Soil Moisture from Metop ASCAT Data at High Latitudes

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Abstract

Several global satellite-derived soil moisture datasets exist to date. They are based on analyses of passive or active microwave data. Resolution is coarse at 25 km, but temporal sampling is very high. A monitoring service for applications at high latitudes is implemented within the European Space Agency (ESA) data User Element (DUE) initiative 'Permafrost.' Measurements are based on Metop ASCAT, a European active microwave instrument (scatterometer, C-band). This study discusses comparisons between these data and in situ measurements from Alaska. Weekly averaged values have been compared to soil moisture records at several USDA stations. Results show that in situ soil moisture measurements at shallow depths reflect variations of satellite-derived relative near-surface soil moisture although the used sensor provides data at only 25 km resolution. There are indications that this relationship is impacted by micro-topography and temporal offsets related to snowmelt and active layer dynamics.

Keywords: remote sensing; active microwave; tundra; time series; soil moisture.

Introduction

Monitoring of soil moisture is valuable at high latitudes, especially in the context of climate change. Large areas at high latitudes are underlain by permafrost. Variations in parameters that 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 parameters for modeling of permafrost extent (Marchenko et al. 2008). The moisture regime is important for active layer development (Shiklomanov et al. 2010). Soil moisture, together with temperature, is also a limiting factor for heterotrophic soil respiration. It is therefore important for estimation of carbon exchange (Kimball et al. 2009).

A range of satellite-derived global soil moisture datasets are currently available. They are derived using passive as well as active microwave sensors. Recently launched satellites (Metop ASCAT, SMOS) allow for continuity in monitoring at the global scale. ScanSAR technology enables the step from coarse (approximately 25 km) to medium (~1 km) resolution (Wagner et al. 2008, Bartsch et al. 2009a, Pathe et al. 2009). However, the majority of validation and application activities of such datasets are largely restricted to the mid- to low latitudes.

Challenges for the derivation of soil moisture in high latitudes include the following (Bartsch et al. 2011):

- 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 surface vegetation such as the moss cover,
- large difference in scale between satellite and ground data.

These issues are addressed within the ESA DUE Permafrost (www.ipf.tuwien.ac.at/permafrost) and STSE ALANIS (www.alanis-methane.info) projects focusing on time series analysis using C-Band active microwave data from scatterometer (ASCAT) and Advanced Synthetic Aperture Radar (ENVISAT ASAR).

This paper details the comparison of the DUE Permafrost pan-Arctic satellite data-based near-surface soil moisture monitoring service with in situ soil moisture measurements in northern Alaska.

Data and Methods

Satellite products

Metop ASCAT is a scatterometer, which is an active microwave sensor operating in the C-band (~5.6 cm). Backscatter is recorded regularly with 25-km resolution, and the entire globe is covered within 2–3 days. Microwave backscatter during freeze/snow-free conditions increases with increasing soil moisture (Ulaby et al. 1982). The applicability for soil moisture retrieval has been demonstrated for C-band scatterometer in the past (e.g., Wagner et al. 1999a, 1999b, Zhribi et al. 2008). The relative surface soil moisture (%) can be derived by time series analyses. The minimum (dry reference) and maximum (wet reference) values are site (pixel) specific. Once they have been determined from a sufficiently long record, the measurements can be scaled between those boundary values and a relative near-surface soil moisture content (Wagner et al. 1999a, 1999b). Metop ASCAT measurements are available since 2007. Its predecessors, the scatterometer onboard the ERS1 and ERS2 satellites, allow a long-term (since 1991) estimate of the reference values (Naeimi et al. 2009).

Moisture can be derived only for unfrozen and snow-free conditions and, thus, high-latitude application requires masking. An algorithm for the detection of the surface status has therefore been implemented using an empirical threshold-analysis algorithm also based on Metop ASCAT (Naeimi et al. 2012).

