

# MODIS-observed spatial and temporal variation in snow cover in Xinjiang, China

Chang-Qing Ke\*, Xun Liu

Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University,  
No. 163 Xianlin Avenue, Nanjing 210046, China

**ABSTRACT:** Temporal and spatial variations in snow cover have a major impact on hydrological resources and the ecological environment in Xinjiang. In this study, we used the MOD10A2 dataset for the period from July 2000 to June 2012, and eliminated cloud cover by combining MOD10A2 with MYD10A2 to analyze the spatial and temporal distribution and variation in snow cover in Xinjiang. The results indicate a distinct periodicity of the seasonal variation in snow area. Snow area reached a maximum in late January and a minimum in mid-August. Snow cover distribution differed based on elevation and exhibited a single peak distribution at elevations below 4000 m. At elevations between 4000 m and 5000 m, there was a long-term stable period of snow cover, and snow areas at elevations above 5000 m were relatively large in the spring and fall. In winter, snow cover frequency was relatively high in the Irtysh River catchment in northern Xinjiang, whereas there was little snow cover in southern Xinjiang. The snow area exhibited a slightly increasing trend over the 12 yr period, but exhibited a decreasing trend in winter at elevations above 4000 m and below 2000 m. The snow cover frequency also generally remained stable, but exhibited a distinctly increasing trend in the inner Tianshan Mountains and a clearly decreasing trend around Yiwu County. The snow cover frequency exhibited a negative correlation with temperature in November and March, and a significant positive correlation with precipitation during the stable period of snow cover.

**KEY WORDS:** MODIS · MOD10A2 · Snow area · Spatio-temporal variations · Trend · Snow cover frequency · Xinjiang

*Resale or republication not permitted without written consent of the publisher*

## 1. INTRODUCTION

In the 4th Climate Change Assessment Report released in 2007, the Intergovernmental Panel on Climate Change (IPCC) stated that in the next 20 yr, the rate of increase in the global temperature will reach  $0.2 \text{ K decade}^{-1}$  (IPCC 2007); this has caused widespread concern among various communities. This report also stressed that snow cover is an important part of the cryosphere, and its physical properties, such as high reflectivity and extensive ground coverage, make it an important variable in the climate system. Snow cover affects the climate system through a series of complex interactions and feedback mecha-

nisms (IPCC 2007). Moreover, as an indicator of climate change, snow cover rapidly responds to global climate warming (Goodison & Walker 1993). Therefore, increasing numbers of scholars are interested in studying climate change by analyzing the spatial and temporal distributions and variations in snow cover (Pu et al. 2007, Lopez et al. 2008, Ke et al. 2009, Pu & Xu 2009, Bulygina et al. 2011, Maskey et al. 2011, You et al. 2011, Foppa & Seiz 2012).

In China, a wide distribution of areas exist that are subject to permanent and seasonal snow cover. The Tibetan Plateau, northern Xinjiang and northeastern China are considered the 3 stable snow cover regions in China (Li & Mi 1983). As the main body of the

\*Corresponding author: kecq@nju.edu.cn

northwest arid region of China, Xinjiang is the area with the richest seasonal snow-water resources in China, accounting for one-third of national snow resources (Li 1988). The spatial and temporal variations in snow cover can affect river runoff in spring, with serious consequences for the economy and the fragile ecological environment of arid areas and may even lead to the occurrence of droughts or flood disasters (Li 1999). In spring, temperatures rise rapidly, causing rapid melting of snow. Consequent runoff can cause flooding (Yan et al. 2009), e.g. in the Juntang Lake Basin, Xinjiang, in March 2005 (Wei 2006), which resulted in huge economic losses. Such floods can also lead to debris flows. In addition, long-duration snowfalls in Xinjiang may lead to snow disasters, causing the death of large numbers of livestock due to food shortages and cold temperatures (Liang et al. 2008). From October 2000 to February 2001, heavy snow disasters occurred in northern Xinjiang, leading to snow depths of approximately 50 cm and up to 2 m in some mountainous areas. Livestock husbandry suffered heavy losses, and the resulting economic loss was estimated at 214 million RMB Yuan (Huang 2009).

The traditional method for analyzing variations and trends in snow cover is to use the snow observation data obtained at ground weather stations. However, because the weather stations in Xinjiang are generally distributed in basins or near residential areas at relatively low elevations, they cannot supply accurate information on the distribution of snow covering different underlying surfaces and at different elevations. Moreover, the data obtained from the weather stations only include daily information regarding the presence or absence of snow and its depth at the station locations (Pu et al. 2007). Thus, ground weather stations cannot provide the data needed to assess the spatial and temporal distribution of snow across the entire Xinjiang region.

Remote sensing, which offers the advantages of large-scale and short-cycle monitoring, has been widely applied for snow observation. For example, remote sensing equipment such as SMMR/SSM/I (Scanning Multichannel Microwave Radiometer/Special Sensor Microwave Imager) (Ke & Li 1998, Derksen et al. 2000, Armstrong & Brodzik 2001); AMSR-E (Advanced Microwave Scanning Radiometer-EOS) (Kelly & Chang 2003, Kelly et al. 2003); NOAA-AVHRR (National Oceanic and Atmospheric Administration—Advanced Very High Resolution Radiometer) (Xu et al. 1993, Wang et al. 2005); Landsat (Dozier 1989); SPOT (Satellite Pour l'Observation de la Terre) (Dankers & De Jong 2004); and MODIS

(Moderate Resolution Imaging Spectroradiometer) have been widely applied in the monitoring of snow cover variations. Maskey et al. (2011) applied MODIS and temperature data to analyze snow variation in the Himalayan area, and found that snow cover has increased in spring and fall and decreased in January, and that there are distinct negative correlations between snow cover and factors such as temperature, net radiation, and wind speed. Pu & Xu (2009) used MOD10C2 data to investigate the relationship between snow coverage and factors such as the slope, aspect, and curvature of the ground on the Tibetan Plateau from 2000 to 2006, and they found that snow cover anomalies are associated with East Asian summer monsoons. Using cloudless MODIS images, Lopez et al. (2008) found that from 2000 to 2006, the extent of snow cover in eastern and western Patagonia fluctuated considerably, controlled by different meteorological factors.

Many scholars have monitored and studied the variation of snow cover in Xinjiang. Based on the data obtained from weather stations and SMMR, Li (2001) found a very clear trend of warming in winter in Xinjiang, but also found that snow cover has increased slightly and fluctuates greatly from year to year. Dou et al. (2010) used MOD10A2 data to analyze the spatial and temporal distribution of snow cover between 2000 and 2006 in the Tianshan Mountains, and found that, over this time period, the snow area increased (decreased) at elevations above (below) 4000 m. Wang & Che (2012) analyzed cloudless snow cover data obtained from a combination of MODIS and AMSR-E, and found that the snow area in arid regions of China, including Xinjiang, has remained essentially unchanged in recent years, and that inter-annual fluctuation has manifested itself mainly in the variation in the number of snow cover days.

