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Evaluation of remotely sensed snow cover product in Central Asia

A. Gafurov, D. Kriegel, S. Vorogushyn and B. Merz

ABSTRACT

Central Asian countries depend highly on water resources from snow and glacier melt, which has to be studied thoroughly to estimate water availability. However, the observation network in Central Asia is poor to carry out such studies in detail. Observations from space using remote sensing techniques might fill this observation gap, which needs to be validated. Therefore, this study evaluates the Moderate Resolution Imaging Spectroradiometer (MODIS) daily snow cover product in Central Asia. For the evaluation, *in situ* snow depth data from 30 meteorological stations and higher resolution Landsat data are used. The results show an overall snow agreement between MODIS and ground observations of 93.1 and 92.7% for MODIS Terra and MODIS Aqua snow products, respectively. The agreement between MODIS and Landsat is 91.9% when considering snow and land agreements. The snow fraction product from MODIS is also validated using Landsat data, and varying accuracies are obtained. The main disadvantage of the MODIS snow cover product are the cloud induced gaps. Therefore, cloud covered pixels are eliminated using the ModSnow algorithm. Using the *in situ* data, the snow agreement of cloud removed snow cover data is checked, and an accuracy of 84.4% is achieved.

Key words | Central Asia, evaluation, Landsat, remote sensing, snow cover

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INTRODUCTION

Central Asian hydrology is highly dominated by seasonal snow and glacier melt from the high altitude mountain ranges of Pamir, Tian-Shan and Hindu-Kush, which feed the Amudarya and Syrdarya rivers (Figure 1). About 78% of the annual water resources are generated from snowmelt, about 3% from rain and about 14–16% from glaciers (Ososkova *et al*. 2000). The rivers Amudarya and Syrdarya reach their highest discharge in summer, when the rate of snow and glacier melt is high. Summer streamflow is used for irrigation in downstream countries. Due to the arid climate, agricultural production is impossible without irrigation and depends on the available water resources in the summer season. Therefore, information on snow storage in the mountains is a prerequisite for a sound assessment of the available water resources.

Information on snow cover and snow depth is usually obtained from meteorological stations, helicopter observations or foot surveys (snow depth measurements during field surveys). However, these measurements provide point information that is not particularly useful in highly heterogeneous mountain areas. Moreover, it is almost impossible to manually take observations at inaccessible remote areas. Thus, vast mountain regions, where most of the Central Asian water resources are stored, are unobserved.

Snow cover retrieval from remote sensing has become a very good alternative for snow cover mapping in mountain regions. There are several remote sensing products for snow retrieval worldwide. Advanced Very High Resolution Radiometer (AVHRR) data, with 1 km spatial and daily temporal resolution and available since 1979, was used in studies on snow dynamics and water availability in Central Asia (Baumgartner *et al*. 2001; Yakovlev 2005). Due to cloud disturbance, these data were used only for areas or

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Figure 1 | Central Asia and locations of snow measurement stations (Aral Sea outlines from Gafurov (2011)).

days with clear sky conditions. Moderate Resolution Imaging Spectroradiometer (MODIS) data, available since 2000, has a spatial resolution of 500 m and daily temporal resolution. The MODIS snow cover data have not been used so far for snow or water related studies in Central Asia, but seem promising due to their high temporal and spatial resolution compared with other available snow information from remote sensing. Another advantage is that MODIS data are freely available.

The MODIS snow cover product has been tested by several researchers with reliable accuracy in different parts of the world. Parajka & Blöschl (2006) compared MODIS snow cover data with *in situ* information over the whole of Austria, and reported an agreement of about 95% between MODIS snow cover and *in situ* data taken from 754 climate stations on cloud free pixels. Klein *et al.* (2003) reported 88% agreement for the Upper Rio Grande Basin. The MODIS snow product accuracy study by Wang *et al.* (2008) reported that under clear sky conditions, the MODIS snow cover product had 94% accuracy for snow and 99% for land when compared against *in situ* snow depth data taken from northern Xingjian, China. A study by Ault *et al.* (2006) showed accuracies of 92 and 86% for two observation sets in the USA, respectively. The study by Tekeli *et al.* (2005) for Turkey stated that 'among 96 observations, 74 observations mapped as snow or land by MODIS agreed with the ground measurements with a matched ratio of 77%'. Huang *et al.* (2011) evaluated MODIS snow cover product in China against observations from 20 stations, and achieved accuracies of 95 and 88.1% for plain and mountain areas, respectively. They also analyzed snow mapping accuracy for different snow depths and reported 29.5–82.5% accuracies for snow depths of 1–3 cm, over 92% accuracies for snow depths of 4–19 cm and almost 100% accuracies for snow depths of over 20 cm. A study by Déry *et al.* (2005) on the validation of MODIS snow fraction using Landsat data for 2 different days resulted in a correlation coefficient of 0.90. They also reported that MODIS underestimates snow cover fraction for patchy snow (for snow fractions less than 20%). Liang *et al.* (2008) compared MODIS Terra data against 20 observation stations in China, and reported an overall accuracy of 86.7%.

These studies show that the quality of snow coverage estimation from remote sensing varies for different sites due to differences in geolocation, topography, land cover and atmospheric conditions. The latitude determines the sun zenith angle and therefore the illumination conditions of each site. The lower the sun zenith, the poorer the back scattering to the satellite sensor. Together with high vegetation and a rugged relief, this can lead to shadowing effects, resulting in loss of surface information. Dense vegetation like forest can cause problems in snow mapping when hiding the snow under the canopy, thus disturbing the average reflectance of a pixel (Klein *et al.* 1998; Metsämäki *et al.* 2004; Negi *et al.* 2009; Xiao *et al.* 2010). Atmospheric content like aerosols, for example, wind-transported desert dust on continental sites, can modify the at-satellite measured radiance by scattering and absorbing solar radiance, as well as shading the surface beneath (Remer *et al.* 2005), and may diminish the reliability of the retrieved snow cover area. Tekeli *et al.* (2005) showed that topography may have a further effect on snow cover mapping algorithms like the one from MODIS. With rising altitude in mountainous areas, the probability of clouds rises, which causes a lower mapping accuracy than in flat areas. They also highlighted the influence of slope aspect, as snow cover on northern and north-western slopes is underrepresented by the MODIS algorithm compared with snow on south and south-eastern slopes. So, in addition to former studies and to complement the range of characteristics, this study focuses on a mid-latitude and mountainous area with sparse vegetation and continental location. The quality of the MODIS snow cover product has not been evaluated for locations with such characteristics. This study compares MODIS snow cover data not only to *in situ* snow measurements, but also to the high resolution Landsat imagery. Moreover, the MODIS fractional snow cover is evaluated using Landsat data. Finally, the ModSnow cloud removal algorithm (Gafurov & Bárdossy 2009) is applied to eliminate cloud cover from snow maps, and the processed results are compared against *in situ* data.

