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Comparison of commonly-used microwave radiative transfer models for snow remote sensing

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ABSTRACT

This paper reviews four commonly-used microwave radiative transfer models that take different electromagnetic approaches to simulate snow brightness temperature (T_B): the Dense Media Radiative Transfer - Multi-Layer model (DMRT-ML), the Dense Media Radiative Transfer - Quasi-Crystalline Approximation Mie scattering of Sticky spheres (DMRT-QMS), the Helsinki University of Technology n-Layers model (HUT-nlayers) and the Microwave Emission Model of Layered Snowpacks (MEMLS). Using the same extensively measured physical snowpack properties, we compared the simulated T_B at 11, 19 and 37 GHz from these four models. The analysis focuses on the impact of using different types of measured snow microstructure metrics in the simulations. In addition to density, snow microstructure is defined for each snow layer by grain optical diameter (Do) and stickiness for DMRT-ML and DMRT-QMS, mean grain geometrical maximum extent (D_{max}) for HUT n-layers and the exponential correlation length for MEMLS. These metrics were derived from either in-situ measurements of snow specific surface area (SSA) or macrophotos of grain sizes (D_{max}), assuming non-sticky spheres for the DMRT models. Simulated T_B sensitivity analysis using the same inputs shows relatively consistent T_B behavior as a function of Do and density variations for the vertical polarization (maximum deviation of 18 K and 27 K, respectively), while some divergences appear in simulated variations for the polarization ratio (PR). Comparisons with ground-based radiometric measurements show that the simulations based on snow SSA measurements have to be scaled with a model-specific factor of Do in order to minimize the root mean square error (RMSE) between measured and simulated T_B. Results using in-situ grain size measurements (SSA or D_{max}, depending on the model) give a mean T_B RMSE (19 and 37 GHz) of the order of 16–26 K, which is similar for all models when the snow microstructure metrics are scaled. However, the MEMLS model converges to better results when driven by the correlation length estimated from in-situ SSA measurements rather than D_{max} measurements. On a practical level, this paper shows that the SSA parameter, a snow property that is easy to retrieve in-situ, appears to be the most relevant parameter for characterizing snow microstructure, despite the need for a scaling factor.

1. Introduction

In snow remote sensing, a better parameterization of the radiative transfer models (RTM) for simulating snow microwave emission improves our ability to retrieve snowpack characteristics from spaceborne observations. Snow microstructure metrics are the main input parameter of the microwave RTM (e.g. Rutter et al., 2009) and its characterization can strongly impact the retrievals from microwave emission measurements for snow monitoring (e.g. Mätzler, 1994; Armstrong and Brodzik, 2002; Kelly et al., 2003; Mätzler et al., 2006; Löwe and Picard, 2015). Thus, given that the available models that are well-defined in the literature and commonly used for snow remote sensing are defined by different snow microstructure parameterizations, a review appears essential. We consider here the following four models: the Dense Media Radiative Transfer- Multi layers (DMRT-ML) model (Picard et al., 2013), the Dense Radiative Transfer Model - Quasi-Crystalline Approximation (QCA) Mie scattering of Sticky spheres (DMRT-QMS) model (Chang et al., 2014), the multi-layer Helsinki

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University of Technology model (HUT-nlayers) (Lemmetyinen et al., 2010a), and the Microwave Emission Model of Layered Snowpacks (MEMLS) (Proksch et al., 2016; Wiesmann and Mätzler, 1999; Mätzler and Wiesmann, 1999). Several aspects of these models are based on different electromagnetic theories or semi-empirical approaches (multiple scattering and absorption coefficient computations, for example), and they are often driven by sets of different measured inputs for snow grain metrics, such as snow specific surface area (SSA), correlation length or snow grain geometrical extent obtained from visual analysis.

Tedesco and Kim (2006) compared earlier simplified single-layer versions of the DMRT, HUT and MEMLS models based on the snow grain metric given by visual inspection (average size over the snowpack depth of representative small, medium, and large grains in each layer measured using a microscope). MEMLS and HUT-nlayers were compared by Lemmetyinen et al. (2010b) and Pan et al. (2016). DMRT theory and IBA were also recently compared and analyzed (Löwe and Picard, 2015), while Roy et al. (2013) compared DMRT-ML and HUT-nlayers. Sandells et al. (2016) compared DMRT-ML, HUT-nlayers and MEMLS models considering only the optical diameter generated by snow models. But the four multi-layer models considered were never compared together using coincident sets of measured snow properties. The main challenge in comparing these RTM models is that the input snow microstructure parameters differ in each model and are in some cases difficult or impossible to measure in the field. Three different snow microstructure representations are considered in these models: optical diameter (D_o) and stickiness for DMRT-ML and -QMS, correlation length (p_c) for MEMLS and maximum geometrical extent (D_{max}) for HUT-nlayers. Consequently, some hypotheses are needed for their estimation allowing coherent intercomparison of models (Löwe and Picard, 2015). For example, it was previously shown that the optical diameter derived from the SSA needs to be scaled by a factor in order to be in agreement with measurements when considering DMRT-ML with non-sticky medium (Brucker et al. 2011; Roy et al., 2013; Montpetit et al., 2013; Picard et al. 2014; Dupont et al., 2014). As the physical aspects of each model had already been extensively analyzed, we put the emphasis in this paper on comparing the models with surface-based measured brightness temperature (T_B). The objective is to compare the simulations using the same in-situ measurements of improved snow parameterization, which had never been done.

