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Satya Prakash

CUNY New York City College of Technology

Hamid Norouzi

CUNY New York City College of Technology

Marzieh Azarderakhsh

Fairleigh Dickinson University

Reginald Blake

CUNY New York City College of Technology

Kibrewossen Tesfagiorgis

CUNY Borough of Manhattan Community College

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Global Land Surface Emissivity Estimation From AMSR2 Observations

Satya Prakash¹, Hamid Norouzi^{1,*}, Marzi Azarderakhsh², Reginald Blake¹,
Kibrewossen Tesfagiorgis³

¹New York City College of Technology,
The City University of New York, Brooklyn, NY 11201 USA

²Fairleigh Dickinson University, Teaneck, NJ 07666 USA

³Borough of Manhattan Community College,
The City University of New York, New York, NY 10007 USA

**Corresponding author's e-mail: hnorouzi@citytech.cuny.edu*

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ABSTRACT: A reliable estimate of emissivity is critical for a wide range of applications for the atmosphere, the biosphere, the lithosphere, the cryosphere, and the hydrosphere. This study uses three years (August 2012 – July 2015) of data from the Advanced Microwave Scanning Radiometer-2 (AMSR2) sensor that is onboard the Global Change Observation Mission 1st Water (GCOM-W1) satellite to explore estimates of instantaneous global land emissivity. A method is adopted to remove the known inconsistency in penetration depths between microwave brightness temperatures and infrared-based ancillary data that could cause differences between day and night emissivity estimates. After removing the diurnal atmospheric effects, the resulting retrieved cloud-free land emissivities realistically represent well-known large-scale features. As expected, the polarization differences of estimated emissivities show noticeable seasonal variations over the deciduous woodland and grassland regions due to changes in vegetation density. The potential of estimated emissivities for high-latitude snow detection and freeze/thaw states identification is also demonstrated.

Keywords: Brightness temperature, Land cover, Land surface emissivity, Passive microwave (PMW) remote sensing

1. Introduction

Accurate estimates of microwave land surface emissivity (the efficiency with which infrared energy is emitted) are crucial for the retrieval of several atmospheric quantities related to land surface processes, to the monitoring of vegetation phenology and surface properties, and for numerical weather prediction (NWP) data assimilation [1]-[6]. Both the numerical modeling as well as satellite-based retrievals of land surface emissivity are challenging due to high variability of emissivity, and its sensitivity to land surface parameters such as soil moisture, land cover type, surface roughness, etc. Passive microwave (PMW) remote sensing of land emissivity has the advantages of considerably high revisit time (at least twice daily) and having multiple channels that are sensitive to different atmospheric variables and surface properties.

In the last three decades, several methods have been proposed to estimate land surface emissivity from a wide range of PMW sensors onboard the low-Earth orbiting satellites e.g., SSM/I [1], [7], AMSR-E [8], AMSU [9], [10], TRMM [11], WindSat [12]. In addition, to improve the retrieval of atmospheric profiles and the direct assimilation of radiances in state-of-the-art NWP models over land, a Tool to Estimate Land Surface Emissivities at Microwave frequencies [13] was developed with the use of a radiative transfer model, which performs reasonably well at lower frequencies [2]. However, all these satellite-estimated land emissivities are based on different algorithms, and they use partially different ancillary data sets. These satellite-derived emissivity products were validated independently at some selected gauge locations by Ferraro *et al.* [3] and Tian *et al.* [5]. Their results suggested that even though all these products show similar variability and seasonal trends, notable differences among these estimates exist at monthly scales. Due to scarcity of ground observations of land emissivity, it is difficult to validate satellite-derived products on the global scale. Recently, Norouzi *et al.* [6] evaluated the consistency among some of the satellite-derived emissivity products at the global scale from 2003 to 2007 and showed that the differences among them might be due to the use of different ancillary data sets and different radiative transfer models that have been used for their computation. Norouzi *et al.* [6] emphasized the importance of using a common algorithm to compute land surface emissivity from different PMW

sensors and thereby produce a comprehensive global multi-satellite “best” emissivity estimate to analyze the diurnal characteristics of land surface processes.

