



Global snow cover estimation with Microwave Brightness Temperature measurements and one-class *in situ* observations



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ABSTRACT

Brightness temperature (BT), which is remotely sensed by the space-borne microwave radiometer, is widely used in snow cover monitoring for its long time series imaging capabilities in all-weather conditions. Traditional linear fitting and stand-alone methods are usually uncertain with respect to the spatial distribution and temporal variation of derived snow cover, as they rarely consider local conditions and scene characteristics but fit the model with static empirical coefficients. In this paper, a novel method utilizing daily ground *in situ* observations is proposed and evaluated, with the purpose for accurate estimation of long-term daily snow cover. To solve the challenge that ground snow-free records are insufficient, a one-class classifier, namely the Presence and Background Learning (PBL) algorithm, is employed to identify daily global snow cover. Benefiting from daily ground *in situ* observations on a global scale, the proposed method is temporally and spatially dynamic such that estimation errors are globally independent during the entire study period. The proposed method is applied to the estimation of global daily snow cover from 1987 to 2010; the results are validated by ground *in situ* observations and compared with available optical-based and microwave-based snow cover products. Promising accuracy and model stability are achieved in daily, monthly and yearly validations as compared against ground observations (global omission error <0.13, overall accuracy >0.82 in China region, and keep stable in monthly and yearly averages). The comparison against the MODIS daily snow cover product (MOD10C1) shows good agreement under cloud-free conditions (Cohen's kappa = 0.715). The comparison against the NOAA daily Interactive Multisensor Snow and Ice Mapping System (IMS) dataset suggests promising agreement in the Northern Hemisphere. Another comparison against the AMSR-E daily SWE dataset (AE_DySno) demonstrates the efficiency of the proposed method regarding to the overestimation problem in thin snow cover region.

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1. Introduction

The seasonal snow cover of the globe, especially in the Northern Hemisphere, has a significant impact on climate, water cycles and biogeochemical cycling, as the surface albedo of the northern areas in winter season is mainly controlled by snow covered area. As snow cover can affect climate dynamics (Cohen & Entekhabi, 1999), the capacity for the accurate estimation of global snow cover and the volumetric storage of water in snowpack limits our ability to monitor climate change and test climate model simulations. Traditional snow cover monitoring was mainly based on isolated ground observations from meteorological stations. However, sparse point observation networks can hardly provide the overall picture on regional and global scales due to their low spatial densities or even complete absence in inaccessible regions (Walker, Derksen, & Goodison, 2005). Remote sensing has been used to monitor continental-scale seasonal snow cover for more than two decades (Allan & David, 1999). Various studies have shown that snow cover

can be detected using both optical sensors (Allen, Durkee, & Wash, 1990; Hall, Riggs, Salomonson, Digirolamo, & Bayr, 2002; Hall, Riggs, & Salomonson, 1995) and space-borne positive microwave radiometers (Klein & Barnett, 2003; Walker & Goodison, 1993).

Since the 1980s, a number of algorithms have been developed for snow cover monitoring using optical sensors, such as the multi-spectral thresholds classification method (Allen et al., 1990; Romanov, Gutman, & Csiszar, 2000), linear spectral unmixing for subpixel snow cover mapping (Romanov, Tarpley, Gutman, & Carroll, 2003; Rosenthal & Dozier, 1996), and the Normalized Difference Snow Index (NDSI) algorithm (Hall et al., 2002; Hall et al., 1995). However, snow cover observations through optical sensors are sensitive to local weather conditions, especially when cloud cover and rainfall are present. Moreover, sunlight is required to receive the reflected signal from snowpack to the optical sensors. Thus it is difficult to find consecutive daily images that are cloud-free or have low cloud cover percentage. Obscuration by cloud cover and inaccessibility in dark regions greatly limit the applicability of optical-based snow cover products in regional and global applications. (Klein & Barnett, 2003; Wang, Xie, Liang, & Huang, 2009).

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Passive microwave observation from space-borne radiometers is another data source for the retrieval of global/regional snow cover or snow water equivalent (SWE) because of its wide swath, all-weather imaging capabilities, day and night time capability, multi-frequency response to the presence of snow pack, and a long archive history dating back to 1978. Progress in retrieving snow cover or SWE has been made since the launch of the Scanning Multi-Channel Microwave Radiometer (SSMR) in 1978 and the Special Sensor Microwave Imager (SSM/I) in 1987. Although these two microwave sensors are not designed for snow detection, they have been found to be effective in detecting snow cover and SWE (Chang, Foster, Hall, Rango, & Hartline, 1982; Chang, Foster, & Hall, 1987; Pulliainen, 2006; Walker & Goodison, 1993). The Advanced Microwave Scanning Radiometer - EOS (AMSR-E), which was launched in 2002 and stopped in 2011, and its successor the Advanced Microwave Scanning Radiometer 2 (AMSR2), which was launched in 2012, provide other microwave data sources with relatively higher spatial resolution for the mapping of the snow cover and SWE (Kelly, Chang, Tsang, & Foster, 2003; Tedesco, Kelly, Foster, & Chang, 2004).

