

Using Ground Data from the Global Terrestrial Network of Permafrost (GTN-P) for the Evaluation of the ESA DUE Permafrost Remote Sensing Derived Products Land Surface Temperature and ASCAT Surface State Flag

Kirsten Elger, Birgit Heim

Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany

Annett Bartsch, Christoph Paulik

Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Vienna, Austria

Claude Duguay, Sonia Hachem, Aiman Soliman,

University of Waterloo, Interdisciplinary Centre of Climate Change, Canada

Hugues Lantuit, Julia Boike

Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany

Frank-Martin Seifert

European Space Agency ESA, Frascati, Italy

Abstract

The ESA Data User Element (DUE) Permafrost project provides a mid-to-long-term Earth observation service for permafrost remote sensing derived applications for northern high-latitude permafrost areas. The DUE Permafrost remote sensing products are land surface temperature, surface soil moisture, frozen/thawed surface status, elevation, land cover, and surface waters. A major component is the evaluation of the DUE Permafrost products to test their scientific validity for high-latitude permafrost landscapes. These case studies evaluate two DUE Permafrost products (MODIS Land Surface Temperature and ASCAT Surface State Flag) by comparing the results with field-based data obtained by the Global Terrestrial Network of Permafrost (GTN-P). First results showed good correlation, which suggests that the DUE Permafrost approach is a promising one for long-term monitoring of permafrost surface conditions. Furthermore, it demonstrates the great benefit of freely available ground truth databases for the evaluation of remote sensing derived products.

Keywords: ESA DUE Permafrost; GTN-P; evaluation of remote sensing products; MODIS LST; ASCAT Surface State flag; Circum-Arctic.

Introduction

Permafrost, or perennially frozen ground, is an important component of the cryosphere and the arctic system. Fieldwork in the Arctic and Subarctic involve challenging logistics; observational sites are scattered, sparse, and mostly located along coastal areas. Satellite sensors (optical, thermal, microwave) provide a spatially and temporally consistent coverage of key parameters for climate and hydrological and permafrost research.

Several medium- to coarse-scale resolution satellite missions operate on a daily basis and deliver data for large areas. Remote-sensing applications to derive land surface temperature and surface moisture from satellite data are operationally established. However, are remote sensing products that have been developed and tested in agricultural, semi-arid to forest landscapes of low to mid-latitudes also valid for high-latitude permafrost landscapes? Permafrost landscapes pose 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 in the near-subsurface (i.e., active layer/permafrost boundary). High spatial resolution remote sensing data are not publicly available but can be acquired, mostly from commercial companies at usually high costs.

In this sense, a service based on publicly available medium- to coarse-scale satellite products is of high value for permafrost-related applications.

ESA DUE Permafrost – a Remote Sensing Permafrost Monitoring System

The ESA Data User Element (DUE) Permafrost project (<http://www.ipf.tuwien.ac.at/permafrost>) provides a mid- to long-term Earth observation service for permafrost remote sensing derived applications for Northern high-latitude permafrost areas (north of 50°N) (e.g., Bartsch et al. 2010, Heim et al. 2011). From the beginning, scientific stakeholders and the International Permafrost Association (IPA) were actively involved in the project. The DUE Permafrost remote sensing derived products are key parameters for permafrost research: land surface temperature, surface soil moisture, frozen/thawed surface status, elevation, land cover, and surface waters.

The DUE Permafrost consortium consists of five project partners. Each is responsible for the development and the evaluation of one or more DUE Permafrost products. The project leader is the Vienna University of Technology (Austria): project coordination and microwave remote-sensing (frozen/ thawed surface status, surface soil moisture, surface waters). Project partners are the University of Waterloo