DATA

MODIS snow cover and snow fraction product

MODIS is an optical sensor installed on the Terra and Aqua satellites as part of NASA's Earth Observing System program. The Terra satellite was launched in December 1999 and began to deliver data in February 2000. The Aqua satellite was launched in May 2002 and started to deliver data in July 2002. Both satellites observe the Earth's surface in daily temporal resolution with a time shift of a few hours. About 40 different environmental parameters are estimated using raw data from 36 spectral bands, and all products are freely available. The snow cover product is estimated by the normalized difference snow index (NDSI) algorithm (Hall *et al.* 2002), which uses MODIS spectral bands 4 and 6. In this study, daily snow cover data with 500 m spatial resolution (MOD10A and MYD10A, version V005), which were obtained from the National Snow and Ice Data Center, are evaluated. This product is distributed as tiles with a size of 10° by 10°, which makes up a total of 36 horizontal (H) and 18 vertical (V) tiles covering the entire globe. The MODIS snow cover data are provided in a hierarchical data format, in which four datasets (daily snow cover, daily albedo, fractional snow cover and quality assessment) are compressed. Figure 2 illustrates the MODIS snow cover product (MOD10A) of two tiles (H23V04 and H23V05) over Central Asian mountains.

As indicated in Figure 2, the main disadvantage of the MODIS snow cover product is the presence of cloud-obscured regions. Several strategies have been developed in the past to reduce or completely eliminate cloud cover from snow cover images (Parajka & Blöschl 2008; Gafurov & Bárdossy 2009; Tong *et al.* 2009; Hall *et al.* 2010).

Additional to snow cover, snow fraction data were processed for the study area in order to evaluate its accuracy using Landsat snow cover data. The snow fraction data have the same geospatial conditions as the snow cover data with 500 m spatial resolution. This product was developed by Salomonson & Appel (2004) using the relationship between NDSI and fractional snow cover from higher resolution remote sensing Landsat snow cover data. Thereafter, a universal relationship between fractional snow cover and NDSI was estimated. After validating the relationship at several test sites in North America, Russia, Canada and South America, it was used for the compilation of MODIS snow fraction data worldwide using the NDSI value. More detailed information on MODIS snow fraction product can be found in Salomonson & Appel (2004). In this study, snow fraction data derived from the universal relationship was validated in Central Asia.

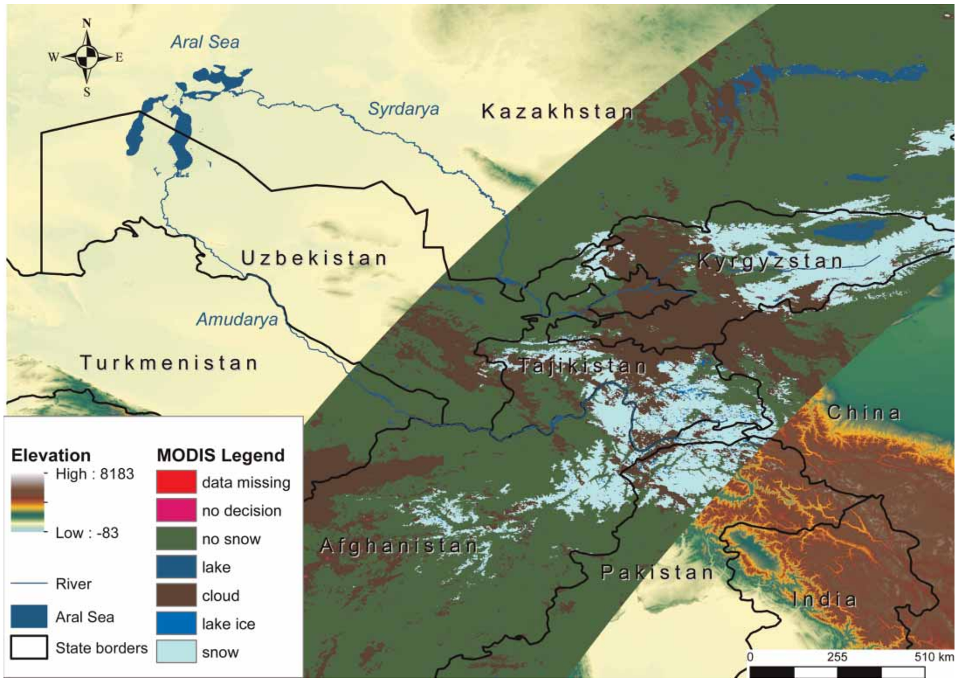

Figure 2 | MODIS snow cover data over Central Asian mountains on 12 April 2003 (Aral Sea outlines from Gafurov (2011)).

Snow depth observation data

Figure 1 shows the locations of 30 snow stations in Central Asia that are used for MODIS snow cover data validation in this study. These stations are located at different elevations ranging from 206 to 3,837 m above sea level (m a.s.l.). The number of observations at each station varies between 35 and 1,307, with a mean of 378. The data originate from the National Climate Data Center (NCDC) Global Historical Climatology Network Data archive, downloaded from the Royal Netherlands Meteorological Institute Climate Explorer webportal (http://climexp.knmi.nl). It is necessary to note that this dataset provides snow depth for the days with snow at the station. Days without information were not necessarily snow free; it is also possible that there was no measurement or that the information from this day is missing (Imke Durre, NCDC 2010, personal communication).

For the evaluation of the MODIS snow cover product, the period from February 2000 to March 2009 was used for the Terra satellite and from January 2002 to December 2009 for the Aqua satellite, respectively. Table 1 shows the annual and monthly number of observations for all stations with a total number of 8,752 *in situ* measurements.

Landsat data

In the frame of the Landsat program, several satellites were launched starting from 1972, with the latest being Landsat 7 launched in 1999. These satellites have acquired Earth observing images from space since the beginning of the Landsat program. Landsat data have a spatial resolution of 30 m and a temporal resolution of 16 days. The Landsat sensor has, in total, eight bands. Among them, six bands are spectral (1, 2, 3, 4, 5, 7), one thermal (6) and one panchrometric (8). The Landsat raw data are public domain data and can be downloaded from United States Geological Survey (USGS) archive. As Landsat is also an optical sensor, its data are also obscured by cloud cover. Given the high spatial resolution of Landsat data, it is not plagued with spatial heterogeneity problems compared to MODIS data. In this study, Landsat raw data are used to create snow cover maps, and these maps are used as ground truth for comparison against MODIS snow cover. For this purpose, Landsat data from 4 clear sky days were downloaded from the USGS archive. The selection of these four landsat images was based on the criteria that these days are nearly clear sky (little or no cloud)

Table 1 | Annual and monthly number of observations at 30 snow stations

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	221	225	92	23	11	2	0	3	8	34	99	202	920
2001	322	263	85	14	10	1	1	0	17	38	54	372	1,177
2002	382	285	115	27	20	3	0	0	2	17	28	313	1,192
2003	256	144	119	21	3	2	0	0	1	6	83	266	901
2004	185	106	58	15	7	1	3	0	2	4	28	198	607
2005	209	332	91	19	6	1	0	0	0	19	39	190	906
2006	302	176	59	8	3	6	1	0	2	7	80	349	993
2007	387	94	74	4	6	2	2	0	2	16	28	217	832
2008	456	293	46	4	1	0	0	0	0	1	4	72	877
2009	224	93	30										347
Total	2,944	2,011	769	135	67	18	7	3	34	142	443	2,179	8,752

days, and that these images are from the snow season. Usually, it is difficult to find clear sky days with enough snow coverage in Landsat. Moreover, the quality of Landsat images after 2003 is deteriorated by blank stripes due to the failure of the scan line corrector (www.landsat.usgs.gov), which affects the visibility of complete Landsat scenes. The obtained four Landsat images are located in three different locations in the study area shown in Figure 3.

