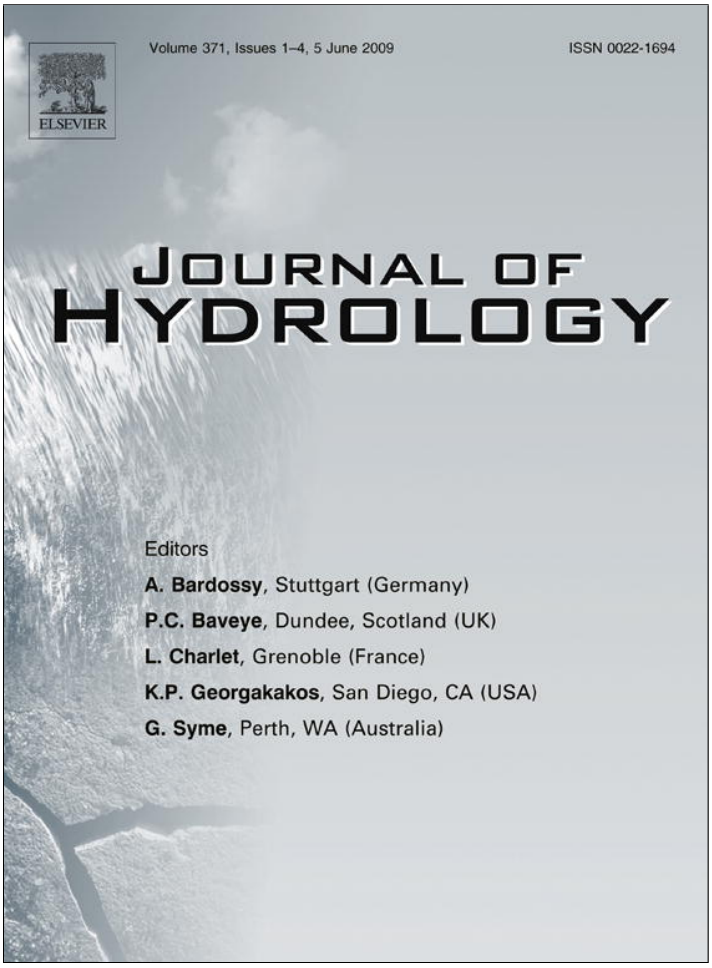
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New methods for studying the spatiotemporal variation of snow cover based on combination products of MODIS Terra and Aqua

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S U M M A R Y

Based on multi-day combination of Terra and Aqua MODIS snow cover products (cloud cover less than 10%), this study developed new snow cover index (SCI), snow-covered duration/days (SCD) map, snow cover onset dates (SCOD) map and snow cover melting dates (SCMD) map, one each per hydrological year, to further examine the spatiotemporal variations of snow cover. Daily *in situ* snow depth observations in northern Xinjiang, China from 2001 to 2005 were used to validate the new maps. Our results indicate that the SCD maps had an overall agreement of 90% with *in situ* observations of snow cover days at 20 stations in the study area, and the SCOD and SCMD maps also had good agreements with the *in situ* measurements, with a mean value of 1 week forward shift and 1 week backward shift, respectively, due to transient snowfall events in early fall and in late spring. The snow cover index (SCI) (km^2 day), first proposed here, contains both snow cover duration and extent for 1 hydrological year and indicates that the 2001–2002 hydrologic year had the most snow cover while the 2005–2006 had the least. While the SCD map provides the snow cover duration/days of each pixel in a hydrologic year, the SCOD and SCMD maps give specific dates when the snow cover begins and when it melts away at the pixel. Together, SCD, SCI, SCOD and SCMD can provide crucial information on spatiotemporal variation of snow cover conditions for any region of interest. This could potentially be critical information for local water agencies for planning water use and for mitigating snow-caused disaster. Long term availability of MODIS type of snow cover data for producing such datasets is key to study the connection between snow cover change and global climate change.

Introduction

Mountain glaciers and snow cover play an important role in water budget of many regions in the world (Ramage and Isacks, 2003). At high-latitude and mountainous regions, snow and glacier melt could be a significant contributor to the total yearly runoff volume. The storage of snow and ice at upper parts of mountains controls the seasonal runoff pattern at lower parts of mountains, especially in areas with dry summer season, where snow/glacier-melting runoff is a substantial source of water supply (Ye et al., 2005; Cui et al., 2005). Water from snow-covered glaciers and seasonal snow supply more than 1/6 of the world's population, which may be at risk due to global warming (Barnett et al., 2005). Monitoring and measuring snow cover and glacier is important for hydrologic modeling of snowmelt-runoff. Accurate and timely measurements of the onset/melting and extent of seasonal snow and glacier are crucial inputs for modeling and forecasting stream discharge, available water resource, and possible floods during spring and summer (Rango, 1997; Schaper et al., 1999; Ye et al., 2005).

With higher spatial resolution than passive microwave sensors, optical instruments on satellites and corresponding algorithms have well been developed to map global snow covered extent (Dozier and Painter, 2004). Snow cover products based on MODerate resolution Image Spectralradiometer (MODIS) carried by both Terra and Aqua satellites launched in 1999 and 2002, respectively, are one of the most successful optical snow cover products; however, the high portion of cloud blockage in the MODIS daily snow cover products severely obstructs their wide applications (Klein and Barnett, 2003; Zhou et al., 2005; Tekeli et al., 2005; Ault et al., 2006; Hall and Riggs, 2007; Liang et al., 2008; Wang et al., 2008, 2009). Since satellite Terra and Aqua passes the equator in ~3 h difference (10:30 am for Terra and 1:30 pm for Aqua) and the cloud is always moving at most cases, the MODIS Terra and Aqua combined snow cover products could provide more clear-sky snow cover maps against either Terra or Aqua alone. Similar results were reported from combining other Terra and Aqua MODIS products, such as vegetation index (Yang et al., 2006) and surface albedo (Salomon et al., 2006). Wang and Xie (submitted for publication) developed such an algorithm to automatically combine the

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daily MODIS Terra and Aqua snow cover products to generate a cloud-less daily snow cover product and a cloud-free (or cloud-low) multi-day snow cover composite product, MODMYD10MC. The central idea of the algorithm is that one pixel on the combined image will be snow if the pixel on either Terra or Aqua MODIS image is snow, while one pixel on the combined image will be cloud only if the pixel on both Terra and Aqua MODIS images is cloud (Wang et al., 2009; Wang and Xie, submitted for publication). The new multi-day composite (MODMYD10MC) has a similar snow classification accuracy and cloud coverage while with much higher temporal resolution (average 2.5 days) than the standard MODIS 8-day products (Wang and Xie, submitted for publication; Wang et al., 2009). The MODMYD10MC is a better representation of the snow cover than the standard 8-day MODIS Terra or Aqua composite alone and is used in this study.

