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Evaluation of MODIS snow cover and cloud mask and its application in Northern Xinjiang, China

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Abstract

Using five-year (2001–2005) ground-observed snow depth and cloud cover data at 20 climatic stations in Northern Xinjiang, China, this study: 1) evaluates the accuracy of the 8-day snow cover product (MOD10A2) from the Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra satellite, 2) generates a new snow cover time series by separating the MODIS cloud masked pixels as snow and land, and 3) examines the temporal variability of snow area extent (SAE) and correlations of air temperature and elevation with SAE. Results show that, under clear sky conditions, the MOD10A2 has high accuracies when mapping snow (94%) and land (99%) at snow depth ≥ 4 cm, but a very low accuracy ($<39\%$) for patchy snow or thin snow depth (<4 cm). Most of the patchy snow is misclassified as land. The mean accuracy of the cloud mask used in MOD10A2 for December, January and February is very low (19%). Based on the ratio of snow to land of ground observations in each month, the new snow cover time series generated in this study provides a better representation of actual snow cover for the study area. The SAE (%) time series exhibits similar patterns during six hydrologic years (2001–2006), even though the accumulation and melt periods do not exactly coincide. The variation of SAE is negatively associated with air temperature over the range of −10 °C to 5 °C. An increase in elevation generally results in longer periods of snow cover, but the influence of elevation on SAE decreases as elevation exceeds 4 km in the Ili River Watershed (IRW). The number of days with snow cover shows either a decreasing trend or no trend in the IRW and the entire study area in the study period. This result is inconsistent with a reported increasing trend based on limited *in situ* observations. Long-term continuance of the MODIS snow cover product is critical to resolve this dilemma because the *in situ* observations appear to undersample the region.

Keywords: Northern Xinjiang; China; MODIS; Cloud; Snow; Validation

1. Introduction

Snow is an appreciable fraction of soil water recharge in the middle and high latitude areas, representing an important source of moisture for agricultural crops (Che & Li, 2005). Snow cover area and snow depth estimation are extremely important for regional climate change studies and water source management (Rodell & Houser, 2004; Tekeli et al., 2005). Due to high albedo, snow cover directly affects the land surface temperature by reflecting incoming short wave solar radiation. The presence of snow cover also influences air and soil moisture, watershed hydrology, and surface energy budgets (Kongoli & Bland, 2000). The insulative properties of deep snow cover prevents soil freezing and reduces the negative effects of freezing air temperature on the over-winter survival of certain crops (Flerchinger et al., 1992). Decreased hydraulic conductivity in frozen soil increases the potential for rapid snowmelt-runoff and flash flooding, while freezing injury causes crop yield loss (Kanneganti et al., 1998). Accumulation of thick snow cover on ranch land in winter and spring typically results in a great number of animal deaths due to a shortage of grazing foliage, e.g., in Northern Xinjiang, China; thick snow cover is a very common type of disaster in pastoral areas and often causes large economic losses (Liu et al., 2003; Zhou et al., 2000, 2001). Therefore, effectively monitoring snow cover and snow depth is an essential component of properly managing agricultural and water resources of a region. In some cases, an early warning of a potential snow related disaster will allow an appropriate response to mitigate damage.

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Traditional *in situ* measurements at different climatic stations provide good snow depth observations in a limited area and are critical ground control for validating remotely sensed estimations of snow cover and snow depth. Because of extreme environmental conditions, ground measurements of snow over the world are very limited, thus it is difficult to capture the spatial variability of snow area extent (SAE) and total snow accumulations. Airborne measurements provide short duration and local scale data for limited campaign-style experiments, like the Cold Land Processes Experiment (CLPX) (Cline et al., 2001). Satellite-based remote sensing snow measurements have revolutionized the monitoring of spatial and temporal distribution and variability of SAE and snow depth in complex natural conditions at regional and global scales, such as those derived from the Interactive Multisensor Snow and Ice Mapping System (IMS), Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Scanning Radiometer–EOS (AMSR-E), Geostationary Observational Environmental Satellite (GOES), Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and Landsat.(Hall et al., 2000). Historical records of remotely sensed hemispherical snow cover maps date back to 1966, as generated by the US National Ocean and Atmospheric Administration (NOAA) (Klein & Barnett, 2003). Microwave remote sensing products, like SMMR, SSM/I, and AMSR-E, are used for global scale studies because of their high temporal resolution (daily) and without the influence of cloud cover despite of low spatial resolution (25 km or coarser). Products derived from optical instruments using reflected solar radiation, such as AVHRR, MODIS, and Landsat, etc., have higher spatial resolution and are better for regional studies, but heavily depend on suitable weather conditions, especially clear sky (no clouds). The high cost and low temporal resolution (16 days) of Landsat data are an obstacle to its wide application in monitoring snow, even though it has much higher spatial resolution (30 m) than MODIS and AVHRR.

Carried aboard the Terra spacecraft launched on December 18, 1999, MODIS snow products became available on February 24, 2000. MODIS snow products are produced as a series, beginning as a swath (scene) product at a nominal pixel spatial resolution of 500 m with nominal swath coverage of 2330 km by 2030 km. The multiple swath observations at 500 m resolution of snow cover (MOD10_L2) are then projected onto a sinusoidal gridded tile (1200 km × 1200 km) of MOD10L2G, which is further processed as a sinusoidal 500 m grid of daily (MOD10A1) and 8-day (MOD10A2) composite tile (1200 km × 1200 km) products, a 0.05° global Climate Modeling Grid (CMG) daily product (MOD10C1), an 8-day product (MOD10C2), and a monthly product (MOD10CM) (Hall et al., 2002; Riggs et al., 2006).

In addition to the summary of MODIS snow cover products by Riggs et al. (2006) and Hall and Riggs (2007), the accuracies and problems of the MODIS snow products have also been identified by other independent validations (Ault et al., 2006; Klein & Barnett, 2003; Tekeli et al., 2005; Zhou et al., 2005). In a validation of the MODIS swath snow product (MOD10_L2) and cloud mask in the Lower Great Lakes Regions, Ault et al. (2006) found that MOD10_L2 has very high accuracy under clear sky; highest errors occur for trace snow (as snow depth <1 cm); and the accuracy increases as snow depth increases. The problem of creating an accurate snow map in cases of thin or patchy snow has also been discussed in a study performed on New England snow cover (Hall et al., 2000). In a study in the eastern part of Turkey, Tekeli et al. (2005) found that the worst match between ground observations and MODIS snow cover maps was only 21% when the sky was cloud-covered on March 24, 2004. The high frequency of cloud cover seriously impairs the accuracy of MOD10A1. In a study at the Upper Rio Grande River Basin during the 2000–2001 snow year, Klein and Barnett (2003) identified that MOD10A1 has very high overall agreement (94%) with *in situ* Snowpack Telemery (SNOTEL) observations under clear skies (defined by $>50\%$ cloud-free MODIS pixels within 1500 m radius, 6×6 pixel patch, centered at the SNOTEL stations). Most of the disagreement between MOD10A1 and SNOTEL observations occurred at the beginning and end of the snow season when thin snowpack conditions were prevalent. The high agreement between MOD10A1 and SNOTEL observation was limited to clear skies (only about half of the data set during October 13 2000 to March 30 2001). In addition, the MODIS cloud mask appears to frequently map edges of snow covered areas as cloud, which is likely due to lower fraction of snow (patchy snow) or thin snow depth, and thus the cloud mask requires improvement in these transition zones (Klein & Barnett, 2003; Riggs et al., 2006; Tekeli et al., 2005). The new fractional snow cover contained in the new MOD10A1 and MOD10A2 (V005) will be likely a better representation of these transition zones (Salomonson & Appel, 2004). Compared with the snow product of National Weather Service National Operational Hydrologic Remote Sensing Center (NOHRSC), MODIS classified fewer pixels as cloud than NOHRSC and significantly greater amounts of snow in the presence of clouds for topographically complex, forested, and snow-dominated areas (Klein & Barnett, 2003; Maurer et al., 2003). At the same basin studied by Klein and Barnett (2003), Zhou et al. (2005) also identified clouds as a major cause affecting the accuracy of MODIS snow classification. The MOD10A2 product has higher classification accuracy for both snow and land than MOD10A1 through cloud suppression, and the MODIS 8-day product minimizes cloud cover and maximizes snow cover, thereby providing better input for snowmelt-runoff models. Thus, the MOD10A2 product was selected for this study.

The Northern Xinjiang Uygur Autonomous Region is one of three major snow distribution regions in China (Che and Li, 2005; Huang & Cui, 2006). Snow-related disasters frequently occur on a large scale in winter and spring, resulting in a large number of animal deaths and significant economic loss (Liu et al., 2003). The frequent occurrences of drifting snow banks severely limit overland transportation and disrupt normal operations in the Yining area of the region (Gao et al., 2005a). Several studies related to snow accumulation have been carried out in the region and were primarily based on weather station observations, which were limited on both spatial coverage and number of

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observations. For example, the study by Li (2001) using 46 ground stations showed that snow accumulation slowly increases over the recent half century from 1951 to 1997 in the entire Xinjiang, and that the increase of snow and winter precipitation follows a consistent pattern with Gao et al. (2005b) for the period of 1967–2000 and Cui et al. (2005), whose study also found that snow depth in the mountainous areas is 3 to 11 times greater than in the plains. The frequency of snow storms has increased since the 1980s, particularly since the 1990s, and an extraordinary snow storm in the 2000–2001 hydrologic year caused significant economic losses in the region (Yang et al., 2005).

