MODIS-based snow cover variability of the Upper River Grande Basin

Beibei Yu , Xianwei Wang , Hongjie Xie

Laboratory for Remote Sensing and Geoinformatics

University of Texas at San Antonio, Texas 78249, USA

Abstract

Snow cover and its spring melting in the Upper Rio Grande Basin provides a major water source for the Upper to Middle Rio Grande valley and Elephant Butte Reservoir. Thus understanding the snowpack and its variability in the context of global climate change is crucial to the sustainable water resources for the region. MODIS instruments (on Terra and Aqua) have provided time series of snow cover products since 2000, but suffering with cloud contaminations. In this study, we evaluated four newly developed cloudless snow cover products (less than 10%) and four standard products: daily (MOD10A1, MYD10A1) and 8-day (MOD10A2, MYD10A2), in comparison with *in situ* Snowpack Telemetry (SNOTEL) measurements for the hydrological year 2003-2004. The four new products are daily composite of Terra and Aqua (MODMYD10DC), multi-day composites of Terra (MOD10MC), Aqua (MYD10MC), and Terra and Aqua (MODMYD10MC). The standard daily and 8-day products can classify land correctly, but daily products had fairly low accuracy in snow classification due to cloud contamination (a average of 39.4% for Terra and 45% for Aqua) and 8-day products tended to overestimate the snow cover and have a much reduced temporal resolution.All the new multi-day composite products tended to have higher accuracy (about 78% for the hydrological year and 83% for winter season) than the daily product, as the cloud cover has been reduced to less than 10% (~5% for the year) under the new algorithm . This result is consistent with a previous study in the Xinjiang area, China (Wang and Xie, 2007). Therefore, MODMYD10MC products are used to get the mean snow cover of the Upper Rio Grande Basin from 2000 to 2007. The change of the mean snow cover showed an unexpected fluctuated trend rather than continuously decrease due to global warming. Since snow melting contributes to the stream flow, we try to study the relationship between the two to see if the snow area extent retrieved from MODIS can be used for run-off prediction. However, there's hardly any linear relationship being found in this study. This may because many parameters influence the process of snow turning into stream flow. Such as topology (elevation , aspect and slope) condition and rainfall.

Key words: Snow cover; Grande Rio Basin; multi-day composite; MODIS; SNOTEL

1. INTRODUCTION

Snow has a major impact on the Earth's energy balance because of its high albedo and low thermal conductivity, and also has a major influence on atmospheric circulation by modifying overlying air masses. Several satellites have the capabilities of mapping snow cover.

First carried aboard the Terra spacecraft (passes the equator at about 10:30 am), which was launched on December 18, 1999, the Moderate Resolution Spectroadiometer (MODIS) began collecting science data on February 24, 2000. And a second MODIS instrument has been carried aboard the Aqua spacecraft (passes the equator in the early afternoon at about 1:30 pm) launched on May 4, 2002. MODIS is an environmental satellite operating in visible, near- and short-wave infrared and thermal portions of the electromagnetic spectrum. It is designed to provide global views of earth processes with its swath width of 2330 km enabling it to view the entire surface of the earth every 2 days. Currently, there is no single means of assessing the performance of the MODIS snow cover products.

Klein and Barnett did a study comparing the MODIS daily product (MOD10A1, MYD10A1)with NOHRSC product. They concluded that the MODIS daily snow-cover product misclassifies fewer snow pixels and classifies fewer cloud pixels, especially in the forested areas. (Klein et al, 2003) However, both snow and land are highly misclassified as cloud. A lot of cloud data were seen in the MODIS daily product. 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. (Zhou *et al.* 2005) Previous study indicated that the classification accuracy of snow (SNOTEL) as snow or land as land by the MODIS 8-day product (MOD10A2, MYD10A2) algorithm is generally high. But the 8-day product reduced the temporal resolution greatly. The largest factor affecting the accuracy of the MODIS snow products is snow cloud confusion. The new algorithms have been developed by Wang et al to combine the Terra (am) and Aqua (pm) images, as well as create multi-day images. The goal of the new algorithms is to get more cloud-free images and expect to have higher accuracy of classification. The aim of this study is to validate 8 MODIS products, and find out the most representative product for mapping the snow cover. And then the trend of the snow cover area on the Upper Rio Grande Basin can be generated based on this MODIS product.And as well, we can have the trend of snow cover change.

2. STUDY AREA

The Upper Rio Grande basin stretches 1885 miles, lying between the headwaters of the Rio Grande in the San Juan Mountains of Colorado and Fort Quitman, Texas.(Figure 1). The upper basin covers approximately 36,000 mi2 (92,000 km2) in southern Colorado, New Mexico and west Texas. It is bounded on the west by the United States Continental Divide and on the east by the Sangre de Cristo Mountain Range and a series of smaller ranges running generally north-south through the state of New Mexico.(Bella *et al.* 1996) Elevations range from over 14,000 feet (4267 m) to less than 4,000 feet (1219 m). The mainstem of the upper Rio Grande is about 725 miles (1160 km) long. The Upper Rio Grande is a typical example of river basins in semi-arid environments. Snowmelt runoff represents an important water resource in this area, and the Upper Rio Grande encompasses a large range of elevations, slopes and vegetation types, providing a wide range of environmental conditions, which make it a good site to study.

3. DATA USE

3.1 MODIS

In the MODIS snow mapping algorithm, snow is distinguished from other surface covers by two primary distinguishing features. The first is its high reflectance in the visible wavelengths (MODIS band 4 at 0.545–0.565 μm) and second its low reflectance in the short-wave infrared (MODIS band 6 at 1.628–1.652 μm). (Hall et al., 2002) Normalized Difference Snow Index (NDSI) For MODIS is calculated as::

$$NSDI = \frac{Band4 - band6}{band4 + band6}$$

In this study, MODIS tile h09v05 MOD10A1, MYD10A1, MOD10A2, MYD10A2 from February 2000 through October 2006 were ordered through the EOS data gateway. They contain snow cover, snow albedo, fractional snow cover, and quality assessment (QA) data in a compressed HDF-EOS format along with corresponding metadata (Riggs et al, 2006). The MODIS snow cover image is a coded raster. In this study, 25 (no snow), 37 (lake), 50 (cloud), 100 (lake ice), 200 (snow) will be used and others will be classified as 255 (no data).

3.2 Snow Water Equivalent Snow (SWE)

SWE is a common snowpack measurement. It is the amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instaneously. (Pulliainen et al, 2005). Instead of Snow Depth, SWE was provided by the automated Snowpack Telemetry (SNOTEL) network maintained throughout the western states by the United States Department of Agriculture's National Resources Conservation Service (NCRS). There are totally 18 stations in the Upper Rio Grande Basin study area. Since 2 of them were missing data or station ID, SWE from 15 stations were used as *in situ* data for comparison.

