RETRIEVING SOIL MOISTURE AND TEMPERATURE USING SMOS OBSERVATIONS AT A TEST SITE IN THE YAMAL PENINSULAR

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ABSTRACT

In this paper, the results of radiothermal remote sensing of soil moisture and temperature is presented for a test site located in Arctic tundra on the Yamal Peninsula, the Russia Federation using full-polarimetry multi-angular brightness temperature (BT) observations at the frequency of 1.4 GHz. The BT data were obtained from the Soil Moisture and Ocean Salinity (SMOS) satellite with the SMOS footprint near the polar weather station Marresale, Yamal Peninsular, the Russia Federation. The SMOS data covered the period of on the ground observations conducted in August, 2015. The method to retrieve soil moisture and temperature is based on solving an inverse problem by minimizing the norm of the residuals between the observed and predicted values of BTs. The calculation of BT was performed using semi-empirical model of radiothermal emission and temperature-dependent dielectric model for an organic-rich tundra soil. The obtained results revealed the applicability of the SMOS data for simultaneous retrieving the soil moisture and temperature for the Arctic tundra environment.

Index Terms— SMOS, microwave radiometry, Arctic tundra, soil moisture, soil temperature, permittivity model.

1. INTRODUCTION

In the Arctic region, the soil moisture and temperature play a crucial role in governing energy fluxes between the soil and the atmosphere, and, therefore, they should be monitored and used for the climate change prediction. At the same time, the weather stations networks are too sparse to provide sufficient data on the soil temperature and moisture in the northern latitudes. Satellite remote sensing techniques of soil temperature and moisture can considerably compliment the data provided by weather stations network. Radiometric data of Soil Moisture and Ocean Salinity (SMOS) satellite are widely used to retrieve soil moisture across the globe. At the same time, soil moisture, measured with using radiometric SMOS data, in the Arctic tundra regions is not still validated sufficiently, and the possibility to retrieve the soil temperature is poorly investigated. In this paper, in contrast to the standard SMOS algorithm, the possibility of simultaneously retrieval of soil moisture and temperature in the region of Arctic tundra are investigated. It is supposed to experimentally investigate the applicability of the emission model [1] and permittivity model of organic tundra soil [2], specially created based on soil samples, collected at the test site, for simultaneously retrieving of soil moisture and temperature from SMOS radiometric data.

2. TEST SITE AND DATA

As a test site of Arctic tundra, the territory of polar weather station Marresale (WS), which is located in the west coast of the Yamal Peninsula, Russia (69.7164 N, 66.8125 E) was chosen. The landscape of the test site is predominantly formed by a grassy Arctic tundra with various kinds of grass, moss, and low shrubs. The total thickness of organic cover on top the soil layer (moss, lichen, turf, and peat) is about 0.1 m. Sand and sandy-loam soils predominate in the near-surface (0-30 cm) mineral soil layer, which has the following texture percentages by weight: sand 26-37%, silt 46-63% and clay 11-17% [3]. On the test site, the soil temperatures at depths of 0.0 cm, 2.5 cm, 5.0 cm, 10.0 cm and 20.0 cm were measured with using the electronic thermometer Testo905-T1. At three different points of the test site, the volumetric soil moisture in three soil layers (0-3 cm, 3-6 cm, and 6-9 cm) was measured using the thermogravimetric-weight method. The mean value and standard deviation of soil moisture, measured in the respective layers appeared to be of 0.32±0.07 cm^3/cm^3, 0.68±0.06 cm^3/cm^3, and 0.65±0.14 cm^3/cm^3. The mean values and standard deviations of dry soil density appeared to be 0.17±0.05 g/cm^3, 0.47±0.18 g/cm^3, and 0.74±0.35 g/cm^3, in the respective layers.

The SMOS 2-D interferometric radiometer measures the BT of the earth surface at vertical and horizontal polarizations in the range of viewing angles from 0° to 65° with the space resolution of 43 km by 43 km. The full polarization BT of Level 1C product (ascending orbits) with Discrete Global Grid (DGG) node closest to coordinate (69.748 N, 68.383E) was employed.