The study area of the present study was the entire Xinjiang region. All of the MOD10A2 snow cover products from July 2000 to June 2012 were included in our analysis, which provided a relatively long analysis period. Our study involved the following: (1) simplified cloud elimination; (2) an analysis of seasonal snow area variation for the entire Xinjiang region at various elevations (because topography and climate vary greatly with elevation, as do variations of snow cover frequency in different months); (3) an analysis of the trends in snow area and snow cover frequency; (4) an examination of the relationships between meteorological factors and snow cover frequency, as well as snow depth.

## 2. STUDY AREA AND DATA

### 2.1. Study area

Xinjiang is located between latitudes 34°25' and 48°10'N and longitudes 73°40' and 96°18'E. The total area encompasses 1.66 million km<sup>2</sup>. Xinjiang has a vast territory with a complex topography that includes a maximum elevation difference of approximately 9000 m, from the Turpan Depression, which is the lowest point in Xinjiang, at 155 m below sea level, to the peak of Mount Qogir, located at the border between China and Pakistan, which is the highest point, at 8611 m above sea level. The overall geographic pattern is characterized by '3 mountains, 2 basins,' which alludes to the low-lying Junggar Basin between the Altai Mountains in the north and the central Tianshan Mountains and the Tarim Basin between the Tianshan Mountains and the Kunlun Mountains in the south. Xinjiang can be divided into 2 parts, southern Xinjiang and northern Xinjiang, with the Tianshan Mountains as the boundary (Fig. 1). Because of the obstruction of the Tianshan Mountains, there is an evident difference in geomorphology and climate between southern and northern Xinjiang. The climate in northern Xinjiang is less arid than that

in southern Xinjiang. The average annual precipitation in the north is 244 mm. The annual average precipitation in southern Xinjiang is 123.9 mm (Han et al. 2003). Snowfall accounts for approximately 30% of the total precipitation in the Junggar Basin, Tacheng Basin, and Ili River Valley (northern Xinjiang) and approximately 80% in the mountainous areas. In southern Xinjiang, snowfall accounts for only approximately 10% of the total precipitation (Liu et al. 2012). In most of northern Xinjiang, the stable snow period is approximately 5 mo long, and the mountainous areas are covered by snow throughout the entire year. In southern Xinjiang, only the Kunlun Mountains are stable snow areas, and the Tarim Basin has an arid climate with very little precipitation and snowfall. In addition, the forest coverage is relatively low in Xinjiang and is mainly distributed on the northern slopes of the Tianshan Mountains and throughout the Altai Mountains (Li et al. 2005).

### 2.2. MODIS snow products

In 1999, the Earth Observation System (EOS) satellite Terra was successfully launched with the MODIS sensor, mainly for the observation of the Earth's ecological systems. MODIS snow products are generated based on the SNOMAP algorithm (Hall et al. 1995). On the basis of the principle that snow has high reflectivity in the visible bands and low reflectivity in the near-infrared bands, a normalized different snow index (NDSI) is applied to distinguish between areas with and without snow cover. In addition, snow and water can be distinguished according to the reflectance of the fourth band of MODIS, with a classification as water below the threshold of 0.11, and snow and forest can be distinguished according to the reflectance of the second band of MODIS, with a classification as forest below the threshold of 0.1 (Hall et al. 2002).

Compared with the daily MOD10A1 data, the MOD10A2 snow cover data from MODIS/Terra involve relatively little cloud coverage (Xie et al. 2009). MOD10A2 is the composite of the MOD10A1 data over 8 d, and the composite criterion is the maximum

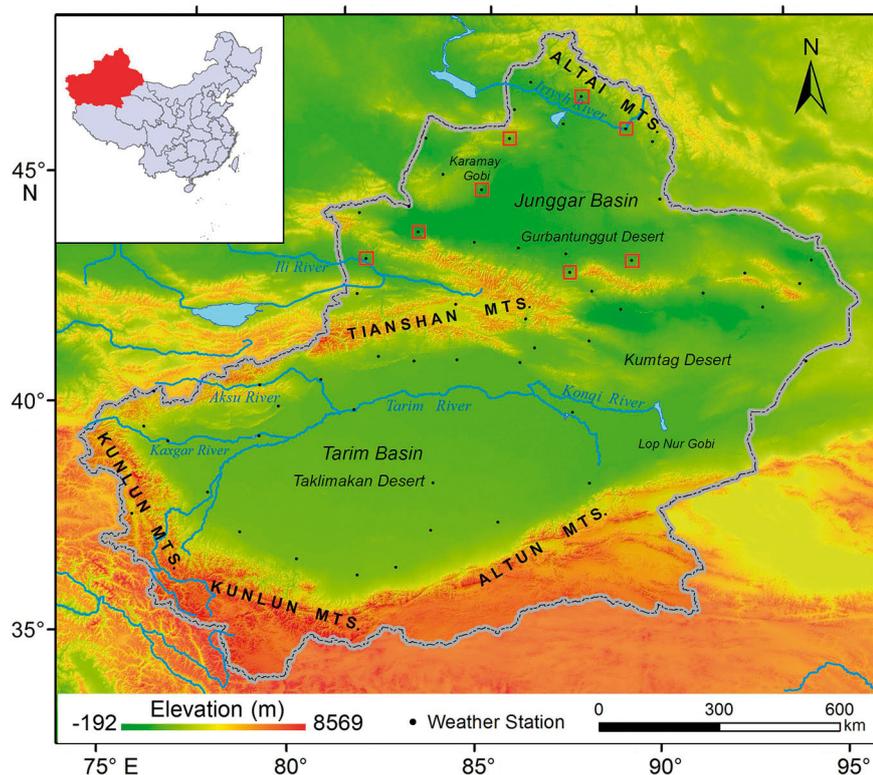


Fig. 1. Location of the study area and the weather stations considered. Red boxes: stations used for correlation analysis

snow coverage area. Specifically, if there is snow for 1 d of the 8 d of MOD10A1, the corresponding pixel of MOD10A2 is identified as snow (Xie et al. 2009). For MOD10A2, different pixel values represent different ground objects: 25 for no snow, 37 for lake, 50 for cloud, 100 for lake ice, and 200 for snow (Riggs et al. 2006). The time range of MOD10A2 selected in this study was from July 2000 to June 2012, which included a total of 552 scenes. The MOD10A2 data from each scene included 6 tile files: h22v05, h22v06, h23v05, h23v06, h24v05, and h24v06. We applied the MODIS Reprojection Tool provided by the National Snow and Ice Data Centre (NSIDC) to merge the aforementioned 6 tile files into 1 scene image. The sinusoidal projection was then converted to the Universal Transverse Mercator (UTM) Zone 45 projection on the World Geodetic System (WGS84), and the resolution was resampled to 500 m. Eventually, the images of Xinjiang were cropped out based on the provincial geographical boundaries.

