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Statistical evaluation of remotely sensed snow-cover products with constraints from streamflow and SNOTEL measurements

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Abstract

Using streamflow and Snowpack Telemetry (SNOTEL) measurements as constraints, the evaluation of the Moderate Resolution Imaging Spectroradiometer (MODIS) daily and 8-day snow-cover products is carried out using the Upper Rio Grande River Basin as a test site. A time series of the snow areal extent (SAE) of the Upper Rio Grande Basin is retrieved from the MODIS tile h09v05 covering the time period from February 2000 to June 2004 using an automatic Geographic Information System (GIS)-based algorithm developed for this study. Statistical analysis between the streamflow at Otowi (NM) station and the SAE retrieved from the two MODIS snow-cover products shows that there is a statistically significant correlation between the streamflow and SAE for both products. This relationship can be disturbed by heavy rainstorms in the later springtime, especially in May. Correlation analyses show that the MODIS 8-day product has a better correlation (r=−0.404) with streamflow and has less percentage of spurious snowmelt events in wintertime than the MODIS daily product (r=−0.300). Intercomparison of these two products, with the SNOTEL data sets as the ground truth, shows that (1) the MODIS 8-day product has higher classification accuracy for both snow and land; (2) the omission error of misclassifying snow as land is similar for both products, both are low; (3) the MODIS 8-day product has a slightly higher commission error of misclassifying land as snow than the MODIS daily product; and (4) the MODIS daily product has higher omission errors of misclassifying both snow and land as clouds. Clouds are the major cause for reduction of the overall accuracy of the MODIS daily product. Improvement in suppressing clouds in the 8-day product is obvious from this comparison study. The sacrifice is the temporal resolution that is reduced from 1 to 8 days. The significance of the results is that the 8-day product will be more useful in evaluating the streamflow response to the snow-cover extent changes, especially from the long-term point of view considering its lower temporal resolution than the daily product. For clear days, the MODIS daily algorithm works quite well or even better than the MODIS 8-day algorithm.

Keywords: Streamflow; SNOTEL; Moderate Resolution Imaging Spectroradiometer; Remote sensing; Snow cover; Geographic Information System

1. Introduction

Specific spectral reflectance of snow (higher reflectance in the visible compared to the mid-infrared electromagnetic spectrum) allows snow-covered areas to be accurately discriminated from snow-free areas (hereafter referred to as land) in the absence of clouds or vegetation canopies using optical remote sensing methods (Rango et al., 2000; Zhou, 2002). Compared with other remote sensing techniques such as microwave remote sensing which can be used to map snow water equivalent (SWE) (Goodison & Walker, 1995; Shi & Dozier, 2000), optical remote sensing which is used to map snow areal extent (SAE) has much higher spatial resolution (Zhou, 2002). SAE has long been recognized as an important hydrologic and climatological variable for surface water runoff prediction in snow watersheds during the snowmelt season (e.g. Hall & Martinec, 1985; Martinec, 1975), for accurate specification of the boundary conditions in surface-atmospheric modeling (Dai et al., 2003; Zeng et al., 2001), and for modeling

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atmospheric, hydrological, and ecological processes (Simic et al., 2004). For a snow watershed, the presence of snow in the basin not only strongly affects local and global climate (Dickinson et al., 1993), but also affects water resources that are stored as frozen water at the surface and are available for warm-season runoff. The association between SAE and water storage in the alpine regions makes SAE an important parameter for forecasting local or even global climate change, seasonal water supply, and flooding potential due to snowmelt (Jain & Lall, 2000). Snow areal extent has been used for hydrological forecasting for decades (Maurer et al., 2003). Recent analysis of the relationship between snow-cover extent and streamflow in the large Siberian watersheds (Ob, Yenise, and Lena basins) using remotely sensed long-term weekly snow-cover extent and ground streamflow data shows that there exists a statistically significant relation between the weekly streamflow and SAE change, which suggests a practical procedure for snowmelt runoff prediction using remotely sensed SAE (Yang et al., 2003). As SAE is not a quantity that directly characterizes the water storage within a snowpack, a variety of approaches for determining SWE based on SAE has been developed to convert the more widely available SAE to the scarcer but hydrologically more useful SWE (Maurer et al., 2003). These approaches can take the form of depletion curves (Liston, 1999; Martinec, 1985; Seidel & Martinec, 1993), regional regressions (e.g. Steinhoff & Barnes, 1976), or statistical inference using scattered ground- and airborne-based snow observations (Carroll et al., 1995; Elder et al., 1997). All these approaches can provide spatial and temporal distributions of SWE when spatial observation density and temporal observation frequency are high. For either SAE-streamflow or SAE–SWE–runoff methods, accurate mapping of the SAE is critical for streamflow prediction. However, optical-sensor observations of the snow cover are frequently interrupted by clouds and vegetation canopy. Different algorithms in handling these adverse effects used to produce the snow-cover map have different accuracies in runoff prediction. Snow mapping algorithms for the Moderate Resolution Imaging Spectroradiometer (MODIS) on Earth Observing System (EOS) Terra and Aqua platforms generate a suite of snow-cover products of various levels (Hall et al., 2002; Riggs et al., 2003) that is distributed by the Distributed Active Archive Center (DAAC) of the National Snow and Ice Center (NSIDC). For watershed streamflow prediction study, the MODIS composite daily and 8-day level 3 products should be better than other products considering its higher spatial resolution (500 m) and optimal selection from multiple observations (see discussion below).

To validate satellite products is generally difficult as the spatial scales used for validation are often different from the satellite products for comparison (Simic et al., 2004; Zhou & Li, 2003). Currently, there is no single means of assessing the performance of the MODIS snow-cover products. To add to the diversity of the methods used for the evaluation of the MODIS land products, which include comparisons of the MODIS products with in situ measurements, products derived from airborne and space-borne sensors, and process-based models (Morisette et al., 1998), we will assess the accuracy and long-term consistency of MODIS Version 4 daily and 8-day snow-cover products (1) by using streamflow as a constraint to intercompare these two products using a closed watershed such as the Upper Rio Grande Basin as a test bed and (2) by comparing them with long-term Snowpack Telemetry (SNOTEL) ground data at selected SNOTEL stations. The objectives of this study are to evaluate (1) which of these two products is more relevant to the response of streamflow to the snow-cover change that could enhance the predictability of snowmelt runoff of a watershed using the remotely sensed SAE data; (2) which of the two products is more statistically consistent with the long-term SNOTEL measurement; and (3) what is the bias for the misclassification of these two products. The method using the streamflow as a constraint is an extension of comparing the MODIS products with in situ measurements. The comparison using streamflow as a constraint, however, is statistical, indirect, and at a large scale rather than intercomparison on a pixel-by-pixel basis, and thus should be especially useful for precipitation products because the streamflow is the eventual product of precipitation–runoff or precipitation–snowmelt–runoff hydrological processes for a watershed.

A comprehensive comparison of presence–absence of snow on per pixel basis was conducted previously between the MODIS daily snow-cover product and the National Operational Hydrologic Remote Sensing Center (NOHRSC) operational product generated from the Advanced Very High Resolution Radiometer (AVHRR) and the Geostationary Operational Environmental Satellites (GOES) and against in situ ground measurement in the Upper Rio Grande River Basin for the 2000–2001 snow year (Klein & Barnett, 2003), in the Missouri River and Columbia River basins during winter and spring of 2000–2001 (Maurer et al., 2003), in Canada from January to June 2001 (Simic et al., 2004), and in the northwest and north central USA from March to June 2001 (Bitner et al., 2002). Results from these comparison studies for a short-term period (≤1 year) show that (1) the MODIS daily product generally maps snow cover at a higher proportion of the basins and a higher accuracy than the NOHRSC snow-cover product when both were compared against the in situ SNOTEL measurements (Klein & Barnett, 2003; Maurer et al., 2003); (2) the MODIS snow daily product has a higher commission error than omission error, especially for dense forests (Klein & Barnett, 2003; Simic et al., 2004); (3) the MODIS daily product maps more snow in forests and less snow in little to no forest regions than does the NOHRSC product (Bitner et al., 2002). When comparing the MODIS daily product with NOHRSC product, the general conclusions derived from these validation studies are: (1) the MODIS daily snow-cover product misclassifies fewer snow pixels; (2) the

MODIS daily product classifies fewer cloud pixels, especially in the forested areas; (3) the MODIS daily product classifies more snow pixels in forested areas than does the NOHRSC product; (4) the MODIS daily product has lower misclassification rate than the NOHRSC product, especially in more topographically complex and heavily forested basins such as the Upper Rio Grande River and Columbia River basins than basins that have less relief and less forest such as the Missouri River basin.

As water supply forecasting in the western USA relies heavily on the accurate estimation of snowpack including both SWE and SAE, improved capability of the MODIS daily product in classifying snow in topographically complex and forested watersheds, typical for the watersheds in the western USA will be of greatest interest to hydrologic modeling and water supply forecast. However, these validation or evaluation activities are mainly focused on the MODIS daily snow product. In this study, we will focus on validation or evaluation of the MODIS daily and 8-day snow-cover products through statistical intercomparison of the MODIS daily and 8-day products with constraints from both the streamflow data and the long-term SNOTEL data at the selected stations.

2. Study sites

The test site selected for this study is the Upper Rio Grande River Basin-upper portions of the Rio Grande, which includes the Upper Rio Grande Basin of southern Colorado and northern New Mexico (Fig. 1). It is the northern headwater portion of the whole Rio Grande River Basin. The Upper Rio Grande Basin, like most of the western US basins, is primarily fed by snowmelt from the snowpack that accumulates over a number of months from winter snowstorms. While precipitation throughout the year can provide runoff for the entire Rio Grande river basin, snow from winter storms is the dominant precipitation contributing to the runoff. Therefore, accurate mapping of the SAE at any time point from remote sensing satellite sensors has an important implication for runoff prediction, water supply forecast, and water resource management.

The Rio Grande provides the essential water supply for flora, fauna, and human society in these regions. Agricultural and pastoral irrigation depends solely on the water derived from the river directly from the Rio Grande and its tributaries or indirectly from surface water in the reservoirs, or ground water supplies which are recharged from the river.

