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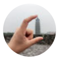

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Accuracy assessment of four cloud-free snow cover products over the Qinghai-Tibetan Plateau

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ABSTRACT

Four up-to-date daily cloud-free snow products – IMS (Interactive Multisensor Snow products), MOD-SSM/I (combination of the MODIS and SSM/I snow products), MOD-B (Blending method basing on the MODIS snow cover products) and TAI (Terra–Aqua–IMS) – with high-resolutions over the Qinghai-Tibetan Plateau (QTP) were comprehensively assessed. Comparisons of the IMS, MOD-SSM/I, MOD-B and TAI cloud-free snow products against meteorological stations observations over 10 snow seasons (2004–2013) over the QTP indicated overall accuracies of 76.0%, 89.3%, 92.0% and 92.0%, respectively. The K_{hat} values of the IMS, MOD-SSM/I, MOD-B and TAI products were 0.084, 0.463, 0.428 and 0.526, respectively. The TAI products appear to have the best cloud-removal ability among the four snow products over the QTP. Based on the assessment, an I-TAI (Improvement of Terra–Aqua–IMS) snow product was proposed, which can improve the accuracy to some extent. However, the algorithms of the MODIS series products show instability when identifying wet snow and snow under forest cover over the QTP. The snow misclassification is an important limitation of MODIS snow cover products and requires additional improvements.

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KEYWORDS
MODIS; IMS; snow-covered area; cloud removal; TAI

1. Introduction

Mid-latitude Alpine snow cover is characterized by rapid seasonal changes and large spatial variations, which play important roles in energy changes, climate, water resources and ecological processes (Dozier and Painter 2004). Known as Asia's water tower, the glaciers and snowpack over the Qinghai-Tibetan Plateau (QTP) provide the headwater for several major rivers in Asia (Xu, Ramanathan, and Washington 2016). The water supplied by this region affects approximately 50–60% of the world's population in China and parts of Asia (Barnett, Adam, and Lettenmaier 2005). In addition, severe snow storms can lead to lower nongrowing season and Normalized Difference Vegetation Index (NDVI), which affect the spring phenology over the QTP (Zhang et al. 2013).

Snow cover maps provide information about the spatial extent of the snow cover and are very useful for snow-related research. The snow cover on the plateau has important influences on the

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atmospheric circulation in the northern hemisphere but also directly affect the climatic and eco-environmental evolution of China (Qin, Liu, and Li 2006). Snow-covered area, duration of snow cover, snow depth and snow albedo over the QTP significantly influence atmospheric circulation at the local or regional scale (Cess et al. 1991; Chen and Sun 2003; Flanner et al. 2011; Thackeray and Fletcher 2016; Wei et al. 1998). Particularly, snow-covered areas affect assessments of radiation and water balance and are important inputs for studying hydrological cycles and regional climate (Cline, Bales, and Dozier 1998; Dozier and Painter 2004; Hall and Martinec 1985; Kirnbauer, Blöschl, and Gutknecht 1994).

Due to the remoteness, topographic complexity and the relative sparsity of meteorological observation over the QTP, remote sensing is the most practical tool for monitoring a snow-covered area over the QTP. Compared with other remote-sensing snow cover data, a set of five MODIS now products (MOD10A1, MOD10A2, MOD10C1, MCD10C2 and MOD10CM) is currently widely applied because of the fine spatial resolution and high temporal resolutions that are available at the National Snow and Ice Data Center (Hall et al. 2002). MODIS snow cover products are compared based on *in situ* measurement or other satellite data and have been validated in different regions of the world (Bitner et al. 2002; Hall and Riggs 2007; Klein and Barnett 2003; Maurer et al. 2003; Parajka and Blöschl 2006; Zhou, Xie, and Hendrickx 2005). The overall accuracy of the well-studied 500 m resolution swath (MOD10 L2) and daily tile (MOD10A1) products is 93% under clear sky conditions and varies with land type (Hall and Riggs 2007). On the QTP, the data quality of MODIS snow products also has been verified by individual studies. The accuracy of the MODIS/Terra Snow Cover 8-Day L3 Global 500-m Grid (MOD10A2) neared 90% when compared with meteorological station observations over the Tibetan plateau (Pu, Xu, and Salomonson 2007). Wang et al. (2013) combined the MODIS and AMSR-E data for snow mapping over the Tibetan Plateau, showing that the accuracy of the MOD10A1 and MYD10A1 products was 81% when SD (snow depth) exceeded 3 cm. Four satellite-based snow products (MOD10A1, MYD10A1 and Interactive Multisensor Snow products-IMS, and Landsat TM snow cover products) are evaluated over the Tibetan Plateau for the 2007–2010 snow seasons. The overall accuracy of MOD10A1 and MYD10A1 is higher than 91% and IMS is only 79% against Landsat TM snow cover images (Yang et al. 2015). However, for hydrologic and climatological applications, the applicability of MODIS snow cover products is significantly restricted by the severe cloud obstruction over the QTP. Although the snow algorithm developed by the MODIS data group can separate snow from the most obscuring clouds, daily MODIS data still have a relatively high cloud-covered fraction (as high as 47.3% over the QTP according to Tang et al. (2013). Cloud cover can significantly limit the application of MODIS snow products (López-Burgos, Gupta, and Clark 2013; Parajka and Blöschl 2006; Wang et al. 2009).

Removing clouds from MODIS data is essentially a reclassification of cloud pixels. Much research has been applied for removing cloud pixels from MODIS data over the past 10 years (Dong and Menzel 2016a; Dong and Menzel 2016b; Gafurov et al. 2015; Gafurov and Bárdossy 2009; Hall et al. 2010; Krajčí et al. 2014; López-Burgos, Gupta, and Clark 2013; Parajka and Blöschl 2008; Qiu, Zhang, and Chu 2017;Wang et al. 2009; Xia et al. 2012; Xie, Wang, and Liang 2009). All the published cloud-reduced techniques from MODIS snow cover products include the combination of multi-products from different sensors, spatial combination, temporal combination, snow season determination, snow line determination and locally weighted logistic regression and *in situ* snow data interpolation. Based on these cloud-removing approaches, four daily cloud-free, high-resolution snow cover products have been mapped over the QTP. The first cloud-free snow cover products were derived from the Interactive Multisensor Snow and Ice Mapping System of the NOAA/NESDIS (Brown et al. 2014). The data have the spatial resolution of 4 km. The various snow information of visible, infrared, passive microwave sensors onboard various satellite and other ancillary data had combined to IMS products. The second cloud-free products are MOD-SSM/I snow cover products (MODIS and SSM/I combining snow products), which were mapped using the MODIS daily snow cover products (Terra and Aqua products) and SSM/I snow depth products and have the spatial resolution of 500 m (Hao et al. 2012; Huang et al. 2012, 2014). The third ones are MOD-B (Blending method based on the MODIS snow cover products) snow cover products (500 m). A suite of daily cloud-removal algorithms, including the temporal and spatial combination, snow season determination and snow line determination, are used to completely remove cloud cover (Qiu et al. 2016). The last ones are TAI (Terra–Aqua–IMS) snow products, which combines the MODIS snow cover products and IMS products to produce a daily cloud-free snow cover products with 500 m spatial resolution (Yu et al. 2016). Previous studies have seldom focused on assessing the cloud-free snow cover data. Yu et al. (2017) assessed the IMS, MOD-SSM/I and MOD-B cloud-free snow cover products using the *in situ* snow data over the high Asia region. The results show the accuracy of IMS and MODIS products is close, but the data quality of MODIS snow product is higher. The studies are, however, conducted at the whole scale under conditions of station network availability and neglecting the topography, land-cover and snow types.