The superiority of the MOD10A2 snow cover product has been affirmed by several scholars. Wang et al. (2008) compared the MOD10A2 with field snow cover data and found the accuracy of the MOD10A2 to be up to 94 % at snow depths  $\geq 4$  cm on cloud-free days. Huang et al. (2007) found the average recognition rate of snow cover by MOD10A2 in pastoral areas of northern Xinjiang to be up to 87.5 %. However, it is difficult for MODIS to recognize snow when the snow depth is  $< 4$  cm (Klein & Barnett 2003). In general, MOD10A2 has relatively high recognition accuracy, and therefore is suitable for snow cover monitoring and the study of variation trends.

### 2.3. Weather station data

Data for temperature, precipitation, and snow cover depth were collected from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). Some of the data at this website are freely accessible. The distribution of weather stations is not uniform; they are generally located at relatively low elevations, and none of them are in high mountainous areas (Fig. 1). The temperature, precipitation, and snow depth data from 8 representative weather stations (Fig. 1, red boxes) in northern Xinjiang were used to analyze the relationships of snow cover frequency and snow depth to temperature and precipitation. The daily snow depth data collected in 2010 from 53 weather stations throughout Xinjiang were used to evaluate the accuracy of the cloud elimination of the MODIS snow product.

### 2.4. SRTM-DEM

The digital elevation model (DEM) utilizes SRTM DEM data (Jarvis et al. 2008) with a spatial resolution of 90 m. Based on this dataset, we divided Xinjiang into 6 elevation zones:  $< 1000$ , 1000–2000, 2000–3000, 3000–4000, 4000–5000 m, and  $> 5000$  m. We then resampled at a resolution of 500 m to compare with MOD10A2 data and to analyze snow cover variations in different elevation zones.

## 3. METHODS

### 3.1. Cloud elimination

Cloud cover is a major obstacle to the MODIS monitoring of snow cover. If the area of cloud cover exceeds 10 %, it is necessary to perform a cloud elimination procedure (Maskey et al. 2011). Although the cloud cover area in the MOD10A2 data for each scene was substantially smaller than for MOD10A1 data, 72 scenes in the MOD10A2 data remained in which the cloud cover area was  $> 10$  %. These 72 scenes accounted for 13 % of the total number of images. In addition, the imaging of 70 scenes occurred during winter (i.e. December to February), when the snow area was relatively extensive. Excessive cloudiness strongly affects analysis of snow cover.

We applied a simplified, combined MOD10A2/MYD10A2 method to eliminate cloud cover (Liang et al. 2008). MYD10A2 composited by MODIS/Aqua 8 d has properties identical to MOD10A2. MYD10A2 was composed from the MODIS sensor on board the Aqua satellite through a similar snow-mapping algorithm. The Terra satellite passed the research area in the morning, and the Aqua satellite passed in the afternoon. In comparison with the relatively stable patterns of snow cover, cloud cover exhibits dynamic variations. A pixel that is identified as cloud cover in the morning may be identified as another ground object in the afternoon, due to the motion and variation of cloud cover. In this study, MOD10A2 and MYD10A2 were combined to determine maximum snow coverage and minimum cloud coverage. More specifically, if 1 pixel was identified as snow cover in any image, then this pixel was considered snow cover after the integration; however, if 1 pixel was identified as cloud cover in both images, then this pixel was considered cloud cover. For example, for the data collected between 1 and 8 January 2011, the cloud cover area of the MOD10A2 data was 13.33 %, whereas the cloud cover area of the MYD10A2 data

was 14.43%. However, the cloud cover area in the superimposed images was 7.62% (Fig. 2), which represents a decrease in the cloud cover area of approximately 50%.

Using the daily weather station data on snow depth, we evaluated the cloud elimination performance for 7 scenes of MOD10A2 data from the winter of 2010 that were in need of such an elimination procedure. The results showed that after cloud elimination with the combined MOD10A2/MYD10A2 method, the accuracy of snow identification increased from 69 to 75% in the 7 scenes (Table 1). Therefore, the cloud elimination method was judged to be effective and capable of improving, to some extent, the accuracy of image recognition.

### 3.2. Calculation of snow area and snow cover frequency

The percentage of snow area was calculated as the ratio between the number of pixels identified as snow and the total number of pixels. The SRTM DEM and MOD10A2 data for each scene were superimposed to compute the percentage of snow area in each elevation zone based on the corresponding images from 2000 to 2012.

For each pixel, the snow cover frequency was defined as the ratio between the identifications as snow and the total number of MOD10A2 images during a given period. A higher snow cover frequency indicates that that pixel is covered by snow for a longer time during the given period. The formula is as follows:

Table 1. Evaluation of cloud elimination (details of procedure in Section 3.1)

	Before cloud elimination			After cloud elimination		
	Accurate	Inaccurate	Cloud cover	Accurate	Inaccurate	Cloud cover
No. of pixels	256	44	71	279	44	48
Percentage (%)	69	12	19	75	12	13

$$\text{snow cover frequency } (a) = \frac{T_{\text{snow}}}{T} \times 100\% \quad (1)$$

where  $a$  represents the given period. When  $a$  represents different months ( $a = \text{January, February, ..., December}$ ),  $T_{\text{snow}}$  stands for the times MOD10A2 identified snow in the same month in different years and  $T$  stands for the total number of MOD10A2 images in that month. Because MOD10A2 is a composite dataset collected over a span of 8 d, the time-spans for some images might include days from 2 different months. In these instances, the 8 d composite data were categorized as occurring in the month that contained the majority of days from the 8 d timespan. If the 8 d span was split evenly across 2 months, it was categorized as occurring in the earlier month. According to this classification method, there were 3 images in February and August of each year, and the length of the time series was 12 yr in this study, so  $T = 36$ , whereas there were 4 images in the other months of each year, so  $T = 48$ . When  $a$  represents different years ( $a = 2001, 2002, \dots, 2011$ ),  $T$  represents the number of MOD10A2 data for each year. The data were incomplete for 2000 and 2012; thus these years were not included in the computation of annual snow cover frequency trends.

