Remote Sensing of Environment 128 (2013) 11–20

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Snow grain size retrieval SGSP from optical satellite data: Validation with ground measurements and detection of snow fall events

Heidrun Wiebe [a,*], Georg Heygster [a], Eleonora Zege [b], Teruo Aoki [c], Masahiro Hori [d]

[a] Institute of Environmental Physics, University of Bremen, Bremen, Germany
[b] Institute of Physics, National Academy of Science, Minsk, Belarus
[c] Meteorological Research Institute, Tsukuba, Japan
[d] Japan Aerospace Exploration Agency (JAXA), EORC, Tsukuba-city, Japan

ARTICLE INFO

Article history:
Received 14 September 2011
Received in revised form 7 September 2012
Accepted 8 September 2012
Available online 22 October 2012

Keywords:
Snow grain size
Retrieval
Satellite
MODIS
Validation

ABSTRACT

The size of snow grains plays an important role for modeling the snow albedo in polar regions. The Snow Grain Size and Pollution (SGSP) retrieval computes the snow grain size using spectral reflectances from the Moderate Imaging Spectrometer (MODIS): the channels at 0.47 μm, 0.86 μm, and 1.24 μm. The unique feature of the SGSP retrieval is that it does not require a-priori information on the snow grain shape.

In this paper, the SGSP-retrieved snow grain size is validated with six data sets from ground measurement campaigns in the Arctic, the Antarctic, Greenland, and Japan. Almost half of the comparison cases have a difference below 15%; the correlation coefficient is 0.86. The application of the SGSP retrieval on the Antarctic Ross ice shelf demonstrates the potential to detect snow fall events by analyzing the snow grain size time series for sudden grain size decreases.

1. Introduction

Snow covered areas reflect a large amount of the incoming solar radiation, influencing the radiative balance of the Earth. The reflectance of snow is a function of wavelength and mainly depends on the size and shape of the single ice crystals, and the pollution amount deposited on the snow surface.

The theory of the spectral reflectance and albedo of snow was first established in the early 1980s by Wiscombe and Warren (1980a, b), and Warren (1982, 1984), where snow is considered as a layer of large independent spherical particles, based on Mie calculations for the snow optical properties and radiative transfer codes to develop look-up-tables (LUT) that are used for the inversion procedure. This theory has widely been used in the past to retrieve the snow grain size from spectral snow reflectance measurements (Aoki et al., 2007; Fily et al., 1997; Hori et al., 2007; Li et al., 2001; Nolin & Dozier, 1993, 2000; Painter et al., 2003; Stamnes et al., 2007).

After several experimental studies on snow optical (Aoki et al., 2000, 2003; Kokhanovsky et al., 2005) and microphysical (Kerbrat et al., 2008; Matzl & Schneebeli, 2006) properties, snow was considered as a medium of multiply-scattering, closely-packed, irregularly-shaped grains. The first model that matches these snow characteristics was introduced by Zege et al. (1998), and developed further in the following years. It uses geometrical optics for the snow optical properties (Kokhanovsky & Zege, 2004) and an analytical asymptotic solution of radiative transfer equations (Zege et al., 1991). This new approach has recently been used for the retrieval of snow grain size using optical satellite data (Lyapustin et al., 2009; Tedesco & Kokhanovsky, 2007; Zege et al., 2008).

Reviews on the research of snow physical properties and remote sensing are given by Dominé et al. (2008); Dozier and Painter (2004); Dozier et al. (2009); Kokhanovsky et al. (2011).

The Zege et al. retrieval (Zege et al., 2011; Zege et al., 2008) has two unique characteristics. First, the dependence on the snow grain shape is reduced, which is important as various particle shapes have different reflection characteristics and the shape information is unknown during the retrieval. Second, the SGSP algorithm is valid at high solar zenith angles up to 75° (i.e., elevation angles as low as 15°), which is important for polar regions where the sun elevation is often low.

