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Comparison and validation of MODIS standard and new combination of Terra and Aqua snow cover products in northern Xinjiang, China

Xianwei Wang,[1] Hongjie Xie,[1]* Tiangang Liang[2] and Xiaodong Huang[2]
[1] *Department of Geological Sciences, University of Texas at San Antonio, Texas 78249, USA*
[2] *College of Pastoral Agriculture Science and Technology Lanzhou University, Lanzhou 730020, China*

Abstract:

Taking northern Xinjiang, China, as an example, this study first compares the standard MODIS Terra and Aqua snow cover classifications, and then compares the accuracy of the standard MODIS daily and 8-day snow cover products with the new daily and multi-day snow cover combination of MODIS Terra and Aqua observations using *in situ* measurements. Under clear sky in both products, the agreement of land classification from MODIS Terra and Aqua daily and 8-day snow cover products is close to 100% for a entire water year. In contrast, the agreement of snow classification from MODIS Terra and Aqua is high only in the winter months, decreasing in the rest of the period. The high agreement mainly concentrates in land or snow-dominated areas, and major disagreements take place in the transitions zones from snow to land. The disagreement (mainly snow–land) in the 8-day products is higher than that in the daily products. In addition, both MODIS Terra and Aqua cloud masks tend to map more areas in the transition zones as cloud. Under clear sky conditions, the three daily products have similar accuracy of snow and land classification, and the 8-day standard products and the multi-day combination product also have similar accuracy of snow and land classification. This further suggests that the algorithm in the combination of Terra and Aqua snow cover products is valid. Moreover, in the actual weather/cloud conditions, the combination products from Terra and Aqua reduce cloud blockage and improve snow classification accuracy against either MODIS Terra or Aqua (51% against 44% and 34% for daily and 92% against 87% and 78% for 8-day, respectively), although Terra snow product (daily or 8-day) has slightly better accuracy than the Aqua snow product. The new combination products can provide better mapping of spatiotemporal variation of snow cover/glacier and for snow-melting modeling.

KEY WORDS MODIS; Terra; Aqua; snow cover; comparison; validation

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INTRODUCTION

The snow cover product series generated from Moderate Resolution Imaging Spectraradiometer (MODIS) instruments carried on the Terra satellite have been elucidated by Hall *et al*. (2002), Riggs *et al*. (2006), and Hall and Riggs (2007). The accuracies and limitations of the MODIS Terra snow cover products have also been explored from different aspects (Klein and Barnett, 2003; Zhou *et al*., 2005; Tekeli *et al*., 2005; Ault *et al*., 2006; Riggs *et al*., 2006; Hall and Riggs, 2007; Liang *et al*., 2008a; Wang *et al*., 2008). Overall, under clear sky, the accuracy of MODIS Terra daily and 8-day snow classification is over 90% (Zhou *et al*. 2005; Liang *et al*., 2008a; Wang *et al*., 2008). However, for the daily product, the most severe problem is cloud blockage, which covers 40–50% of the study area in the snow season (Zhou *et al*., 2005; Liang *et al*., 2008a,b; Wang and Xie, in review). Below the cloud cover, no decision can be made in those products. In all weather conditions, for example, the snow agreement of Terra daily product is only 34–50% (Zhou *et al*., 2005, Liang *et al*. 2008a, b), while it is up to 80–90% for the Terra 8-day product (Zhou *et al*. 2005; Wang *et al*., 2008), since the cloud covers were reduced to around 5% in annual average (Wang and Xie, in review). The second error in the MODIS snow cover product is from mapping the thin snow or fractional snow. For example, MODIS Terra maps more transition areas (snow to land) as cloud (Klein and Barnett, 2003; Tekeli *et al*., 2005; Ault *et al*., 2006). In addition, dense forest, sand or desert, complex topography and other factors also add a challenge to accurately map the land surface snow cover.

However, as pointed out by Hall and Riggs (2007), the accuracy of a similar snow cover product series from MODIS instruments on the Aqua satellite, Launched in May 2002, has not been assessed in detail. The Terra satellite passes the equator at 10:30 am, while the Aqua satellite passes the equator at 1:30 pm. Both spacecrafts carry the same MODIS instrument and use almost identical algorithms to generate two analogue snow cover products except for the non-functional detector of band 6 (1·628–1·627 μm) on the Aqua MODIS. Therefore, the Aqua/MODIS snow-mapping algorithm

* Correspondence to: Hongjie Xie, Department of Geological Sciences, University of Texas at San Antonio, Texas 78249, USA.
E-mail: hongjie.xie@utsa.edu

uses band 7 (2·105–2·155 μm) instead of band 6 used in Terra/MODIS snow-mapping algorithm (Hall and Riggs, 2007). This replacement might impact the accuracy of snow detections through the calculation of normalized difference of snow index (NDSI), although the spectral signature of snow is similar in MODIS band 6 and band 7. This replacement also indirectly affects snow detection by the Aqua/MODIS cloud mask (MYD35), which also replaces band 6 with band 7 (Hall and Riggs, 2007). Thus, questions arise about the difference between MODIS Terra and Aqua snow cover products. Therefore, accuracy assessment of the Aqua snow cover products as well as inter-comparison with its corresponding Terra snow cover products are necessary and should be significant.

Since MODIS Terra and Aqua pass the equator at different times 3–4 hours apart and the cloud is moving in most cases, one pixel (or a group of pixels) which is blocked by cloud in the morning (10 : 30 am) could be clear in the afternoon (1 : 30 pm), and vice versa. Therefore, an algorithm and implementation have been developed to automatically combine the daily MODIS Terra and Aqua snow cover products to generate a cloudless daily snow cover product, MODMYD10DC, and a cloud-free (or cloud-low) multi-day snow cover composite product, MODMYD10MC (Wang and Xie, in review). The basic idea of the algorithm is that one pixel on the combined image will be snow if the pixel on either MODIS Terra or Aqua image is snow, while one pixel on the combined image will be cloud only if the pixel on both MODIS Terra and Aqua image is cloud. Thus, the combined image has maximum snow and minimum cloud against the MODIS Terra or Aqua snow cover image. The daily combination is similar to the algorithm of Parajka and Bloschl (2008), which then adds a spatial filter considering the neighboring pixels to further reduce the cloud-blocked pixels after the daily combination, while the present algorithm uses multi-day images to further reduce the cloud blockage instead of using a spatial filter. The new daily (MODMYD10DC) and multi-day composites (MODMYD10MC) offer an important complement to the standard MODIS daily and 8-day products. Thus validation of and comparison among different MODIS products through *in situ* observation is very important, and is the objective of the work reported.