3.3 Stream Flow

The streamflow station of the Rio Grande at Otowi Bridge, NM is 1 of the 679 national network stream waterquality stations (Alexander et al., 1997). The drainage area corresponding to this station is 37,037 km2. 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/. (station number 08313000) 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.

Three products were used to complete the intercomparison between stream flow, which are MODIS am-pm combined daily product (MODMYD10DC), combined morning and afternoon 8-day product (MODMYD10A2) , and multi-day am-pm combination images (MODMYD10MC).

The output streamflow data of the Upper Rio Grande Basin at the Otowi Gage south of Espanola, New Mexico at latitude 35852V29WN, longitude 106808V30WW (NAD27) are used as constraints to evaluate the products for streamflow prediction.

4. METHOD

4.1 Processing MODIS Data

Daily or 8-day HDF-EOS files were converted to GeoTIFF files on the UNIX platform. Then GeoTIFF files were converted to Grid file for inputting into Geographic Information System (GIS). With the projection of UTM zone 13 and datum of WGS 84 a rectangle area covering the Upper Rio Grande Basin was extracted using An ArcInfo Arc Macro Language (AML) script. And then a value-attribute table (VAT) of each grid is uploaded to a text file for further process and analysis.

4.2 Generating multi-day or combination products

A multi-day composite image based on both Terra and Aqua daily images with flexible starting and ending dates as long as cloud cover reducing to less than 10% is generated based on the new algorithm developed by Wang et al. Besides the 4 standard MODIS data (MOD10A1, MYD10A1, MOD10A2, MYD10A2), four new products were generated: multi-day am composite images (MOD10MC), (2) multi-day pm composite images (MYD10MC), (3) daily am-pm composite images (MODMYD10DC), and (4) multi-day am-pm composite images (MODMYD10MC) by running AML scripts.

4.3 Comparing with SNOTEL

Comparisons of each products were made against daily in situ snow water equivalent measurements made at 15 SNOTEL sites scattered at high elevations throughout the Upper Rio Grande River Basin. The comparison were completed in excel with VB scripts. Several confusion matrixes or error matrixes were generated to assess the accuracy of remotely sensed data.

4.4 Relationship with Streamflow and MODIS Snow Melting

4.4.1 Combine Daily Streamflow to Muilti-day

To study the correlation between the SAE and streamflow, the downloaded daily streamflow data can be used directly for the MODIS am-pm combined daily snow-cover product. However, for the MODIS am-pm combined 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. Similarly, streamflow were combined as the same period of time the multi-day product were combined, and the mean was retrieved to represent the the average of the period. Two Visual Basic Scripts were written to combine the streamflow in excel.

4.4.2 Filter the Base Flow

Baseflow is the portion of streamflow that comes from groundwater and not runoff. It is assumed that 50% of the water that percolates down to shallow ground water contributes to baseflow. Thus to study the correlation between stream flow and only snow melting. We have to filter out the portion of stream flow not to be contributed by snow melting.

The baseflow filter estimates baseflow and groundwater recharge from streamflow records using the methodology outlined in *Automated methods for estimating baseflow and groundwater recharge from streamflow records* by J.G. Arnold and P.M Allen published in Journal of the Americam Water Resources Association. Five steps to run the program: (1)USGS provides several options for the date format when downloading the stream data. YYYYMMDD (the last one in the list) must be selected for the date format; (2) Delete all of the header information that USGS places at the top of the data file in excel and save the data in space delimited forma.(3)Create a text file named “file.lst”. The program will look for a file by this name. (4) Copy the streamflow data files, the master input file, and bflow.exe (from the download) into the same directory. Open a DOS prompt window and move to the directory containing all the files. At the command prompt, type: bflow.exe .When a new command prompt appears, the program is finished.(5) Output from the baseflow filter program will be listed in the text file “baseflow.dat”. If IPRINT was set to 1 in the master input file, daily filter data is printed also.

4. RESULTS AND DISCUSSION

4.1 Validation of MODIS Products

Table 1 illustrates the comparison between all ground observations and MODIS snow cover daily morning product MOD10A1 at the 15 climatic stations in the 2003-04 hydrologic year There are total 2699 data of land (without snow) and 2626 data of snow (SWE≥1 cm). In the 2699 in situ data of land/no snow, the MOD10A1g product

misclassifies 40 of them as snow and 922 of them as cloud. The accuracy of land classification is 64%. The omission error classifying land as snow is 1% and as cloud is 34%. If the 922 cloud data pairs (corresponding to both MODIS and in situ) are removed from the calculation, the accuracy of land classification is 98% under clear sky conditions. The removal of the cloud data here (and hereafter) is only for comparison purpose under so-called clear sky conditions, and the accuracy of MODIS snow/land classification is not really improved.In the 2626 in situ observed data of snow, the MOD10A1 product misclassifies 364 of them as land and 1344 of them as cloud. The accuracy of snow classification is 35%. The omission error of classifying snow as land is 14% and as cloud is 51%. If the 1344 cloud data (pairs) are removed, the accuracy of snow classification increases to 72%, and the overall accuracy of MODIS land and snow classification increases from 50% to 87%.

Table 2 illustrates the comparison between all ground observations and MODIS snow cover daily afternoon product MYD10A1 at the 15 climatic stations in the 2003-04 hydrologic year. The omission error of classifying snow as cloud is even higher than the morning product, which may indicate that there is generally more cloud appear in the afternoon than in the morning. The land classification is as high as 99% under clear sky condition and only 23 pairs of data were misclassified as snow. The patch snow (SWE<1-4cm) and deep snow (SWE>=4cm) classification are 33% and 59% respectively, if the misclassified cloud is removed.

Compared to the results showed in table 1, Error matrix between MODMYD10MC and ground measurements in the 2003-04 hydrologic year at 15 stations on Rio Grande Basin showing in table 8 displayed a better result of classifying both land and snow. There are totally 2430 data, 1462 are land, and the others are snow. In the 1462 land data, 1330 were accurately classified as land, only 4% and 5% were misclassified as cloud and snow, respectively. Though the accuracy after cloud data is removed of the daily products is high, but the cloud in that case is statically removed. The multi-day am-pm composite products reduced the cloud cover to less than 10%, which provide us with better representative images.

The comparison between the winter season Multi-day am-pm composite products and SNOTEL SWE are showed in table 9. The accuracy of the deep snow cover has increased from 78% to 83% (after cloud is removed).