Using the Terra and Aqua MODIS combined snow cover products, the purpose of this study is to examine the spatiotemporal variation of snow cover conditions through developing new snow-covered duration/days (SCD) map, snow cover onset dates (SCOD) map and snow cover melting dates (SCMD) map and snow cover index (SCI), one each per hydrological year. The northern Xinjiang, China and the central Tianshan Mountains, mainly in China, partly covering Kazakhstan and Kyrgyzstan, are used as a test bed to illustrate the development and validation of those new maps.

Traditionally, the SCD is calculated according to limited *in situ* snow depth measurements to represent the duration of snow cover on a particular region within a hydrologic year (typically from September to next August) (Gao et al., 2005). Because of the great heterogeneity of topography and human activities, SCD estimations from sparse ground-based stations are not many enough to represent the actual spatial distributions of SCD across a large region, especially at mountainous areas. SCOD and SCMD usually refer to the starting date and ending date of a continuous winter snow-covered period, although the transient snowfall events in the early fall and in the late spring cause multiple beginning-dates and ending-dates of snow cover at cold regions (Brown et al., 2007). The SCD map shows the spatial distribution of the overall snow cover duration within a hydrologic year, and SCOD and SCMD maps can tell when the specific snow-covered duration starts and when it ends for each pixel or area. Together, the spatially distributed SCD, SCOD and SCMD maps to be generated in this study has a potential significance for local water resource, live-stock industry, agriculture and emergency management.

Inspired from snow-melting index utilized in Antarctic sea ice/snow melt analysis (Zwally and Fiegles, 1994; Liu et al., 2005) where the snow/ice-covered period is dominant, a snow cover index (SCI) is first proposed in this study to measure the overall snow cover conditions on the land surface, where the snow-free period is dominant. The SCI (km^2 day) contains both SCD and snow cover area information of 1 hydrological year and is one single number to represent the overall snow cover condition for a region in 1 hydrological year.

Test area and data sources

Fig. 1 shows the test area on which the central Tianshan Mountains is indicated as a white polygon and is under the umbrella of two MODIS tiles of h23v04 and h24v04, which cover the entire northern Xinjiang and adjacent countries as shown in the inset map of Fig. 1. Background of the figure is the elevation map from NASA's Shuttle Radar Topography Mission (SRTM) with 90 m spatial resolution. The white polygon is used to constrain the geographic region in examining the overall spatial and temporal variations of snow cover conditions by the snow cover index (SCI). All new maps (SCD, SCOD and SCMD), however, are produced for the entire region under the umbrella of the two tiles, but are only illustrated as examples on the central Tianshan Mountains.

The central Tianshan Mountains are a part of Tianshan Mountain ranges, which stretch over 1500 km from west to east. The highest peak on the Tianshan Mountains is Tuo Mu Er (or Jengish Chokusu) at 7435 m. The second highest peak is Khan Tengri at 6995 m, just a couple of kilometers to the north of the highest peak. Both are on the central Tianshan Mountains and are labeled in Fig. 1. The major elevation zone is 1–2 km at the Ili River basin to the north and the Taklamakan desert to the south, and 3–4 km high plateau in the middle of the central Tianshan Mountains. The major perennial snow/glaciers locate at areas with elevation higher than 4 km. Snow/glacier melt provides primary water sources to the Ili River, the Tarim River (in the desert), and other rivers around the region. Although there are continuous ground records of glacier extent and thickness at the Tianshan No. 1 glacier monitoring station in the east Tianshan Mountains (43°06′N, 86°49′E, outside the test area) since 1950s, little effort has been performed in the central Tianshan Mountain area mainly due to its inhospitable environment and inaccessible location (Li et al., 2004, 2008; Ye et al., 2005; Gao et al., 2005).

The advanced multi-day combination of MODIS Terra and Aqua snow cover products from September 2002 to August 2006 (MODMYD10MC) and multi-day composite of Terra MODIS from September 2000 to August 2002 (MOD10MC) were generated based on the method presented in Wang and Xie (submitted for publication) and were used for the study. *In situ* snow depth data (2001–2005) at 20 stations (red[1] dots in the inset map of Fig. 1) from the local meteorological agencies are used to validate the SCD, SCOD, and SCMD maps. Detailed description of the geographic feature of northern Xinjing and snow depth data from climate stations were documented by Wang et al. (2008) and Liang et al. (2008). The snow depth data were daily records with the nearest integer values of centimeter (cm).

Methodology

SCD and SCI

Using our cloud-low multi-day MODIS composite products (MODMYD10MC and MOD10MC), the SCD is calculated at a pixel scale (500 m) using all images within a hydrologic year from September 1 to next August 31 by

$$\mathrm{SCD} = \sum_{i=0}^{N}(D_{i2} - D_{i1}) \tag{1}$$

where N is the total number of available composite images within a hydrologic year; D_{i1} and D_{i2} are the beginning and ending-dates of each image composite, respectively. For instance, the first image composite for the hydrological year of 2003–3004 is mod03244-myd03245, which is a two-day composite from MODIS Terra and Aqua, i.e., D_{i1} = 244, D_{i2} = 245. If a pixel value on the image is equal to 200 (i.e., snow), the SCD value at this pixel for this image is 2. Otherwise, if the pixel value on the image is not equal to 200, the SCD value at this pixel for this image is 0.

The mean SCD map is the average of annual SCD maps in the period of study, i.e., 6 years in this test study. The SCD anomalies are the difference between the SCD value in a specific year and the mean SCD values at each pixel.

The SCI (unit: km^2 day) in a hydrologic year is defined as

[1] For interpretation of color in Figs. 1–8, the reader is referred to the web version of this article.