Measurements are not available daily or at regular intervals (every two to three days). To provide a value for each day and to compensate for missing data, weekly averages have been derived for each single day. All available measurements from the day of interest and the preceding six days are used as input for the averaging at each grid point. At the same time, data are projected from orbit format onto a regular grid (Naeimi et al. 2009). The final projection is the EASE Grid (polar stereographic). The data represent the relative near-surface soil moisture content in % (saturation). Records for the years 2007–2009 have been analyzed.

In situ data

The in situ soil moisture measurements are available through the United States Department of Agriculture- Natural Resources Conservation Service (USDA-NRCS). Seven sites from Arctic Alaska have been chosen; their locations are shown in Figure 1. The instrumentation differs, especially regarding the minimum depth of probes (Table 1). Stations Barrow 1, Betty Pingo, Atqasuk, Sagwon 1 & 2, and Toolik were selected. These sites have been investigated in many permafrost studies in the past (Hinkel & Nelson 2003). West Dock was not used due to its proximity to the coast. Barrow is also 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, Shiklomanov et al. 2010). Measurements at Betty Pingo provide detail on the differences between the center, rim, and trough of a high-centered ice-wedge polygon.

Figure 1. Location of arctic USDA stations.

Both in situ and satellite data relate to the dielectric properties of the soil. In situ measurements shown in the comparison were not masked when frozen. This allowed comparison of time periods in spring and autumn when the ground was not completely unfrozen.

Comparison

Time series for the three years are plotted for all selected stations in Figures 2 and 3. In all cases, the minimum probe depth has been chosen. Other depths are displayed in the case of Toolik and Sagwon 1. The Pearson correlation coefficient and corresponding soil depths are shown in Figure 4.

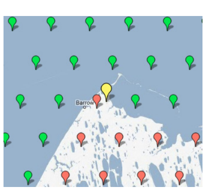
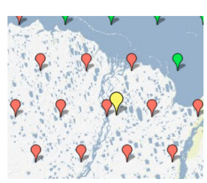
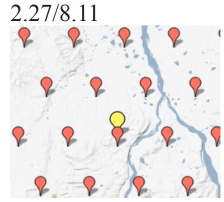
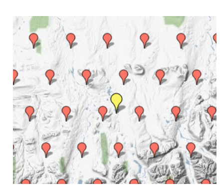
The satellite data show, in all cases, the characteristically high moisture after snowmelt and the gradual drying afterward. This is not reflected in all the in situ records (such as Atqasuk). The minimum depth of measurement at this site is comparably deep at 15 cm, and soil moisture values are rather stable all summer. However, the magnitude of change in the ASCAT data at Atqasuk was also lower than at the other sites.

Inter-annual dynamics

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 small for Barrow 1 in 2007 and 2008 as the probe is at a shallow depth.

Periods of increasing moisture occasionally occurred during the summer (Fig. 2). The level exceeded the spring maximum in the in situ measurements in a few instances. This is not the case for the ASCAT surface soil moisture, although variations are visible. An exception is the Barrow site, where variations are well reflected in magnitude and timing. The ASCAT footprint also includes numerous water bodies for this location (Table 1), which may introduce errors. If the distribution of

Table 1. Location of in situ soil moisture measurements sites (USDA) related to the ASCAT grid (satellite orbit oriented- http://www.ipf.tuwien.ac.at/radar/dv/dgg/) and available minimum depth of soil moisture probes.

Station name	Barrow 1, 4 sub-sites	Atqasuk	Betty Pingo, polygon sub-sites	Sagwon 1/2	Toolik
Distance (km) to closest ASCAT grid point	3.77 	6.6 	2.73 	2.27/8.11 	5.56 
Minimum in situ depth (cm)	5	15	10	10	9

