Remote Sensing of Environment 215 (2018) 284–299

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Developing a composite daily snow cover extent record over the Tibetan Plateau from 1981 to 2016 using multisource data

Xiaona Chen[a], Di Long[a,*], Shunlin Liang[b], Lian He[a], Chao Zeng[a], Xiaohua Hao[c], Yang Hong[a]

[a] State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Geographical Sciences, University of Maryland, College Park 20740, USA
[c] Northwest Institute of Eco-Environmental and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

ARTICLE INFO

Keywords:
Tibetan Plateau
Snow cover extent
AVHRR surface reflectance CDR
Climate change

ABSTRACT

Snow cover condition across the Tibetan Plateau (TP) is not only a significant indicator of climate change but also a vital variable in water availability because of its water storage function in high-mountain regions of Southwest China and the surrounding Asian countries. Limited by low spatial resolution, incomplete spatial coverage, and short time span of the current snow cover products, the long-term snow cover change across the TP under the climate change background remains unclear. To resolve this issue, a composite long-term gap-filled TP daily 5-km snow cover extent (SCE) record (TPSCE) is generated by integrating SCE from the Advanced Very High-Resolution Radiometer (AVHRR) surface reflectance climate data record (CDR) and several existing snow cover data sets, with the help of a decision tree snow cover mapping algorithm, for the period 1981–2016. A snow discrimination process was used to classify the land surface into snow (pre-TPSCE) and non-snow using AVHRR surface reflectance CDR. To fill gaps caused by invalid observations and cloud contamination in pre-TPSCE, several existing daily SCE products, including MOD10C1, MYD10C1, IMS, JASMES, and a passive microwave snow depth data set are employed in the composition process. The daily snow discrimination accuracy, tested by ground snow-depth observations during 2000–2014, shows that the TPSCE captures the distribution of snow duration days (R^2 = 0.80, bias = 3.93 days) effectively. The comparison between the TPSCE and fine-resolution snow cover maps (MCD10A1-TP) indicates high comparability between the TPSCE and MCD10A1-TP. In addition, cross-comparisons with changes in temperature, precipitation, and land surface albedo indicate that the TPSCE is reliable in climate change studies. In summary, the TPSCE is spatially complete and covers the longest period among all current snow cover products from satellite observations. The TPSCE seamlessly records changes in snow cover across the TP over the past 36 years, thereby providing valuable snow information for climate change and hydrological studies.

1. Introduction

Snow cover is a critical component of the cryosphere and climate system on both the local and the global scales. As the “third pole” and “Asian water tower” with the highest mid-latitude mountains and largest cryosphere extent outside the polar regions, the Tibetan Plateau (TP) largely affects the regional environment and controls climatic and environmental changes in China, Asia, and even the Northern Hemisphere (NH) at large (Kang et al., 2010; Larson, 2011; Ma et al., 2009; Pu et al., 2008; Yao et al., 2012). Snow cover on the TP has large potential to influence the regional hydrological cycle (Qian et al., 2011), affects the frequency of heat waves in northern China (Wu et al., 2012), and results in anomalies in vegetation greenness onset (Dong et al., 2013), the atmosphere–land interaction (Ma et al., 2009), and the East Asian summer monsoon (Pu et al., 2008). Furthermore, seasonal snow cover across the TP constitutes a vital source of surface water for Southwest China and the surrounding Asian countries (e.g., Pakistan, India, Nepal, Bangladesh, and Bhutan). Thus, quantifying snow cover conditions across the TP is essential for meteorological, hydrological, ecological, and societal implications.

Satellite remote sensing has been employed to map and monitor snow cover for more than forty years (Brown et al., 2010; Frei et al., 2012), because data collection by traditional field snow surveying is time consuming, costly, and extremely difficult. Using data sets, such as the binary daily snow cover mask derived from the Interactive Multisensor Snow and Ice Mapping System (IMS) (Helfrich et al., 2007), the Northern Hemisphere Weekly Snow Cover and Sea Ice Extent (NHSCE) (Helfrich et al., 2007; Robinson et al., 1993), the Moderate-Resolution

* Corresponding author.
E-mail address: dlong@tsinghua.edu.cn (D. Long).

https://doi.org/10.1016/j.rse.2018.06.021
Received 21 October 2017; Received in revised form 10 June 2018; Accepted 16 June 2018
0034-4257/

Imaging Spectroradiometer (MODIS) snow cover products (Hall et al., 1995), the Suomi National Polar-orbiting Partnership (NPP) snow cover suite (Key et al., 2013), the European Space Agency (ESA) Global Snow Monitoring for Climate Research (GlobSnow) (Pulliainen, 2010), and snow water equivalent (SWE) products from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) (Kelly et al., 2003) and GlobSnow, the continental-scale snow cover anomalies are well quantified. Nevertheless, owing to complex topography, heterogeneous land cover types, and scattered snow cover distributions over the TP, as well as the limitations of the current snow cover data sets, the long-term snow cover condition across the TP remains unclear. Among the current snow cover products, the Suomi-NPP has high snow classification accuracy (> 90%) (Key et al., 2013), the MODIS snow cover products provide moderate spatial resolution (500 m) and high temporal resolution (Hall et al., 1995), the IMS provides complete spatial coverage (Helfrich et al., 2007), and the NHSCE provides the longest time span (4 October 1966 to the present) (Helfrich et al., 2007; Robinson et al., 1993). However, incomplete spatial coverage (e.g., Suomi-NPP and MODIS), short time span (e.g., Suomi-NPP and IMS), and low spatial resolution (e.g., NHSCE and GlobSnow) largely restrict the application of these products in snow cover studies across the TP.