STUDY AREA AND DATA SOURCES

Comparison of the MODIS Terra and Aqua daily and 8-day snow cover products uses the two tiles (H23V04 and H24V04) covering the corner region of seven countries (Russia, Mongolia, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and China) as shown in Figure 1. The two MODIS tiles cover the entire Tianshan Mountains in the South and Altai Mountains in the north. Over 80% precipitation concentrates on the mountainous areas, providing crucial water resources for this arid

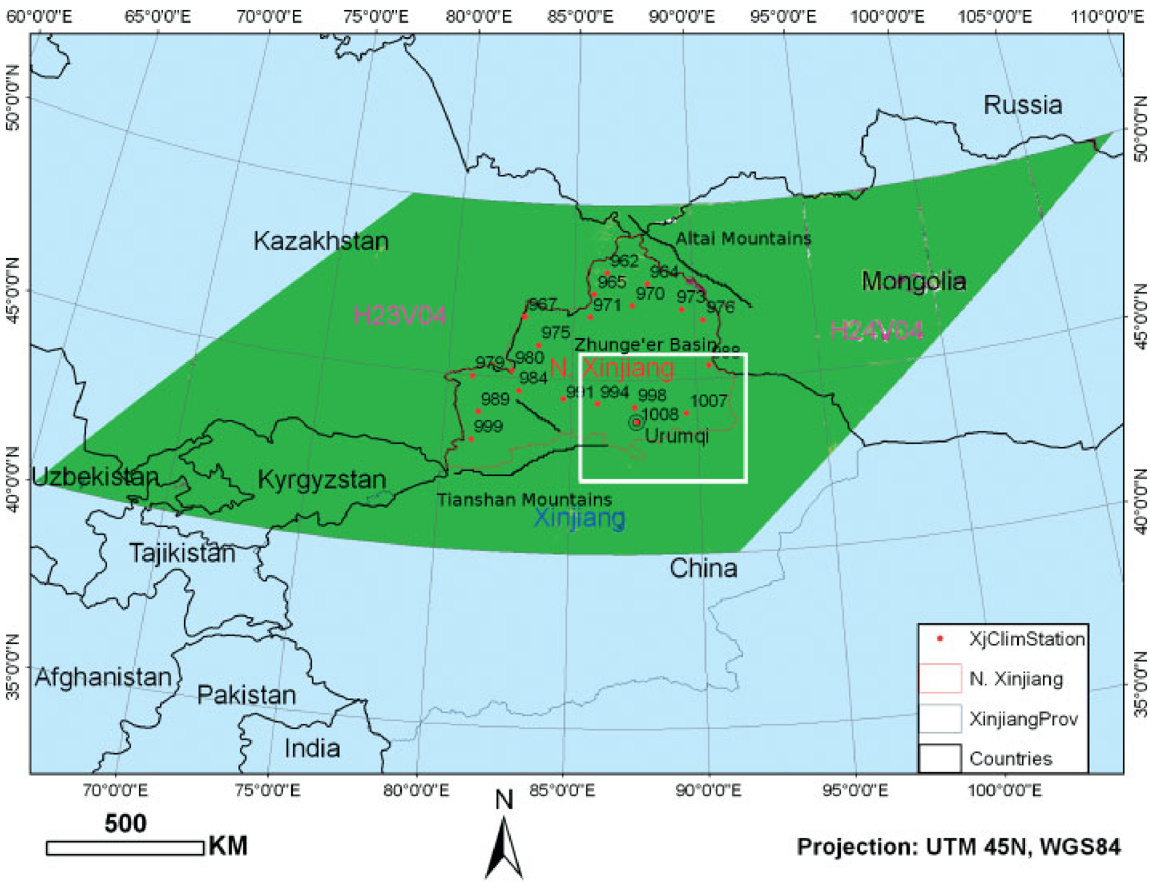

Figure 1. Study area of the two MODIS tiles- H23V04 (left green region) and H24V04 (right green region), and northern Xinjiang with climatic stations (red spots), China. The white rectangle inside the map is the area of the comparison map in Figures 3 and 5

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and semiarid region (Cui *et al.*, 2005). The validation of different MODIS snow cover products uses the *in situ* snow depth data from 20 climatic stations in the northern Xinjiang, China (Figure 1). Northern Xinjiang consists of two large mountain ranges, the Tianshan Mountains to the south and the Altai Mountains to the north, with the Zhunge'er Basin (desert) in between. The complex topography, various land types and varying climate regimes cause significant differences in the extent of snow cover and snow accumulation in different basins. The 20 ground stations recorded the daily snow depth value to the nearest 1 cm (Wang *et al.*, 2008). The locations of these stations are indicated on Figure 1. More detailed descriptions of the region and the ground snow depth data can be found in Wang *et al.* (2008) and Liang *et al.* (2008a).

The snow cover products used in the validation within the hydrologic year from 1 September 2003 to 31 August 2004 include respectively 355 and 365 standard MODIS daily snow cover images of Terra (MOD10A1) and Aqua (MYD10A1), 46 standard MODIS 8-day snow cover images of Terra (MOD10A2) and Aqua (MYD10A2), and 355 new daily combinations of Terra and Aqua (MODMYD10DC) and 155 multi-day combinations of Terra and Aqua (MODMYD10MC).