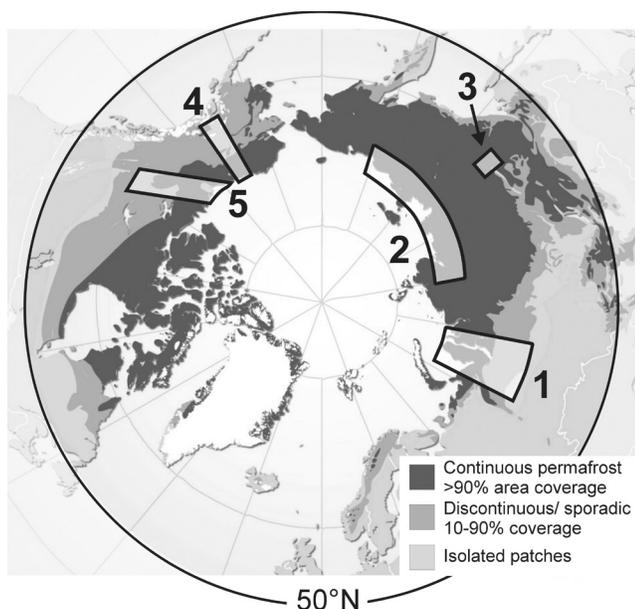


Figure 1. Coverage of DUE Permafrost Circum-Arctic products (>50° N) with five test regions (boxes) and permafrost zones of the Northern Hemisphere (modified after Permafrost Extent in the Northern Hemisphere, 2007).

(Canada): land surface temperature; Friedrich Schiller University Jena (Germany): land cover, surface waters; Gamma Remote Sensing (Switzerland): elevation; and Alfred Wegener Institute for Polar and Marine Research (Germany): ground data management, interaction between the permafrost scientific community and remote sensing experts.

The DUE Permafrost products are provided for the entire permafrost area north of 50°N. Circum-Arctic land surface temperature, frozen/ thawed surface status, and surface soil moisture are provided with weekly and monthly averages from 2007–2010 with 25-km pixel resolution. The global land cover has a spatial resolution of 350 m. The new Circum-Arctic DEM dataset north of 55°N has a 100-m pixel resolution. In addition, five case study regions were defined, for which products with higher spatial resolution (pixels ranging from 150 m to 1 km) than the Circum-Arctic products were developed (Fig. 1).

The tests regions are (1) the Russian Laptev Sea and Eastern Siberian Sea Region (continuous very cold permafrost/tundra), (2) the Yakutsk Region, Russia (continuous cold permafrost/taiga), (3) the Western Siberian transect including Yamal Peninsula and Ob Region, Russia (continuous to discontinuous permafrost/taiga-tundra), (4) the Alaskan Highway Transect, USA (continuous to discontinuous permafrost/taiga-tundra), and (5) the Mackenzie Delta and Valley, Canada (continuous to discontinuous permafrost/taiga-tundra). All DUE Permafrost products will be freely available via the worldwide web in 2012.

The studies described here show the evaluation of two DUE Permafrost products by comparing the satellite data with in situ measurements derived from the Global Terrestrial Network of Permafrost. The products are MODIS land surface temperature and Metop ASCAT Surface State Flag (SSF) for frozen and thawed surface state.

The Global Terrestrial Network of Permafrost (GTN-P)

The Global Terrestrial Network for Permafrost (GTN-P) was initiated by the International Permafrost Association (IPA) to organize and manage a global network of permafrost observatories for detecting, monitoring, and predicting climate change. The network, authorized under the Global Climate Observing System (GCOS) and its associated organizations, consists of two observational components: the Circumpolar Active Layer Monitoring (CALM) and the Thermal State of Permafrost (TSP) (IPA 2011).

Both have been thoroughly overhauled during the fourth International Polar Year (IPY 2007–2009) and extended their coverage to provide a true circumpolar network, which is the most important source of ground truth data for the evaluation of DUE Permafrost products. A major part of the DUE Permafrost core user group is contributing to GTN-P. All GTN-P data are freely accessible via the worldwide web.

Circumpolar Active Layer Monitoring (CALM)

In the arctic and subarctic lowland of the Northern Hemisphere, active-layer depth was measured with a metal rod in regular grids (1 ha to 1 km²), in thaw tubes, or points at ~125 sites in 15 countries in different permafrost zones (Brown 2010). The active layer thickness was measured at least once a year (in late summer) for at least the last 12 years. Many sites recorded data from the beginning of the 1990s onward. In addition to the active layer depth, detailed descriptions of vegetation and landform, as well as occasionally temperature and soil moisture measurements, are available via the CALM website (<http://www.udel.edu/Geography/calm>).