We then constructed the linear regression equation  $y = ax + b$ , where  $x$  represents years ( $x = 2001,$

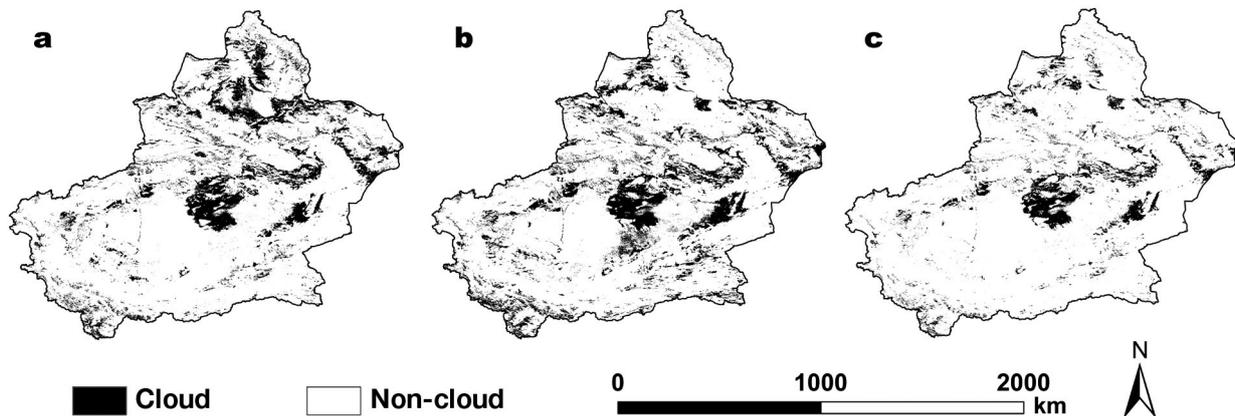


Fig. 2. Cloud elimination according to MOD10A2 and MYD10A2 data (1–8 January 2011): (a) MOD10A2 image, (b) MYD10A2 image, (c) combined image

2002, ..., 2011),  $y$  represents the annual snow cover frequency of each pixel, and the slope  $a$  represents the annual trend in the snow cover frequency at each pixel.

## 4. RESULTS AND DISCUSSION

### 4.1. Seasonal variation

The seasonal variation in snow cover in Xinjiang was distinct (Fig. 3). Snow cover reached a maximum in late January at approximately 0.66 million km<sup>2</sup>, or approximately 40% of the total area of Xinjiang. Snow began to melt in late February, and the percentage of snow area decreased to 12% in early April. Snow melt was fastest in early and mid-March. After March, the percentage of snow area gradually decreased and dropped below 5% after late June. The minimum snow area occurred in mid-August and was approximately 0.05 million km<sup>2</sup>, or approximately 3% of the total area of Xinjiang. The snow area then began to increase and accumulated rapidly in November, increasing from 12% of the total area to nearly 30%.

The seasonal variation in snow area in regions at elevations below 4000 m was similar to that for Xinjiang on the whole (Fig. 4). These regions had a distinct maximum snow cover period (winter), a snow ablation period (spring, i.e. March to May), a minimum snow cover period (summer, i.e. June to August), and a snow accumulation period (fall, i.e. September to November). At elevations below 1000 m, snow melted quickly in March, and the snow area decreased from >30% to a very small percentage. In regions at elevations below 1000 m, snow accumulated rapidly in November.

The snow area did not consistently increase as the elevation increased, even in winter. The Tarim Basin, in which snow was very rare throughout the entire year, was mostly located at elevations between 1000 and 2000 m, and the snow area in this region was the lowest among all the elevation zones for most of the year. In the winter, the snow area was most extensive at elevations between 2000 and 3000 m, which included the foothill regions of the Altai Mountains, Tianshan Mountains, and Kunlun Mountains. In summer, no snow was observed at elevations below 2000 m, and very little snow was observed at elevations between 2000 and 3000 m, whereas snow cover was observed at elevations above 3000 m in the Tianshan Mountains and Kunlun Mountains. At elevations between 4000 and 5000 m, there was a slight

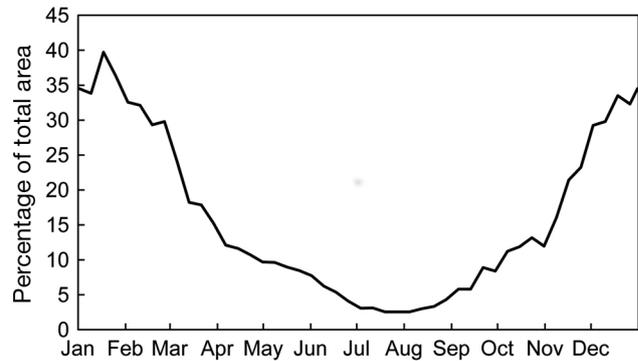


Fig. 3. Seasonal variation in snow cover area (as percentage of total area) in Xinjiang

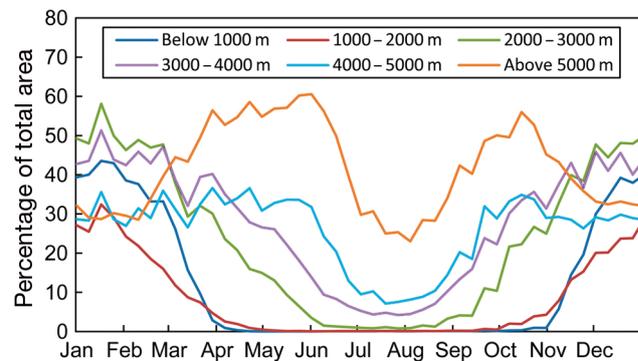


Fig. 4. Seasonal variation in snow cover area (as percentage of total area) at different elevations in Xinjiang

change in the snow area between October and May of the following year, with approximately 30% area covered by snow. June–September was a period of snow ablation and reduced accumulation for these regions, and the snow area reached a minimum (approximately 8%) in early August. In mountainous areas above 5000 m, the change in snow area exhibited a bimodal pattern; the snow area was relatively extensive in both the spring and fall, and the snow area in the spring was slightly larger than that in the fall. The maximum snow area occurred at the end of May and exceeded 60%. In this elevation zone, snow was relatively infrequent in winter, and the wind was strong; consequently, wind transported snow to regions at lower elevations (Pu & Xu 2009), leading to smaller snow area percentages in this zone than in some low-lying regions in winter. Our results for all other elevation zones were consistent with the observations reported by Ma et al. (2013) regarding snow cover in different elevation zones of Xinjiang, except for the elevation zone between 1000 and 2000 m. Ma found that snow accumulated earlier and melted later in that zone than we did, which may be due to

the shorter time series used in Ma's study (Ma et al. 2013). Our results concerning snow cover variations at different elevations in Xinjiang were also similar to results reported for the Tibet Plateau (Pu et al. 2007, Tang et al. 2013). Snow variation in Xinjiang at elevations between 4000 and 5000 m and above 5000 m were similar to those in Tibet at elevations between 4000 and 6000 m and above 6000 m, respectively.

