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Investigation of snow single scattering properties based on first order Legendre phase function

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ABSTRACT

Angularly resolved bidirectional reflectance measurements were modelled by approximating a first order Legendre expanded phase function to retrieve single scattering properties of snow. The measurements from 10 different snow types with known density and specific surface area (SSA) were investigated. A near infrared (NIR) spectrometer was used to measure reflected light above the snow surface over the hemisphere in the wavelength region of 900–1650 nm. A solver based on discrete ordinate radiative transfer (DISORT) model was used to retrieve the estimated Legendre coefficients of the phase function and a correlation between the coefficients and physical properties of different snow types is investigated. Results of this study suggest that the first two coefficients of the first order Legendre phase function provide sufficient information about the physical properties of snow where the latter captures the anisotropic behaviour of snow and the former provides a relative estimate of the single scattering albedo of snow. The coefficients of the first order phase function were compared with the experimental data and observed that both the coefficients are in good agreement with the experimental data. These findings suggest that our approach can be applied as a qualitative tool to investigate physical properties of snow and also to classify different snow types.

1. Introduction

In research dealing with models to approximate physical properties of snow one important aspect is often the angular and spectral structure of snow's bidirectional reflectance distribution function (BRDF) [1,2]. The BRDF describes a surface reflectance as a function of illumination and viewing angles apart from the wavelength. The corresponding retrieval models for single and/or multiple scattering are mostly based on ray tracing (e.g., Monte Carlo method) [3–5] or the discretisation of a standard variation of the radiative transfer equation (e.g., discrete-ordinates method, DISORT) [6–8]. Solutions to the radiative transfer in snow based on the DISORT method involve estimating a scattering phase function, which describes the angular distribution of scattered radiation from a given medium at a given wavelength [9,10]. A scattering phase function can be expanded as an infinite series of Legendre polynomials and a relation between Legendre coefficients of the phase function and snow physical properties is therefore expected [11].

Several studies have concluded that the spectral bidirectional reflectance of snow can be coupled to radiative transfer calculations in order to investigate the physical properties such as snow grain size, roughness, impurity content and cloud cover. These models assume spherical snow grains and were based on δ-Eddington approximation for multiple scattering and Mie theory for single scattering [12–14]. Aoki et al. [15] measured spectral albedo and bidirectional reflectance on flat snow in the wavelength region of 350–2500 nm, and analysed the effect of grain size on the observations. They showed that the normalised BRDF of snow agreed better with the Henyey–Greenstein (HG) phase function rather than with the Mie phase function. Warren [16] reviewed the snow albedo dependence on wavelength, solar zenith angle, cloud cover, snow pack thickness and snow density. He also reported that these parameters can be interpreted by a single or multiple scattering radiative transfer theory. Li and Zhou [17] and Painter and Dozier [18] simulated, respectively, hemispherical directional reflectance using the DISORT and the bidirectional reflectance using the adding-doubling method [19]. They showed that their models have better agreement with spherical medium grain snow than non-spherical. They also noticed that accurate computation of single scattering properties such as single scattering albedo, asymmetry parameter and phase function is essential to simulate snow bidirectional reflectance accurately. Xie et al. [20] compared the applicability of three radiative transfer models: DISORT, adding-doubling method

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and Mishchenko model [10]. They further investigated the sensitivity of snow's bidirectional reflectance to its single scattering properties and concluded that accurate computation of single scattering properties from snow's BRDF is essential in order to investigate the sensitivity of grain shape and grain size.

All these studies lead to a conclusion that the angularly and spectrally resolved bidirectional reflectance measurements can be accurately modelled and a scattering phase function can be approximated to investigate single scattering properties of snow. There are common analytic functions to approximate the true scattering phase function of snow such as HG phase function, modified HG phase function and Legendre expanded phase function [21–23]. Pfeiffer and Chapman [23] and Piskozub and McKee [24] have investigated a multiple scattering problem by a one-term and two-term HG phase function and compared the results with the Monte Carlo simulations. They showed that the HG phase function can provide a theoretical basis for the multiple scattering case. Wiscombe and Warren [12,13] modelled snow reflectance measurements using a two-stream radiative transfer model. One of their findings was that the single scattering albedo decreases and the asymmetry parameter increases as snow grain size increases. Several studies have showed that the one parameter HG phase function is sufficient to approximate the scattering direction in terms of backward or forward peak scattering [10,15,25,26]. Our previous study [11] showed that the first two coefficients of the first order Legendre expanded phase function can be an estimate of the asymmetry parameter and possibly the single scattering albedo with an improved experimental design.

The present study involves investigating a relation between the measured bidirectional reflectance of various snow types and the first two coefficients of the first order Legendre phase function. The presented bidirectional reflectance measurements were obtained for 10 different snow types in a walk-in climate chamber using a NIR spectrometer in the wavelength region of 900–1650 nm.