The detection of snow cover and SWE from microwave observations is based on the fact that the presence of snowpack on land surface causes a difference of microwave scattering and can be detected by space-borne instruments. On snow covered surfaces, brightness temperature (BT), a measure of microwave emission, tends to decrease with increasing snow depth since larger number of snow crystals scatter more microwave signal. Traditional snow cover retrieval methods model the snow depth (or SWE) as a function of the difference between of multi-frequency BTs. The algorithm proposed by Chang et al. (Chang et al., 1987) is a typical example. Based on this work, a number of studies were carried out to improve the accuracy and stability of snow cover and snow depth (or SWE) retrievals by taking into account the effects of grain size, snow density and vegetation canopy, etc. (Foster, Chang, & Hall, 1997; Kelly, Chang, Foster, & Hall, 2001; Pulliainen, Grandell, & Hallikainen, 1999).

Although previous studies achieved acceptable accuracies for some regions and seasons, the snow cover and SWE estimates based on microwave data are found to be spatial and temporal bias (Pulliainen, 2006). Moreover, most microwave snow cover retrievals are reported to underestimate the snow cover in regions of low elevation and overestimate the snow cover in mountainous areas (Foster et al., 1997; Koenig & Forster, 2004). These problems probably result from insufficient considerations of spatial and temporal heterogeneity of snowpack and land cover in these stand-alone algorithms. Besides, the empirical regression coefficients in these models are often calibrated by insufficient ground observations of snow information, i.e., dozens of sparse observations in short time period. The accuracy of such snow cover retrievals is closely dependent on local conditions and scene characteristics, crippling the applicability of these models for producing a promising snow cover datasets for a long-term period.

One potential solution to overcome these challenges is to integrate a global long-term series of ground snow observations with microwave-based snow cover modeling. The Global Surface Summary of Day (GSOD) dataset, which is provided by the National Climatic Data Center (NCDC), is a potential data source to provide sufficient ground snow cover observations. The GSOD dataset is contributed by more than 29,000 meteorological stations across the globe (see Fig. 3). It provides various meteorological elements, including snow depth information, dating back to 1929. Currently, approximately 9000 stations are functional in acquiring ground snow cover information. However, snow-free records in the GSOD dataset are mixed with missing observation records, i.e., we cannot identify whether a record is snow-free or an unreported snow presence. Without observed snow-free records, traditional binary classifier-based methods of snow cover discrimination (e.g., support vector machine, maximum likelihood estimation) are not applicable to the modeling of snow cover over selected attributes.

The purpose of this study is to develop and test a one-class method, namely the Presence and Background Learning (PBL) algorithm, to estimate the global snow cover even though there are no reliable reports of snow-free on the ground. By integrating long-term daily ground snow cover information with space-borne microwave BT measurements, the proposed method is different from previous static stand-alone algorithms, but expected to be temporally and spatially dynamic. The accuracy and variation of our model estimation are independent from local conditions and scene characteristics such that the method is applicable for accurate long-term snow cover estimation under all-weather conditions. The proposed method involves two steps. First, space-borne microwave BT measurements and massive one-class ground *in situ* snow cover observations are combined to train the PBL model to estimate the probability of snow cover presence. Second, an appropriate threshold is automatically selected to segment the estimated probability into binary class: snow-free and snow cover. Since the model utilized ground observations and microwave measurements on a daily basis, the proposed model should be temporally and spatially dynamic such that estimation errors are independent from local conditions and scene characteristics.

2. Datasets used in the study

2.1. The SSM/I Brightness Temperature (BT) dataset

The SSM/I brightness temperature dataset (Armstrong, Knowles, Brodzik, & Hardman, 1994) used in this study is collected from the Special Sensor Microwave/Imager (SSM/I) sensors, which are boarded on the Defense Meteorological Satellite Program (DMSP) series satellites. The SSM/I sensor is a multi-frequency (19-, 22-, 37- and 85-GHz) microwave radiometric system. Both vertical and horizontal polarization are measured for all but not 22-GHz, for which only the vertical polarization is measured. The foot print varies with channel energy, ranging from $69 \times 43 \text{ km}^2$ at 19-GHz to $15 \times 13 \text{ km}^2$ at 85-GHz (Hollinger, 1991). The SSM/I BT data are gridded into NSIDC Equal-Area Scalable Earth grids (EASE-Grids) for each day and projected into the cylindrical equal-area projection (Armstrong & Brodzik, 1995). The spatial resolution is $25 \times 25 \text{ km}^2$ for all channels, and the 85-GHz channel is additionally available at $12.5 \times 12.5 \text{ km}$ resolution.

2.2. The Global Surface Summary of Day (GSOD) product

The Global Surface Summary of Day (GSOD) product is provided by the National Climatic Data Center (NCDC, <https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod>), and is based on data exchanged under the World Meteorological Organization (WMO) World Weather Watch Program according to WMO Resolution 40 (Cg-XII). It is comprised of a dozen daily averaged weather parameters computed from global hourly station data. Snow depth is one of the 14 daily weather elements included in this dataset. The dataset is available since 1929, with around 29,000 meteorological stations covering over the globe. Currently more than 9000 stations are typically functional. The GSOD data provides snow depth information in inches to tenths; however, most stations do not report 0 values on days with no snow cover on the ground. Instead, the value of 999.9 will be archived in the dataset, which is the same value to denote a missing observation. Thus we cannot determine the occurrence of snow if a particular station reports a 999.9 value. This becomes the challenge of using the GSOD dataset as most records contain only presence data (observed snow cover) but lacking absence information (observed snow absence). Traditional two-class classifiers, such as support vector machine, maximum likelihood estimation, are not applicable due to the deficiency of absence data. The one-class PBL model investigated in this study is an attempt to overcome this challenge.

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