Remote Sensing of Environment 115 (2011) 3695–3706

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Correcting for the influence of frozen lakes in satellite microwave radiometer observations through application of a microwave emission model

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ARTICLE INFO

Article history:
Received 20 April 2011
Received in revised form 18 August 2011
Accepted 12 September 2011
Available online 19 October 2011

Keywords:
Snow water equivalent
Passive microwave
Lake ice

ABSTRACT

The spatial resolution of passive microwave observations from space is of the order of tens of kilometers with currently available instruments, such as the Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer (AMSR-E). The large field of view of these instruments dictates that the observed brightness temperature can originate from heterogeneous land cover, with different vegetation and surface properties.

In this study, we assess the influence of freshwater lakes on the observed brightness temperature of AMSR-E in winter conditions. The study focuses on the geographic region of Finland, where lakes account for 10% of the total terrestrial area. We present a method to mitigate for the influence of lakes through forward modeling of snow covered lakes, as a part of a microwave emission simulation scheme of space-borne observations. We apply a forward model to predict brightness temperatures of snow covered sceneries over several winter seasons, using available data on snow cover, vegetation and lake ice cover to set the forward model input parameters. Comparison of model estimates with space-borne observations shows that the modeling accuracy improves in the majority of examined cases when lakes are accounted for, with respect to the case where lakes are not included in the simulation. Moreover, we present a method for applying the correction to the retrieval of Snow Water Equivalent (SWE) in lake-rich areas, using a numerical inversion method of the forward model. In a comparison to available independent validation data on SWE, also the retrieval accuracy is seen to improve when applying the influence of snow covered lakes in the emission model.

1. Introduction

The cryosphere is an important component in the Earth's climate system. Its importance is underlined by the variability and the change in physical properties of its components. The highly varying snow component of the climate system includes many positive feedbacks e.g. the temperature–ice-albedo feedback. These have a strong impact on the surface energy budget especially at higher latitudes (Lemke et al., 2007). Presently, the only method available for global snow cover monitoring on a revisit time sufficient for addressing needs of climate modeling studies is through satellite remote sensing. Optical and high frequency sensors provide information on snow extent and e.g. snow albedo, while microwave frequencies can be employed to detect snow volume and water content, as well as the extent of snow cover. Microwaves provide the unique advantage of being only lightly affected by weather and unaffected by lighting conditions, a critical factor in polar areas (Tedesco & Wang, 2006). Furthermore, passive microwave sensors (radiometers) provide near-global coverage with a high revisit time, up to several times a day.

However, current operational spaceborne microwave radiometers have a weak spatial resolution, originating from a large field of view, typically in the scale of tens of kilometers. As a result, the heterogeneity of land cover has an important role in the interpretation of observations. In particular, the presence of freshwater lakes and other water bodies in the field of view of a satellite instrument can cause a significant effect on the observed brightness temperature, as the emissivity of water differs considerably from that of dry ground at microwave frequencies (Rees et al., 2006). The differing background affects the total microwave emission observed, the effect depending on the penetration depth of a given frequency (Hall et al., 1981).

Several methods have been proposed for detection of snow cover properties, such as snow depth and water equivalent, through the interpretation of microwave radiometer observations. Typical inversion algorithms rely on a linear regression formula between snow depth and the difference of two observed frequency bands, as proposed by Chang et al. (1987). Different empirical fits and derivates of this approach have been proposed in the literature for both region specific and global applications (Derksen et al., 2003, 2005, 2010; Foster et

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doi:10.1016/j.rse.2011.09.008

al., 1997; Goodison & Walker, 1995; Hallikainen & Jolma, 1992; Kelly et al., 2003). Variations in land cover can be taken into account through e.g. a fractional vegetation correction (e.g. Foster et al., 1997) or through the application of region-specific algorithms (e.g. Derksen et al., 2003).

Approaches have also been proposed to apply a radiative transfer model to predict the emitted microwave brightness temperature from snow covered ground, using numerical model inversion to calculate snow properties from observations (Pulliainen & Hallikainen, 2001). Compared to purely empirical methods this approach has the distinct advantage of accounting for differing snow properties, such as temperature, density or snow grain size, all of which affect the total observed brightness temperature. However, both the purely empirical algorithms and the emission modeling approach are susceptible to inaccuracies related to heterogeneity of the land cover. For SWE retrieval algorithms formulated following Chang et al. (1987), this presents a source of error as the background signal may vary depending on the amount of e.g. water bodies present in the field of view of the satellite instrument. The effect increases with increasing wavelength, due to increased penetration depth, thus affecting most the lower frequency (typically K band, e.g. 19 GHz see Gunn et al., 2011). Water bodies in a satellite's field of view will thus generate a bias on a SWE estimate based on a fixed ratio of this frequency and a higher frequency (typically at Ka band, e.g. 37 GHz). The bias is usually negative, as the water bodies in the observation lower the average K band signal, causing the typically positive K–Ka band signal difference to decrease, which is in turn interpreted as a lower value of SWE. Recent studies have shown a correlation between airborne and space-borne observations of brightness temperature of snow-covered ground and fractional lake cover (Derksen et al., 2009; Lemmetyinen et al., 2009). The resulting error in estimation of SWE holds also for approaches relying on emission model inversion, if the differing background emission is unaccounted for.