All the MODIS products used in this study are based on collection 4 or V4. The version 5 products are now available with changes between this new version and the previous ones. For example, the cloud mask input products have been improved, permitting more snow to be mapped (Hall and Riggs, 2007; Riggs *et al.*, 2006).

METHODS

Comparison

Since the MODIS/Terra daily and 8-day snow cover products have been well studied and have good accuracy in clear sky conditions (Klein and Barnett, 2003; Zhou *et al.*, 2005; Tekeli *et al.*, 2005; Ault *et al.*, 2006; Riggs *et al.*, 2006; Hall and Riggs, 2007; Liang *et al.*, 2008a; Wang *et al.*, 2008), they are used as a reference for comparison with MODIS/Aqua daily and 8-day products, respectively. The comparison is carried out pixel by pixel for all available 355 daily images and 46 8-day images within the hydrological year 2003–2004. Table I lists the codes used to represent the comparison results. In Table I, the codes for different classes of MODIS Terra/Aqua snow cover products are assigned as 1, 2, 3, 4, and 5 to represent land, water, cloud, snow and other, respectively. Correspondingly, for example, the comparison resulting code 11 means that the land (1) in Terra is classified into land (1) in Aqua, code 43 means that snow (4) in Terra is classified into cloud (3) in Aqua, and so on.

Validation

Since the mismatching effect, if any, between *in situ* stations and MODIS pixels, did not cause obvious differences in validation accuracy (Zhou *et al.*, 2005), the value of one MODIS pixel co-located with one *in situ* station was retrieved for comparisons. As the comparison of *in situ* point observation versus areal mapping (500 m × 500 m) of MODIS snow cover image is concerned, the *in situ* snow depth is a critical factor for the accuracy of MODIS snow mapping. The 8-day Terra/MODIS snow cover product has poor performance as snow depth is less than 4 cm in this area (Wang *et al.*, 2008). Therefore, the *in situ* snow depth data is classified into three groups to represent the snow cover conditions at one MODIS snow cover pixel, i.e. land/no snow (snow depth = 0 cm), fractional snow (snow depth = 1–3 cm), and snow (snow depth ≥4 cm). Because of the challenge in mapping fractional or patchy snow, snow mapping comparison across different MODIS snow cover products in this study is based on the snow data with snow depth ≥4 cm, although other threshold values of snow depth, such as 1 cm (Maurer *et al.*, 2003) and 2·54 cm (Simic *et al.*, 2004; Tekeli *et al.*, 2005), were used in literature. In addition, corresponding to the MODIS 8-day and multi-day maximum snow cover map, the *in situ* snow depth has also been processed as the maximum snow depth in the corresponding periods.

Table I. Codes for comparing the Aqua/MODIS snow cover products with the Terra/MODIS snow cover products

Aqua / Terra		Land 1	Water 2	Cloud 3	Snow 4	Others 5
Land	1	11	12	13	14	15
Water	2	21	22	23	24	25
Cloud	3	31	32	33	34	35
Snow	4	41	42	43	44	45
Others	5	51	52	53	54	55

RESULTS AND DISCUSSIONS

Comparison of MODIS daily Terra and Aqua snow cover products

Figure 2 summarizes the snow and land classification agreements, snow/land disagreements (snow–land and land–snow), and their total snow (percentage) under clear skies (in both morning and afternoon) from 1 September 2003 to 31 August 2004 using two tiles (H23V04 and H24V04) on a pixel by pixel basis. Table II provides the annual mean total percentage of land, snow and cloud fractions on MODIS Terra/Aqua daily and 8-day products. For example, in the study year, the annual mean cloud at MOD10A1 and MYD10A1 were 43·8% and 47·3%, snow 20·4% and 18·8%, land 36·7% and 36·8%, respectively. In addition, another small part is the water body about 1% (not shown in the table). The agreement of land classification of the two products is close to 100% over the entire year except for a few slightly lower values in the winter months. In contrast, the agreement of snow classification is high in the winter months (from November to March), and decreases in the rest of the period (from April to October) when snow cover is less than 10% of the area

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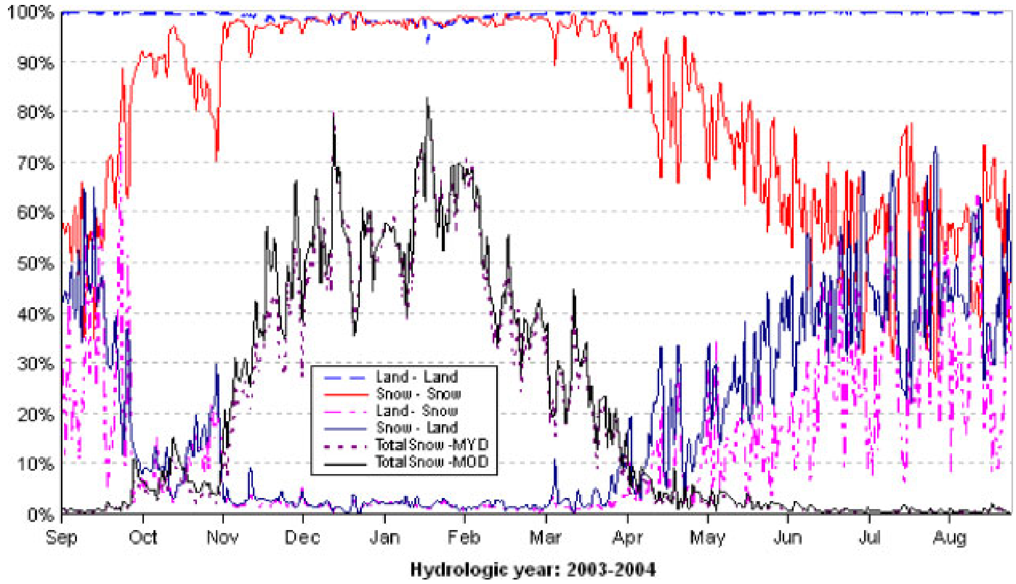

