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Coupling SNOWPACK-modeled grain size parameters with the HUT snow emission model

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ABSTRACT

We studied whether the physical snow evolution model SNOWPACK could be used together with the HUT snow emission model to simulate microwave brightness temperatures (TB) of snow cover and to parameterize key a priori variables in the retrieval of snow water equivalent (SWE). We used the extensive in situ measurement data set collected in Sodankylä, Finland, during the Nordic Snow Radar Experiment (NoSREx) campaign in 2009–2013 to model the evolution of snow with SNOWPACK. Resulting snow profiles were validated with manual in situ measurements. Mean agreement scores (for a winter) were 0.85–0.91 for traditional grain size, 0.74–0.75 for optical grain size, 0.65–0.80 for density, and 0.71–0.83 for temperature. Grain sizes modeled with SNOWPACK were compared to effective grain size retrieved from tower-based microwave radiometer measurements. The bias and RMS error of SNOWPACK optical grain size were −0.03 mm and 0.20 mm, respectively, and those of SNOWPACK traditional grain size were 0.30 mm and 0.33 mm, respectively. SNOWPACK snow profiles were used as input to the HUT snow emission model for calculation of TB, which was compared to microwave radiometer measurements. TB calculated with SNOWPACK optical grain size exhibited lower biases (from −12.5 K to 16.2 K, depending on year and frequency) and RMS errors (from 3.3 K to 18.5 K) than TB calculated with SNOWPACK traditional grain size (bias from −42.2 K to −9.9 K, RMS error from 12.0 K to 44.7 K). Grain sizes, temperature, and density modeled with SNOWPACK were used as a priori snow data in the retrieval of SWE from tower-based microwave radiometer observations. The lowest overall bias and RMS error were reached when traditional grain size from SNOWPACK was used, either directly with modelled snow density and temperature (−33 mm and 58 mm, respectively) or with an effective grain size correction and static snow density and temperature applied (22 mm and 59 mm, respectively).

1. Introduction

Seasonal snow has a significant effect on the Earth's surface energy balance (Groisman et al., 1994) and surface-atmosphere interaction through its high albedo and low thermal conductivity. It also affects hydrological processes by storing and releasing water, making snow crucial to one-sixth of the world's population living in areas where solid precipitation dominates annual runoff (Barnett et al., 2005). The magnitude of snow feedback mechanisms on climate change remains uncertain (Qu and Hall, 2014). Therefore accurate information on snow cover parameters, especially snow water equivalent (SWE), is needed in many applications, e.g. as input and validation data for climate models.

Global snow data are available from in situ measurements and remote sensing observations. In situ measurement networks in the areas covered with seasonal snow are insufficient due to difficulties in maintaining and operating measurement stations in sparsely populated areas with minimal infrastructure. Moreover, measurements are concentrated in easily accessible areas, and point-wise measurements do not necessarily represent the overall snow conditions well. Remote sensing offers unique possibilities for global daily snow monitoring. Passive microwave remote sensing of SWE is based on the extinction of microwave radiation, originating from soil, in the snowpack. Extinction is a sum of absorption and scattering, which vary with frequency, the amount of snow, and its dielectric and structural properties. Retrieval of SWE is often achieved from the difference of a higher (typically 36.5 GHz) and a lower (typically 18.7 GHz) frequency brightness temperature (TB). The first algorithm to exploit this relationship between TB and SWE was introduced by Chang et al. (1987). The algorithm relies on an empirical, linear relationship of the frequency difference and SWE. Variants of the algorithm have been used with SSM/I (Special

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Sensor Microwave Imager) and AMSR-E (Advanced Microwave Scanning Radiometer for Earth Observing System) (Kelly and Chang, 2003). However, the algorithm assumes constant snow density and grain size, and therefore exhibits large errors on areas where snow conditions differ from the assumptions (Davenport et al., 2012). In the newer AMSR-E algorithm (Kelly, 2009) this has been taken into account with coefficients adjusting with the measured TBs. This modification partially compensates for changes in snow microstructure and density.

An alternative method for SWE retrieval is to utilize an inversion of a forward model for microwave emission of snow-covered ground. Emission models published in the literature include Microwave Emission Model of Layered Snowpacks (MEMLS) (Wiesmann and Mätzler, 1999), Dense Media Radiative Transfer Multi-Layer (DMRT-ML) model (Picard et al., 2013), and the Helsinki University of Technology (HUT) snow emission model (Pulliainen et al., 1999). In this paper we focus on the HUT model. It is operationally used in the GlobSnow SWE retrieval algorithm, which also incorporates the assimilation of in situ snow observations with passive microwave retrievals (Pulliainen, 2006; Takala et al., 2011). We apply the original 1-layer version (Pulliainen et al., 1999) of the HUT model in the retrievals of an effective grain size and SWE, and the modified n-layer version (Lemmetyinen et al., 2010) in the TB simulations.

Snow microstructure is the key parameter affecting the scattering of microwave radiation in snow. Snow consists of a continuous ice structure and pore space (Fierz et al., 2009), and may contain ice, air, liquid water, water vapor, and impurities. After initial precipitation, natural snowpacks form complex structures of ice grains in different stages of metamorphism. The internal structural variations of snow at distances comparable to wavelength affect scattering of electromagnetic waves in the snowpack, and must therefore be incorporated in SWE retrieval algorithms. In microwave emission models, snow microstructure is typically described with a proxy parameter related to grain size: MEMLS uses correlation length (p_c), DMRT-ML uses the diameter of spheres representing snow grains together with a stickiness parameter, and the HUT model uses traditional grain size (E). Recently efforts have been made to simulate scattering behavior of microwaves in snow through applying a numerical solution to Maxwell's equations of simulated microstructures (Tsang et al., 2013). All the symbols for different snow parameters and their short descriptions are listed in Table A1 in the Appendix.