In this paper, the SMOS observations covered the period from August 1 to August 31, 2015 the same time when the expedition took place in Yamal Peninsular. Typical SMOS BTs for the test area are shown in Fig. 1. Also, MODIS LST L3 Global 1 km (V041) data were used as reference data.

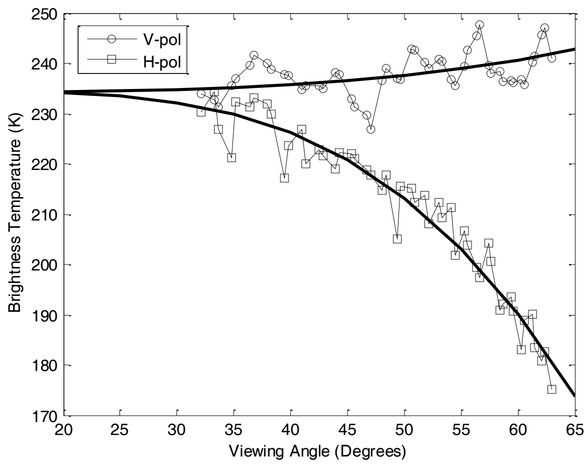

Fig. 1. The SMOS brightness temperature as a function of viewing angle, measured in August 18, 2015. Solid lines are the fits obtained with the use of the model discussed in Section 3.

3. MICROWAVE BRIGHTNESS TEMPERATURE MODEL AND METHOD FOR RETRIEVING SOIL TEMPERATURE

To model the BT, $T^{th}_{B,p}(\theta)$, as a function of viewing angle, θ, for the horizontal, *p*=*H*, and vertical, *p*=*V*, polarizations, we used the semi-empirical model for microwave emission [1]:

$$T^{th}_{B,p}(\theta) = \left(\left[1-(1-Q)\left|R_p(\theta,\varepsilon_s)\right|^2 + \ldots \right. \right. \quad (1)$$
$$\left. \left. Q\left|R_q(\theta,\varepsilon_s)\right|^2 \right] e^{-H_r \cos^N \theta} \right) \cdot T_s$$

Combinations *p*=*H*, *q*=*V* and *p*=*V*, *q*=*H*, are possible. Here T_s is the physical soil temperature, $R_p(\theta, \varepsilon_s)$ is the Fresnel reflection coefficient, $Q=0.118H_r$ is the depolarization factor, which accounts for polarization mixing effects, $N=1.615[1-exp(-H_r/0.359)]$ is the parameter, which modifies the angular dependence of the BTs due to roughness, H_r, of soil surface, ε_s is the soil complex permittivity. The largest error 6.5K of model (1), was estimated from the experiments [1] carried out with predominantly mineral soils in thawed condition, at only one specific location (PORTOS 1993 data set, Avignon, France). For calculation BT in model (1) was used the temperature dependent dielectric model for arctic tundra organic-rich soil [2]. Creation of dielectric model was based on soil samples, which were collected at the point with coordinate (70.4311N, 68.4219E) close to the test site. The sample was extracted from the organic layer at depths from 9 to 14 cm, and it consists of mineral solids and decomposed organic matter. In vivo, the air-dry bulk density of the sample equals to 0.26 g/cm^3. The percentages of organic matter and mineral solids components are as follows: organic matter ~50%, quartz ~30%, potassium feldspar ~5-10%, plagioclase ~5-10%, and chlorite, mica, smectite in trace amount (< 1 percent). The dielectric model ensures predictions of the real and imaginary parts of complex permittivity in the ranges 0.03 g/g $< m_g < 0.55$ g/g, –30°C< *T*< 25°C, and 0.05 GHz < *f* < 15 GHz. The model was validated by the good agreement with the measured data.

