SOIL MOISTURE MAPPING IN PERMAFROST REGIONS – AN OUTLOOK TO SENTINEL-1

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ABSTRACT

Soil moisture is of high importance in permafrost regions. Within the DUE Permafrost project, adjustments to the 1 km Surface Soil Moisture (SSM) product, derived from ENVISAT ASAR Global Monitoring mode data, have been made to account for some of the conditions encountered at high latitudes. Soil moisture retrieval from SAR requires taking into account the presence of water bodies. This is challenging in regions of permafrost, as the majority of lakes in tundra environments are smaller than the spatial resolution of global and regional land cover datasets. A method to account for the presence of water bodies at and below the 1 km scale in support of SSM retrieval is presented. A high potential for transfer of the presented methodologies to the Sentinel-1 mission is apparent due to the consistency of measurements with ENVISAT ASAR.

Index Terms— *Synthetic aperture radar, Permafrost, Soil moisture, Open water bodies*

1. INTRODUCTION

Soil moisture plays a dominant role in geomorphological, ecological and pedogenic processes in cold regions [1]. It is a key parameter in permafrost regions, as the thermal properties of the soil layers are functions of soil type and liquid water content [2, 3].

Global soil moisture products with spatial resolution in the range of 25-50 km are currently provided e.g. by the Soil Moisture and Ocean Salinity (SMOS) mission [4, 5] and by the ASCAT sensor onboard the METOP-A satellite [6-8]. As of yet, there is no medium or high spatial resolution soil moisture product delivering data with global coverage. However, the 1 km Surface Soil Moisture (SSM) product, derived from ENVISAT ASAR Global Monitoring (GM) mode data, regularly delivered soil moisture maps with 1 km resolution covering Australia, southern and central Africa and parts of South America for several years [9, 10]. The 1 km SSM model has been developed and evaluated mainly for retrieval outside of high latitudes [11-15]. Within the European Space Agency DUE Permafrost project, adjustments in the SSM retrieval methodology have been made to account for some of the conditions encountered in permafrost regions [16]. However, the adjustments so far did not explicitly account for the presence of water bodies below the spatial scale of the SSM retrievals. For coarse resolution sensors such as scatterometers, it has been found that contributions of lakes and rivers to the overall backscatter characteristics is small and can be neglected [17]. However, this assumption is not generally applicable to SAR observations at or below the 1 km scale.

The approach for the 1 km SSM product outside of high latitudes has been to mask pixels representing water bodies based mainly on land cover classification datasets. However, the majority of lakes within tundra environments are smaller than the spatial resolution of global and regional land cover datasets which ranges between 300 m and 1 km. The objective of this paper, therefore, is to develop a method to account for the presence of water bodies at and below the 1 km scale in support of SSM retrieval in permafrost regions.

2. TEST SITE

As part of the Earth Observation component of the Permafrost project, 1 km SSM maps were provided for the years 2006-2011 for five regional sites in Russia, Alaska and Canada covering a total of 1.5 million km^2 [18]. In order to provide regular temporal sampling, which often is desirable for data assimilation, the SSM maps were provided as 7-day composites. The selected site in this paper is part of one of the five DUE Permafrost focus regions and one of the five primary sites of the European Union FP7 project PAGE21. It covers parts of the lower Indigirka basin around Chokudarkh/Kytalyk and is characterized by abundant thaw lakes.

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3. METHOD

3.1 Soil moisture retrieval

The 1 km SSM retrieval model estimates the water saturation in the uppermost layer of the soil by comparison of each backscatter measurements to backscatter reference maps corresponding to dry and wet soil conditions [11]. The same authors also formulated a corresponding error model by propagating the uncertainties of the backscatter acquisitions and the retrieval model parameters. The error model has been shown to provide reliable a priori estimates of the retrieval error [15]. Modifications to the method has been done to improve the retrieval of the dry soil backscatter reference within permafrost regions [16].