Thermal State of Permafrost (TSP)

Within the polar region of the Northern Hemisphere, ground temperatures are now measured in ~575 boreholes throughout Russia, North America, and the Nordic countries (Romanovsky et al. 2010b). The existing permafrost database was greatly enhanced during the IPY years 2007–2009. This included the establishment of new boreholes (more than half of the Northern Hemisphere boreholes were drilled during the IPY), the integration of existing permafrost observatory sites, and the collection of historical data. The main focus for the establishment of new sites was to close geographical gaps in the monitoring network. Air, surface, and ground temperatures are measured in boreholes ranging from a few meters to depths greater than 125 m (Brown 2010, Romanovsky et al. 2010a, http://www.gi.alaska.edu/snowice/Permafrost-lab/projects/projects_active/proj_tsp.html).

Evaluation, Ground Data, and Satellite Products

Evaluation concepts

A major component of the project is the evaluation of the DUE Permafrost products using in situ data, ERA interim reanalysis data, and cross-validation studies with other remote

sensing products. These evaluation studies were performed by the project partners who are responsible for the realization of the products. Case studies are described in Hachem et al. (2012), Naeimi et al. (2012), and Park et al. (2011).

This study shows the comparison of two DUE Permafrost products with field-based GTN-P data. The DUE Permafrost project largely benefits from the extensive and freely available ground data acquired within the GTN-P program. In addition to using GTN-P data, user groups were directly involved in providing ground data and evaluating the products (e.g., Helmholtz University Young Investigators Group HGF-Sensitivity of Permafrost in the ARctic [SPARC] at AWI, and the Land Use Land Cover Change programme LCLUC Yamal [NASA]).

For the evaluation of MODIS land surface temperature (LST) and ASCAT surface state flag (SSF), we used air, surface or upper soil temperature time series for the years 2007–2010. Ideal for the evaluation is ground data with high temporal resolution (i.e., time series of at least daily averages).

Satellite products: ASCAT Surface State Flag

Information on the soil surface state is very valuable for the monitoring of permafrost regions. Variation in the state or amount of water in the soil results in significant alteration of dielectric properties that can be observed in the backscattered signal. The ASCAT scatterometer onboard Metop satellite is an active microwave sensor. Long-wave C-band scatterometer data have been identified as a good indicator for the surface frozen or thawed state (Naeimi et al. 2012). The surface state flag (SSF) is the output product of a threshold analysis representing the frozen/ thawed surface status. Within the DUE Permafrost project, SSF is one of two products for the frozen/thawed surface status. SSF is derived from the ASCAT Circum-Arctic product (with 25-km pixel resolution). For regional frozen/thawed surface status products, synthetic aperture radar data from the ASAR sensor are used.

Naeimi et al. (2012) compared ASCAT SSF data with air temperature time series from global climate stations and with air, surface and ground temperature time series from GTN-P permafrost observation sites.

Satellite products: Land Surface Temperature

The current operational satellite sensors operating in the thermal infrared part of the electromagnetic spectrum offer the potential to retrieve land surface skin temperatures on a daily basis over large areas at the 1-km² horizontal resolution. Measurements are at-satellite temperatures that are calculated to land surface temperature (LST) using an operational atmospheric correction. NASA offers atmospherically corrected LST from two Moderate Resolution Imaging Spectroradiometer (MODIS) satellite missions (Aqua and Terra) with day and night acquisitions.

The quality assessments for the DUE Permafrost Product MODIS LST were done by matching the MODIS Aqua and Terra LST against high temporal-resolution air temperature datasets (hourly measurements to daily averages) from climate and GTN-P permafrost monitoring stations.

