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Snow specific surface area remote sensing retrieval using a microstructure based reflectance model

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ABSTRACT

The snow specific area (SSA) is a quantity to describe the size of snow grains, which controls the albedo of snow surface. The remote sensing retrieval of snow SSA is important for large scale energy and snow physical properties studies. The previous SSA retrieval algorithms are based on snow reflectance forward models with shape assumptions of snow grains, which may cause bias in the quantitative retrieval of SSA. In this paper, a new SSA retrieval algorithm based on a recently developed snow reflectance model is presented. In the reflectance model, the microstructure of snow medium is simulated by computer and the light scattering process is modeled by Monte Carlo ray tracing and radiative transfer theory. Validation shows the model can accurately simulate snow surface reflectance even at large incident or observation zenith angles. Three datasets were used to validate the SSA retrieval algorithm. The validation results show that the SSA can be accurately estimated using MODIS data. The difference of SSA by using reflectance of different wavelengths are studied by MODIS band 5 and band 6 data. The SSA retrieval algorithm is then applied to seasonal snow cover to study the temporal and spatial pattern of snow surface optical grain size.

1. Introduction

Snow cover is an important part of earth system and plays an important role in the earth's energy and water cycle. The snow specific surface area (SSA) is defined as the ice surface area per unit mass of snow, which is directly related to snow grain size. The SSA or snow grain size is a fundamental parameter of snow to characterize snowpack properties, because many variables are related to the SSA or grain size (Lyapustin et al., 2009). For example, the grain size is related to the thermodynamic state of a snowpack because the metamorphism is related to the temperature gradient, temperature and vapor (*e.g.*, Jordan, 1991; Lehning et al., 2002); the specific snow area and snow diffusivity, which are primary factors in snow chemistry of gases, are related to the snow grain size (Lyapustin et al., 2009); spectral snow albedo, playing a key role in the Earth energy balance, is largely controlled by the grain size (*e.g.*, Flanner et al., 2011; Fletcher et al., 2012; Fernandes et al., 2009; Domine et al., 2008). The snow SSA is also related to the mechanical properties of snow, such as the threshold friction velocity of blowing snow, which is highly correlated with the snow surface grain size (*e.g.*, Jdoorschot et al., 2004).

Satellite remote sensing retrieval of snow SSA can produce large scale, spatial and temporal continuous products, and this is especially important for difficult-to-access polar regions. Many studies have been conducted to estimate the snow surface grain size from satellite remote sensing. These retrieval algorithms can be classified into different types according to the forward model used. The classical models based on assumption of spherical particles have been extensively applied in the modeling of snow reflectance and retrieval of snow properties (Scambos et al., 2007; Painter et al., 2009; Tanikawa et al., 2002; Fily et al., 1997; Aoki et al., 2007; Mary et al., 2013). However, it is not very realistic and may cause significant bias in modeling directional reflectance (Tanikawa et al., 2006; Xie et al., 2006; Kokhanovsky et al., 2011), thus the estimated absolute value of snow SSA or grain size may have bias. Theoretically, the snow grain shape has significant impact on the phase function of snow medium (which influence directional reflectance), but has limited impact on the extinction and absorption coefficient of snow (Jin et al., 2008). This is the reason for that if hemispherical reflectance can be measured, satisfied accuracy of snow grain size retrieval can be achieved by using reflectance model of spherical particles (Grenfell and Warren, 1999; Zege et al., 2011). But in the case of satellite remote sensing, only bidirectional reflectance measurement under certain sun and satellite sensor position is available. This motivated some studies to estimate snow grain size using satellite remote sensing based on non-spherical particle models (Zege et al., 2011; Jin et al., 2008; Kokhanovsky and Schreier, 2009; Kokhanovsky et al., 2011; Lyapustin et al., 2009; Negi and Kokhanovsky, 2011; Tedesco and Kokhanovsky,

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2007; Wiebe et al., 2013; Mary et al., 2013). However, the models used in these studies have assumptions on the actual grain shape of snow (fractal, aggregates, …). The actual microstructure of snow is highly complicated and it is unrealistic and questionable to model it with idealized particles with a single shape.

In a previous study, we proposed a snow reflectance model based on ray-tracing technique and radiative transfer theory, in which a bicontinuous medium was used to model the snow microstructure (Xiong et al., 2015). The bicontinuous medium is a good approximation to real snow microstructure, and the model in Xiong et al. (2015) has been demonstrated to offer an improved ability to simulate bidirectional reflectance compared with models based on Mie theory and on radiative transfer theory. Especially at large solar or observation zenith angles, or small relative azimuth angles, the model can still give relatively accurate bidirectional reflectance simulation. This is especially important for satellite remote sensing in high latitude regions, where large zenith angle are more likely to occur. Moreover, the SSA of the bicontinuous medium adopted in the model can be analytically derived, which directly links the simulated bidirectional reflectance and SSA, and this makes the SSA retrieval based on reflectance straightforward.

In this paper, we try to quantitatively estimate the snow SSA using this new model. Three sets of data including SSA measurement in Antarctic are used to validate the retrieved SSA from MODIS data. Time series and spatially distributed snow SSA of seasonal snow cover are also derived to study the spatial and temporal characteristics of snow SSA.