The aim of this study is to provide a quantitative assessment of the performance of the currently available four daily cloud-free snow cover products and which product is more efficient for use in hydrologic and climatological applications over the QTP. Two types of validation are used in this paper: absolute validation and relative validation. For absolute validation, the MODIS maps are compared with *in situ* snow depth measurements, which are considered as 'truth' data in this work. Depending on the climate zone and land-cover data, the accuracy is assessed for different climate zones and land-cover types. Relative validation is achieved through intercomparisons of all the snow cover products, most of which have unknown accuracies. In addition, there are some differences in quality and characteristics between IMS and MODIS snow cover products, but both have their own advantage. Based on the cloud removal algorithm, the combined ability of IMS and MODIS is further discussed.

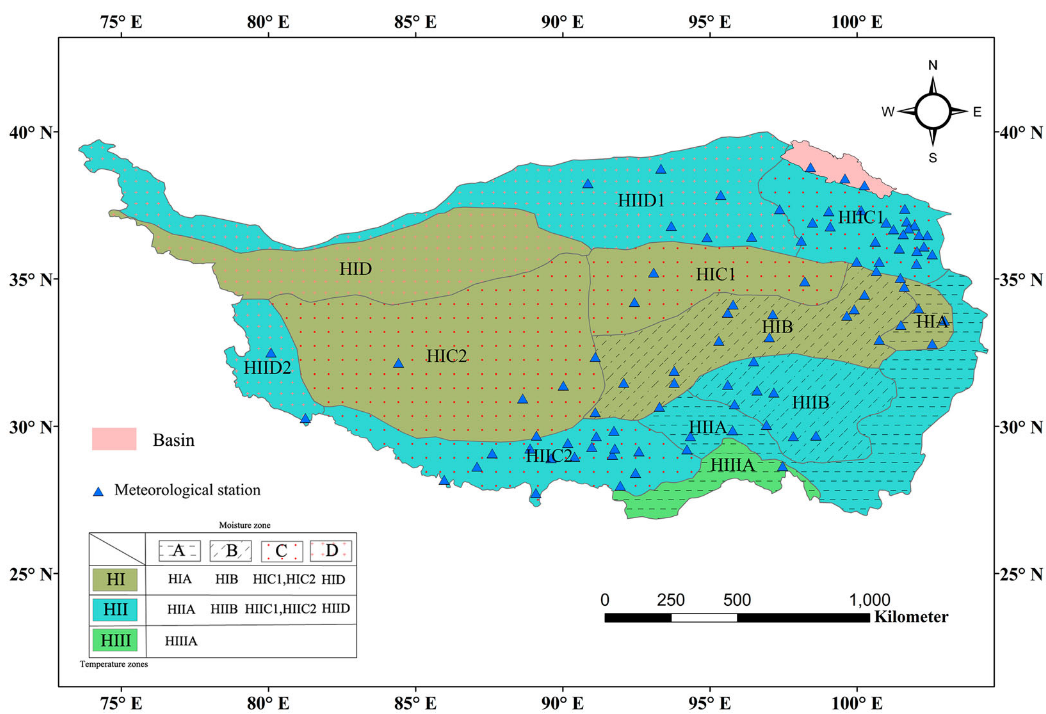

Figure 1. Spatial distribution of the climatic zones and meteorological stations along with the measured snow depths across the QTP.

2. Study area

The QTP is located between 73°19′–104°47′N and 26°00′–39°47′E in Southwestern China (Figure 1). As the 'roof of the world', the QTP has an average elevation over 4000 m and with an area of approximately 2.57×10^6 km^2 and is the highest and largest plateau in the world. The annual mean temperature over the QTP is only 1.6°C, and more than 13.3% of the QTP is permanently covered by snow. The QTP was selected for this study for several reasons. First, most of the snow was distributed in three regions in China, the QTP, North Xinjiang and northeastern China (Qin, Liu, and Li 2006). The QTP is one of the largest three areas with stable seasonal snow cover in China (Paudel and Andersen 2011). Second, the QTP represents an alpine snow region in terms of major land-cover classes and the elevation range of the QTP and is hence considered as a validation region. Finally, the snow over the QTP has become a hot topic worldwide due to its important influence on climate, hydrological cycle and ecosystem. Continuous satellite-based time series of daily snow cover products are expected to support climatic, hydrologic and ecological modelling studies of this region.

3. Data and methodology

3.1. In situ *snow data and other ancillary data*

In situ measurements of snow depth were provided by the meteorological stations' network maintained by the China Meteorological Administration (CMA). The meteorological stations record the daily snow depth along with other meteorological data, such as temperature and precipitation. In this study, snow depths from 91 meteorological stations in the study area were used that were obtained between 2004 and 2014 (downloaded from the CMA Sharing Service System at http://cdc.cma.gov.cn). Figure 1 shows all the meteorological stations located over the QTP. The elevations of the meteorological stations ranged from 1400 to 4900 m, and the average elevation was approximately 3500 m. Twenty-eight meteorological stations are located in high elevation zones (>4000 m), and 55 meteorological stations are located in the east (>95°E). The snow depths were measured daily at each station if more than 50% snow cover was present and were recorded in centimeters by using the round-off method. The snow depths at less than 50% snow cover were recorded as missing data, which would not be used in validation. In addition, the snow pressure (g/cm^2) was measured at some meteorological stations when the snow depth was greater than 5 cm based on the Specifications for surface meteorological observation-9 (China Meteorological Administration 2007).

To understand the effects of climatic zones, elevation and land cover on the accuracy of snow cover products, auxiliary data were obtained. When considering the zonal air temperature as an index of climate, the QTP was recently divided into 9 moisture regions and 12 climatic sub-regions (Zheng, Yin, and Li 2010), ranging from a plateau subtropical zone in the southeast and a plateau

Table 1. Scheme of 3 temperature zones, 9 moisture regions and 12 climatic sub-regions over the QTP.

Temperature zones	Moisture zones	Climatic sub-regions	Representative stations	Number of stations
(HI) Plateau sub-frigid zone	(A) Humid zone	HIA	Zoige	6
	(B) Sub-humid zone	HIB	Dariag	14
	(C) Sub-arid zone	HIC1	Maduo	3
		HIC2	Amdo	5
	(D) Arid zone	HID	Ungauged	0
(HII) Plateau temperate zone	(A) Humid zone	HIIA	Mainling	3
	(B) Sub-humid zone	HIIB	Dingqing	8
	(C) Sub-arid zone	HIIC1	Menyuan	25
		HIIC2	Cona	16
	(D) Arid zone	HIID1	Dulan	8
		HIID2	Purang	2
(HIII) Plateau subtropical zone	(A) Humid zone	HIIIA	Zayu	1

temperate zone in the southeast to a plateau sub-frigid zone in the northwest (Figure 1). Table 1 provides details regarding the temperature zones, the moisture regions and the climatic sub-region classifications. A DEM of the area with a spatial resolution of 500 m was created from SRTM (Shuttle Radar Topography Mission) data at 3 arc-seconds, which is 1/1200th of a degree of latitude and longitude or approximately 90 m, as a source for topographic analysis. From the DEM dataset, information about the slope, aspect and illumination according to the solar angle (solar zenith and azimuth) and elevation were generated for validation of snow cover products. In addition, the land-cover data used in the study were derived from MCD12Q1. MCD12Q1 employs an ensemble decision tree algorithm to acquire a composite of time series within each year for annual mapping (Friedl et al. 2002, 2010). The product classification scheme contains the 17-class International Geosphere-Biosphere Program (Loveland and Belward 1997) land-cover layer. The tile data of MCD12Q1 from 2010 were merged and re-projected with the UTM by using the MODIS Reprojection Tool (MRT). As shown in Table 2, only six land-cover types (evergreen needleleaf forest, mixed forest, grasslands, open shrublands, urban and build-up land, barren or sparsely vegetated) were observed over the meteorological stations over the QTP. Tables 1 and 2 also show the classification, representative stations and number of stations in detail. The representative stations from different climatic zones or land-cover types are ranked by the number of snowfall days that occur each year.

