Remote Sensing of Environment 191 (2017) 402–418

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors

Masahiro Hori [a,*], Konosuke Sugiura [b], Kazufumi Kobayashi [c], Teruo Aoki [d,e], Tomonori Tanikawa [e], Katsuyuki Kuchiki [e], Masashi Niwano [e], Hiroyuki Enomoto [f,g]

[a] Earth Observation Research Center, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505, Japan
[b] University of Toyama, 3190 Gofuku, Toyama 930-8555, Japan
[c] Remote Sensing Technology Center of Japan, 3-17-1 Toranomon, Minato-ku, Tokyo 105-0001, Japan
[d] Graduate School of Natural Science and Technology, Okayama University, 3-1-1, Tsushima-Naka, Kita-Ku, Okayama 700-8530, Japan
[e] Meteorological Research Institute, Japan Meteorological Agency, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan
[f] National Institute of Polar Research, 10-3, Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan
[g] The Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan

ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 8 January 2017
Accepted 20 January 2017
Available online xxxx

Keywords:
Snow cover extent
Snow cover duration
Remote sensing
Long-term data
Climate
AVHRR
MODIS

ABSTRACT

A long-term Northern Hemisphere (NH) daily 5-km snow cover extent (SCE) product (JASMES) was developed by the application of a consistent objective snow cover mapping algorithm to data from historical optical sensors on polar orbiting satellites from 1978 to 2015. A conventional decision tree algorithm with multiple threshold tests was employed to analyze radiances for the five spectral bands available across the full analysis period. The accuracies of the analyzed SCE maps were evaluated against in-situ snow data measured at ground stations along with the SCE maps from the National Oceanic and Atmospheric Administration Climate Data Record (NOAA-CDR) product. The evaluation showed the JASMES product to have a more temporally stable producer's accuracy (PA; 1–omission error) than NOAA, which is a key factor in the analysis of long-term SCE trends. Comparison of seasonal NH SCE trends from the two products showed NOAA to have opposite trends to those of JASMES in the fall and winter seasons, and to have overestimated SCE decreasing trends in the spring and summer. These tendencies are consistent with the increasing spatial and temporal resolutions of information over time, which were used in generating the NOAA snow analysis. An estimation of unbiased SCEs based on the accuracies of SCE maps also endorses the long-term trends of the JASMES product. The JASMES NH seasonal SCE exhibited negative slopes in all seasons but was only statistically significant in the summer (JJA) and fall (SON). Delayed snow cover onset was observed to be the main driver of decreasing annual snow duration (SCD) trends. The spatial pattern of annual SCD trends exhibited noticeable asymmetry between continents, with the largest significant decreases observed over western Eurasia with relatively few statistically significant decreases over North America.

1. Introduction

Snow cover is an essential geophysical parameter for understanding the Earth's climate system. Its high shortwave albedo and longwave emissive properties significantly impact Earth's climate system via the radiation budget (Warren, 1982). Snow cover also plays an important role as a thermal insulator in cold continental areas (Armstrong and Brun, 2008). In addition, because of its long duration after snowfall, snow cover itself provides regional terrestrial drainage and freshwater to downstream oceans during melting seasons (e.g., Dyer, 2008; Arnell, 2005; Tan et al., 2011). Thus, since the beginning of the satellite era in the 1960s, the areal extent of snow cover has been a key satellite observation target for the purposes of daily weather forecasting and a better understanding of the Earth's climate system and hydrological cycle (Robinson et al., 1993; Frei et al., 2012; Estilow et al., 2015).

Snow cover extent (SCE) was initially determined from imagery taken by optical television cameras in the 1960s and 1970s, first by the Television Infrared Observation Satellite (TIROS-1) and subsequently by the Very High Resolution Radiometer (VHRR) and the Advanced Very High Resolution Radiometer (AVHRR) onboard polar orbiting weather satellites (POSs) launched by the National Oceanic and Atmospheric Administration (NOAA). Since then, weekly SCE charts with

* Corresponding author at: Earth Observation Research Center, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505, Japan
E-mail address: hori.masahiro@jaxa.jp (M. Hori).

http://dx.doi.org/10.1016/j.rse.2017.01.023
0034-4257/

spatial resolutions of about 190 km have been derived, mainly for numerical weather forecasts using visible satellite imagery (Matson et al., 1986; Matson, 1991; Robinson et al., 1993).