Arguably the best metric to describe the scattering behavior of microwaves in snow is the correlation length, p_c (Mätzler, 2002). Correlation length can be objectively determined from structural samples of natural snowpacks (Wiesmann et al., 1998) using e.g. microcomputed tomography (micro-CT) of snow samples (Heggli et al., 2009), but this method is time-consuming and not suitable for large-scale use. A novel method of extracting p_c from SnowMicroPen measurements (Proksch et al., 2015) shows promising results, but some problems with calibration yet remain. Another emerging method is to estimate correlation length from near-infrared (NIR) photography (Toure et al., 2008).

Traditional grain size E is the average of the greatest extension of individual grains in a layer (Fierz et al., 2009). It is measured in the field by comparing snow grains to a grid and estimating grain size visually. Empirical relationships between E and p_c can be established (Durand et al., 2008; Hallikainen et al., 1987), but they may not hold for the whole range of natural snow types. While it is possible to measure the size of a single grain with great accuracy, variability between observers arises e.g. from the definition of a single grain in case they are bonded, and from the definition of the average grain size of a layer, which is difficult if a wide distribution of different grain sizes and shapes exist in a layer, as is often the case with e.g. depth hoar. Thus the method is subjective, and the variation between estimations by different observers generally increases with the age of the snow sample (and the variation of grain sizes in a layer) (Baunach et al., 2001). Moreover, the greatest extension of a snow grain is not in all cases the appropriate measure governing the scattering of microwaves in snow (Mätzler, 2002); even though the diameter of a dendritic snow flake equals that of a large depth hoar crystal, we may assume that their effect on microwave scattering differs from one another. Despite these problems, observations of E were used in the development of the extinction coefficient model (Hallikainen et al., 1987) applied in the HUT snow emission model, and field measurements of E are therefore relevant to this study.

Optical grain size D_o is the diameter of identical ice spheres that have the same optical properties as the snow in question. The same properties are achieved when surface area to volume ratio (or specific surface area, SSA) of the spheres is equal to that of snow grains (Grenfell and Warren, 1999). SSA is becoming the most widely used microstructure parameter because it is clearly defined, reproducible, and relatively easy to measure in the field. It can be measured using several methods, including methane adsorption (Legagneux et al., 2002), NIR photography (Matzl and Schneebeli, 2006), spectroscopy (Painter et al., 2007) and IR reflectance (Gallet et al., 2009). In addition, D_o and SSA can be related to p_c through theoretical relations (Debye et al., 1957). However, the relation of microwave scattering in snow to p_c, derived through D_o, is not straightforward; empirical relations have been proposed by e.g. Mätzler (2002). Roy et al. (2013) argued that since larger particles scatter much more microwave radiation than smaller ones, a collection of identical spheres does not represent a collection of variable sized spheres with the same SSA in the microwave range.

The GlobSnow algorithm presents a method to compensate for the effects of spatio-temporal variations of snow microstructure in the retrieval of SWE. In the GlobSnow algorithm, an effective grain size (a proxy parameter for snow microstructure) is first retrieved for observations of TB coinciding with meteorological stations where in situ snow depth (HS) data are available. This is done by finding for each station the grain size value which minimizes the error of modeled TB compared to the satellite observation, giving an effective grain size applicable for each station location. Spatial (Kriging) interpolation is then used to extend the retrieved effective grain size over the whole area of interest. The spatially interpolated effective grain size values are then used as a priori information in the retrieval of SWE from the satellite observations. The method is thoroughly presented by Pulliainen (2006) and Takala et al. (2011) and (2016). However, the GlobSnow algorithm has been criticized (Richardson et al., 2014), since the retrieval of effective grain size using constant density is unphysical; all errors in e.g. density and vegetation modeling are corrected by adjusting the effective grain size. Nevertheless, Lemmetyinen et al. (2015) studied the ability of the HUT snow emission model to account for spatial and temporal changes in snow structure using ground-based and airborne radiometer measurements of snow. They found that while the effective grain size accounts for changes in snow structure, vegetation properties and other uncertainties, the retrieved effective grain size can still be related to physical properties of snow for a wide temporal and spatial scale of snow conditions, including satellite scale observations. This suggests that information on snow physical properties, obtained from a physical snow evolution model, may be used as a priori information to enhance a SWE retrieval scheme based on the HUT model. One such snow cover model is SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b). We applied it here to model grain size, density and temperature to be used as a priori data in the HUT snow emission model.

This study focused on the application of E and D_o in the context of forward simulations of microwave emission and retrieval of SWE. We studied the possibility to use snow parameters simulated with SNOWPACK with the HUT snow emission model to increase the accuracy of TB simulation and SWE retrieval. Specifically, we applied experimental data from four consecutive winters, from 2009 to 2013, to

1. validate SNOWPACK snow profiles by comparing them to in situ measurements;
2. compare E and D_o from SNOWPACK to effective grain size retrieved from tower-based microwave radiometer measurements;