Overall, these limited ground observations revealed some temporal and minor spatial variations related to snowfall in the region over the last 50 years. However, all of the climatic stations are present in readily accessible and low elevation areas and may present some locational bias. The spatial variation of snow in mountainous and remote areas of the region may not be accurately represented in the data sets. Due to accessibility limitations, it is difficult, if not impossible, to accurately estimate the total snow accumulation, snow cover extent and snow depletion curve for the entire region based on those ground observations. As a companion paper to this study, supported by a Chinese National Science Foundation grant, Liang et al. (in press) mainly evaluated the accuracy of the MOD10A1 snow cover product for the region and developed an algorithm to generate user-defined multiple-day composite images based on MOD10A1.

The purpose of this study is to assess the temporal and spatial variation of snow cover in the entire Northern Xinjiang using readily available MOD10A2 product. Initially, the ground snow observations were used to evaluate the MOD10A2 snow cover and cloud mask; then the effects of cloud cover and snow depth on the accuracy of MODIS snow classification were explored. Subsequently, an algorithm was developed to separate the MODIS cloud-masked pixel as snow or land, resulting in a new snow cover time series. Finally, the new snow cover time series was used to study the spatial and temporal variation of snow cover, the relationship between snow cover and air temperature, and the effect of elevation on snow cover.

2. Study area

Xinjing Uygur Autonomous Region is separated into north and south portions by the Tianshan Mountains. Precipitation varies significantly between the north and south portions of the region with mean annual precipitation of 255 mm in the north and 106 mm in the south. The north portion of the region or Northern Xinjiang is the study area of the paper and has a relatively rich seasonal snow water source due to winter circulation around the Siberian High and southern mountain blockage. Over half of precipitation in the study area falls as snow in the cold season (November to April), and over 84% of precipitation concentrates in the mountains, resulting in great differences in water source distribution between mountains and plains (Cui et al., 2005). The annual mean duration of snow cover in the study area is about 130 days per year, generally from the middle of November through March (Average Weather Data for Cities in China, 1997). The study area is an important grazing resource, where livestock is an integral part of the social and economic system. Due to special geographic features, limited weather information, and great spatio-temporal variation of snowfalls in the region, large scale snow-related disasters frequently occur in winter and spring seasons (Liu et al., 2003).

The Northern Xinjiang includes 47 counties, with a total area of 0.39 million km^2 (Fig. 1). The area consists of two large mountain ranges, the Tianshan Mountains to the south and the Altai Mountains to the north, with the Zhunge'er Basin (desert) in between. The area can be separated into six watersheds: Ili River Watershed (IRW), Aibi Lake watershed, Zhunge'er Basin watershed, E'ming River (Tacheng) watershed, Wulungu River watershed and E'erqisi River watershed. The complex topography, various land types, and varying climate regimes cause significant differences in the extent of snow cover and snow accumulation in different sub-regions or watershed basins. Among these sub-regions, the IRW basin is surrounded on three sides by the Tianshan Mountains, and the outlet of the Ili River is west to the Republic of Kazakhstan. The elevation in the IRW changes dramatically from several hundred meters to over six thousand meters. The Ili River is the biggest river in the entire Xinjiang, and snow melt from the Tianshan Mountains is the major water source for the river. The snow amount in the mountains and melting rate control the stream water level. The snowpack is the primary available water source in spring and early summer for the region. This suggests that the IRW is an ideal watershed to study the process of snow accumulation and melt. However, as an international river in a semiarid region, water right issues are complicated and have resulted in limited access to stream gauge flow data, thus limiting possibilities for further study.

3. Data source and pre-processing

3.1. MODIS snow cover

The MODIS snow cover algorithm is based on the high reflectance of snow in the visible band (band 4, 0.545–0.565 μm) and low reflectance in the near infrared band (band 6, 1.628–1.652 μm). These two bands are used to calculate the normalized difference snow index (NDSI) (Hall et al., 1995). Besides a mask for dense forest stands, three other masks are used; namely a thermal mask, cloud mask, ocean and inland water mask. These masks have been incorporated in the snow cover algorithm to get the best estimation of snow. The detailed algorithm and processing steps have been documented in several sources (Hall et al., 2002; Riggs et al., 2006).

To cover study area, two MODIS tiles h23v04 and h24v04 are needed. The MOD10A2(V004) data from February 2000 through April 2006 were ordered through the Earth Observing System (EOS) data gateway. The 8-day maximum SAE (500 m pixel size) product was used in this study. We developed several scripts to automatically retrieve information (snow cover, land, cloud, etc.) from time series MODIS images:

- mosaic the two tiles as one image using MODIS Reprojection Tool (MRT) tools in Linux;

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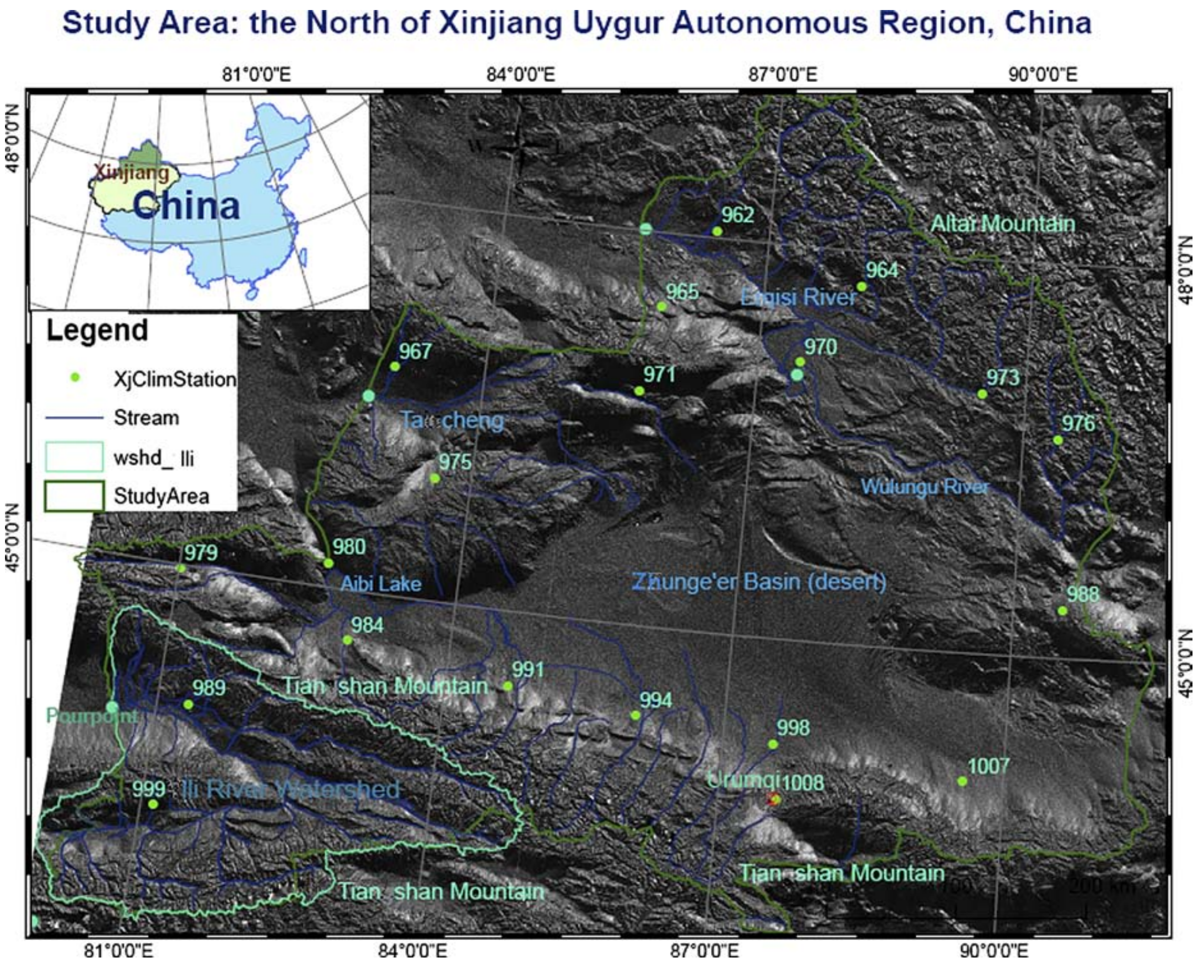

Fig. 1. Study area (green outline) of the Northern Xinjiang Uygur Autonomous Region (green region of the inset), China; cyan outline of lower left corner is the Ili River watershed; green dots are climatology stations with station ID associated; blue line stream flow network derived from 90 m SRTM DEM available at http://seamless.usgs.gov/Website/Seamless/. Background image is the hillshaded DEM (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

- converting the MODIS Hierarchical Data Format (HDF) files to GeoTiff files with WGS84 Datum and UTM projection (UTM zone 45) using MRT tools in Linux;
- converting the GeoTiff files into GIS grid format in ArcInfo;
- clipping to a sub-grid of the study area and outputting the value attribute table (VAT) of each sub-grid into a text file for further analysis;
- extracting the coded pixel value where the climate stations are located, and outputting them into another text file for comparison with ground observations.

As suggested by Zhou et al. (2005), the mismatching effect, if any, between *in situ* stations and MODIS pixels did not cause obvious differences in validation accuracy, so the value of one MODIS pixel co-located with an *in situ* station was retrieved for comparison.

3.2. *In situ measurements*

There are 20 climate stations operated by a local Meteorological Bureau in the study area. The snow depth was recorded to the nearest 1 cm, with intermediate values rounded up or down as appropriate, and reported in integer form. The *in situ* measurements of snow depth from January 2001 through December 2005 were used to evaluate the MODIS snow cover product. Because the 8-day maximum SAE from MOD10A2 product was used in this study, the daily *in situ* measurements were also processed as the maximum snow depth of the same 8-day period, while the air temperatures were processed as the average of the same 8-day period.