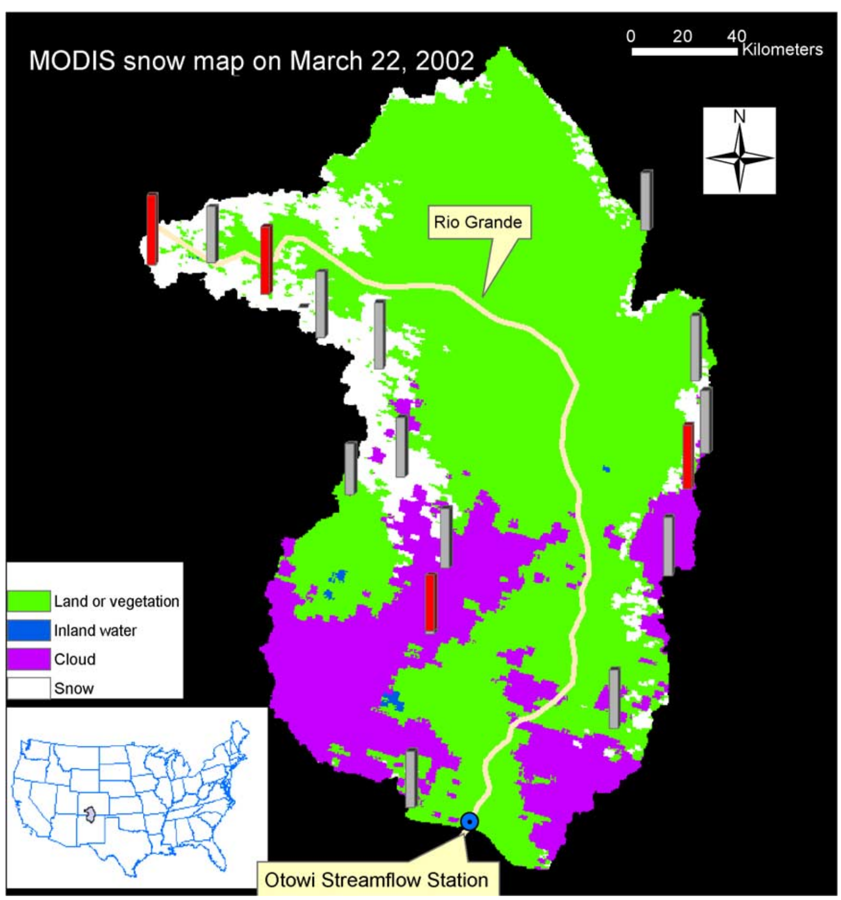

Fig. 1. Study site of the Upper Rio Grande River basin. There are 16 SNOTEL stations in the basin, in which 12 stations are denoted by gray columns with the vertical length indicating the altitude, and 4 are denoted by red columns and are selected for detailed comparison study with the MODIS daily and 8-day products. Streamflow outlet is the Otowi station. The backdrop is the MODIS 8-day snow-cover map on March 22, 2002. White pixel=snow, dark blue pixel=inland water, violet pixel=cloud, and green pixel=land or vegetation without snow. Bisque line=Rio Grande River digital line graph (DLG).

Expanding urban populations along the Rio Grande River have also created growing demands for municipal and industrial uses of water (Costigan et al., 2000). The Rio Grande River is highly regulated by reservoir systems, especially in the middle Rio Grande basin. However, compared to the lower portions of the river, the Upper Rio Grande River basin is relatively much more unregulated, pristine, and stable. From its headwaters in the San Juan Mountains of southwestern Colorado to the Otowi Bridge streamflow station, bounded by the southern Rocky Mountains, the Upper Rio Grande Basin covers about 37,037 km^2 (Fig. 1). The basin's eastern flank is the Sangre de Cristo Range and its western flank is San Juan Mountains, La Garita, and Sawatch Ranges. The outlet of the basin shown in Fig. 1 is Otowi streamflow station south of Espanola, New Mexico. The northern (Colorado) part of the basin falls in the Rio Grande Drainage climate division, while the southern (New Mexico) part of the basin falls in the Northern Mountains climate division.

We select the Upper Rio Grande River Basin as a test site mainly due to the following reasons: (1) The Upper Rio Grande Basin from the northern rocky mountains to the Otowi station is a closed watershed. The streamflow at the Otowi station represents the runoff from the whole basin. The response of the watershed to the snowmelt processes should be represented in fluctuation of streamflow at Otowi streamflow record. The streamflow record at Otowi station has been available since 1895. (2) The Upper Rio Grande encompasses large ranges of elevation, slopes, aspects, and vegetation biomasses ranging from evergreen forest at higher elevations to shrubland and grassland at lower elevation and at the valley floor, representing a typical snowmelt recharging watershed (Klein & Barnett, 2003). The basin is sufficiently large for the medium resolution (250 m–1 km) of the MODIS data but small enough for the management of data retrieval. (3) Within this basin, there are 16 automated SNOTEL stations (Fig. 1) for snowpack conditions monitoring and recording. These SNOTEL stations are generally located at mid- to high-elevation mountainous areas. The in situ snowpack data from these SNOTEL observation stations can be freely obtained from the National Resources Conservation Service. (4) Several snowmelt–runoff modeling studies have been carried out for the basin (e.g. Klein & Barnett, 2003; Rango & Martinec, 1994; Rango & van Katwijk, 1990). These studies provide insights for the present evaluation study and results from the present study provide insights for future snowmelt–runoff modeling using remotely sensed snow products.

3. Data sources

3.1. Snow-cover products

The MODIS snow-cover data products are generated by various algorithms as a suite of products, ranging from the initial, swath-based snow-cover product, MOD10_L2, to an 8-day global gridded product, MOD10C2. As the development of the products is described in detail elsewhere (Hall et al., 2002; Riggs et al., 2003), we only present a brief overview here, with focus on the MODIS daily and 8-day snow-cover products. It is important to note that the 8-day product represents the maximum snow cover during the 8-day composite period.

The MOD10A1 daily level 3 snow-cover product is the result of selecting an observation from the multiple observations of the day mapped to each cell of the MOD10_L2G product using a scoring algorithm (Riggs et al., 2003). The rationale of such an algorithm is to select the observation nearest to nadir with greatest coverage at highest solar elevation angle that is mapped into the grid cell so that the number of pixels with large off-nadir looking angle is minimized. Each granule of the daily snow-cover product is a tile of data gridded in a sinusoidal projection. The snow-cover map for a day is constructed by examining the multiple observations acquired for the day that were mapped to cells of the grid by the L2G algorithm. A selection of the best observation is made based on a ratio of percentage coverage of an observation in a cell to the distance of that observation from nadir. The observation that was closest to nadir with the greatest coverage in the cell is selected as the observation of the day to create the daily snow cover. The snow-cover data are stored as coded integers, with values being the same as assigned in MOD10_L2, which are shown in Table 1 for convenience of the following discussion.

MOD10A2 is an 8-day composite product of snow cover that is made by compositing from 2 to 8 days of the MOD10A1 product. Eight-day periods begin on the first day of the year, continue consecutively and extend a few days (3 days for a regular year and 2 days for a leap year) into the next year. For a predefined 8-day period, fewer than 8 days (2–7 days) are used to calculate the 8-day product when fewer than eight daily files corresponding to the 8-day period are available for various reasons such as MODIS shutdown or data loss on the satellite platform. However, an 8-day product will not be generated if only one daily data

Table 1
Coded integers and their meanings for MOD10A1 and MOD10A2 products

Coded integer	Meaning or surface type
0	Sensor data missing
1	No decision
4	Erroneous data
11	Darkness or night, terminator or polar
25	Land (free of snow)
37	Inland water (or lake)
39	Ocean
50	Cloud obscured
100	Snow-covered Lake Ice
200	Snow
254	Sensor saturated
255	Fill data—no data expected

set is available (Riggs, private communication). An 8-day compositing period was chosen mainly because it is the exact global pattern repeat period of the Terra and Aqua platforms. For the MOD10A2 8-day snow-cover product, the intent of the algorithm is to maximize the number of snow pixels while minimize the number of cloud pixels. A cell is labeled as cloud only when the pixel is cloud-covered for all the 8 days. If snow cover is found for any of the 8 days, then the pixel in the "Maximum_Snow_Extent" Scientific Data Sets (SDS) is labeled as snow. If no snow is found for the pixel, but there is one value (corresponding to one type of surface, except for cloud; see Table 1) that occurs more than once, that value is placed in the pixel.

Cloud pixels in both MODIS daily and 8-day products are inherited from the MOD10_L2 snow product that is generated using the cloud mask product (MOD35_L2) as input for cloud pixels detection. The MODIS cloud-screening algorithm includes new individual spectral tests techniques and incorporates many of the existing techniques to detect obstructed fields of view (Ackerman et al., 2002). The MOD35_L2 data are checked to determine if a pixel is cloud-covered during the MODIS daily and 8-day products generation. For the conservative cloud mask, the unobstructed field-of-view flag from MOD35_L2 was used for snow identification. The liberal cloud mask is that generated by using only a subset of cloud spectral tests results and reflectance characteristics from MOD35_L2 for cloud detection (Riggs et al., 2003). For the purpose of snow mapping, such a cloud mask is necessary to reduce cloud obscuration and enhance the capability of classifying as snow the snow pixels that are contaminated with translucent or very thin clouds.

For a regional watershed study such as streamflow prediction, the MODIS snow-cover daily (MOD10A1) and 8-day (MOD10A2) products are preferred for the following reasons: (a) Compared to the global gridded products (MOD10C1 and MOD10C2), they have higher resolution (500 m vs. 5.57 km); (b) compared to MOD10_L2, they have less bowtie effect (geometrical deformation at the edges) (Gomez-Landesa, private communication); (c) for MOD10_L2G, multiple observations are just stacked, no optimal selection is performed to reduce cloud and shade effect. Both products are level 3 products and each tile of these products covers a ground area of 1200×1200 km. The temporal resolution is 1 day for MOD10A1 and 8 days for MOD10A2.

Both the MODIS daily and 8-day products have 500-m spatial resolution, higher than the nominal 1 km resolution of the NOHRSC product. Several spectral bands are employed to provide multiple indices so that multiple criteria are available to be used to discriminate snow surface from other types of terrestrial surface (Klein et al., 1998), which will enhance the snow mapping capability, especially in forested and topographically complex regions (Maurer et al., 2003). MODIS product algorithms are automated so that the consistency in mapping of snow in different areas and at different times is improved (Hall et al., 2002; Riggs et al., 2003).