GTN-P in situ data used for the evaluation

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 2 gives an overview of the location of all GTN-P sites with near-surface temperature time series (small circles) and those for which data are shown in this paper (larger circles). The Alaskan north-south transect covers continuous to discontinuous permafrost zones of the tundra and taiga (Fig. 2 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 region stretches from Novaya Zemlya in the West, across the Yamal Peninsula, to the western half of the Gydan Peninsula

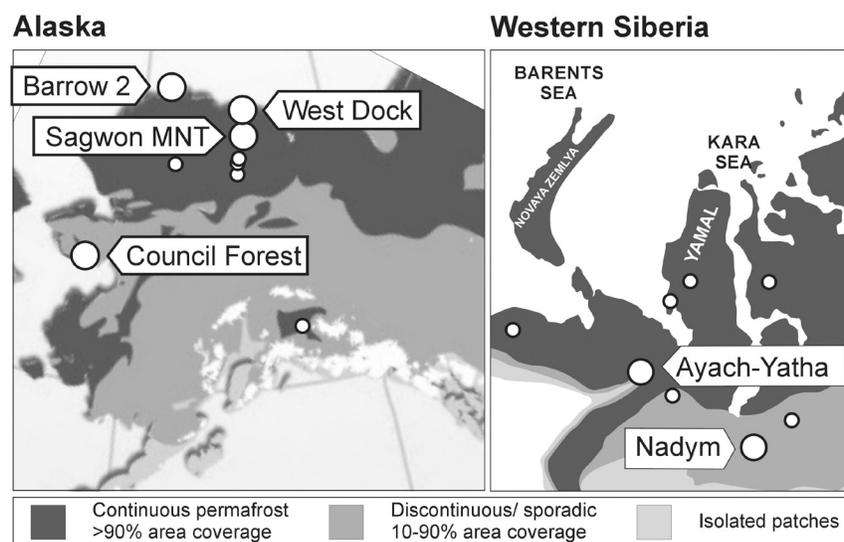


Figure 2. Location of GTN-P sites (circles) in Alaska and Western Siberia and within permafrost zones. Larger circles represent sites for which data are presented in this paper. The Alaskan map shows only GTN-P sites with air and soil temperature for the first meter. “MNT” = moist non-acidic tundra.

in the East, and reaches ~150 km southward (Fig. 2 right). The eight West Siberian GTN-P sites are located in different permafrost zones.

The temperatures used for the evaluation are mostly daily-averaged time series. In addition, for some sites, data with hourly resolution are available (i.e., 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 the database allows the selection of temperature data measured within only a couple of hours of the satellite overflight.

Results

Time series of daily averaged GTN-P temperature data (T_{air} , T_{surface}) 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 hourly and daily resolution. The following subsections show examples of the comparison 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, Fig. 3 right), 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 program.

The SSF generally shows frozen surface during negative

temperatures and unfrozen surface when temperatures are positive. Between September and the 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 (Fig. 3 right).

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 (Fig. 3 left). Generally, the accuracy is highest in summer and winter and lowest during transitional periods (see also Naeimi et al. 2012). The deeper a ground temperature was measured, the smaller is the agreement with the SSF since the microwaves emitted by ASCAT penetrate only the uppermost centimeters 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 Fig. 3 left). SagwonMNT shows the overall highest percentual 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