Cloud cover observations from the *in situ* stations were recorded four times per day at 2:00, 8:00, 14:00 and 20:00 (Beijing time) with integers from 0 to 11 as follows: clear sky (0), scatter sky (1–4), broken sky (5–8), and overcast sky (9–11). The cloud cover data were only available in January, February and December during 2001 to 2005. These ground-based cloud observation data were used to evaluate the MODIS cloud mask used in MOD10A2 and its effect on MODIS SAE accuracy. Since the Terra satellite passes locally at ~10:30 (12:30 Beijing time), the cloud value at 14:00, about one and a half hours later than the Terra satellite overpass, was used for the study. It should be noted that the time discrepancy of cloud cover observation could produce some uncertainty in the comparison, but it is the best available data for the study. In the 8-day

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maximum SAE product, the corresponding MODIS cloud mask represents the 8-day minimum cloud cover. Therefore, ground observations of cloud cover were also processed as the minimum value of the same 8-day period.

3.3. Elevation

The Shuttle Radar Topography Mission (SRTM) is an international project led by the U.S. National Geospatial-Intelligence Agency (NGA), U.S. National Aeronautics and Space Administration (NASA), the Italian Space Agency (ASI) and the German Aerospace Center (DLR). SRTM obtained elevation data on a near-global scale to generate the most complete high resolution digital topographic database of Earth, including three resolution products, of 1 km and 90 m resolutions for the world, and a 30 m resolution for the US (USGS, 2004). The elevation data used in this study is the 90 m resolution (3-arc SRTM), which consists of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. All SRTM data are freely available at: http://seamless.usgs.gov/Website/Seamless/.

The background of Fig. 1 is the hillshaded digital elevation model (DEM) derived from the SRTM data. The IRW boundary, which does not exactly match the international boundary and the Chinese administration boundary (see Fig. 1), was also delineated from the 90-m SRTM elevation data. In the IRW, the elevation data is reclassified into five classes as follows: <1 km, 1–2 km, 2–3 km, 3–4 km, and >4 km. These five raster classes were subsequently converted into polygon coverage, which was further used to clip the MODIS snow cover images to examine the influence of elevation on snow cover.

4. Results and discussion

4.1. Accuracy of MODIS snow cover product

Table 1 illustrates the comparison between all ground observations and MODIS snow cover classification at the 20 climatic stations in the five-year period (2001 to 2005). There are total 2826 data of land (without snow) and 1714 data of snow (snow depth ≥1 cm). In the 2826 *in situ* data of land/no snow, the MOD10A2 product misclassifies 31 of them as snow and 47 of them as cloud. The accuracy of land classification is 97%. The omission error classifying land as snow is 1% and as cloud is 2%. If the 47 cloud data pairs (corresponding to both MODIS and *in situ*) are removed from the calculation, the accuracy of land classification is 99% under clear sky conditions. The removal of the cloud data here (and hereafter) is only for comparison purpose under so-called clear sky conditions, and the accuracy of MODIS snow/land classification is not really improved.

In the 1714 *in situ* observed data of snow, the MOD10A2 product misclassifies 256 of them as land and 234 of them as cloud. The accuracy of snow classification is 71%. The omission error of classifying snow as land is 15% and as cloud is 14%. If the 234 cloud data (pairs) are removed, the accuracy of snow classification increases to 83%, and the overall accuracy of MODIS land and snow classification increases from 87% to 93%.

Table 1
Error matrix between MOD10A2 and ground measurements during 2001 to 2005 at 20 stations in Northern Xinjiang, China

Ground observations		MOD10A2			Accuracy after cloud removed[a]
		Snow	Land	Cloud	
Land (Snow = 0 cm)	2826	31	2748	47	99%
	62%	1%	97%	2%	
Snow (Snow ≥1 cm)	1714	1224	256	234	83%
	38%	71%	15%	14%	
Snow = 1 cm	123	6	98	19	6%
	7%	5%	80%	15%	
Snow = 2 cm	79	12	50	17	19%
	5%	15%	63%	22%	
Snow = 3 cm	83	23	36	24	39%
	5%	28%	43%	29%	
Snow = 4 cm	81	45	17	19	73%
	5%	56%	21%	23%	
Snow ≥ 4 cm	1429	1183	72	174	94%
	83%	83%	5%	12%	
Overall Accuracy (given snow depth ≥1 cm as snow, other as land)				87%	93%
Overall Accuracy (given snow depth ≥4 cm as snow, other as land)				91%	97%

[a] After removing pairs of data (in situ and MODIS) masked as cloud in the MOD10A2 product, creating an accuracy in clear sky condition.

The 1714 observed snow data is further separated into five groups according to the snow depth (1 cm, 2 cm, 3 cm, 4 cm, and ≥4 cm) (Table 1). There are 123, 79, 83, and 81 observed snow data in the snow depth of 1 cm, 2 cm, 3 cm, and 4 cm groups, respectively. The accuracies of snow classification for those groups are respectively 5%, 15%, 28%, and 56%, showing increased accuracy as snow depth increases. After removing cloud data, the accuracy of snow classification are respectively 6%, 19%, 39%, and 73%; the omission error of classifying snow as land are respectively 80%, 63%, 43%, and 21%, a deceased trend as snow depth increases. In the group of snow depth ≥4 cm, there are 1429 observed snow data. The accuracy for snow classification is 83%; the omission error of classifying snow as land is only 5%; the overall accuracy is 91%. After removing cloud data, the accuracy of snow is 94%, and the overall accuracy of snow and land is 97%.

Fig. 2 indicates MODIS accuracies of snow classification as well as the omission errors of snow to land and snow to cloud at individual stations for snow depths ≥1 cm (A) or 4 cm (B) during the period of 2001 to 2005. In Fig. 2A, it is found that the accuracies of observed snow classified as snow (snow_snow) are very low (<50%) for the four stations (ID: 999, 1008, 980, 971). These results are caused by (1) the high portion of cloud obstacle (inferred by more than 20% of observed snow classified as cloud by MODIS (or snow_cloud) in those four stations, and (2) the relatively large omission error of classifying snow as land (snow_land) due to thin snow cover. After removing the cloud data pairs, the accuracy of snow to snow (Snow_Snow_No-Cloud) dramatically increases, except for those stations with large omission errors of snow_land, due to thin snow depth in

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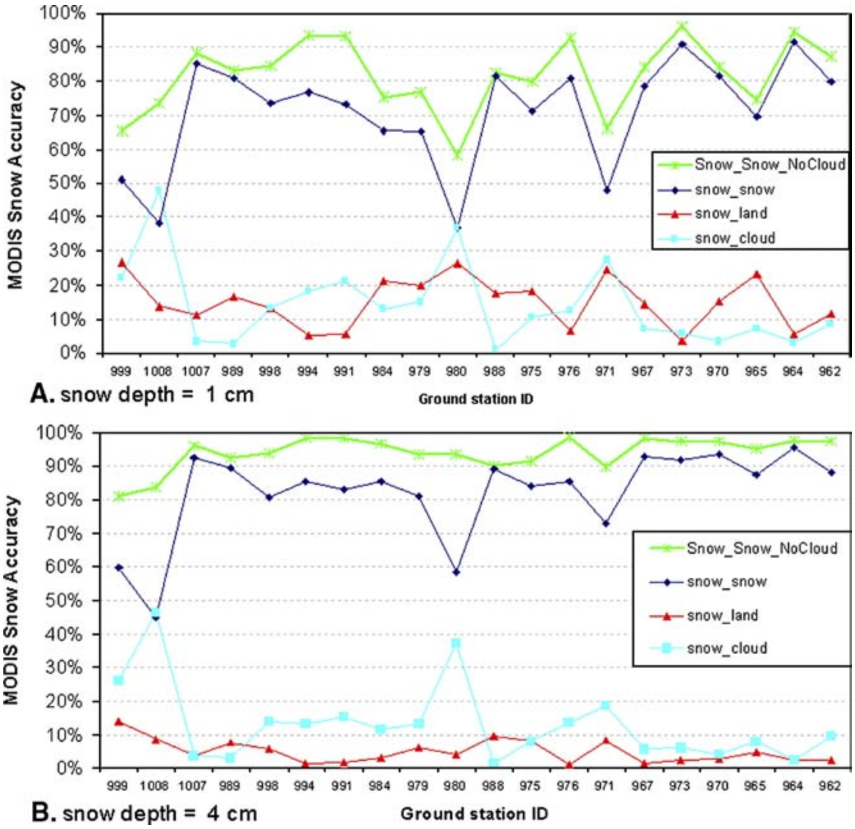

Fig. 2. Accuracies of MODIS snow classification as well as the omission errors at the individual climatic stations given snow depth larger or equal to 1 cm (A) or 4 cm (B) from January 2001 to December 2005. In the legend, snow_snow, snow_land, or snow_cloud refer to that MODIS classifies ground-observed snow as snow, land, or cloud, respectively; Snow_Snow_NoCloud is converted from snow_snow after removed the cloud data pairs, thus a clear sky condition.

urban environments such as stations 980 (Alashankou), 965 (Jimunai), 999 (Zhaosu), and 1008 (Urumqi), and in dense shrub stands at 971 (Hebukesaeir). As shown in Table 1, the major omission error of classifying snow as land is caused by the thin snow depth or patchy snow (snow depth less than 4 cm). When examining these six stations (ID: 999, 984, 979, 980, 971, 965) with high snow_land omission errors of 27%, 21%, 20%, 26%, 25%, and 23%, respectively (Fig. 2A), it is found that the percentage of the dataset with snow depths from 1 cm to 3 cm are 15%, 44%, 21%, 58%, 38%, and 21%, respectively (not shown in the Figure). In Fig. 2B, however, when the snow depths are larger than or equal to 4 cm, the omission error of classifying snow as land greatly decreases, resulting in very high accuracy (>90%) of classifying snow to snow under clear sky conditions (i.e. after removing cloud data), particularly in stations 980, 971, and 965.