In order to differentiate between these images, they are labeled with the name of the snow station that lies inside each image frame, namely Alma-Ata, Naryn and Djalal-Abad images. Four Landsat images are obtained for these three test sites, with Alma-Ata and Naryn sites having one image each, and Djalal-Abad site having two images.

In order to evaluate MODIS snow fraction product in the study area, the percentage of Landsat snow cover fraction for each MODIS 500 m grid cell was computed. The

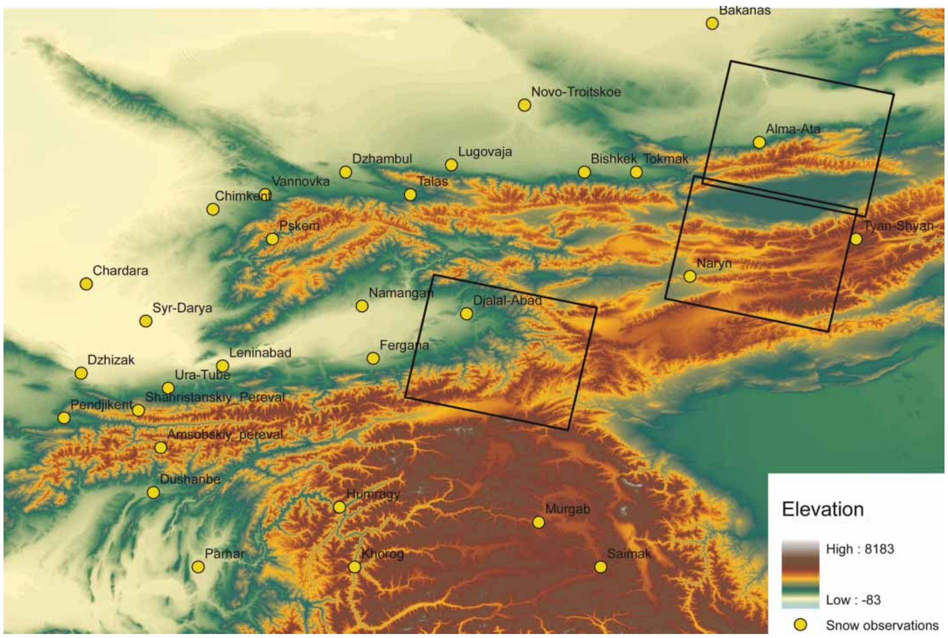

Figure 3 | Locations of three Landsat scenes used for the comparison with MODIS data.

resulting Landsat 500 m snow cover fraction map was then compared against the MODIS 500 m snow fraction map.

METHODOLOGY

Data preprocessing

For the period 2000–2009, daily MODIS snow cover maps were prepared for comparison with the station data for the entire Central Asian mountainous region, where observation stations also exist. As the original MODIS snow data are obscured by cloud cover, only clear sky pixels were used for comparison against observations on each day. Some observation stations were removed for the evaluation as they had very few data. Only stations that had more than 10 available datasets (clear sky MODIS pixels and available observation data on that location) were used for the comparison. As a result, 23 and 19 observation stations were used for the comparison with the MODIS Terra and MODIS Aqua products, respectively. The comparison was carried out by checking MODIS snow product pixels that correspond to station locations.

Cloud elimination from MODIS snow cover maps

As MODIS snow cover data are obscured by clouds, the ModSnow algorithm (Gafurov & Bárdossy 2009) was applied to remove the cloud cover and estimate the snow coverage without clouds. The ModSnow algorithm removes clouds step by step using spatial and temporal information. It has six subsequent steps in which each step removes some portion of clouds until all clouds are eliminated. The ModSnow algorithm uses elevation as a key information for cloud removal in some of the steps and, due to this fact, the algorithm functions better in mountainous areas, where spatial snow cover variability is mainly elevation dependent. Using this algorithm, cloud free snow cover maps were obtained for each day in the period 2000–2009 for the entire mountainous region of Central Asia. Combination of Aqua and Terra images is one of the ModSnow steps, and for this reason, the output from ModSnow is only one snow cover map for each day. Figure 4 shows cloud covered and cloud removed images of the study area on 30 November 2004. For further details on ModSnow, see Gafurov & Bárdossy (2009).

Snow cover mapping using Landsat data

Furthermore, the MODIS snow cover product was compared against higher resolution Landsat data. In order to create snow cover maps using different Landsat bands, reflectances were calculated following the method of Chander *et al.* (2009), and a snow mapping algorithm was developed in this study. In this algorithm, spectral bands 2 (0.53–0.61 μm) and 5 (1.55–1.75 μm), which are suitable for snow cover estimation and correspond to MODIS bands 4 (0.545–0.565 μm) and 6 (1.628–1.652 μm), are used to estimate binary snow cover data using the NDSI methodology. As a threshold value for NDSI, 0.4 was taken, which is the value also taken for the MODIS snow cover product. Additionally, spectral band 3 (0.70–0.80 μm) was used to better classify snow cover by setting its threshold value to 20. All pixels with NDSI greater

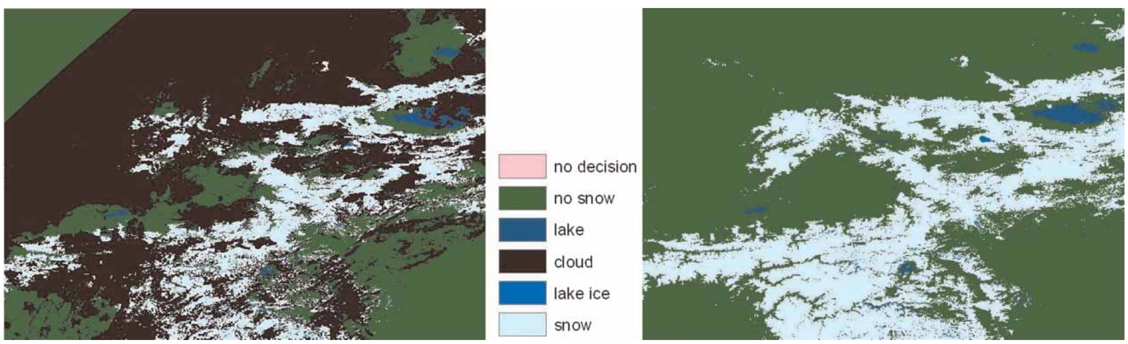

Figure 4 | MODIS snow maps: original with cloud cover (left) and processed with ModSnow (right) for 30 November 2004.