Figure 1 shows the comparison results of 6 MODIS products validation. Generally, 3 of the multi-day composite products (MOD10A2, MYD10A2, and MODMYD10MC) have higher accuracy in overall, snow, as well as land classification than the daily products (MODA1, MYDA1, MODMYD10DC). The am-pm daily products display better results than the standard daily products. And all the products are good at classifying land pixels. Daily products show relatively low ability of classifying snow, which might because of very high percentage of total cloud. As we can see from the graph, those products, which have low total cloud, have higher accuracy in classifying both land and snow. In that case, snow is recognized as the biggest disturbance in the MODIS snow mapping work. MOD10A2 and MOD10A2, which are the MODIS 8 day products showed generally high accuracy in classifying snow and their total cloud percentages are snow. However, MODIS 8-day composite product (MOD10A2) reduces the original temporal resolution of daily to 8 days, In algorithm of 8 day products, a pixel is classified as cloud only when the pixel is snow-covered in all the 8 days, but a pixel will be classified as snow even if there is only one day covered by snow. In that case, eight-day products tend to overestimate the snow cover, particularly in early or end of the snowfall periods when snow is easily melted away. In addition, the 8-day MODIS product using fixed starting and ending dates looses its flexibility in monitoring particular snowfall events. (Wang). 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.

4.2 Mean Snow and Cloud Comparison Between MODIS products

Table 10 showed the results of the comparison between eight different products. MOD10A1 and MYD10A1 represent the standard morning and afternoon daily products, respectively. There are totally 356 morning images and 365 afternoon images. As 10 of the morning images are missing, only use 355 images were used for comparison (As a requirement for the new algorithm, the number of MOD10A1 image files and MYD10A1 image files should be equal). Based on those daily am and pm images, 350 daily am-pm composite images (MODMYD10DC) are generated. Showing in the table, the mean cloud cover of the standard daily morning product is as high as 39.5%, and even higher (45.1%) for the afternoon product. Clouds are the major cause for reduction of the overall accuracy of the MODIS daily product, which cause the mean snow cover of the afternoon product come out fairly low (3.5%). These two products might underestimate the snow cover, due to the high cloud cover. Therefore, it is difficult to use these products for daily snow monitoring and forecasting. The daily am-pm composite images have annual mean cloud cover about 30.6%, which are 15% to over 20% less than the am or pm images. The multi-day composite image products generating under the new algorithm reduced the cloud cover to less than 10%. The new algorithm generated 129 multi-day am images, 111 multi-day pm images and 162 am-pm combined images. Cloud cover percentages were reduced to 6.0%, 6.8% and 5.3%, respectively. And at the same time, the snow cover increased to about 15.2%, 12.2% and 15.1%, respectively, which tend to be best representation of snow cover.

Figure 3 is a sample image of MOD10A1 product for the date December 4th, 2003. In the image, high cloud coverage, which is in green color, is displayed. Figure 4 is a sample image of MYD10A1 product of afternoon image for the same date. Comparing with the morning image, there seems less cloud coverage. Some area has cloud in the morning, however, the cloud clears in the afternoon. After combining these two images, an am- pm composite image can be generated. Further combination of several days' images using the algorism we mentioned previously, a multi-day am-pm composite image is created. Figure 5 is the sample image of the MODMYD10MC product of the combination of two days (Dec 4th , and Dec 3rd, 2003). As can be seen from this image, snow coverage has been increased, while cloud coverage has been decreased. Thus, the composite product has removed the disturbance of cloud contamination efficiently, which provide us with a more representative image of snow cover extent.

4.3 Trend of Snow Cover Change between 2000 and 2007

Based on the results of validation and mean snow and cloud cover comparison, the following mean snow cover change chart is generated under the results of multi-day am-pm images from 2002-2007. 2000 and 2001 are years which have only am images. The results were got from the multi-day am images.

Figure 2 displays the trend of the snow cover change of the Upper Rio Grande Basin during the period of 2000 to 2007. The snow area extent dropped slightly in 2000 to 2002, and then had a sharp increase in the period of 2002 to 2003, from 6.2% to 24.9%. Unexpectedly, it started to decrease in 2003 and then increase in 2004. Apparently, the mean snow cover in the year 2005-2006 has the largest decrease from over 30% to approximately 10%. The lowest mean snow cover happened in the period of 2001-2002 (6.2%), and the highest mean snow cover was in the period of 2004-2005. And we can foresee the increase of snow cover in the year 2006 and 2007. Overall, it is found there is no fixed trend of increase or decrease in mean snow cover from the year 2000 to 2007, while an increased fluctuation of mean snow cover is clearly observed. This might be due to global warming caused unusual climate change for a particular area: extremely wet in one year or dry in another year. A longer term of snow cover data since 1980's will help to understand the trend and will also enable us to further examine the relation between the snow cover change and El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)”

4.4 Correlation between Snow Melting and Stream Flow

Snow melting is believed to contributes to the stream flow, we try to study the relationship between the two to see if the snow area extent retrieved from MODIS can be used for run-off prediction. However, there’s hardly any linear relationship being found in this study. This may because many parameters influence the process of snow turning into stream flow. Such as topology (elevation , aspect and slope) condition and rainfall.Snow-melting and runoff is a complicated and changeable model. Previous study found some good linear relationship with logarithm snow melting and streamflow in a particular period. That might because such period of time has few rainfall event and the little atmospheric variability. To find a better relationship between stream flow and snow melting, a model take several parameters into account has to be used.

5. CONCLUSION

Among the 8 MODIS standard and generated products, the multi-day am-pm composite product is believed to be the best representative one in mapping snow area extent. Comparing to the daily products, which has relatively high cloud coverage, the new products alleviated the contamination of cloud blockage by reducing the cloud cover to less than 10%. Besides, the composite product generated more cloud-free images (162) than 8-day products (47), and had a better temporal resolution. However, the overall validation accuracy of MODIS products is not as good as the one did in Xinjiang area. (Wang, in press). The difference of these to studies is the ground data used for comparison. Instead of using typical snow depth for comparison with MODIS data, the Snow Water Equivalent (SWE) is used, which has limitation especially during rainfall season, since the SWE might be contaminated by rainfall. The cryosphere integrates climate variations over a wide range of time scales, making it a natural sensor of climate variability and providing a visible expression of climate change. (IPCC, 2007). Snow cover change trend derived by the MODIS composite product displayed a fluctuated curve. Climate change associated with increased greenhouse gas emissions may indeed affect future snow cover extent over North America. However, the response to greenhouse gas forcing may be nonlinear. There's hardly any linear relationship between stream flow and snow area extent changing being found in this study. This may because many parameters influence the process of snow turning into stream flow. Such as topology (elevation , aspect and slope) condition and rainfall. Snow-melting and runoff is a complicated and changeable model. Modeling is a good way to use snow area extent predicting run-off.