According to the equation (1) and soil permittivity model [2], the BT $T^{th}_{B,p}(\theta)$ can be presented by function of following variables: $T^{th}_{B,p}(\theta) = T^{th}_{B,p}(\theta,\ \mathrm{m_v} = \mathrm{m_g} \cdot \rho_\mathrm{d}, \mathrm{T_s}, \mathrm{H_r})$. To reduce amount of the parameters to be retrieved, the dry bulk density was set equal to the mean dry bulk density, ρ_d=0.32 g/cm^3, of topsoil layer 0-6cm, which was measured *in situ* in August 12-20, 2015 at the area of test site. Method to retrieve soil temperature is based on solving inverse problem by minimizing norm of the residuals between the observed, $T^m_{B,p}(\theta_i)$, and predicted, $T^{th}_{B,p}(\theta_i)$, values of BTs

$$F(\mathrm{m_v}, \mathrm{T_s}, \mathrm{H_r}) = \sum_{p=H,V} \sum_{i=1}^{N} \left| T^m_{B,p}(\theta_i) - T^{th}_{B,p}(\theta_i) \right|^2, \qquad (2)$$

here *N* is the total number of viewing angles in the range of 0°≤θ_i≤°60. The convergence of functional (2) at varying of the parameters: soil moisture, m_v, from 0.2cm^3/cm^3 to 0.8cm^3/cm^3, soil temperature, T_s, from 273.15 to 290, and roughness parameter, H_r, from 0 to 2 should be investigated to confirm the unique solution of the problem (2). It was shown, that under such variations of parameters there is the only set of soil moisture, soil temperature and soil surface roughness parameter, which reduce the functional (2) to the global minimum (see Fig. 2).

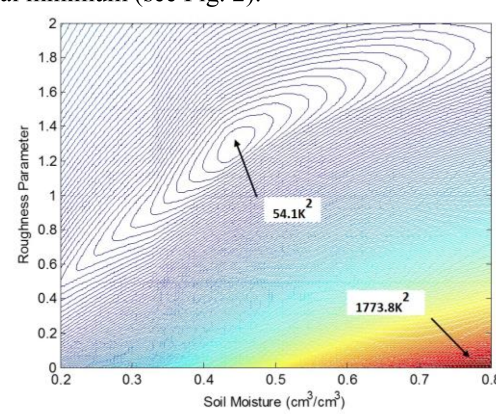

Fig. 2. Topography of functional (2), in coordinates of soil moisture and roughness parameter, at the soil temperature equal of 276.6K, which reduces the functional (2) to the one global minimum (SMOS brightness temperature data: August 18, 2015).

Thus, in the process of minimizing of functional (2), the only solution of the problem will be found.

4. RESULTS

The solving of the problem (2) has been conducted for three cases. In the first case, the soil moisture, the roughness parameter, the soil temperature were retrieved. In the second case, the soil moisture, the roughness parameter were retrieved, but the soil temperature was set as fixed values of LST MODIS for corresponding days. In the third case, the roughness parameter and the soil temperature were retrieved for fixed mean value of the soil moisture from August 1 to 30, 2015. For all cases, retrieved values of soil moisture and soil temperature are depicted in Fig 3 and Fig. 4, respectively.

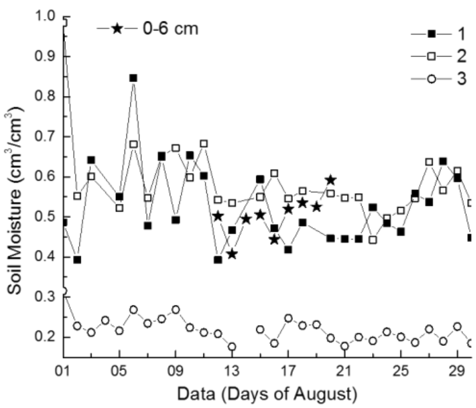

Fig. 3. Retrieved values of soil moisture for the first case (1), when all parameters are retrieved, for the second case (2), when soil temperature was equal LST MODIS. Soil moisture values, which were acquired from SMOS L2 product (3). Asterisks denote the values of soil moisture measured in situ in different soil layers from August 12-20, 2015.

Soil moisture values (SMOS L2 product) best of all correspond to soil moisture, which were measured in situ in the topsoil layer at 0-3 cm (see Fig. 3). Soil moisture values (SMOS L2 product) correspond best of all to soil moisture which were measured in situ in the topsoil layer at 0-3 cm (see Fig. 3), but these are systematically lower than last. Retrieved values of soil moisture best of all correspond to soil moisture, which were measured in situ in the topsoil layer at 0-6 cm (see Fig. 3). Root-mean square error (RMSE) between soil moisture retrieved in first and second cases was found to be 0.13cm^3/cm^3. RMSE between retrieved and in situ (0-6 cm) measured values of soil moisture were found to be 0.08 cm^3/cm^3 and 0.07 cm^3/cm^3, respectively for the first and second cases, respectively. Difference between soil moisture values (SMOS L2 product) and in situ measured soil moisture are less than 0.13 cm^3/cm^3.

