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Integrated assessment on multi-temporal and multi-sensor combinations for reducing cloud obscuration of MODIS snow cover products of the Pacific Northwest USA

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Abstract

MODIS (Moderate Resolution Imaging Spectroradiometer) snow cover products, of daily, freely available, worldwide spatial extent at medium spatial resolution, have been widely applied in regional snow cover and modeling studies, although high cloud obscuration remains a concern in some applications. In this study, various approaches including daily combination, adjacent temporal deduction, fixed-day combination, flexible multi-day combination, and multi-sensor combination are assessed to remove cloud obscuration while still maintain the temporal and spatial resolutions. The performance of the resultant snow cover maps are quantitatively evaluated against in situ observations at 244 SNOTEL stations over the Pacific Northwest USA during the period of 2006–2008 hydrological years. Results indicate that daily Terra and Aqua MODIS combination and adjacent temporal deduction can reduce cloud obscuration and classification errors although an annual mean of 37% cloud coverage remains. Classification errors in snow-covered months are actually small and tend to underestimate the snow cover. Primary errors of MODIS daily, fixed and flexible multi-day combination products occur during transient months. Flexible multi-day combination is an efficient approach to maintain the balance between temporal resolution and realistic estimation of snow cover extent since it uses two thresholds to control the combination processes. Multi-sensor combinations (daily or multi-day), taking advantage of MODIS high spatial resolution and AMSR-E cloud penetration ability, provide cloud-free products but bring larger image underestimation errors as compared with their MODIS counterparts.

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1. Introduction and background

Snow cover is one of the most important climatic factors affecting surface albedo, energy balance and hydrological circulation. Snow cover mapping has been utilized in operational snowmelt, runoff forecasting, data assimilation and the calibration or validation of various hydrological models (Andreadis & Lettenmaier, 2006; Blöschl et al., 1991; Grayson et al., 2002; Parajka & Blöschl, 2008; Udnaes et al., 2007). Daily and freely available, worldwide spatial extent, and relatively high spatial resolution MODIS snow products have been widely applied in regional snow cover and modeling studies (Brown et al., 2007; Rodell & Houser, 2004). Many studies (i.e., Hall & Riggs, 2007; Liang et al., 2008a; etc.) have demonstrated that MODIS daily snow cover products in clear-sky condition are in quite good agreement with ground based observations or other satellite-based snow cover products, however high cloud obscuration is a real problem in using MODIS snow cover products for various applications (Ault et al., 2006; Bitner et al., 2002; Klein & Barnett, 2003; Lopez et al., 2008; Simic et al., 2004; Tekeli et al., 2005; Wang et al., 2008; Xie et al., 2009; Zhou et al., 2005). Obtaining cloud-free or even cloud percentage less than 10% of daily MODIS images remains a challenge. Various approaches have been proposed to reduce cloud obscuration by altering the cloud mask, separating cloud-masked pixels, and applying spatial–temporal or multi-sensor combinations.

For example, an improved cloud mask was used in the MODIS snow cover mapping algorithm to better separate snow from cloud (Riggs & Hall, 2003). The improvement, however, is usually small as the cloud indeed exists (Parajka & Blöschl, 2008). Wang et al. (2008) attempted to separate the cloud-masked pixels into “snow” and “land” based on the ratio of snow to land from ground observations in each month, which can estimate overall snow percentage but cannot identify actual snow distribution under cloud. Spatio-temporal or multi-sensor combinations are effective approaches to reduce cloud obscuration and identify snow distribution under cloud.

Spatial approaches aim at replacing cloud pixels by the majority of non-cloud pixels in an eight pixel neighborhood (Parajka & Blöschl, ...
This can effectively reduce cloud blockage of daily MODIS snow products by ∼ 7%. The method is really effective for scattered cloud cover, not for massive area of cloud cover (i.e., all the neighboring pixels are cloud-covered).

Temporal approaches merge daily or multi-day MODIS snow cover products to minimize cloud coverage and maximize snow coverage, by the sacrifice of temporal resolution. Daily combination of Terra and Aqua MODIS, which have a 3 hour difference, can reduce ∼ 10–20% cloud obscuration (Parajka & Blöschl, 2008; Wang et al., 2009; Xie et al., 2009; Yang et al., 2006). The MODIS 8-day Snow Cover Product (MOD10A2/MYD10A2) is the representative of fixed-day combined products. It combines 2 to 8 days of Terra/Aqua MODIS daily snow cover products (MOD10A1/MYD10A1) over defined periods. Using the same algorithm, some user-defined multi-day snow cover products are produced through combining MOD10A1 products in fixed temporal windows (Houborg et al., 2007; Liang et al., 2008a; Parajka & Blöschl, 2008; Sorman et al., 2007; Yang et al., 2006). These approaches largely reduce cloud coverage, but the fixed temporal windows reduce the products’ ability to monitor snowfall events to some degrees. Based on a predefined maximum cloud coverage threshold such as 10%, other multi-day composite products with flexible starting and ending dates are produced (Wang et al., 2009; Xie et al., 2009). These products have higher temporal resolution (average 2–3 days per image) and relatively low cloud coverage, but ignore some special situations. For example, when weather conditions remain overcast for over a week, this method may result in a composite product of over 8 days or even several weeks. Hall et al. (2010) develop a new method to fill the cloud gap based on the most recent cloud-free observations for each cloud pixel. This gap-filling strategy is a useful and dynamic method which uses all the nearest non-cloud observations. One disadvantage of this method is that it does not control the cloud percentage for the entire image area.

Multi-sensor approaches can generate cloud-free snow cover maps through the merging of MODIS and AMSR-E snow products at the expense of spatial resolution. This spatial resolution. This approach takes advantage of both high spatial resolution of optical sensors and cloud penetration of passive microwave sensors (i.e., Foster et al., 2007; Hall et al., 2007a; Liang et al., 2008b; Gao et al., 2010). The snow classification accuracy of the MODIS and AMSR-E blended snow cover products is 85.6%, which is much higher than the 30.7% of MODIS daily products in all-sky condition (Liang et al., 2008b). This method sacrifices spatial resolution due to the coarse spatial resolution of the AMSR-E snow product (25 km).

The objectives of this paper are i) to improve some current cloud reducing approaches and generate new daily or multi-day blended snow cover maps based on Terra/Aqua MODIS and Aqua AMSR-E snow products; ii) to evaluate and compare those improved snow cover products in terms of spatial extent of cloud coverage, snow coverage and overall classification accuracy; and iii) to analyze the tradeoff between image classification accuracy and cloud reduction, between temporal resolution and spatial resolution reservation, and to assess the performance of different products. The purpose is to obtain various cloud-free snow cover products with reasonable temporal and spatial resolutions, whose performances are suitable for different applications. All works performed in this paper are based on MODIS and AMSR-E data for the Pacific Northwest USA during three hydrological years from September 2005 to August 2008. Observations from 244 SNOwpack TELemetry (SNOTEL) stations are used to validate these products.

2. Study area and data

2.1. Study area

The study area is located in the Pacific Northwest USA. It includes most of Washington, northeastern Oregon, northern and eastern Idaho, southwestern Montana, and northeastern Wyoming (Fig. 1). The area is selected for this study for several reasons. First, the prevalent snowpack is an important water resource of this area. Rapid snowmelt events even cause major floods in this area (Kunkel et al., 2007). Second, this area encompasses diverse topographic and climate regions, thus it can provide opportunities for comparison and evaluation under various environmental conditions. Finally, there are 244 SNOTEL stations covering a wide range of elevation zones, which provide comprehensive ground observation data.