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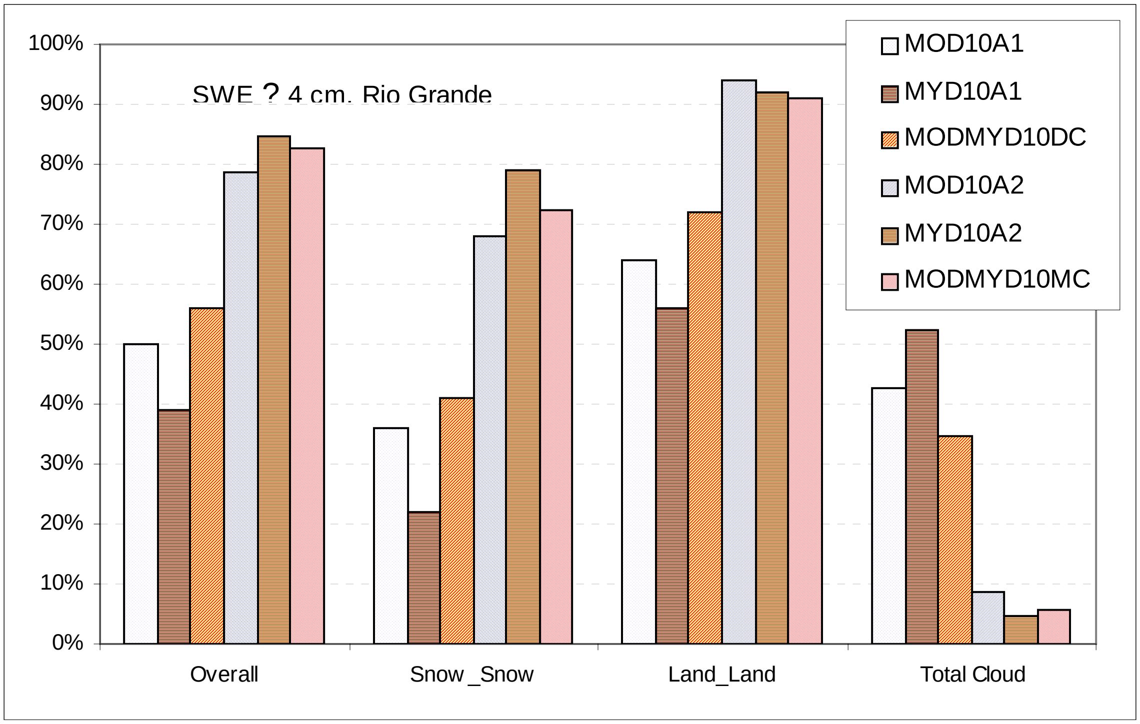


Figure 1 Comparison accuracies of 6 MODIS Snow cover products in terms of overall classification, cloud to cloud, snow to snow, and land to land.

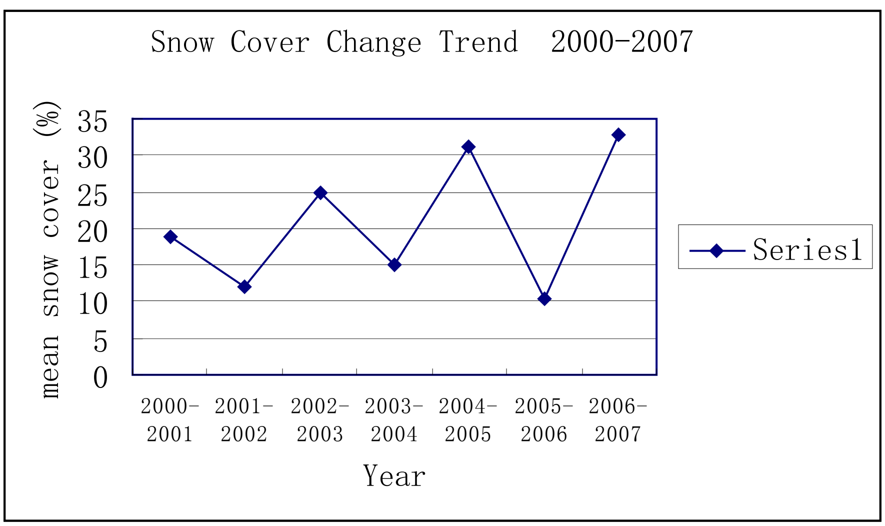


Figure 2 Time series of snow cover change from 2000 to 2007 generated based on the MODIS MODMYD10MC product

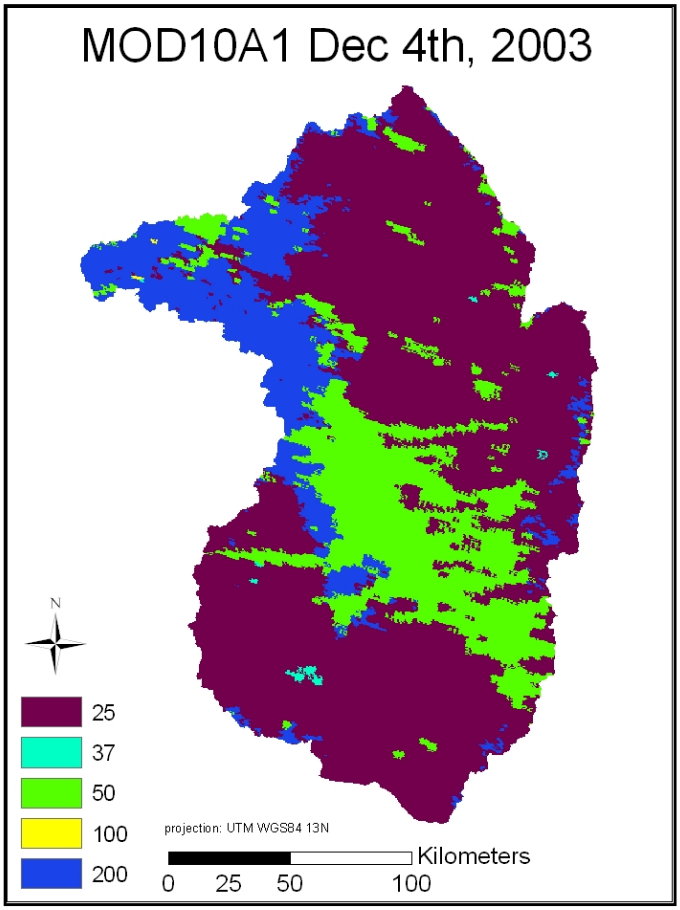


Figure 3 Map of MOD10A1 image of December 4th , 2003, showing the snow, cloud and land coverage in the morning of the day.