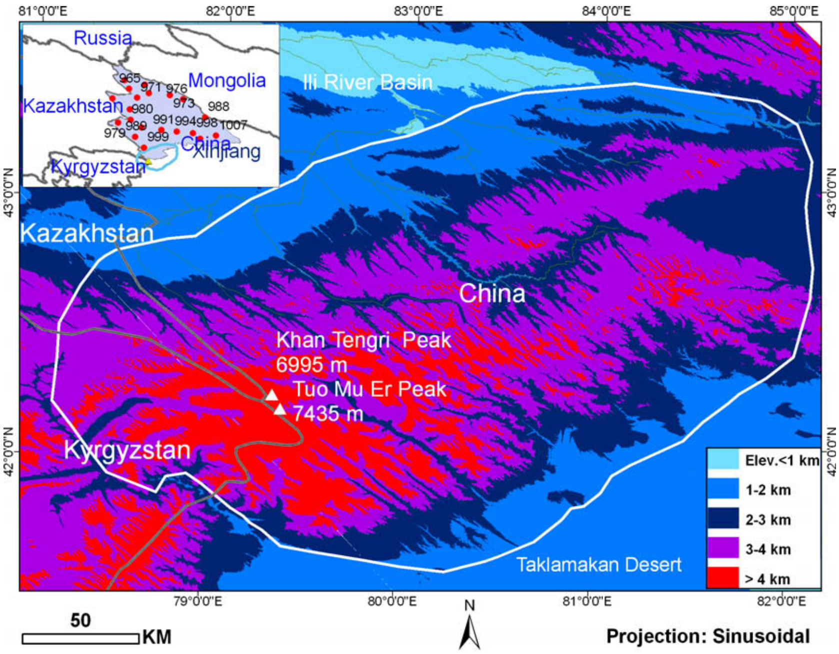

Fig. 1. Test area showing elevation distribution on central Tianshan Mountains. The white polygon corresponding to the cyan polygon of the inset map covered by two MODIS tiles h23v04 and h24v04. The shaded area on the inset map is the northern Xinjiang, China, with red dots (numbers) as locations (IDs) of climate stations used for the study. The Ili River basin is at the north foot of central Tianshan Mountains. The Taklamakan desert is in the south.

$$\mathrm{SCI} = \sum_{i=0}^{N} A \times \mathrm{SCD}_i \tag{2}$$

where A is the area of a pixel (in km^2; for MODIS, it is 0.25 km^2); SCD(i) is the value (days) of SCD at pixel i within a hydrologic year; N is the total pixel number on an image.

The SCD values are validated using *in situ* daily snow depth measurements at the 20 climate stations in the northern Xinjiang (Fig. 1) from 4 hydrological years (2001–2005). Ground measured SCD is the days when the snow depth is larger or equal to 1 cm, which includes all transient snow cover before and after the continuous winter snowpack. One MODIS pixel's (500 m) SCD value is extracted to compare with the collocated ground measurements since the influence of MODIS pixel's geolocation on the snow cover accuracy is limited (Zhou et al., 2005). Similarly, only one pixel's value of MODIS SCOD and SCMD is extracted to compare with ground snow depth measurements. Uncertainties caused by the single point ground measurements and areal MODIS pixel value must be concerned in the comparisons.

Agreement (%) between MODIS-derived SCD and ground calculated SCD is determined by

$$A = \left(1 - \frac{\left|\mathrm{SCD}_{\mathrm{mod}} - \mathrm{SCD}_{\mathrm{grnd}}\right|}{\mathrm{SCD}_{\mathrm{grnd}}}\right) \times 100 \tag{3}$$

where A is the agreement (%), $\mathrm{SCD}_{\mathrm{mod}}$ and $\mathrm{SCD}_{\mathrm{grnd}}$ are SCD in a hydrologic year for MODIS and ground, respectively. The mean agreement is the average A for all 20 stations in the 4 hydrologic years from 2001–2002 to 2004–2005.

SCOD and SCMD

Using MOD10MC and MODMYD10MC, an algorithm is developed to calculate the snow cover onset dates or melting dates displayed only on one map. In order to calculate the snow cover onset dates, the initial snow cover duration/days (SCD′) is first calculated for each pixel using Eq. (1) from September 1 to December 1 (total 92 days), when snow starts to cover this region. Then, the SCOD (Julian day) is calculated by

$$\mathrm{SCOD} = D - \mathrm{SCD}' \tag{4}$$

where the SCD′ is the snow-covered days within the period from September 1 to December 1 (the specific dates are depended on the specific image composite starting and ending date around the two dates). In this study, D is the Julian day of December 1 (D = 336 or 335) or other date, when this area is supposed to be covered by snow. In practice, the D value is flexible and depended on specific climate at a study area.

For example, if the SCD′ at a pixel is 91 days, the D is 336 (Julian day of December 2, 2003), and the SCOD of this pixel is on September 2 (245). If the SCD′ in a pixel is 62 days, then the SCOD of this pixel is October 1 (274), and so on. One assumption of this calculation is that snow does not melt away once it falls until the next spring. This is not always true since the possible transient snowfall events, which are melted away before the continuous snow cover period (based on *in situ* measurements), are still part of the total MODIS SCD′ during this snow cover onset dates' period (like from September 1 to December 1), thus resulting in an earlier SCOD (or a forward shift thereafter) as compared with the real starting date of the continuous winter snow cover period from *in situ* observations.

Similarly, in order to calculate SCMD, the SCD′ is first calculated from February 1 to May 1 (total 91 days like in 2004), when most snow melts away at this area. Then, SCMD (Julian day) is calculated by

$$\mathrm{SCMD} = D + \mathrm{SCD}' \tag{5}$$

where D is the beginning date of SCD′ and should be a constant (i.e., 32, February 1 in this case); SCD′ is the snow cover days within the period. Similarly with calculating SCOD, D here is also depended on the specific image composite starting date around February 1.

For example, if the SCD′ at a pixel is 2 days, the SCMD of this pixel is on February 3 (34). If the SCD′ at a pixel is 60 days, the SCMD of this pixel is on April 1 (92), like in 2004. Similarly, an assumption of this calculation is that the pixel will not be snow-covered again until the next fall once the (continuous) winter snow is melted away. This is not always true either because of the possible transient snowfall events after the continuous snow cover period (based on *in situ* measurements). Those transient snowfall events are included in the total MODIS SCD′ during the melting period (like from February 1 to May 1), thus leading to a later SCMD (or a backward shift thereafter) as compared with the real ending date of the continuous winter snow cover period from *in situ* observations.

Perennial snow/glacier cover

On the central Tianshan Mountains, August has the least cloud, highest air temperature, and the minimum snow in a year according to ground observations. Therefore, the 31 daily MODIS Terra and Aqua snow cover images in this month are combined to generate multiple cloud-free images (cloud ratio <5% at each image, mean cloud cover 2%) using the same algorithm presented by Wang and Xie (submitted for publication). Based on these cloud-free images, a minimum snow cover map in this month during each hydrological year is then generated. The least of six minimum snow cover maps is assumed to represent the maximum map of potential perennial snow cover or glacier distribution.