The total study area is ∼ 565,000 km² and extends from 103°W to 124.2°W and from 41.5°N to 49.5°N. Elevation ranges from 0 to 4394 m. The elevation of the western coast region is relatively low, except for volcanic areas. The central and eastern parts of this area are mountainous and are part of the Rocky Mountains. The mountainous areas are covered with snow from November to early May which highlights the importance of snow as a major water resource for this area. The mean annual precipitation is less than 200 mm in the northwest and almost 2800 mm in the central and eastern parts of this area. Land use is mainly cultivated crops and pasture in the lowlands, scrub and grassland in the medium elevation regions, and forest in the mountainous areas.

2.2. In situ observation datasets

The in situ observation datasets (SNOTEL) used in this study include daily snow depth measurements at 244 stations from September 1, 2005 to August 31, 2008. To compare with satellite image observations, the in situ records are defined as snow cover (snow) when the value of snow depth is larger than or equal to 0.1 in (or 2.5 mm), or snow-free (no snow) otherwise. Fig. 1 shows the locations of these SNOTEL stations with mean annual snow cover duration for each station, calculated based on three hydrological years.

![Fig. 1. Topography of the study area and spatial distribution of 244 SNOTEL stations. The color symbols of stations represent the mean annual snow cover duration (days) in 2006–2008 hydrological years.](image-url)
years' data from September, 2005 to August, 2008. The elevations of the stations vary from 308 to 3005 m. Fig. 2 shows the percentage of different elevation zones of the entire study area and the frequency distribution of stations in different elevation zones. The majority of the SNOTEL stations are distributed at elevations between 1000 m and 3000 m where most snowfalls occur. 25% of the study area has an elevation lower than 1000 m while 8 SNOTEL stations are located in this elevation zone. Only 1.5% of the study area is above 3005 m elevation where the highest station is located. Therefore, the spatial distribution of these SNOTEL stations is expected to capture the variability of snowfall for this region.

2.3. Remote sensing data

The snow cover images used in this study consist of MODIS daily snow cover products MOD10A1 and MYD10A1 (MODIS Terra/Aqua Snow Cover Daily L3 Global 500 m SIN GRID V005) (Hall et al., 2007b) and AMSR-E daily Snow Water Equivalent (SWE) product AE_DySno-2 (AMSR-E/Aqua daily L3 Global Snow Water Equivalent EASE-Grids) (Kelly et al., 2007) from September 1, 2005 to August 31, 2008. Details about the MODIS and AMSR-E snow products can be found in Lobl et al. (2002), Kawanishi et al. (2003), Hall and Riggs (2007) and Kelly et al. (2003).

Two MODIS tiles (H09V04 and H10V04) are needed to cover the entire study area. We first mosaic two tiles and then reproject them into Albers equal-area conical projection using the MODIS Reprojection Tool (MRT, 2004). Totals of 1090 MOD10A1 images and 1095 MYD10A1 images, covering a period of 3 years, are used in this study (Table 1). The pixel values in those snow cover images are recategorized to three categories: snow, no snow (land), and cloud. The snow-covered ice and snow classes are merged into a single snow category; the land and inland water classes are merged into the no snow category; and the cloud, data missing and no decision data classes are merged into the cloud category. In this study area, it's found that the total of MODIS-recorded snow-covered lake ice, data missing and no decision data classes were less than 0.4%, while the other four original classes (night, ocean, detector saturated, and fill) do not occur.

The AMSR-E onboard Aqua satellite provides daily SWE products at 25 km spatial resolution. A total of 1091 AE_DySno images are used in this study (Table 1). These images are reprojected into Albers equal-area conical projection using the HDF EOS-to-GeoTIff (HEG) tool (Taaheri et al., 2007), in order to match with MODIS data. The pixel values of AMSR-E SWE include 0–240 (multiplying by 2 for true SWE values in mm), 248 (off-earth), 252 (land or snow impossible), 253 (ice sheet), 254 (water) and 255 (data missing) (Kelly et al., 2007). The AE_DySno classes are reclassified to three categories: snow, no snow (land), and missing data. For example, SWE values 1–240 representing snow-covered area are merged into the snow category; SWE value 0 represents snow-free land and is transformed to the no snow (land) category; and the data missing class is retained as data missing class. The other remaining original classes do not occur in the SWE products of the study area during the period of study.

3. Methods

Various approaches including daily combination, adjacent temporal deduction, multi-temporal (fixed-day and flexible multi-day), and multi-sensor combinations are tested to map snow cover while reducing cloud obscuration. First, information from different MODIS products acquired on the same day, nearest day or over multi-day is used to reduce cloud obscuration. Then AMSR-E products with lower spatial resolution and higher retrieval rate are introduced. Fig. 3 shows the workflow chart of data processing.

3.1. MODIS daily combination and adjacent temporal deduction

Daily combination means that MOD10A1 (Terra) and MYD10A1 (Aqua) acquired on the same day are merged into one MODIS Daily Combined (MODISDC) snow cover product. The composite rule, similar to the generation of standard MOD10A2 snow cover products, follows the priority principle (Xie et al., 2009). A low-priority integer value is always replaced by a high-priority integer value, with the priority order being snow > no snow (land) > clouds. If only MOD10A1 is present (no MYD10A1 available on that day), no combination is performed and the MOD10A1 is directly used for the next process, and vice versa.

Adjacent temporal deduction is an approach to deduce the surface conditions under the remaining cloud pixels using the information of the preceding and following days on the same pixel basis, without any sacrifice of spatial or temporal resolution (similar as Gafurov & B’ardossy, 2009; Li et al., 2008). It differs from direct replacement using previous snow mapping results with the loss of 1 day temporal resolution (Zhao & Fernandes, 2009) and also from the spatial filtering which replaces cloud pixels with the majority class of the neighboring eight pixels in the same image (Parajka & Blöschl, 2008). In adjacent temporal deduction, assuming that a pixel belongs to the cloud class in the image of the current day, three different situations may occur. (1) If the corresponding pixel values in both images of the preceding and following days are snow, the cloud pixel of the current day image is deduced as snow; (2) if the corresponding pixel values in both images of the preceding and following days are land, the cloud pixel in the current day image is deduced as land; and (3) if the pixel values in the preceding and following day images are different (one snow, the

Table 1

<table>
<thead>
<tr>
<th>Hydrological year</th>
<th>MOD10A1 missing date</th>
<th>MOD10A1 total no.</th>
<th>MY10A1 missing date</th>
<th>MY10A1 total no.</th>
<th>AE_DySno missing date</th>
<th>AE_DySno total no.</th>
</tr>
</thead>
</table>
other land or cloud) or are both cloud, the cloud pixel of current day image remains as cloud. This assumption should hold true for a continuous snow-covered or snow-free period. For the snow accumulating and melting periods, the snow cover might change daily. Thus, in these two periods, the adjacent temporal deduction method may lose its effectiveness towards cloud reduction. The input image of this process is MODISDC and the resultant image is defined as MODIS adjacent temporal deduction (MODISATD) snow cover maps.

3.2. Multi-temporal combination

Two types of multi-temporal combination, fixed-day and flexible multi-day combinations, are tested to replace cloud pixels by the most recent clear-sky observations of the same pixel. The first one is based on fixed temporal windows of 2-, 4-, 6-, and 8-day, respectively. The other is based on flexible temporal windows. The daily MODISATD snow cover maps are the inputs for these multi-temporal combinations. The resultant images for fixed-day combination are named as MODIS2DC, MODIS4DC, MODIS6DC, and MODIS8DC respectively for the 2-, 4-, 6-, and 8-day combinations.