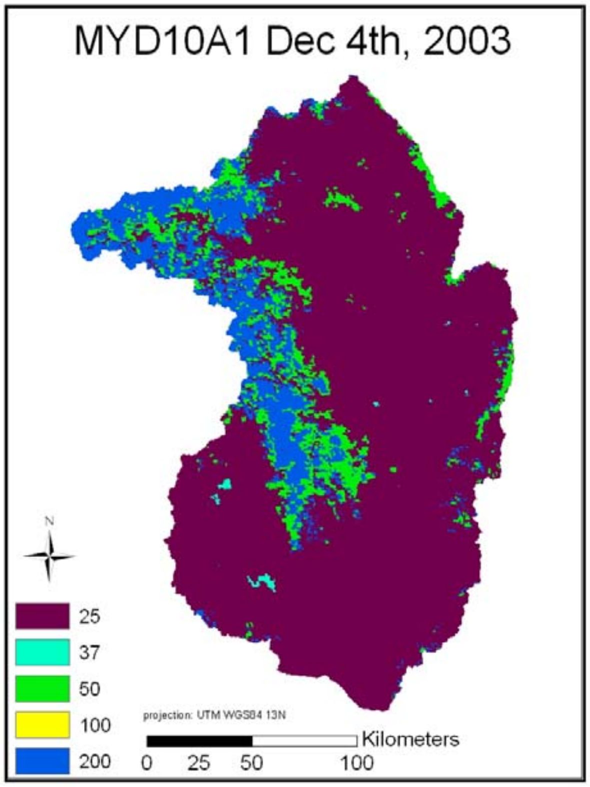


Figure 4 Map of MYD10A1 image of December 4^{th} , 2003, showing the snow, cloud and land coverage in the afternoon of the day

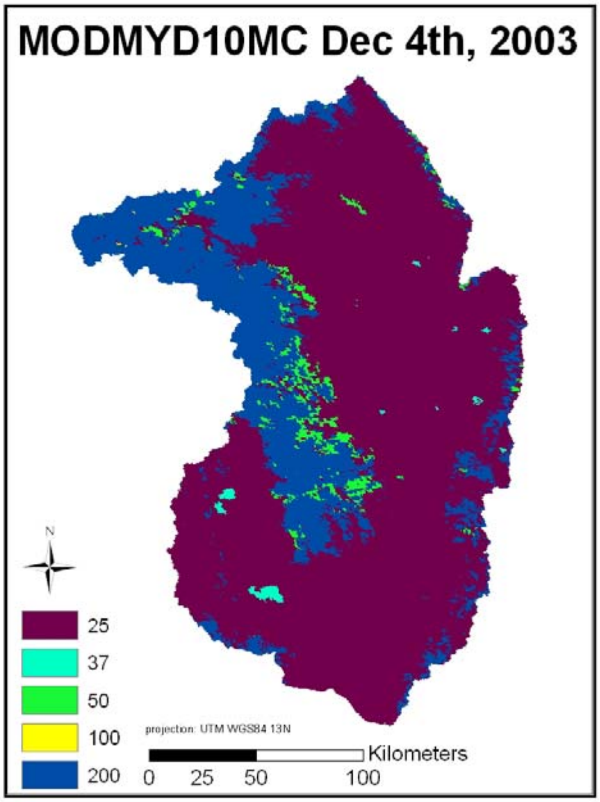


Figure 5 Map of MODMYD10MC image of December 3rd and 4th, 2003. It is the multi-day composite image of am-pm, showing snow, cloud and land coverage.

Table 1. Error matrix between MOD10A1 and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MOD10A1			Accuracy after cloud removed*
	5325	Snow	Land	Cloud	
Land (SWE < 1 cm)	2699	40	1737	922	98%
	51%	1%	64%	34%	
Fractional Snow (SWE =1 - 4 cm)	284	86	72	126	54%
	5%	30%	25%	44%	
Snow (SWE >= 4 cm)	2342	832	292	1218	74%
	44%	36%	12%	52%	

Table 2. Error matrix between MYD10A1 and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MYD10A1			Accuracy after cloud removed*
	5325	Snow	Land	Cloud	
Land (SWE < 1 cm)	2699	23	1522	1154	0%
	51%	1%	56%	43%	
Fractional Snow (SWE =1 - 4 cm)	284	40	83	161	33%
	5%	14%	29%	57%	
Snow (SWE >= 4 cm)	2342	515	354	1473	59%
	44%	22%	15%	63%	

Table 3. Error matrix between MOD10A2 and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MOD10A2			Accuracy after cloud removed*
	690	Snow	Land	Cloud	
Land (SWE < 1 cm)	328	9	307	12	97%
	48%	3%	94%	4%	
Fractional Snow (SWE =1 - 4 cm)	26	8	16	2	33%
	4%	31%	62%	8%	
Snow (SWE >= 4 cm)	336	228	62	46	79%
	49%	68%	18%	14%	

Table 4. Error matrix between MYD10A2 and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MYD10A2			Accuracy after cloud removed*
	690	Snow	Land	Cloud	
Land (SWE < 1 cm)	328	23	303	2	93%
	48%	7%	92%	1%	
Fractional Snow (SWE =1 - 4 cm)	26	15	8	3	65%
	4%	58%	31%	12%	
Snow (SWE >= 4 cm)	336	266	43	27	86%
	49%	79%	13%	8%	

Table 5. Error matrix between M0D10MC and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MOD10A1			Accuracy after cloud removed*
	1815	Snow	Land	Cloud	
Land SWE <= 1 cm	1051	29	967	55	97%
	58%	3%	92%	5%	
Fractional Snow SWE=1-4 cm	125	53	62	10	46%
	7%	42%	50%	8%	
Snow SWE>= 4 cm	639	489	106	44	82%
	35%	77%	17%	7%	

Table 6. Error matrix between MYD10MC and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MYD10A2			Accuracy after cloud removed*
	714	Snow	Land	Cloud	
Land (SWE < 1 cm)	450	44	83	323	65%
	63%	10%	18%	72%	
Fractional Snow (SWE =1 - 4 cm)	101	16	70	15	19%
	14%	16%	69%	15%	
Snow (SWE >= 4 cm)	163	129	20	14	87%
	23%	79%	12%	9%	

Table 7. Error matrix between MODMYD10DC and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

Ground observations	Total	MODMYD10DC			Accuracy after cloud removed*
	5325	Snow	Land	Cloud	
Land (SWE < 1 cm)	2699	118	1944	637	94%
	51%	4%	72%	24%	
Fractional Snow (SWE =1 - 4 cm)	284	64	111	109	37%
	5%	23%	39%	38%	
Snow (SWE >= 4 cm)	2342	969	280	1093	78%
	44%	41%	12%	47%	