than 0.4 and band 3 value less than 20 were classified as snow. As some Landsat images also contain a small fraction of cloud cover and water surface, the water and cloud detecting conditions were also included in the snow mapping algorithm. Landsat bands 4 and 5 were therefore employed for water surface detection, with a threshold value of 5 for both bands. Pixel values in bands 4 and 5 smaller than 5 were assigned as water surface. Finally, cloud cover was estimated by means of thermal band 6. This band represents the at-sensor temperature of a reflecting object (an object on the Earth's surface or cloud). As the cloud surface temperature is much lower than the Earth's surface temperature, a threshold value allows the differentiation of reflecting objects as either being the Earth's surface or the top of clouds. As the elevation difference between clouds and the Earth's surface is high, their temperature is different. The threshold value for the thermal band was set to be different for different days to consider the temperature variations during the 4 days of Landsat observations. However, differentiating snow cover from cloud cover becomes difficult if the snow covered area is in high elevation zones where low clouds may be present. This leads to similar at-sensor temperatures. Cloud cover was observed only in two of the images of Landsat, and the threshold values for the at-sensor temperatures were set to 265 and 261 K for the images on 9 May 2000 and 29 April 2003, respectively. After creating snow cover maps from Landsat, two different remote sensing snow cover maps are available with different spatial resolution and very little observation time difference (few hours) within 1 day. The derived Landsat snow maps were visually validated using the original Landsat data in true color, which is acceptable to carry out ground truth validation. The threshold values for detecting different objects on the Earth's surface (water, land, snow, etc.) were adjusted during this visual validation process. Finally, the Landsat snow cover data were aggregated to 500 m resolution taking the majority of non-cloud 30 m Landsat snow pixels within 500 m MODIS snow pixel in order to carry out pixel-to-pixel comparison. An aggregated Landsat pixel was assigned as snow covered, if at least 50% of its area were identified as snow. Figure 5 illustrates the original Landsat image, the Landsat snow cover map and the MODIS snow cover map for different days. For the comparison of two snow maps, only cloud free pixels were taken into consideration.

In the MODIS snow cover algorithm, the normalized difference vegetation index is also used for estimating snow cover in forested areas; this is not considered for Landsat snow mapping in this study. The original Landsat images (top row, Figure 5) show clear differences between main objects on the surface (land, water, snow and clouds). The MODIS snow cover maps show some clouds for all days, whereas Landsat shows no clouds on 2 April 2000 and 2 November 2002. One reason for this may be that clouds are dynamic features and that they appeared during the MODIS observation, but were not visible any more during the Landsat observation. Another reason may be misclassification of cloud cover by MODIS. There are also days with cloud observation by the Landsat sensor, and these pixels are detected by the Landsat snow algorithm as cloud (lower right corner of Naryn site on 29 April 2003 and right-hand side middle of Alma-Ata test site on 5 September 2001). The Djalal-Abad test site on 2 April 2000 and on 2 November 2002 was cloud free during Landsat observation. In general, Figure 5 shows similar snow coverage over the test sites by Landsat and MODIS products. Unfortunately, there were no observations available from the snow stations Alma-Ata, Djalal-Abad or Naryn for those 4 days to compare Landsat snow data with station observations. However, the Landsat data are assumed to be good enough to be accepted as ground truth data for MODIS snow cover comparison.

RESULTS AND DISCUSSION

Evaluation of original MODIS Terra and MODIS Aqua snow products

As a first step, the original MODIS Terra and Aqua snow maps were compared against observed snow data. The accuracy for each station was based on the proportion of MODIS snow to station snow agreement for all observation available days. For example, station Alma-Ata had 228 valid observations (clear sky MODIS and available observed snow data), and on 212 days snow to snow hit was observed, which yields an accuracy of 93%. Table 2 shows the

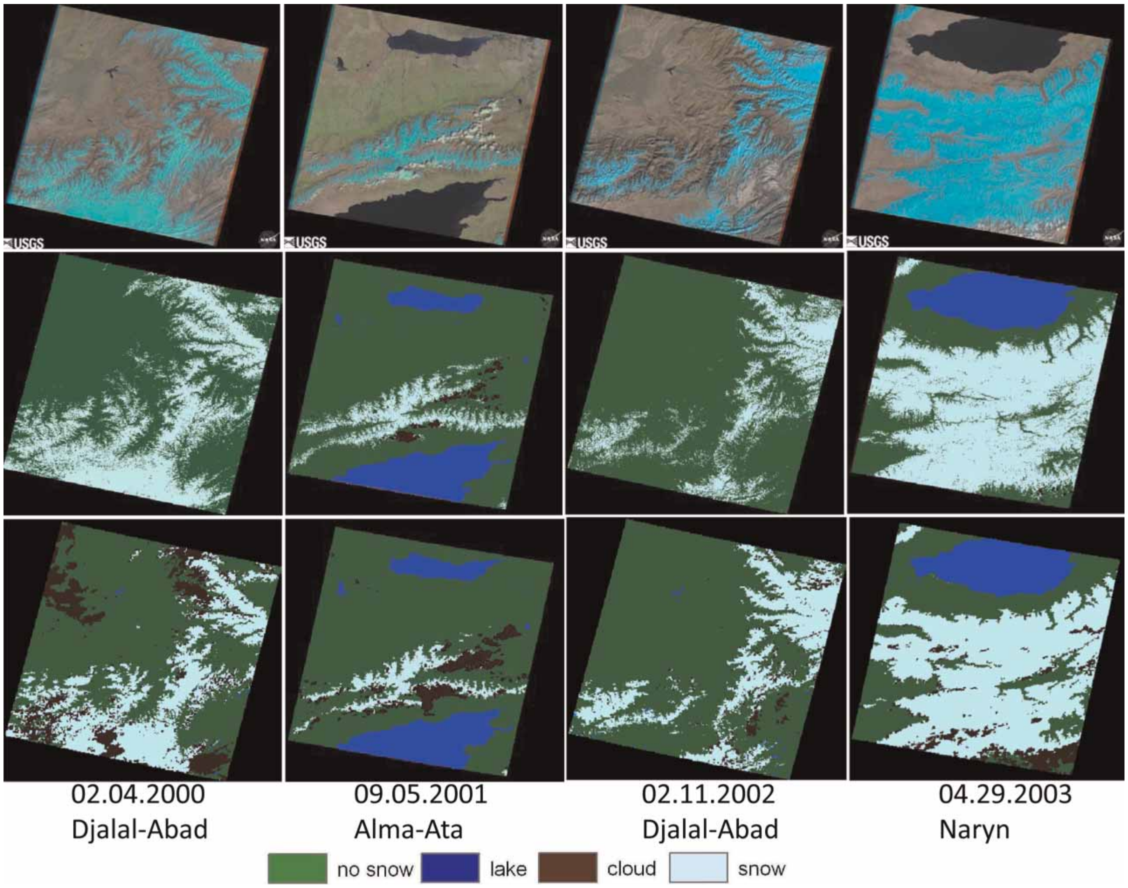

Figure 5 | Original Landsat image of band 2 (above), Landsat aggregated snow map (middle), and MODIS snow map (below) for different days (the legend does not apply for original Landsat images).

comparison results for snow to snow agreement, as well as snow to land disagreement for Terra and Aqua snow products against ground observations.

The accuracy of the MODIS product varies from station to station. The lowest accuracy for the MODIS Terra product is 65% at Namangan station. The highest accuracy is 100% at Novo-Troitskoe station. For the MODIS Aqua product, the accuracy varies between 48% at Chimkent station and 100% at the stations Novo-Troitskoe and Pskem. The low accuracy is generally obtained for low-elevation stations located below 1,000 m a.s.l. elevation line. Some of the low accuracies may be the result of a small number of observations, where a few disagreements can lead to low accuracy. Another reason for disagreement could be the different spatial measurement scales. MODIS is an areal observation, and the *in situ* data are a point observation. Figure 6 plots the accuracy of the MODIS snow product against elevation. The two stations with an elevation higher than 2,000 m a.s.l. have high accuracies, whereas the accuracy of low elevation stations varies considerably.