In this study, the removal of cloud obscurations is the main feature of all four snow cover products. To evaluate the performances of cloud-free snow cover products, some meteorological stations located in the frequently cloud-covered regions were selected and assessed individually. As shown in Figure 2, MODIS cloud cover data (MOD35) from July 2003 to 31 December 2012 were used to map the spatial distribution of the annual average cloud mask. Among the 91 stations, 9 stations that were covered by clouds for more than half of each year and 3 of the meteorological stations (Gande, Dariag and Jiali) that received the most snowfall were selected for evaluation.

3.2. Cloud-free snow datasets and algorithm description

The aim of this study is to provide a quantitative assessment of the performances of the currently available four daily cloud-free snow cover products over the QTP. Figure 3 shows a flow chart of the processing process used for the four cloud-free snow cover products.

The first snow cover products are the IMS products of the NOAA/NESDIS (Ramsay 1998). These data are derived from a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.), mapped products (USAF Snow/Ice Analysis, AMSU, AMSR-E, NCEP models, etc.) and *in situ* snow observations (Brown et al. 2014). Currently, the daily snow cover products are provided in ASCII text and GeoTIFF formats in three different versions, 1.1, 1.2 and 1.3, with resolutions of 24, 4 and 1 km, respectively. The spatial resolution of version 1.1 (24 km) did not meet the application needs. Although version 1.3 has a spatial resolution of 1 km, the dataset only includes a short period of the time series (from 2 December 2014 to present). Hence, the IMS version 1.2 snow cover images (4-km resolution and 6144-by-6144 grid) available from 23 February 2004 to 31 December 2014 were downloaded (http://nsidc.org/data/g02156) and used in this study. The pixel values of the IMS are coded with 1 for sea/lake, 2 for land, 3 for sea/lake ice, 4 for snow and 0 for outside.

Table 2. Land-cover types of the meteorological stations from MCD12Q1 (2010) over the QTP from IGBP.

QTP land cover (IGBG)	Representative stations	Number of stations
Evergreen needleleaf forest	Mainling	1
Mixed forest	Zayu	2
Open shrublands	Jiangzi	3
Grasslands	Maduo	60
Urban and build-up land	Gande	19
Barren or sparsely vegetated	Shiquanhe	6

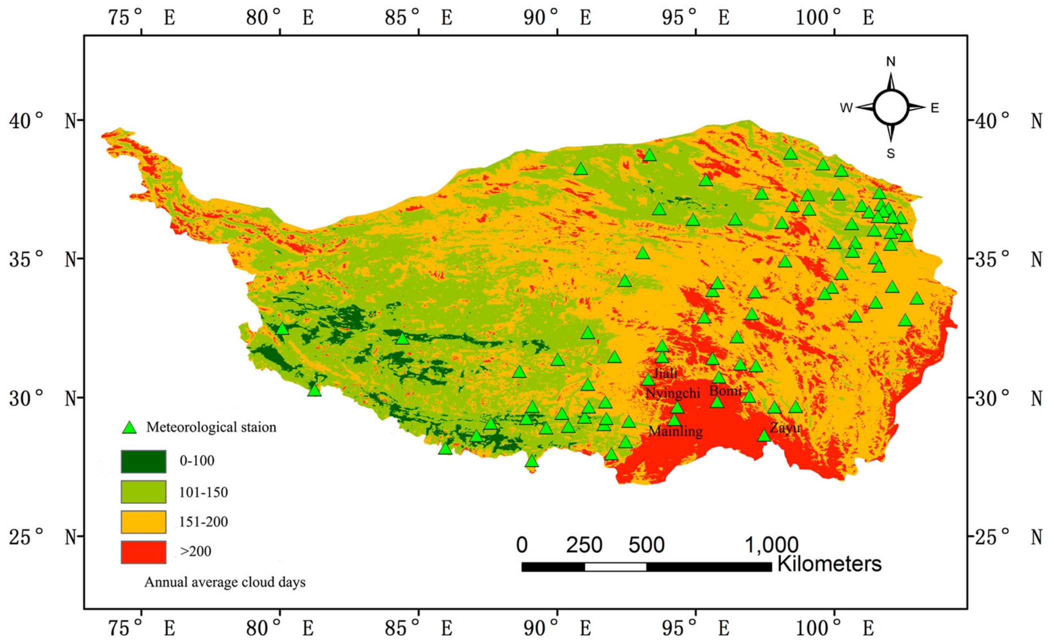

Figure 2. Spatial distributions of the annual average number of cloud-covered days and the meteorological stations from which snow depth measurements were obtained over the QTP.

The other three snow cover products (MOD-SSM/I, MOD-B, TAI) are essentially produced by MODIS snow cover data. The MODIS snow products are provided as a sequence of products beginning with a swath product and progressing through spatial and temporal transformations to an 8-day global-gridded product. This algorithm mainly depends on a Normalized Snow Difference Index (NDSI) approach, and the NDVI criteria are applied to enable the detection of snow cover under

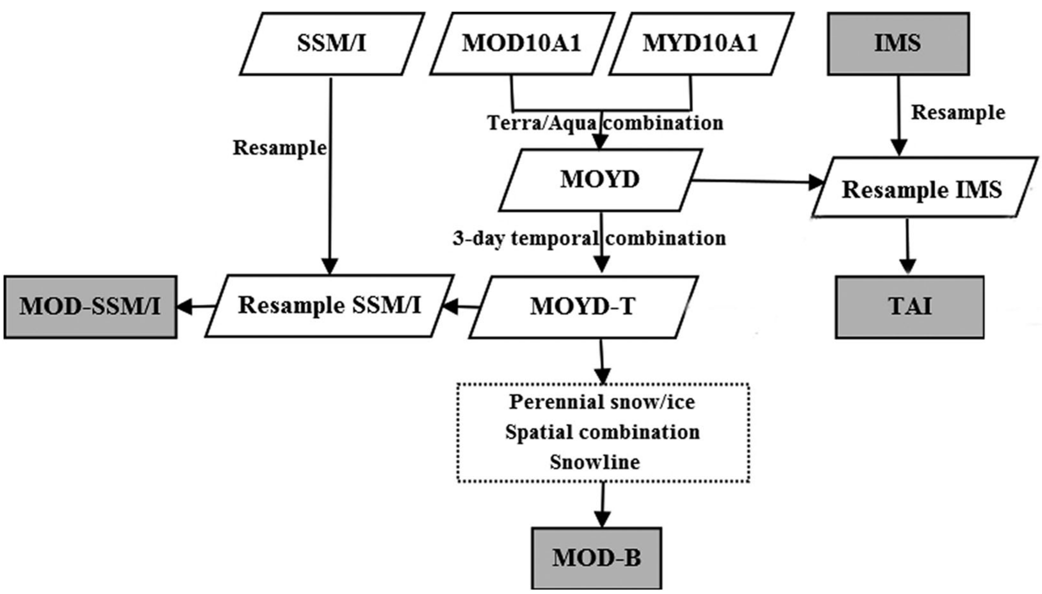

Figure 3. Processing flow chart of the four cloud-free snow cover products.

dense vegetation. In addition, the MODIS cloud mask products (MOD35) and water mask are used to mask cloud and water pixels (Riggs, Hall, and Salomonson 2006). In this study, the MODIS 'Collection 5' daily snow products (MOD10A1 and MYD10A1) were downloaded through the Earth Observing System Data and Information System (EOSDIS, http://reverb.echo.nasa.gov/) from 23rd February 2004 to 31st December 2014. Six MODIS tiles (h23v05, h24v05, h25v05, h26v05, h2506 and h26v06) were combined to cover the entire QTP. The MRT was used to execute the data format conversion (HDF to GeoTIFF), image-mosaic and reprojection (Sinusoidal to WGS84-UTM).