Flexible multi-day combination approach is presented in Fig. 4. The flexible temporal windows are controlled by two thresholds, namely, maximum cloud percentage ($P$) and maximum composite days ($N$). Both are user-defined parameters that can be assigned depending on the application. In this study, we defined the $P$ as 10% and $N$ as 4 days or 8 days. The approach first calculates the cloud percentage ($P$) of the study area in the first input image. If it is less than the threshold $P$, the image directly outputs; else, it is combined with the second input image, and the cloud percentage of the study area in the combined image is updated. The process will not stop until either the cloud percentage is less than the threshold $P$, or the number of composite days equals to the threshold $N$. The resultant images from this process were named as MODIS Multi-day Combined (MODISMC) snow cover map, MODISMC4 for $N$ as 4 days and MODISMC8 for $N$ as 8 days.

3.3. Multi-sensor combination

Multi-sensor combination uses AMSR-E to map those areas where MODIS cannot map because of clouds or polar nights (Foster et al., 2007, 2008). It takes advantage of high spatial resolution and high accuracy in clear-sky condition of MODIS images and the cloud transparency ability of AMSR-E snow products (Liang et al., 2008b; Gao et al., 2010). Since there are AMSR-E image gaps and the locations of these gaps change daily, the pixel values within the image gaps are replaced by the previous day’s AMSR-E image (Liang et al., 2008b; Romanov et al., 2000). Based on the three MODIS snow cover products (MODISATD, MODISMC4, and MODISMC8), three cloud-free multi-sensor snow cover products, daily MODISATD_AE, multi-day MODISMC4_AE, and MODISMC8_AE, are therefore generated.

3.4. Evaluation of the resultant snow cover maps

The evaluation includes three parts: the spatial extent of cloud and snow, the misclassification and classification accuracies against in situ observations. The percentages of cloud ($P_c$) and snow ($P_s$) coverage over the entire study area are used to reflect the performance on cloud reduction and snow retrieval from different combinations. They are expressed as below (in percentage):

$$P_c = \frac{N_c}{N_t} \quad (1)$$

$$P_s = \frac{N_s}{N_t} \quad (2)$$

where $N_c$ is the number of cloud pixels; $N_s$ is the number of snow pixels; $N_t$ is the total number of the pixels in the entire study area.

To quantitatively assess the classification accuracy of standard and combined images, in situ snow measurements are used as “truth value” for the image pixel (named as station-pixel) that includes such an in situ station. When the station-pixel observation matches the station observation (i.e. station-pixel snow with station snow, or station-pixel no snow with and station no snow), we say the observation (or classification) of the image is in agreement; otherwise, it is not in agreement. For multi-day combined products, we compared the composite image with observations from stations for individual days. For example, in the 4-day composite product, if a station-pixel shows snow class, while the corresponding station (SNOTEL) shows snow for 3 days and land for 1 day, we say that image agrees in 3 days and disagrees in 1 day.

Image underestimation error (IU, image misclassification of snow as land) and image overestimation error (IO, image misclassification of land as snow) are widely used in assessing the misclassification of remote sensing images (Parajka & Blöschl, 2008; Pu et al., 2007), both expressed as below (in percentage):

$$IU = \frac{b}{a + b + c + d} \quad (3)$$

$$IO = \frac{c}{a + b + c + d} \quad (4)$$

where $a$, $b$, $c$, $d$, $e$, and $f$ in Eqs. (3)–(10) represent the number of station-pixels in each particular classification category (Table 2).

The agreement of remote sensing image classification is evaluated by overall accuracy and snow accuracy (Klein & Barnett, 2003; Liang et al., 2008b; Parajka & Blöschl, 2006). Generally the accuracy of MODIS only considers clear-sky (or cloud-free) condition. However, in order to compare with AMSR-E and MODIS/AMSR-E blended snow cover maps which have no cloud, two types of accuracies are used.
one in clear-sky condition and the other in all-sky condition. The overall accuracy in clear-sky \( (O_c) \) or in all-sky \( (O_a) \) condition is respectively defined as the sum of matched number of station-pixels for snow and for no snow divided by the total number of station-pixels in clear-sky condition or in all-sky condition, both expressed as below (in percentage):

\[
O_c = \frac{a + d}{a + b + c + d}
\]

\[
O_a = \frac{a + d}{a + b + c + d + e + f}.
\]

The sum of \( a, b, c, \) and \( d \) represents the total data under clear-sky, and the sum of \( a, b, c, \) \( d, e, \) and \( f \) represents the total data for all-sky. The overall accuracy in all-sky condition considers both the classification accuracy and retrieval rate, so it can reflect the overall performance of a product.

The snow accuracy in clear-sky \( (S_c) \) or in all-sky \( (S_a) \) conditions is respectively calculated by the number of station-pixels with snow that agreed with station snow divided by the total snow-covered station-pixels in clear-sky condition or in all-sky condition. The land accuracy in clear-sky \( (L_c) \) or in all-sky \( (L_a) \) is also defined in a similar way. They are expressed as below (in percentage):

\[
S_c = \frac{a}{a + b}
\]

\[
S_a = \frac{a}{a + b + e}
\]

\[
L_c = \frac{b}{a + b}
\]

\[
L_a = \frac{b}{a + b + e}.
\]

### 4. Results

#### 4.1. MODIS daily combination and adjacent temporal deduction

The cloud and snow coverage (%) monthly distribution of Terra, Aqua, daily combined and adjacent temporal deduction products are presented in Fig. 5. Fig. 5A shows that the cloud coverage of standard daily MODIS products (MOD10A1 and MYD10A1) is high especially in winter months and that MOD10A1 (Terra) has slightly lower cloud coverage than MYD10A1 (Aqua). Daily Terra and Aqua combined products (MODISDC) reduce monthly cloud coverage by 5–14%. The adjacent temporal deduction products (MODISATD) reduce monthly cloud coverage by another 6–9%. Fig. 5B shows that monthly snow retrievals of these four products change in reverse trend. The snow coverage increases from the standard daily MODIS products (MOD10A1 and MYD10A1), to the Terra/Aqua combined products (MODISDC), and to the adjacent temporal deduction products (MODISATD). Those changes are mostly obvious in the cold season, while almost no change happens from June to September since there is almost no snow cover in those months. All of these indicate that daily combination and adjacent temporal deduction are efficient to reduce cloud coverage and reveal the real snow coverage especially in cold season.