3.2. Streamflow

For the reasons listed above (Section 3.1), we will focus on the intercomparison between the MODIS daily (MOD10A1) and 8-day (MOD10A2) products using streamflow of a closed watershed such as Upper Rio Grande Basin as a constraint. The output streamflow data of the Upper Rio Grande Basin at the Otowi Gage south of Espanola, New Mexico at latitude 35°52′ 29″ N, longitude 106°08′ 30″ W (NAD27) (see Fig. 1) are used as constraints to evaluate MOD10A1 and MOD10A2 products for streamflow prediction.

The streamflow station of the Rio Grande at Otowi Bridge, NM is 1 of the 679 national network stream water-quality stations (Alexander et al., 1997). The drainage area corresponding to this station is 37,037 km^2. Daily streamflow data at this station are available since February 1, 1895 and can be downloaded from the USGS water resources website at http://www.water.usgs.gov/. At the outlet of the Upper Rio Grande Basin, over 50% of the annual streamflow at this point originates as snowmelt, which indicates that snowpack exerts a very strong control on the hydrology of the basin.

3.3. SNOTEL in situ data

In situ measurement of snowpack parameters such as snow water equivalent, snow density, snow depth, and related climatic data such as temperature are provided by the extensive and automated SNOTEL network (over 660 remote sites) throughout the 11 western states (including Alaska) installed, operated, and maintained by the National Resources Conservation Service (NCRS) of the United States Department of Agriculture (DOA) for the purpose of estimating water resources (Crook, 1977; Natural Resources Conservation Service, 1997). The SNOTEL data sets are available on the public domain at NRSC's homepage (http://www.wcc.nrcs.usda.gov/snotel/). Not only for snowpack measurement, the data from the SNOTEL network are also used for climate studies, air and water quality investigation, water resource management, and monitoring and forecast of natural disasters such as floods.

3.4. Rainfall

Rainfall events in this study are derived from the National Weather Service's (NWS) Next Generation Weather Radar WSR-88D (NEXRAD) Stage III precipitation products. NEXRAD data are widely used in hydrology and climatology for rainfall estimation (e.g., Krajewski & Smith, 2002; Seo et al., 1999). Since the NEXRAD Stage III precipitation product involves the correction of radar rainfall rates with multiple surface rain gauges and has a significant degree of meteorological quality control by trained personnel at individual river forecast centers (RFCs) (Fulton et al., 1998), the daily and 8-day areal mean precipitations for the study area are retrieved using the method we developed previously (Xie et al., 2003, 2005). Rainfall data retrieved are used to study the disturbance of rainstorms on the relation between the streamflow and the snow-cover extent.

4. Data retrieving algorithms

4.1. SAE retrieval from the MODIS products

The two MODIS snow-cover products: daily (MOD10A1) and 8-day (MOD10A2) 500-m sinusoidal (SIN) grid (level 3) data are ordered and downloaded from the National Snow and Ice Data Center (NSIDC) or through EOS Data Gateway. A single MODIS tile (h09v05) covers the entire study area.

The accuracy of the SNOTEL site position is not known, but from the significant figures of the station position we can infer that the uncertainty of the station position is 0.01° (corresponding to about 1100 m). We design three patches of various sizes (1×1, 3×3, and 5×5 pixel^2) to represent the ground station considering the uncertainty of the position accuracy of the SNOTEL stations so that the sensitivity of the classification accuracy of the MODIS snow-cover algorithms as compared to the accuracy of the ground stations can be evaluated (see Section 5). Automated procedures are developed to retrieve (1) the total snow-covered area for the entire Upper Rio Grande Basin and (2) pixel values of a 5×5 matrix corresponding to the ground SNOTEL station from the MODIS daily and 8-day snow-cover products for the period of February 26, 2000 to June 10, 2004. The algorithm for the MODIS data reprojection and resampling is based on a resample program (part of the MODIS Reprojection Tool (MRT)). But note that using MRT to reproject and resample an image from one coordinate system to another does not eliminate distortion due to the bowtie effect. MRT is developed by the South Dakota School of Mines and Technology and USGS EROS Data Center MODIS Team (SDSM & T MODIS Team) and is used for mosaicking and reprojecting the MODIS level-2G, level-3, and level-4 land data products (SDSM & T MODIS Team, 2004). A brief summary of the development of the automated procedures is given as follows:

(1) A UNIX script is first developed to call the resample program to automatically convert the time series of daily or 8-day HDF-EOS files to GeoTIFF files. The output projection of UTM zone 13, with datum of WGS 84 is defined and a subset of a rectangle area covering the Upper Rio Grande Basin is clipped during this procedure.

(2) An ArcInfo Arc Macro Language (AML) script is developed to batch convert the subset GeoTIFF files to Geographic Information System (GIS) grid format. The study area of the Upper Rio Grande Basin area is exactly clipped from the created grid files, and then a value-attribute table (VAT) of each grid is uploaded to a text file for further process and analysis. The VAT table includes each coded integer (Table 1) of the image recorded and its corresponding number of pixels in the image. Therefore, the total SAE can be calculated for the image.

(3) A second ArcInfo AML script is developed for each SNOTEL station to extract pixel values of a 5×5 matrix, which centers at the pixel where the SNOTEL station lies. Similar to (2), these pixel values (coded integers) are uploaded to a text file through a VAT for post processing. The value of each patch corresponding to 1×1 (SNOTEL station pixel), 3×3, and 5×5 pixel^2 size is then retrieved from the text file based on the value of the majority of the pixels. For instance, if the central pixel of the 5×5 matrix has a value of 200 (snow, see Table 1), and the majority of the 5×5 pixels have a value of 50 (cloud), while the majority of the 3×3 pixels have a value of 25 (land), then the 1×1 patch gets a value of 200, the 3×3 patch gets a value of 25, and the 5×5 patch gets a value of 50. The value of each patch represents the retrieved coded integer from the MODIS image and is to be compared with the SNOTEL observation of the same day or the same period of 8 days.

4.2. Eight-day mean streamflow

To study the correlation between the SAE and streamflow, the downloaded daily streamflow data can be used directly for the MODIS daily snow-cover product. However, for the MODIS 8-day snow-cover product, the daily streamflow data have to be processed so that they represent the same 8-day period as the MODIS 8-day snow-cover data. Although the MODIS 8-day snow-cover products represent maximum snow cover retrieved from multiple observations during the period, we take them as the true average of the period so that they are regression-analyzed with the 8-day average streamflow in the following discussion. Following the convention in creating the MODIS 8-day snow-cover data sets, the 8-day average streamflow for each date is defined as the average of the value of the day and those of the following 7 days. Therefore, the 8-day streamflow corresponding to the days of the MODIS 8-day snow-cover product is retrieved.

4.3. Rainfall data retrieval for the Upper Rio Grande from the Next Generation Weather Radar (NEXRAD) data

The daily areal mean precipitation (DAMP) in the study area is retrieved from the National Weather Services' NEXRAD Stage III precipitation product (hourly and 4×4 km^2 cell). Since the NEXRAD hourly products use the

Coordinated Universe Time (UTC) as their time stamp, to create daily (Mountain Standard Time (MST)) precipitation, we developed an Arc Micro Language (AML) script to add 24 h starting from the UZTC eighth hour to the seventh hour of the next day. The DAMP for the Upper Rio Grande Basin is then retrieved from the new daily precipitation data set (GIS grid) by selecting (SELECT, an AML function) the statistics info table and EXPORT the MEAN to a text file. Daily accumulative rainfall amount (DARA) of a basin is defined as the integration of daily rainfall over the area of the entire basin. Thus, the DAMP and DARA retrieved from NEXRAD data for the Upper Rio Grande Basin take the following forms

$$DAMP = \sum_{i=1}^{N} R_i/N$$

and

$$DARA = \sum_{i=1}^{N} R_i L^2$$

where N is the total NEXRAD cell number covered by the Upper Rio Grande Basin, R_i the daily accumulative rainfall rate (mm/day) for the i-th cell, and L the cell size (4 km in this case). An 8-day DAMP (8-day DARA) is defined as the average of the DAMPs (DARAs) of the 8 days that is assigned to the first day, a convention similar to the MODIS 8-day snow-cover product.

4.4. Coded integer values for the SNOTEL stations

Downloaded SNOTEL daily snow water equivalent data for a specific station are scanned to determine which day has snow and then are coded in the same way as the MODIS snow-cover data according to Table 1. If the SWE of a specific day for a station is not zero, it is then coded as 200 (snow), otherwise as 25 (land).

5. Results and analysis

5.1. Spurious snowmelt events

The time series of the total snow-cover depletion for the Upper Rio Grande Basin during snow decay season of 2001 is shown in Fig. 2. Snow depletion generally occurs from February through June. March and April are the months that snow disappears at the fastest rate. The time series of snow SAE and streamflow at Otowi station from February 2000 to June 2004 are shown in Fig. 3. Both snow-cover products show that the change in snow-cover area and streamflow is in opposite phase, indicating the decrease of streamflow during the snow accumulation phase (late fall to early spring) and increase of streamflow during snowmelt phase (spring to early summer).