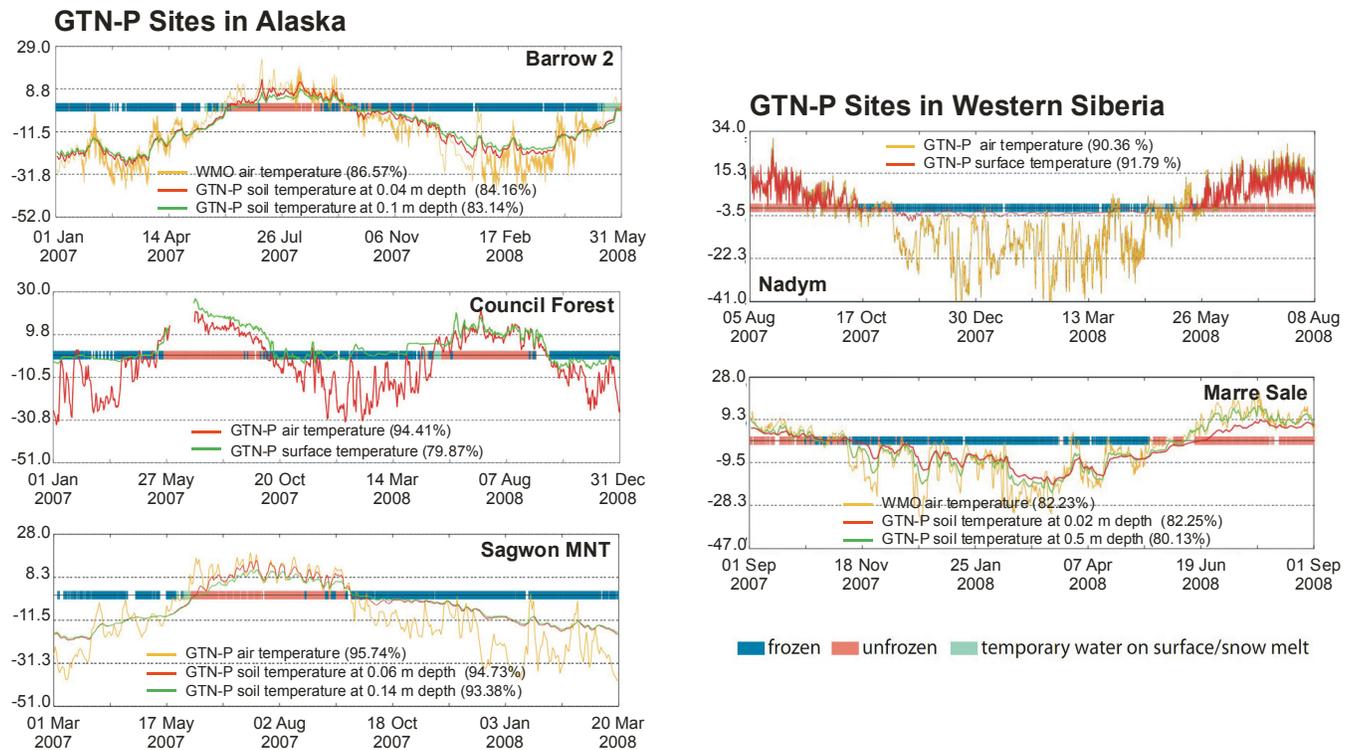


Figure 3. Time series of SSF and temperature data (2007–2008) for GTN-P sites in Alaska (Barrow 2, Council Forest, SagwonMNT) and Western Siberia (Nadym and Mare Sale). Color-coded in the middle of each plot is the satellite-derived Surface State Flag (SSF). Each vertical line represents one day. Blue 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 and WMO Climate stations. The quality of the correlation is given in % agreement for each graph.

Siberia (Nadym, Ayach-Yatha-Vorkuta, Fig. 4) 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. 8, 2009 to Aug. 3, 2010) and $n = 150$ at Ayach-Yatha-Vorkuta (from Jan. 3 to Sept. 24, 2007).

The right graphs of Figure 4 show that the agreement between air temperature and MODIS LST is very good for Nadym ($R^2 = 0.9686$). For Ayach-Yatha-Vorkuta the correlation coefficient is smaller ($R^2 = 0.6222$) and there is more scatter in the data with the largest errors during the summer months. We assume that disagreement is caused by erroneous MODIS LST values due to incorrect cloud masking. Erroneous LST measurements due to undetected clouds have also been 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 temperature from May 2005 to November 2008 (Fig. 5). The correlation coefficient for the period of almost four years is high ($R^2 = 0.98$), and there is no scatter in the data (Fig. 5 right). This shows that it is also possible to evaluate LST products with time series of daily average air temperatures, which are available for many more sites than data with hourly resolution.