3.2 Water body classification

Due to the characteristically low microwave backscatter from calm water surfaces as a result of specular reflection, radiometric threshold methods may be used to distinguish open water from land. It has been shown that such a radiometric threshold approach applied to 150 m resolution ASAR Wide Swath (WS) data can identify 50% more open water surfaces than land cover maps based on 500 m resolution MODIS data [19]. A disadvantage of this approach is the sensitivity to local wind conditions, as waves and ripples on the water surface significantly increase the backscatter intensity due to diffuse reflection. Temporal compositing helps to overcome this issue. However, temporal compositing also imposes a demand for frequent SAR observations and reduces the temporal resolution. The availability of ASAR WS data for the test site varied typically between 10 and 20 acquisitions per summer season for the years 2007-2011. Therefore, annual maps representing water body extent for the summer months of July and August were generated [20]. A pixel was classified as water if the backscatter was below a threshold of -14 dB for at least one SAR measurement during the two months.

3.3 Accounting for small water bodies

For modeling the influence of water bodies smaller than the 1 km SAR footprint on the land backscatter response a first order non-coherent model was formulated according to Eq. (1).

$$\sigma^0(\alpha) = \alpha\sigma^0_W + (1-\alpha)\sigma^0_L \quad (1)$$

Here, $\sigma^o(\alpha)$ is the total backscatter of a pixel representing land and water, α the fraction of open water and σ^o_W and σ^o_L, respectively, the backscatter for the water and land components. Solving Eq. (1) for σ^o_L in order to achieve an estimation of the land backscatter component within the footprint was not considered feasible as σ^o_W is unknown at the time of acquisition and backscatter from water surfaces varies strongly, e.g. due to local wind conditions. Instead, a statistical approach was implemented in order to identify pixels for which the fraction of open water could adversely affect the SSM retrievals. The influence of the fraction of water bodies on the backscatter ($|\Delta\sigma^o|$) can be formulated with the use of Eq. (1) as

$$\left|\Delta\sigma^0\right| = \left|\sigma^0(0) - \sigma^0(\alpha)\right|. \quad (2)$$

The error of the SSM retrievals is dominated by the radiometric noise of the ASAR GM acquisitions [11]. Therefore, the requirement $|\Delta\sigma^o| < 0.5\eta$ was postulated, where η is the radiometric noise (1.2 dB). Inserting Eq. (1) in Eq. (2) and solving for α gives the criterion

$$\alpha < \left|\frac{0.5\eta}{\sigma^0_L - \sigma^0_W}\right|. \quad (3)$$

Eq. (3) defines the criterion for the fraction of open water for which SSM estimations are not significantly affected.

The fraction of open water (α) at the 1 km scale was estimated based on the 150 m resolution water body maps using an ellipsoidal footprint model with equal weight given to each pixel within the footprint.

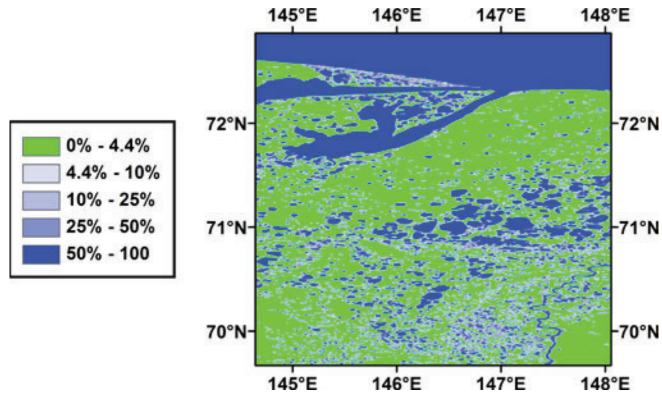

Figure 1. Fraction of water bodies at the 1 km scale for the test site in northern Siberia.

4. RESULTS AND DISCUSSION

An example of the resulting map of fractional water body coverage is shown in Figure 1.

