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Impact of climate and elevation on snow cover using integrated remote sensing snow products in Tibetan Plateau

Xiaodong Huang [a],*, Jie Deng [a], Wei Wang [b], Qisheng Feng [a], Tiangang Liang [a]

[a] *Key Laboratory of Grassland Agro-ecology System, Ministry of Agriculture, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China*
[b] *Key Laboratory of Arid Climatic Change and Reducing Disasters of Gansu Province, Institute of Arid Meteorology, China Meteorological Administration, Lanzhou 730020, China*

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ABSTRACT

Climate change is rapidly altering snow cover conditions in seasonal snow-covered regions of the Tibetan Plateau. This study presents a systematic analysis of the changes in snow cover and its response to climate change on the Tibetan Plateau during the period 2001–2014 using MODIS daily snow cover products under cloud free conditions and AMSR-E SSM/I daily SWE products. The results indicated that 1) the snow-covered area (SCA) tended to increase at elevations below 2000 m.a.s.l., whereas it decreased at elevations above 2000 m.a.s.l. The SCA exhibited a mean decrease over the entire plateau. 2) The SCD and SWE tended to decrease on the Tibetan Plateau, particularly at high elevations. 3) Decreased snowfall and increased rainfall and temperature are the main reasons for the SCD and SWE decrease over the Tibetan Plateau during the period 2001–2014. 4) Snowfall had a positive feedback effect, whereas rainfall and temperature both had negative feedback effects on the attenuation of snow cover. 5) With increasing elevation, the positive feedback of snowfall on snow cover increased significantly, whereas the negative feedback effect of rainfall and temperature also increased.

1. Introduction

Since the 1990s, temperature rise has accelerated on the Tibetan Plateau in the context of global warming, resulting in rapid melting of most glaciers and permanent snow cover, rising snow lines, reduced wetland area, and a deteriorating ecological environment (Li, 1995, 2001; Yao et al., 2015; Xu et al., 2015). The ecosystems of the Tibetan Plateau are among the most sensitive to global change. Global climate change rapidly alters the snow cover conditions in seasonal snow-covered regions, and the snow mass in some regions of the Tibetan Plateau is increasing with global warming, which is in stark contrast to the trend of decreasing snow-covered area (SCA) in temperate lowlands in the Northern Hemisphere (Chen et al., 2000). The snow cover on the Tibetan Plateau affects the East Asian atmospheric circulation and weather systems, thereby affecting the climate in China (Qian et al., 2003; Zhao et al., 2007). Snow is an essential feature of the hydrology of river basins with headwaters on the Tibetan Plateau, and it affects freshwater supplies, lake levels, agriculture, and hydro-power generation (Zhang et al., 2012; Sharma et al., 2014; Li et al., 2014). Thus, the snow cover on the Tibetan Plateau is of great hydrologic, climatic, and ecologic significance (Hahn and Shukla, 1976; Verma et al., 1985). Previous studies have indicated that changes in snow depth across the Tibetan Plateau can markedly affect summer monsoons and precipitation over the Indian Ocean (Bai and Feng, 1994; Chen et al., 2000).

Remote sensing technology provides an extremely important advantage for in-depth exploration and research of snow cover monitoring (Gafurov and Bárdossy, 2009). Dozens of satellites have been used for monitoring snow cover, including those with optical remote sensing and both passive and active microwave remote sensing (Salomonson and Appel, 2004; Hall and Riggs, 2007; Che et al., 2014; Shi and Dozier, 2000a, b; Leinss et al., 2014; Wang et al., 2014). However, due to the similar reflective spectral characteristics of snow cover and clouds and in instances where there is no spectral similarity with other types of land cover, weather conditions have substantially limited the use of optical remote sensing data for snow cover monitoring (Hall et al., 2002; Wang and Xie, 2009). Passive microwave snow cover products are unaffected by weather conditions (Armstrong et al., 1993). However, their spatial resolution is coarse, and they are primarily used in research on snow depth, snow cover range, and snow water equivalent (SWE) on a global scale; they also yield large deviations in dynamic monitoring of regional snow cover. Many studies involving SWE retrieval based on active microwave remote sensing have been performed, including those based on scattering models and theory, inversion algorithms, and *in situ* and airborne experiments. Compared with passive microwave remote sensing, the active counterpart still poses problems in distinguishing between backscattering signals from soil and dry snow, and there are no mature snow parameter products nor any satellites for global SWE observations based on space borne radar that meet

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* Corresponding author.
E-mail address: huangxd@lzu.edu.cn (X. Huang).