The LST MODIS soil temperature corresponds very well to in-situ measured soil temperature (see Fig. 4), RMSE and determination coefficient was found to be 1.1°C and 0.77, respectively. Since in August, 2015, at the test site, in situ soil temperature data were not available, other than those are shown in Fig. 4, retrieved values of soil temperature were compared with LST MODIS ones. RMSE between LST MODIS and retrieved soil temperature were found to be 7.5°C for the first case, when all parameters were retrieved, and 6.1°C for the third case, when soil moisture was fixed as mean value of 0.58 cm^3/cm^3. Determination coefficients between LST MODIS and retrieved soil temperature were found to be 0.13 and 0.32, respectively for these cases. When comparing between the retrieved soil temperature and LST MODIS we have neglected by the soil temperature variation within SMOS pixel 43x43 km. Also, it found within the SMOS pixel standard deviation of LST MODIS was about 3K. For all cases mean value and a standard deviation of roughness parameter was found to be 0.13±0.02.

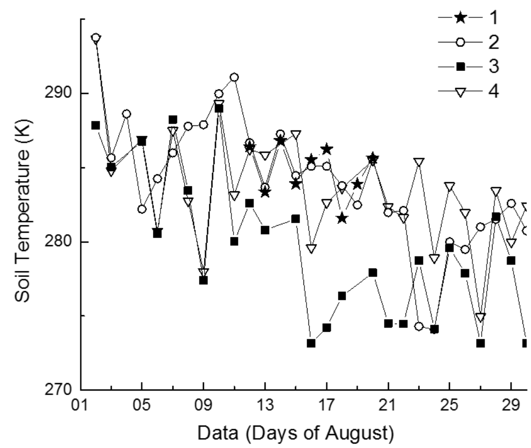

Fig. 4. Time series of soil temperature, measured in situ (1) from August 12-20, 2015; 2) LST MODIS; 3) retrieved values of soil temperature when all parameters were retrieved and 4) when soil moisture was fixed as mean value of 0.56 cm^3/cm^3.

Apparently, it is possible to obtain more reliable estimates for the mean value of the parameters, which were retrieved for a few days. Indeed, the average value of soil moisture and soil temperature measured in situ from 12 to 22 August, were equal to 0.51 cm^3/cm^3 and 284.8K, respectively. The difference between the average measured and average retrieved values of soil moisture during this period were equal to -0.04 cm^3/cm^3 and 0.05 cm^3/cm^3, in the first case, when all parameters were retrieved, and in the second case, when soil temperature was equal LST MODIS, respectively. The difference between the average measured and average retrieved values of soil temperature during this period were equal to -6.7K and 0.4K, in the case, when all parameters were retrieved, and when soil moisture was fixed as mean value of 0.56 cm^3/cm^3.

5. CONCLUSION

As a result, the soil moisture and temperature can be simultaneously retrieved from radiometric SMOS data with using of the emission [1] and the dielectric [2] models. The proposed retrieval method was conducted with the use of SMOS brightness temperature data over a test site on the Yamal Peninsula spanning a time period from August 12, to August 20, 2015. It was shown that for the chosen test site the retrieved soil moisture are better correlated with the soil moisture, measured in 0-6 cm layer, than it is with soil moisture, measured in situ in 0-3 cm layer. Using LST MODIS as input values of soil temperature in algorithm does not allow to increase, the accuracy of the soil moisture retrieval, relative to the case when simultaneously retrieved both soil moisture and temperature. Error of soil temperature retrieval simultaneously with the soil moisture is relatively highly (~± 3.3K). However, the accuracy of the reconstructed values is possible to increase in several times, if to make estimates between the measured and retrieved values of soil temperature, which are averaged over several days. For the proposed approach a comprehensive and a serious testing over a longer time period and for a more representative number of ground-based test site located in the Arctic region are needed.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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