Remote Sensing of Environment 194 (2017) 248–263

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Observations of Arctic snow and sea ice cover from CALIOP lidar measurements

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ARTICLE INFO

Article history:
Received 3 November 2016
Received in revised form 23 March 2017
Accepted 30 March 2017
Available online xxxx

Keywords:
Sea ice
Snow
CALIOP
Surface type identification

ABSTRACT

This paper describes the development and validation of a method to accurately identify snow/ice cover, surface melting, land surface and open water in polar regions using polar-orbiting Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar measurements from the Cloud and Aerosol Lidar and Infrared Pathfinder Observation (CALIPSO) mission. The technique is based on the relationship between integrated attenuated backscatter color ratio and integrated depolarization ratio, and is proven to efficiently separate snow/ice cover and surface melting from open water and land surfaces. The method has been applied to 10 years (2006–2016) of CALIOP data to study the seasonal and inter-annual variability of Arctic sea ice cover and its declining trend. Results show that the area fraction of snow cover over land at latitudes >60°N varied between 0.9 during winter and 0.1 in summer. The CALIOP observations of Arctic sea ice cover exhibit a strong seasonal cycle and significant inter-annual variability, which are consistent with the passive microwave-based sea ice results. The >10 years of CALIOP continuous observations of the snow/ice cover will benefit the communities modeling snow/ice melting and climate change.

1. Introduction

Over 30% of the Earth's land surface is seasonally covered by snow, and 10% is permanently covered by glaciers (Dozier, 1989; Lemke et al., 2007; Wolff, 2013). Snow and ice play important interactive roles in the Earth's radiation balance, because they have a higher albedo than any other natural surface. Fresh snow reflects up to 80% or more of the incoming solar energy, which compares drastically with only 20% or less for bare ground (König et al., 2001). The most notable positive feedback is the sea ice albedo feedback, which results from the large contrast between the albedos of sea ice (>0.6) and open water (~0.07) (Perovich et al., 2007). Due to the Arctic temperature rise, the ice or the overlying snow cover of high albedo is increasingly replaced with open water or bare soil of lower albedo. This results in additional absorption of solar radiation, which accelerates further snow/ice loss. However, understanding the interaction of solar energy with the ice cover is a complex task. First, it is not easy to determine how much solar energy is reflected/or absorbed by the ice and how much is subsequently transmitted into the ocean. Second, the seasonal evolution of the ice albedo depends on the characteristics of the snow cover in spring and melt ponds in summer (Perovich et al., 2002; Perovich and Polashenski, 2012). For example, in summer time, the surface conditions in the Arctic can vary from deep snow, to bare ice, to melt ponds, to open leads within small areas that are often <1 km^2 (Perovich et al., 2002) and to bare or grass soils. These surface types have different physical and optical properties and interact with the incoming solar energy differently. Because of the importance of the sea ice albedo feedback mechanism, the ability to identify different surface types at fine spatial scales is important for predicting snow and ice melt as well as for understanding the ice extent loss, which in turn affects the global energy budget and therefore climate.

Satellites are proven to be well suited to measure snow/ice cover because the high reflective nature of snow/ice at visible wavelengths presents a good contrast with other natural surface covers. For example, the NASA Earth Observing System (EOS) MODerate-Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites identify snow cover based on a Normalized Difference Snow Index (NDSI) spectral band ratio, which is the difference of reflectances in a visible band and a shortwave infrared band divided by the sum of the two refectances (Hall and Riggs, 2007; Hall et al., 2002). The NDSI

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http://dx.doi.org/10.1016/j.rse.2017.03.046
0034-4257/

approach takes advantage of the fact that snow reflectance is high in the visible wavelengths and has low reflectance in the shortwave infrared wavelengths (Hall and Riggs, 2007; Parajka et al., 2012).

The polar-orbiting Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) has been providing continuous global measurements at two-wavelengths (532 and 1064 nm) between 82°S and 82°N since June 2006 (Winker et al., 2010). These valuable datasets can be used to study the snow and sea ice cover in the Arctic where in-situ observations are relatively rare due to the extreme weather conditions in high latitudes. In contrast to MODIS passive remote sensor that can only provide useful surface type measurements during daylight seasons and are not reliable at low solar angles, the CALIOP lidar makes reliable measurements both day and night, and at low solar angles through considerable aerosol loads and thin clouds (Behrenfeld et al., 2013; Josset et al., 2012). The CALIOP lidar has a 70 m footprint on the Earth's surface that is sampled along track every 333 m. The advantage of using CALIOP measurements is that the CALIOP has a small sample footprint size compared to passive sensors.

In this paper, we develop a new retrieval method for surface type identification in the Arctic that is based upon the relationship between CALIOP's integrated attenuated backscatter color ratio and integrated depolarization ratio. In Section 2 we present CALIOP observations of integrated attenuated backscatter color ratio and depolarization ratio, and describe other datasets used in this paper. The surface type separation method and its application to 10 years of the CALIOP Arctic sea ice measurements are described in Sections 3 and 4. The results from CALIOP measurements shown in this study are compared with datasets from both MODIS and passive microwave sensors measurements. Section 5 gives the summary and conclusions.