Comparison between Fig. 3(a) and (b) shows that the SAE of the Upper Rio Grande derived from the MODIS daily product changes much more rapidly within a short time period than the MODIS 8-day product. For instance, snow extent area of the basin on February 1, 2002 is 32,618 km^2. It drops to 2.5 km^2 on February 2, 2002 within a day and then returns back to 28,357.25 km^2 on February 3, 2002. From the corresponding streamflow data, this “disappearance” of snow cover seen from the MODIS daily data (Fig. 3(a)) is not due to snowmelt because the corresponding streamflow does not change. Therefore, the

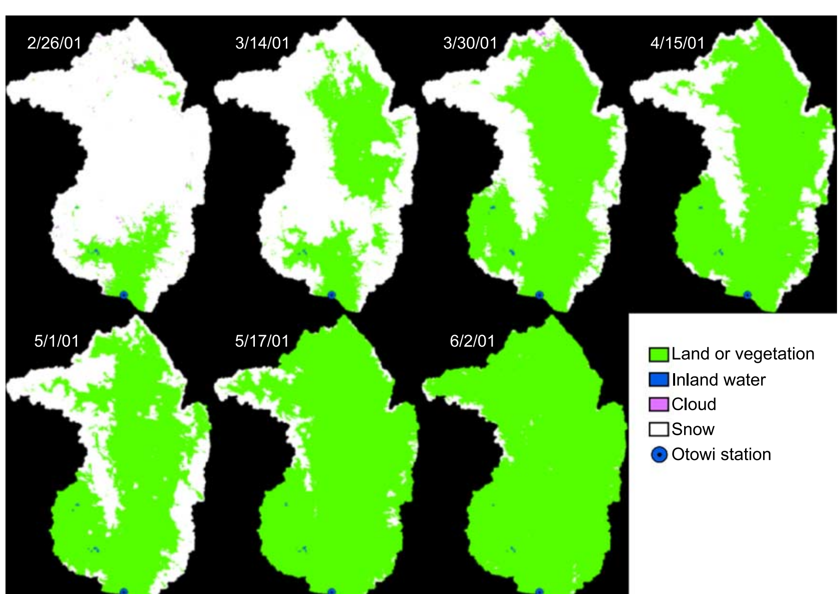

Fig. 2. MODIS 8-day snow products (MOD10A2) showing the progression of snow melt from February 26 to June 2, 2001. The time interval is 16 days. February represents the period with maximum snow cover. Snowmelt occurs from the end of February to the early of June.

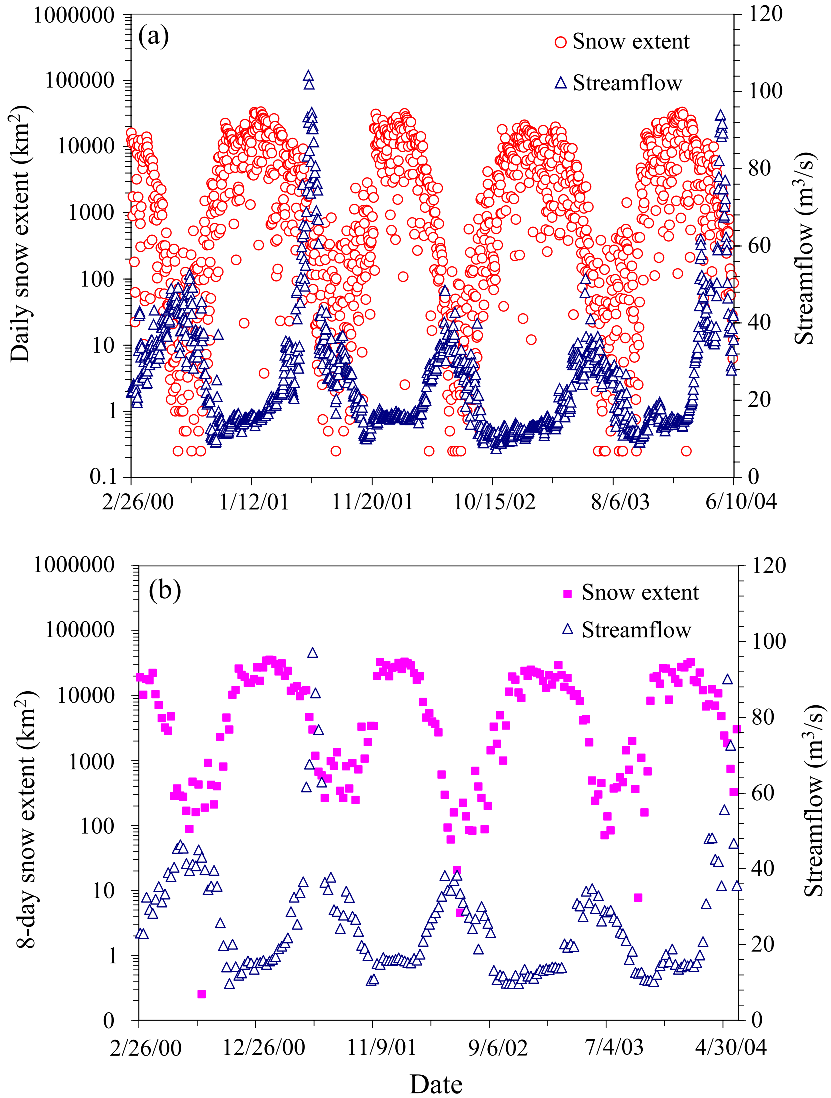

Fig. 3. Time series of (a) the daily and (b) the 8-day MODIS snow area extent of the Upper Rio Grande River Basin and the corresponding daily and 8-day mean streamflow at Otowi gauge station (outlet of the river basin), NM from February 26, 2000 to June 10, 2004.

snowmelt events associated with sudden disappearance of snow cover are spurious. The large temporal fluctuation of snow cover in the wintertime as derived from the MODIS daily product is frequent. The reason for the "spurious snow cover"—large changes in snow-covered area in a short time in the daily product—is mainly due to very cloudy conditions (see Section 5.3).

For the 1326 daily data points shown in Fig. 3(a), the number of events that SAE changes between 2 adjacent days by more than 9259.25 km^2 (25% of the entire Upper Rio Grande Basin) at a 1-day time scale is 168, almost 13% of all the days. Ninety-two such events occurred in the wintertime (November to January). The maximum daily change of the snow extent area derived from the MODIS daily product is 87.2% of the total area of the basin (occurred from February 1 to February 2 of 2002). Out of these 168 events, 89 (about 6.7% of total days) are for the events that the snow cover decreases by 25% of the whole Upper Rio Grande Basin within 1 day. Out of 89 such events, 49 events occurred in wintertime (Nov–Jan), about 3.7% of all days. For the 195 8-day data points shown in Fig. 3(b), the number of events that SAE changes by 25% of the whole basin area at an 8-day scale is 21, almost 10.8% of all the data points. The maximum SAE change at an 8-day scale from the 8-day product is 48.2% of the total basin area and occurred from December 3 to 11 of 2003. If these changes occurred uniformly within the 8 days, then the number of events with daily changes amounting to 25% is zero. Thus, the maximum daily change of the snow extent area derived from the MODIS 8-day product is 6% of the total area of the basin. Of the 21 events, 11 are for snow cover decrease ("snowmelt"), 12 occurred in wintertime (November–January). Of the 11 "snowmelt" events, 8 occurred in wintertime. These remarkable snow surface depletion events in wintertime are most likely due to mapping error or misclassification. The above comparison between the MODIS daily and 8-day products shows that the 8-day product has few spurious snowmelt events and less amplitude of the temporal fluctuation of SAE than the MODIS daily product.

5.2. Response of streamflow to snow-cover change

For the daily snow-cover product, if there is no pixel of value 200, we just discard the data for the day in the regression analysis for the reason that they appear in the summer time and regression analysis does not make sense when there is no snow at all. This results in 1326 out of 1511 total data sets (or daily images) for streamflow-SAE regression analysis. Scatter plots of streamflow vs. snow-cover extent area for both the daily and 8-day products are shown in Fig. 4(a)–(b). Both products show that the streamflow decreases with increase of snow SAE. Various fitting functions are tried, but only the logarithmic fits the best, which is the same as for streamflow-SAE relation in the large Siberian watersheds (Ob, Yenisei, and Lena basins) found by Yang et al. (2003). The logarithmic decay function of the streamflow vs. SAE is statistically significant ($p<0.001$) for both cases. But the correlation coefficient from the 8-day product ($r=-0.403$) is larger than that from the daily product ($r=-0.300$).

For the streamflow-SAE derived from the 8-day product (MOD10A2) (Fig. 4(b)), there are a few outliers. To assess how the outliers affect the streamflow-SAE relations, we focus on the outliers at the upper right part of the scatter plots in Fig. 4, which are enclosed in the ellipses. We can see that these outliers are streamflow-biased, which means the streamflow is over that expected from the corresponding amount of snow extent area. In contrast to the streamflow-biased outliers, we also encircled a non-streamflow-biased point at the low left part of Fig. 4(b).

For the daily data (Fig. 4(a)), 63 outliers are encircled. These outliers cluster in four time periods: May 2–8, 2001, May 11–June 14, 2001, March 26–29, 2004, and May 4–25, 2004. If these outliers are excluded in the regression analysis, the correlation coefficient increases from $r=-0.300$ to $r=-0.437$. From these data, we can see that 59 of the 63 streamflow-biased outliers occur in May, with the other 4 occurring in March. None of them occurred in 2000, 2002, and 2003. It is thus expected that the correlation between streamflow and SAE is better for these years. Fig. 5(a) shows the relationship between the streamflow and SAE derived from MOD10A1 for 2002. Correlation coefficient $r=-0.623$ (with $p<0.001$) is much better than -0.300 from the full data sets in Fig. 4(a). This indicates that the correlation is quite good for year 2002. The encircled 13 outliers in Fig. 4(b) mainly correspond to the 8-day values of May 1, 9, 17, 25 and June 2, 10 of 2001 and March 21, 29, April 6, 14, 30, May 8, 16 of 2004. If these 13 outliers are excluded in the regression analysis, the correlation coefficient changes from $r=-0.403$ to -0.615. No such outliers are found for year 2000 and 2002. It is thus expected that the correlation between streamflow and SAE is better for these years. Fig. 5(b) shows the relationship between the streamflow and SAE derived from MOD10A2 for year 2002. Correlation coefficient $r=-0.779$ with $p<0.001$ indicates that the correlation is statistically significant in 2002. Comparison of Fig. 5(a) to (b) also shows that the 8-day product outperforms the daily product for 2002 ($r=-0.779$ vs. -0.615). Results from Fig. 5 demonstrate two points: (1) the logarithmic decay relationship might exist between streamflow and snow-cover extent as observed here and in literature (Yang et al., 2003); (2) the MODIS 8-day product results in a better correlation between streamflow and snow cover. However, the logarithmic relation is not a perfect fitting between streamflow and snow-cover extent. This might be due to two reasons: (a) there are errors in snow-cover extent mapped; (b) the streamflow is a function of not just snow-cover extent. Snow water equivalent should be another important parameter too. This may indicate that using just snow-cover extent may not be enough in streamflow prediction.