In this paper, we present a validation study of the SGSP-retrieved snow grain size (Section 3) with data from six different measurement campaigns, which were carried out in different regions (Arctic, Antarctic, Greenland, and Japan) on different subsurfaces (land, land ice, sea ice, and lake ice) in the years 2001 to 2009. Secondly, we present a large scale application of the SGSP retrieval on the Antarctic Ross ice shelf (Section 4) to study whether snow fall events can be detected by a sudden decrease in snow grain size time series data. The Ross ice shelf is a level region with a rather homogeneous surface. There are several Automatic Weather Stations (AWS) in the Ross ice

* Corresponding author. Tel.: +49 42121862184.
E-mail addresses: hwiebe@uni-bremen.de (H. Wiebe), heygster@uni-bremen.de (G. Heygster).

0034-4257/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2012.09.007

shelf region; seven of them are equipped with an Acoustic Depth Gauge (ADG) allowing to measure snow depth changes.

2. SGSP algorithm and retrieval

2.1. Algorithm description

The SGSP algorithm, developed in Zege et al. (1998, 2008, 2011), computes the snow grain size and impurity amount from optical satellite data (here MODIS Channels 3, 2, and 5 at wavelengths 0.47 µm, 0.86 µm, and 1.24 µm). It uses a snow reflectance model based on an analytical asymptotic solution of the radiative transfer theory and on geometrical optics for the optical properties of snow. The basic equation of light reflected by a semi-infinite snow layer, which is considered as a multiply scattering medium with randomly-oriented, irregularly-shaped, closely-packed grains, is (Kokhanovsky & Zege, 2004; Zege et al., 1991, 2008):

$$R_i(\theta,\theta_0,\phi) = R_0(\theta,\theta_0,\phi)\exp\left(-A\sqrt{\gamma_i a_{ef}}f(\theta,\theta_0,\phi)\right) \quad (1)$$

where $\gamma_i = 4\pi(\chi_i + \kappa C_S)/\lambda_i$, and $f(\theta,\theta_0,\phi) = K_0(\theta)K_0(\theta_0)/R_0(\theta,\theta_0,\phi)$.

The indices i refer to the MODIS Channel number i (here: 3, 2, and 5). R_i is the normalized snow reflectance which is the reflectance received by the instrument divided by the cosine of the solar zenith angle. R_0 is the bidirectional reflectance distribution function (BRDF) defining the amount of light reflected at an opaque surface. Both are functions of the solar zenith angle θ_0, the viewing zenith angle θ, and the relative azimuth angle *hi*. A is a form factor depending on the shape of the ice crystals. In this work $A = 5.8$ is used, which is an average over a fifty-fifty mixture of randomly oriented hexagonal plates (with aspect ratio of 1/4) and columns (with aspect ratio of 4/1) with rough surfaces (Zege et al., 2011). K_0 is the escape function that determines the angular distribution (for θ or θ_0) of light escaping from a semi-infinite medium. λ_1 is the wavelength, and χ_i the imaginary part of the complex refractive index of ice (Warren & Brandt, 2008). The value of κ depends on the type of pollutant, in this work it is assumed that $\kappa = 0.2$ (Zege et al., 2008). C_s is the relative volumetric soot concentration, and a_{ef} the effective snow grain size (optical snow grain size, i.e., the radius of a sphere with the same volume to surface area ratio the snow would have).

In general, the BRDF of a semi-infinite non absorbing scattering medium may depend on wavelength due to the spectral dependence of the refractive index of the medium and due to changes of the ratio of the particle size to the wavelength, but snow grain size is much larger than the wavelength (the geometrical optics range) and changes of the real part of the refractive index are small enough for snow in the used spectral interval 400–1200 nm. This is why the spectral variation of R_0 is negligible. As for the escape function K_0, it was shown more than once in radiative transfer theory that it practically does not depend on the scattering phase function and hence on the spectral variation of the refractive index. This spectral independence of R_0 and K_0 in the used spectral range is one the grounds of the SGSP algorithm (Zege et al., 2011).