The two lowest accuracies (48.4 and 54.5%) are from MODIS Aqua snow products for Chimkent and Dushanbe stations. These stations have a lower number of datasets for comparison (Table 2), where a few disagreements may lead to lower accuracy. Such disagreements may also arise due to station characteristics where different objects may exist within 500 m² pixel location (buildings, roads, single trees, small water surfaces), which would influence the overall reflectance of this area and deliver different NDSI values for snow classification. For example, the Naryn station is located inside Naryn city and is very close (100–200 m distance) to the city asphalt road and urban areas with dense houses (personal visits to the station and observations can be made using Google Earth Software, www.earth.google.com),

Table 2 | Comparison of Terra and Aqua snow products against *in situ* data (MS: MODIS snow, ML: MODIS land, GS: ground snow; column MS to GS: MODIS and ground station identify snow; column ML to GS: MODIS identifies land, whereas ground station identifies snow)

			Terra			Aqua		
Stations	**Elevation m a.s.l.**	**Observations**	**MS to GS**	**ML to GS**	**Accuracy (%)**	**MS to GS**	**ML to GS**	**Accuracy (%)**
Alma-Ata	847	645	212	16	93.0	40	8	83.3
Bakanas	396	506	152	16	90.5	124	22	84.9
Bishkek	756	392	133	13	91.1	43	6	87.8
Chardara	240	161	42	1	97.7	39	1	97.5
Chimkent	606	383	95	34	73.6	15	16	48.4
Djalal-Abad	771	330	81	22	78.6	56	14	80.0
Dushanbe	803	110	31	14	68.9	18	15	54.5
Dzhambul	642	329	102	8	92.7	82	5	94.3
Dzhizak	392	124	17	5	77.3			
Fergana	578	98	22	1	95.7	26	1	96.3
Khorog	2,077	398	149	1	99.3	75	3	96.2
Lugovaja	682	402	175	1	99.4	142	5	96.6
Namangan	474	112	11	6	64.7			
Naryn	2,039	708	244	21	92.1	159	9	94.6
Novo-Troitskoe	455	455	161	0	100.0	159	0	100.0
Pendjikent	1,015	35	10	3	76.9			
Pskem	1,259	717	298	2	99.3	179	0	100.0
Syr-Darya	264	146	34	4	89.5	30	6	83.3
Talas	1,217	538	195	11	94.7	129	8	94.2
Tokmak	816	353	113	18	86.3	56	13	81.2
Tyan-Shyan	206	1,307	482	5	99.0	277	1	99.6
Ura-Tube	1,043	93	18	5	78.3			
Vannovka	809	360	156	10	94.0	138	8	94.5
Sum		8,702	2,933	217		1,787	141	
Overall Mean					93.1			92.7

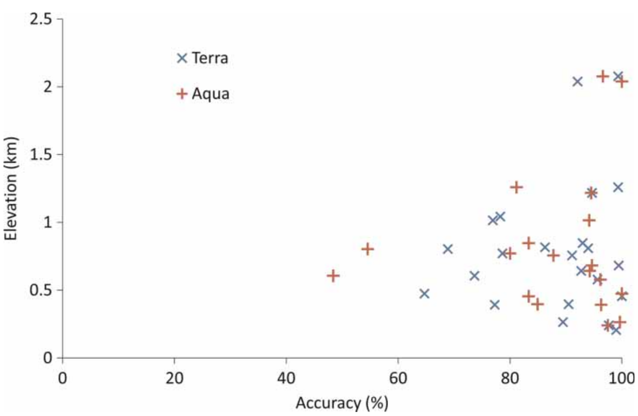

Figure 6 | Accuracy of MODIS snow product against elevation.

on which the snow melts faster than in grass areas (where the snow measurement device is installed), and which deliver different reflectances during observations from space. The areal proportion of these different objects per pixel is over 50% around the Naryn station. Thus, depending on where MODIS pixel borders are, it is possible that MODIS classifies a pixel as no snow due to the fact that less than 50% area of the 500 m² pixel is covered by snow, but the snow measurement device is in the snow covered part of this pixel and the station records the area as snow covered. Such misclassifications can be especially expected from meteorological stations if they are located close to the city. Dushanbe and Chimkent are urban areas in Central Asia such as Naryn city where other possible objects in the surrounding surface area may deliver varying reflectances for the remote sensing instrument.

The overall accuracies computed taking the snow to snow (2,933 and 1,787 for Terra and Aqua, respectively) and the snow to land (217 and 141 for Terra and Aqua, respectively) proportion for all station observations together in the entire region are 93.1 and 92.7% for Terra and Aqua snow maps, respectively. In general, the achieved accuracies in this study are similar to those reported by other studies in China (Pu *et al*. 2007; Liang *et al*. 2008; Huang *et al*. 2011).

Evaluation of cloud removed snow maps

Using the ModSnow algorithm, cloud covered pixels from original snow maps were eliminated by estimating the real coverage for those pixels (snow or land). Cloud free MODIS snow cover maps were then used to validate the performance of the ModSnow algorithm against observed station data. For this purpose, only cloud removed pixels using ModSnow were compared against observed station data. The procedure for accuracy assessment was the same as with the original MODIS data, which is based on the proportion of ModSnow snow to station snow agreement for all observation available days. Table 3 shows the comparison results of the MODIS snow cover product after cloud removal against ground observation data.

The accuracies range from 16.7% for station Parhar to 98.6% for station Bishkek. This can be associated with the elevation of each station and surrounding topography. Figure 7 illustrates the accuracy of the ModSnow processed snow product at each station against its elevation. Lower stations (approximately lower than 1,000 m a.s.l.) show low to high accuracy, whereas the three higher stations above 1,500 m a.s.l. have high accuracy. This is due to the fact that in three steps of the ModSnow algorithm, the elevation of each pixel is a major indicator for estimating real coverage for cloud covered pixels. Elevation information from neighboring pixels to cloud covered pixel is used for estimating pixel coverage. If the elevation of neighboring pixels has little difference to cloud covered pixel, snow or land cover estimation from ModSnow can lead to misclassification. For this reason, the ModSnow algorithm

Table 3 | Comparison of ModSnow processed snow product against *in situ* data (MODS: ModSnow snow, MODL: ModSnow land, GS: ground snow; column MODS to GS: ModSnow and ground station identify snow; column MODL to GS: ModSnow identifies land, whereas ground station identifies snow)

Stations	Elevation	Observations	MODS to GS	MODL to GS	Accuracy (%)
Alma-Ata	847	645	97	11	89.8
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Dushanbe	803	110	16	18	47
Dzhambul	642	329	52	9	85.3
Dzhizak	392	124	21	22	48.8
Fergana	578	98	25	10	71.4
Khorog	2,077	398	82	4	95.4
Lugovaja	682	402	82	10	89.1
Namangan	474	112	13	42	23.6
Naryn	2,039	708	103	12	89.6
Novo-Troitskoe	455	455	91	9	91
Parhar	446	16	2	10	16.7
Pskem	1,015	35	132	3	97.8
Syr-Darya	264	146	33	17	66
Talas	1,217	538	102	7	93.6
Tokmak	816	353	61	26	70.1
Tian-Shan	3,614	1,307	251	8	96.9
Vannovka	809	360	74	3	96.1
Sum			1,617	299	
Overall Mean					84.4