Worst case 1-σ backscatter values for land and open water were obtained from the so-called Signature Database which was developed within the ESA Sigma Nought project [21]. The Signature Database contains statistics of C-band backscatter representing several land cover types and polarization configurations for local incidence angle (θ) intervals between 18° and 42°. For HH polarization at

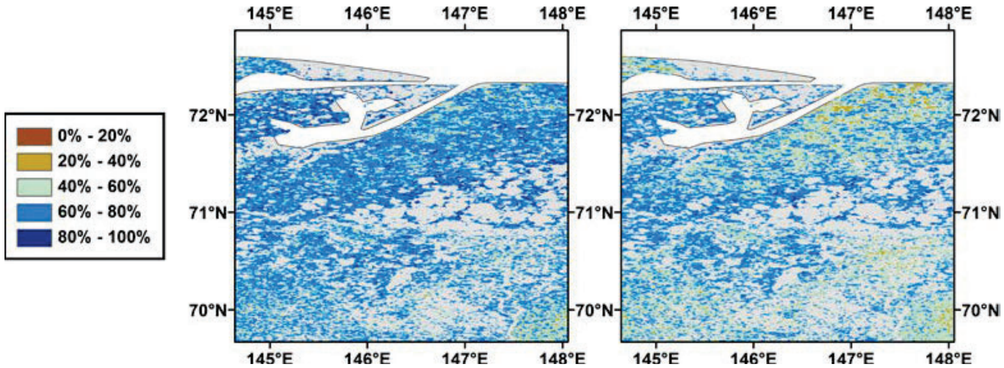

Figure 2. Weekly mean Surface Soil Moisture maps for a region in northern Siberia in 2009. Left: July 2nd – July 9th. Right: July 30th – August 6th.

θ=30°, the class "Open Water" had a mean (μ) of -15.1 dB and standard deviation (σ) of 3.5 dB. This class had the lowest μ and greatest σ among the land cover classes in the Signature Database. The highest value for μ+σ was found for the class "Ground Cover with Dwarf Trees and Shrubs" which had μ=-8.0 dB and σ=3.0 dB. Thus, inserting σ^o_W=-18.6 dB and σ^o_L=-5.0 dB in Eq. (4) resulted in a water body fraction threshold of 4.4%.

Accordingly, pixels in the SSM product with a water body fraction above 4.4% were masked. Two examples of weekly 1 km SSM maps masked in this way are shown in Figure 2. It should be noted that in the Permafrost project's SSM maps pixels were also masked if their sensitivity to soil moisture (a model parameter) was below 5.5 dB to minimize uncertain retrievals. More pixels are therefore masked in Figure 2 than is to be expected from Figure 1.

The water body map used in this paper was retrieved from ASAR WS 150 m data. The accuracy of the water body fraction estimates can be improved upon by using a water body map with higher spatial resolution. The difference between real and assumed values of the backscatter components for open water and land is expected to be a significant source of error. As an example, using mean backscatter values for σ^o_W and σ^o_L in Eq. (3) instead of the applied worst case scenario increased the masking threshold from 4.4% to 8.5%. It is expected that more realistic values of σ^o_W and $\sigma^o_{L,}$ could be retrieved by analyzing the σ^o image subject to SSM retrieval using the water body map.

The Sentinel-1 mission will be the first SAR mission to deliver sufficiently regular and frequent observations globally to render a global medium to high resolution soil moisture product feasible [22]. The main mode of operation will be the 5x20 m^2 resolution Interferometric Wide Swath (IW) mode which will operate at C-band with acquisitions consistent with the ENVISAT ASAR instrument, albeit with much improved radiometric qualities [23]. It is therefore foreseen that the ENVISAT ASAR Surface Soil Moisture algorithm will be transferrable to future Sentinel-1 observations [24], with improved parameter estimation accuracy considering the higher signal-to-noise ratio [25]. While the 1 km SSM product could be retrieved from multilooked Sentinel-1 IW data, the full-resolution IW data could be used to classify water bodies. It is therefore foreseen that the methodology to account for small water bodies presented in this paper can be transferred to the Sentinel-1 case.

5. CONCLUSION

Robust soil moisture retrieval from SAR requires taking into account the presence of water bodies at and below the spatial scale of the soil moisture estimates. The relatively high frequency of small water bodies in tundra regions makes this issue highly relevant for permafrost regions. This paper presented a statistical approach to identify backscatter measurements suitable for soil moisture retrieval from SAR in the presence of sub-pixel water bodies. Further work is required to assess the errors associated with the approach. Surface soil moisture and water body information were retrieved, respectively, from ENVISAT ASAR GM (1 km resolution) and ASAR WS (150 m resolution) data. A high potential for transfer of the methodologies presented in this paper to the Sentinel-1 mission is apparent due to the consistency of measurements with ENVISAT ASAR.

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