Fig. 3 is an example of time series *in situ* observed mean snow depth, accuracy of MODIS snow classification, and the omission errors of classifying snow as land or cloud at the 20 ground stations in the 2003–2004 hydrologic year. The high portion of cloud masked pixels results in low accuracy of MODIS snow classification. Similar to Table 1 and Fig. 2, when snow depths are small (i.e. early accumulation or late melt periods), lower producer accuracies of snow classification and higher omission errors of classifying snow as land occur. The same pattern was also observed by Klein and Barnett (2003). In addition, the MOD10A2 product missed four snowfall events (misclassified all of them as land) on September 22, 2003, November 1, 2003, April 5, 2004, and May 1, 2004, when the mean snow depth was only 1 cm. These omission errors were most likely caused by (1) patchy snow, and (2) image composite algorithm dealing with cloud blockage in an 8-day period (see an example and discussion in the paragraph below). Aside from this error, MODIS misclassified waterbodies as land in December 2004, January, February, March and April 2005 (see an example in Fig. 4). It seems that the inland water body mask has not been incorporated into the snow cover algorithm in this area, and that the waterbodies must be masked as water or snow covered when we use the product for application in the region. The above results indicate:

(1) MOD10A2 has very low accuracy when ground snow depth is less than 4 cm even under clear sky (6%–39%, Table 1). This is much lower than that obtained in a study of MOD10_L2 (daily swath snow cover product) (Ault et al., 2006), in which the accuracy of snow classification is 41% for snow depth <1 cm. In the companion study of MOD10A1 in the same area (Liang et al., in press), the MODIS snow cover accuracies are 45.2%, 76.2% and 94.3% when the ground snow depth is 1 cm, 2 cm, and 3 cm, respectively. The observed difference in cases of thin snow depths between MOD10A1 and MOD10A2 is more likely caused by the algorithm used to generate the 8-day composite product of maximum snow cover. For

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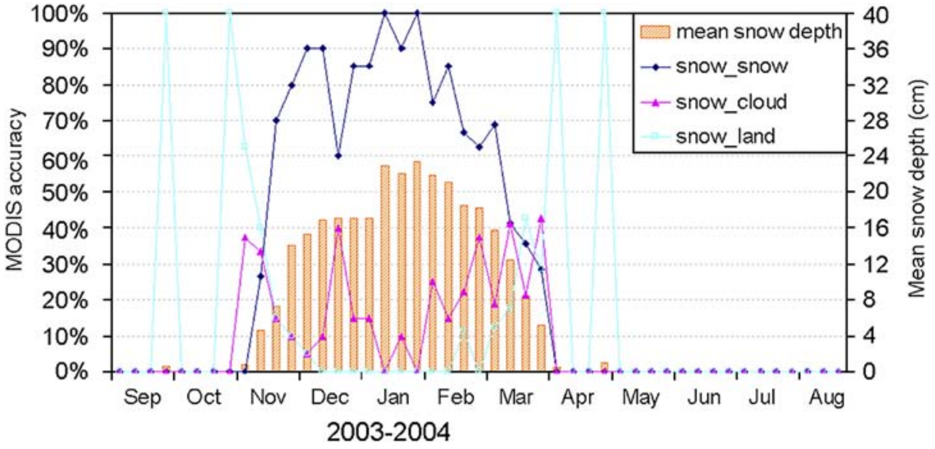

Fig. 3. Time series of observed mean snow depth, accuracy of MODIS snow classification, and the omission errors of snow_land or snow_cloud at the 20 climatic stations given the snow depth ≥1 cm during September, 2003 to August, 2004. All values are assigned as zero when ground is free of snow.

example, during January 1st–8th, 2001, ground snow depth was 1 cm at the station 984 from 1st–5th days under cloudy conditions and 0 cm on the 6th to 8th days under clear sky conditions, so the *in situ* maximum snow depth for the 8 days was 1 cm. In the clear sky of the 6th to 8th days, when both the *in situ* and MOD10A1 over the three days observed were land, resulting in the 100% classification accuracy for MOD10A1. But for the MOD10A2 product, the accuracy in this case was 0% since the maximum snow depth was 1 cm over the 8-day *in situ* composite while MODIS did not see any snow under clear sky. This example highlights the reason that a major omission error occurred in the MOD10A2 product of this study by classifying snow as land (43%–80%, Table 1) when snow depths are less than 4 cm. In these thin snow conditions, snow cover is more likely to melt away as cloud cover disappears and temperature rapidly increases. As patchy snow or thin snow depth prevails at the beginning and end of the snow season, MODIS and other sensors lose accuracy of snow cover classification due to the complex topography, presence of forest stands, and human activities (Ault et al., 2006; Hall et al., 2000; Klein & Barnett, 2003; Liang et al., in press; Riggs et al., 2006; Tekeli et al., 2005). Thus, the new fractional snow cover product will likely be a better representation of the actual land surface conditions in those areas (Salomonson & Appel, 2004).

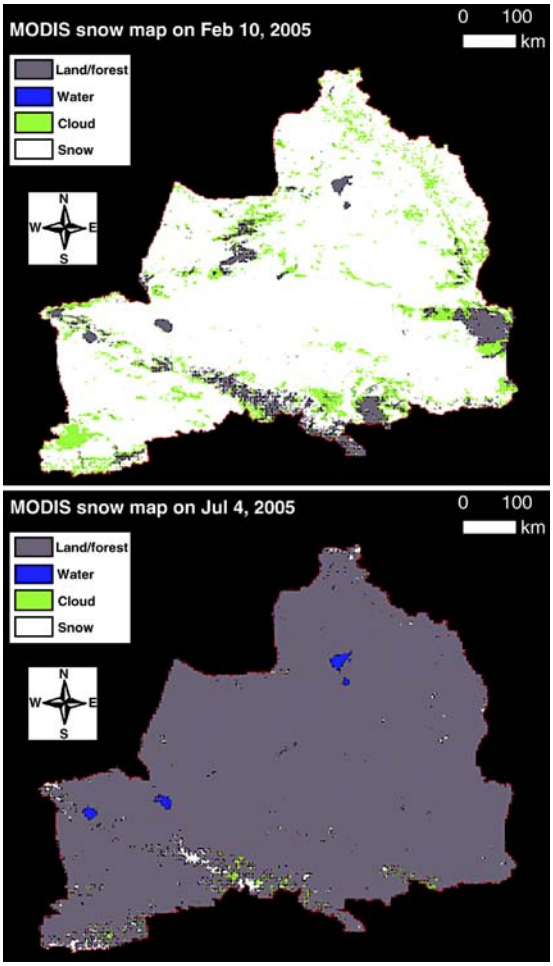

Fig. 4. MOD10A2 snow cover maps of Feb. 10, 2005 (top) and July 4, 2005 (bottom), indicating the waterbodies clearly seen in the bottom map, but misclassified as land in the top map.

(2) The MOD10A2 accuracy of land to land is very high (97%) when snow depth is <1 cm, as identified in other studies (Ault et al., 2006; Klein & Barnett, 2003; Tekeli et al., 2005; Zhou et al., 2005). Slight decreases in accuracy occur as the snow depth threshold increases. The high accuracy of land classification contributes to a high overall accuracy of MODIS land and snow classification.

(3) When comparing the *in situ* point measurements of snow depth with MODIS areal snow cover, a defined threshold value of *in situ* snow depth is very important (it is assumed that land is covered by snow as snow depth becomes larger than the threshold value). Our results show that a high threshold value increases the accuracy, and vice versa. For example, Simic et al. (2004) and Tekeli et al. (2005) used a snow depth threshold of 2.54 cm, while Maurer et al. (2003) used 1 cm as a

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threshold. In our case, 4 cm snow depth is a satisfactory threshold as snow accuracy is 83% in all weather conditions and 94% under clear skies (Table 1). The 73% of accuracy at snow depth of 4 cm under clear skies is much larger than the 6%, 19%, 39%, as snow depth respectively equals to 1 cm, 2 cm, and 3 cm under clear skies. This means that the accuracy of the MODIS product is not satisfactory for snow depths less than 4 cm, which accounts for about 17% of total *in situ* snow observations in the study case.

(4) Clouds are a major reason for degradation in the accuracy of MODIS snow classification in addition to the omission error of classifying snow as land for thin snow depth (Klein & Barnett, 2003; Tekeli et al., 2005; Zhou et al., 2005).

(5) The accuracy of snow classification for MOD10A2 in this study is lower than MOD10A1 in the companion study under clear sky at the same snow depth threshold of 1 cm (Liang et al., in press). Three factors may contribute to this discrepancy. One is the difference between the MOD10A2 8-day composite product as compared with the 8-day maximum snow depth of a climatic station as discussed above, especially for the situation of thin or patchy snow cover under mostly cloudy skies. The second factor is the difference in defining a clear sky. In the MOD10A1 of Liang et al. (in press), clear sky was defined as all pixels in a 5 by 5 pixel window (centered in the ground station) free of clouds. These data (only 21% of all data) under clear skies were used for comparison with *in situ* observations, thus biasing the comparison to higher accuracy. In our study using MOD10A2, clear sky is defined as the pixel collocated with a ground station free of clouds, and 94% of data are used for comparison. The third factor is related to differences in the comparison periods. This study uses all MOD10A2 data for an entire year, but the MOD10A1 data used in the companion paper only from November to the following March was used. This did not represent the patchy snow conditions in the beginning of the snow accumulation season in September and October or the end of melt season in April and May.

4.2. Accuracy of MODIS cloud mask

The purpose of this section is to evaluate the accuracy of cloud mask used in MOD10A2 and the effect of *in situ* observed cloud data on the accuracy of MODIS snow cover product. Table 2 summarizes the cross comparison among *in situ* cloud cover observations, *in situ* snow depth measurements, and MOD10A2 snow classification (snow, land and cloud) under four types of observed cloud cover situations: clear sky, scatter sky, broken sky, and overcast during January, February, and December in 2001–2005.