Figure 2. Land and snow classification agreements of MYD10A1 in comparison with MOD10A1 (land—land and snow—snow), disagreement of MYD10A1 in comparison with MOD10A1 (land-snow and snow-land) under clear skies, and the total snow percentage over the area (TotalSnow—MYD and TotalSnow—MOD) covered by the two MODIS tiles h23v04 and h24v04, from 1 September 2003 to 31 August 2004. In the legend for land-land, snow-snow, land-snow, and snow-land, the first land/snow is for MOD10A1, and the second land/snow is for MYD10A1; for example, land-land means that land in MOD10A1 is also classified into land in MYD10A1, and so on

Table II. Annual mean percentage of land, snow and cloud fractions of the MODIS Terra/Aqua daily and 8-day products in the 2003–2004 hydrologic year, in the study area

	Land-MOD	Snow-MOD	Cloud-MOD	Land-MYD	Snow-MYD	Cloud-MYD
max-daily	87·1	82·8	87·9	87·1	80·5	89·6
min-daily	3·5	0·1	6·2	3·6	0·1	8·0
Mean-daily	36·7	20·4	43·8	36·8	18·8	47·3
max-8day	97·1	71·6	27·5	97·3	69·6	27·4
min-8day	23·3	1·0	0·0	25·1	0·9	0·0
Mean-8day	70·1	25·6	3·9	71·4	23·5	5·6

covered by the two tiles. The low agreement in snow classification from April to October is mainly caused by the classification of snow in Terra to land in Aqua (snow–land) as shown in Figure 2. In spite of the low agreement of snow classification in this period, the total snow percentages are similar since some land pixels in Terra are classified into snow by Aqua (land–snow). In other words, some snow pixels in Aqua are also classified into land by Terra, and the two datasets have similar uncertainty in the summer time. Thus, the major reason for this disagreement (snow–land and land–snow) is probably due to the patchy snow conditions in the period, especially from May to September when the total snow cover is less than 5%. In the winter months, the total snow detected by MODIS Terra and Aqua is also similar (close to 100%). But in the snow accumulating and melting period, MODIS Terra has slightly higher snow cover percentage than that of MODIS Aqua. The lower value from MODIS Aqua is probably caused by the higher cloud blockage in the afternoon (Aqua) than in the morning (Terra) and/or by that some snow cover appearing in the morning may melt away in the afternoon (Wang *et al.*, 2008; Wang and Xie, in review).

To illustrate the comparison spatially, a small area is chosen (the rectangle area of Figure 1) and is shown in Figure 3 at pixel by pixel scale (3 January (top) and 21 March (bottom), 2004). Except for cloud areas in Terra (C-L, C-C, and C-S) and in Aqua (L-C, C-C, and S-C), the disagreements (L-S and S-L) mainly take place in the transition areas from snow to land because of the patchy snow conditions. Both Terra and Aqua have very strong agreement in the major land or snow-covered area when it is clear in both morning and afternoon. Some scattered disagreement pixels (L-S) surrounded by land area could be the snow misclassification of MODIS/Aqua (Figure 3, Top). Moreover, C-L and C-S represent areas covered by cloud in the morning but cleared in the afternoon. The strong agreement of land and snow classification and the open areas in the afternoon (while being blocked in the morning) are the basis to combine the two daily products to generate a new snow cover product of more open areas (Wang and Xie, in review). In addition, similar to the cloud mask (C-L, C-C, C-S) from Terra (Klein and Barnett, 2003; Tekeli *et al.*, 2005; Riggs *et al.*, 2006), the cloud mask (L-C, C-C, S-C) from Aqua also seems to map more pixels in the transition zones (land to snow) as cloud (Figure 3).