The three year in situ observations at 244 SNOTEL stations are used to verify these snow cover products. Table 3 presents the mean IU and IO errors against ground observations at both monthly and annual basis. Overall, the IU errors of all four products are larger than the corresponding IO errors except in August and September, which means that all four products tend to underestimate the snow extent. The distribution of IU and IO errors shows a typical seasonal pattern of low values in snow-covered period (December–March) and snow-free period (July–September) and of high values in transitional periods (October–November, snow accumulating period; and April–June, the snow melting period). Overall, the IU and IO values of Terra products are less than those of the Aqua products (Table 3), which indicate that Terra products have less bias than Aqua products. The comparison of four different products indicate that IU errors have a decreasing trend from Aqua or Terra products, to daily combined products, and to adjacent temporal deduction products especially in transitional period. For example, in May the mean IU error was reduced from 34.0%, 30.7% to 28.1%, and to 27.4%, respectively. Those reductions of classification indicate the improvement in snow detection from single type (Terra or Aqua), to daily combined, and to adjacent temporal deduction products. As compared with the IU errors, the IO errors are relatively small and almost have no change in the snow cover period and snow-free period among those products. The major IO errors come from those transitional months.
the IO errors keep increasing. In the stable periods, the magnitudes of annual error and most of the monthly IU errors keep reducing while daily products (Table 3). From 2-day to 8-day snow-free) and high in transitional periods, which is similar to those of IO errors is again typically low in stable periods (snow-covered or high cloud coverage (Hall & Riggs, 2007; Pu et al., 2007). All of these suggest maximum snow cover product of the 8 days, is known to overestimate coverage at different locations in different days. That’s why the NASA/Aqua MODIS sensor in Aqua has similar and consistent performance as the MODIS sensor in Terra for all other months, except for October for the 3 years in a row. Therefore, further explanation for this observation remains open.

4.2. Multi-temporal combination of Terra and Aqua MODIS snow cover products

Fig. 6 shows the mean monthly distributions of cloud and snow coverage of fixed 2-, 4-, 6-, and 8-day and flexible multi-day combined snow cover products. It is clear that fixed-day combination progressively decreases cloud coverage and increases snow coverage as the increase of composite days. In the same period, the greatest cloud reduction and snow increase are from 2-day to 4-day, followed by 4-day to 6-day, and 6-day to 8-day combinations. For example, in January, the cloud reductions from 2-day to 4-day, from 4-day to 6-day, and from 6-day to 8-day are 17.5%, 11.2% and 4.7% and the corresponding snow increases are 13.9%, 10.2% and 5.1%, respectively. This means that the magnitude of those improvements slows down although the losses of temporal resolution are the same (2 days). Comparing the magnitude of cloud coverage decrease and snow coverage increase between 6-day and 8-day combined products, the mean annual increase of snow coverage (3.5%) eventually exceeds the decrease of cloud coverage (2.7%), and so does the monthly changes. These excess snow increases might be due to the accumulation of snow coverage at different locations in different days. That’s why the NASA/MODIS standard 8-day products (MOD10A2/MYD10A2), that is called maximum snow cover product of the 8 days, is known to overestimate snow coverage (Hall & Riggs, 2007; Pu et al., 2007). All of these suggest that persistent combinations indeed overestimate snow coverage. Thus, the persistent combination should be stopped at an appropriate time to reduce the occurrence of snow coverage overestimation.

Table 4 summarizes the IU and IO errors of the fixed-day and flexible multi-day combined snow cover products against three year ground observations at 244 stations. The seasonal variability of IU and IO errors is again typically low in stable periods (snow-covered or snow-free) and high in transitional periods, which is similar to those of daily products (Table 3). From 2-day to 8-day fixed combinations, the annual error and most of the monthly IU errors keep reducing while the IO errors keep increasing. In the stable periods, the magnitudes of those changes are small, while, in the transitional periods, those changes are relatively large. The largest IO error in October increases from 15.7% for 2-day to 22.1% for 4-day, 28.2% for 6-day and 31.9% for 8-day products. This indicates that along with the increase of temporal windows, the overestimation increases.

An example of 2- to 8-day MODIS snow cover combined maps from October 26 to November 2, by fixed-day combination and flexible multi-day combination, is presented in Table 5. The three columns on the left show the date, cloud and snow percentage of the daily products; the three columns on the middle show those of persistent fixed-day combined maps; and the three columns on the right show those of flexible multi-day combined maps. Among the 8 daily products, 3 of them have cloud coverage over 10%. The maximum snow coverage is 20.7% on November 1 while the cloud coverage of this day is 4.9%. For the fixed-day combined maps, cloud coverage is reduced from 11.9% of the first day to less than 1% for 2-day combined (0 of most other combined products), while the snow coverage is increased to 24.1% for 2-day combined, and continuously is increased up to 39.1% for the 8-day combined map. Obviously, except the first 2-day combination, the other combinations are not needed since in those combinations almost no cloud coverage can be reduced while excess snow coverage is accumulated. This reveals that in persistent combinations, some unneeded combinations really exist, particularly in the snow onset and melting periods. These unneeded combinations do not reduce the cloud coverage, instead, lower the time resolution and bring more classification errors. So, some thresholds should be used for the useful combinations to remain and reduce the unneeded combinations. This provides a strong justification for the flexible multi-day combined approach.
For example, our flexible multi-day combinations generated 6 images over the 8-day period with snow coverage ranging from 11.6% to 24.1% and cloud coverage ranging from 0.4% to 9.2% (Table 5). From them, we can map and track two snow melting and one snow accumulating events. The first snow melting event happened between the late afternoon of October 27 and October 28 (raw cloud coverage of those 2 days were 1.4% and 6.3%, respectively), that reduced the snow coverage from 24.1% to 11.6%. Then a big snowfall event on October 29 and 30 (raw cloud coverage were 19.5% and 15.7%, respectively) followed, in which snow cover increased to 20.4% and remained until snow melted again on November 2, 2008.

Fig. 6 also shows the mean monthly cloud and snow coverage of flexible multi-day combined snow cover products MODISMC4 and MODISMC8. The cloud coverage of MODISMC4 (MODISMC8) ranges from 3.1% (3.1%) in July to 27.7% (11.9%) in December and the monthly snow percentage ranges from 0.4% (0.4%) in July to 56.2% (70.3%) in January. The curves of cloud and snow coverage for MODISMC4 are similar to those of the fixed 4-day combined products (MODIS4DC). The curves of cloud and snow coverage for MODISMC8 are similar to those of the fixed 6-day combined products (MODIS6DC), while the cloud coverage of these flexible multi-day combined products in snow-covered period is lower than that of MODIS6DC. The IU and IO errors of flexible multi-day combined products (MODISMC4 and MODISMC8) have a similar pattern as the fixed 4-day combined products, and their seasonal variability is also low in stable periods and high in transitional periods (Table 4). MODIS flexible multi-day combined snow cover products have more images available during the whole hydrological year (160 MODISMC4 vs. 91 MODIS4DC and 141 MODISMC8 vs. 61 MODIS6DC), also even in the transitional months (68 MODISMC4 vs. 39 MODIS4DC and 61 MODISMC8 vs. 27 MODIS6DC; please refer to Table 7). This should enable a more reliable identification of the onset and ending date of snow cover, and provide a better monitoring of the temporal variability of snow coverage.

4.3. Multi-sensor combination of MODIS and AMSR-E

The distributions of mean monthly snow coverage of AMSR-E and multi-sensor combined snow cover products are presented in Fig. 7. Passive microwave remote sensing has the ability to penetrate clouds, so the AMSR-E product has no cloud obscuration. The mean snow coverage of daily AMSR-E ranges from 0.9% in July to 75.4% in January. After multi-sensor combinations, the three new products, daily MODISATD_AE, and multi-day MODISMC4_AE and MODISMC8_AE, remove the annual cloud coverage by 36.2% from MODISATD, 14.3% from MODISMC4, and 7% from MODISMC8, and increase the annual snow cover retrieval by 13.3%, 5.3%, and 2.3%, respectively.