MOD-SSM/I snow cover products combined the MODIS daily snow cover products and SSM/I snow depth products (Hao et al. 2012; Huang et al. 2012, 2014; Liang et al. 2008). The MODIS snow products utilized the Terra/Aqua combination and temporal combination algorithm (Parajka and Blöschl 2008). The Terra/Aqua combination allows for an opportunity to reduce cloud obstruction and retrieve some omitted snow cover pixels due to their different orbits and transit times. The other gap pixels from Terra or Aqua images can be replaced with snow or land. The temporal combination of cloud-covered pixels employs the same concept as the combination of Terra/Aqua images, which assumes that the snow conditions in the study area remain constant (no snowfall or ablation) during the gap-filling period. Actually, the duration of seasonal snowpack is short, and snowpack can disappear within one or two days over the QTP. Therefore, a temporal window of three days was used to execute the temporal combination in this paper. A detailed description of this temporal combination was introduced by Gafurov and Bárdossy (2009). Even after the above two methods are applied, a large number of cloud pixels remains in the MODIS snow cover data. Hence, the MOD-SSM/I snow cover products combined the Special Sensor Microwave Imager (SSM/I) snow depth data that were not affected by clouds. Because the global algorithm of SSM/I underestimates the snow depth over the QTP (Che et al. 2008), the modified SSM/I data that consider the influences of vegetation, wet snow, precipitation, cold desert and frozen ground and used to calibrate the SSMR, SSM/I and SSMI/S brightness temperature (Tb) data were combined with the MODIS snow cover product in this study. The detailed procedure used for this temporal combination is described in previous studies (Dai, Che, and Ding 2015). The snow depth data of SSM/I (25 km) were resampled to the same cell size as the MODIS data (500 m) by the nearest neighbor interpolation method and were converted into snow-covered area data when the snow depth was more than 0 (Liang et al. 2008). Then, the residual cloud pixels of the MODIS images obtained by the Terra/Aqua combination and temporal combination are filled by the SSM/I snow cover data.

The MOD-B snow cover products utilized the MODIS snow cover product and DEM data. An eight-step daily cloud-free algorithm, including the Terra/Aqua combination, temporal combination, filtering by elevation and the identification of perennial ice and land cover, the spatial interpolation of adjacent pixels and the model of the snowline, was developed to completely remove cloud cover (|Qiu et al. 2016, 2017). Some fraction of the cloud cover was removed in every pixel. The resulting snow product generated from each step was used as the input for the next step of cloud removal. Terra/Aqua combination and temporal combination are same as the MOD-SSM/I product. The third step was to identify perennial snow/ice and land cover based on elevation. When the cloud pixels were at elevations higher than 5800 m, they could also be assigned to a snow-covered pixel. The fourth step was based on the spatial combination of adjacent pixels. Four direct 'side-bordering' adjacent pixels of the cloud pixel were examined. If at least three of four pixels are defined as snow, then the cloud pixel was also assigned to snow. The last steps adopt the model of the snowline. The aim of this step was to identify the minimum elevation where snow exists and the snow-covered elevation where all pixels above this level were covered by snow. Next, these elevation lines are set as threshold elevations to remove the cloud pixels.

The TAI products algorithm combines the MODIS snow cover data and IMS products to produce a daily cloud-free snow cover product over the QTP (Yu et al. 2016). A two-step procedure was developed for removing cloud cover. The first step consists of the Terra/Aqua combination described above, and the second step is the combination of MODIS images and IMS data, which is the same method used for the MOD-SSM/I snow cover products. The IMS data (4 km) were resampled to the same cell size as the MODIS data (500 m) by the nearest neighbor interpolation method. The cloud pixels of the MODIS images were replaced by the IMS data.

Figure 3 shows a flow chart of all four cloud-free snow cover products. The data source algorithms, methods, spatial resolution and codes over all products are shown in Table 3. We combined data from both tiles and re-projected the data to the Albers Conical Equal Area projection by using the MRT.

4. Results

To validate the cloud-free snow cover products, absolute and relative validation were used in this paper. Absolute validation is the comparison of the four cloud-free snow cover products against *in situ* snow depth ground measurements. Relative validation is the intercomparison of the four snow cover products, most of which have unknown accuracy.

4.1. Comparisons snow products by in situ data

Based on the long-term meteorological and *in situ* snow depth data over the QTP, we define the snow season as the period between 1st November of one year and 31st March of the next year. Using the snow depth data over snow season prevents the interference from snow-free conditions and allows for a better assessment of the accuracy of snow cover products.

IMS products were obtained for the period after 23 February 2004. Hence, the TAI snow cover products are available for the study until 23 February 2004. The MOD-SSM/I and MOD-B products are available after the launch of Aqua (4 July 2002). To make the comparison more convincing, the study employed 10 snow seasons that began on 1 November 2004, and ended on 31 March 2014.

A confusion matrix or error matrix is widely used to assess the accuracy of snow cover data by comparing the generated snow cover data with reference data. Table 4 presents four confusion matrices comparing IMS, MOD-SSM/I, MOD-B and TAI snow maps to *in situ* snow depth data for the 2004–2013 snow seasons. Approximately 135,000 datasets were utilized, and 380 datasets were missing. The overall accuracies of the IMS (76.0%), MOD-SSM/I (89.3%), MOD-B (92.0%) and TAI (92.0%) and products indicate that the latter three products present a good agreement with the *in situ* observations. The overall accuracies of the MOD-B and TAI products are similar, while the accuracy of the MOD-SSM/I products has the lowest accuracy.

However, as shown in Table 4, the snow mapping errors for the four products are different. Compared with the *in situ* snow depth observations, the snow mapping omission error rates (missing snow when it is present) for IMS, MOD-SSM/I, MOD-B and TAI were 68.4%, 39.9%, 64.2% and 45.3%, respectively. The snow mapping commission errors rates (mapping snow when none is present) were 19.2%, 7.6%, 1.9% and 4.0%, respectively. The IMS products show both the highest omission error rate (68.4%) and commission error rate (19.2%) among all the products. Thus, IMS products appear to both falsely identify and miss some snow. MOD-SSM/I products have the lowest

Table 3. Properties of the four cloud-free snow cover products.

Data product	Data source	Method	Spatial resolution
IMS	AVHRR, GOES, SSMI, USAF Snow/Ice Analysis, AMSU, AMSR-E, NCEP data	Blending	4 km
MOD-SSM/I	MOD10A1, MYD10A1, Modified SSM/I	Terra/Aqua combination, Temporal combination, Blending	500 m
MOD-B	MOD10A1, MYD10A1, DEM	Terra/Aqua combination, Temporal combination, Perennial snow/ice, Spatial interpolation, snowline	500 m
TAI	MOD10A1, MYD10A1, IMS	Terra/Aqua combination, Blending	500 m

Table 4. Confusion matrices for the IMS, MOD-SSM/I, MOD-B and TAI cloud-free snow cover products compared with *in situ* snow depth data.

