was cross-compared with the existing Wetness Index product (CTI) and with the spatial distribution of the open water bodies and areas permanently saturated with water. This classification was conducted using ASAR WS time series statistics of 2007 and a decision tree method. Differences occur mainly in the Ob river floodplain and in the peat zone of the West Siberian lowland areas permanently highly saturated with water, where the CTI underestimates the wetness of the areas compared to the RTM WI. The occurrence of artifacts is lower as well.’
6.4 Future observation strategy recommendations

6.4.1 General recommendations

The following parameters had been identified as sufficiently mature (although not ideal) to be included into the Permafrost Information System – Earth Observation (PEO): Land surface temperature, land cover (incl. vegetation and water bodies), soil moisture and terrain parameters. Snow extent and snow water equivalent is currently available from DUE GlobSnow.

Due to the launch of new satellites improved services can become possible in the future. The GMES Sentinel series will be of benefit for the majority of the selected parameters:

- Regular & frequent acquisitions would allow for the extent of regional services to the circumpolar domain.
- Continuation of services after the lifetime of especially ENVISAT and its sensors could be provided.

SMOS enables further developments for the characterization of ground status. Indirect measures via mass changes (as available from the Gravity Recovery And Climate Experiment (GRACE) satellite mission) as indicators of long-term changes in the hydrological budget would be of added value for permafrost monitoring.

Future SAR missions such as Tandem-L may be of high value for terrain, moisture and thermokarst lake monitoring. Snow depth and structure are of high interest for permafrost modeling since these parameters influence winter time heat conductivity. Therefore dedicated missions such as the proposed CoReH2O would be beneficial for future permafrost monitoring.

The international permafrost research community requires easy access to end-products which provide information on the current status of permafrost and add value to existing networks. Data interchange ability with respect to existing data platforms such as the Arctic Portal (Inter-map) and the NSIDC archiving system is a basic requirement. This has been addressed within DUE Permafrost and should be continued by future services.

The following sections detail recommendations for specific parameters included in the current service.

6.4.2 Landsurface temperature

AATSR onboard ENVISAT has an orbital period of 100.6 min, with a repeat cycle of 35 days (it looks at the same point on Earth every 35 days) but there are possibilities to maximize the revisit time by taking advantage of the overlapping of the scanning swaths above 50 degrees north. It was found that for a 3-day composite various revisiting periods are achieved depending on the latitude. 50-60 °N: 1-3 times; 60-70 °N: 3-6 times; 70-80 °N: 6 – 20 times and 80-90 °N: 4-16 times. It means that the same point can be revisited before the third day. Some locations at very high latitudes can be revisited (unexpected revisit) every 12 hours. Nevertheless, despite the theoretical number of the ENVISAT revisits in the high Arctic, the measurements retrieved at 46 stations over Canada show that there are on average no more than 50 or 60 measurements during a complete year.

The comparison of L2 MODIS and L2 AATSR shows that MODIS observations are more numerous than AASTR observations except for very high latitude (Alert station). Then the UWL3 AATSR product should be less accurate than the UWL3 MODIS product. Nevertheless the L2 AATSR and L2 MODIS show very good agreement, more, the comparison of UW level 3
AATSR LSTs with Tair shows a good agreement comparable to the MODIS one. AATSR should be used to complete MODIS when the MODIS observations are very low. Blending of the two data sets to improve the quality of the LST weekly and monthly products has not been tested yet. However, the very small amount of AATSR data available for weekly and even monthly calculations suggests that using AATSR in a blend product may not provide much improvement compared to using MODIS data alone to generate the LST products in latitude below 80°N. This is the option that we have chosen at the moment. In the future, the availability of data to be acquired by the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3 satellite (to be launched in 2013) could alleviate the current problem encountered with AATSR (i.e. frequency of acquisitions).

The L2 MODIS product has good agreement with Tair for weekly and monthly averages, more often during the warm season. These experiments have not been made yet for the 1 km UWL3 MODIS product, but let us think that the more suitable months will be the warmest ones. On one hand, the amount of undetected cloud is small enough in warm period to not influence the LST. Despite the very cold temperature in winter the higher amount of undetected cloud during the cold period should influence the LST in particular when temperatures are not too cold (> -15°C).

6.4.3 Landcover

Pan-Arctic Scale:

The DUE Permafrost has shown the potential of extracting percentage cover information for different vegetation types and barren areas from thematic land cover information with the special focus on the northern hemisphere and arctic regions. MODIS VCF (Vegetation Continuous Field) is the only product, which is providing information about percentage cover information for different land cover types (e.g. trees, herbaceous vegetation as well as barren areas) on global scale. Therefore, it is suggested to focus on the extraction of percentage cover information from remote sensing data for future investigation and product developments. Various sources of global coarse resolution land cover information are available and will be produced in the future. For upcoming investigation it is suggested to integrate state of the art global land cover information (e.g. CCI Land Cover Product).

The user community of the DUE Permafrost has been shown the requirement of tundra specific land cover information on pan-arctic scale, which are used as input variable for various model simulations (e.g. arctic vegetation models). Moreover, special focuses on the arctic vegetation types (e.g. mosses, sedges, etc.) need to be addressed in future coarse resolution global land cover maps.