Conclusions and Outlook

In this paper, we showed results from the comparison of field-based data from the Global Terrestrial Network of Permafrost (GTN-P) with the remote sensing derived products ASCAT SSF and MODIS LST for selected sites in Western Siberia and Alaska. The field-based and remotely sensed data showed good correlation, which suggests that the DUE approach is a promising one for long-term monitoring of permafrost surface conditions.

The evaluation of remote sensing products shown here requires ground data with high temporal resolution (time series of daily or hourly averages). For both products, temperature

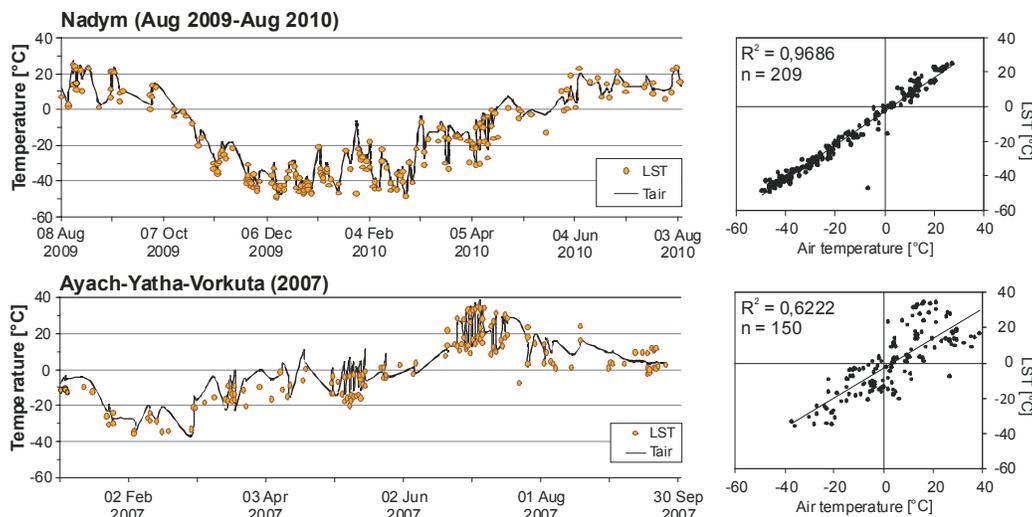


Figure 4. Comparison between LST and air temperature at Western Siberian GTN-P Sites Nadym and Ayach-Yatha/Vorkuta. To the left: LST overlaid on the air temperature graph. To the right: relation between air temperature and LST. Only air temperatures within two hours of satellite flyover were considered for the calculation.

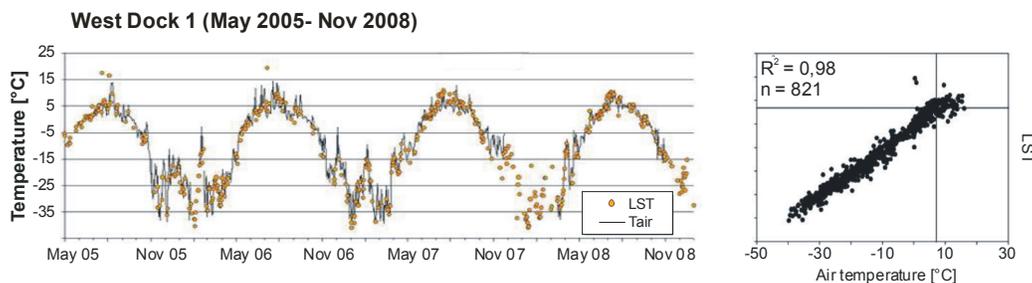


Figure 5. Comparison between the mean daily LST and mean daily air temperature at GTN-P site West Dock (Alaska). To the left: LST overlaid on in situ air temperature (daily averages). On the right: relation between the two sets of measurements (modified after Hachem et al. 2012).

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 LST and SSF, even for satellite data with coarse resolution (1-km and 25-km pixel size).

The evaluation of the DUE Permafrost surface soil moisture product with in situ data is presented in Bartsch et al. (this volume). The final DUE Permafrost remote sensing products will be released and freely available in 2012. The FP7 project PAGE21 “Changing Permafrost in the Arctic and its Global Effects in the 21st Century” will make use of the DUE Permafrost database.