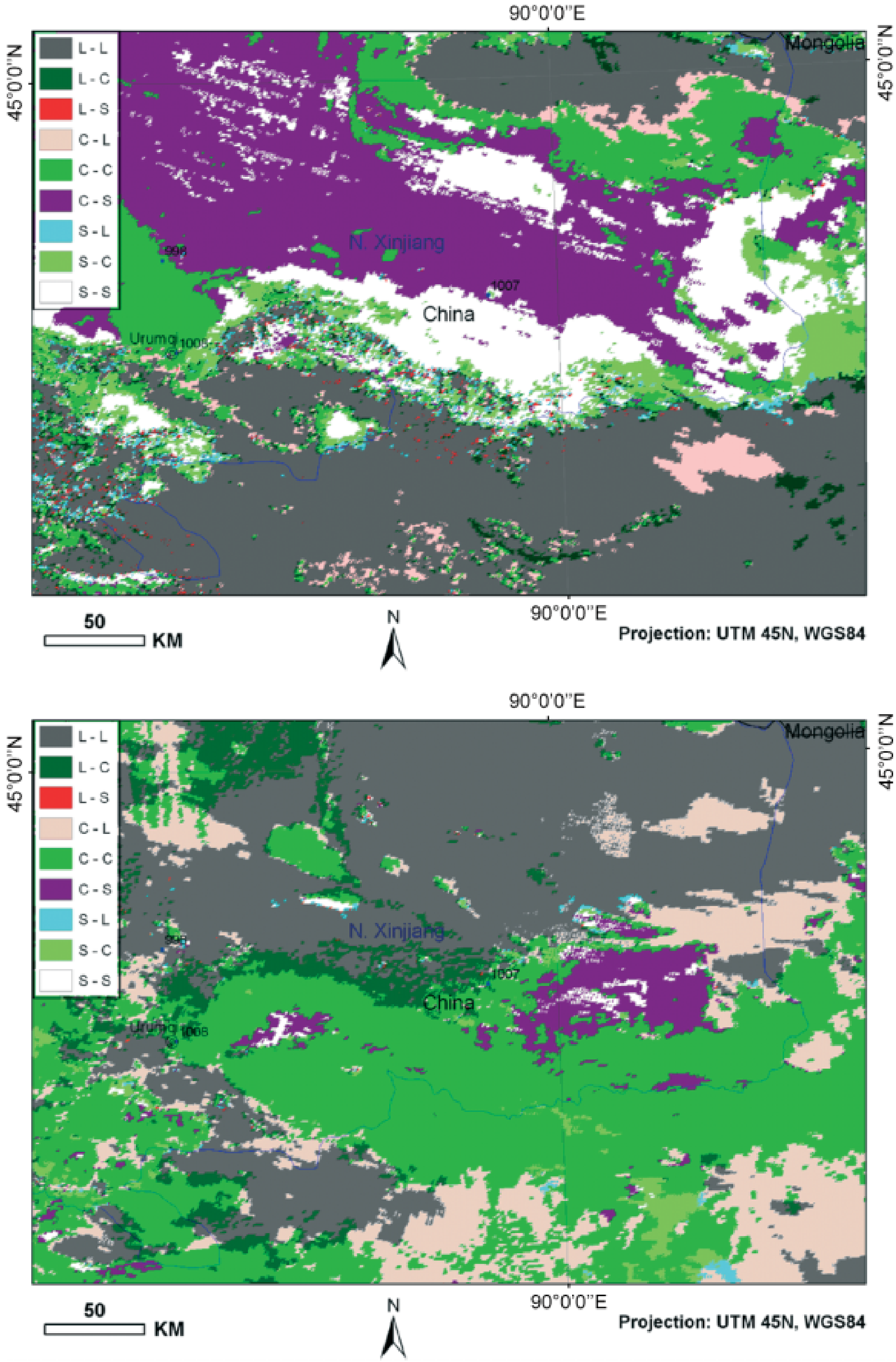

Figure 3. Examples of the comparison map of MOD10A1 and MYD10A1 at pixel by pixel scale on 3 January (top) and 21 March (bottom), 2004. L, C, and S respectively represent land, cloud and snow. The first letter is for MOD10A1; the second letter is for MYD10A1. For example, L-S means that 'Land' in MOD10A1 is classified as 'Snow' in MYD10A1. The map area is shown as a rectangle in Figure 1

Comparison of MODIS 8-day Terra and Aqua snow cover products

Figure 4 shows comparison results for the 8-day products. Similar to the daily comparison in Figure 2, the 8-day products also have strong agreement of land classification. However, the period (from late November to early March) of strong agreement of snow classification is about one month shorter than the daily products. Similar as the daily products, the lack of agreement of snow classification is also accompanied by strong disagreements (snow–land and land–snow) and mainly concentrates in the summer time; the total snow covered area from Terra is also slightly higher than that from Aqua in most cases except for the summer time.

Figure 5 shows two examples of the comparison map of MOD10A2 and MYD10A2 at the pixel by pixel scale on 1–8 January (top) and 21–28 March (bottom) 2004, for the same area as for Figure 3. Similar to the daily comparison in Figure 3, except for cloud-blocked areas in Terra (C-L, C-C, C-S) and Aqua (L-C, C-C, S-C),

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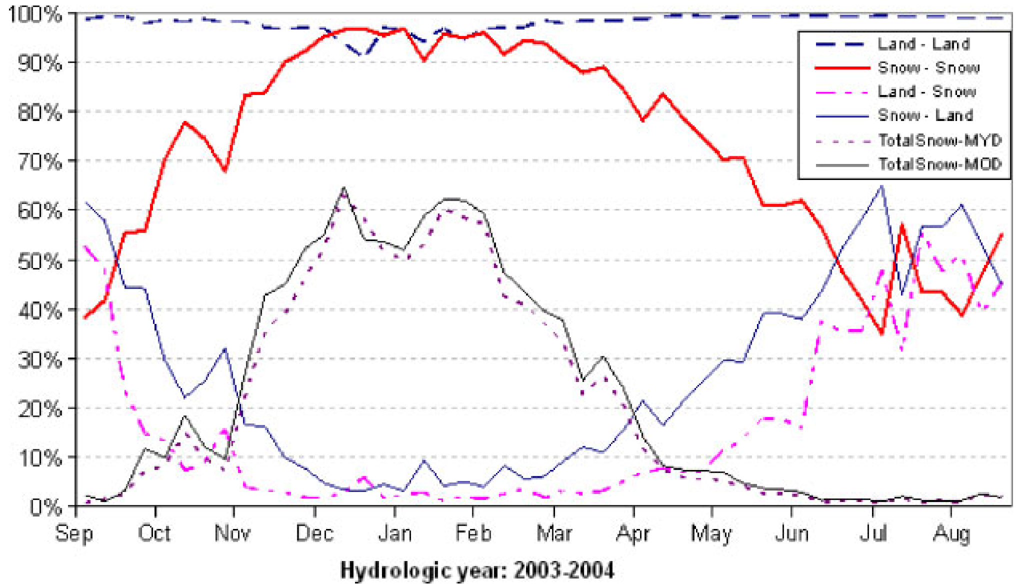

Figure 4. Land and snow classification agreements of MYD10A2 in comparison with MOD10A2 (land–land and snow–snow), disagreement of MYD10A2 in comparison with MOD10A2 (land–snow and snow–land) under clear skies, and the total snow percentage over the area (TotalSnow—MYD and TotalSnow—MOD) covered by the two MODIS tiles, from 1 September 2003 to 31 August 2004. In the legend of the land–land, snow–snow, land–snow, and snow–land, the first land/snow is for MOD10A2, and the second land/snow is for MYD10A2; for example, land–land means that land in MOD10A2 is also classified as land in MYD10A2, and so on

the snow and land disagreements (S-L and L-S) mainly take place in the transition areas from snow to land; meanwhile, many land pixels are classified as snow (L-S), particularly in the melting time on 21–28 March 2004, scattered inside the land areas. This further suggests that these snow pixels from MODIS/Aqua (MYD10A2) might be a result of misclassification. Compared with the small number of disagreements of snow to land (S-L) in the daily product in Figure 3, MYD10A2 classified a much larger area of snow in MOD10A2 as land. The number of disagreements of land to snow (L-S) in the 8-day products is also higher than that in the daily products. This suggests that the 8-day composite of maximum snow cover magnifies the disagreement between MODIS daily Terra and Aqua. Moreover, the disagreement (S-L or L-S) in the melting time (21 March) is higher than that in the winter time (1 January) as also shown in Figures 2 and 4. In addition, similar to the daily products, both 8-day MODIS Terra and Aqua snow products map more pixels in the transition zones (land to snow) as cloud.