Since 1997, NOAA has produced a weekly SCE map derived from various sensor sources using the Interactive Multisensor Snow and Ice Mapping System (IMS), which has improved spatial and temporal resolutions of 24 km and a daily update interval, respectively (Ramsay, 1998; Helfrich et al., 2007). To create snow maps with higher frequency and thereby reduce errors in the near-surface temperature forecasts, the IMS has used optical imagery from POSs and geostationary satellites as well as multiple data sources from passive microwave radiometers, ground stations, and the previous day's snow maps. In addition, several other optional inputs have been added to the IMS including, for example, data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Earth observing satellites Terra and Aqua of the National Aeronautics and Space Administration (NASA), and an experimental automated snow mapping system over North America that uses visible, near-infrared, middle-infrared, infrared, and microwave imagery. These additional data sources have enabled the IMS to produce daily snow maps with 4-km spatial resolution since 2004 (Helfrich et al., 2007). Since 2014, the spatial resolution of the IMS SCE has been improved to 1 km (National Ice Center, 2008, accessed in 2016).

Currently, the longest available records of the Northern Hemisphere (NH) SCE that are widely used in climate-related studies are the climate data record (CDR) versions of the NOAA weekly NH SCE charts. These CDR charts have a resolution of approximately 190 km, span a period from 1966 to the present day, are prepared by Rutgers University, and are archived by NOAA's National Climatic Data Center (NOAA/NCDC) (Robinson et al., 2012; Brodzik and Armstrong, 2013; Estilow et al., 2015). The NOAA/NCDC CDR weekly SCE charts are derived both from the original NOAA weekly SCE charts for the period 1966–1997 and the daily IMS products for the recent period from 1997–present. The more current IMS SCE data with higher spatial resolution (24 km) are converted to conform with the older weekly NH SCE data with the reduced spatial resolution of 190 km, using data from the overlapping period of 1997 to 1999 to ensure continuity in evaluating this longest NH SCE record (Ramsay, 2000; Robinson, 2013; Estilow et al., 2015).

Although NOAA initiated production of the weekly SCE charts for the purpose of numerical weather forecasting, the historical long-term SCE charts have been used extensively for a wide range of studies including trend analyses (e.g., Armstrong and Brodzik, 2001; Brown et al., 2010), evaluation of climate models (e.g., Derksen and Brown, 2012; Brutel-Vuilmet et al., 2013), and analyses of snow cover-atmosphere linkages and feedbacks (e.g., Flanner et al., 2011; Cohen et al., 2012).

In response to operational requests for weather forecasts and to the technological advances made from the 1960s to the present, the analysis methods of the NOAA NH SCE and IMS SCE have repeatedly been improved in terms of various spatial and temporal resolutions of the data sources (Brown et al., 2010; Frei et al., 2012). The original NOAA weekly SCE charts were hand-drawn snow line maps based on a visual interpretation of photographic copies of visible imagery by trained meteorologists and then digitized at a pixel size of 190.5 km at 60° latitude (Robinson et al., 1993). Since 1997, the IMS SCE had also been manually derived in an interactive process, but analysis of the SCE charts was made automatic when geographic information systems (GIS) began to be utilized in 1999 (Helfrich et al., 2007; Brown et al., 2010). In addition, the spatial resolution of the IMS SCE, which is reduced to 190.5 km resolution to produce the CDR time series of the NH SCE, has improved over time from 24 km (1997–2004) to 4 km (2004–2012) to 1 km (2014–present).