2. Data products

2.1. CALIOP level 1 data products

CALIOP flies aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, which deploys both active and passive sensors designed for atmospheric cloud and aerosol research. CALIOP is the first space-borne polarization-sensitive lidar (with cross-polarization and co-polarization channels at 532 nm) to provide vertical profiles of the elastic backscattering from a near nadir-viewing during both day and night between 82°N and 82°S (Hunt et al., 2009; Winker et al., 2009). In this paper, we use the new CALIOP level 1 version 4 data product to derive the integrated attenuated backscatter that is a major parameter used in the surface type identification method described in Section 3. Because the CALIOP lidar receiver's transient response yields a long tail in the attenuated backscatter profile below the

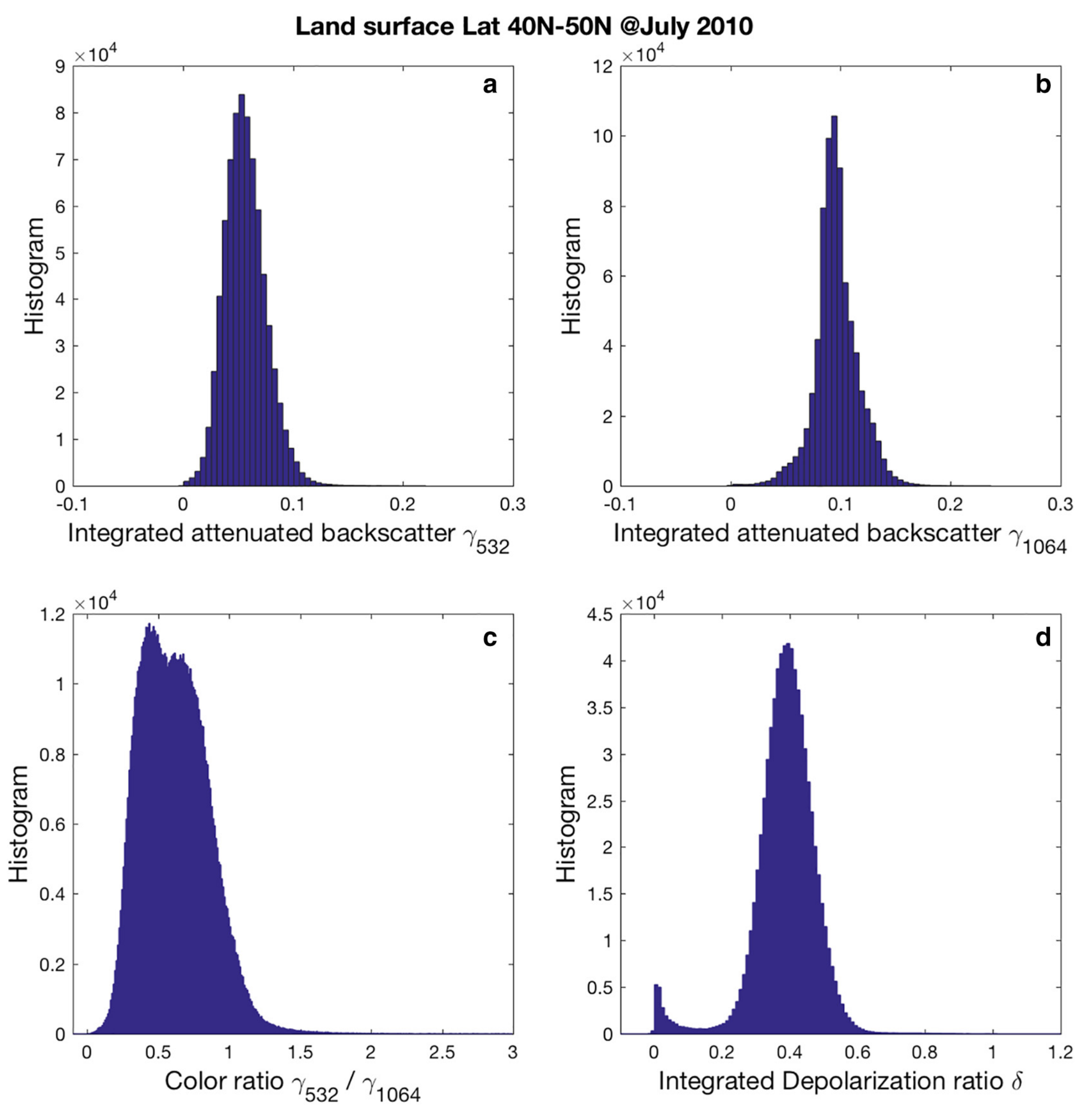

Fig. 1. Histogram of land surface integrated attenuated backscatter γ_λ at 532 nm (a), 1064 nm (b), color ratio x (c) and depolarization ratio δ (d).