Validation of MODIS daily snow cover products

Tables III–V compare the results of *in situ* observations and the three daily MODIS snow cover products at the 20 climatic stations of northern Xinjiang in the hydrologic year 2003–2004 (1 September 2003–31 August 2004). For the daily comparison, there are 4247 land/no snow data items, 252 fractional snow, and 1997 snow according to the *in situ* measurements. In the 4247 *in situ* land data, the accuracy of land classification in MOD10A1, MYD10A1 and MODMYD10DC is 65%, 62%, and 72%, respectively (Tables III–V). The misclassification of land as snow is 1% in these three products. The cloud blockage in the three products is 34%, 37%, and 27%, respectively. If all the cloud data pairs (corresponding to both MODIS and *in situ*) are removed from the calculation, the accuracy of land classification is 99–100% under clear sky conditions. Removal of the cloud data here (and hereafter) is only for comparison purposes to evaluate the algorithm accuracy under so-called clear sky conditions; the accuracy of MODIS snow/land classification in the real situation is not improved.

In the 252 *in situ* fractional snow condition data, the accuracy of snow classification in MOD10A1, MYD10A1 and MODMYD10DC is only 13%, 5% and 15%, respectively (Tables III–V). The misclassification of snow as land is 12%, 17%, and 20% in these three products. The cloud percentage in the three products is 75%, 78%, and 65%, respectively. These cloud percentages in the fractional snow condition are much higher than for the land and snow conditions. This supports the previous finding that the MODIS Terra and Aqua cloud mask tends to frequently map edges of snow-covered areas as cloud, which is probably due to the lower fraction of snow cover (patchy snow) or thin snow depth in these transition zones (Klein and Barnett, 2003; Tekeli *et al*., 2005; Riggs *et al*., 2006). A fractional snow cover product based on the algorithm in Salomonson and Appel (2004) has been generated and included in the MODIS snow cover products in the new version (V5). In this case, the fractional snow cover value should be a better representation than snow or no snow. Even when all the cloud data pairs are removed, the accuracy of snow classification under clear sky conditions is still only 50%, 22%, and 41%, respectively, and the rest are misclassified as land.

In the 1997 *in situ* snow condition data, the accuracy of snow classification in MOD10A1, MYD10A1 and

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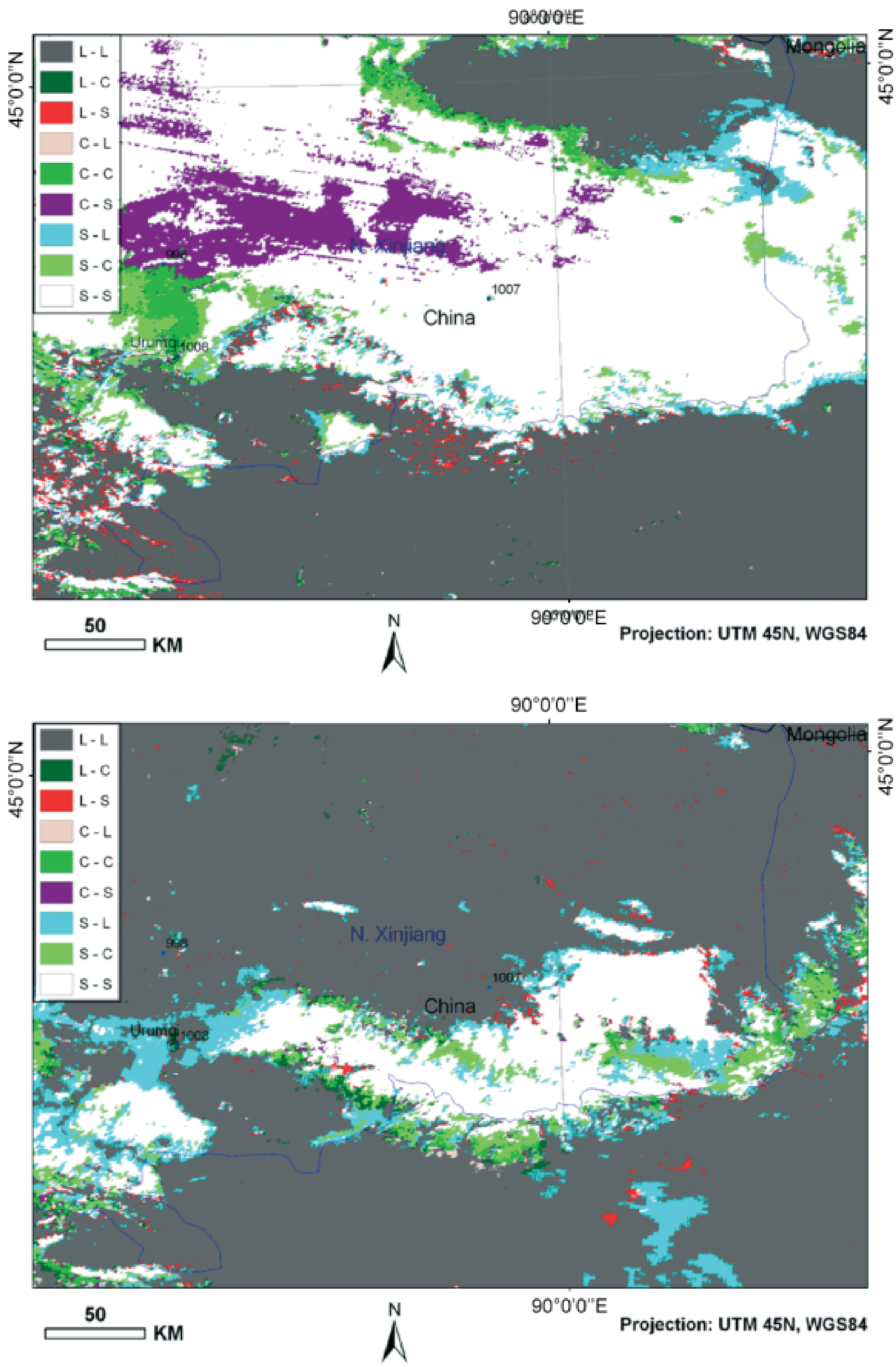