The Advanced Microwave Scanning Radiometer-2 (AMSR2), a seven-channel conical scanning passive microwave radiometer having incidence angle of 55° , onboard the Global Change Observation Mission 1st Water (GCOM-W1 or “SHIZUKU”) satellite was placed in orbit on 18 May 2012 as a successor of AMSR-E and AMSR instruments onboard NASA’s Aqua and ADEOS-II satellites, respectively to achieve long-term global comprehensive Earth monitoring. The sampling interval of 6.925, 7.3, 10.65, 18.7, 23.8 and 36.5 GHz channels is 10 km, and 5 km for 89 GHz. The basic characteristics of AMSR2 are similar to AMSR-E, but AMSR2 has several advancements in terms of additional channels in C-band to mitigate radio frequency interference; it also has a larger main reflector antenna and an improved calibration system as compared to its predecessor [14]. The objective of this study is to estimate instantaneous global land surface cloud-free emissivity from AMSR2 observations for the period of August 2012 to July 2015. The potential of the estimated land emissivity for high-latitude snow detection, and freeze/thaw states identification is also demonstrated.

2. Data and Methods

All the seven-channels with vertical and horizontal polarizations of AMSR2 level-3 global swath spatially resampled brightness temperatures (Tbs) at 0.25° latitude/longitude for the study period (August 2012 to July 2015) were obtained from the GCOM-W1 data providing service at the Japan Aerospace Exploration Service (JAXA). To remove the influence of atmospheric effects from the passive microwave measurements, near-simultaneous skin temperature (Ts), and profiles of air temperature and humidity are used. The Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua version 5 cloud-free land surface temperature daily L3 swath global product (MYD11C1) [15] available at 0.05° climate modeling grid (~ 5.6 km at the equator), and global integrated water vapor and air temperature profile from the Atmospheric Infrared Sounder (AIRS)/Aqua version 6 daily L3 gridded standard retrieval swath product using AIRS infrared-only (AIRS3STD) [16] available at 1° latitude/longitude grid are used. It is to be noted that the local equatorial crossing time for

both AMSR2 and Aqua is approximately 01:30 (descending) and 13:30 (ascending). Thus, the estimated land emissivity estimates would essentially benefit from the near-simultaneous observations from the Aqua satellite.

As all the orbital data sets from the three distinct instruments are at different spatial resolutions, they are re-projected to a common equal-area grid (0.25° at equator). The instantaneous global land surface emissivity (ε) at polarization “ p (H or V)” and frequency “ ν ” is computed from the corresponding Tbs and surface skin temperature (T_s) using the following expression by Prigent *et al.* [7], [10]:

$$\varepsilon_{(p,\nu)} = \frac{Tb_{(p,\nu)} - T\uparrow - T\downarrow e^{-\tau(0,H)/\mu}}{e^{-\tau(0,H)/\mu} (T_s - T\downarrow)} \quad (1)$$

where, $T\uparrow$ and $T\downarrow$ are upwelling and downwelling Tbs from the atmosphere and they depend on the incidence angle, atmospheric absorption and extinction. These terms are determined by the procedures described by Norouzi *et al.* [8].

The estimated cloud-free land emissivity using the above-mentioned procedures consists of undesired diurnal variations due to the use of infrared-based surface skin temperatures. The main issue is the significant difference between Tbs and the infrared skin temperatures’ diurnal cycle amplitude and phase time in arid regions. To mitigate this discrepancy, a correction factor is applied at instantaneous emissivity primarily over the arid regions (a region over which this influence is amplified due to moisture and vegetation scarcity) based on a simplified version of the procedures described by Norouzi *et al.* [17]. A correction factor given by equation (2) is computed for each month (t) separately based on the mean of day and night Tbs , and then applied to average daily surface skin temperature (T_s). This modified skin temperature is finally used to retrieve emissivity instead of using the original T_s .

$$T_{s(t)}^C = T_{s(t)} \pm \frac{\overline{Tb_{day(t)}} - \overline{Tb_{night(t)}}}{2} \quad (2)$$

where, $\overline{Tb_{day(t)}}$ and $\overline{Tb_{night(t)}}$ are the mean composite Tbs for all the day and night overpasses for a specific month, and $T_{s(t)}$ is the mean daily skin temperature. The

effect of implementing this correction factor on the land emissivity estimates is also discussed in the later section.