#### 4.2. Variation in snow cover frequency

Northern Xinjiang was covered extensively by snow in winter, and higher snow cover frequency occurred on the windward side of the moist westerly airflow (Fig. 5), which mainly included 2 regions: the Irtysh River watershed in the north of the

Junggar Basin and in the south of the Altai Mountains and the Ili River Valley, which is surrounded by mountains on 3 sides (north, east, and south). There was also snow in the Gurbantunggut Desert of the Junggar Basin, where the snow cover frequency was slightly lower than that in other regions of the basin. A low snow cover frequency in northern Xinjiang occurred in the Karamay Gobi and the northern piedmont areas of the eastern section of the Tianshan Mountains. From March to April, there was a high snow cover frequency in the Altai Mountains in northern Xinjiang; however, there was essentially no snow at this time in the Junggar Basin because of the distinct snow melting process. From November to December, there was distinct snow accumulation in the Junggar Basin, gradually expanding from the edge to the center

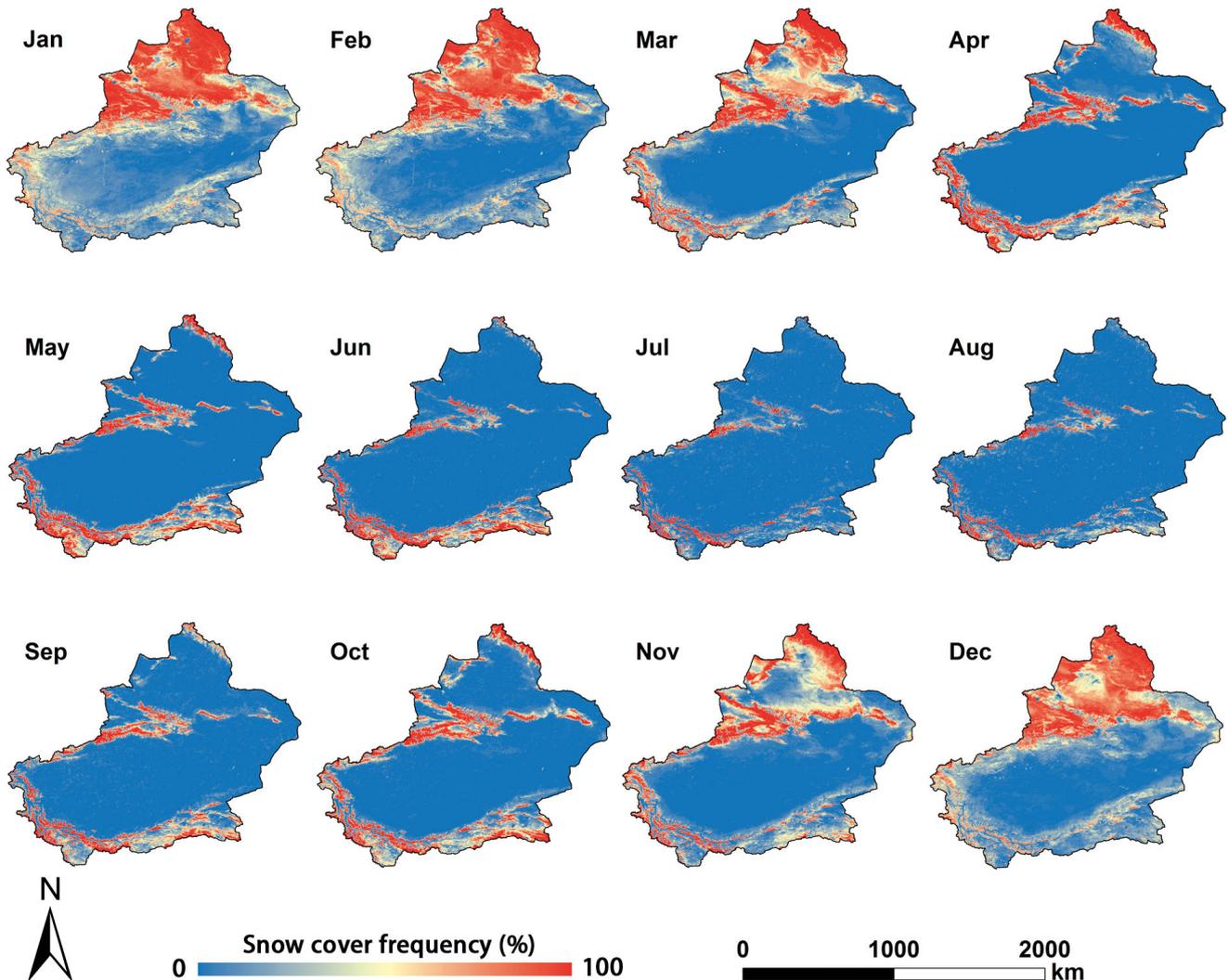


Fig. 5. Monthly snow cover frequency in Xinjiang

of the basin. However, in May, snow cover over the Altai Mountains began to melt, and no snow was present in summer until September, at which point snow appeared again. In the Tianshan Mountains, snow cover decreased in summer, especially in the eastern Tianshan Mountains, and remained stable in other seasons.

The climate in southern Xinjiang was dry. Due to the presence of the Taklimakan Desert, the Lop Nur Gobi region, and the Kumtag Desert, snow cover only occurred occasionally in the piedmont areas of the high mountains and the boundary areas of the deserts in winter, and no snow occurred in other seasons. The variation in the snow cover frequency in the Kunlun Mountains also exhibited a distinct bimodal pattern: the snow cover frequency was very low in the winter and was very high in the spring and fall.

### 4.3. Trends in snow cover

#### 4.3.1. Snow area

The results obtained concerning the snow area percentages in similar elevation zones during similar seasons over the 12 yr study period indicated that the trends in snow area were different for the different seasons and at different elevations (Table 2), we did not calculate snow area trends below 3000 m in summer because the snow area was very small. In winter, there was a decreasing trend in snow area at elevations below 2000 m and above 4000 m, and there was an increasing trend at elevations between 2000 and 4000 m. These results indicated that, in winter, snow area shrank steadily in the basin regions, gradually decreased in the mountainous regions, and increased steadily in the foothill regions. In spring, the snow areas in all elevation zones exhibited increasing trends. In summer, all of the elevation zones displayed an increasing trend above 3000 m. In fall, there was a slight decreasing trend in snow area at elevations below 2000 m, and an increasing trend existed at elevations above 2000 m. The increasing trend was particularly distinct at elevations above 3000 m. In general, the changing rate of snow area in winter, whether expanding or shrinking, was greater than that in other seasons. In addition, a decreasing trend in snow area predominated in winter, whereas an increasing trend was predominant in other seasons. However, the length of the time series was only 12 yr; therefore, the trends were not significant.