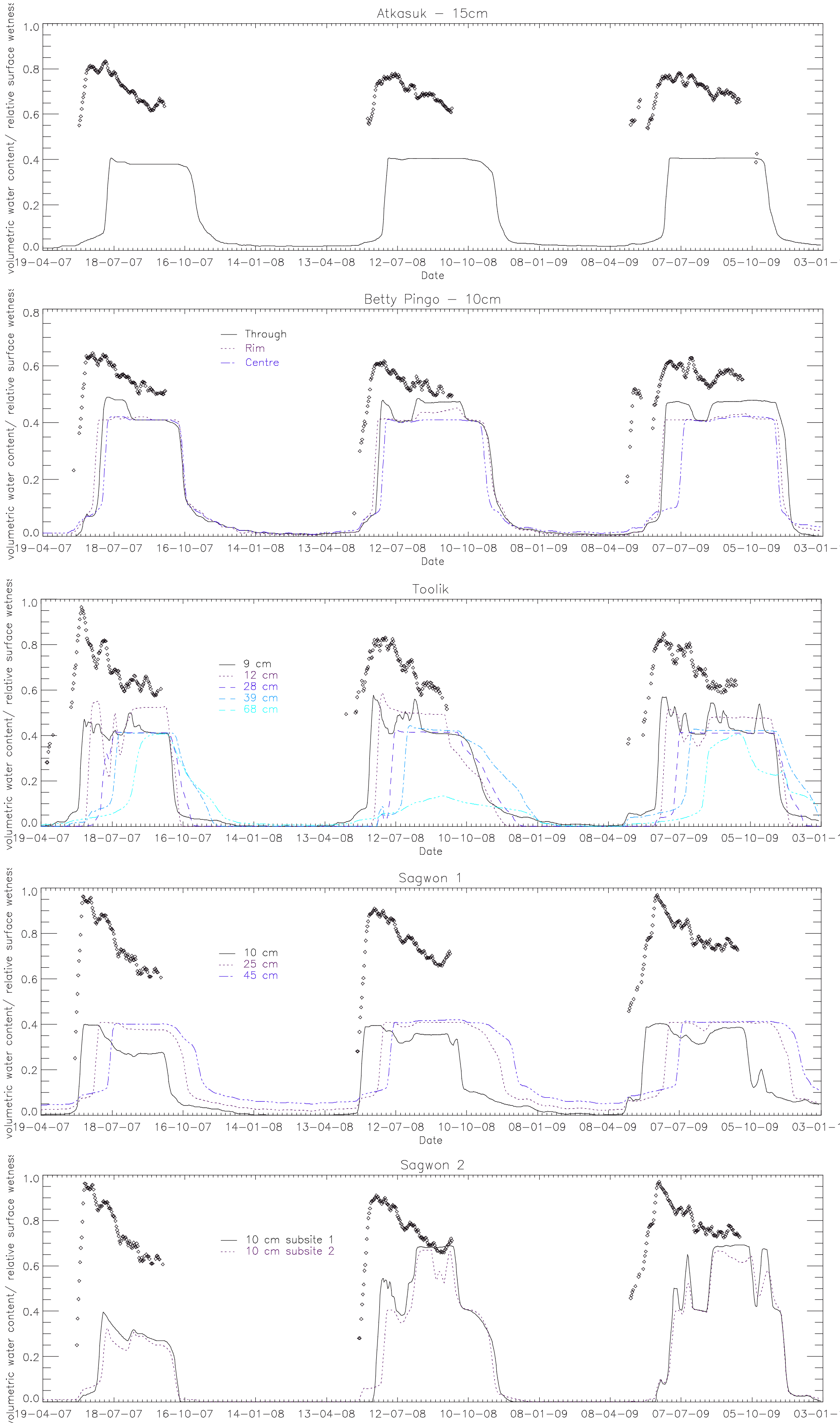


Figure 2. Comparison of Metop ASCAT relative surface soil moisture (diamonds) and USDA soil moisture measurements at various depths (lines) and locations.