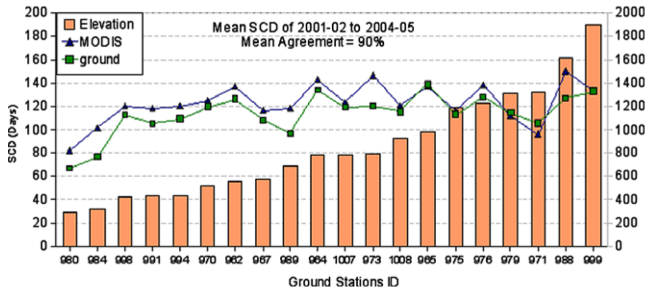

Fig. 2. Comparison of MODIS mean snow-covered duration/days (SCD) and *in situ* observations of mean SCD at 20 climate stations with elevation at ascending order from left to right (right *y*-axis, unit meter). The mean agreement is the average Agreements defined in Eq. (3) for all 20 stations in the 4 hydrologic year from 2001–2002 to 2004–2005.

Results and discussion

Snow-covered duration/days

Fig. 2 displays the validation results between MODIS-derived mean SCD and *in situ* measured mean SCD within 4 hydrologic years (2001–2002, 2002–2003, 2003–2004, and 2004–2005) at the 20 climatic stations in northern Xinjiang, China. Generally, MODIS-derived SCDs agree well (90%) with *in situ* SCD and are relatively higher than *in situ* SCDs, except for the slightly lower values at three stations (ID 979, 971, and 965). The average MODIS SCD at the 20 stations is 9 days more than the average *in situ* SCD, with exceptionally much higher values at the four stations (989, 984, 988 and 973) where the MODIS SCD is about 20 days more than *in situ* SCD. The overall higher MODIS SCD value is partly due to the multi-day composite algorithm that generates maximum days of snow cover during a composite period, resulting in more snow-covered days than the daily ground measurements within a year. Another contribution to this disagreement is the comparison between point ground measurements and areal observation (500 m × 500 m) of MODIS images. The third factor is the uncertainties caused by the cloud-blocked pixels, which are about 5% of a multi-day composite image and are ignored in calculating the SCD. In addition, other factors related to the MODIS standard daily snow cover classification, such as patchy snow, haze, dry bright sand, transition zones between snow and land, and between cloud-covered and cloud-free area, trees and forest, shaded areas by cloud, mountains, trees and buildings, and so on, also contribute to the SCD overestimation. It is also found that the agreement does not have obvious association with elevation (when elevation is less than 2000 m) although the relative agreements at the two lowest elevation locations (ID: 980 and 984) are lower than other locations at the higher elevations.

It should be realized, however, since the cloud-blocked pixels are not counted in the computation of SCD, this will also bring some uncertainties into the products. For example, the mean cloud cover at the composite images is ~5% in a year and the mean snow cover fraction is ~32% (Wang and Xie, submitted for publication; Wang et al., 2009), this would result in ~2% underestimation

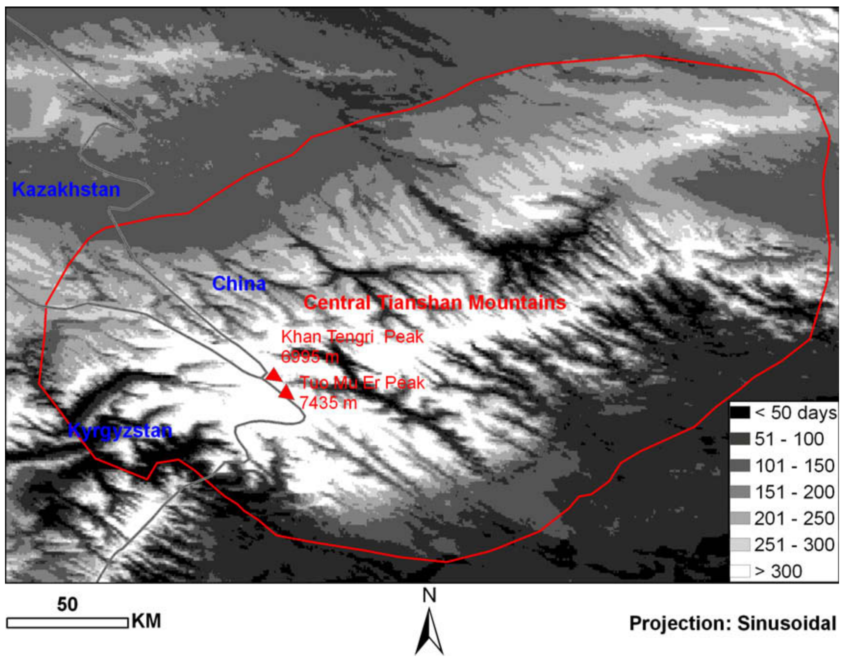

Fig. 3. Spatial distribution of mean snow-covered duration/days (SCD) of the 6 hydrologic years from 2000–2006 on the central Tianshan Mountains.

(uncertainties) of SCD. Meanwhile, the composite image is a maximum snow cover map during the composite period (mean 2.5 days), leading to an overestimation of SCD especially for the transient small snowfalls in the middle fall and late spring. The resultant effect of underestimation and overestimation of SCD could lead to reduced uncertainty or even cancel out each other.

Fig. 3 shows the mean SCD map within the 6 hydrologic years on the central Tianshan Mountains. The mean SCDs are grouped into seven classes on a 50-days interval basis (actual SCD stretches from a few days to 365 days at individual pixels). The mean SCD is larger than 50 days in most of the area. Only scattered pixels in the valley, forested areas and some desert areas have less than 50 days of snow cover duration. Compared to Fig. 1, the SCD map is closely associated with the elevation distribution. SCDs are generally less than 100 days as elevation is lower than 1 km at the bottom of Ili River basin and in part of the desert with elevation of 1–2 km. Dominant areas, however, have SCD from 101–150 days, corresponding to the 1–2 km and part of 2–3 km elevation areas. Part of the 2–3 km elevation areas has SCD of 151–250 days. When elevations are from 3 to 4 km, SCD spans from 200–300 days. At the top of the mountains as elevations are higher than 4 km, SCD is generally larger than 300 days. As the challenge in demanding snow cover maps of high temporal and spatial resolution is concerned, MODIS provides unprecedented snow cover maps and now SCD maps for various applications.