To identify why the outliers occur, we test the hypothesis that these streamflow-biased outliers may be due to rainfall storms on those days. The NEXRAD Stage III precipitation product is used to quantify the rainfall on those days. Table 2 shows the 8-day DARA (in unit of 10^{-3} km^3/day) and 8-day DAMP (in unit of mm/day) of the whole basin when the outliers occurred (the NEXRAD Stage III data for 2004 are not yet available from the Internet). It is clear that there are large rainfall storms associated with the days when outliers located in the upper right part of Fig. 4(b) occurred. Rainstorms cause dramatic increase in the streamflow, causing streamflow-biased outliers in the streamflow-SAE regression analysis. On the other hand, very little rainfall was observed on September 22 of 2003 (corresponding to the SAE-biased outlier located in lower left part of Fig. 4(b)) as expected. The cause of the occurrence of the SAE-biased outlier may be the commission error in the mapping of the SAE. In fact, no snow was observed from the SNOTEL stations in the basin on September 22, 2003, but the MODIS 8-day snow-cover product mapped 7.8 km^2 of SAE on the day. For 2004, in situ observations by the National Weather Service (NWS) of the US National Oceanic and Atmospheric Administration (NOAA) and the Department of Agriculture (DOA) Natural Resources Conservation Service (NRCS) show that heavy rains at the lower elevations in April 2004 had increased river and stream flow across southern and eastern New Mexico, while the snowfall at higher elevations attempted to make up for some of the snowpack that was lost in March 2004 due to warm temperatures and early snowmelt as observed from SNOTEL stations (Polasko & Murray, 2004). These further analyses using the NEXRAD rainfall data and SNOTEL data do indicate that there were rainstorms for most of the dates when outliers occurred. These results suggest that for a mid-latitude snow watershed, rainfall storms in the later spring may disrupt the relationship between snow-cover extent and streamflow.

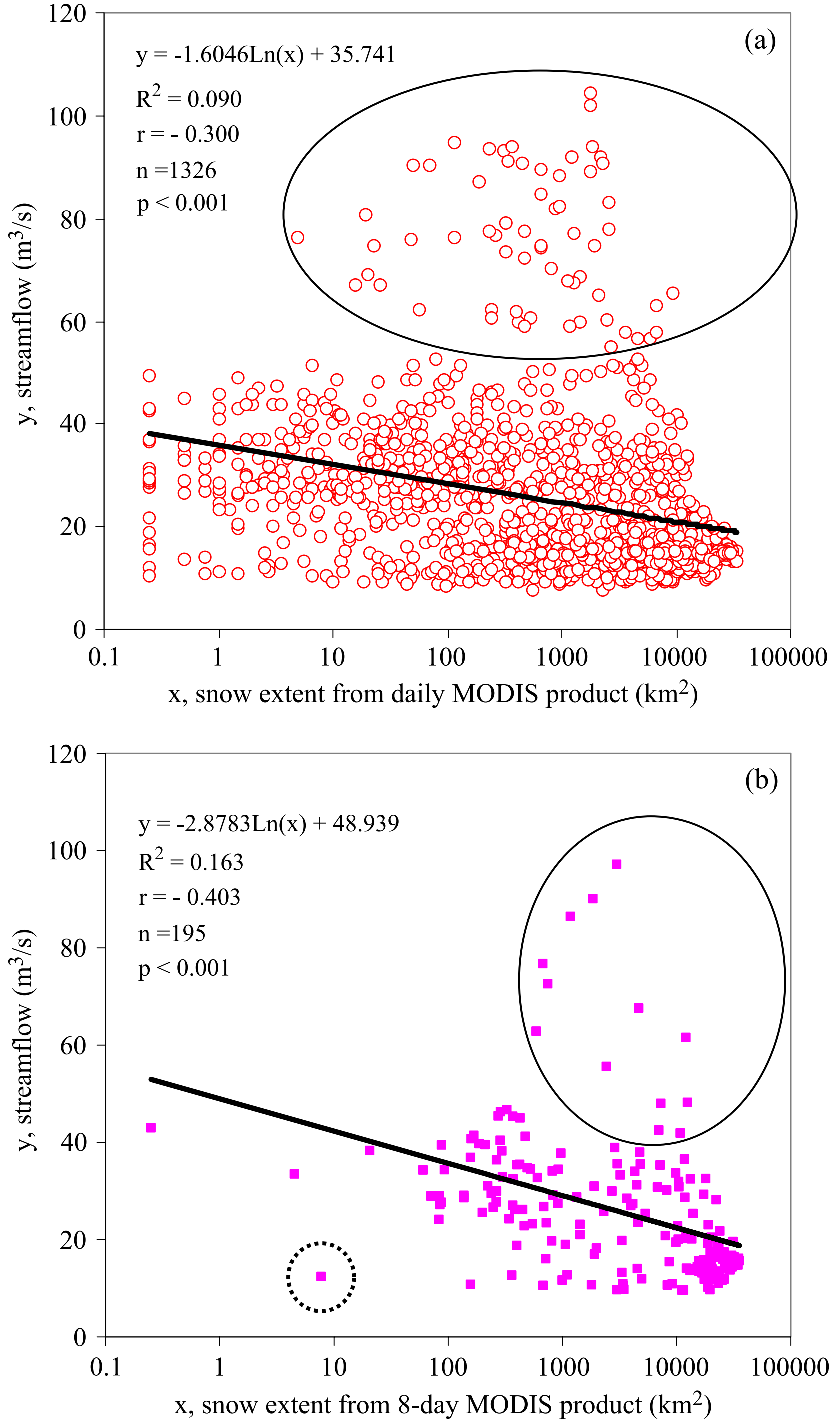

Fig. 4. Scatter-plot of (a) the daily and (b) the 8-day MODIS snow extent and the corresponding daily and 8-day mean streamflow at Otowi gauge station, NM from February 26, 2000 to June 10, 2004. Logarithmic fitting shows that 9% and 16.3% of the variance of the daily and 8-day streamflow, respectively, can be explained by model function of snow extent. Correlation coefficient r=−0.300 and −0.403 for the daily and 8-day MODIS products, with statistical significance >99.999%. For the 8-day product, if the 14 outliers (within the two ellipses) are discounted, the correlation coefficient r=−0.615. See text for more discussion.

Comparison of the scatter plots of streamflow vs. snow-cover extent between the MODIS daily and 8-day products (Fig. 4(a)–(b)) shows that there exists a good relationship between streamflow and snow-cover area change. The absolute value of the correlation coefficient is higher for the MODIS 8-day product than for the daily product. Comparing Fig. 4(a) to (b), we can also see that there are fewer data points for lower snow-cover extent for the 8-day product as compared to the daily product. For instance, data points (or 8-day images) that have SAE smaller than 100

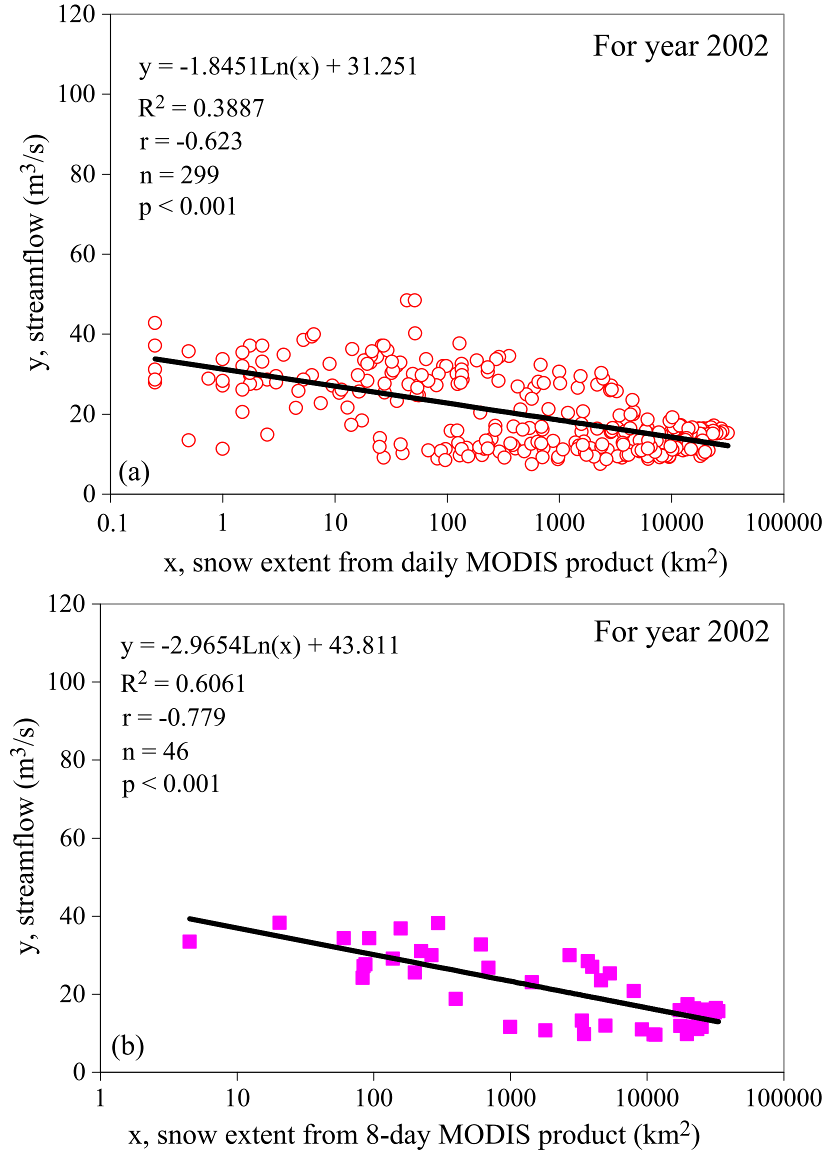

Fig. 5. Scatter-plot of (a) the daily and (b) the 8-day MODIS snow extent area and the corresponding mean streamflow at Otowi gauge station, NM for year 2002. Logarithmic fitting shows that 39% and 61% of the variance of the daily and 8-day snow extent, respectively, can be explained by model function of streamflow. Correlation coefficient r=−0.623 and r=−0.779 for the daily and 8-day MODIS products, respectively, with statistical significance >99.999%.

km^2 are 12 out of 195, or 6.2%, while they are 345 out of 1326 daily data sets, or 26.0%. Fig. 6 shows that the monthly distribution of the frequency of snow-cover occurrence of images of snow cover as mapped by the MODIS daily and 8-day snow mapping algorithms. Both products show that dates that have very low (<100 km^2) snow-cover extent center in July for the time period studied (February 26, 2000 to June 10, 2004). But the spectrum of the distribution for the MODIS daily product covers every month in a year, while it covers only months from May to September for the MODIS 8-day product (see Fig. 6). Considering that the snow cover for the whole Upper Rio Grande River Basin is unlikely to be smaller than 100 km^2 (about 0.3% of the whole basin) in the winter and spring, it is inferred that the MODIS 8-day algorithm is more effective in suppressing the misclassification of snow pixels

Table 2
The 8-day DARA (unit: 10^{-3} km^3/day)/8-day DAMP (unit: mm/day) corresponding to the 8-day outliers in Fig. 4(b)

	2001						2003
	5/1	5/9	5/17	5/25	6/2	6/10	9/22
NEXRAD	2.908/0.0821	6.843/0.1933	5.103/0.1441	5.763/0.1628	13.132/0.3709	0.624/0.0176	0.049/0.0014

NEXRAD data of 2004 are not yet available at this moment.