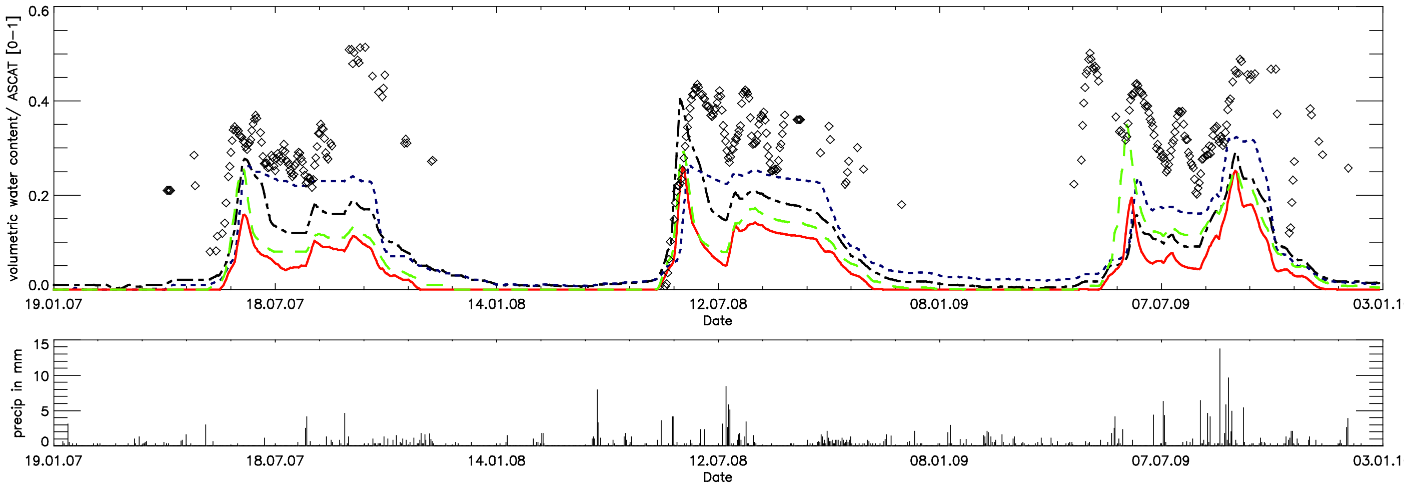


Figure 3. Comparison of Metop ASCAT surface wetness and USDA soil moisture measurements (5 cm depth) at site Barrow 1 (subsites : 1 – black, 2 –blue, 3-red, 4-green). Top: time series plot of weekly averages for ASCAT relative soil moisture scaled between 0 und 1 (diamonds), volumetric soil moisture values at USDA sub-sites (lines); Bottom: total daily precipitation in mm (WMO 512 dataset).

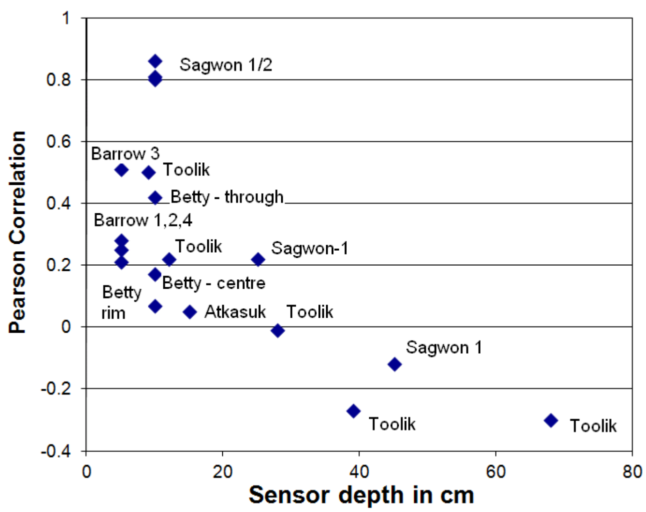


Figure 4. In situ volumetric and ASCAT relative near-surface soil moisture ($p<0.05$ for sites with $R>0.2$).

water is stable within the footprint, variations over time can nevertheless be attributed to soil moisture changes. The agreement is best at Sagwon 1 (10 cm), Sagwon 2 (10 cm), and Barrow (sub-site 3, 5 cm) (Fig. 4).