SCD and SCI variation

Fig. 4 displays the spatial distribution of annual SCD difference against the mean SCD of the 6 hydrologic years and the minimum snow cover (or perennial snow hereafter) in August. The differences of SCD in each year have also been grouped into seven categories, i.e., <−60 days, −60 to −31 days, −30 to −11 days, −10 to 10 days (assumed as no change), 11–30 days, 31–60 days, and >60

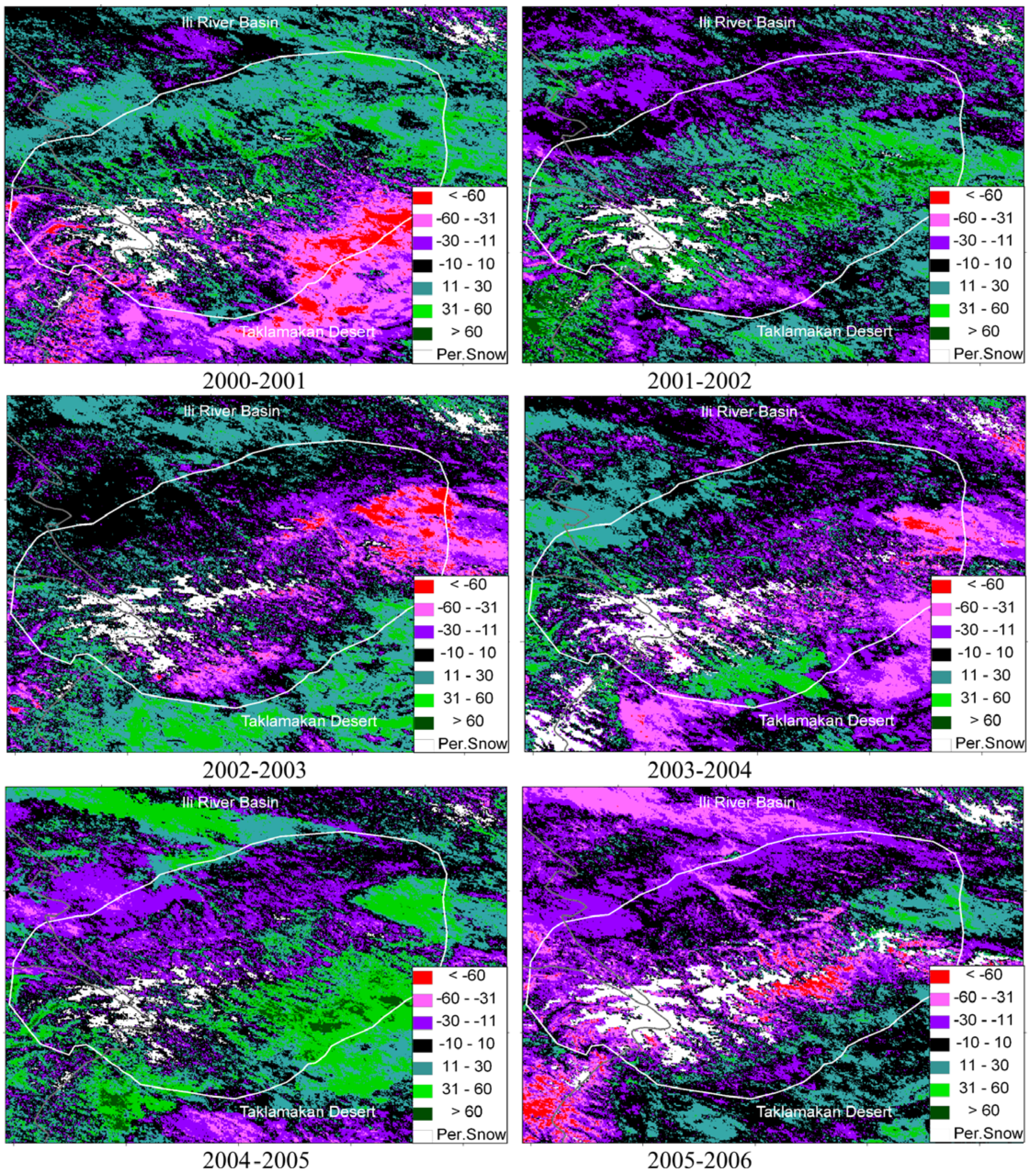

Fig. 4. Spatial distribution of SCD difference map in each hydrological year on the central Tianshan Mountains. The mean SCD map of the 6 years was used as a basis. The white area represents the minimum snow cover or perennial snow in August of each year.

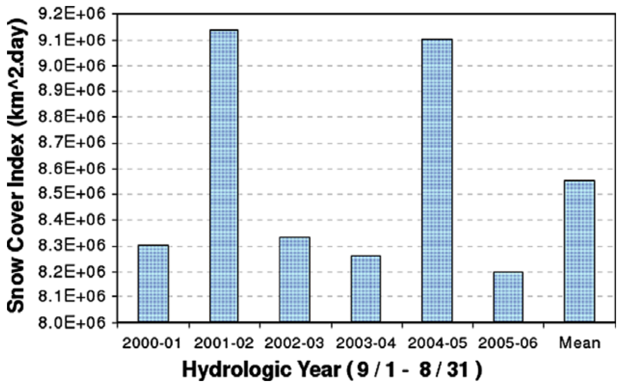

Fig. 5. Variation of snow cover index (SCI) on the central Tianshan Mountains within the 6 hydrologic years from 2000 to 2006.

days. One obvious feature of the six maps is that there is no obvious change on the top of the mountains surrounding the peak areas or the perennial snow cover. Compared to the mean SCD of the 6 hydrologic years, the SCD in the 2001–2002 and 2004–2005 hydrological years had overall higher values than the mean. In contrast, both 2003–2004 and 2005–2006 years had lower values than the mean in most of the areas, especially in 2005–2006 year.

Fig. 5 shows the quantitative variation of overall snow cover conditions as indicated by the SCI on the central Tianshan Mountains. It has a similar pattern with Fig. 4 that 2001–2002 and 2004–2005 have overall higher SCD values than the mean SCD of the 6 years, resulting much higher SCI in the 2 years than in other years. The 2 years in 2003–2004 and 2005–2006 have overall lower SCD than the mean SCD in Fig. 4, leading to lower SCIs in the 2 years than in the other years. SCI in this short period (2001–2006) does not show any obvious trend. The longer records of snow cover products using NOAA's AVHRR data may provide a better change trend of snow cover in the recent 30 years. The continuing MODIS-type snow cover data is also critical to monitor the change trend of the snow cover conditions at this region and other regions of the world.