According to ground observations, in the 8-day minimum cloud cover composite, 87% of data is clear sky, and 13% of the data is covered at least by scattered clouds. Among the 865 *in situ* observations under clear sky conditions, 850 (or 98%) were observed as snow (with snow depth ≥1 cm) and 15 were observed as land. The MODIS accuracy of snow classification (snow_snow) is 86%. Omission errors of snow_land is 3%, and snow_cloud is 11%. In the 15 *in situ* land observations (free of snow), the accuracy of MODIS land classification is 40%. The omission error of classifying land as snow is 60%. 11% of clear sky data is misclassified as cloud by the MODIS cloud mask.

Table 2

Error matrix between MODIS snow and cloud mask classification and *in situ* snow and cloud cover observations in January, February, and December from 2001 to 2005 at the 20 stations in Northern Xinjiang (snow depth threshold is 1 cm)

	Clear sky		Scatter sky		Broken sky		Overcast		Cloud total	
*In situ*_total	865	87%	91	67%	28	21%	16	12%	135	13%
*In situ*_snow	850	98%	86		27		16		129	
MODIS_snow	729	86%	74	86%	18	67%	7	44%	99	76%[b]
MODIS_land	22	3%	1	1%	5	19%	1	6%	7	5%[b]
MODIS_cloud	99	11%	11	13%	4	15%	8	50%	23	19%[b]
*In situ*_land	15	2%	5		1		0		6	
MODIS_snow	9	60%	2	40%	0		0		2	33%[b]
MODIS_land	6	40%	1	20%	1	100%	0		2	33%[b]
MODIS_cloud	0		2	40%	0		0		2	33%[b]
MODIS_cloud total	99	80%[a]	13	11%[a]	4	3%[a]	8	6%[a]	124	
Overall accuracy	85%				75%				84%[c]	

[a] Is the commission error of cloud classification (e.g., the percentages of MODIS cloud in each of the 4 types of observed cloud cases over MODIS cloud total).

[b] Is the snow accuracy or omission error of cloud classification (e.g., the percentage of MODIS classifications (snow, land and cloud) over the *in situ* cloud total of *in situ*_snow or *in situ*_land case.

[c] Is the overall accuracy for both *in situ* cloud free and cloud cover conditions.

Ground stations observed 91 scattered sky conditions during the study period, among which 86 were actually covered by snow and 5 were snow free or land (Table 2). The accuracy of the MODIS cloud mask in scattered sky conditions was only 13%, meaning that most of the scattered sky (87%) recorded by *in situ* observations are marked as cloud free by the MODIS cloud mask. This could be true for particular pixels or regions because of the difference between *in situ* observations of scattered sky and remote sensor detections of scattered sky. Of the 86 observations with snow cover, the MODIS's accuracy for snow classification is 86%, which is similar to the clear sky condition. Omission errors of snow classified as land is 1% and snow as cloud is 13%. For the land case (5 observations), the MODIS's accuracy for land classification is 40% and omission error of land classified as snow is 60%.

Ground stations observed 28 broken sky conditions, among which 27 were actually covered with snow and 1 was snow free. The accuracy of the MODIS cloud mask in broken sky conditions was only 15% (4 observations), which is slightly higher than that in the scattered sky condition. In the 27 snow covered cases, the MODIS's accuracy for snow classification is 67%, which is less than in the clear sky and scattered sky conditions.

Under overcast sky conditions, the accuracy of the MODIS cloud mask is 50%, while the accuracy of MODIS snow classification is 44%, the lowest of the four cases.

As cloud cover increases from scattered sky, to broken sky, and to overcast sky, the accuracy of the MODIS cloud mask increases from 13%, 15% to 50%, respectively, and the mean accuracy of the cloud mask for the three types of cloud cover situations is only 19%. Even in clear sky conditions, 11% (99) of MOD10A2 pixels were masked as cloud. For all 124 data masked as cloud by MOD10A2, ground stations observed 99 of them (80%) as clear sky, 13 (11%) as scattered sky, 4 (3%) as broken sky and 8 (6%) as overcast. In other words, only 20% of pixels masked as cloud in MOD10A2 are observed as cloud at the ground stations. This accuracy is much lower than the cloud mask of MOD10_L2 identified by Ault et al. (2006), in which 82% of the pixels masked as cloud were identified as either overcast or broken sky by student observers. The discrepancy most likely results from similar causes to that discussed in Section 4.1 regarding the accuracy of the 8-day snow product, through maximum snow cover vs minimum cloud cover. In addition, the time differential between *in situ* observations (14:00 h for Beijing time) and MODIS overpass (local 10:30, or 12:30 for Beijing time) may contribute to the loss of accuracy. Further comparison should be based on daily ground cloud cover and daily MOD10A1 cloud mask used, i.e. the daily MOD35 cloud mask product.

Overall, in Table 2, under all cloud cover conditions (including clear sky) during the three months of December, January, and February, the accuracy of the MODIS snow product is 78% (not shown in Table 2). This is higher than 71% for the entire year (Table 1). The difference is caused mainly by inaccurate classification due to the thin snow depth in early and late snow season months. A similar pattern is observed in Fig. 3 which shows that MODIS snow accuracies are lower for thin snow depths, e.g., in November, March and April. The accuracy of MODIS snow classification decreases from 86% to 44% as cloud cover increases from clear sky to overcast sky, thus indicating that cloud is a major factor limiting the accuracy of MODIS snow classification (Ault et al., 2006; Tekeli et al., 2005; Zhou et al., 2005).

Under clear sky conditions observed from ground stations, the accuracy of MODIS snow classification is 86% over the three winter months (Table 2). This is slightly higher than 83% for the entire year (Table 1). Similarly, the primary reason for this difference is due to the lower accuracy of MODIS snow classification for patchy and thin snow conditions. As we see in Table 1, the accuracy of MODIS land classification is very high (97%) over the entire year; however, in January, February, and December (Table 2), the accuracy is only 40% under clear skies. The low accuracy of MODIS land classification is accompanied with high omission error of classifying land as snow (60%). This is likely caused by patchy snow cover conditions. In this case, the influence of this omission error is considered to be minor because patchy snow is a small portion (2% or less) of the snow cover over the three winter months.

In addition, the overall accuracy of snow and land classification during the three winter months is 85% under clear skies, 75% under cloud skies, and 84% under all sky conditions (Table 2), which are less than 93% under clear skies and 87% under all sky conditions for the entire year (Table 1). The high overall accuracy for the entire year is mostly due to the high accuracy of land classification (99% in clear sky condition and 97% in all sky conditions). It is much higher than the accuracy of snow classification even in the three winter months when the 98% of land is covered by snow.

4.3. Separating MODIS cloud as land and snow

From Table 1, 2% of the *in situ* land data and 14% of *in situ* snow data are masked as cloud in MOD10A2. However, in Table 2, during January, February, and December, 13% of all data are masked as cloud in MOD10A2. These observations, together with information presented in Fig. 2, indicate that the existence of clouds greatly degrade the accuracy of MODIS snow classification and underestimate the total snow cover. Fig. 5 illustrates that MODIS cloud cover during each hydrologic year in the study area varied from 0% up to 40%, and that most of the cloud cover occurred during the cold season (from November to March) when most land was covered with snow. The trend of decreasing snow cover (%) as the cloud cover increases in Fig. 5 does not translate to an actual reduction in total snow cover, but, rather indicates that the existence of cloud cover reduces the capability of MODIS to detect the actual ground cover types.

In order to study the spatial features of snow cover using MODIS snow cover products, the influence of MODIS cloud masked pixels must be removed or minimized. According to *in situ* ground observations in Table 1, for the total of 281 cloud data masked by MODIS, 234 were snow covered, and 47 were land (free of snow). Therefore, 83% of the cloud-covered areas were actually covered by snow. This percentage accounted for the entire year, while most cloud covered pixels occurred in the cold season. According to Table 2, 98% of the data in January, February and December were actually covered by snow (snow depth ≥ 1 cm). However, in November, March and April, only 42% of the cloud covered pixels were covered by snow (snow depth ≥ 1 cm). Therefore, MODIS cloud masked pixels could be separated into snow covered pixels and snow-free pixels (land) based on the ratio of snow to land in each month (i.e. about 98% of cloud pixels in December, January, and February and 42% of cloud pixels in November, March and April could be classified as snow covered). Using this technique, a new snow cover time series has been generated by adding the converted pixels into the raw snow cover time series (Fig. 5). Compared with the raw time series of snow cover, the new snow cover corrected the dramatic decrease of raw snow cover caused by cloud masking in the cold season. The new snow cover time series provides a better representation of actual *in situ* snow cover. Based on our review of previous works, this is the first time that pixels masked as cloud in MODIS are converted into snow or land classifications. This conversion greatly mitigates the influence of cloud blockage and provides a better estimation of the snow coverage over an entire watershed, particularly for snowmelt-runoff modeling where a snow depletion curve is derived. However, it is difficult to determine whether a specific cloud-masked pixel is covered by snow or not if only using the ratio of the snow to land. More factors, like elevation, land surface/air temperature, latitude, must be provided together with time to determine whether a cloud-masked pixel is covered by snow or not. The succeeding analyses are based on the new snow cover time series.