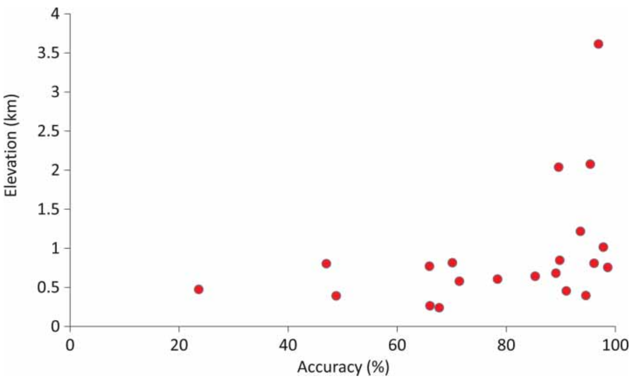

Figure 7 | Accuracy of ModSnow processed snow product against elevation.

should work better in higher elevated areas than in flat areas. The low elevation stations Parhar and Namangan have the lowest accuracy, and this can be explained with the latter argument. However, these stations have a small number of observations, which can also influence the accuracy result. For the tradeoff between cloud reduction and accuracy change, Gafurov & Bárdossy (2009) reported that the main error arises from step 6, which is based on threshold days for snow melt out and snow accumulation. This step removes remaining cloud cover from snow maps. The misclassifications from steps 1 to 5 (step 1 – combination of MODIS Terra and Aqua snow maps, step 2 – temporal combination of each pixel, step 3 – snow transition line, step 4 – spatial combination of neighboring pixels, step 5 – combination of neighboring pixels and elevation difference between them) would lead to less than 5%, and step 6 would lead to the highest errors of about 10%. The overall accuracy of the ModSnow algorithm when taking all station measurements in the region together is 84.4%.

The achieved overall accuracy shows a reliable estimation by ModSnow for cloud covered pixels, especially in heterogeneous topography. The performance is very good for some stations, such as Tian-Shan where only 8 out of 259 cloud covered pixels were incorrectly estimated. However, there are also some stations like Dzhizak or Namangan where accuracies are low. These stations have a smaller number of comparison datasets (ModSnow applied days and observation available days), which can also influence the accuracy assessment. The overall accuracy in Table 3, computed by taking the sum of snow to snow and snow to no snow hits, shows that out of 1,916 cloud removals, 1,617 of them were estimated correctly, which results in 84.4% accuracy. These results show the ability of the ModSnow algorithm to eliminate cloud cover in mountainous areas with improved accuracy. This makes it possible to obtain snow information from highly inaccessible areas in mountainous regions, even if the day was cloud covered during remote observation.

Comparison of Landsat and MODIS snow cover products

As a next step in the evaluation process, the Landsat snow maps (Figure 5, middle) generated in this study were used as 'ground truth' to assess the accuracy of MODIS snow cover maps (Figure 5, bottom). This was done by building a contingency table between MODIS and Landsat pixel classifications. Columns 2 and 3 in Table 4 show the contingency values for the comparison between MODIS and Landsat snow maps. The table gives the amount of agreement for snow and land, the disagreements of snow being identified as land and vice versa in percentages for each test site and test date.

The total agreement (sum of snow to snow and land to land) for these test sites and test dates is at least 89.5%. Column 6 in Table 4 shows the accuracy on each date.

Table 4 | Comparison of MODIS and Landsat snow cover data (TS: Terra snow, TL: Terra land, AS: Aqua snow, AL: Aqua land, LS: Landsat snow, LL: Landsat land, SAI: snow area index, MS: MODIS snow, MC: MODIS cloud, LC: Landsat cloud). Columns 2 and 3 give contingency of MODIS and Landsat snow cover

	LS (%)	LL (%)	Date	Test site	Accuracy (%)	SAI	MS (%)	LS (%)	MC (%)	LC (%)
1	2	3	4	5	6	7	8	9	10	11
TS	25.34	4.30	02.04.2000	Djalal-Abad	89.5	0.70	25.23	34.81	14.65	0
TL	6.22	64.14								
TS	6.20	1.33	09.05.2001	Alma-Ata	95.3	0.56	6.05	8.65	5.73	2.07
TL	3.39	89.08								
TS	15.09	6.56	02.11.2002	Djalal-Abad	91.1	0.62	20.68	18.01	3.32	0
TL	2.35	76.00								
AS	56.79	4.07	29.04.2003	Naryn	92.2	0.87	48.58	52.14	6.22	1.03
AL	4.08	35.07								
AS	13.43	6.20	02.11.2002	Djalal-Abad	91.3	0.61	17.96	18.01	7.41	0
AL	2.49	77.87								

The highest accuracy was obtained from Alma-Ata test site on 9 May 2001 when the snow coverage was the least among the other test sites. However, this can be biased due to high land-to-land agreement on this day. On 9 May 2001, only 6% of the area was covered by snow according to MODIS. Landsat shows 8.6% snow coverage, and this slight difference can be due to different cloud coverage on both images. About 90% of the area is covered by no snow pixels, which highly contributes to the overall agreement. In order to overcome this bias, the so-called snow area index (SAI) methodology is used to assess the accuracy associated to only snow covered pixels. This methodology is well suited for comparing binary maps. It is based on the contingency values given in Table 4. It has been originally developed to compare flooded areas using binary information (wet/dry) from remote sensing against model outputs of flood inundation areas (Horritt & Bates 2001). The formula for this comparison methodology is:

$$\mathrm{SAI} = \frac{\mathrm{SS}}{\mathrm{SS} + \mathrm{SL} + \mathrm{LS}} \tag{1}$$

where SS, SL and LS correspond to snow–snow, snow–land and land–snow agreements, respectively. As the land-to-land agreement is not included in the equation, the comparison methodology considers only pixels detected as snow, either from MODIS or from Landsat or from both. Thereby, the frequency of land-to-land agreement is neglected, as it can be orders of magnitude larger than the other elements in the contingency table. The resulting SAI values are given in column 7 of Table 4. For perfect matching, the SAI value is 1, for no matching at all, the SAI value becomes 0. As shown in Table 4, the accuracy that MODIS snow and land pixel match with Landsat snow and land pixels becomes over 95% for 9 May 2001, although the snow coverage on that date is only about 6% (MODIS) or 8% (Landsat). Correspondingly, the SAI value becomes 0.56, meaning slightly over half of the pixels (from 6 to 8% snow) meet snow agreement. This is acceptable, as disagreements can occur mainly in transition zones from snow to land cover, especially when the spatial aggregation from 30 to 500 m is carried out before the comparison. The test date 29 April 2003 for the Naryn test site shows the highest snow coverage with almost half of the test site being covered by snow. The accuracy on this site is about 92%, and the SAI becomes 0.87. This corresponds to 87% snow-to-snow agreement among the snow observed pixels, either from MODIS or Landsat. The overestimation or underestimation of the MODIS snow cover product compared to Landsat can be observed from contingency values and columns 8 and 9 in Table 4. On 2 April 2000 and 9 May 2001, the snow cover area is underestimated by MODIS, as the MODIS land to Landsat snow proportion is higher than the MODIS snow to Landsat land proportion. On 2 November 2002, the MODIS overestimates the snow cover and on 29 April 2003, both proportions are similar. Therefore, it is difficult to extract a clear overestimation or underestimation trend from MODIS and Landsat using the obtained accuracies. However, two MODIS underestimations were obtained from the snow melting season, and one MODIS overestimation was obtained from the snow accumulation season, although the obtained results are insufficient to draw the conclusion on systematic seasonal differences.