To improve the understanding of snow cover changes over the TP under the climate change background, a long-term series, temporally consistent, and high-quality composite snow cover data set is needed. Accordingly, the objective of this study was to develop a composite long-term TP daily 5-km snow cover extent (SCE) record (TPSCE). To generate the preliminary daily TPSCE (pre-TPSCE) at the highest achievable spatial resolution and longest time span, we employed the newly published National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) surface reflectance Climate Data Record (CDR) (Vermote et al., 2014) as primary data. To overcome the shortage of optical AVHRR images in snow discrimination (mainly caused by invalid observations and cloud contamination), several ancillary data sets were jointly used in this study. Moreover, to test the reliability of the TPSCE in climate change studies, temperature, precipitation, and land surface albedo data were employed for cross-comparison purposes.

This study comprises six sections. Section 2 describes the data sets used in the study. Section 3 presents the processing flowchart for the TPSCE. In Section 4, we compare the TPSCE with ground snow-depth observations and fine-resolution snow cover maps. We analyze the spatiotemporal variability in SCE from the TPSCE in Section 5 and present cross-comparisons with temperatures, precipitation, and land surface albedo. Finally, in Section 6, we summarize this study and present our conclusions.

2. Data sets and methodology

2.1. Data sets

2.1.1. AVHRR surface reflectance CDR

The AVHRR surface reflectance CDR is processed from the AVHRR Global Area Coverage (GAC) Level 1b data set. The AVHRR GAC observations are packaged into data arrays, with latitudinal and longitudinal dimensions of 3600 × 7200, covering the globe at 0.05° spatial resolution (Vermote et al., 2014). The spectral bands of AVHRR surface reflectance CDR are summarized in Table 1. The quality control descriptions are listed in Table 2.

Compared with AVHRR data sets used in previous studies (Hori et al., 2017; Zhou et al., 2013), AVHRR surface reflectance CDR provides consistent daily average surface reflectance and brightness temperatures that are derived from the AVHRR sensors onboard seven NOAA polar orbiting satellites, including NOAA-7, NOAA-9, NOAA-11, NOAA-14, NOAA-16, NOAA-17, and NOAA-18 (Vermote et al., 2014). Moreover, AVHRR surface reflectance CDR calibrates different instruments from 1981 to the present and facilitates their use in current snow mapping studies. Evaluating the AVHRR surface reflectance CDR performance by cross-comparison with MODIS in the monitoring of United States wheat yield demonstrated that the utility errors of AVHRR surface reflectance CDR were equivalent to those derived from MODIS (Franch et al., 2017). Therefore, this AVHRR historical data set was found to be reliable in land cover classification, especially for years before 2000. In addition, to reduce the snow discrimination error caused by distortions in pixel geometry, only images with a view zenith angle of < 45° were used in this study.

Compared with binary snow cover products, fractional snow cover products would provide better accuracy because of fragmented snow distributions in the TP. However, due to complex topography and relatively low spatial resolution of AVHRR surface reflectance CDR (0.05°), the selection of end-members within a grid cell across the TP is variable and uncertain, which limits the application of spectral unmixing algorithms among images with different times and locations. Thus, we developed binary snow products instead of fractional snow cover products in this study.

Table 1
Details of spectral bands of AVHRR surface reflectance CDR used in this study.

Bands	Wavelength (mu)	Description
1	0.58–0.68	Surface reflectance at 640 nm (SR1)
2	0.725–1.00	Surface reflectance at 860 nm (SR2)
3	3.55–3.93	Surface reflectance at 3.75 µm (SR3)
4	3.55–3.93	Brightness temperature at 3.75 µm (BT37)
5	10.30–11.30	Brightness temperature at 11.0 µm (BT11)
6	11.50–12.50	Brightness temperature at 12.0 µm (BT12)
7	–	Quality control flag

Table 2
Quality control descriptions of AVHRR surface reflectance CDR used in this study.

Bit	Description	Value = 1	Value = 0
15	Polar flag (latitude over 60 degrees (land) or 50 degrees (ocean))	Yes	No
14	BRDF-correction issues	Yes	No
13	RHO3 value is invalid	Yes	No
12	Channel 5 value is invalid	Yes	No
11	Channel 4 value is invalid	Yes	No
10	Channel 3 value is invalid	Yes	No
9	Channel 2 value is invalid	Yes	No
8	Channel 1 value is invalid	Yes	No
7	Channels 1–5 are valid	Yes	No
6	Pixel is at night (high solar zenith)	Yes	No
5	Pixel is over dense dark vegetation	Yes	No
4	Pixel is over sunglint	Yes	No
3	Pixel is over water	Yes	No
2	Pixel contains cloud shadow	Yes	No
1	Pixel is cloudy	Yes	No

2.1.2. Ancillary data

2.1.2.1. MODIS daily snow cover products. The MODIS Terra/Aqua Snow Cover Daily L3 Global 0.05° Climate Modeling Grid (CMG) (MO/YD10C1) (Hall et al., 1995) reports the percentage of snow-covered land at 0.05° spatial resolution for the period 2000 to the present and 2002 to the present, respectively. The percentages are computed from snow cover observations in the MODIS Terra/Aqua Snow Cover Daily L3 Global 500-m Grid (MO/YD10A1) data set (Hall et al., 1995). The overall absolute accuracy of MOD10A1 is higher than 93% under ideal conditions of illumination, clear skies, and several centimeters of snow on a smooth surface (Hall and Riggs, 2007). A study by Polashenski et al. (2015) indicated that Collection 5 MODIS data, particularly that of Terra, showed systematic temporal trends in visible and near-infrared bands. To avoid uncertainties induced by this issue in MO/YD10C1, we used collection 6 MO/YD10C1 in our study.