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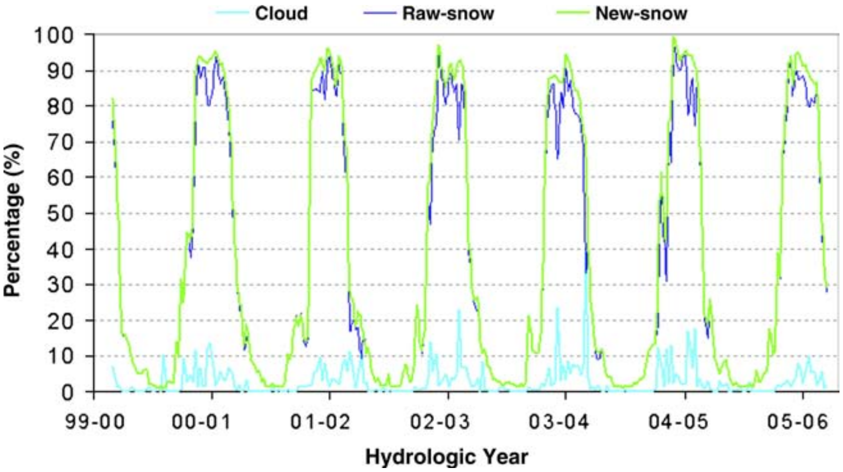

Fig. 5. Time series plot (%) of MOD10A2 raw snow cover (raw-snow), cloud cover, and new snow cover (new-snow) after cloud-masked pixels were converted into snow cover and land, in Northern Xinjiang, from 2000 to 2006.

4.4. Temporary variation of snow cover in the Northern Xinjiang

Overall, the SAE (%) shows a similar pattern during the six hydrologic years from 2000–2001 to 2005–2006 as shown in the new MODIS 8-day snow cover time series (Fig. 6A). One obvious feature is that SAE covers about 90% of the entire area during December, January and February. Another feature is that the starting dates of snow accumulation and snow melt vary from year to year, especially the snow accumulation period. The third feature is the corresponding inverse relationship between SAE (6A) and air temperature (6B). For example in the 2001–2002 hydrologic year, the SAE was ~18% on November 25 (usually SAE is >50% in early November); then, the SAE

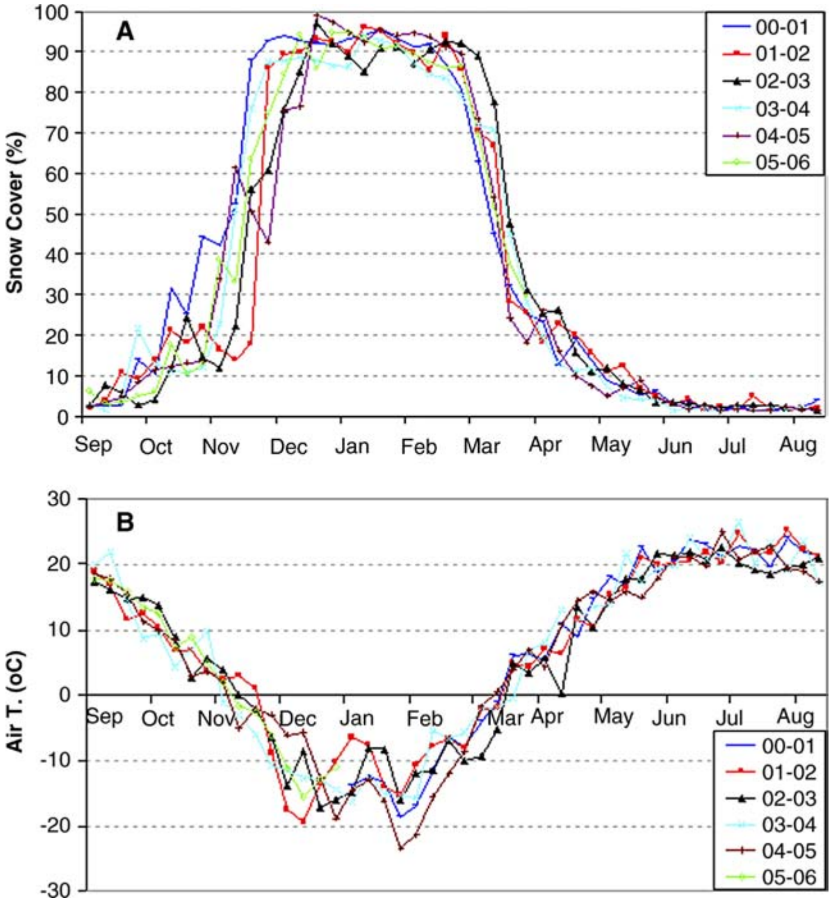

Fig. 6. New time series of snow area extent (after separating cloud cover into snow and land) in percent (A) and mean air temperature in Celsius at the 20 climate stations (B) arranged in hydrologic years of 2000 to 2006 period.

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dramatically increased to 86% within one week on December 3, which is closely associated with air temperature decrease in Fig. 6B. The mean air temperature was ~1.2 °C on November 25, then dramatically decreased to −8.8 °C on December 3, and to −17.5 °C on December 11. The decrease of SAE caused by the increase of air temperature also appeared in October of 2002, January of 2003, and November of 2004.

Snow covered days, or the duration of snow cover, defined here as the number of days when snow covers an assigned percentage of area, are used to quantitatively compare the variation of duration and spatial extent of snow cover from year to year as shown in Fig. 7. First, it is very clear and reasonable that, as the SAE threshold increased from 40% to 80%, the snow covered days decreased within a water year. While no clear trend of change from year to year is observed, except when the threshold is at 80%, the snow covered days gradually decreased from 2000–2001 to 2004–2005 hydrologic year, and then slightly increased in 2005–2006 year in the study area (Fig. 7A). A clear decrease of snow covered days at thresholds of 40% and 50% for the 2001–2002 water year is related to the exceptionally high air temperature in November, 2001 (see Fig. 6B). The snow-poor hydrologic year of 2001–2002 in this region was also identified by Che and Li (2005) and Cui et al. (2005). The snow-poor hydrological year (2001–2002) is more serious in the IRW where fewer snow covered days were observed in all 4 SAE thresholds (Fig. 7B). In most cases, the snow covered days at different SAE thresholds in IRW are higher than in the entire Northern Xinjiang, and there is a general decreasing trend during the six hydrologic years (ignoring the 2001–2002 year), which suggests a reduction of snow area extent and general decrease of snow-water resources in the IRW.

The MODIS derived trends of SAE and snow covered days in the Northern Xinjiang and IRW regions during the period (2000–2006) differs from the long-term ground-based records from Li (2001) and Gao et al. (2005b) in which a overall increase of SAE from 1950s–1990s is presented. This discrepancy between *in situ* observation and MODIS is likely caused by the different spatial and temporal observation scales. These are detailed as follows: (1) the limited *in situ* ground records may not represent the mean conditions of the entire area; (2) the short

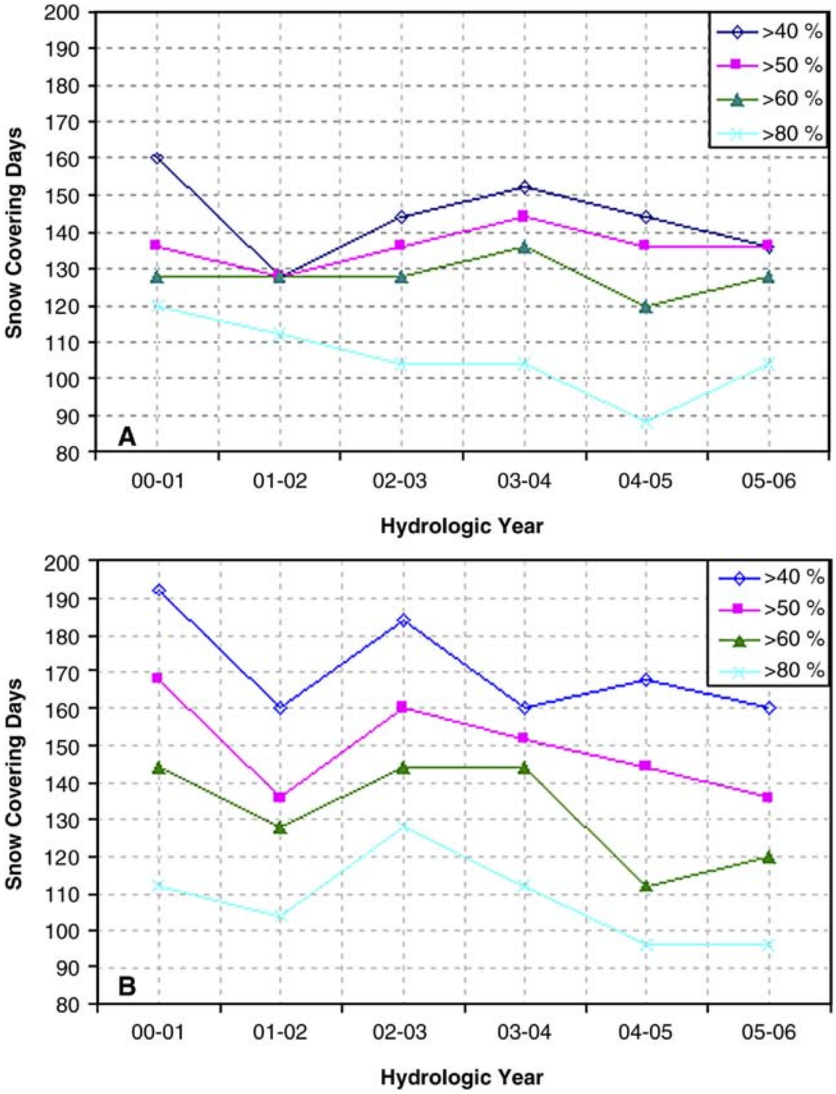

Fig. 7. Snow covered days based on different SAE thresholds at the entire Northern Xinjiang (A) and Ili River Watershed (B) vs hydrologic years of 2000–2006 period.