Table 8. Error matrix between MODMYD10MC and ground measurements in the 2003-04 hydorlogic year at 15 stations on Rio Grande Basin, USA

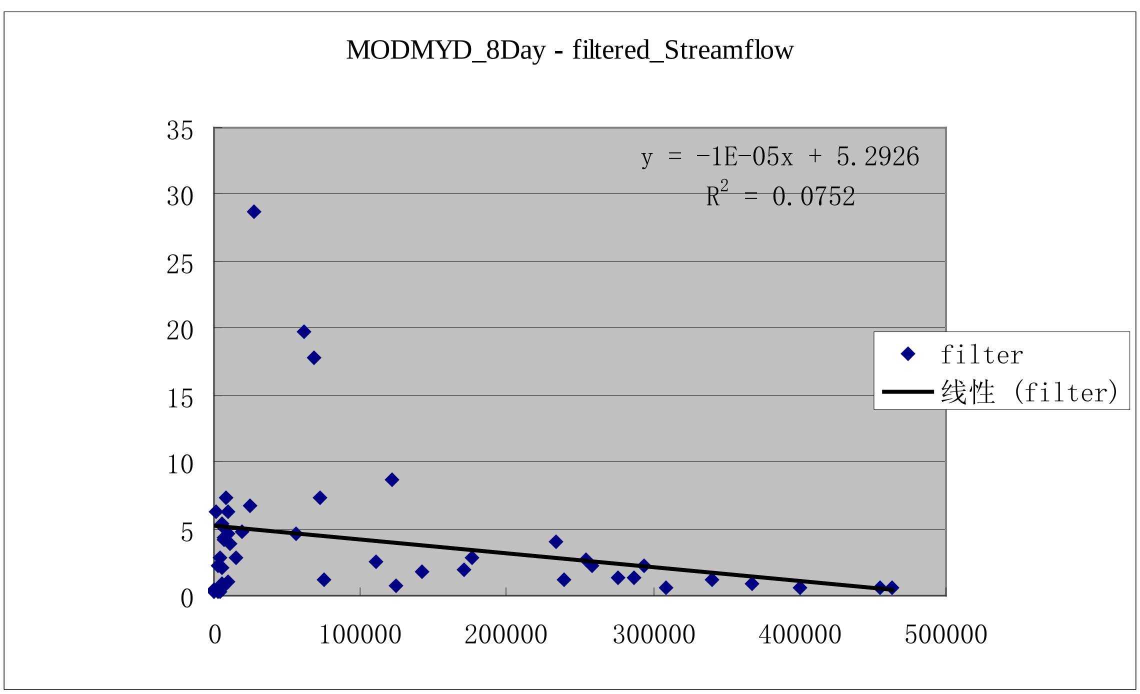
Ground observations	Total	MODMYD10MC			Accuracy after cloud removed*
	2430	Snow	Land	Cloud	
Land (SWE < 1 cm)	1462	68	1330	64	95%
	60%	5%	91%	4%	
Fractional Snow (SWE =1 - 4 cm)	91	40	46	5	47%
	4%	44%	51%	5%	
Snow (SWE >= 4 cm)	877	635	174	68	78%
	36%	72%	20%	8%	

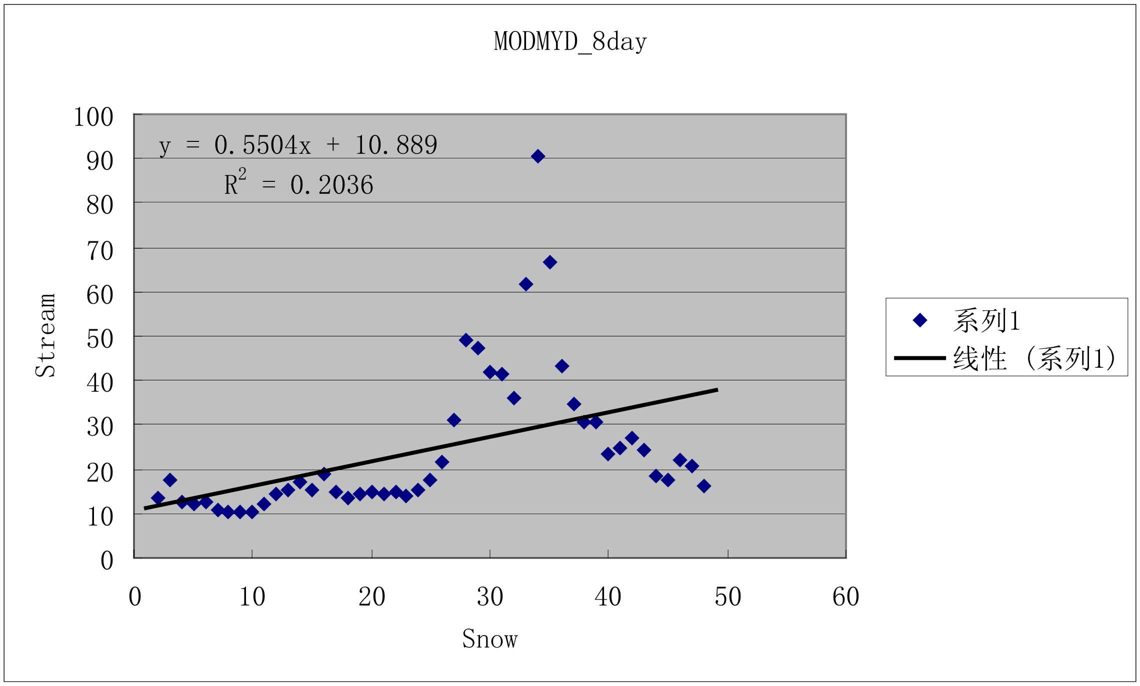
Table 9. Error matrix between MODMYD10MC and ground measurements in the 2003-04 winter time at 15 stations on Rio Grande Basin, USA