This paper briefly recalls the main basic fundamentals of these four models and more specifically the different grain size definitions involved (Section 2). After presenting datasets and snow microstructure measurement methods (Section 3), we first compare the four models using a synthetic snowpack to perform a sensitivity analysis (Section 4.1), and we then compare the simulated T_B using sets of measured snow properties against measurements of surface-based radiometric T_B at 11, 19 and 37 GHz (Section 4.3).

2. Models and their respective snow microstructure metric

A synthesis matrix of the four models considered in this study is presented in Table 1. These models are all publicly available (thus specific details of their implementations can be known) and are extensively described in the references given in Table 1. Readers are invited to consult these references for detailed descriptions of the models, which are based on conceptually different approaches for computing snow electromagnetic properties and radiation transfer in the multi-layers of the snowpack. In this paper, all the simulations were performed using the recommended configuration for DMRT-ML and -QMS, the Improved Born Approximation (IBA) (option 12) for MEMLS and the original version of the extinction coefficient in HUT (see Table 1).

One of the main difficulties in snow radiative transfer is the parameterization of snow microstructure consisting of a high density of scatterers per unit of volume. DMRT-ML and -QMS consider the snow as a collection of sticky spherical ice particles defined by their radius and stickiness (Tsang and Kong, 2001; Tsang et al., 2007), while MEMLS parameterizes snow microstructural properties by a second order statistical function, the two-point correlation function, giving the mutual relationships between two scatterers within a given volume, such as the autocorrelation function (the exponential correlation length p_{ex} is generally used, see Section 2.2 below). HUT is based on empirical scattering and extinction coefficients fitted with the observed maximum dimension of snow grains (D_{max}), or more recently an effective grain size radius (Kontu and Pulliainen, 2010). When using in-situ ground-based measurements of snow microstructure parameterization, practical comparison of these models requires hypotheses to retrieve and link the different metrics. The metrics used in this study are briefly defined below.

2.1. DMRT snow microstructure metric

DMRT-ML considers snow grains as spherical particles of ice defined by their radius. Their position (clustering) is controlled by stickiness. For snow having a wide range of grain shape, the radius of equivalent spheres can be objectively defined by their optical radius (Ro), which can always be derived from the SSA via the optical equivalent radius. The snow SSA is the surface of the air/snow interface (S) per unit of mass: $M = \rho_{snow}$volume: $SSA = S/M = S/(\rho_{ice}\text{volume})$ in $m^2\ kg^{-1}$, where ρ_{ice} is the ice density (917 kg m^{-3}). SSA measurements are described in Section 3. For spheres or snow assimilated as sphere equivalent (see the review paper by Domine et al., 2008), the optical radius (Ro) is expressed as (Ro in mm, ρ_{ice} in kg m^{-3} and SSA in $m^2\ kg^{-1}$):

$$Ro = 3.10^3/(\rho_{ice}\ SSA) \quad (1)$$

Since any measurements can be used to estimate stickiness, Brucker et al. (2011), Roy et al. (2013), Dupont et al. (2014) and Picard et al. (2014), considering a non-sticky medium, have shown that Ro should be multiplied by the scaling factor ϕ_{DMRT} when Ro is derived from SSA measurements (R'o in mm):

$$R'o = \phi_{DMRT} Ro = 3.10^3 \phi_{DMRT}/\rho_{ice}\ SSA \quad (2)$$

This scaling factor is discussed in Section 2.4. Roy et al. (2013) also showed that the following relationship (inspired by Kontu and Pulliainen, 2010) can be used for an effective optical radius of snow grains derived from SSA measurements:

$$R''o[mm] = 1.1\left[1 - \exp(-24.6.10^3/(\rho_{ice}\ SSA)\right] \quad (3)$$

The stickiness parameter (τ), used by DMRT theory (Tsang and Kong, 2001), is inversely proportional to the contact adhesion between spheres. It can be linked to the cohesion or to a degree of connectivity between grains. Thus, for non-sticky spheres: $\tau = \infty$; for snow with clusters (aggregates) or grains with high strength of adhesion, τ decreases (for example $\tau = 1$ to 0.2 or less). DMRT-ML uses the “short range” approximation (Tsang and Kong, 2001) which implies that grains and aggregates should remain small compared to the wavelength. Roy et al. (2013) hypothesized that the needed scaling factor (ϕ_{DMRT}) is related to the assumption of non-sticky spheres ($\tau = \infty$) and to the assumption of monodisperse grain size distribution. This scaling factor is therefore a surrogate of the stickiness parameter which cannot practically be measured in the field (see Löwe and Picard, 2015).

2.2. MEMLS snow microstructure metric

MEMLS uses the correlation length (p_c) for describing snow microstructure, which is the slope of the spatial autocorrelation function at the origin (i.e. the derivative of this function). This parameter might be derived from micro-computed tomography measurements (micro-CT) (Löwe et al., 2013) or by high-quality stereological method (see