In situ snow depth	IMS		MOD-SSM/I		MOD-B		TAI	
	Snow	No snow	Snow	No snow	Snow	No snow	Snow	No snow
Snow	4179 (31.6%)	9037 (68.4%)	7954 (60.1%)	5282 (39.9%)	4735 (35.9%)	8472 (64.2%)	7220 (54.7%)	5981 (45.3%)
No snow	23,461 (19.2%)	98,841 (80.8%)	9295 (7.6%)	113,206 (92.4%)	2338 (1.9%)	120,064 (98.1%)	4885 (4.0%)	117,068 (96.0%)
Overall accuracy (%)	76.0		89.3		92.0		92.0	
K_{hat}	0.084		0.463		0.428		0.526	

omission error rate (39.9%) but a higher commission error rate (7.6%). MOD-B products have a higher omission error rate (64.2%) but the lowest commission error rate (1.9%). Thus, the MOD-SSM/I products generally map too much snow, while the MOD-B products generally miss snow. TAI products have omission error rates (45.3%) and commission error rates (4.0%).

The Kappa statistic (K_{hat}) is commonly used to compute the inter-rater reliability coefficient (Cohen 1960) and can be used to indicate agreement between snow cover products and *in situ* observations. The K_{hat} values of the IMS, MOD-SSM/I, MOD-B and TAI products are 0.084, 0.463, 0.428 and 0.526, respectively. According to the guidelines presented by Landis and Koch (1977), the IMS products were classified as 'Slight' and the other three products were classified as 'Moderate'. The K_{hat} values of the MOD-B products have the lowest K_{hat} values, and the K_{hat} values of the TAI products were the highest among the latter three 'Moderate' products. These comparisons indicate that the TAI products appear to offer the best level of agreement for accurate snow mapping of the QTP among the four cloud-free snow products.

To evaluate the effects of the different temperature and moisture zones over the QTP, the confusion matrices for the IMS, MOD-SSM/I, MOD-B and TAI snow cover products were compared from individual representative stations in different temperature and moisture zones. Table 5 presents the average overall accuracy and Kappa coefficients obtained from the different temperature zones and moisture zones. In the HI (Plateau sub-frigid zone) temperature zones, the TAI products presented the highest average overall accuracy (85.9%) and Kappa coefficient (0.505). The IMS products had the lowest overall accuracy (68.2%) and Kappa coefficient (0.095). In the HII (Plateau temperate zone) temperature zones, the IMS products had the lowest overall accuracy (67.0%) and Kappa coefficient (0.068). The TAI products had the highest average overall accuracy (86.6%), and the MOD-SSM/I products presented a highest Kappa coefficient (0.487) than the TAI products (0.456). Based on the Kappa coefficient as a guideline, the IMS products are 'slight', the MOD-B products are 'fair' and the other two products are classified as 'moderate' in the two temperature zones. However, in the HIII (Plateau subtropical zone), the K_{hat} values of the IMS, MOD-SSM/I, MOD-B and TAI products are 0.046, 0.027, 0.011 and 0.003, respectively. All the products are classified as 'slight'. This result

Table 5. Overall agreement and Kappa coefficients for the IMS, MOD-SSM/I, MOD-B and TAI snow cover products compared at representative stations in different temperature zones and moisture zones over the QTP.

	IMS		MOD-SSM/I		MOD-B		TAI	
	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}
Temperature zones								
HI	68.2	0.095	84.0	0.440	84.3	0.365	85.9	0.505
HII	67.0	0.068	84.6	0.487	85.8	0.261	86.6	0.456
HIII	76.9	0.046	50.2	0.027	57.7	0.011	66.7	0.003
Moisture zones								
A	80.6	0.100	70.4	0.187	78.2	0.171	79.4	0.197
B	53.4	0.040	81.4	0.405	85.2	0.308	85.5	0.416
C	69.1	0.043	87.0	0.536	85.9	0.409	87.4	0.539
D	63.4	0.138	86.1	0.597	80.8	0.124	85.6	0.590

indicates that the accuracy of snow cover products may depend on the temperature. Both IMS and MODIS cloud-free snow cover products could fail to map snow on plateau subtropical zone. Additional comparisons of the different moisture zones show similar results. In a relatively hot and moist environment, both the IMS and MODIS series products have lower discrimination abilities. The snow mapping algorithms of IMS and MODIS need further improvement.

In addition, to evaluate the effects of the different land-cover types over the QTP, confusion matrices for the IMS, MOD-SSM/I, MOD-B and TAI snow cover products were compared at individual representative stations with different land cover. Table 6 only shows the overall agreement and Kappa coefficients. In evergreen needleleaf forests, the overall accuracies of the IMS (89.1%), MOD-SSM/I (77.5%), MOD-B (94.7%) and TAI (86.1%) products indicate that the products present instability. In mixed forests, the overall accuracy for the IMS (76.9%), MOD-SSM/I (50.2%), MOD-B (57.6%) and TAI (66.7%) products showed similar trends. The K_{hat} values of all snow cover products for these two land-cover types were classified as 'slight'. The omission and commission errors of all snow cover products are high. Thus, all products appear to falsely map and miss some snow. These results indicate that the agreement between the snow cover products and *in situ* forest observations is very low. Two explanations contribute to this result. The first explanation is that the number of comparisons of snow days at representative stations is small (58 and 25 snow days in total 1478 days in evergreen needleleaf forest and mixed forest). A large number of comparisons for snow-free samples would reduce this accuracy. On the other hand, at least for the forests over the QTP, both the IMS and MODIS series products must be improved. Under the other four land-cover conditions, the TAI products all showed the highest overall accuracy and the IMS products performed the worst. In open shrublands, the overall accuracy is high. Nevertheless, the number of snow days at representative stations is small (only 19 snow days during 1478 days) and the K_{hat} values are low. In our study, although a snow season was used for validation, care must be taken in interpreting these results because the conditions at the individual stations during snowfall may not represent the larger area viewed by satellites, especially in the forests and shrublands where the stations are located. In the urban and built upland areas, the MOD-SSM/I (77.6%), MOD-B (77.7%) and TAI (80.3%) products present a higher overall accuracy than the IMS (64.5%) product. The MODIS series products (MOD-SSM/I, MOD-B and TAI) resulted in similar K_{hat} values. All the products presented high omission errors. This result was attributed to rapid snowmelt in the city. In the grassland and on barren or sparsely vegetated land, the TAI products all had higher accuracy and K_{hat} values.

As stated previously, although the performances of the four snow cover products were evaluated in different temperature and moist zones and for different land-cover types, care must be taken when assessing the cloud removal ability at individual stations because the conditions during the cloudy days may not be representative. As shown in Figure 2, the annual average cloud-covered days are mainly distributed in the southeast region of the QTP. Three representative stations (Gande, Dariag and Maqu) with more cloud cover (183, 184 and 183) and snowfall days (35.1%, 31.0% and 19.7%) were selected for evaluation. Table 7 shows a confusion matrice comparing the IMS, MOD-SSM/I, MOD-B and TAI snow maps to the data from the three individual stations for the 2004–2013 snow

Table 6. Overall agreement and Kappa coefficients for the IMS, MOD-SSM/I, MOD-B and TAI snow cover products compared at stations with different land-cover types over the QTP.