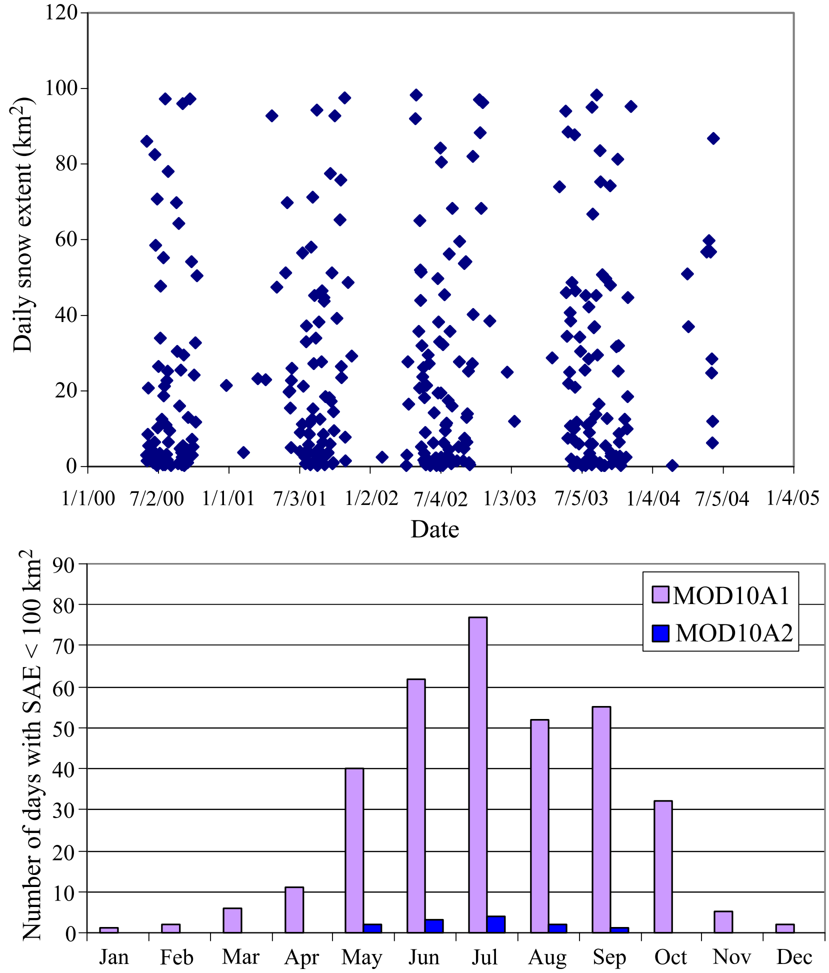

Fig. 6. Distribution of the dates when daily snow extent is smaller than 100 km^2.

as other types of surface than the MODIS daily algorithm. It suggests that the optimal selection of snow pixel based on multiple observations from 8 days as in MOD10A2 product is better than the multiple observations from just a single day as in MOD10A1 product.

5.3. Statistical long-term comparison of the MODIS daily and 8-day snow-cover products with the SNOTEL measurements

The purpose of this section is to investigate the long-term statistics of the intercomparison between the MODIS daily and 8-day products and the ground SNOTEL sites, and to investigate if there is any consistent bias of misclassification of the MODIS snow product algorithms when they are compared with the SNOTEL stations. The position of these stations is shown in Table 3 (also in Fig. 1 denoted as red columns).

For the MODIS images, 1511 daily images and 195 8-day images corresponding to February 24, 2000 to June 10, 2004 were employed. The retrieved coded values at the 1×1, 3×3, and 5×5 patches for these 4 stations from the daily product include 255, 254, 200, 50, 25, 1, and 0, while from the 8-day product they are 200, 50, and 25. The ground truth is either snow or land without snow. Thus viewing from space, these stations should be either snow (200), land (25), or cloud (50). The MODIS 8-day product captures all the three possibilities. The MODIS daily data at these stations capture these three possibilities (snow, land, and

Table 3
Overall accuracy comparison using different methods of retrieval for the MODIS MOD10A1 product and SNOTEL stations during 2000–2004 (total number of images or days: 1511)

Station (altitude: m)	Position (lat./long.)	1×1 patch	3×3 patch	5×5 patch
Bateman/NM (2835)	36.51°/–106.32°	55.5% (1484)	55.0% (1487)	55.1% (1487)
Beartown/CO (3536)	37.71°/–107.51°	50.3% (1489)	50.6% (1489)	51.1% (1488)
Middle Creek/CO (3429)	37.62°/–107.03°	50.9% (1487)	50.8% (1485)	51.7% (1485)
North Costilla/NM (3231)	36.99°/–105.26°	55.7% (1484)	55.9% (1485)	56.8% (1486)

The numbers in parentheses under overall accuracy (in percentage) are the valid data sets (see text). Overall accuracy underscored is the best using the three retrieval methods for each station.

cloud), but the pixel value of the daily product also includes other possibilities (255, 254, 1, and 0; see Table 1), which is not due to algorithm itself. But the daily product deteriorates due to the inclusion of these other possibilities from the point of view of application. This demonstrates the more convergence of the pixel values of the 8-day product. As the purpose here is to evaluate the performance of the daily algorithm as compared to the 8-day algorithm, factors other than the algorithm itself are not considered. Thus, when the retrieved coded value from the MODIS daily data corresponding to any of the patches is any of 255, 254, 1, or 0, that day is discarded and not used for comparison with the ground SNOTEL data. This results in 1484 valid daily data sets out of 1511 for the 1×1 patch retrieval method and 1487 for the 3×3 and 5×5 patch retrieval methods at Bateman station. Table 3 summarizes these results for the 4 SNOTEL stations.

5.3.1. MODIS daily product

Detailed intercomparison between the MODIS daily snow cover and the SNOTEL ground stations for the whole Upper Rio Grande Basin was carried out by Klein and Barnett (2003) for the 2000–2001 snow year. They found that the agreement between the MODIS daily product and the SNOTEL stations within the Upper Rio Grande Basin is generally very good (>90%) (see Table 5 of Klein & Barnett, 2003) except for some stations where the agreement is not. Based on their results, we only consider four representative stations in which two stations (Middle Creek of Colorado and Bateman of New Mexico) are in good agreement with the MODIS daily snow-cover data and the other two (Beartown of CO and North Costilla of NM) are not.

Table 3 gives the overall classification accuracy of the MODIS daily snow product, which is defined as the ratio of the total number of days that both MODIS and SNOTEL concurrently mapped the station as snow or land to the total valid data sets for all the three patch retrieval methods. We can see that the overall accuracy is not sensitive to the retrieval methods, with the maximum difference between different retrieval methods being 1.1%. This indicates that the intercomparison results are not sensitive to the accuracy of the SNOTEL station position (up to 1250 m). The main cause may be due to the continuity of the snow surface or large covariance of snow pixels in general. Even though, the 5×5 patch method does show consistently better results than the other two. The overall accuracy is quite similar at the four stations, varying from 50.3% to 56.8% if we do not discriminate clear days from cloudy days.

To assess what is the bias of the disagreement, Table 4 shows more detailed comparison using only the 5×5 patch retrieval method for all valid data sets (no discrimination of cloudy and clear conditions). In Table 4, accuracies are shown in bold font style, while errors are shown in regular style. At Bateman station, out of 1487 data sets, SNOTEL observations show that 737 are snow and 750 are land.

Table 4
Error matrix for the intercomparison between the MOD10A1 product and SNOTEL stations for all valid data sets during 2000–2004 (no discrimination is made between clear and cloudy days)

Station (overall accuracy/ data sets)	Land type (data sets) identified by SNOTEL	MODIS daily (MOD10A1)		
		Snow	Land	Cloud
Bateman/NM (55.1%/1487)	Snow (737)	**332 (45.0%)**	70 (9.5%)	335 (45.5%)
	Land (750)	1 (0.1%)	**487 (64.9%)**	262 (35.0%)
Beartown/CO (51.1%/1488)	Snow (924)	**478 (51.7%)**	16 (1.7%)	430 (46.5%)
	Land (564)	23 (4.1%)	**283 (50.2%)**	258 (45.7%)
Middle Creek/CO (51.7%/1485)	Snow (892)	**423 (47.4%)**	66 (7.4%)	403 (45.2%)
	Land (593)	0 (0%)	**345 (58.2%)**	248 (41.8%)
North Costilla/NM (56.8%/1486)	Snow (725)	**353 (48.7%)**	34 (4.7%)	338 (46.6%)
	Land (761)	2 (0.3%)	**491 (64.5%)**	268 (35.2%)

Land surface types as identified by the SNOTEL stations are assumed to be the truth.