2.2. Atmosphere model

In Section 2.1, the bidirectional reflection function of snow is described for measurements directly on the ground, i.e., without atmospheric influence. For snow grain size retrievals using satellite data, the snow-atmosphere radiative interaction has to be taken into account. The top-of-the-atmosphere reflectance R_i^{TOA}, measured by the satellite sensor, can be modeled by (Zege et al., 2011):

$$R_i^{TOA}(\theta,\theta_0,\phi) = R_i^{Atm}(\theta,\theta_0,\phi) + (R_i(\theta,\theta_0,\phi) - r_i)t_i(\theta_0) + \frac{T_i(\theta)}{r_i - r_i^{Atm}} \quad (2)$$

$R_i^{Atm}(\theta,\theta_0,\phi)$ is the atmospheric reflectance when illuminated from above with black underlying surface. t_i is the atmospheric transmission of quasi-direct light. $r_i = \exp\left[-A\sqrt{\gamma_i\, a_{ef}}\right]$ is the snow albedo. T_i is the diffuse transmission coefficient of the atmosphere when illuminated from above. $R_i(\theta,\theta_0,\phi)$ is the snow bidirectional reflection function (Eq. 1). r_i^{Atm} is the atmospheric albedo when illuminated from below.

The atmospheric characteristics R_i^{Atm}, t_i, T_i, and r_i^{Atm} are calculated by the radiative transfer code RAY described in Tynes et al. (2001). In this work, constant atmospheric conditions are used: subarctic winter of a molecular atmosphere (describing the Rayleigh scattering and gases absorption) (Lenoble, 1986) and Arctic Background aerosols (the minimal amount of aerosols observed in the Arctic) (Tomasi et al., 2007).

2.3. Data pre-processing

The SGSP retrieval requires two steps of data pre-processing (for more details see Wiebe (2011)):

1. Removing horizontal striping artifacts in the MODIS images. The single detectors of the detector array were calibrated independently leading to a regular striping pattern. The de-striping routine used here is based on Weinreb et al. (1989). The idea of the method is matching the Empirical Distribution Functions (EDF) of the data from the single detectors. As there are a large number of data points, the distribution of the measured values should be almost identical for the different detectors, as they statistically see identical scenes.
2. Separating snow from non-snow pixels (e.g. soil or clouds). The simple threshold approach of Normalized Difference Snow Index (NDSI) (Hall et al., 1995) $= (R_4 - R_6)/(R_4 + R_6) > 0.4$, $R_2 > 0.11$, and $R_4 > 0.1$ maps pixels above the threshold value as snow. It works fine for separating snow pixels from other surface pixels, but for separating snow from clouds, it works only partially. Therefore, the MODIS cloud mask product (Ackerman et al., 1998), based on several more thresholds, is applied in addition. However, it still does not remove speckle cloud patterns, so an additional spatial variability cloud mask (Martins et al., 2002) is applied, based on the idea that the reflectance of the snow on ground does not change strongly between neighboring pixels. It calculates the standard deviation of a 3×3 neighborhood for the MODIS channel 2 reflectances and masks out pixels exceeding the standard deviation of 0.01. The mask is smoothed by a median filter of size 15×15 and then applied to the data.

2.4. Retrieval characteristics

The two main characteristics of the SGSP retrieval that distinguishes it from other existing retrievals are as follows:

1. the reduced dependency on the snow particle shape, which is important, as the snow grains have various kinds of shapes (plates, columns, fractals) with different optical properties;
2. the applicability at high solar zenith angles up to 75° (Zege et al., 2011; Zege et al., 2008), which is important, as the largest snow extent is in the polar regions, where the solar zenith angle is often higher than 60° (elevation angle less than 30°).

The new approach of the SGSP retrieval is to use three channels (conventionally two channels are used) in order to determine the two parameters snow grain size and soot concentration, and to exclude the BRDF term R_0 from the retrieval. The BRDF depends on the phase function and thus on the particle shape, which is not known a priori on large scale for remote areas in polar regions. Therefore, the SGSP retrieval uses the additional third channel in order to eliminate the BRDF term R_0 from Eq. (1), as it strongly depends on