Table 2. Trends in snow cover area (% per annum) at different elevations and in different seasons from 2000 to 2012. NA: not analyzed

Elevation (m)	Winter	Spring	Summer	Fall
<1000	-0.31	+0.14	NA	-0.06
1000–2000	-0.25	+0.02	NA	-0.03
2000–3000	+0.30	+0.10	NA	+0.06
3000–4000	+0.29	+0.17	+0.05	+0.20
4000–5000	-0.28	+0.15	+0.14	+0.29
>5000	-0.34	+0.11	+0.10	+0.16

#### 4.3.2. Snow cover frequency

As shown in the graph of the annual variation trends (Fig. 6), the increasing trend of snow cover frequency was very distinct in the inner Tianshan Mountains. The snow cover frequency showed an increasing trend in the middle Kunlun Mountains, in the Bayinbuluke Basin, in Habahe County in the northwest of Ulungur Lake, and near Urumqi. This increasing trend in snow cover frequency led to increasing runoff into the Aksu River, which flows through the interior of the Tianshan Mountains. Similar findings have been reported by Chen et al. (2006). Furthermore, because the Bayinbuluke Basin and the area near Urumqi are places where livestock are raised, increasing snow cover frequency increased the risk of snow disasters, which can hamper the raising of livestock. The snow cover frequency decreased in several regions, such as the Fuhai area southeast of Ulungur Lake, in eastern Karamay,

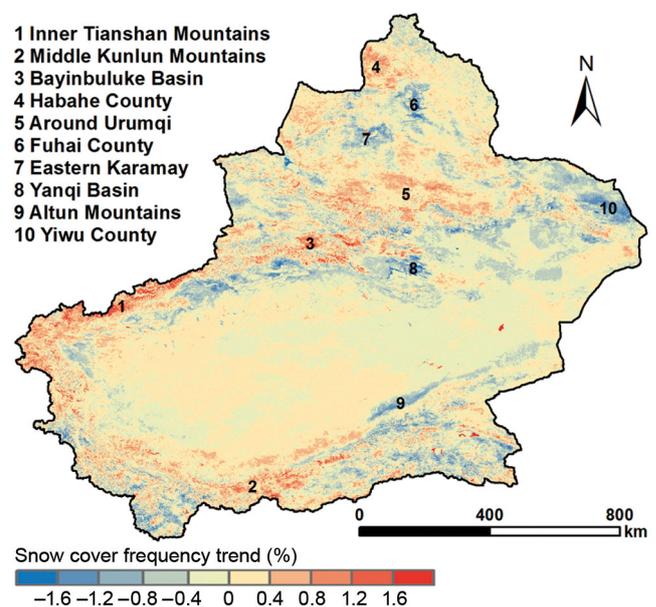


Fig. 6. Trends in annual snow cover frequency in Xinjiang

Yiwu County, the Yanqi Basin in the central Tianshan Mountains, and the Altun Mountains, and a decreasing trend in snow cover frequency was most commonly observed in Yiwu County.

#### 4.4. Relationships between snow cover and meteorological factors

The variation in snow cover was closely related to temperature and precipitation in winter, low temperature and snowfall being the necessary climatic conditions for the formation and maintenance of snow cover. As shown in the graph of snow cover frequency (Fig. 5), the process from snow accumulation to ablation started in November and ended in March of the following year in most regions of Xinjiang. Therefore, these 5 mo were defined as the snow cover season, which consisted of 3 stages: (1) November was the snow accumulation period, (2) the period from December to February of the following year was the stable snow cover period (January having the maximum snow cover), and (3) March was the snow ablation period. Due to the scarcity of snow in the Tarim Basin of southern Xinjiang, we selected 8 weather stations (Altay, Fuyun, Hoboksar, Karamay, Jinghe, Qitai, Urumqi, and Yining) in northern Xinjiang (Fig. 1) for our correlation analysis. This analysis was conducted to identify correlations between the monthly average temperature and monthly precipitation during the snow cover season over the 12 yr analysis period and the monthly snow cover frequency at the pixels corresponding to the locations of the weather stations. We also calculated correlations between the 2 meteorological factors and the monthly average snow depth measured at the same weather station.

Table 3. Correlation coefficients between snow cover frequency and meteorological factors. Significance: \* $p < 0.1$ ; \*\* $p < 0.05$

Month	Temperature (°C)	Precipitation (mm)
Nov	-0.65*	+0.58
Dec	-0.18	+0.85**
Jan	-0.06	+0.82**
Feb	-0.29	+0.57
Mar	-0.66*	+0.21

A negative correlation was detected between the monthly average temperature and the snow cover frequency at the pixels corresponding to the locations of weather stations in November and March, but they only satisfied the significance test at a level of  $p < 0.1$ , due to lack of weather station data. Temperature was found to exhibit a very weak negative correlation during the stable snow cover period (Fig. 7a, Table 3). The monthly precipitation and snow cover frequency were found to be significantly correlated, with correlation coefficients of 0.85 and 0.82 in December and January, respectively. Both parameters satisfied the significance test at a level of  $p < 0.05$ . These results indicate that the higher the precipitation, the higher the snow cover frequency (Fig. 7b, Table 3). The positive correlation was also found to be relatively strong in November and February, whereas the correlation was weak in March.

The correlation between the monthly average temperature and the snow depth at each weather station during the snow cover season was similar to that for the snow cover frequency (Table 4). Relatively distinctive negative correlations during the snow accumulation and melting periods in November and March were detected. In contrast, the monthly precipitation and snow depth had significantly positive

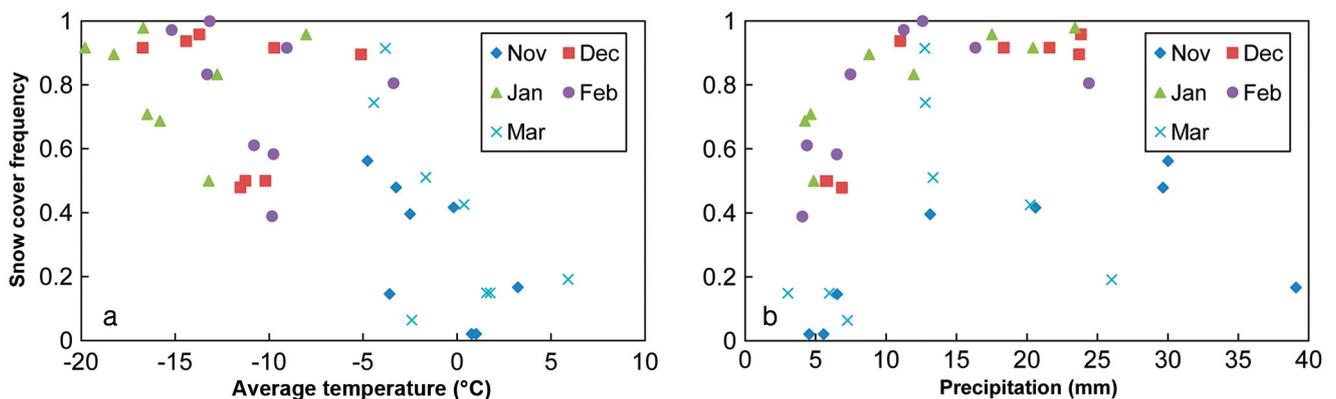


Fig. 7. Relationship between snow cover frequency and mean monthly (a) temperature and (b) precipitation during the snow cover season