While out of the 737 snow data sets, the MODIS daily product algorithm correctly classified 332 (accuracy: 45.0%) as snow but also classified 70 as land (error: 9.5%) and 335 as cloud (error: 45.5%) by error. Out of the 750 land data sets, the MODIS daily product algorithm correctly classified 487 (accuracy: 64.9%) as land but also classified 1 as snow (error: 0.1%) and 262 (error: 35.0%) as cloud by error. Similar description applies to the other three stations. From Table 4, we can see that at the four study sites, the accuracies of classifying snow (SNOTEL) as snow (MODIS) (varies from 45.0% to 51.7%) and land (SNOTEL) as land (MODIS) (varies from 50.2% to 64.9%) by the MODIS daily product algorithm are generally low. From the point view of snow, the omission errors of classifying snow (SNOTEL) as cloud (MODIS) are very high (varies from 45.2% to 46.6%), but the omission errors of classifying snow as land are generally low (1.7–9.5%). The commission errors of classifying land (SNOTEL) as snow (MODIS) are very low (0.0–4.1%). From the point view of land, the omission errors of classifying land (SNOTEL) as cloud (MODIS) are very high (35.0–45.7%), but the omission errors of classifying land as snow are very low (0.0–4.1%). The commission errors of classifying snow as land are generally low (1.7–9.5%). Both snow and land are highly misclassified as cloud. As there is no ground truth data for cloud condition at these SNOTEL sites, these error rates can not be taken as malfunction of the MODIS daily algorithm, but we do see that the MODIS daily product includes a lot of cloud data.

To evaluate the performance of the MODIS daily product during clear days, we assume the cloud mask employed in the algorithm is accurate so that the cloudy days as identified in the MOD10A1 product are the true cloudy

Table 5
Error matrix for the intercomparison between the MOD10A1 product and SNOTEL stations for clear days during 2000–2004

Station (overall accuracy/ data sets)	Land type (data sets) identified by SNOTEL	MODIS daily (MOD10A1)	
		Snow	Land
Bateman/NM (92.0%/890)	Snow (402)	**332 (82.6%)**	70 (17.4%)
	Land (488)	1 (0.2%)	**487 (99.8%)**
Beartown/CO (95.1%/800)	Snow (494)	**478 (96.8%)**	16 (3.2%)
	Land (306)	23 (7.5%)	**283 (92.5%)**
Middle Creek/CO (92.1%/834)	Snow (489)	**423 (86.5%)**	66 (13.5%)
	Land (345)	0 (0%)	**345 (100%)**
North Costilla/NM (95.9%/880)	Snow (387)	**353 (91.2%)**	34 (8.8%)
	Land (493)	2 (0.4%)	**491 (99.6%)**

Land surface types as identified by the SNOTEL stations are assumed to be the truth.

days. Table 5 is the corresponding table of Table 4 but only for clear-sky days. Overall accuracy for these stations ranges from 92.0% to 95.9%. Accuracy of mapping snow and land ranges from 82.6% to 96.8% and from 92.5% to 100%, respectively. The cross-classification errors of snow to land range from 3.2% to 17.4% and from land to snow range from 0.0% to 7.5%. From these results, we can infer that for clear-sky days, the MODIS daily algorithm works quite well, especially for land-to-land classification. The major error seems to result from the misclassification of snow as land, especially at Bateman and Middle Creek stations.

Comparison of the overall classification accuracies of the MODIS daily product at the individual SNOTEL stations for the clear days of 2000–2004 (Table 5) with the results from Klein and Barnett (2003) for the 2000–2001 snow season (Table 5 of Klein & Barnett, 2003) shows that the agreement at the Bateman (NM) station and Middle Creek (CO) station is very good (92% vs. 91% for Bateman, 92% vs. 98% for Middle Creek), while at the Beartwon (CO) and North Costilla (NM) stations, long-term clear-day data sets show better agreement (95% vs. 76% for Beartown, 96% vs. 78% for North Costilla). If all the valid data sets are considered (Table 3), the overall accuracies at the individual stations for 2000–2004 are all lower than those for 2000–2001 snow season (Table 5 of Klein & Barnett, 2003) (55% vs. 91% for Bateman, 51% vs. 76% for Beartwon, 52% vs. 98% for Middle Creek, and 57% vs. 78% for North Costilla). As discussed above, the overall accuracies of the MODIS daily data are largely reduced due to clouds, but the agreement among different stations is generally consistent (51–57% for all valid data sets, 92–96% for clear-day data sets). From this comparison, we may conclude that the longer-term comparison of the MODIS daily snow-cover data with the SNOTEL station measurements may result in more consistent agreement among all individual stations.

5.3.2. MODIS 8-day product

Comparison of the MODIS 8-day snow-cover data with the SNOTEL measurement is slightly more complicated. First, we need to define an 8-day period data at each SNOTEL station. Here we opt to define the 8-day SNOTEL data in two ways. The first one (referred as SNOTEL method 1) is similar to the MODIS 8-day product algorithm, i.e., if 1 of the 8 days has snow, the 8-day period is defined as snow. The other one (referred as SNOTEL method 2) is that the 8-day value is defined as snow only when more than 4 days (≥4 days) have snow. The method 2 should be more reasonable as the measurement is from ground and no disturbance such as cloud affects the measurement, which is usually the case from satellite data. Even though, we still include method 1 in the following discussion to assess the sensitivity of the comparison on the methods used to retrieve the SNOTEL data. Based on the above definitions, the 8-day SNOTEL data coincident with the MODIS 8-day images (February 26, 2000 to June 10, 2004) are then retrieved. Retrieval of the MODIS 8-day data at each SNOTEL station in three different ways (1×1, 3×3, and 5×5) is similar to the daily data retrieval discussed above. As both data sets (MODIS vs. SNOTEL) are coded in the same way, subtraction of the two data sets will be used to identify easily the agreement. Of the total 195 data pairs, overall accuracy is shown in Table 6 for the four selected stations and for the combination of 6 data retrieval methods (3 for the MODIS data times 2 for the SNOTEL data). For each station, the overall accuracy underscored is the best among the 6 combinations of retrieval methods. The

Table 6
Overall accuracy comparison using different methods of retrieval for both the MODIS MOD10A2 product and SNOTEL stations for 2000–2004 (total number of images or days: 195)

Station		1×1 patch	3×3 patch	5×5 patch
Bateman/NM	SNOTEL method 1	90.8%	91.3%	90.8%
	SNOTEL method 2	**91.8%**	<u>92.3%</u>	**91.8%**
Beartown/CO	SNOTEL method 1	89.7%	90.8%	<u>91.3%</u>
	SNOTEL method 2	88.2%	89.2%	**89.7%**
Middle Creek/CO	SNOTEL method 1	83.6%	84.1%	85.6%
	SNOTEL method 2	85.1%	85.6%	<u>87.2%</u>
North Costilla/NM	SNOTEL method 1	86.2%	86.7%	86.2%
	SNOTEL method 2	**87.2%**	<u>87.7%</u>	**87.2%**

The SNOTEL method 1: if 1 day of the 8 days has snow then the station has snow for the 8-day period; the SNOTEL method 2: the 8-day period has snow only when more than 4 days of the 8 days have snow.

accuracy value in bold at each station is for the combination with the SNOTEL data retrieved from the SNOTEL method 2 and the MODIS data retrieved at the 5×5 patch. At Bateman station, overall accuracy ranges from 90.8% to 92.3% for all the six combinations of retrieval methods. It ranges from 88.2% to 91.3% at Beartown, 83.6% to 87.2% at Middle Creek, and 86.2 to 87.7% at North Costilla. For all the four stations and for each SNOTEL data retrieval method, the difference of the overall accuracy between the MODIS data retrieval methods is smaller than 2.1%. It is even smaller between 3×3 and 5×5 patch methods (ranges from 0.5% to 1.6%). This again demonstrates the insensitivity of the overall accuracy to the ground truth size for each SNOTEL station due to the snow or land surface continuity. Except for Beartown station, the SNOTEL method 2 outperforms method 1 for any of the MODIS data-retrieval methods, as expected.

Similar to the daily data, for assessing the bias of disagreement for the MODIS 8-day product, Table 7 shows a more detailed comparison using only the combination of the SNOTEL method 2 and the MODIS 5×5 patch retrieval method for all valid data sets (no discrimination of cloudy and clear conditions). From this table, we can see that for the four study sites, the overall accuracy (87.2–91.8%) is high. The classification accuracy of snow (SNOTEL) as snow or land as land by the MODIS 8-day product algorithm is generally high (varies from 84.5% to 95.9% for snow, or 88.0% to 97.9% for land). The omission error of classifying snow (SNOTEL) as land or as cloud (MODIS) is relatively low or very low (1.6–11.7% for snow-as-land or 1.6–4.2% for snow-as-cloud). The commission error of classifying land as snow is 2.1–15.1% and omission error of classifying land as cloud is 0.0–5.4%.

Table 7
Statistics of intercomparison between the MOD10A2 product and SNOTEL stations during 2000–2004 (total 8-day data sets: 195)

Station (overall accuracy)	Land type (data sets) identified by SNOTEL	MODIS 8-day (MOD10A2)		
		Snow	Land	Cloud
Bateman/NM (91.8%)	Snow (98)	**84 (85.7%)**	11 (11.2%)	3 (3.1%)
	Land (97)	2 (2.1%)	**95 (97.9%)**	0 (0.0%)
Beartown/CO (89.7%)	Snow (122)	**117 (95.9%)**	2 (1.6%)	3 (2.5%)
	Land (73)	11 (15.1%)	**58 (79.5%)**	4 (5.4%)
Middle Creek/CO (87.2%)	Snow (120)	**104 (86.7%)**	14 (11.7%)	2 (1.6%)
	Land (75)	5 (6.7%)	**66 (88.0%)**	4 (5.3%)
North Costilla/NM (87.2%)	Snow (97)	**82 (84.5%)**	11 (11.3%)	4 (4.2%)
	Land (98)	9 (9.2%)	**88 (89.8%)**	1 (1.0%)

Land surface types as identified by the SNOTEL stations are assumed to be the truth.

Table 8
Error matrix for the intercomparison between the MOD10A2 product and SNOTEL stations for the clear 8-day data during 2000–2004

Station (overall accuracy)	Land type (data sets) identified by SNOTEL	MODIS 8-day (MOD10A2)	
		Snow	Land
Bateman/NM (93.2%)	Snow (95)	**84 (88.4%)**	11 (11.6%)
	Land (97)	2 (2.1%)	**95 (97.9%)**
Beartown/CO (93.1%)	Snow (119)	**117 (98.3%)**	2 (1.7%)
	Land (69)	11 (15.9%)	**58 (84.1%)**
Middle Creek/CO (90.0%)	Snow (118)	**104 (88.1%)**	14 (11.9%)
	Land (71)	5 (7.0%)	**66 (93.0%)**
North Costilla/NM (89.5%)	Snow (93)	**82 (88.2%)**	11 (11.8%)
	Land (97)	9 (9.3%)	**88 (90.7%)**

Land surface types as identified by the SNOTEL stations are assumed to be the truth.