	IMS		MOD-SSM/I		MOD-B		TAI	
Land cover	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}	Overall accuracy (%)	K_{hat}
Evergreen needleleaf forest	89.1	0.080	77.5	0.083	94.7	0.159	86.1	0.041
Mixed forest	76.9	0.046	50.2	0.027	57.6	−0.011	66.7	0.003
Open shrublands	53.1	0.011	97.6	0.211	98.9	0.189	98.7	0.235
Grasslands	53.1	0.051	82.8	0.559	84.5	0.526	85.4	0.612
Urban and build-upland	64.5	0.116	77.6	0.475	77.7	0.393	80.3	0.480
Barren or sparsely vegetated	72.6	0.158	92.8	0.609	93.0	0.502	93.4	0.597

Table 7. Confusion matrices for the IMS, MOD-SSM/I, MOD-B and TAI snow cover products compared with the observations at the individual stations.

		IMS		MOD-SSM/I		MOD-B		TAI	
Stations	*In situ* snow depth	Snow	No snow	Snow	No snow	Snow	No snow	Snow	No snow
Gande	Snow	145 (30.0%)	339 (70.0%)	298 (61.4%)	187 (38.6%)	174 (36.0%)	309 (64.0%)	217 (45.0%)	265 (55.0%)
	No snow	197 (19.2%)	828 (80.8%)	152 (14.8%)	874 (85.2%	28 (2.7%)	999 (97.3%)	32 (3.1%)	991 (96.9%)
	Overall accuracy (%)	64.5		77.6		77.7		80.3	
	K_{hat}	0.116		0.475		0.394		0.480	
Dariag	Snow	178 (42.8%)	238 (57.2%)	272 (65.5%)	143 (34.5%)	132 (31.9%)	282 (68.1%)	275 (66.1%)	141 (33.9%)
	No snow	361 (33.0%)	732 (67.0%)	173 (15.8%)	923 (84.2%)	14 (1.3%)	1082 (98.7%)	124 (11.4%)	965 (88.6%)
	Overall accuracy (%)	60.3		79.1		80.4		82.4	
	K_{hat}	0.089		0.487		0.383		0.554	
Maqu	Snow	69 (24.1%)	217 (75.9%)	151 (52.8%)	135 (47.2%)	115 (40.5%)	169 (59.5%)	161 (56.3%)	125 (43.7%)
	No snow	81 (6.6%)	1142 (93.4%)	40 (3.3%)	1185 (96.7%)	9 (0.7%)	1217 (99.3%)	42 (3.4%)	1177 (96.6%)
	Overall accuracy (%)	80.3		88.4		88.2		88.9	
	K_{hat}	0.214		0.568		0.507		0.595	
Average overall accuracy (%)		68.4		81.7		82.1		83.9	
Average K_{hat}		0.140		0.510		0.428		0.543	

seasons. The average overall accuracy for the IMS (68.4%), MOD-SSM/I (81.7%), MOD-B (82.1%) and TAI (83.9%) products indicated that the MODIS series products present a good agreement with the observations at the three stations. The average K_{hat} values of the IMS, MOD-SSM/I, MOD-B and TAI products were 0.140, 0.510, 0.428 and 0.543, respectively. The IMS products were classified as 'Slight', and the other four products were classified as 'Moderate'. The agreement of the TAI product was the highest, followed by the MOD-SSM/I and MOD-B products. These comparisons indicate that TAI appears to offer the best cloud removal ability over the four snow products, at least over the QTP.

Additional comparisons of the omission and commission errors of the individual stations indicated that the TAI products tend to miss some snow but do not falsely identify snow. The MOD-SSM/I products had the lowest omission error rate but a higher commission error rate, especially at the Gande and Dariag stations. The MOD-B products presented a higher omission error rate but the lowest commission error rate. These results indicate that the MOD-SSM/I products appear to map too much snow, while the MOD-B products tend to miss snow at the three stations with the most cloud cover. Overall, the TAI products performed the best for cloud removal among the daily snow cover products considered for the QTP.

4.2. Intercomparisons of the four snow cover products

The Geographic Information System technology was used to facilitate the intercomparisons of the four cloud-free snow cover products over the QTP. As a first step, the snow maps were re-projected to an Albers Conical Equal Area projection. To match the MODIS series products, the IMS maps were oversampled to a spatial resolution of 500 m based on the nearest neighbor interpolation method. All the classification schemes were simplified as snow and snow free. Particularly, the lake ice categories were classified as snow free.

For the 10 snow seasons (from 2004–2005 to 2013–2014), the mean snow-covered areas over the QTP are displayed in Figure 4. The changes in the snow-covered area obtained from the four products were consistent among the snow seasons. All the snow cover products showed two obvious troughs (2005.2006 and 2012.2013) and two obvious peaks (2006.2007 and 2011.2012). In the 2010–2011 snow season, the area of snow cover observed by the MOD-SSM/I product obviously increases. However, the area of snow cover identified by using the other products slightly decreased. This result indicates that MOD-SSM/I snow-covered area products may be unstable. Overall, the

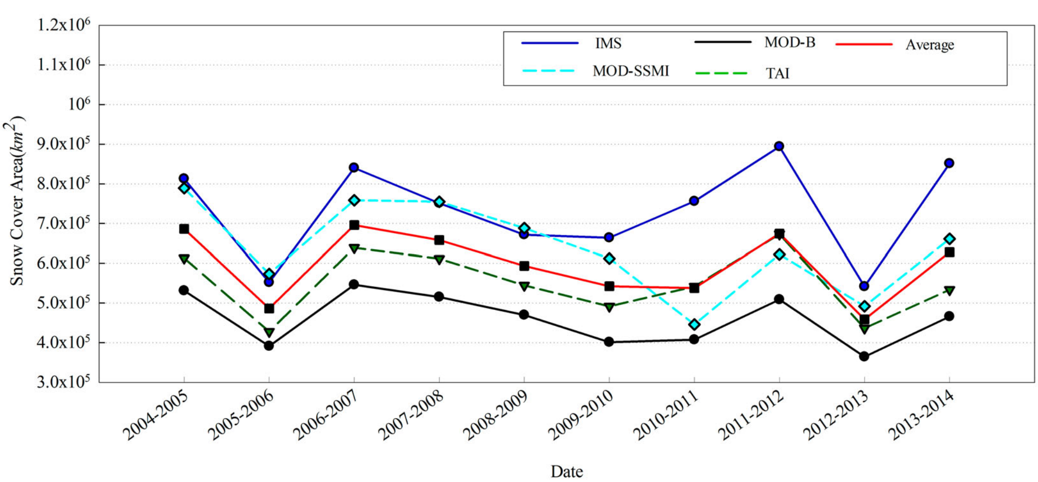

Figure 4. Snow-covered area for the IMS (blue line), MOD-SSM/I (cyan), MOD-B (black line) and TAI (green line) products and the average snow-covered area (red line) during the 10 snow seasons over the QTP.

IMS products resulted in the largest snow-covered area observed among the four products during the investigated snow seasons. The MOD-B products showed the smallest snow-covered area, and the MOD-SSM/I products indicated a larger snow-covered area, except during the 2010–2011 snow season. The TAI products were similar to the mean snow-covered area.