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certain spatial and temporal requirements (Shi et al., 2016). Land surface process models and snow process models can simulate the SWE evolution with some degree of accuracy using forcing data. However, the SWE obtained using snow process models have large spatial and temporal uncertainties, and the results may be far from adequate for practical applications (Slater et al., 2001). Therefore, its high temporal and spatial dynamicity for snow parameters make remote sensing the only method to obtain accurate surface parameters simultaneously and with good temporal and spatial continuity.

In recent years, many researchers have been concerned with cloud removal from MODIS snow products and have developed several algorithms and snow cover products (Liang et al., 2008a, b; Xie et al., 2009; Hall et al., 2010; Dietz et al., 2012; Wang et al., 2014). Multi-day synthesis of optical snow cover products can effectively remove the majority of cloud contamination. Longer synthesis periods yield better cloud removal, but the time resolution is sacrificed, making it difficult to adequately perform real-time dynamic monitoring of snow-covered regions. Additionally, the synthesis of optical snow cover products and passive microwave data can completely eliminate cloud contamination; however, due to the low spatial resolution of microwave data, the synthesis of the two products results in less-precise synthetic snow cover products in instances of extensive cloud cover. The SNOWL (Snow Line) cloudless algorithm is a new algorithm for removing clouds in which cloud pixels are reclassified based on their elevations (Parajka et al., 2010). Based on the above algorithms, Huang et al. (2014) developed new highly accurate MODIS daily cloud-free snow cover binary products by combining the advantages of the algorithms. Recently, the accuracy of the new daily cloud-free snow cover products was verified against ground meteorological station data and Landsat ETM+ images. The new products achieved a snow-cover classification accuracy of 85% and an overall classification accuracy of 98% across the Tibetan Plateau (Wang et al., 2015), which demonstrates their great value for real-time monitoring of dynamic changes in snow cover on the Tibetan Plateau.

The SCA generally increased during the period 1957–1992 (Gao et al., 2003; Qin et al., 2006), the winter and summer snow-covered days (SCD) increased in the 1980s but started decreasing in the 1990s, and the stable SCA gradually expanded while the perennial SCA shrank during the period 2000–2010 (Wang et al., 2015). The perennial annual average SCA on the Tibetan Plateau is 16% over the entire year and 25% during the hydrologic year (early October to late April) (Pu et al., 2007; Shen et al., 2015). The monthly SCA reaches a maximum in January (approximately 37%) and a minimum in August (2%). The trend in the snow cover decrease is 4.0% per decade, with a total reduction of 5.7% from February 4, 1997, to March 15, 2012 (Pu et al., 2007; Shen et al., 2015). Across the Tibetan Plateau, only the Nyainqentanglha, parts of the Pamirs, and parts of the Qilian range displayed a marked increase in SCD, whereas the majority of the plateau area displayed a significant decrease, and the overall interannual changes in total snow mass displayed a fluctuating downward trend (Sun et al., 2014).

Snow cover distributions and variations are directly controlled by climate change in alpine areas, particularly on the Tibetan Plateau (Qin et al., 2006; Barnett et al., 2005). According to a report by the intergovernmental panel on climate change (IPCC), the global mean temperature has increased by an average of 0.74 °C over the previous 100 years (1906–2005), and the warming trend over the previous 50 years was 0.13 °C per decade; there was a nearly 2-fold increase in the rate of warming over the previous 100 years. In China, the mean temperature rise was 1.3 °C over the previous 50 years (1951–2005) (IPCC, 2013), and the largest temperature rise occurred on the Tibetan Plateau. In this context, what changes in snow cover would occur across the Tibetan Plateau?