<table>
<thead>
<tr>
<th>Month</th>
<th>Fixed-day combined</th>
<th>2-day</th>
<th>4-day</th>
<th>6-day</th>
<th>8-day</th>
<th>Multi-day combined</th>
<th>MODISMC4</th>
<th>MODISMC8</th>
</tr>
</thead>
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<tr>
<td>Sep.</td>
<td>2.1</td>
<td>5.4</td>
<td>2.2</td>
<td>9.8</td>
<td>2.1</td>
<td>13.7</td>
<td>2.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Oct.</td>
<td>10.8</td>
<td>15.7</td>
<td>8.6</td>
<td>22.1</td>
<td>7.8</td>
<td>28.2</td>
<td>6.3</td>
<td>31.9</td>
</tr>
<tr>
<td>Nov.</td>
<td>10.7</td>
<td>6.0</td>
<td>8.0</td>
<td>7.6</td>
<td>6.3</td>
<td>8.5</td>
<td>4.8</td>
<td>10.2</td>
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<td>Dec.</td>
<td>4.5</td>
<td>0.2</td>
<td>3.6</td>
<td>0.3</td>
<td>3.0</td>
<td>0.3</td>
<td>2.2</td>
<td>0.3</td>
</tr>
<tr>
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<td>3.4</td>
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<td>2.4</td>
<td>0.2</td>
<td>2.1</td>
<td>0.2</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Feb.</td>
<td>3.1</td>
<td>0.2</td>
<td>2.0</td>
<td>0.2</td>
<td>2.0</td>
<td>0.2</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Mar.</td>
<td>4.6</td>
<td>0.5</td>
<td>3.4</td>
<td>0.6</td>
<td>2.4</td>
<td>0.7</td>
<td>1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Apr.</td>
<td>10.9</td>
<td>1.2</td>
<td>8.0</td>
<td>1.7</td>
<td>6.2</td>
<td>2.1</td>
<td>4.9</td>
<td>2.4</td>
</tr>
<tr>
<td>May.</td>
<td>24.4</td>
<td>3.7</td>
<td>19.1</td>
<td>5.6</td>
<td>17.6</td>
<td>7.1</td>
<td>15.0</td>
<td>8.7</td>
</tr>
<tr>
<td>Jun.</td>
<td>11.4</td>
<td>3.1</td>
<td>10.5</td>
<td>5.4</td>
<td>9.5</td>
<td>7.6</td>
<td>8.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Jul.</td>
<td>1.6</td>
<td>1.2</td>
<td>1.6</td>
<td>2.1</td>
<td>1.6</td>
<td>3.2</td>
<td>1.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Aug.</td>
<td>0.0</td>
<td>1.6</td>
<td>0.0</td>
<td>3.0</td>
<td>0.1</td>
<td>4.6</td>
<td>0.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Annual</td>
<td>7.0</td>
<td>3.5</td>
<td>5.7</td>
<td>5.3</td>
<td>5.1</td>
<td>6.7</td>
<td>4.2</td>
<td>8.0</td>
</tr>
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</table>

Table 4: Monthly and annual mean image under- (IU) and overestimation (IO) errors (%) of the multi-temporal (fixed-day and flexible multi-day) combined snow cover products for the period of 2006–2008 hydrological years.

Table 5: Percentage of cloud coverage (Pc) and snow coverage (Ps) of daily MODIS adjacent temporal deduction maps, their fixed-day combined and flexible multi-day combined snow cover maps.

<table>
<thead>
<tr>
<th>MODISATD</th>
<th>Pc (%)</th>
<th>Ps (%)</th>
<th>Combined</th>
<th>Pc (%)</th>
<th>Ps (%)</th>
<th>MODISMC</th>
<th>Pc (%)</th>
<th>Ps (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 26, 2008</td>
<td>11.9</td>
<td>16.1</td>
<td>1 day</td>
<td>11.9</td>
<td>16.1</td>
<td>Oct. 26–27</td>
<td>0.4</td>
<td>24.1</td>
</tr>
<tr>
<td>Oct. 27, 2008</td>
<td>1.4</td>
<td>19.6</td>
<td>2 days</td>
<td>0.4</td>
<td>24.1</td>
<td>Oct. 28</td>
<td>6.3</td>
<td>11.6</td>
</tr>
<tr>
<td>Oct. 28, 2008</td>
<td>6.3</td>
<td>11.6</td>
<td>3 days</td>
<td>0.1</td>
<td>25.7</td>
<td>Oct. 29</td>
<td>9.2</td>
<td>20.4</td>
</tr>
<tr>
<td>Oct. 29, 2008</td>
<td>19.5</td>
<td>9.5</td>
<td>4 days</td>
<td>0.0</td>
<td>26.6</td>
<td>Oct. 30</td>
<td>0.0</td>
<td>31.9</td>
</tr>
<tr>
<td>Oct. 30, 2008</td>
<td>15.7</td>
<td>18.6</td>
<td>5 days</td>
<td>0.0</td>
<td>36.1</td>
<td>Oct. 31</td>
<td>8.4</td>
<td>19.6</td>
</tr>
<tr>
<td>Oct. 31, 2008</td>
<td>8.4</td>
<td>19.6</td>
<td>6 days</td>
<td>0.0</td>
<td>38.7</td>
<td>Nov. 1</td>
<td>4.9</td>
<td>20.7</td>
</tr>
<tr>
<td>Nov. 1, 2008</td>
<td>4.9</td>
<td>20.7</td>
<td>7 days</td>
<td>0.0</td>
<td>38.7</td>
<td>Nov. 2</td>
<td>3.9</td>
<td>15.2</td>
</tr>
<tr>
<td>Nov. 2, 2008</td>
<td>3.9</td>
<td>15.2</td>
<td>8 days</td>
<td>0.0</td>
<td>38.7</td>
<td>Nov. 3</td>
<td>5.9</td>
<td>20.7</td>
</tr>
</tbody>
</table>
AMSR-E products. In other words, the more cloud coverage is replaced, the more uncertainty (i.e. IU error) is introduced to the multi-sensor combined products, as compared with their MODIS counterparts. The IO errors, however, from both multi-sensor products and their MODIS counterparts are similar (see Tables 4 and 6).

4.4. Accuracies in clear-sky condition of different snow cover products and its tradeoff for cloud reduction

The accuracies of different snow cover products are quantitatively evaluated against three year observations at 244 stations. Table 7 summarizes the annual overall accuracies in clear-sky condition and mean cloud percentage of different snow cover products. In the clear-sky condition, the original Terra snow cover product MOD10A1 has the highest accuracy of 90.4% while the cloud coverage is high at 52.2%. Terra and Aqua combined products give a similar accuracy with a loss of 0.7% compared with MODIS Terra product. The cloud coverage decreases by 7.7%. In contrast, the adjacent temporal deduction products not only reduce the cloud coverage with respect to daily combined products, but also achieve higher accuracy in every month. Differing from the annual change trend, monthly accuracies for daily, 2-, 4-, 6- and 8-day combined products (cross and circles with different gray scale) show some seasonal patterns. In June, July, August, September and October, as the temporal combinations applied, the cloud coverage reduces continuously, so does the monthly accuracy. However, during the other 7 months, the cloud coverage reduces, with the monthly accuracy progressively increasing. The patterns of flexible multi-day combined products MODISMC4 and MODISMC8 (triangles with different gray scale) are respectively similar with that of 4-day combined and 6-day combined products except in May.