The paper is organised as follows. The theoretical considerations of the bidirectional reflectance of snow and the radiative transfer model are described in Section 2. In Section 3 experimental design, measured snow types and measurement approach are detailed. In Section 4 results of the work are presented while discussions of the observations are detailed in Section 5. Finally, the conclusions are given in Section 6.

2. Theoretical considerations

2.1. Bidirectional reflectance

The BRDF is a common method to model the bidirectional reflective properties of a matter. The bidirectional reflectance measurements are observed in an infinitesimally small solid angles considering both incoming light and outgoing light as directional. The bidirectional reflectance of the matter is essentially related to the absorption, reflectance and roughness of the matter. Therefore, these measurements provide essential information on the optical properties of the matter. It is in principle not possible to measure reflected light within an infinitesimally small solid angle, therefore reflectance quantities in this study are measured within finite solid angles. Integration over all the finite solid angles describes the total reflectance properties of a matter [27,**?**,29].

The BRDF is defined as the ratio of the radiance reflected (L_r) into a specific direction (Θ_r) to the incident irradiance (E_i) coming from a particular direction (Θ_i):

$$BRDF_\lambda(\Theta_i, \Theta_r) = \frac{dL_r(\Theta_i, \Theta_r; \lambda)}{dE_i(\Theta_i; \lambda)} \quad [\mathrm{sr}^{-1}]. \tag{1}$$

The λ in Eq. (1) specifies that the BRDF is further resolved in wavelength. For practical reasons the $BRDF_\lambda$ specified in this study is normalised by a bidirectional reflectance measurement from a pack (2 cm thick) of white papers. More details are given in Section 3.1. The BRDF is further referred by the bidirectional reflectance in this study.

2.2. Radiative transfer model

The model/solver used in this study is based on the radiative transfer theory [6] and a special case of the DISORT method developed by Stamnes and Swanson [8]. This model was developed to describe the single scattering of radiation in a snow pack, assumed to be plane parallel and having semi-infinite optical depth. In the DISORT method, integral terms in the radiative transfer equation are approximated with a numerical quadrature sum converting into a system of ordinary differential equations. The description of the radiative transfer model we developed is detailed in our previous work [11].

The scattering phase function is a fundamental concept in the radiative transfer theory and describes the angular distribution of scattered photons in the case of a single/multiple scattering event. The scattering phase function is usually specified in terms of its Legendre polynomial expansion coefficients:

$$p(\Theta) = \sum_{l=0}^{N} w_l P_l(\cos\Theta), \tag{2}$$

where $w_{l=0}$ is the single scattering albedo, $w_{l=1}$ is the asymmetry parameter, $P_l(\cos\Theta)$ are Legendre base functions, N is the order of the phase function and Θ is the relative scattering angle.

Our previous work [11] showed that the first order phase function (N=1) is sufficient to investigate snow physical properties based on the Legendre coefficients. Therefore the Legendre phase function is approximated by its first two moments and only the coefficients w_0 and w_1 are considered in this study.

Our model solves an inverse problem of finding the scattering phase function from the angularly and spectrally resolved bidirectional reflectance measurement. This is done by defining a cost function which iteratively minimises the mean squared error (χ) between an experimental dataset and a solution to the RTE, by finding the correct Legendre coefficients w_0, w_1. The solver takes random initial values for the coefficients and solves the inverse problem until a global minimum of χ is obtained.

$$\chi = E[I_{exp} - I_{RTE}(w_0, w_1; \lambda)]^2 . \tag{3}$$

Furthermore, the coefficients are subject to the constraints

$$0.0001 \le w_0 \le 0.9999, \quad -1 \le w_1 \le 1. \tag{4}$$

The physical meaning of the coefficient w_0=1 is that all energy that enters a small volume is completely scattered while w_0=0 means total absorption. The coefficient w_1=−1 models complete backscattering and w_1=1 complete forward scattering. It was shown in our previous work that the coefficients w_0 and w_1 provide valuable information about the optical characteristics of a snow pack [11].

3. Methods and experiments

In the following sections the experimental setup, classification of snow types and measurement procedure are detailed. In Section 3.1 the experimental setup is explained. Classification of measured snow types is detailed in Section 3.2. The measurement approach and data processing are explained in Section 3.3.

3.1. Experimental setup

The experimental setup shown in Fig. 1 consists of a freeze box, an illumination source and a NIR spectrometer. A NIR InGaAs spectrometer (STE-DWARF-Star NIR) with an extra aperture (field of view 3°, ⌀5 mm) was used to measure the bidirectional reflectance from snow surfaces within the wavelength range of 900–1650 nm with spectral resolution of 1.75 nm. The illumination source was a 150 W EKE