2. The snow surface reflectance model and SSA retrieval algorithm

The snow reflectance used in this paper is generally a two stage model, which contains two major parts. The first part is to calculate the scattering properties (extinction coefficient, absorption coefficient and phase matrix) from computer generated bicontinuous medium. The second part is to simulate the reflectance of snow covered soil system by applying radiative transfer equation (RTE). The solution of RTE gives the snow surface reflectances in various incident and reflectance directions.

The bicontinuous medium is used to simulate the snow microstructure in the reflectance model. Three input parameters is used for the bicontinuous medium generation: the mean particle size parameter $\langle\varsigma\rangle$, the particle size distribution parameter b, and volume fraction of ice f_v. The SSA of the computer generated bicontinuous medium can be analytically expressed using these input parameters (Xiong et al., 2015):

$$SSA = \frac{2\langle\zeta\rangle e^{-(\mathrm{erf}^{-1}(1-2f_v))^2}}{\rho_{ice} f_v \pi\sqrt{3}}\sqrt{\frac{b+2}{b+1}}$$

where ρ_{ice} is the density of ice.

The optical grain size R_e can be calculated in terms of SSA as follows:

$$R_e = \frac{3}{\rho_{ice} SSA} = \frac{3\sqrt{3}\pi f_v}{2\langle\zeta\rangle e^{-(\mathrm{erf}^{-1}(1-2f_v))^2}}\sqrt{\frac{b+1}{b+2}}$$

The detail of bicontinuous medium generation and the derivation of SSA and optical grain size are described in Appendix A.

For example, Fig. 1 presents a two dimensional section image of real snow from a field measurement, and a computer generated bicontinuous medium. There are good resemblances between the microstructure of real snow and bicontinuous medium (Ding et al., 2010). From visual interpretation, there are good resemblances between the grain shape, grain size variation of them, and more importantly, the bicontinuous medium can mimic the random feature of real snow microstructure.

Then the scattering properties of bicontinuous medium are calculated using ray-tracing technique. The ray-tracing algorithm is applied to the computer generated sample bicontinuous medium to calculate the extinction coefficient, absorption coefficient and phase matrix of the sample bicontinuous medium. Then the radiative transfer equation (RTE) is applied to describe the propagation, scattering, and absorption of light in snow-soil system using the scattering properties of bicontinuous medium. The RTE is solved numerically by eigen-analysis method, which produces reflectance in the upper hemisphere. A total of 16 streams in the upper hemisphere are used in the solution of RTE. The application of RTE instead of ray-tracing makes the bidirectional reflectance simulation fast enough for retrieval purpose, especially at short wavelengths. Detailed description of the reflectance model can be found in Xiong et al. (2015). The validation of the model was performed by using measured bidirectional reflectance of snow in Antarctic, and part of the validation results are shown in Appendix B. In general, this model shows an improved ability to simulate bidirectional reflectance compared with models based on Mie theory and on radiative transfer theory.

To estimate snow SSA from bidirectional reflectance using this snow reflectance model, look-up table (LUT) is used. The single layer snow reflectance model described above is used to produce the LUT. We directly estimate the SSA from absolute value of reflectance at single wavelength, instead of using several reflectances at different wavelengths simultaneously. Thus, in our algorithm, different SSA estimation can be obtained by using reflectances at different wavelengths due to the different penetration depths and the vertical variation of snow grain size. For the same reason, no multiple snow layer model is used because every SSA retrieval is performed using reflectance at only one wavelength, not using reflectances at multiple wavelengths together. Because of the vertical variation of snow grain size, if reflectances at significantly different wavelengths are used simultaneously, multiple layer snow should be used, such as Jin et al. (2008), they choose MODIS channel 6(1.64 μm) for the top layer snow grain size retrieval and channel 1(0.64 μm) for the bottom layer size retrieval. In Tanikawa et al. (2015), 0.443 μm, 0.87 μm and 1.225 μm wavelength are used simultaneously for two-layer snow grain size (0–1 cm and 1–3 cm) retrieval. In the SSA retrieval algorithm used in this study, the different snow grain size retrieved by using reflectance at different wavelength is also an indicator of vertical variation of grain size.

In this study, the MODIS 1240 nm and 1629 nm reflectance is used because of their sensitivity to grain size and insensitivity to dust and soot. At these wavelengths, over 90% contribution of reflectance of snow surface is from the uppermost 0.5 cm snow layer (Picard et al., 2016). Because the *in-situ* data used in this study is from ground measured surface albedo (700–1050 nm, 1310 nm), or from snow samples taken from top 1 cm, it is not very necessary to consider multiple layers within the uppermost 1 cm layer snow.

Also, band ratio of reflectances is not used in our algorithm, because in reality reflectances of different bands are sensing different depths, and snow SSA is usually not vertically homogenous; but in the model simulation, single layer snow is assumed.

Bidirectional reflectance of snow under different conditions (sun zenith angle, sun azimuth angle, sensor zenith angle, sensor azimuth angle, snow SSA) is first simulated using the reflectance model under many wavelengths. Sun and observation zenith angle of 0–82°, relative azimuth angle of 0–360° and optical grain size of 0.005–0.52 mm are included in the LUT. Single layer and optically thick snow is assumed in the simulations, which means the snow is enough deep for visible and