The potential of LCCS (Land Cover Classification System) should be used for upcoming harmonization approaches of land cover maps from different sources. A standardized classification system, such as LCCS, simplifies the combination of land cover legends from various sources. Upcoming investigations on global land cover product generations should focus on using standardized land cover classification systems for their legends.

Future satellite missions, such as Sentinel-3, will be the source for the continuation of a sustainable monitoring of the land surface (land cover, vegetation activity and fire affected areas).

Local Scale Water Body Change and Vegetation Mapping:

Within the DUE Permafrost project spatial very high resolution (VHR) multispectral data from various Earth observation missions have been used. For future observation strategies a high repetition rate of the observation
systems is a key requirement for successful data acquisitions for land surface mapping in boreal or arctic latitudes. Cloud coverage and a very short vegetation period very much limited the acquisition window for multispectral data acquisitions within the DUE Permafrost. It is therefore suggested to use sensor concepts that utilize a constellation approach (with 5-7 platforms) with spatial resolution of 1-5 m and the potential for daily revisits. Within the DUE Permafrost data from the RapidEye constellation was used.

Overall the vegetation mapping and local scale water body change mapping within the DUE Permafrost indicated that spatially distributed local scale vegetation type reference data is difficult to get for mapping of large regions with 5 m multispectral data. Even if long time measurements have been undertaken on specific sites there is a lack of spatially distributed reference measurements. Therefore a dedicated validation and local site reference data collection campaign should be part of a future local scale observation strategy. Though expensive and time consuming such a ground reference and training data field campaign would create a spatially distributed network of samples and class descriptions as needed by VHR Earth observation mapping and would be the basis for a validated change analysis both for water body objects and vegetation types within the next decades.

6.4.4 Terrain

A Circum-Arctic DEM was compiled with a 3 arcsec spatial resolution based mostly on information originating from topographic maps due to lack of suitable satellite products. In future, the German Tandem-X will provide a global DEM with an unprecedented vertical resolution of 2m on 12m by 12m grids.

SAR interferometry has been shown to be a reliable tool to detect seasonal surface subsidence due to permafrost thaw on many regions thanks to the short repeat interval of 11 days of TerraSAR-X. The time-series of displacement highlighted that subsidence is occurring within a relatively short time period. Similar results are expected in future using the Sentinel-1 SAR sensor which has a similar repeat interval (12 days). In our investigations we found coherent annual interferograms only using the low frequency ALOS PALSAR data. Both annual as well as seasonal surface information is however required to identify long-term changes.

6.4.5 Land surface hydrology

Challenges for the derivation of soil moisture in high latitudes are (Bartsch et al. 2011, 2012b):

- frozen/snow covered ground conditions,
- landscape heterogeneity,
- seasonal variation in landcover type (water - nonwater),
- micro-topographic patterning,
- scarcity of ground data,
- issues related to the overlaying vegetation such as moss cover,
- Large difference in scales between satellite and ground data

Surface soil moisture has been shown as especially of interest for climate model evaluation. This parameter and relevant applications are currently within focus of the ESA Climate Change Initiative Soil Moisture.

Tundra environments which are characterized by a multitude of ponds below the resolution of Metop ASCAT and also ENVISAT ASAR global monitoring mode (1km) which serves as input for regional monitoring of near surface wetness in the DUE Permafrost project remain, however, a challenge. Regular, higher spatial resolution SAR acquisitions would be essential for moisture and frozen ground mapping.
Characterization of open water fraction and seasonal dynamics is essential for soil moisture monitoring in the arctic as well as permafrost monitoring itself. C-band SAR can capture these variations depending on data availability and weather conditions (Bartsch et al. 2012a).

Sentinel-1 could provide the necessary data coverage for soil moisture, freeze/thaw and open water dynamics. Future L-Band missions such as Tandem-L may be especially of benefit for addressing the impact of overlying and from water emerging vegetation.

6.4.6 Snow

The presence of seasonal snow cover during the cold season has a significant influence on the ground thermal regime. Snow is a strong insulator and therefore limits the efficient transfer of heat between the atmosphere and the ground. Where there is snow cover in the winter, the mean annual ground surface temperature is warmer than the mean annual air temperature due to the insulating effect of snow. The timing, rate of accumulation, duration, density, and depth of snow cover during the winter season play an important role in determining how the air temperature signal propagates into the ground. The impact of increasing snow depth can cause an increase of the mean annual ground and permafrost surface temperature by several degrees, whereas in discontinuous and sporadic permafrost regions the absence of seasonal snow cover may be a key factor for permafrost development. In seasonally frozen ground regions, snow cover can substantially reduce the freezing depth.

Snow water equivalent (SWE) and snow depth derived from satellite-borne microwave radiometry is presently the only option for mapping these parameters over large areas. Such products are currently available through ESA’s GlobSnow Project. Due to the coarse resolution of passive microwave data, these products are suitable for extended regions with homogenous snowpack and land cover, but are missing the requirements in mountainous terrain. Even in areas with moderate topography the snowpack can be quite heterogeneous due to snowdrift or complex land cover, affecting the quality of the derived snow cover product. The CoReH2O Earth Explorer candidate satellite mission will provide SWE, snow extent and snow depth at medium resolution (200-500 m) required by the permafrost community for global to regional scale applications.


Symposium. 23-27 July 2007, Barcelona, Spain, Article number 4423647, 3702-3705.


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