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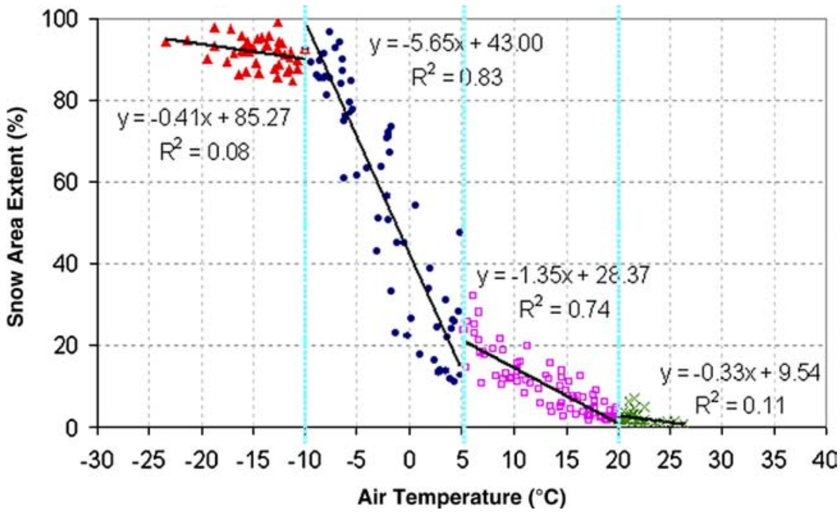

Fig. 8. Scatter plot of mean air temperature and snow area extent at different temperature ranges in the Ili River Watershed: <−10 °C, −10 °C to +5 °C, +5 °C to +20 °C, and >20 °C.

term MODIS records over the entire area may lie within the normal range of variation for longer temporal scales. Long-term continued provision of MODIS snow cover products is critical for assessing water resources of the study area, as well as for larger scale global environment monitoring.

4.5. Relationship between SAE and temperature

Overall, SAE has an inverse relationship with mean air temperature as shown in Fig. 6, especially during the snowfall and melting periods. Fig. 8 explores the relationship one step further by examining different temperature ranges. It is found that, at < −10 °C, temperature and SAE are not correlated ($R^2=0.08$). As shown in Fig. 6, SAE is higher than 90% when air temperature < −10 °C (in December, January and February), and the further decrease of air temperature does not cause SAE increase. As temperature varies between −10 °C and +5 °C, which corresponds to the periods of snow accumulation and melt processes, SAE has a very good linear relation by $R^2=0.83$ and steep slope of −5.65, indicating a rapid response of SAE to

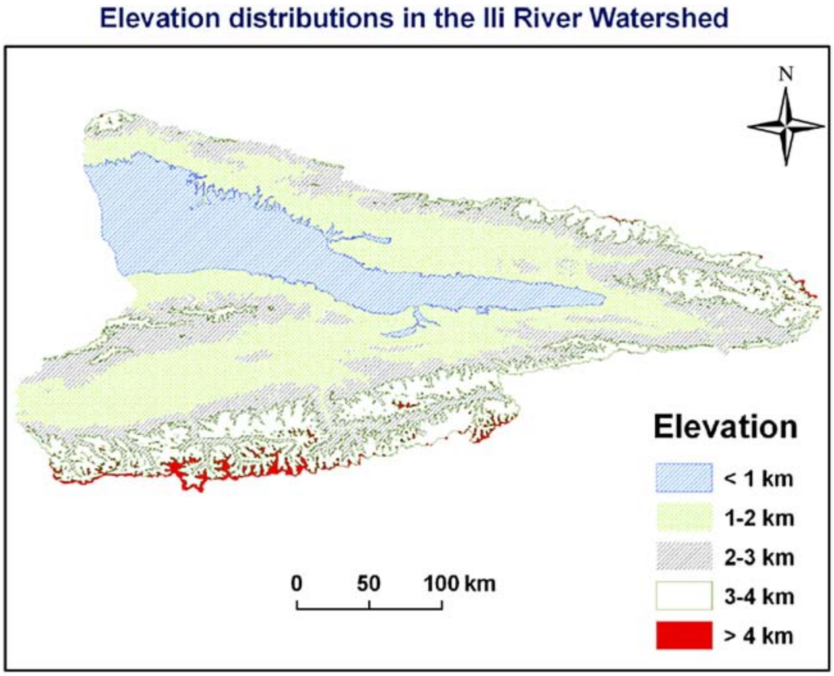

Fig. 9. Elevation distributions in the Ili River Watershed. Data from global Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 90 m spatial resolution.

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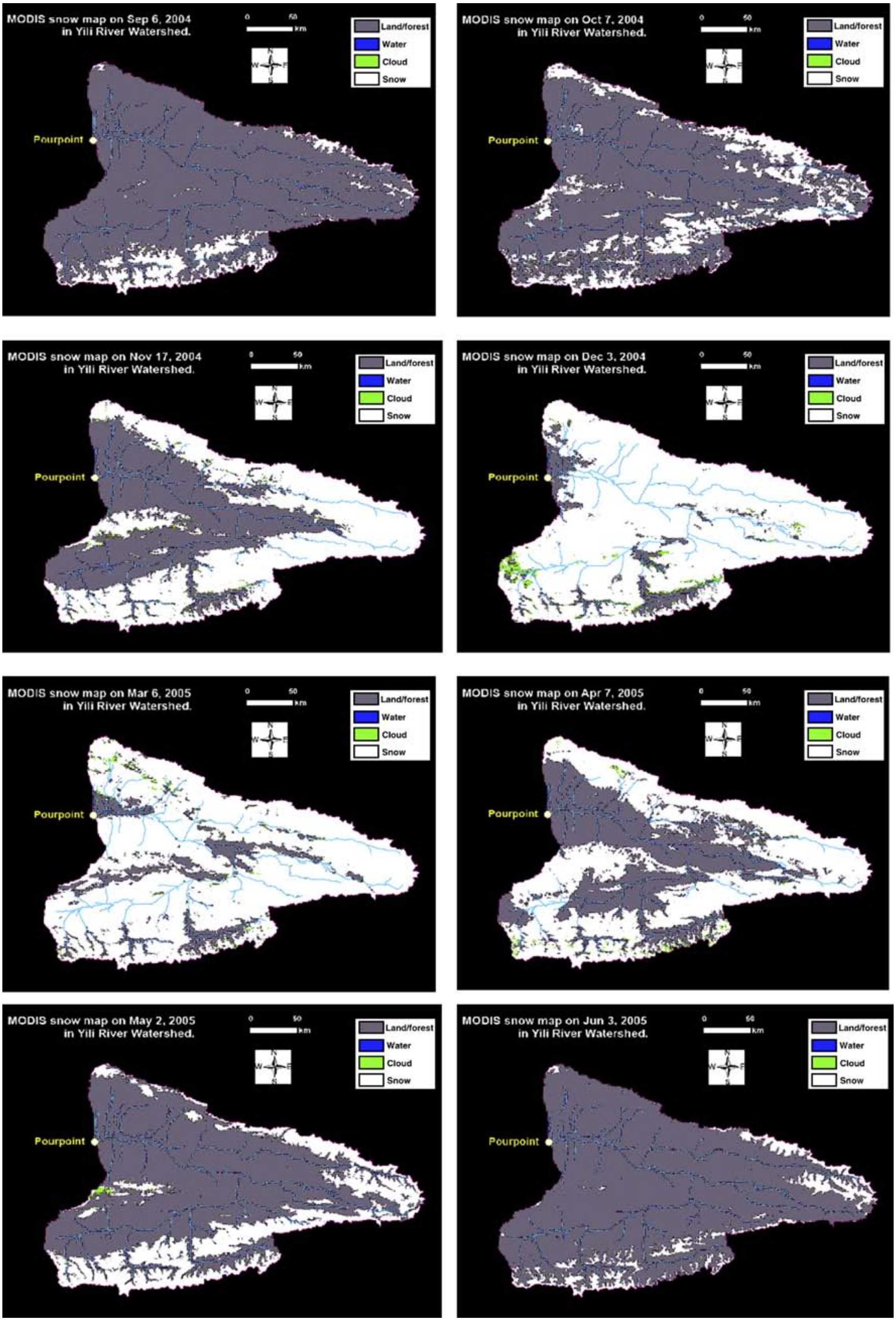

Fig. 10. Snow coverage in the Ili River Watershed in 2004–2005 hydrologic year.

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temperature. As temperature increases from +5 °C to +20 °C, SAE also has a fairly good linear relationship with $R^2=0.74$ and flat slope of −1.35. But this is actually a false relation. It can be seen from the Figs. 6 and 8 that most of the SAE is less than 20% in this temperature range, with average of ~10%. This means that most of the snow covered areas is actually in the high elevation area, where the temperature may still be around 0 °C; meanwhile most of the climate stations are located at the low elevation region where the temperature is in the +5 °C to +20 °C range and there is probably no snow cover at all. When the temperature is > +20 °C, snow cover almost completely disappears (see Fig. 6), except in some local areas with very high elevations (mountain tops), and there is no obvious linear relationship with mean air temperature ($R^2=0.11$). Again, the mean air temperature recorded at the ground stations can not represent conditions on high elevation mountain tops where air temperature may be around or less than 0 °C through the entire year.

4.6. Influence of elevation on SAE in IRW

Air temperature is a major factor that influences snowfall and accumulation/melting as discussed in Sections 4.4 and 4.5. Air temperature, however, has an inverse relationship with elevation (i.e., due to the adiabatic lapse rate, the air temperature generally decreases ~6 °C per 1 km elevation or air height increase). Thus, SAE will likely show different spatial and temporal characteristics at different elevation ranges. Cui et al. (2005) identified that maximum snow depth and total snow covered days in mountains are about 1.6 times greater than in the plains. This factor is particularly applicable in the IRW, where the elevation increases from 500 m to over 6000 m. The dramatic range of elevation changes in the watershed provides an ideal setting to examine the influence of elevation on SAE.