The purpose of this study was to explain the reasons for changes in snow cover across the Tibetan Plateau based on daily integrated optical remote sensing snow products and passive microwave SWE products, analysis of the snow-cover dynamics during the period 2001–2014, a digital elevation model (DEM), and climate data from meteorological stations.

2. Tibetan Plateau

The Tibetan Plateau is located in the central Eurasian continent. According to latest advancement in research on the Tibetan Plateau, such as long-term fieldwork, geomorphic characteristics have been used to define the boundary of the Tibetan Plateau (Harrison et al., 1992; Zheng, 2000; Zhang et al., 2002). The plateau starts along the southern edge of the Himalayan Mountains, abuts India, Nepal and Bhutan, connects with the northern edge of the Kunlun, Altun and Qilian mountains, and joins the Tarim Basin and Hexi Corridor in Central Asia. The western boundary is the Pamirs and Karakorum mountains, bordering Kirghizistan, Tajikistan, Afghanistan, Pakistan and Kashmir. The eastern boundary is the Yulong, Daxue, Jiajin and Qionglai mountains and the southeastern piedmont of the Min Mountains. The Tibetan Plateau joins the Qinling Mountains and Loess Plateau along its eastern and northeastern part. The Tibetan Plateau in China's territory starts from the Pamirs in the west and extends to Hengduan Mountain in the east. It ranges from 26°00′12 ″N to 39°46′50″ with a length of 1532 km from north to south and from 73°18′52″E to 104°46′59″ with a length of 2945 km from west to east, covering an area of 2572.4×10^3 km^2 (Fig. 1). The Tibetan Plateau has a mean elevation exceeding 4000 m above sea level (m.a.s.l.), and it is one of the regions most sensitive to global climate change (Qin and Ding, 2009). The region is rich in snow and glacier resources and is the source of many rivers in Asia, including the Yellow, Yangtze and Lancang rivers. Due to global warming, accelerated melting of glaciers and the redistribution of precipitation lead to frequent floods and snowstorms over the Tibetan Plateau (Yao et al., 2012; Lee et al., 2013; Wang et al., 2013). Recently, it has been challenging to evaluate cryospheric changes on the Tibetan Plateau.

3. Materials and methods

3.1. Meteorological station data

The daily mean temperature (°C) and daily mean precipitation (mm) data of 106 meteorological stations spanning the period 2001–2014 were retrieved from the China Meteorological Data Sharing Network (http://data.cma.cn/, accessed June 17, 2015). These stations are located at elevations of 1285 to 4850 m (Fig. 1).

3.2. Daily cloud free SCA and SWE products

The SCD, SCA and SWE are the three most commonly used parameters in snow cover research. The SCD and SCA are primarily acquired from optical imaging instruments, such as MODIS, while SWE can be determined using passive microwave radiometers, such as AMSR-E and AMSR-2 (Hall et al., 2002; Kelly et al., 2003; Lee et al., 2015). The SCD represents the total number of days with snow cover in an area during a year, and the SCA is the percentage of snow-covered area within a given study area. The SCA products used in this study were obtained from the Environmental and Ecological Science Data Center for West China, namely, the MODIS daily cloud-free snow cover products of the Tibetan Plateau (2001–2014) developed by the first author of this paper (Huang et al., 2014). The algorithm used to produce these products consists primarily of four steps. (1) Daily MODIS snow cover images are synthesized. Daily snow images including MOD10A1 and MYD10A1 are synthesized using the maximum SCA fusion method in accordance with the different acquisition times of the Terra and Aqua satellites and the characteristics of cloud movement. If a cloud pixel is present in MOD10A1 but snow or land is observed in MYD10A1, then the pixel is classified as snow or land accordingly. (2) Images from consecutive days are analyzed. The land-class attributes of partial-cloud pixels of a given day are determined using the MODIS standard snow cover