Figure 5. Examples of the comparison map of MOD10A2 and MYD10A2 at pixel by pixel scale on 1–8 January (top) and 21 March (bottom), 2004. L, C, and S respectively represent land, cloud and snow. The first letter is for MOD10A2; the second letter is for MYD10A2. For example, L-S means that the 'Land' in MOD10A2 is classified as 'Snow' in MYD10A2. The map area is shown as a rectangle in Figure 1

MODMYD10DC is 44%, 34%, and 51%, respectively (Tables III–V). The misclassification of snow as land is only 1–2% in the three products, which is much lower than in the fractional snow cover condition. The cloud percentages in the three products are 55%, 64%, and 47%, respectively. If all the cloud data pairs are removed, the accuracy of snow classification under clear sky conditions is very high, 98%, 96%, and 97%, respectively. This is consistent with previous studies (Klein and Barnett, 2003; Zhou *et al*., 2005; Liang *et al*., 2008a,b).

Overall, under the so-called clear sky conditions (after removing the cloud data pairs), the three products have similar accuracy of snow and land classification. This suggests that the algorithm is valid in the combination of Terra and Aqua snow cover products (Wang and Xie, in review). Moreover, in the actual weather/cloud conditions, the daily combination of Terra and Aqua can reduce the cloud blockage and improve the land and snow classification accuracy. For example in this case, the land classification accuracy is 72% for MODMYD10DC

Table III. Error matrix between MOD10A1 and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MOD10A1			Accuracy after cloud removed*
	6 496	Snow	Land	Cloud	
Land (Snow depth = 0)	4 247	13	2 764	1 441	**99%**
	65%	1%	**65%**	**34%**	
Fractional snow (Snow depth = 1–3 cm)	252	31	31	190	**50%**
	4%	**13%**	12%	**75%**	
Snow (Snow depth ≥4 cm)	1 997	868	21	1 108	**98%**
	31%	**44%**	1%	**55%**	

* After removing pairs of data (*in situ* and MODIS) masked as cloud in the MOD10A1 product, creating an accuracy in clear sky conditions.

Table IV. Error matrix between MYD10A1 and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MYD10A1			Accuracy after cloud removed*
	6 496	Snow	Land	Cloud	
Land (Snow depth = 0)	4 247	11	2 647	1 587	**100%**
	65%	1%	**62%**	**37%**	
Fractional snow (Snow depth = 1–3 cm)	252	12	43	197	**22%**
	4%	**5%**	17%	**78%**	
Snow (Snow depth ≥4 cm)	1 997	688	30	1 279	**96%**
	31%	**34%**	2%	**64%**	

Table V. Error matrix between MODMYD10DC and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MODMYD10A1			Accuracy after cloud removed*
	6 496	Snow	Land	Cloud	
Land (Snow depth = 0)	4 247	38	3 052	1 157	**99%**
	65%	1%	**72%**	**27%**	
Fractional snow (Snow depth = 1–3 cm)	252	36	51	165	**41%**
	4%	**15%**	20%	**65%**	
Snow (Snow depth ≥4 cm)	1 997	1 020	35	942	**97%**
	31%	**51%**	2%	**47%**	

against 62% from MYD10A1 and 65% from MOD10A1; the snow classification accuracy is 51% from MODMYD10DC against 34% for MYD10A1 and 44% for MOD10A1.

Validation of MODIS 8-day and multi-day snow cover products

Tables VI and VII display error matrices between *in situ* observations and the 8-day MODIS Terra and Aqua snow cover classification at the 20 climatic stations of northern Xinjiang in the hydrologic year 2003–2004. For the 8-day composite within this year, there are 497 items of land data, 46 fractional snow data, and 315 snow data according to *in situ* measurements at the 20 stations.

In the 497 *in situ* land/no snow data, the accuracy of land classification in MOD10A2 and MYD10A2 is 100% and 99% (Tables VI and VII). The misclassification of land as snow and the cloud blockage is negligible (≤1%). In the 46 *in situ* fractional snow data, the accuracy of snow classification in MOD10A2 and MYD10A2 is only 13% and 11%, respectively (Tables VI and VII). Most (78%) of the fractional snow areas in both products have been misclassified as land, while the cloud percentages in the two products are only 9% and 11%, respectively. These cloud percentages are much less than the 65%–78% for the daily products for the same fractional snow condition. In the 315 snow data, the accuracy of snow classification of Terra (87%) is higher than Aqua (78%), while Aqua also has a higher percentage of cloud and a higher misclassification of snow–land than Terra.