Similar to the daily data evaluation, Table 8 is the corresponding table of Table 7 but only for clear days. Overall accuracy for these stations is just slightly better than the all-data-set case (see Table 7). Accuracies of mapping snow (88.1–98.3%) and land (83.1–97.9%) for the clear-sky are also just slightly better than the all-data-set case (84.5–95.9% for snow-snow and 79.5–97.5% for land-land). The clear-sky cross-classification error of snow to land is similar to the all-data-set case (Table 8), and that from land to snow (0.0–7.5%) is a little bit lower than the all-data-set case (2.1–15.1%). From these results, we can infer that the MODIS 8-day algorithm works quite well for the all-data-sets. Suppression of cloud in the MODIS 8-day algorithm is very effective. Major bias in misclassification is site-dependent. For instance, the major bias at Bateman and Middle Creek stations is the misclassification of snow as land. At Beartown, the major bias is misclassification of land as snow. At North Costilla, misclassification of snow as land is similar to that of land as snow (see Table 8). The amplitude of the bias at a specific site may depend on the forest condition and the surrounding topography.

6. Discussion and conclusions

The MODIS snow-cover products are generated using the snow mapping algorithms with calibrated radiance data (MOD02HKM), the MODIS cloud mask (MOD35), MOD03 geolocation product, and solar and satellite viewing geometries. Improvements in instrument calibration, cloud-masking capability, accuracy in geolocation, snow detection in forests (Hall et al., 2002; Klein et al., 1998) will eventually improve the snow-cover products and its potential application in both climate change studies and snow water resource management. In this paper, we focused on the statistical evaluation of the MODIS daily and 8-day snow-cover data products in the Upper Rio Grande River Basin using the streamflow and long-term SNOTEL observations as constraints.

For seasonal snow cover within a mountainous river basin, snowmelt and associated streamflow is the eventual hydrological output from a river basin. Correlation analysis between streamflow and snow-cover extent area at the Upper Rio Grande Basin for the time period from February 2000 to June 2004 indicates that decrease of streamflow during the snow accumulation phase (late fall to early spring) and increase of streamflow during snowmelt phase (spring to early summer) are closely related to the snow-cover extent changes as mapped by the MODIS daily and 8-day products, but the correlation coefficient is higher for the MODIS 8-day product than the daily product. The time series of snow-cover extent as derived from the MODIS daily product shows that the temporal change of SWE is much more rapid within a short time scale (daily) than the MODIS 8-day product. The number of spurious snowmelt events associated with the large reduction of snow cover within a 1-day scale (over 25% of the whole watershed) but no change of streamflow in the wintertime as derived from the MODIS daily product is more frequent than that from the MODIS 8-day product. This kind of large reduction of snow cover is due to the misclassification of snow to cloud during the cloudy days.

A regression analysis of streamflow vs. snow-cover extent shows that a logarithmic decay function of the streamflow with SAE is statistically significant ($p<0.001$) for both products, but the correlation coefficient from the 8-day product ($r=-0.403$) is larger than that from the daily product ($r=-0.300$). This kind of relation was also found previously in the large Siberian watersheds (Ob, Yenisei, and Lena basins) by Yang et al. (2003). This coincident agreement might indicate a general rule in streamflow response to snow extent area change in snow watershed, though the relationship between the snowpack and the amount of snowmelt runoff is generally complex and depends on many temporally variable factors such as soil moisture content, ground water contributions, precipitation patterns, fluctuation in air temperature, use of water by plants, frequency and intensity of storm events, wind field, and topography of the watershed (Flerchinger et al., 1992; Marks et al., 2002).

Causes for the outlier-occurrence in the streamflow-SAE relationship as derived from both the daily and 8-day products suggest that they occur mainly in later spring and coincident with heavy rainfall events as derived from NEXRAD rainfall data. This suggests that the response of streamflow to the snow-cover change may be complicated by the rainfall events during the snowmelt season. For individual years, the correlation coefficient can be as good as $r=-0.623$ (with $p<0.001$) for the MODIS daily product and $r=-0.779$ (with $p<0.001$) for the MODIS 8-day product in 2002. Comparison between these two products also shows that the days when snow cover is low (<0.3% of the whole basin area) occur in much broader spectrum ranging from January to December for the MODIS daily product, while they occur only in May to September for the MODIS 8-day product, which is more reasonable, considering the decrease of SAE to less than 10 km^2 in wintertime for the whole Upper Rio Grande Basin is unlikely, though the number of such days reaches a maximum in July for both products. The significance of these results is that the 8-day product will be more useful in evaluating the long-term streamflow response to the snow-cover extent changes than the daily product. But note that for the 8-day product evaluation, the streamflow for an 8-day period represents the average value of the period while the snow cover is the maximum of the 8-day period mapped by MODIS. This discrepancy in the average streamflow vs. maximum snow cover may result in errors at certain times of the year when snow cover changes significantly.

Detailed statistical analysis and comparison between the MODIS snow-cover products and the selected four SNOTEL stations have been carried out using different data retrieval methods—different patch sizes around the station pixel (the pixel the station lies in). We found that the overall accuracy of classification of both the MODIS daily and 8-day algorithms is not sensitive to the patch sizes due to the continuity of snow surface, but we do observe that the 3×3 and 5×5 patch methods generate better results than the 1×1 patch method.

Using the SNOTEL data at the four selected stations as a baseline, comparison between the MODIS daily and 8-day data during 2000–2004 shows the following differences:

(1) Overall accuracy for all retrieval method combinations ranges from 50.3% to 56.8% for the MODIS daily product vs. from 83.6% to 92.3% for the MODIS 8-day product (see Table 3 vs. Table 6).
(2) Without discrimination of clear from cloudy conditions, comparison between MODIS daily (Table 4) and 8-day (Table 7) products shows that the classification accuracy of snow (from SNOTEL) to snow of the MODIS daily product is much lower than that of the MODIS 8-day product; the classification accuracy of land (from SNOTEL) to land (MODIS) of the MODIS daily product is also lower than that of the MODIS 8-day product; the omission error of classifying snow as land is similar for the two products; the commission error of classifying land as snow of the MODIS daily product is lower than that of the MODIS 8-day product; the omission error of classifying snow as cloud of the MODIS daily product is much higher that that of the MODIS 8-day product. For land classification, the omission error of classifying land as cloud of the MODIS daily product is also much higher than that of the MODIS 8-day product. These results are summar-

Table 9
Summary of the statistics of intercomparison from Tables 5 and 8 between the MODIS daily and 8-day products with the SNOTEL station data as baseline during 2000–2004 for four SNOTEL stations

	S→S	S→L	S→C	L→S	L→L	L→C
MODIS daily	45.0–51.7%	1.7–9.5%	45.2–46.6%	0.0–4.1%	50.2–64.9%	35.0–45.7%
MODIS 8-day	84.5–95.9%	1.6–11.7%	1.6–4.2%	2.1–15.1%	79.5–97.9%	0.0–5.4%

S=snow, L=land, C=cloud. "S→L" means snow observed by SNOTEL is classified as land by the MODIS daily or 8-day algorithms. Accuracy or error ranges are derived from the selected four SNOTEL stations.

ized in Table 9, which shows that: (1) the MODIS 8-day product has higher classification accuracy in both snow and land; (2) the misclassification rate of snow as land is similar for both products, both are low; (3) the MODIS 8-day product has a little bit higher misclassification rate of land as snow than the MODIS daily product; and (4) the MODIS daily product has a much higher misclassification rate of both snow and land as cloud. Considering that there is not much difference in the misclassification error rates of snow to land and land to snow between these two products, the major factor that reduces the overall accuracy of the MODIS daily product is the clouds. Improvement of suppressing clouds in the 8-day product is obvious from this comparison. The sacrifice is the temporal resolution that is reduced from 1 to 8 days.

(3) Assuming the cloud condition detected by the cloud mask employed in both algorithms is the truth, eliminating the cloudy days in the comparison analysis shows that the MODIS daily algorithm works quite well or even better than the MODIS 8-day algorithm (Table 5 vs. Table 8). For instance, except for the Bateman station (92.0% vs. 93.2%), the overall accuracy derived from the MODIS daily product is better than the MODIS 8-day product for the other three stations. Besides, there are more clear-sky data sets available from the MODIS daily product at each specific position than the total 8-day data sets. For instance, at Beartown station, there are 800 clear-day data sets (53%) from the daily product (1511), while there are only 188 clear 8-day data sets (96%) derived from the 8-day product (195). However, this comparison is only statistical. On a specific day, a clear-sky condition at Bateman does not mean clear-sky at Beartown. A database of clear MODIS snow cover on a pixel basis can be derived from the long-term series of the MODIS daily product, but it will be very time-consuming for a large watershed.

From the above comparison and analysis study, we can see that the major factor that affects the overall accuracy of the MODIS daily product is the clouds. Cloud-masked snow pixels need to be unmasked. Although using the liberal cloud mask technique can reduce the omission error of snow pixel as clouds, quite a lot of snow pixels are still not correctly classified. A possible disadvantage of using a liberal cloud mask is that some types of ice clouds are falsely identified as snow, especially during the summer or in regions where snow is not expected. Then, it may be advantageous to use the conservative cloud mask. Investigation on how to alleviate the snow confusion with ice clouds when using the liberal cloud mask approach continues (Riggs et al., 2003). From our study here, we did not find the misclassification of land as snow by the daily product is worse than the 8-day product. On contrary, the commission error from land to snow by the MODIS daily algorithm is lower than the 8-day algorithm (0.0–4.1% vs. 2.1–15.1%). This may suggest a more liberal cloud mask might be necessary to reduce the omission error of classifying snow as clouds by the daily algorithm, or as pointed out by Simic et al. (2004), combination with microwave sensor data may help alleviate the misclassification problem caused by clouds. Improved snow-cover products will eventually enhance the capability of regional or global climate change models for climate change prediction and snowmelt runoff models for streamflow forecast by assimilating remotely sensed snow-cover data.

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