In contrast to varied seasonal patterns of monthly overall accuracy (OA) presented in Fig. 8, the monthly snow accuracy (SA) in clear-sky condition in all months shows only one trend, increase trend, as the cloud coverage reduces (Fig. 9). The snow accuracies are very high in snow-covered months (November to April), and are even very close to 100% for all products from December to March. The very low snow accuracies (<20% or less) in July and August, however, do not affect the overall accuracy for those 2 months (98% or higher) (Fig. 8), since numbers of those misclassified pixels are very small. Lower snow accuracies (30–80%) in May, June, September, and October indeed affect the overall accuracies in those 4 months (Fig. 8). The higher snow accuracies (>80%) in November do not result in higher overall accuracies in this month (Fig. 8), due to lower land accuracies (not shown). This means that fixed-day combinations do bring uncertainty and more combination will bring larger uncertainty. The flexible multi-day combined snow cover products MODISMC4 and MODISMC8 have an overall accuracy of 89.2% and 89.3%, which is slightly lower than Terra snow products by 1.2% and 1.1%, respectively. However the cloud coverage decreases to 14.3% and 7.2%, which can meet most of user requirements.

Table 7 also shows the snow and land accuracies in clear-sky and all-sky conditions among different snow cover maps, in the period of 2006–2008 hydrological years. In the daily products, the land accuracies are larger than those of snow accuracies in clear-sky condition, while much larger in all-sky condition. For the multi-day (fixed and flexible) combination products, the differences between those accuracies in clear-sky or in all-sky condition are smaller.

More details about the tradeoff between the overall accuracies in clear-sky condition (OA) and the cloud reduction of different snow cover maps are illustrated in Fig. 8. Similar to the change trend of the annual overall accuracy and cloud reduction, the Terra snow cover products have slightly higher accuracy and lower cloud coverage than the Aqua products in every month (squares with different gray scale). The adjacent temporal deduction products (star) not only reduce the cloud coverage with respect to daily combined products, but also achieve higher accuracy in every month. Differing from the annual change trend, monthly accuracies for daily, 2-, 4-, 6- and 8-day combined products (cross and circles with different gray scale) show some seasonal patterns. In June, July, August, September and October, as the temporal combinations applied, the cloud coverage reduces continuously, so does the monthly accuracy. However, during the other 7 months, the cloud coverage reduces, with the monthly accuracy progressively increasing. The patterns of flexible multi-day combined products MODISMC4 and MODISMC8 (triangles with different gray scale) are respectively similar with that of 4-day combined and 6-day combined products except in May.

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![Fig. 7. Mean percentage (monthly) of snow coverage (\(P_s\)) of AMSR-E (AE_DySno) and multi-sensor combined daily (MODISATD_AE) and multi-day (MODISMC4_AE and MODISMC8_AE) snow cover maps, during 2006–2008 hydrological years.](image)
4.5. Regional variability of accuracy in all-sky condition and trade off between temporal resolution and spatial resolution

The overall accuracies in all-sky condition can evaluate the real performance of different snow products in applications such as hydrological modeling. Table 7 also shows the annual overall accuracies in all-sky conditions and the mean number of images within one hydrological year (transition period: October–November and April–June), snow accuracies in clear-sky ($S_c$) and all-sky conditions ($S_a$), land accuracies in clear-sky ($L_c$) and all-sky conditions ($L_a$), among different snow cover maps, in the period of 2006–2008 hydrological years.

Table 7: Comparisons of overall accuracies in clear-sky ($O_c$) and all-sky conditions ($O_a$), mean cloud percentages ($P_c$), the number of images in one hydrological year (transition period: October–November and April–June), snow accuracies in clear-sky ($S_c$) and all-sky conditions ($S_a$), land accuracies in clear-sky ($L_c$) and all-sky conditions ($L_a$), among different snow cover maps, in the period of 2006–2008 hydrological years.

<table>
<thead>
<tr>
<th></th>
<th>$O_c$ (%)</th>
<th>$P_c$ (%)</th>
<th>$O_a$ (%)</th>
<th>Total images</th>
<th>$S_c$ (%)</th>
<th>$S_a$ (%)</th>
<th>$L_c$ (%)</th>
<th>$L_a$ (%)</th>
</tr>
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<tr>
<td>Terra</td>
<td>MOD10A1</td>
<td>90.4</td>
<td>52.2</td>
<td>40.0</td>
<td>363</td>
<td>79.5</td>
<td>25.4</td>
<td>98.5</td>
</tr>
<tr>
<td>Aqua</td>
<td>MYD10A1</td>
<td>88.3</td>
<td>56.2</td>
<td>34.3</td>
<td>365</td>
<td>76.7</td>
<td>20.0</td>
<td>95.8</td>
</tr>
<tr>
<td>Daily combined</td>
<td>MODISDC</td>
<td>89.7</td>
<td>44.5</td>
<td>45.6</td>
<td>365</td>
<td>82.2</td>
<td>31.1</td>
<td>95.6</td>
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<tr>
<td>Adjacent temporal deduction</td>
<td>MODISATD</td>
<td>90.0</td>
<td>37.1</td>
<td>51.5</td>
<td>365</td>
<td>83.0</td>
<td>36.0</td>
<td>95.8</td>
</tr>
<tr>
<td>Fixed-day combination</td>
<td>2 days</td>
<td>89.5</td>
<td>27.0</td>
<td>60.8</td>
<td>183</td>
<td>85.5</td>
<td>47.7</td>
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</tr>
<tr>
<td></td>
<td>4 days</td>
<td>89.0</td>
<td>12.5</td>
<td>73.9</td>
<td>91</td>
<td>85.1</td>
<td>66.4</td>
<td>88.9</td>
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<td></td>
<td>6 days</td>
<td>88.2</td>
<td>6.5</td>
<td>79.9</td>
<td>61</td>
<td>90.9</td>
<td>77.8</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td>8 days</td>
<td>87.8</td>
<td>3.8</td>
<td>82.6</td>
<td>46</td>
<td>92.6</td>
<td>83.9</td>
<td>81.6</td>
</tr>
<tr>
<td>Multi-day combined</td>
<td>MODISMC4</td>
<td>89.2</td>
<td>14.3</td>
<td>72.0</td>
<td>160</td>
<td>87.6</td>
<td>64.3</td>
<td>91.1</td>
</tr>
<tr>
<td></td>
<td>MODISMC8</td>
<td>89.3</td>
<td>7.2</td>
<td>79.4</td>
<td>81</td>
<td>90.2</td>
<td>75.5</td>
<td>89.4</td>
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<td>AMSR-E</td>
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<td>/</td>
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<td>79.2</td>
<td>365</td>
<td>/</td>
<td>67.6</td>
<td>/</td>
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<td>Multi-sensor combined</td>
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<td>79.2</td>
<td>365</td>
<td>/</td>
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<td>86.0</td>
<td>141</td>
<td>/</td>
<td>81.4</td>
<td>/</td>
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</table>

Fig. 8. Trade off between the monthly overall accuracy in clear-sky condition $O_c$ (Eq. (5)) and cloud coverage $P_c$ (Eq. (1)) of different snow cover products in 2006–2008 hydrological years (S is September, O is October, and etc.).
stations. Namely, 48 stations in elevation zone 0–1500 m, 64 in elevation zone 1500–2000 m, 77 in elevation zone 2000–2500 m, and 55 in elevation zone over 2500 m. Overall, the MODIS products (two left panels) have much lower accuracies from November to May as compared to those from June to October. AMSR-E products (top right) and daily AMSR-E and MODIS combined products (bottom right) have higher accuracies (over 60%), except in transitional periods. This is mainly due to the scale difference from point (SNOTEL station) to pixel (MODIS pixel). Remote sensing images really have difficulty to detect scattered (minority) objects in transitional periods, or minority

Fig. 9. Trade off between the monthly snow accuracy in clear-sky condition $S_c$ (Eq. (7)) and cloud coverage $P_c$ (Eq. (1)) of different snow cover products in 2006–2008 hydrological years (S is September, O is October, and etc.).