Table 4. Correlation coefficients between snow depth and meteorological factors. Significance: \* $p < 0.1$ ; \*\* $p < 0.05$

Month	Temperature (°C)	Precipitation (mm)
Nov	-0.63*	+0.57
Dec	-0.35	+0.88**
Jan	-0.24	+0.95**
Feb	-0.32	+0.38
Mar	-0.65*	+0.09

correlation in December and January, with correlation coefficients of 0.88 and 0.95, respectively, and both satisfying the significance test at a level of  $p < 0.05$ . In November, the snow cover frequency and snow depth during the accumulation period were controlled by 2 factors: temperature and precipitation. In December, January, and February, temperatures were very low and snow could not melt; therefore, the snow cover frequency and snow depth were mainly controlled by precipitation. In March, temperatures increased and the precipitation type changed from snow to rain; as a result, the snow cover frequency and snow depth were controlled by temperature and rainfall, which transported sensible heat into the snow cover and accelerated the snow melting process. Although the transport of sensible heat had an effect on snow melting, its influence was very limited; in our opinion, temperature was the main factor (Tables 3 & 4).

## 5. CONCLUSIONS

Unlike the traditional method of monitoring snow cover, the application of remote sensing imagery makes it possible to quickly and accurately identify the spatial and temporal distribution of snow cover over a large area. As a new-generation sensor with moderate resolution, MODIS possesses exceptional merits with respect to snow cover monitoring. Compared to NOAA-AVHRR, MODIS can provide snow cover data with a higher spatial resolution and can provide more types of snow cover products. Based on the MODIS snow cover products for the period from 2000 to 2012, we analyzed seasonal variations in the area and frequency of snow cover in Xinjiang. Furthermore, we explored the relationships among snow cover variation, temperature, and precipitation. The main conclusions are summarized below.

1. The seasonal change in snow cover area is very dramatic (Figs. 3 & 4). The area percentage ranges from a maximum of 40% (late January) to a minimum

of 3% (August), showing distinct accumulation and ablation patterns. The seasonal variation in snow cover distribution is relatively prominent at elevations below 4000 m, and the snow area is relatively stable at elevations between 4000 and 5000 m, except in the summer months. In mountainous areas above 5000 m, the snow area reaches a maximum in the spring and fall every year.

2. Due to the complex topographical features in Xinjiang, the distribution pattern of snow cover differs in different areas and at different elevations. As one of the regions with the richest seasonal snow cover in China, northern Xinjiang displays a distinct seasonal variation in snow cover frequency (Fig. 5). Due to the impact of moist westerly airflow, there is greater snow cover in the Irtysh River Basin and the Ili River Valley, whereas there is less snow cover in the Gobi area near Karamay and in the northern piedmont areas of the eastern Tianshan Mountains. There is a small amount of snow cover in the boundary areas of the Tarim Basin, whereas there is no snow cover throughout the entire year in other regions of southern Xinjiang (Fig. 6).

3. The snow area increases in all elevation zones in spring and summer and increases in the elevations zones above 2000 m in the fall. The variation trends in winter differ from those in the other seasons: the snow area exhibits a decreasing trend at elevations below 2000 m and above 4000 m and an increasing trend at elevations between 2000 and 4000 m (Table 2). The changing rate of snow area in winter is relatively large; at elevations above 5000 m, the rate of change in snow cover reaches  $-0.34\% \text{ yr}^{-1}$ . The snow cover frequency exhibits a distinctive increasing trend in the inner Tianshan Mountains but a distinctive decreasing trend in Yiwu County.

4. During the accumulation and ablation periods of snow cover, different meteorological factors influence the snow cover frequency and snow depth in different months. Precipitation is the predominant factor in the snow cover frequency in December, January, and February. In November, the snow cover frequency is affected by both temperature and precipitation, while it is mainly affected by temperature in March (Fig. 7, Tables 3 & 4).

Although the method of cloud elimination was applied in this study, the effect of cloud reduction was not ideal for a small portion of images due to the complex climate and terrain conditions in Xinjiang. The resolution of MODIS is 500 m, which leads to limitations in alpine terrain because of shadowed pixels (Hall et al. 2002). The accuracy of MODIS products for snow cover monitoring in forest areas

needs to be further improved (Klein et al. 1998). Although forests cover only 2% of the area of Xinjiang, forest coverage still has a certain influence on snow recognition. Moreover, we did not analyze some important parameters such as snow cover days. Therefore, snow cover changes in Xinjiang in response to global warming need to be further explored.

*Acknowledgements.* This work was financially supported by the National Natural Science Foundation (No. 41371391), the National Key Technology Research and Development Program (No. 2012BAH28B02), the Specialized Research Fund for doctoral candidates in higher education, China (No. 20120091110017), and a project funded by the Priority Academic Program Development of the Jiangsu higher education institutions (PAPD). The MODIS snow data used in this study were obtained from the National Snow and Ice Data Center (<http://nsidc.org>).