Snow cover onset and melting dates

Fig. 6 shows two examples of comparison between *in situ* snow depth measurements and MODIS-derived SCOD and SCMD at two climate stations of different elevations at the Ili River basin, the north foot of central Tianshan Mountains (Fig. 1). At the station Yining (ID: 989) with lower elevation of 660 m (bottom panel of the Fig. 6), the MODIS-derived SCOD and SCMD generally match well with the *in situ* observations of continuous snow-covered duration, i.e., the snow cover onset date and the snow cover melting date, with a few exceptions. For example, the early transient snowfall in October, 2004 melted away after it fell, resulting in 1 week forward shift of SCOD (as compared with the starting date of the continuous snow cover period based on daily *in situ* measurements). The spring transient snowfall events led to backward shift of SCMD (as compared with the ending date of the continuous snow cover period based on *in situ* measurements), like in 2004 and 2005. At the station Zhaosu (ID: 999) of higher elevation (1890 m) (top panel of Fig. 6), there were more early transient snowfall events that melted away after falling, resulting in a longer forward shift (fall 2001 and fall 2004) of SCOD than that in the lower elevation station Yining. The early transient snowfall events also occur in both 2002 and 2003, but the forward shifts of SCOD were very short. The backward shift of SCMD at the Zhaosu station is rather very short as compared with that in the spring 2004 and spring 2005 at the Yining station.

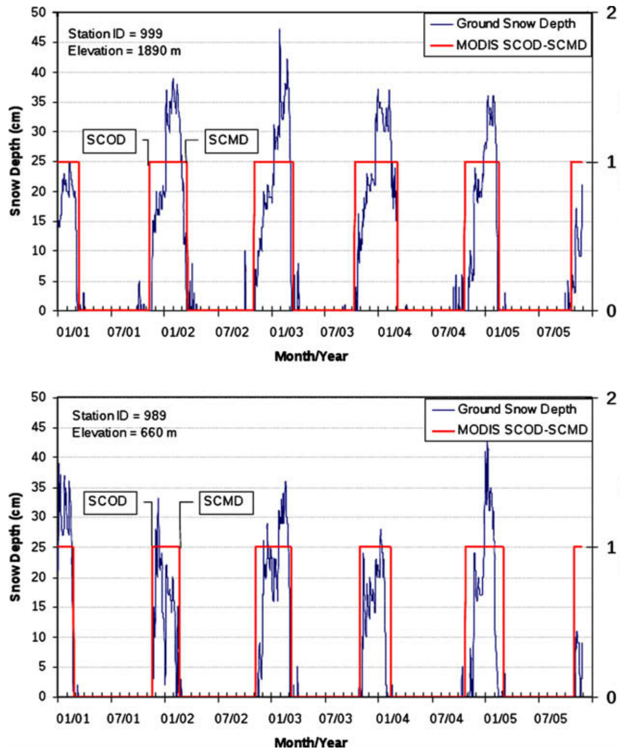

Fig. 6. Examples of *in situ* snow depth-defined snow cover onset days and melting days (continuous period of snow cover) as compared with MODIS-derived SCOD and SCMD at two stations at the Ili River basin on the northwest of central Tianshan Mountains. *In situ* snow depth data are daily observations with minimum record of 1 cm.

Overall, MODIS-derived SCOD and SCMD have good agreement with the continuous snow-covered duration of *in situ* observations. At the 20 stations within the 5 years, the early Fall transient snowfall events led to forward shift of SCOD by a mean value of 6 days, and the late spring transient snowfall events resulted in backward shift of SCMD by a mean value of 7 days. The overestimation of multi-day maximum snow cover composite may also contribute to the forward and backward shifts. As pointed out by Brown et al. (2007) that the transient snowfall events in the early fall and in the late spring usually cause the multiple starting-dates and ending-dates of snow cover at cold regions. The MODIS-derived SCOD and SCMD maps are needed contribution to and critical information for snow cover duration on the mountainous areas since they contain information of both continuous snow cover duration and transient snowfall events in, which (the latter) lead to the forward shift of SCOD and backward shift of SCMD as being referenced to the ground-observed continuous snowpack period. The mean shift values (6 days for SCOD and 7 days for SCMD) for all 20 stations in the 4 years are not excluded in the SCOD and SCMD maps in Figs. 7 and 8, but could be applied (add and subtract) in the SCOD and SCMD to obtain a better/realistic SCOD and SCMD maps.

Fig. 7 shows the spatial distribution of SCOD on the central Tianshan Mountains in the fall of 6 years and the perennial snow cover. The SCOD values are categorized into seven classes: before (<) September 15 (or O1), September 16–30 (O2), October 1–15 (O3), October 16–31 (O4), November 1–15 (O5), November 16–30 (O6), and after (>) December 1 (O7). One common feature is that SCOD on the top of the mountain (elevation >4 km) always begins in early September (O1) or it is always covered by perennial snow. Another feature is that SCOD in the south desert, mostly in O7 followed by O6, is much later than other areas. The Ili River basin has SCOD mostly in O6, led by O5 and followed by O7. In the fall 2005, however, the O7 is the dominant SCOD in the Ili River basin. Among the 6