The Aqua snow map from 2 November 2002 is not shown in Figure 5 as the MODIS Terra snow map is shown for this day in the Djalal-Abad site. In general, the agreement between the MODIS and Landsat snow products is good. One reason for disagreements is the different spatial resolution. Aggregation of Landsat snow cover from 30 to 500 m can lead to incorrect classification, especially in snow transition zones. The accuracy agreement between MODIS and Landsat also depends on the fraction of snow covered pixels lying in the transition zone. This was clearly recognizable in the case of 9 May 2001, with the highest fraction of transition pixels and lowest SAI value (0.56). In contrast, on 29 April 2003, the fraction of snow transition pixels is low, and the accuracy is high (SAI = 0.87).

Validation of MODIS snow fraction data using Landsat snow cover data

As a final step in this study, the evaluation of MODIS snow cover fraction product against Landsat snow fraction data is conducted. The evaluation was based on pixel to pixel comparison of the MODIS snow fraction map and the Landsat snow fraction map explained in the data section. In order to assess the accuracy, the distribution of errors (Figure 8) and scatterplots (Figure 9) are presented.

Figure 8 illustrates the error distribution between MODIS and Landsat snow fraction. As shown, the error distribution is related to the extent of the snow cover. A larger snow covered area leads to a better snow fraction agreement between both datasets. The best accuracy was achieved for 29 April 2003, where the test site was covered by 48.6% snow observed from MODIS. The least accuracy was achieved for 9 May 2001, where the test site was covered by only 6% snow. It is expected that most of the errors occur in the transition zone, the snow line where rapid snow to land, or vice versa, changes occur. Pixels with 100% snow cover should lead to an accurate fraction agreement. The lowest accuracy on 9 May 2001 can be assumed to arise from the highest portion of transition zone pixels. Contrary to this, the image on 29 April 2003 should have the least amount of transition zone pixels compared with the other images. Most of the snow covered pixels on this day contain 100% snow fraction, which is expected to match well with the Landsat snow fraction.

Similar to snow cover comparison, land pixels (0% snow) and cloud obscured pixels were not considered for fractional evaluation. Figure 9 illustrates scatterplots for MODIS and Landsat snow fractions. The legend shows the frequency of agreements/disagreements. For example, on 2 April 2000, the frequency of agreements with 100% snow fraction adds up to 22.3% of all pixels. The rest of the agreements sum up to a maximum of 3%. Most of the disagreements occur at most 0.1% only (points inside the scatterplot), however, there are some agreements among this class along the 1:1 correlation line. The scatterplots also show underestimation or overestimation of MODIS snow fraction. This is visible in cases where Landsat has some snow fraction and MODIS has no snow fraction (points along the *x*-axis). However, there is also overestimation from MODIS, especially for the cases when Landsat snow fraction is over 80% (right hand side of upper *x*-axis). This leads to the conclusion that MODIS clearly underestimates snow fraction for patchy snow when Landsat identifies some snow (usually up to 20% snow fraction). The underestimation of MODIS in this study is similar to that reported by Déry *et al.* (2005), where clear

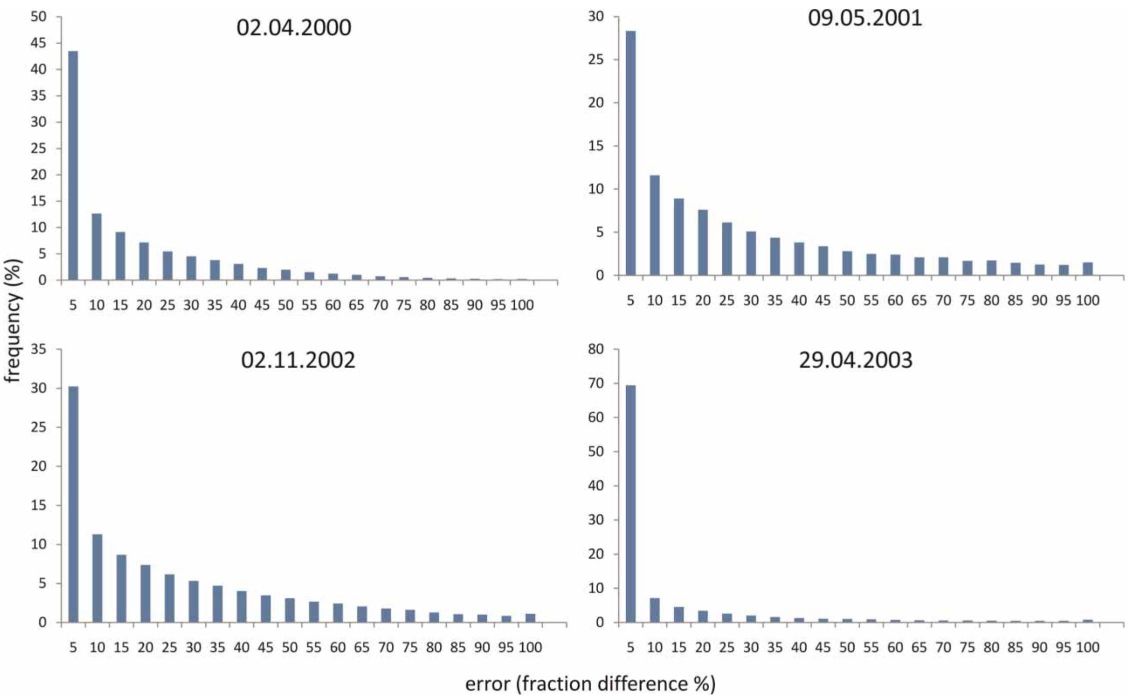

Figure 8 | Accuracy of MODIS and Landsat snow cover difference for different days.