#### LITERATURE CITED

- Armstrong RL, Brodzik MJ (2001) Recent northern hemisphere snow extent: a comparison of data derived from visible and microwave satellite sensors. *Geophys Res Lett* 28:3673–3676
- Bulygina ON, Groisman PY, Razuvaev VN, Korshunova NN (2011) Changes in snow cover characteristics over northern Eurasia since 1966. *Environ Res Lett* 6:045204. doi:10.1088/1748-9326/6/4/045204
- Chen Y, Deng ZW, Shi HZ (2006) Temporal change of annual runoff volume of the Aksu River, a source stream of the Tarim River. *Arid Zone Res* 23:21–25 (in Chinese)
- Dankers R, De Jong SM (2004) Monitoring snow-cover dynamics in northern Fennoscandia with SPOT VEGETATION images. *Int J Remote Sens* 25:2933–2949
- Derksen C, LeDrew E, Walker A, Goodison B (2000) Influence of sensor overpass time on passive microwave-derived snow cover parameters. *Remote Sens Environ* 71:297–308
- Dou Y, Chen X, Bao AM, Li LH (2010) Study of the temporal and spatial distribute of the snow cover in the Tianshan Mountains China. *J Glaciol Geocryol* 32:28–34 (in Chinese)
- Dozier J (1989) Spectral signature of Alpine snow cover from the landsat thematic mapper. *Remote Sens Environ* 28: 9–22
- Foppa N, Seiz G (2012) Inter-annual variations of snow days over Switzerland from 2000–2010 derived from MODIS satellite data. *Cryosphere* 6:331–342
- Goodison BE, Walker AE (1993) Use of snow cover derived from satellite passive microwave data as an indicator of climate change. *Ann Glaciol* 17:137–142
- Hall DK, Riggs GA, Salomonson VV (1995) Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data. *Remote Sens Environ* 54:127–140
- Hall DK, Riggs GA, Salomonson VV, DiGirolamo NE, Bayr KJ (2002) MODIS snow-cover products. *Remote Sens Environ* 83:181–194
- Han P, Xue Y, Su HC (2003) Precipitation signal of the climatic shift in Xinjiang region. *J Glaciol Geocryol* 25: 179–182 (in Chinese)
- Huang XD (2009) Snow cover monitoring based on remote sensing and GIS technologies in pastoral area of the northern Xinjiang, China. PhD dissertation, Lanzhou University, Lanzhou, Gansu (in Chinese)
- Huang XD, Zhang XT, Li X, Liang TG (2007) Accuracy analysis for MODIS snow products of MOD10A1 and MOD10A2 in northern Xinjiang area. *J Glaciol Geocryol* 29:722–729 (in Chinese)
- IPCC (Intergovernmental Panel on Climate Change) (2007) Summary for policymakers. *Climate Change 2007: the physical science basis. Contribution of Working Group I to the 4th assessment report of the IPCC*. Cambridge University Press, Cambridge
- Jarvis A, Reuter H, Nelson A, Guevara E (2008) SRTM. Available at: <http://srtm.csi.cgiar.org> (accessed 15 January 2013)
- Ke CQ, Li PJ (1998) Spatial and temporal characteristics of snow cover over the Qinghai-Xizang Plateau. *Acta Geogr Sin* 53:209–215 (in Chinese)
- Ke CQ, Yu T, Yu K, Tang GD, King L (2009) Snowfall trends and variability in Qinghai, China. *Theor Appl Climatol* 98:251–258
- Kelly RE, Chang AT (2003) Development of a passive microwave global snow depth retrieval algorithm for Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer-EOS (AMSR-E) data. *Radio Sci* 38:8076. doi:10.1029/2002RS002648
- Kelly RE, Chang AT, Tsang L, Foster JL (2003) A prototype AMSR-E global snow area and snow depth algorithm. *IEEE Trans Geosci Remote Sens* 41:230–242
- Klein AG, Barnett AC (2003) Validation of daily MODIS snow cover maps of the Upper Rio Grande River Basin for the 2000–2001 snow year. *Remote Sens Environ* 86:162–176
- Klein AG, Hall DK, Riggs GA (1998) Improving snow cover mapping in forests through the use of a canopy reflectance model. *Hydrol Processes* 12:1723–1744
- Li PJ (1988) Preliminary evaluation of seasonal snow resources in China. *Acta Geogr Sin* 43:108–119 (in Chinese)
- Li PJ (1999) Variation of snow water resources in northwestern China, 1951–1997. *Sci China B Chem Life Sci Earth Sci* 42:72–79
- Li PJ (2001) Response of Xinjiang snow cover to climate change. *Acta Meteorol Sin* 4:491–501 (in Chinese)
- Li PJ, Mi DS (1983) Distribution of snow cover in China. *J Glaciol Geocryol* 5:9–18 (in Chinese)
- Li H, Wang XF, Chen SJ, Hou P (2005) Dynamic analysis and evaluation of Xinjiang forest resources: based on RS and GIS. *J Geogr Sci* 15:346–352
- Liang TG, Huang XD, Wu CX, Liu XY, Li WL, Guo ZG, Ren JZ (2008) An application of MODIS data to snow cover monitoring in a pastoral area: a case study in northern Xinjiang, China. *Remote Sens Environ* 112:1514–1526
- Liu Y, Ruan HH, Zhang YH, Li Y (2012) Spatio-temporal characteristics of the snow cover evolution in the northern region of Xinjiang over the period of 1961–2008. *Resour Sci* 34:629–635 (in Chinese)
- Lopez P, Sirguy P, Arnaud Y, Pouyaud B, Chevallier P (2008) Snow cover monitoring in the northern Patagonia icefield using MODIS satellite images (2000–2006). *Global Planet Change* 61:103–116
- Ma YG, Huang Y, Chen X, Bao AM (2013) Analysis of the temporal and spatial variations of snow cover in Xinjiang, China. *Adv Water Sci* 24:483–489 (in Chinese)
- Maskey S, Uhlenbrook S, Ojha S (2011) An analysis of snow

- cover changes in the Himalayan region using MODIS snow products and *in situ* temperature data. *Clim Change* 108:391–400
- Pu ZX, Xu L (2009) MODIS/Terra observed snow cover over the Tibet Plateau: distribution, variation and possible connection with the East Asian Summer Monsoon (EASM). *Theor Appl Climatol* 97:265–278
- Pu ZX, Xu L, Salomonson VV (2007) MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. *Geophys Res Lett* 34:L06706. doi:10.1029/2007GL029262
- Riggs G, Hall D, Salomonson V (2006) MODIS snow products user guide to Collection 5. Available at: [www.nsidc.org/data/docs/daac/modis\\_v5/dorothy\\_snow\\_doc.pdf](http://www.nsidc.org/data/docs/daac/modis_v5/dorothy_snow_doc.pdf) (accessed 15 January 2013)
- Tang Z, Wang J, Li H, Yan L (2013) Spatiotemporal changes of snow cover over the Tibetan plateau based on cloud-removed moderate resolution imaging spectroradiometer fractional snow cover product from 2001 to 2011. *J Appl Remote Sens* 7:073582
- Wang ZY, Che T (2012) Spatiotemporal distribution of snow cover in arid regions in China. *Arid Zone Res* 29:464–471 (in Chinese)
- Wang L, Sharp M, Brown R, Derksen C, Rivard B (2005) Evaluation of spring snow covered area depletion in the Canadian Arctic from NOAA snow charts. *Remote Sens Environ* 95:453–463
- Wang XW, Xie HJ, Liang TG (2008) Evaluation of MODIS snow cover and cloud mask and its application in northern Xinjiang, China. *Remote Sens Environ* 112:1497–1513
- Wei J (2006) Snowmelt floods of the Juntanghu River in Xinjiang region. *J Glaciol Geocryol* 28:530–534 (in Chinese)
- Xie HJ, Wang XW, Liang TG (2009) Development and assessment of combined Terra and Aqua snow cover products in Colorado plateau, USA and northern Xinjiang, China. *J Appl Remote Sens* 3:033559, doi:10.1117/1.3265996
- Xu H, Bailey JO, Barrett EC, Kelly RE (1993) Monitoring snow area and depth with integration of remote sensing and GIS. *Int J Remote Sens* 14:3259–3268
- Yan Y, Liu ZH, Ye ZX (2009) Establishment and validation of early-warning model for snowmelt flood in North Xinjiang. *Arid Land Geogr* 32:552–557 (in Chinese)
- You Q, Kang S, Ren G, Fraedrich K, Pepin N, Yan Y, Ma L (2011) Observed changes in snow depth and number of snow days in the eastern and central Tibetan Plateau. *Clim Res* 46:171–183

*Editorial responsibility: Bryson Bates,  
Wembley, Australia*

*Submitted: June 10, 2013; Accepted: November 4, 2013  
Proofs received from author(s): January 21, 2014*