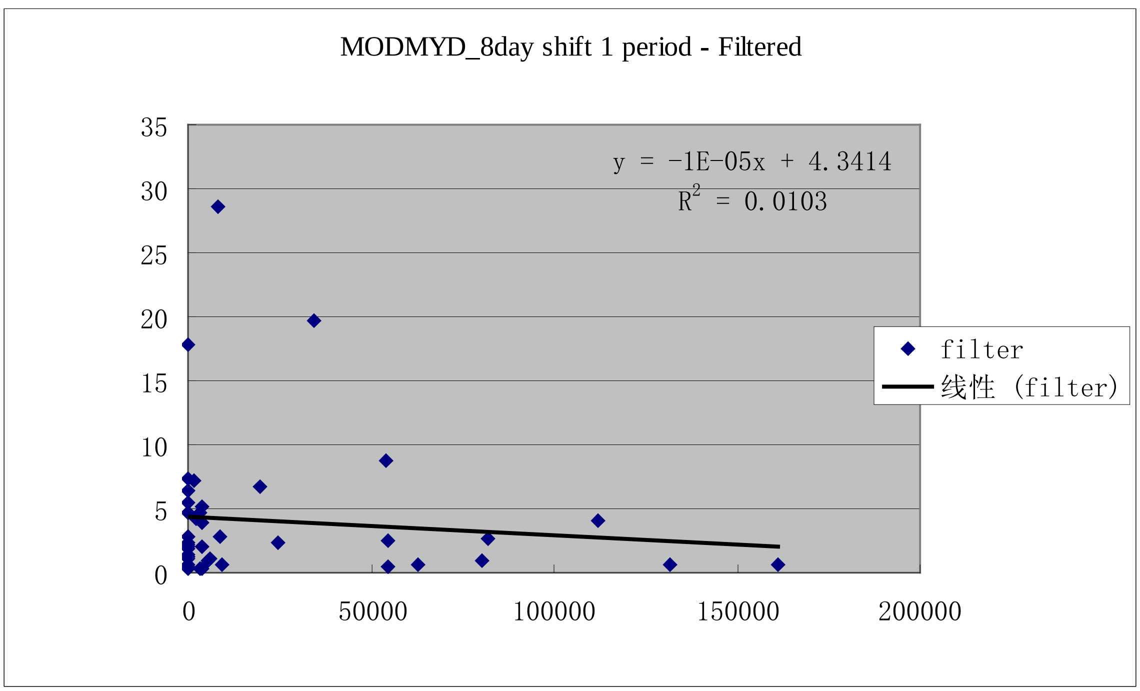
Ground observations	Total	MODMYD10MC			Accuracy after cloud removed*
	765	Snow	Land	Cloud	
Land (SWE < 1 cm)	18	1	16	1	94%
	2%	6%	89%	6%	
Fractional Snow (SWE =1 - 4 cm)	41	16	24	1	40%
	5%	39%	59%	2%	
Snow (SWE >= 4 cm)	706	546	112	48	83%
	92%	77%	16%	7%	

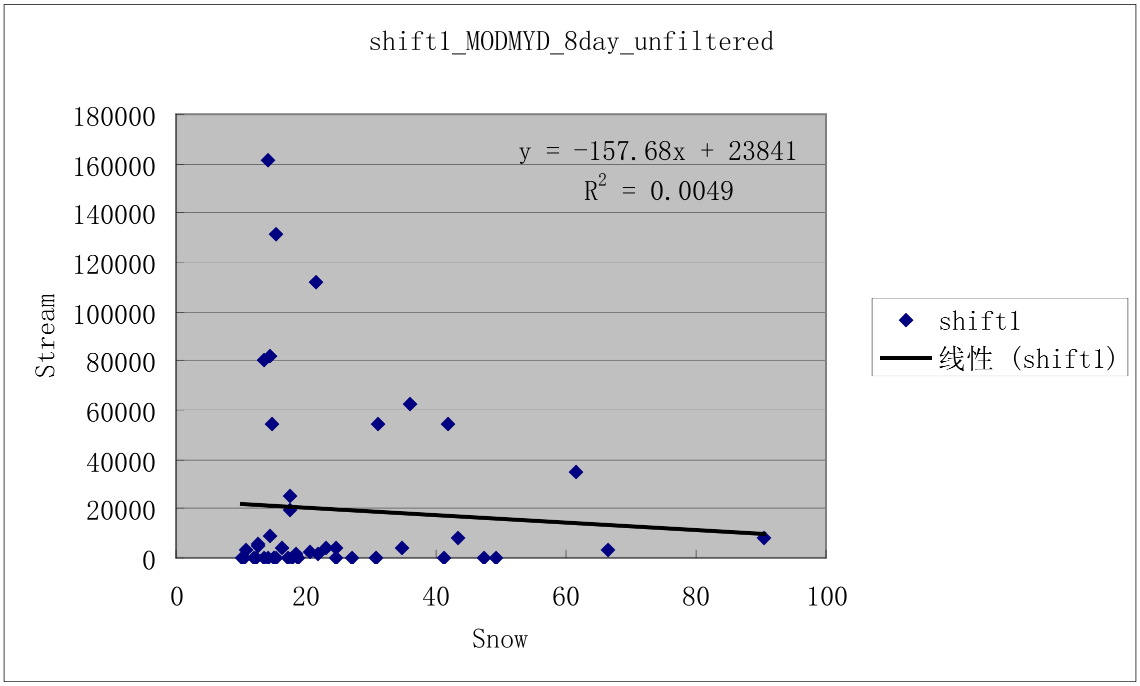
Table10. Comparison of mean cloud and snow cover percentage of different MODIS Terra and Aqua snow cover products during 2003-2004 hydrologic year in Colorado Plateau

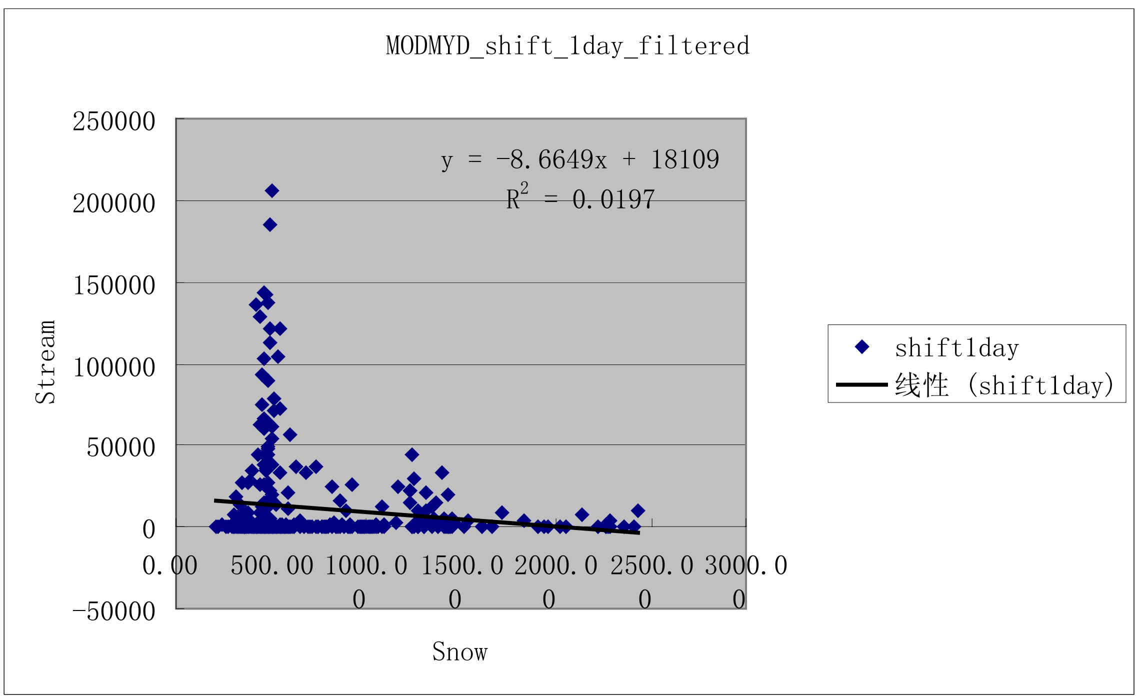
	Total images	Mean cloud	Mean snow
MOD10A1	355	39.5%	5.8%
MYD10A1	365	45.1%	3.5%
MODMYD10DC	355	30.6%	6.6%
MOD10A2	47	2.7%	17.1%
MYD10A2	47	4.1%	18.0%
MOD10MC	129	6.0%	15.2%
MYD10MC	111	6.8%	12.2%
MODMYD10MC	162	5.3%	15.1%