Fig. 10. The monthly overall accuracy in all-sky condition $O_a$ (Eq. (6)) and cloud coverage $P_c$ (Eq. (1)) of different snow cover products in 2006–2008 hydrological years (S is September, O is October, and etc.).
surface objects are not big enough to be resolved in coarser resolution images (Gao et al., 2010). For all products in the period of November to April, the accuracies clearly depend on elevation. The highest accuracy occurs at the highest mountain zone (above 2500 m), while the lowest accuracy occurs at the lowest elevation zone (less than 1500 m). This is the same reason as discussed for the transitional months, that snow cover at lower elevation is more changeable and can be a scattered minority object that can be seen in a station, but not necessary in the corresponding image pixel scale. In other months, the accuracies show no consistent relationship to elevation. In July, August and September (snow-free period), the accuracies of every product are relatively high. For MODIS products, the Terra MODIS product has slightly high accuracies than Aqua MODIS product in all months at all elevations; the daily combined Terra and Aqua MODIS (MODISDC) product has higher accuracy than either Terra MODIS (MOD10A1) or Aqua MODIS (MYD10A1) in all months at all elevations; and the adjacent temporal deduction product (MODISATD) has a higher accuracy than the MODISDC in all months at all elevations.

Similar to Fig. 11, the only difference in Fig. 12 is that it shows the accuracies for all eight multi-day products. Overall, multi-day products have higher accuracies than the daily products, and accuracy increases as the combination day increases, although the magnitude of increase decreases. The most obvious increase for all the MODIS fixed and flexible multi-day combination products is achieved during the period from November to May when the accuracies are generally
lower than those of other months in the MODIS daily products (Fig. 11). Also during this period, all products exhibit better accuracy at higher elevation. This is also similar to what is seen for the daily products (Fig. 11). It is very clear that the accuracies in the two transitional periods (October–November and April–June) are lower than other months in all multi-day combination products. This is due to the larger mapping errors in those months as discussed earlier (Tables 3, 4, and 6).

5. Discussion and conclusions

The overall accuracies in clear-sky condition (88–90%) of daily Terra and/or Aqua MODIS products in the area of study (Table 7) are slightly lower than the ~93% from other areas (Hall & Riggs, 2007). This could be attributed to several reasons. One is the different mapping accuracies and physiographic characteristics of the SNOTEL stations. Among the 244 stations, ~20% of them are located at elevations lower than 1500 m. As shown in Figs. 11 and 12, from this group of elevation/SNOTEL stations, MODIS shows the lowest overall accuracy since the scale difference from SNOTEL point to MODIS pixel (Gao et al., 2010). This would have contributed in reducing the overall mapping accuracy of the study area. Second, as shown in Fig. 8, there is a big difference in overall accuracy from month to month or from season to season. In particular, the overall accuracy for snow-covered months are actually very high over 95%, while for those transitional months (October, November, April, May, and June), the values are much lower. Those low values from the five transitional months have lowered the overall accuracy for the area. Last but not the least, the threshold value of 0.1 m (or 2.5 mm) of snow depth in this study used to define snow/no snow from SNOTEL station would also contribute to the lower overall accuracy of MODIS products, since many other studies used 1–4 cm of snow depth to define snow or no snow from in situ measurements (Liang et al., 2008a; Maurer et al., 2003; Tekeli et al., 2005; Wang et al., 2008; Xie et al., 2009; etc.). In the 1–4 cm snow depth range, remote sensing, of course, would achieve high overall accuracy, since remote sensing has difficulty to map thin and marginal snow covers as discussed before.

The primary objective of this study is to examine different approaches in reducing cloud obscuration and to generate products that satisfy the requirements for different applications. Various approaches including daily combination, adjacent temporal deduction, fixed-day combination, flexible multi-day combination and multi-sensor combination are examined and applied in the Pacific Northwest USA. The overall performances of different snow cover map products are quantitatively evaluated through cloud and snow percentages, misclassification error and overall accuracy against three year observations at 244 SNOTEL stations.

Daily combination merges two MODIS snow products on a pixel basis according to the priority principle, i.e. snow>no snow (land)>clouds. Terra and Aqua MODIS combination reduces the cloud obscuration by 11.7% over MOD10A1 and 7.7% over MYD10A1. Thus the accuracy in all-sky condition increases from 40%/34.4% to 45.6%. Similar results have been reported in many other researches (Parajka & Blöschl, 2008; Wang et al., 2009; Wang & Xie, 2009; Xie et al., 2009; Yang et al., 2006). The adjacent temporal deduction method uses the information of two temporal adjacent images to deduce cloud pixels on the current day image. If one pixel in the current image is cloud, while land (snow) is shown in the corresponding pixel in both preceding and following images, this cloud pixel of the current image is then assigned as land (snow). Application of this method results in an additional 7.4% reduction in cloud coverage, with respect to the daily combined snow cover map. In addition, this method reduces the IU/IO errors and increases the overall accuracies in all-sky condition to 51.5%. Therefore, the adjacent temporal deduction is an efficient method to reduce cloud obscuration and improve the overall accuracy. However, it should be noticed that although the adjacent temporal deduction shows the advantage and improvement on snow mapping accuracy, it is by no means that one has to use it before any multi-day or multi-sensor combinations can be performed. In particular, there is no way that the method can be used in operational context. However, an image in a previous day can always been used for this approach.

Fixed-day combined approaches merge 2- to 8-day consecutive images to produce maximum snow coverage and minimum cloud coverage. The results reveal that combination reduces the mean annual cloud coverage over the study area from 37.1% (MODIS daily adjacent temporal deduction snow cover map) to 27.0% (2-day combined), 12.5% (4-day combined), 6.5% (6-day combined), and to 3.8% (8-day combined), while the overall accuracy in clear-sky condition slightly decreases from 90.0% to 89.5%, 89.0%, 88.2% and 87.8%, respectively. A similar temporal filter was tested by Parajka and Blöschl (2008) over Austria and verifies against daily snow depth observations at 754 climate stations. Their results demonstrate that 63% cloud coverage of the Aqua images is reduced to 52% for combined Aqua–Terra images, 46% for the spatial filter, 34% for the 1 day temporal filter, and 4% for the 7-day temporal filter, and the corresponding overall accuracies are 95.5%, 94.9%, 94.2%, 94.4% and 92.1%, respectively. In all months except December, the cloud coverage decreases, so does the accuracy as progressively more data are merged. In this study, however, from 2- to 8-day combinations, the variability of monthly overall accuracy (in clear-sky condition) shows a typically seasonal pattern, reduces from June to October (not much change in July and August) as cloud decrease, but increases from November to May (Fig. 8). This suggests that, in the snowfall and most snow-covered months, the overall accuracies actually increase due to the progressive combinations to reduce cloud coverage. The snow accuracies in clear-sky for all products (Fig. 9), however, are very similar and very high from November to April, although they are much lower in other months or even less than 20% in July and August. As the temporal window gets larger, the cloud coverage decreases and the snow coverage increases progressively. Meanwhile, the accuracy in all-sky condition for the fixed 2-, 4-, 6- and 8-day combined products increases from 60.8%, to 73.9%, to 79.9%, and to 82.6%, respectively. Interestingly, although from 2-day to 4-day, from 4-day to 6-day and from 6-day to 8-day, the losses of temporal resolution are all the same 2 days, the magnitude of cloud reduction and accuracy increase slows down, while the excess snow indeed happens since the accumulation of snow coverage at different locations in different days. Our monthly and annual results indicate that some unneeded combinations really exist in the persistent combinations, particularly in the snow onset and melting periods (transition periods). Therefore the persistent combination should be stopped at an appropriate time for the useful combinations to remain and reduce the unneeded combinations.