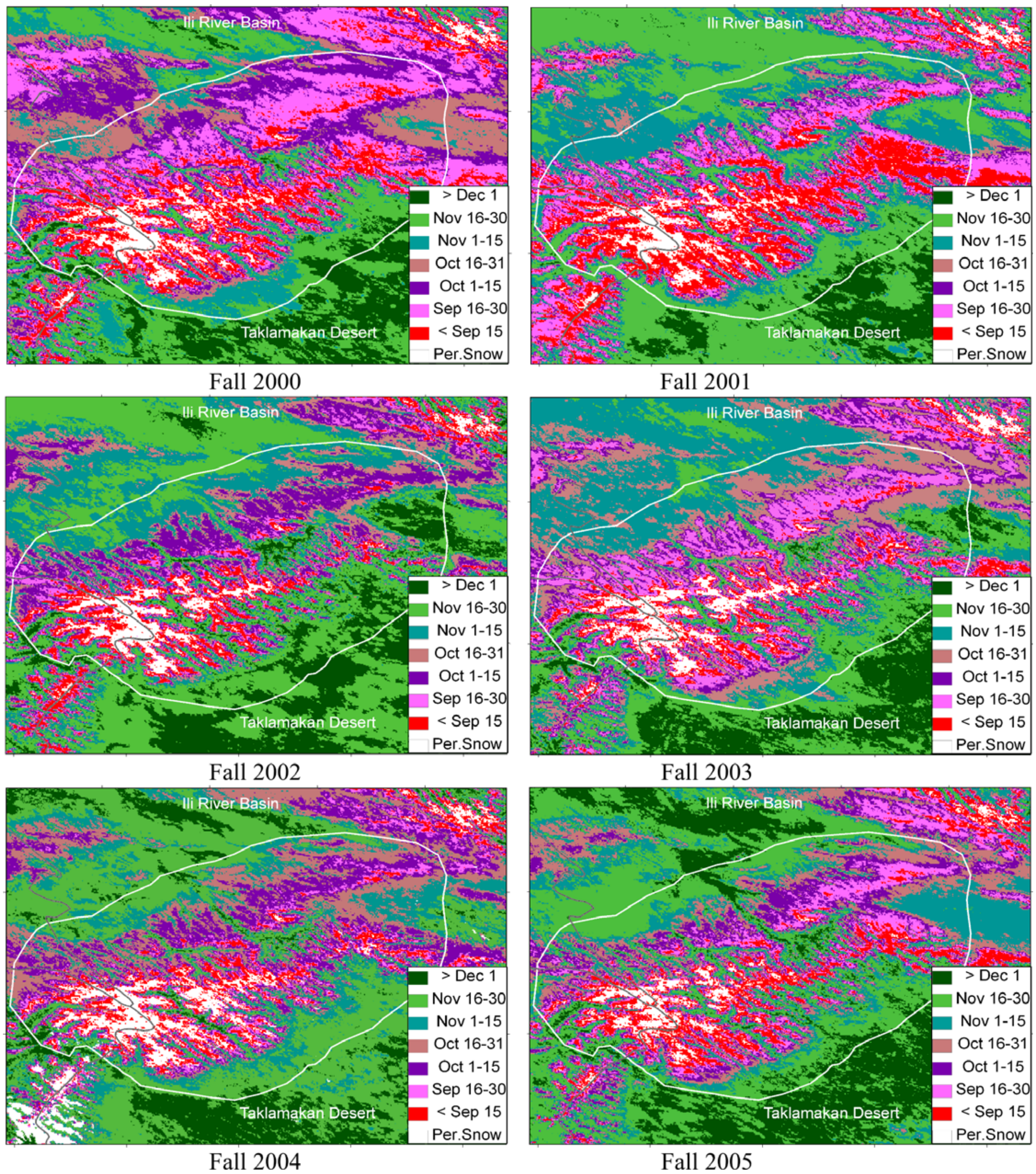

Fig. 7. Spatial distribution of snow cover onset dates (SCOD) maps on the central Tianshan Mountains in the six fall seasons. The white area represents the minimum snow cover or perennial snow in August of each year.

years, the fall 2000 is a typical season with early snow cover at most areas, while fall 2002 and fall 2005 have the late SCODs.

Fig. 8 shows spatial distribution of SCMD on the central Tianshan Mountains in the spring of the 6 hydrologic years and the perennial snow. Similar as SCOD, the SCMD values are also categorized into seven classes: after (>) May 1 (or M1), April 16–30 (M2), April 1–15 (M3), March 16–31 (M4), March 1–15 (M5), February 16–28 or 29 (M6), and before (<) February 15 (M7). At the higher elevation areas (>3 km), SCMD is later than May 1 (or M1), or some of them do not melt at all as covered by perennial snow or glacier. Although the spatial distributions of SCMD vary year by year, their general patterns are similar except for the south desert, obvious early melting in spring 2001 and late melting of 2003 and 2005 springs. Was the early melting of snow cover at the south side of Tianshan Mountains in the spring of 2001 related to the desert sand storm activities? Further studies are needed to examine impacts of dust soil disturbance from the desert on the variation of SCD and especially on the SCMD over the Tainshan Mountains as being indicated in the San Juan Mountains (Painter et al., 2007), but are beyond the subject of this study.

While Figs. 3–5, respectively, give the general spatial distribution of the mean SCD, the overall spatial distribution of SCD changes of each year and the overall snow cover conditions (SCI) in each year, Figs. 7 and 8 provide the spatial distribution of the specific dates when the snow cover begins and when the snow cover melts away at the scale of one pixel (500 m), respectively. Therefore, Figs. 3–5, 7 and 8 together provide important information on the snow cover conditions in the study area and could be applied to any other region of interest in a period of time.

Perennial snow

The spatial distribution of perennial snow is illustrated in Figs. 4, 7 and 8. The perennial snow cover had similar spatial distribution pattern on the top of the high-elevation (>4 km) mountains in spite of yearly variation. The perennial snow cover in each year