3. Results

Figure 1 presents the monthly mean composites of estimated land emissivities at horizontal polarization for January and July 2013 at 6.925, 18.7 and 89 GHz. In general, the known large-scale emissivity features and their seasonal variations are well characterized by the present estimates. Lower emissivity over the arid regions e.g., over the Sahara desert in Africa, Arabian Desert and Gobi desert due to smaller surface roughness are observed as compared to the vegetated regions. Additionally, lower frequency channels show smaller magnitude of emissivity than that from the higher frequency channels. The seasonal variations of emissivity, especially over the high-latitudes associated with land cover changes, are also well depicted by the AMSR2 estimates. The permanent ice covered areas (e.g., permafrost) such as Greenland and regions around the South Pole always indicate smaller emissivity. A contrasting feature between 6.925 GHz and 89 GHz derived emissivities is observed during the month of January in the Northern high-latitudes. As high frequency channels are more sensitive to snow or ice particles, the difference of emissivities between these two channels will be more useful for snow detection and for the identification of freeze/thaw states. Recently, Shahroudi and Rossow [4] proposed an algorithm based on emissivity differences of higher and lower frequencies of SSM/I for snow detection.

The mean land emissivity features from the present estimates (i.e., from AMSR2) are compared with AMSR-E derived land emissivity [8]. Figure 2 shows mean land emissivity from both the sensors at horizontal polarization for January at 6.925, 18.7 and 89 GHz channels. It is to be noted that the periods are different for both the sensors (e.g., 2013-2015 for AMSR2 and 2003-2008 for AMSR-E) based on their availability. The well-known global features are in good agreement with each other. The pattern correlation between both the estimates also shows higher correlation at lower frequency channels. However, the correlation decreases with increase in frequency channel. The use of distinct ancillary data sets for the emissivity computation is one of major reasons for this discrepancy. Norouzi *et al.* [8] showed that an error of 25% in the atmospheric water

vapour would lead to 3% error in emissivity estimates at 89 GHz, but the error would be negligible for the lower frequency channels. Hence, the use of concurrent ancillary data sets would essentially improve the accuracy of the present estimates.

The emissivity estimates at horizontal and vertical polarizations do not necessarily show similar characteristics due to their different dielectric constant responses. The time-series of daily estimated emissivity polarization difference (vertical minus horizontal) from all the frequency channels of AMSR2 for the study period averaged over four distinct land cover types in the Northern Hemisphere are shown in Figure 3. These land cover types are classified using 10 broad classes from 32 distinct classes defined by Prigent *et al.* [7]. Larger differences in emissivity due to polarization are observed in lower frequency channels as compared to higher frequency channels in all the land cover types. Deserts have the largest polarization difference and evergreen rainforests exhibit the smallest. The vegetated land areas like deciduous woodland and grassland show noticeable seasonal variations associated with seasonal changes in vegetation density. Since evergreen rainforest areas have high vegetation density throughout the year, they do not show any significant seasonal variation [6]-[8]. The results clearly show that the emissivity differences due to polarizations can be used to identify vegetation types and land cover. Moreover, land emissivity is sensitive to vegetation density and soil moisture. Hence, emissivity estimates have the potential for precipitation retrieval over the land and drought monitoring.