In this study, two thresholds, i.e. maximum cloud percentage ($P$) and maximum composite days ($N$), are used to control the flexible temporal windows and generate flexible multi-day combined snow cover products. These two thresholds are user-defined parameters that can be changed depending on the application. In our case of three year data for the study area, most of the procedures were terminated by the threshold $P$ (10%). For example, for the threshold $N = 4$, the procedures were terminated by $P$ for 366 times and by $N$ for 114 times; for the threshold $N = 8$, the procedures were terminated by $P$ for 404 times and by $N$ for 19 times. This means that, in the 3 years, there were 19 cases of continuous 8 days or 114 times of continuous 4 days, with mean cloud cover of the area over 10%. The accuracy in all-sky condition of flexible 4-day and 8-day combined products is 72.0% and 79.4%, respectively. Its spatial resolution is 500 m and its mean temporal resolution is 2.3 and 2.6 days/image, which is consistent with Xie et al. (2009) in cases of Colorado Plateau and in Northern Xinjiang, China. Compared with fixed-day combinations, this product should enable a more reliable identification of the onset and ending date of snow cover, and be more suitable to map and
track the temporal variability of snow coverage. Therefore, it is argued that such a flexible combination method is relevant to maintain the balance of temporal resolution and realistic estimation of the snow cover extent.

The most interesting outcomes from this study are summarized as:

1) The primary errors of image underestimation (IU) and overestimation (IO) occur during transition months. In the snow-covered months, these errors are actually small, and the IU errors are always slightly larger than IO errors for all fixed-day combined products;

2) The annual IU errors of fixed 2- and 4-day combined products are larger than the IO errors, which are similar to the daily products. This indicates an overall underestimation of snow cover from those products (1-, 2-, and 4-day); an overall overestimation of snow cover only occurs with longer composite days (6-8 days);

3) The IU and IO errors of flexible multi-day combined products (MODISMC4 and MODISMC8) have a similar pattern to the fixed 4-day combined products, although the monthly percentages of cloud and snow cover change in the MODISMC8 (MODISMC4), which match better with the fixed 6-day (4-day) combined products; and

4) the MODISMC4 and MODISMC8 have the same overall accuracy in clear-sky (89.1%), while overall accuracy of MODISMC4 in all weather conditions is slightly less than that of MODISMC8 (72.3% vs. 80.2%), but with more images available (one image per 2.3 days vs. 2.6 days).

These findings have important implications as indicated below.

1) Although the standard MODIS 8-day product represents the maximum snow cover of the 8-day period, it actually slightly underestimates snow cover in those snow-covered months, while significantly overestimates the snow cover in transitional months, especially during snow accumulation period;

2) Among the fixed-day compositions, the fixed 4-day combination products seem to be a good compromise to maintain the balance of temporal resolution and realistic estimation of the snow cover extent; and

3) While flexible multi-day combination is found to outperform the fixed-day combined products in reducing cloud reduction and improving image accuracy, the flexible 8-day combination can reduce more cloud (less than 10%), but may cause more snow overestimation in transitional months. Meanwhile, the flexible 4-day combination may leave more cloud cover in the winter months (over 10%), which offers more available images. The use of 4 and/or 8 days combinations as a threshold remains to be determined by the user as required for their specific application and/or study area.

The multi-sensor combined approach utilizes the information from AMSR-E to update the remaining cloud pixels in the MODIS daily or multi-day combined snow cover maps. The assessment shows that the overall accuracy of daily AMSR-E snow cover products, with the coarse spatial resolution of 25 km, is 74.1% with the retrieval rate of 100%. This (74.1%) is lower than the overall accuracy (90.4%) in clear-sky condition, which reflects the effectiveness of the MODIS’s high spatial resolution. However, the retrieval rate of Terra MODIS is below 50% due to high cloud coverage. The low retrieval rate depletes the effectiveness of the MODIS’s high spatial resolution and decreases the overall accuracy of MODIS Terra in all-sky condition to only ~40% (Table 7). Daily MODIS and AMSR-E combined products with the pixel size of 500 m have the highest overall accuracy in all-sky condition of 79.2% among the daily snow cover products. This is because these blended snow cover products utilized advantages of the effectiveness of MODIS high spatial resolution and AMSR-E cloud penetration ability. The overall accuracy in all-sky condition of multi-day and multi-sensor combined products MODISMC4_AE and MODISMC8_AE is 83.8% and 86.3%, respectively. Its pixel size is 500 m and its mean temporal resolution is 2.3 and 2.6 days/image, respectively.

Similar evaluations for multi-sensor combined products have been performed in diverse regions and for various sensors, but not as comprehensive as what we tested here. For example, Liang et al. (2008b) produces new daily snow cover products through combining information of Terra MODIS daily snow cover product (MOD10A1) (the Aqua MODIS snow cover products not included) and AMSR-E daily SWE product (AE_DySno) in Northern Xinjiang, China during the period from November 1 to March 31 of years 2002 to 2005. The combination significantly increases the snow accuracy in all-sky condition from 33.4% (MOD10A1) to 75.4%. Gao et al. (2010) generated new daily snow cover products utilizing Terra/Aqua MODIS and AMSR-E snow products in Fairbanks and Upper Susitna Valley, Alaska area, but only for one hydrological year (October 2006 to September 2007). Their results indicate that the accuracy of multi-sensor combined products has the snow accuracy in all-sky condition of 86% with respect to 31% (MOD10A1), 45% (MYD10A1) and 85% (AMSR-E). Romanov et al. (2000) develops a method of automated monitoring snow cover over North America using GOES and SSM/I and validates their products against in situ land surface observations during the winter season of 1998/1999. They found that snow identification from the combined products outperformed the ones based on a single satellite. Simic et al. (2004) validated MODIS MOD10A1 (500 m) and NOAA GOES + SSM/I (4 km) products for the period between January and June 2001 against 2000 surface snow depth measurements across Canada. The MODIS and NOAA products show similar monthly agreements ranging from 80% to 100%, while the retrieval rates are 40% for MODIS and 100% for NOAA. Therefore the coarser resolution NOAA product may be sufficient for basin- or sub-basin-scale applications. All of these studies indicate that multi-sensor combination is a useful method to improve the snow retrieval rate.

Overall, our results demonstrate that flexible multi-day and multi-sensor (i.e., MODIS and AMSR-E) combined approaches are robust techniques which cannot only reduce the cloud coverage, but also remain in good agreement with ground observations. The difference between them is that multi-day combined methods sacrifice some temporal resolution while multi-sensor methods sacrifice some spatial resolution. The multi-day combined map with higher spatial resolution has higher accuracy in clear-sky condition, but retains some cloud coverage; multi-sensor combined products can eliminate the effects of cloud obscuration, but lose some spatial resolution, while significantly increasing the overall performance since its 100% retrieval rate. The multi-sensor approach is the practical method that yields cloud-free snow cover products. The choice of different approaches will depend on the requirement of specific applications and the meteorological conditions of various regions.

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