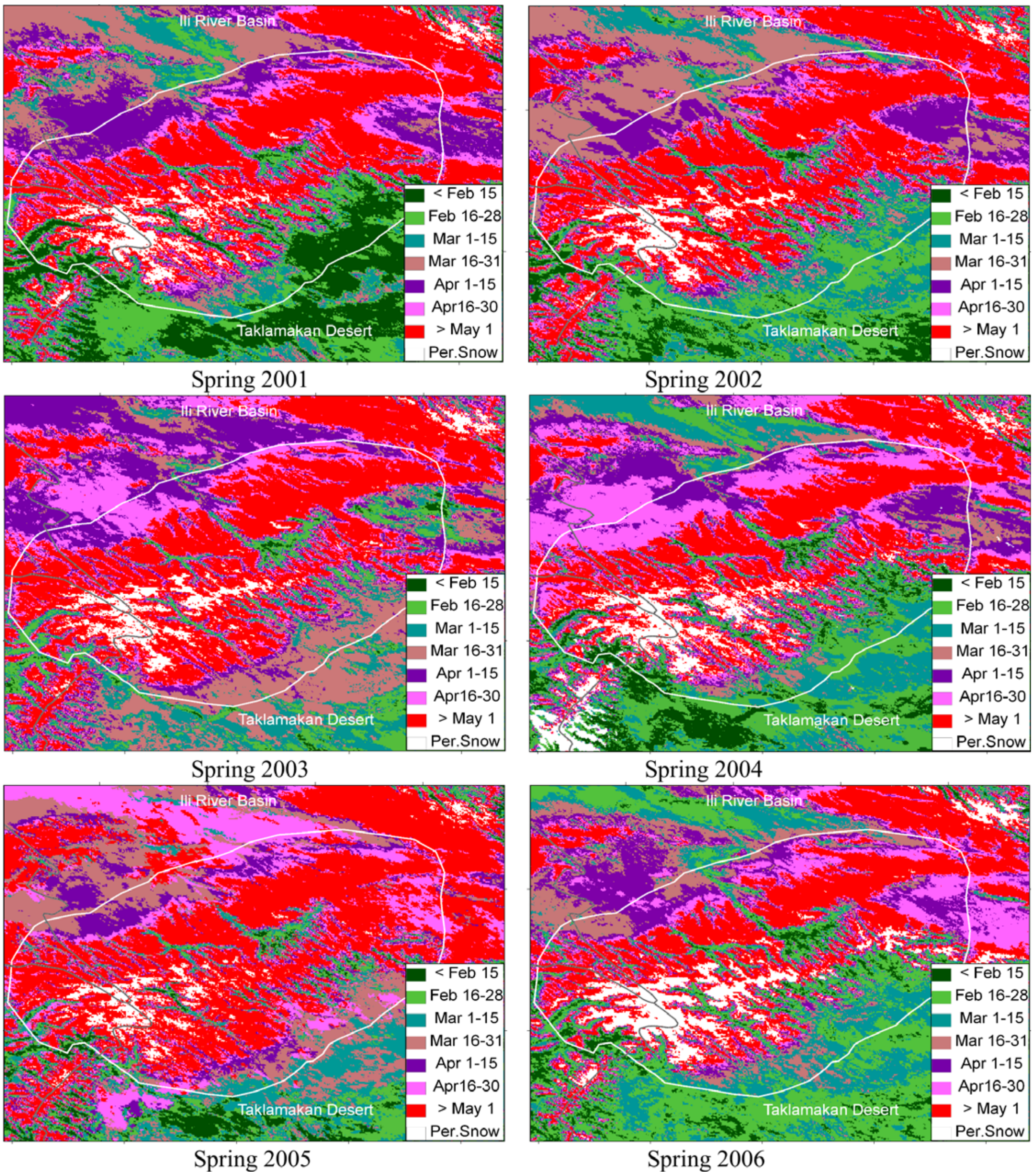

Fig. 8. Spatial distribution of snow cover melting dates (SCMD) maps on the central Tianshan Mountains in the six spring seasons. The white area represents the minimum snow cover or perennial snow in August of each year.

did not vary at the same trend with the overall snow cover duration. For example, in Fig. 4, although 2003–2004 and 2005–2006 has overall lower SCD and SCI, their perennial snow cover shown in August of 2004 and 2006 has larger areas than other years, especially in the August of 2004 when a relatively large area of perennial snow cover appeared at the southwestern corner of the map. The 2004–2005 had overall higher SCD and SCI, but its perennial snow cover shown in the August of 2005 had the least extent in the 6 hydrologic years. This least snow cover extent is assumed to represent the maximum glacier distribution since it is not possible to distinguish perennial snow cover from glacier using the MODIS snow cover products. The perennial snow/glacier cover mainly distributes on the top of the mountains with elevation >4 km and has a spatial extent ~2380 km^2 according to the least perennial snow cover map in the August of 2005. However, we must cautiously state that these regions are likely covered with perennial snow cover or glacial. Uncertainty from cloud cover is one factor. The coarse spatial resolution (500 m) of MODIS image is another one because of the complex topography on these high elevation mountainous areas. The size (extent) of many glacial and perennial snow cover on the top of the mountains is less than 500 m. Higher resolution image, like Landsat image (30 m), are required to accurately quantify them at these situations (Li et al., 2004). Further study will examine the glacier coverage and its elevation (volume) change through integrating accurate laser elevation measurements (i.e., ICESat).

Summary and conclusion remarks

Applying the advanced cloud-low snow cover combination images of MODIS Terra and Aqua, this study develops new methods to examine the spatiotemporal variations of snow cover for any region of interest. The central Tianshan Mountains and northern Xinjing, China are used as a test bed to illustrate the development and validations of the new maps in the 6 hydrological years (2000–2006).

MODIS-derived snow cover duration/days (SCD) map (one per hydrological year) shows a good agreement of 90% with the *in situ* observed snow cover days, and the average MODIS SCD at the 20 stations within the 4 hydrologic years is 9 days higher than the *in situ* SCD. Compared to the mean SCD map in the 6 hydrologic years, the difference map of SCD between a specific year and the mean values of the 6 years illustrates the spatiotemporal variation of snow cover duration in each year.

This study proposes, for the first time, a new snow cover index (SCI) based on MODIS data to quantify the overall snow cover conditions for a region within a hydrologic year. The SCI value (km^2 day), one single number per year, contains both snow cover duration and extent and is ideally used to examine the inter-seasonal or annual variation of snow cover situation. Both the SCD difference maps and SCI values show that, in the test area, the 2001–2002 hydrologic year had the most snow cover while 2005–2006 year had the least, of the 6 years.

Beside the SCI, this study also develops algorithms to calculate snow cover onset dates (SCOD) map and snow cover melting dates (SCMD) map, one each per hydrological year. Generally, MODIS-derived SCOD and SCMD have a good agreement with the continuous snow-covered duration from *in situ* observations by 1 week forward and 1 week backward shift because of transient snowfall events in the early fall and in the late spring, respectively. While the SCD map gives the overall spatial distribution of snow cover duration, the SCOD and SCMD maps provide the spatial distribution of the specific dates when the snow cover starts and when the snow cover melts away at the pixel scale of 500 m.

In addition, this study also uses the advanced cloud-low snow cover combination images in August, when there is the least cloud cover, highest air temperature, and minimum seasonal snow cover in a year, to map the spatial distribution of potential perennial snow/glacier. The minimum snow cover in August, 2005 is found to be the least extent in the 6 hydrologic years and is thus assumed to represent the potential perennial snow/glacier cover, which mainly distributes on the top of the mountains with elevation >4 km and has an extent of 2380 km^2. More accurate map of glacier distribution can be obtained using Landsat or other higher resolution images.

Together, SCD, SCI, SCOD and SCMD provide important information on the snow cover conditions for any region of interests in a period of time. This information could potentially be critical for local government, such as land use planning, agriculture, live stock, and water resource management, for example, to mitigate snow-caused disasters and to plan for agriculture and industry water use for coming spring and summer seasons. Long term availability of MODIS type of snow cover data for producing such datasets is key to study the connection between snow cover change and global climate change. For example, possible applications of these data are to study the relation between SCI and annual (hydrologic year) mean temperature change, to study the relation between SCI and El Nino-Southern Oscillation (ENSO), and to examine the time series change of annual mean SCD, SCOD and SCMD for a region. Additional questions can also be addressed through the type of data presented. Does global warming reduce the mean snow cover days for a region? Does global warming have potential to forward shift or backward shift the mean snow cover onset date and/or mean snow cover melting date? How does the spring sand-storm or dust soil from the south desert impact the melting of snow cover for the Tianshan Mountain region?

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