Furthermore, the inter-annual variability of the snow-covered area for the four products was analyzed in detail. Figure 5 shows the variability of the snow-covered area for the four products from 1st January to 31st December 2009, over the QTP. The intra-annual variability trends of the snow-covered area for the four products were generally consistent. Every snow cover product accurately recorded the snowfall events. During the snow seasons (2009.1–2009.7; 2009.10–2009.12), the IMS products presented the largest snow-covered area and the MOD-B product present the smallest snow-covered area. However, opposite results were observed during the snow-free seasons (2009.7–2009.10). The MOD-B products presented the largest snow-covered area, and the IMS products presented the smallest snow-covered area. These results show that the IMS algorithms obviously overestimate snow cover during the snow season and that the MOD-B algorithms overestimate snow cover during the snow-free season. Sometimes, the MOD-SSM/I products present the area peak in advance, which indicates that the MOD-SSM/I snow-covered area products may be unstable due to the integration of the largely different MODIS and SSM/I products. Likewise, the TAI products showed similar snow-covered areas to the mean snow-covered area.

As previously stated, differences in the snow maps between the four products do exist. Figure 6 shows a typical early spring example for 14 February 2009, over the QTP. The proportions of the snow-covered area over the QTP are 21.0%, 20.2%, 11.9% and 14.7% for the IMS, MOD-SSM/I, MOD-B and TAI products, respectively. The first discrepancy is the Qaidam Basin, which is located in the northern part of the QTP. Only the IMS and TAI products mapped snow pixels. The IMS products mapped more snow pixels than the TAI products. Another discrepancy is in the southwest region of QTP, which is located in the western Himalayan Mountains. The MOD-B products mapped less snow pixels than the other products. The third discrepancy occurs in the southeast patch snow region over the QTP, which is part of the Tanggula and Nyenchen Tanglha Mountains. The IMS products mapped more snow pixels than the other products. In addition, MOD-SSM/I mapped more snow pixels than other three products in the northwest region of the QTP, where the Kunlun Mountains are located. Visual examination of the MOD-SSM/I map indicates that some serrated pixels resulted from the integration of the MODIS and SSM/I products. The MOD-B product mapped fewer snow pixels. The results are similar with the *in situ* validations.

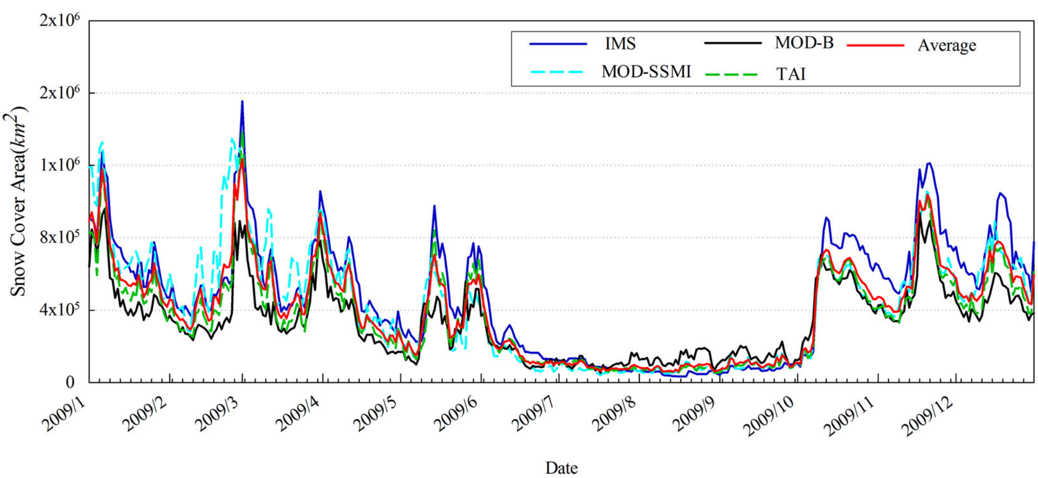

Figure 5. Variability of the snow-covered area for the four products over the QTP from 1st January to 31st December 2009.

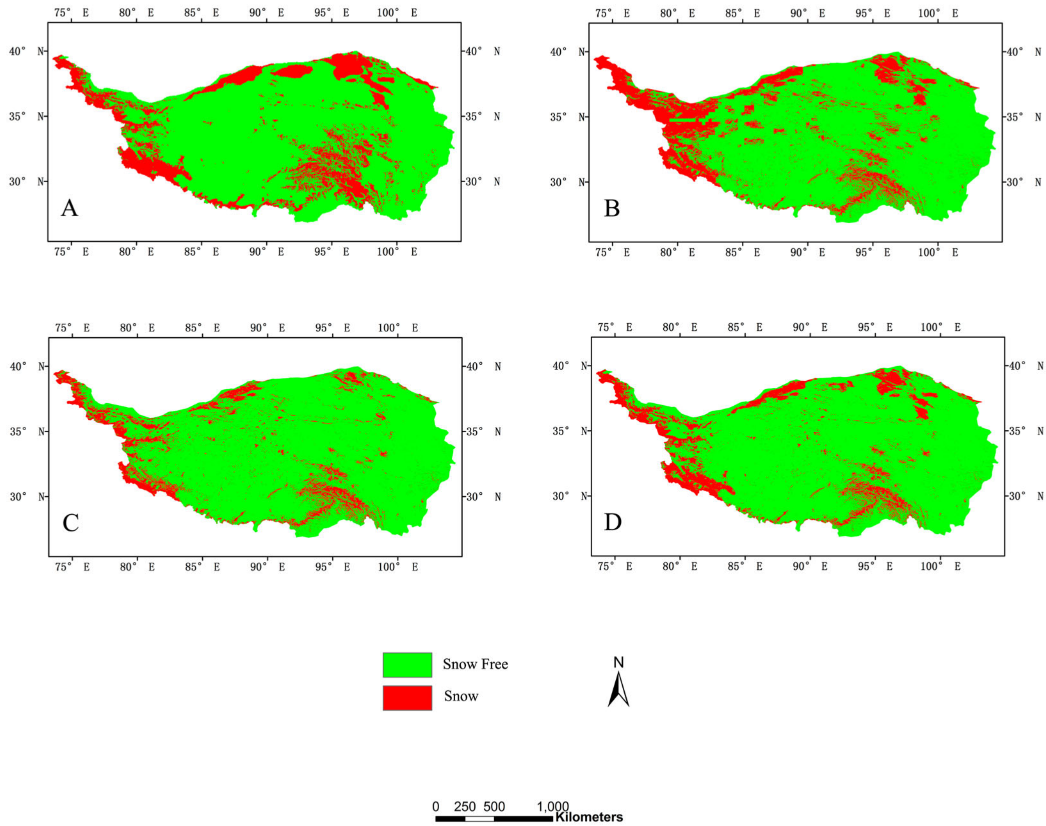

Figure 6. Snow cover maps for the IMS (a), MOD-SSM/I (b), MOD-B (c) and TAI (d) products over the QTP on 14 February 2009.

5. Discussion

This study comprehensively assessed the four daily cloud-free snow products (IMS, MOD-SSM/I, MOD-B and TAI) over the QTP by using a comparison of the situ data from stations and intercomparisons and comparisons with the model results. All the comparisons show differences in snow mapping between the four products. The differences between the four products are attributed to the different algorithms of the four products.

Only one meteorological stations located in Plateau subtropical zone and nine meteorological stations located in Humid zone. Most of meteorological stations located in grasslands and urban and build-up land area. Only six meteorological stations located in forest and shrublands land cover. In addition, the observation field of meteorological stations is relatively flat and could have different land cover and locations; they possess different validation capability for the nearby snow cover. All of these factors lead to the uncertainties of the results. Therefore, the more data record can increase the performance of validation.