Acknowledgments

The ESA DUE Permafrost project is an initiative of the European Space Agency (ESA ESRIN 22185/09/I-OL). The DUE Permafrost project gratefully acknowledges the support by the International Permafrost Association (IPA). Alaskan MRC field data (GTN-P) from the University of Alaska Fairbanks (UAF) were derived from the Network of Permafrost Observatories in North America and Russia via the Cadis gateway. Western Siberian field-based data were derived via the CALM website. We also thank the reviewers for their fruitful comments.

References

- Bartsch, A., Wiesmann, A., Strozzi, T. Schmillius, C., Hese, S., Duguay, C., Heim, B., & Seifert, F.M. 2010. Implementation of a satellite data based permafrost information system – The DUE Permafrost Project. *Proceedings of the ESA Living Planet Symposium*, Bergen 2010.
- Brown, J. 2010. Report from the International Permafrost Association: The IPY Permafrost Legacy. *Permafrost and Periglacial Processes* 21: 215-218.
- Hachem, S., Duguay, C.R., & Allard, M. 2012. Comparison of MODIS-derived land surface temperatures with near-surface soil and air temperature measurements in continuous permafrost terrain. *The Cryosphere* 6, 51-69, 2012. doi: 10.5194/tc-6-51-2012.
- Heim, B., Bartsch, A., Elger, K., Lantuit, H., Boike, J. Muster, S., Langer, M., Duguay, C., Hachem, S., Soliman, A., Paulik, Chr., Strozzi, T., & Seifert, F.-M. 2011. ESA DUE Permafrost: an Earth Observation (eo) Permafrost Monitoring System. *EARSeL eProceedings* 10, 2/2011, pp. 73-82.
- IPA (International Permafrost Association). 2011. The Global Terrestrial Network of Permafrost (GTN-P). In: The International Permafrost Association website. Retrieved September 15, 2011, from <http://ipa.arcticportal.org/activities/gtn-p.html>.
- Langer, M., Westermann, S., & Boike, J. 2010. Spatial and temporal variations of summer surface temperatures of wet polygonal tundra in Siberia – implications for MODIS LST based Permafrost monitoring. *Remote Sensing of Environment* 114(9): 2059-2069.
- Naeimi, V., Paulik, Chr., Bartsch, A., Wagner, W., Kidd, R., Park, S-E., Elger, K., & Boike, J. 2012. ASCAT Surface State Flag (SSF): Extracting Information on Surface Freeze/Thaw Conditions From Backscatter Data Using an Empirical Threshold-Analysis Algorithm. *IEEE Transactions on Geoscience and Remote Sensing* (accepted).
- Park, S.-E., Bartsch, A., Sabel, D., Wagner, W. Naeimi, V., & Yamaguchi, Y. 2011. Monitoring freeze/ thaw cycles using ENVISAT ASAR Global Mode. *Remote Sensing of Environment* 115, 12, p. 3457-3467.
- Permafrost extent in the Northern Hemisphere. 2007. In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 12:47, August 17, 2011 from <http://maps.grida.no/go/graphic/permafrost-extent-in-the-northern-hemisphere>.
- Romanovsky, V.E., Drozdov, D.S., Oberman, N.G., Malkova, G.V., Kholodov, A.L., Marchenko, S.S., Moskalenko, N.G., Sergeev, D.O., Ukraintseva, N.G., Abramov, A.A., Gilichinsky, D.A., & Vasiliev, A.A. 2010a. Thermal State of Permafrost in Russia. *Permafrost and Periglacial Processes* 21: 136-155.
- Romanovsky, V.E., Smith, S.L., and Christiansen, H. 2010b. Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007-2009: a Synthesis. *Permafrost and Periglacial Processes* 21: 106-116.
- Westermann S, Langer, M., & Boike, J. 2011. Spatial and temporal variations of summer surface temperatures of high-arctic tundra on Svalbard – Implications for MODIS LST based Permafrost monitoring. *Remote Sensing of Environment* 115(3): 908-922.