The 58,361 km^2 drainage area of the IRW is divided into five categories based on elevation ranges of <1 km, 1–2 km, 2–3 km, 3–4 km, and >4 km, accounting 18%, 36%, 26%, 19%, and 1% of the drainage area, respectively (Fig. 9). Fig. 10 shows a series of monthly observations of spatial variation in snow cover for the 2004–2005 hydrological year. In early September 2004, snow cover was present in areas where elevation is higher than 4 km, and to a limited degree in the 3–4 km areas. In the early October, snow cover extended to most of the 3–4 km areas. By the mid-November, snow cover was present over the 2–3 km elevations and partly covered the 1–2 km elevations. In December, January and February, the 1–2 km elevation areas were mostly covered, except for some steeply sloping areas or dense forest-stand areas. In the early March 2005, snow cover began to melt in areas with elevations less than 1 km. Snow cover disappeared at 1–2 km elevations in April, 2–3 km elevations in May, and 3–4 km elevations in June. As discussed earlier, in June, July and August (not shown), snow cover only remained on the tops of some high elevation mountains, where elevation is >4 km.

Fig. 11 shows that SAE (%) increases as elevation increases before mid-November and after early March, while an inverse relation appears between mid-November to early March when SAE is above 90% in almost every elevation range. A possible explanation for this inverse relationship is due to that steep slope in higher elevation areas (mountains tops) prevents the snow build-up. This means that, as elevation increases, the percentage of steep slope increases, resulting in the decrease in percentage of area that could be used for snow to build-up. When there are enough snowfalls available in winter time, the SAE (%) decrease occurs as elevation increases. We refer this phenomenon as “snow cover saturation”. This phenomenon is clearly seen in the snow maps of November to February in Fig. 10. Snow covers almost 100% of the high elevation regions (≥2 km), but the steeply sloping areas are always snow free or misclassified as land. Another feature of Fig. 11 is that SAE increases dramatically from 5% to 95% in one week and decreases rapidly from 90% to 10% in one week in the elevation range <1 km, the valley of the basin. This is reasonable as one big snowfall could rapidly cover the lower elevation area, or snow cover of the lower elevation range could be rapidly melt away as temperature increases to a threshold value. At high elevation ranges (>4 km), the response of snow accumulation and melt is more gradual, as the elevation moderates temperature change above the threshold.

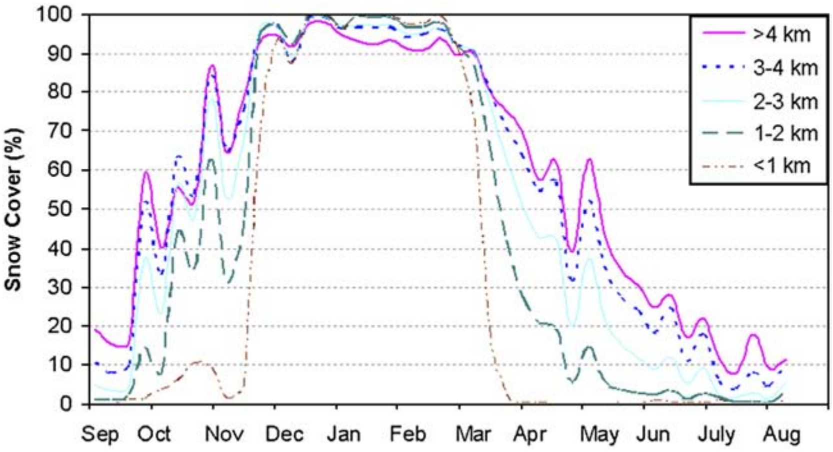

Fig. 11. Mean snow area extent at different elevations in the Ili River Watershed during 2000–2001 to 2005–2006 hydrologic years.

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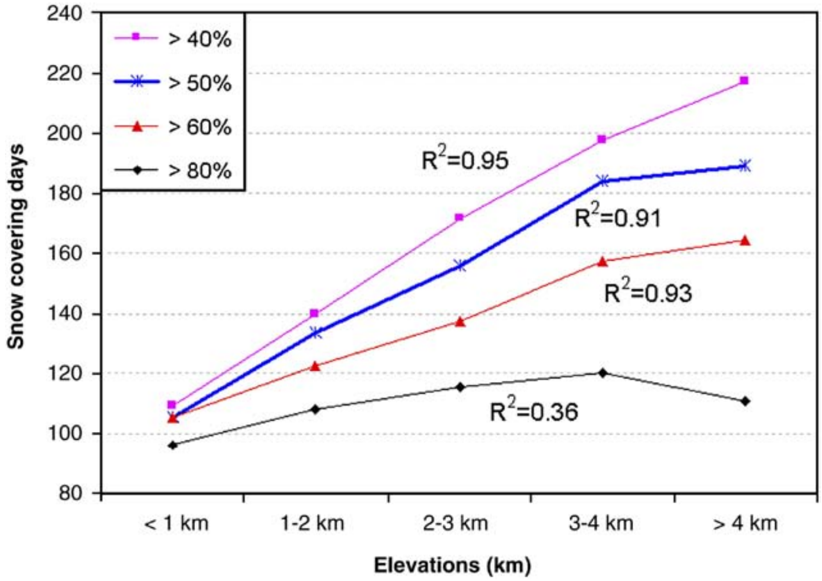

Fig. 12. Mean snow covered days at different snow cover thresholds of >40%, >50%, >60%, and >80% during the 2000–2001 to 2005–2006 hydrologic years vs elevations in the Ili River Watershed. *R* is the Spearman ranked correlation coefficient.

Peaks in the SAE time series show corresponding snowfall events that occurred in that period; thus, Fig. 11 also shows that snow falls through the whole year at elevations >1 km, with more events at higher elevations.

Fig. 12 shows that a good linear relationship between snow covered days and elevation as expected by $R^2 = 0.95, 0.91, 0.93$ (Spearman's ranked correlation) respectively as SAE >40%, >50%, and >60%. The R^2 is only 0.36 for SAE >80%, which is easily explained from Fig. 11, in which a positive relationship between SAE and elevation still exists when SAE are between 80% and 90%, while an inverse relationship occurs when SAE is >90%. So the overall result is a much reduced relationship between SAE and elevation in this range (SAE>80%). Fig. 12 also shows that elevation has a more important influence on snow accumulation at elevations <4 km in the IRW, and the influence decreases at elevations >4 km, since the air temperature at high elevations is lower than the melt threshold and the surface is covered by snow through the entire year. Other factors, like terrain aspect, wind speed and other atmospheric variables also have an important influence on SAE, but the effects are not as obvious as elevation and slope.

5. Summary

Snow accumulation in the Northern Xinjiang is an important water resource supporting agricultural and commercial activities across international boundaries. Despite these obvious benefits, heavy snow storms and excess snow accumulations often cause severe problems for the area. As supplements to ground based *in situ* observations, the MODIS snow cover products provide invaluable information for regional snow monitoring and snow-related disaster mitigation. This study examined the accuracy of the 8-day MOD10A2 snow product in the study area during 2001–2005 as compared with ground based observations and presented an empirical technique to improve the accuracy of snow area identification by reclassifying cloud obscured pixels into snow or land.

The comparison between long-term ground-based snow observations of 20 stations and the MOD10A2 product during January 2001 to December 2005 gives the following results. MOD10A2 has high classification accuracies for snow (83%) and land (99%) under clear skies. MOD10A2 has very low accuracy for patchy or thin snow. Most of the time patchy or thin snow is misclassified as land when snow depth is less than 4 cm. This is especially true during early snow accumulation and late snow melt periods. If the threshold for saying snow exists at a ground station is at 4 cm or greater, the agreement between MODIS snow cover and *in situ* observations increases to 94% when the cloud-masked pixel and *in situ* observation pairs are removed (83% before removed).

Comparisons of *in situ* observations of snow depth and cloud cover and the related MOD10A2 classifications in January, February, and December during 2001 to 2005, show that the accuracy of the cloud mask in MOD10A2 is low (mean 19%). When *in situ* station observed cloud cover increases from clear sky to scattered sky, broken sky, and to overcast sky, the accuracies of MODIS snow classification decrease from 86%, 86%, 67% to 44%, respectively. The MODIS land classification accuracy is much lower in January, February, and December, when most of the land is covered by snow, than in other months.

In MOD10A2, the cloud masked pixels for each hydrologic year in the entire Northern Xinjiang vary from 0% up to 40%, and most appear in the cold season when the surface is covered by snow. The existence of cloud cover reduces the capability of MODIS to detect the actual ground cover types and affects the full use of MODIS snow cover products. Based on a ratio of snow to land obtained from *in situ* ground observations in different periods, MODIS cloud-masked pixels are reclassified

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into snow covered pixels and snow-free pixels (land). This technique generates a new snow cover time series that corrects the dramatic decrease of raw snow cover caused by cloud mask in the winter, thus yielding a better estimation of the actual snow coverage in a watershed.

During the six hydrologic years from 2000–2001 to 2005–2006, SAE exhibits similar patterns, although there is variation at the beginning of snow accumulation and at the ending of snow melt in different years. In general, the 2000–2001 year has the most snow cover, and the 2001–2002 year has the least snow cover. The variation of SAE is closely associated with air temperature. The increase of elevation generally accompanies the decrease of air temperature, resulting in more snow and longer snow duration. The influence of elevation on SAE decreases when the elevation is larger than 4 km in the IRW. The snow covered days when SAE exceeds 80% has a decreasing trend in the entire Northern Xinjiang, while in IRW, all snow covered days at four SAE thresholds have a general decreasing trend. This is inconsistent with a general increasing trend based on the long-term climatic station observations. However, as we point out, the limited point-based observations may not represent the range of regional variation. Remotely sensed snow products should provide a better spatiotemporal representation for large areas such as the Northern Xinjiang. Thus, the continued long-term provision of MODIS snow cover products is critical for assessing water resources of the study area, as well as for larger scale global environment monitoring that can offer critical inputs for hydrologic and climatic modeling, forecasting, and climate change analyses.

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