Overall, the IMS products show the highest omission and commission error rates among all of the products. However, the main difference is the high commission error rate, which appears to map too much snow. The strategy of IMS products can be identified as much as possible for snow. The MOD-SSM/I products were combined with the MODIS daily snow cover products and SSM/I snow depth products. The pixels of SSM/I with a resolution of 25 × 25 km were directly resample at 500 × 500 m by using the nearest neighbor method. Hence, combining the MODIS and SSM/I products caused some pixels to become serrated, as shown in Figure 6(b), and enlarged the snow-covered area. The MOD-B products used an eight-step daily cloud removal algorithm that included the following steps to completely remove cloud cover: Terra/Aqua combination, temporal combination, filtering by elevation and the identification of perennial ice and land cover, spatial interpolation of adjacent pixels, and modeling of the snowline. The major error is the omission error, which likely resulted from the algorithms used for elevation filtering and determining the average snowline. However, the algorithm can significantly reduce the commission error. As stated previously, the TAI products are significantly more accurate and show the more robust cloud removal ability than the MOD-SSM/I and MOD-B products.

To better assess the cloud removal ability of TAI and how these products are different, intercomparison maps between the different products were constructed. A 3-day temporal combination filter is applied to the TAI product before the combination of the MODIS and IMS products. The proposed products named as I-TAI (Improvement of Terra–Aqua–IMS) products were used as a reference for comparison with the other snow product maps. Figure 7 shows the intercomparison of the snow cover maps between the I-TAI and IMS (A), I-TAI and SSM/I (B), I-TAI and MOD-B (C), I-TAI and TAI (D) products for 14 February 2009, over the QTP. The IMS mapped more snow in the Qaidam Basin, the western Himalayan and Tanggula Mountains and the Nyenchen Tanglha Mountains. However, the I-TAI snow maps can distinguish snow in the eastern Himalayan Mountains where the IMS does not. The MOD-SSM/I product map shows more snow in the Kunlun Mountains in the northwest region of the QTP. The I-TAI snow maps show snow in the Qaidam Basin where the MOD-SSM/I does not. The I-TAI product maps show more snow in the western Himalayan Mountains, the Qaidam Basin and the Qilian Mountains. A small discrepancy occurs in the western Himalayan Mountains, where the TAI products indicate snow but the I-TAI products do not. Further comparison with the TAI products and the I-TAI products showed the I-TAI products have higher omission errors and lower commission errors. To a certain extent, the temporal combination of cloud-removal algorithms can improve the accuracy. However, snow misclassification is still another limitation of MODIS snow cover products. The MODIS snow cover products should be improved for forest and mountain areas, especially for regions with wet and patchy snow

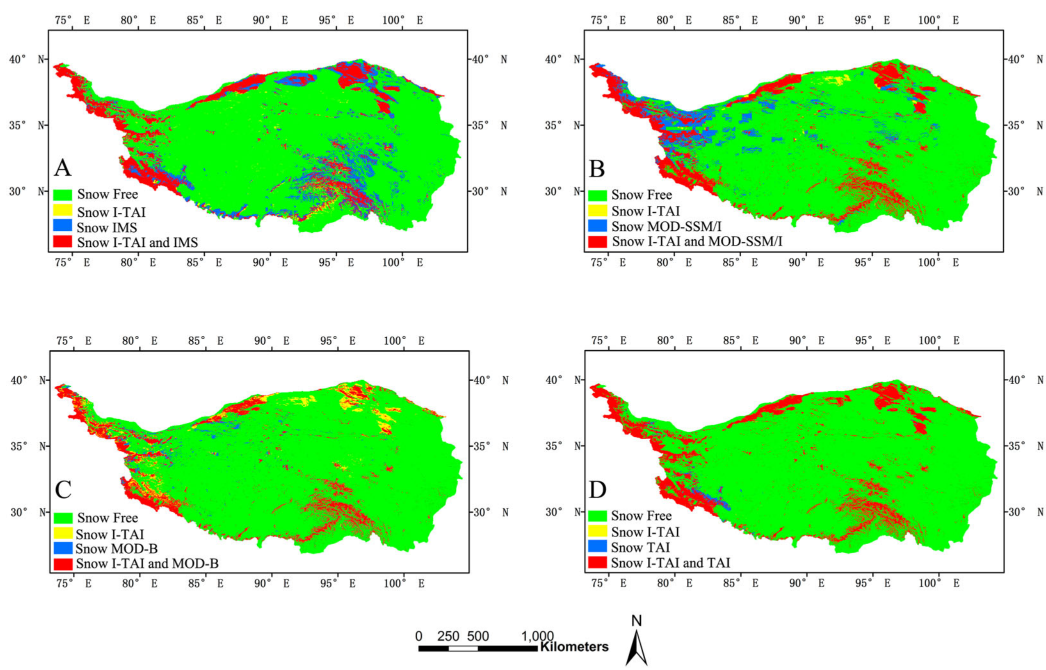

Figure 7. Intercomparison of snow cover maps between the I-TAI and IMS (a), I-TAI and MOD-SSM/I (b), I-TAI and MOD-B (c), I-TAI and TAI (d) products over the QTP on 14 February 2009.

cover over the QTP. With the improvement of the MODIS snow cover products, a more feasible cloud-free snow cover product could be obtained for the QTP.

6. Conclusions

Two methods were used to evaluate the accuracy of cloud-free snow products for the IMS, MOD-SSM/I, MOD-B and TAI products. The comparisons of the four cloud-free snow cover products against the *in situ* snow depth and the intercomparisons of the four snow cover products provide a comprehensive accuracy assessment.

Comparisons of the IMS, MOD-SSM/I, MOD-B and TAI cloud-free snow products against the meteorological stations observations during the 2004–2013 snow seasons over the QTP indicated that the TAI products appear to offer the best level of agreement in snow mapping accuracy for the four snow products over the QTP. The omission and commission classification error rates indicate that the IMS products tend to falsely identify and miss some snow. The MOD-SSM/I products appear to map too much snow, while the MOD-B products tend to miss snow.

Comparisons of the IMS, MOD-SSM/I, MOD-B and TAI snow products against the *in situ* data from the individual representative stations in different temperature and moisture zones and with different land cover revealed that the MODIS series products (MOD-SSM/I, MOD-B and TAI) have higher agreement with the observations than the IMS products. However, in relatively hot and moist environments, the MODIS series products show poor performance. In the grassland, barren or sparsely vegetated and urban and build-upland areas, the TAI products all show the highest overall accuracy. In the evergreen needleleaf forests and mixed forest shrublands, the agreement between all four snow cover products and *in situ* stations is quite low. The algorithms of the MODIS series products show instability in wet snow and forest covered conditions and still require further improvement. The evaluations over the three cloud representative stations indicate that the TAI products appear to offer the best cloud-removal ability over the four snow products, at least over the QTP.

The mean variations of snow cover from 2004–2005 to 2013–2014 and the inter-annual variability in 2009 of the snow-covered area for the IMS, MOD-SSM/I, MOD-B and TAI reveal that the snow-covered area changes from the four products are consistent. However, the IMS products resulted in the largest snow-covered area observed among the four products during the investigated snow seasons. The MOD-B products showed the smallest snow-covered area, and the MOD-SSM/I products indicated a larger snow-covered area. The TAI products show the more accuracy and were similar to the mean snow-covered area.

The temporal combination of cloud-removal algorithms can improve the accuracy to some extent. The intercomparisons of the I-TAI and the other four snow maps illustrate differences in the snow maps between the four products. Overall, the I-TAI products appear to offer better agreement in snow mapping accuracy over the QTP.

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Disclosure statement

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