Over the desert regions, low frequency PMW signals penetrate the land surface due to minimal vegetation and negligible moisture content. This causes considerable errors in emissivity retrievals due to diurnal variations of skin temperature and Tbs [17], [18]. To minimize the errors in instantaneous emissivity retrievals, the method described by equation (2) was used to correct the estimated AMSR2 emissivities after correcting the effective temperature. For instance, Figure 4 illustrates the monthly mean composites of estimated land emissivity differences between ascending (day) and descending (night) orbits at 6.925, 18.7 and 89 GHz for July 2013 before and after applying correction. Large differences in emissivities (more than 5%) can be seen over the major desert regions if correction is not applied. Since the equatorial crossing time of AMSR2 is around the daily maximum temperature in daytime but not near the daily minimum

temperature at nighttime, the differences in emissivity estimates are pronounced. The differences are larger for lower frequency channels than for higher frequency channels [18]. A noticeable improvement in emissivity differences can be clearly seen after applying the correction. The mean and standard deviation (SD) are considerably reduced after applying the correction factor to the emissivity estimates, which indicates an improvement in corrected emissivity estimates. Hence, the corrected instantaneous emissivity estimates were used throughout this study.

To demonstrate the potential applicability of estimated AMSR2 emissivities, the time-series of daily day-time (at 1330 local time) snow depth, precipitation, air temperature, 5 cm soil temperature and 5 cm soil moisture for a ground station located at Gobblers Knob, Alaska (66.75° N and 150.67° W) and corresponding AMSR2 estimated emissivities at 6.925, 18.7, 36.5 and 89 GHz and the difference of 89 GHz from three lower frequencies for 2013 are shown in Figure 5. Air temperature shows more variations than does soil temperature. Snow cover and soil temperature appear to be consistent. The satellite-derived emissivities also show qualitative sensitivities to snow cover and to freeze/thaw states. The difference between 19.35 and 85.5 GHz of SSM/I derived emissivities was recently used to develop an algorithm for snow detection over the high-latitude regions [4]. AMSR2 has the advantage of additional lower frequency channels. However, *Tbs* from the PMW sensors are used for freeze/thaw states identification [19], [20], which is largely influenced by atmospheric effects. Emissivity is estimated by delineating the atmospheric effects and it does not show diurnal variations due to physical temperature. The use of emissivity rather than *Tbs* would be more ideal for high-latitude applications. Hence, the difference of AMSR2 derived emissivity between 6.925- and 89-GHz channels appears to have significant potential and advantages for snow detection as well as freeze/thaw states identification.

4. Summary and Conclusions

In this study, instantaneous global land emissivity is estimated at all channels and polarizations of AMSR2 for cloud-free regions. The pronounced diurnal effect in estimated emissivities was corrected primarily over the arid regions. The estimated emissivities were able to capture all the major large-scale features such as lower

magnitude over deserts than vegetated areas. The time-series of daily difference of estimated emissivity between vertical and horizontal polarizations for the three-year study period showed significant seasonal variations over the deciduous woodland and grassland areas as expected. Moreover, the differences between 6.925 and 89 GHz emissivities showed great potential for snow detection and freeze/thaw identification in high-latitude regions.

In order to study the diurnal characteristics of emissivities, there is a need for multi-satellite emissivity estimates from all available PMW sensors employing a common algorithm. Since a significant portion of the global land areas is covered by cloud at any instant, it considerably limits the spatial coverage of estimated instantaneous emissivity. The use of multiple sensors would essentially enhance spatiotemporal coverage of the emissivity estimates.

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Figure 1 Monthly mean composite maps of AMSR2 derived land emissivity at 6.925, 18.7 and 89 GHz horizontal polarization for January and July 2013

Figure 2 Spatial distributions of mean land emissivity from AMSR2 (averaged for 2013 to 2015) and AMSR-E (averaged for 2003 to 2008) at 6.925, 18.7 and 89 GHz horizontal polarization for the month of January. The pattern correlations of emissivities from both the sensors are also provided.

Figure 3 Time-series of daily AMSR2 derived emissivity difference between vertical and horizontal polarizations averaged over different land cover types in the Northern Hemisphere for August 2012 to July 2015.

Figure 4 Monthly mean composite maps of AMSR2 derived land emissivity difference between ascending and descending orbits for July 2013 before and after correction. Mean and standard deviation (SD) are also given for each plot.

Figure 5 Time-series of daytime snow depth (in yellow shaded area), precipitation (in black bars), air temperature, soil temperature and soil moisture at 5 cm observed at a ground station in Alaska for 2013. The corresponding AMSR2 derived horizontally polarized emissivities and their differences are also shown.