Operational SWE retrieval algorithms typically mask out areas with significant lake coverage (Takala et al., in press); however, for areas such as Finland and e.g. parts of the Canadian tundra region, this results in the exclusion a significant portion of the observations. The purpose of this study is to examine brightness temperature emissions from freshwater bodies as a potential source of error in snow parameter retrieval methods applying passive microwave observations. We employ an electromagnetic forward model to estimate the brightness temperature of snow covered ground over a lake-rich area, and examine the model's capability to account for the influence of snow covered frozen lakes. Next, we propose a method to account for fractional lake cover in the inversion of the emission model for retrieval of snow water equivalent (SWE). The goal is to extend the applicability of SWE retrieval also to cover lake rich areas, thus potentially improving overall estimations of accumulated SWE.

Despite the existing global applications for retrieval of SWE from passive microwave observations (e.g. Takala et al., in press), this study is restricted to the geographic area of Finland. Finland has an area of 338 424 km^2, of which freshwater lakes account for 34 525 km^2. Snow typically covers close to 100% of the land areas during winter months, with snow cover lasting for typically 75–100 days in southern parts of the country, and up to over 200 days in northern parts above the 67th parallel (Drebs et al., 2002). Furthermore, Finland has an extensive network of in situ observations on snow cover and lake ice available. These factors make the area ideal for applying and testing the methodology presented in this study.

2. Forward model for satellite scenery brightness temperature

In this first part of this study, we apply an electromagnetic forward model for simulation of brightness temperature sceneries at different frequencies, as observed from a satellite, during three winter seasons (2005–2008) in Finland. The applied model is the HUT snow emission model (Pulliainen et al., 1999), adapted for multiple layers of snow or ice (Lemmetyinen et al., 2010). The simulation is performed to a common grid with available AMSR-E data. Model inputs for the simulation of individual observations (grid cells) are derived from available land cover, snow and meteorological data. The simulated sceneries are compared to AMSR-E observations on several channels, in order to examine the effect of lakes and other freshwater bodies on the simulation outputs.

The aim of the forward model experiment was

1. To demonstrate how lakes and other freshwater bodies affect spaceborne passive microwave observations over the winter period,
2. To examine to what degree the effect can be simulated by applying the presented forward emission model for lakes.

2.1. Modified HUT snow emission model for snow covered lake ice

The original HUT snow emission model describes microwave emission in the frequency range of 1–90 GHz for frozen ground covered by a homogeneous snowpack (Hallikainen et al., 1987; Pulliainen et al., 1999). Separate models account vegetation and atmospheric effects (Kruopis et al., 1999; Pulliainen et al., 1997). The ground layer is treated with a semi-empirical model, modifying Fresnel reflection coefficients based on microwave observations of soils (Wegmüller & Mätzler, 1999). The effect of the vegetation layer (forests) is accounted by applying a model by Kruopis et al. (1999); the model is based on airborne observations of snow-covered forests with differing values of biomass (stem volume, m^3/ha). An expansion to the snow emission model, allowing the simulation of multiple layers of snow, was presented by Lemmetyinen et al. (2010).

The model expansion for multiple layers (Lemmetyinen et al., 2010) also allows the inclusion of ice layers within the simulated snowpack, describing the ice as a simple non-scattering layer of absorptive media. Reflection and refraction at all layer interfaces are calculated considering only incoherent effects. The emissivity of water underneath the ice-snow system is considered by calculating the dielectric constant according to Klein and Swift (1977).

A schematic diagram of the structure of snow covered frozen lakes is presented in Fig. 1. The present emission model considers only congelation (black) ice covered by snow (Fig. 1a). This is a simplification of lake ice characteristics especially in the late winter period, when slushing events cause water to surge above the ice level as the combined weight of accumulated snow and ice overcomes the buoyancy of the ice (e.g. Adams & Lasenby, 1985). Refreezing of the water after these events results in the formation of a snow-ice (or: white ice) layer between the black ice and snow cover. This is depicted in Fig. 1b. This layer of white ice differs in terms of density, and thus dielectric properties, from the pure congelation ice below and the snow cover on top. Adams and Lasenby (1978) give measured density values of 0.838–0.886 g/cm^3 for the white ice layer over lakes in Canada, compared to the value of 0.916 g/cm^3 for pure ice.

In the model, all surfaces are considered ideally smooth with the exception of the lowest boundary between soil and snow, or that between ice and water in the case of lakes. The lowest boundary roughness is considered as an empirical fitting parameter. This boundary forms the largest dielectric contrast in the model, emphasizing the effect of applying an empirical parameter for roughness. The layer beneath the lowest interface is considered to be quasi-infinite; therefore, the upwelling microwave emission is only dependant on the physical temperature of the layer, and the transmissivity characteristics of the interface. The lowest interface is considered to be a flat horizontal surface, superimposed only by small random variations of surface height. In the case of natural lake and sea ice, deformation of ice could also cause larger variations in comparison to microwave wavelengths, and would result in the appearance of incoherent