The above-mentioned changes in data sources over time, coupled with procedural and personnel changes have potential to introduce inconsistencies into the accuracy of snow cover mapping over time (Frei et al., 2012). For example, Brown and Derksen (2013) demonstrated that the increasing trend in the NOAA October SCE, as highlighted by Cohen et al. (2012), was inconsistent with trends inferred from several independent snow cover datasets, including surface observation, reanalysis, and satellite passive microwave snow water equivalent (SWE) data. Peng et al. (2013) also revealed, based on in-situ daily snow depth (SD) observations, that there is a trend of snow cover onset toward later dates in the NH, which is also inconsistent with the increasing trend of NOAA's October SCE chart. Another issue with the NOAA weekly dataset is that the spatial resolution is too coarse for many applications and for connecting to datasets derived from recent state-of-the-art satellite sensors, such as MODIS and the Visible Infrared Imaging Radiometer Suite (VIIRS). In light of these documented issues with the NOAA product, it is important to use consistent and objective criteria to re-analyze the visible satellite data record at finer spatial and temporal resolutions.

In this study, our objective is to develop a long-term hemispherical SCE product with a spatial resolution of 5 km that spans a period from late 1978 to the present day in order to create a climatological baseline of snow cover by analyzing the radiances of satellite-borne optical sensors using objective analysis criteria. For this purpose, we developed an algorithm for deriving an SCE map that utilizes radiance data at only five fixed spectral bands that are available for the whole analysis period. We then evaluated the accuracies of the analyzed SCE map using in-situ measured SD and regional snow coverage data obtained at ground meteorological stations from around the world. In addition, we corrected the satellite-derived SCEs using the in-situ measured snow data to estimate unbiased SCEs. As a benchmark SCE product, in the same manner, we also evaluated the accuracies of the NOAA/NCDC CDR weekly snow charts. Finally, as an application example of the derived SCE map product, we examined the long-term trends of SCE, snow cover frequency (SCF), and snow cover duration (SCD).

This paper comprises six sections, as follows. Section 2 describes the preparation of the long-term radiance data, particularly the correction of the AVHRR sensor degradation effect on radiances. Section 3 explains the method for deriving SCE from radiance data using a conventional threshold technique. Next, we describe our SCE validation with in-situ snow data (Section 4) and present our analysis results and discuss the long-term SCE data (Section 5). Finally, Section 6 summarizes and concludes this paper.

2. Satellite data: preparation of long-term calibrated radiance datasets

In this study, we used radiance data acquired with the AVHRR and MODIS series of satellite-borne optical sensors. Specifically, we used NOAA's AVHRR Global Area Coverage (GAC) radiance data from November 1978 to December 2005 (covering the satellites of TIROS-N, NOAA-7, -9, -11, -14, and -16) and MODIS radiance data (MOD02SSH of Terra, MYS02SSH of Aqua) from March 2000 to December 2015. We used the MODIS data of Collection 5 (C5) for the period before June 3, 2013 and Collection 6 (C6) after June 4, 2013, which we obtained from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS) webpage (https://ladsweb.nascom.nasa.gov/). The radiance (*Rad*) of MODIS was converted to reflectance (*Ref*) by $Ref = Rad * \pi * d^2 / (F_0 \cos\theta_0)$, where d is the Earth-solar distance in astronomical units, F_0 is solar irradiance, and θ_0 is the solar zenith angle. The spatial resolutions of the original data are 4 km for the AVHRR GAC data and 5 km for the MODIS data. Table 1 summarizes the spectral band specifications of both satellite sensors and the data period used for SCE generation in our study. Because the AVHRR band-5 data on the TIROS-N satellite is a copy of the band-4 data, we used the TIROS-N data only to derive the NH SCE and not to analyze long-term trends without making error adjustments.

Of the above sensors, MODIS has the ability to calibrate observed radiance (Xiong et al., 2003), and thus the MODIS data were used without additional calibration in this study. It should be noted here, however, that some studies suggest that the C5 MODIS data show systematic temporal trends in the visible and near-infrared bands, particularly for Terra