Table VIII evaluates the new multi-day combination of Terra and Aqua snow cover product (MODMYD10MC) using *in situ* observations. The *in situ* snow depth data has also been processed as the maximum snow depth in the corresponding multi-day periods. In all composite periods of this year, there are 2090 items of land data, 69 fractional snow data, and 521 snow data at the 20 stations. In the 2090 *in situ* land/no snow data, the accuracy of land classification in MODMYD10MC is 97% (Table VIII). The misclassification of land as

Table VI. Error matrix between MOD10A2 and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MOD10A2			Accuracy after cloud removed*
	858	Snow	Land	Cloud	
Land (Snow depth = 0)	497	1	495	1	**100%**
	58%	0%	**100%**	**0%**	
Fractional snow (Snow depth = 1–3 cm)	46	6	36	4	**14%**
	5%	**13%**	78%	**9%**	
Snow (Snow depth ≥4 cm)	315	276	15	24	**95%**
	37%	**87%**	5%	**8%**	

Table VII. Error matrix between MYD10A2 and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MYD10A2			Accuracy after cloud removed*
	858	Snow	Land	Cloud	
Land (Snow depth = 0)	497	2	490	5	**100%**
	58%	0%	**99%**	**1%**	
Fractional snow (Snow depth = 1–3 cm)	46	5	36	5	**12%**
	5%	**11%**	78%	**11%**	
Snow (Snow depth ≥4 cm)	315	244	26	45	**90%**
	37%	**78%**	8%	**14%**	

Table VIII. Error matrix between MODMYD10MC and *in situ* measurements in the 2003–2004 hydrologic year at 20 stations in northern Xinjiang, China

Ground observations	Total	MODMYD10MC			Accuracy after cloud removed*
	2 680	Snow	Land	Cloud	
Land (Snow depth < = 0)	2 090	13	2032	44	**99%**
	78%	1%	**97%**	**2%**	
Fractional snow (Snow depth = 1–3 cm)	69	15	44	10	**25%**
	3%	**22%**	64%	**14%**	
Snow (Snow depth ≥4 cm)	521	478	18	25	**96%**
	19%	**92%**	3%	**5%**	

snow and the cloud blockage is limited (1% and 2%, respectively). In the 69 *in situ* fractional snow data, the accuracy of snow classification in MODMYD10MC is only 22%, and 64% of the fractional snow has been misclassified as land. The cloud percentage is 14%. In the 521 snow data, the accuracy of snow classification of MODMYD10MC is 92%, while misclassifications of snow as land and cloud percentage for MODMYD10MC are only 3% and 5%, respectively.

Overall, under the so-called clear sky conditions, the three composite products (MOD10A2, MYD10A2, and MODMYD10MC) have similar accuracy of snow and land classification. However, in actual weather/cloud conditions, Aqua has slightly higher cloud and lower accuracy than Terra, while the multi-day combination of Terra and Aqua reduces cloud blockage and improves the snow classification accuracy over either Terra or Aqua. For example in this case, the snow classification accuracy is 92% from MODMYD10MC against 78% from MYD10A2 and 87% from MOD10A2. Considering the fixed composite period and limited available images of the 8-day MODIS Terra and Aqua snow cover products, the advantage of the combination of Terra and Aqua MODIS products with flexible composite period and more images (over 3 times that of the 8-day products) is obvious and significant (Wang and Xie, in review).

SUMMARY

Being launched two years earlier, the Terra satellite is more widely used than its counterpart, Aqua satellite. For instance, issues about the MODIS Terra snow cover product have been investigated from different aspects for many world regions; however, MODIS Aqua snow cover products have not been systematically assessed although they use an almost identical algorithm to the MODIS Terra snow cover products. Taking northern Xinjiang, China as an example, this study first compares the MODIS Terra and Aqua snow classification, then validates them using *in situ* snow depth observations, and finally compares the accuracy of the standard MODIS snow cover products with the new daily and multi-day snow cover combination of MODIS Terra and Aqua observations.

Under clear sky in both morning and afternoon, the agreement of land classification from MODIS Terra and Aqua daily snow cover products is close to 100% over the entire year. In contrast, the agreement of snow classification from MODIS Terra and Aqua is high only in the winter months, decreasing throughout the rest of the period. As the comparison maps show, both MODIS Terra and Aqua have very good agreement in the major land and snow-covered areas in clear skies, and major disagreements take place in the transition zones from snow to land because of the patchy snow conditions. In addition, the open areas in the afternoon (morning) while being blocked in the morning (afternoon) highlight the advantage of combining the two products to generate a new one with more open areas or less cloud cover.

Compared to the daily products, the agreement of land classification from the 8-day MODIS Terra and Aqua products is similarly high. However, the period of high agreement of snow classification is much shorter than the daily products. This can be explained by their composite algorithm that MOD10A2 and MYD10A2 are the 8-day composite with maximum snow cover during the 8 days, leading to larger shift between the morning and afternoon than the daily products. The exaggeration of the disagreement in 8-day products is also illustrated in the comparison maps, where disagreement areas from land to snow and from snow to land are much larger than with the daily products. One common feature of the daily and 8-day comparison is that major disagreements take place in the transition zones from snow-covered areas to snow-free areas. Another feature is that cloud mask in MODIS Terra and Aqua seems to map more areas in the transition zones (snow and land) as cloud.

When comparing with the *in situ* snow depth observations, under so-called clear sky conditions after removing the cloud data pairs, the three daily products have similar accuracy of snow and land classification. This suggests that the algorithm is valid for the combination of Terra and Aqua snow cover products. Moreover, in the actual weather/cloud conditions, the daily combination of MODIS Terra and Aqua reduces the cloud blockage and improves both the land and snow classification accuracies, although it still has high cloud percentage.

Under clear sky conditions, the three composite products (MOD10A2, MYD10A2, and MODMYD10MC) also have similar accuracy of snow and land classification. Similarly, in the actual weather/cloud conditions, the new multi-day combination of MODIS Terra and Aqua reduces cloud blockage and improves snow classification accuracy against either the 8-day MODIS Terra or Aqua snow cover product. Moreover, considering the fixed composite period and limited images of the 8-day MODIS Terra or Aqua snow cover products, the multi-day combination of MODIS Terra and Aqua with flexible composite period and many more available images than 46 within a year are of significant importance. This new product can provide better mapping of the spatiotemporal variation of snow cover/glacier and better snow-melting modelling.

Overall, the accuracy of the MODIS Terra snow classification (daily or 8-day) is generally higher than that of MODIS Aqua (daily or 8-day), which can be seen from Tables III, IV, VI and VII, but lower than the respective combination (daily or multi-day) of the products from the two satellites (compare Tables V and VIII).

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