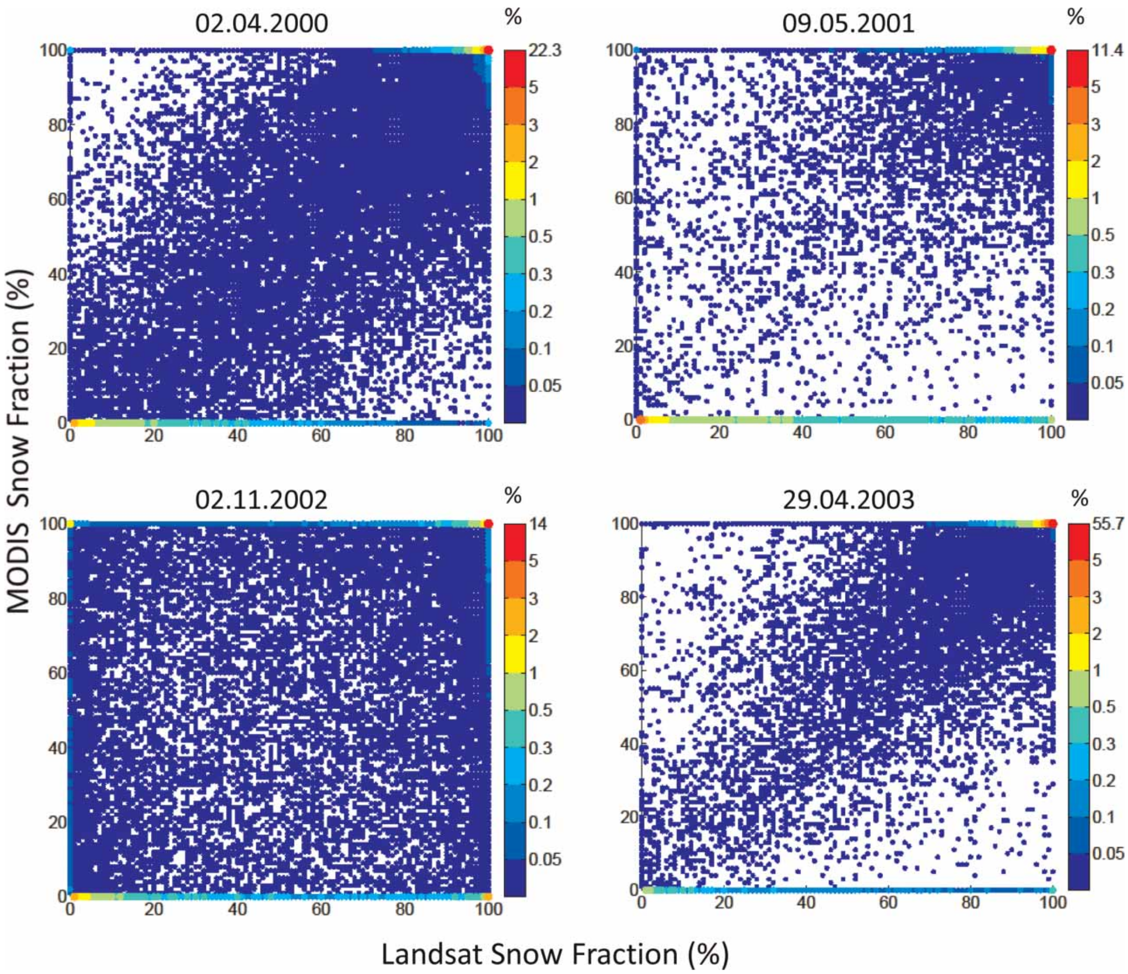

Figure 9 | Frequency of MODIS and Landsat snow cover agreements/disagreements for different days. The color bar denotes point frequency within the scatterplot. The full color version of this figure is available online at http://www.iwaponline.com/nh/toc.htm.

underestimation was also observed for patchy snow. However, it is also visible from Figure 9 that MODIS overestimates snow fraction in the study area if the Landsat snow fraction is over 80%. This can possibly be linked to the fact that the universal relationship obtained by studies in other parts of the world may differ slightly for Central Asia. Adjusting the parameters of this linear relationship for Central Asia may improve the results. Surprisingly, there are some cases when MODIS identifies 100% snow fraction and Landsat identifies no snow on those pixels (upper left corner). Contrary to this, there are also cases when Landsat identifies 100% snow fraction at some pixels and MODIS identifies no snow on those pixels (lower right corner). However, their frequency is marginal (in the range 0.2–0.3%) compared with other point frequencies. Errors with this magnitude may arise from misclassification of clouds as snow. In general, the frequency of matches is the highest for fractional snow cover of 100% in both MODIS and Landsat. MODIS often underestimates the fractional snow cover by indicating a zero fraction where Landsat shows a non-zero fraction. In particular, the underestimation is frequent for a Landsat snow cover fraction up to 10%. On the other hand, MODIS overestimates the snow fraction for pixels covered up to 80% by indicating them as 100% covered with snow.

CONCLUSIONS

MODIS snow cover products were evaluated for Central Asia using observed *in situ* data and higher resolution

Landsat data. The processed MODIS snow cover product was compared with 30 snow measurement stations. The overall accuracy of MODIS Terra snow product was 93.1%, with an accuracy ranging from 64.7% at Namangan station to 100% at Novo-Troitskoe station. For the MODIS Aqua snow product, the accuracy was 92.7%. Low elevation stations had low and high accuracy, whereas the few high elevation stations showed high accuracy. The obtained accuracy results are similar to those obtained by other studies in China (Pu *et al*. 2007; Liang *et al*. 2008; Huang *et al*. 2011). Lower accuracies originating from lower located stations can be linked to the fact that these stations could be located in areas with heterogeneous land cover where other surrounding surface objects may influence the reflectance of pixel extent for MODIS instrument.

As the MODIS snow cover product is obscured by clouds, the cloud coverage was removed using the ModSnow algorithm. The resulting cloud free snow maps were also validated using station data. For the accuracy assessment, only cloud removed pixels were considered. An overall accuracy of 84.4% was achieved for ModSnow processed snow maps taking snow observations from all stations together. Better results were observed for high elevation stations. This shows that the ModSnow algorithm functions better in mountainous regions compared to flat areas, taking into consideration that three out of six steps in the ModSnow algorithm use elevation as main indicator for cloud elimination.

In order to evaluate MODIS snow cover data against Landsat data, a snow cover algorithm was developed to estimate snow maps using Landsat raw bands. Thereby, snow cover maps for four clear sky Landsat images were created. The pixel-to-pixel agreement between MODIS and Landsat snow maps show an overall accuracy of 91.9%, with the accuracy varying from 89.5 to 95.3%. These accuracies are, however, dominated by land-to-land agreements. An SAI was introduced to limit the evaluation to snow concerned areas only. The SAI values also showed positive results with respect to snow fraction for whole test site. Higher SAI values were obtained for sites with more snow. The main error sources are snow transition areas where the MODIS snow cover classification may be different to the Landsat snow classification due to the coarser resolution of MODIS. Underestimation of MODIS snow cover was observed for two images from the snow melt season, and overestimation of MODIS was observed for one image during the snow accumulation season. However, the number of images is too low to suggest that MODIS systematically underestimates snow cover during snow melt and vice versa.

As a last step, MODIS snow fraction product was evaluated using Landsat snow cover data. The accuracy assessments showed that the agreement between MODIS snow cover fraction and Landsat snow fraction was acceptable. However, it was also visible from the results that MODIS underestimates snow fraction if the pixel is less snow covered by Landsat. This shows that MODIS cannot detect areas with patchy snow as snow covered. On the other hand, overestimation of MODIS snow fraction was obtained for pixels with more than 80% snow coverage. The main error magnitudes can be related to snow cover fraction on each test site and to the proportion of transition zone pixels from snow to land or vice versa. Moreover, the overestimation and underestimation of MODIS snow fraction may also be caused by the linear relationship between MODIS snow fraction and NDSI, as it is used for the development of the MODIS snow fraction product globally. This relationship may slightly differ for Central Asia, taking the obtained disagreements into consideration. However, the frequency of disagreements is minor in this study to fully support the latter argument.

This study shows that MODIS derived snow data are rather reliable for Central Asia. Snow is a dominant parameter in Central Asian hydrology, and daily snow cover maps such as those from MODIS can be very useful to model and better understand Central Asian hydrology. The snow covered area has usually been observed using helicopters or has been interpolated on the basis of station measurements. However, snow measurements are very rare in very high altitudes due to inaccessibility or due to the high survey costs. In such conditions, snow extent information from remote sensing can be a very good alternative. Snow mapping from remote sensing may give better and more detailed spatial information about the snow covered area than estimations using the temperature precipitation methodology, where some local conditions such as orographic effects are usually not considered. On the other hand, it is possible to reliably classify snow covered areas by remote sensing due to the fact that snow has more distinct reflecting properties than other objects on the Earth's surface. The globally available MODIS snow cover product can be well applied to study meso-scale snow dynamics in Central Asia.

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