Variations in mid- to late summer coincide with rain events at Barrow (Fig. 3). The mid-summer surface increase in wetness is often initialized earlier in the soil than is seen from the satellite data at other stations. This can be observed in 2009 at Betty Pingo, 2008 at Toolik, and 2007–2008 at Barrow.

Seasonal variations show better agreement with near-surface probes (<12 cm depth) compared to deeper probes (25 cm). Especially interesting is that the measurements for the polygon trough at Betty Pingo compare better with the ASCAT measurements than the polygonal rim and center.

Intra-annual dynamics

The difference of mid-summer surface soil moisture levels between the years can be inferred from ASCAT. For example, at Sagwon 2, soil moisture values are higher in 2008 and 2009 than in 2007. This is similar for Sagwon 1 and the polygon through measurements of Betty Pingo.

Discussion

The results from the Betty Pingo polygon measurements differ from a previous study on Samoylov in the Lena Delta (Heim et al. 2010, 2011). The Samoylov polygons are low-centered. The agreement was highest for the polygon center compared to slope measurements, whereas records at Betty Pingo indicate that satellite measurements corresponded better to the variations in the polygon trough. This can be explained by the impact of micro-topography; both polygon (low) centers and polygon troughs represent the topographically lower and wetter parts. The localized drying of the higher parts of the features seems to be uncoupled from the general moisture conditions in the surroundings, which are captured by the satellite data. Persistent saturation at low-lying sites may contribute in general to the observed differences. Variation is locally lower than what might be characteristic for the surrounding.

In some cases there are seasonally differing offsets between the satellite and in situ measurements. The advance of the soil moisture peak in spring reflects the earlier snowmelt and soil thaw at the surface. The summer lag may relate to the gradual increase of active-layer depth and increased availability of liquid water.

The possibility of capturing intra-annual variations also allows for studies of natural hazards. The ERS1/2 scatterometer historical data of ASCAT (Naeimi et al. 2009) allows derivation of long-term averages and anomalies. For example, dry anomalies can be related to fire events (Bartsch et al. 2009b). However, intra-annual variation observed at the tundra sites analyzed in this study are rather large compared to inter-annual variations that should be taken into consideration.

Many previous studies have investigated the possibility of satellite-derived soil moisture validation with in situ data. In general, very shallow measurements correspond best to the satellite records. This has also been demonstrated in this paper. Greater moisture depth measurements are, however, required for many applications. These profile values of soil moisture can be modeled by temporal filtering which reflects percolation (e.g., SWI, Wagner et al. 1999). This cannot be directly applied, since the actual depth of the active layer would need to be taken into account in the case of permafrost. A previous study suggested that near-surface soil moisture (upper 7 cm) relates to greenness (NDVI) of vegetation of the North Slope in Alaska (Engstrom et al. 2008). C-band-derived soil moisture represents depths of up to 5 cm. There is, however, a significant scale difference in the satellite datasets investigated in this and the NDVI study, and this difference needs to be investigated in the future. Tools for downscaling may provide SAR (Synthetic Aperture Radar, <1 km spatial resolution) with measurements (Wagner et al. 2008, Pathe et al. 2009).

Conclusions

In situ soil moisture measurements at shallow depths reflect variations of satellite-derived relative near-surface soil moisture, although the sensor used provides data at 25-km resolution. There are indications that this relationship is impacted by micro-topography and temporal offsets related to snowmelt and active layer dynamics. These issues, and relationships to other environmental parameters such as vegetation, need to be further investigated.

Acknowledgments

This study has been carried out in the framework of the ESA initiatives DUE Permafrost (ESRIN Contr. No. 22185/09/I-OL). A. Bartsch has been the recipient of a research fellowship by the Austrian Science fund (FWF Elise Richter Program, V150- N21) during the course of the study.

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