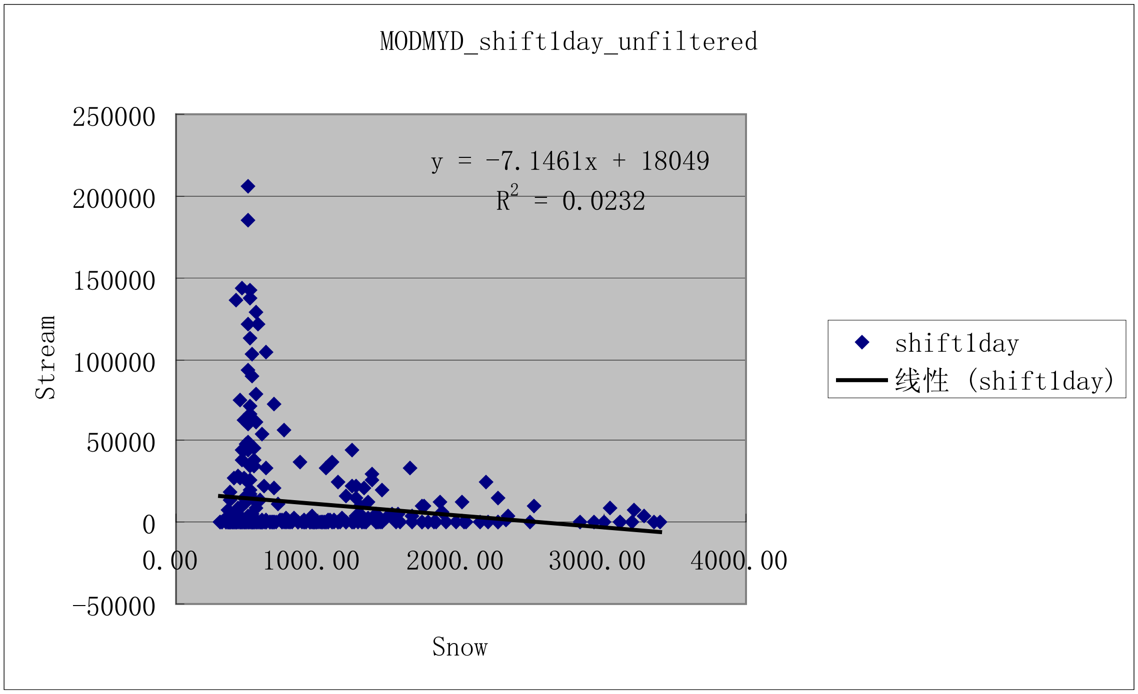


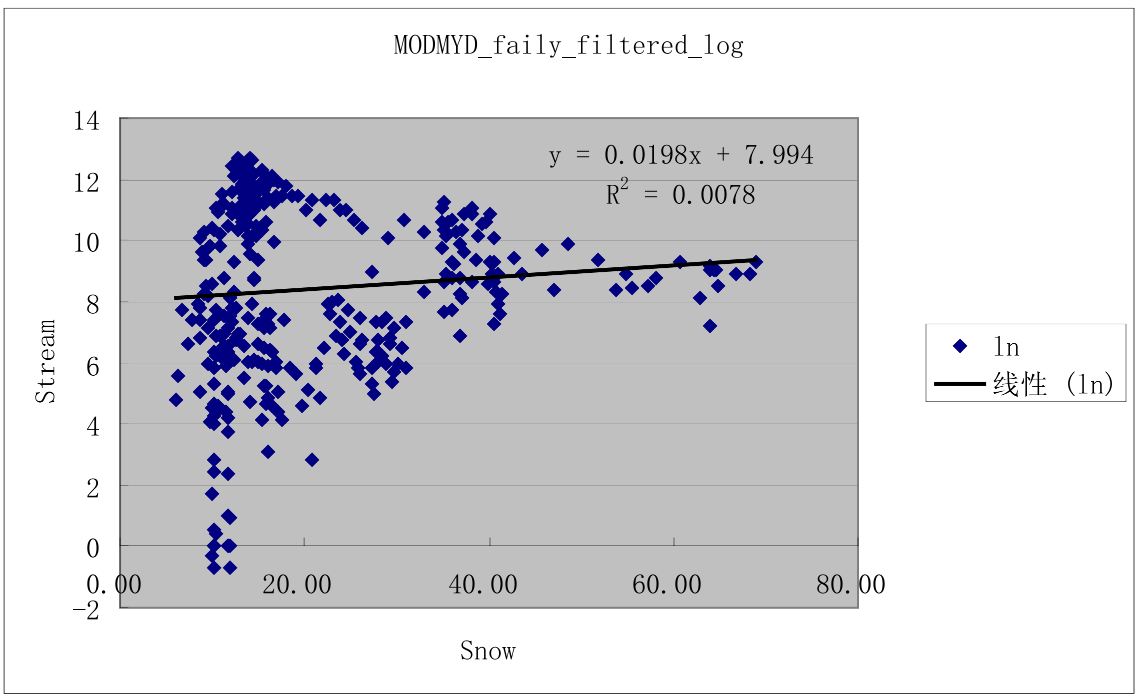

MODMYD_8day
y = 0.5504x + 10.889
R^2 = 0.2036
Stream
Snow
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
系列1
线性（系列1）

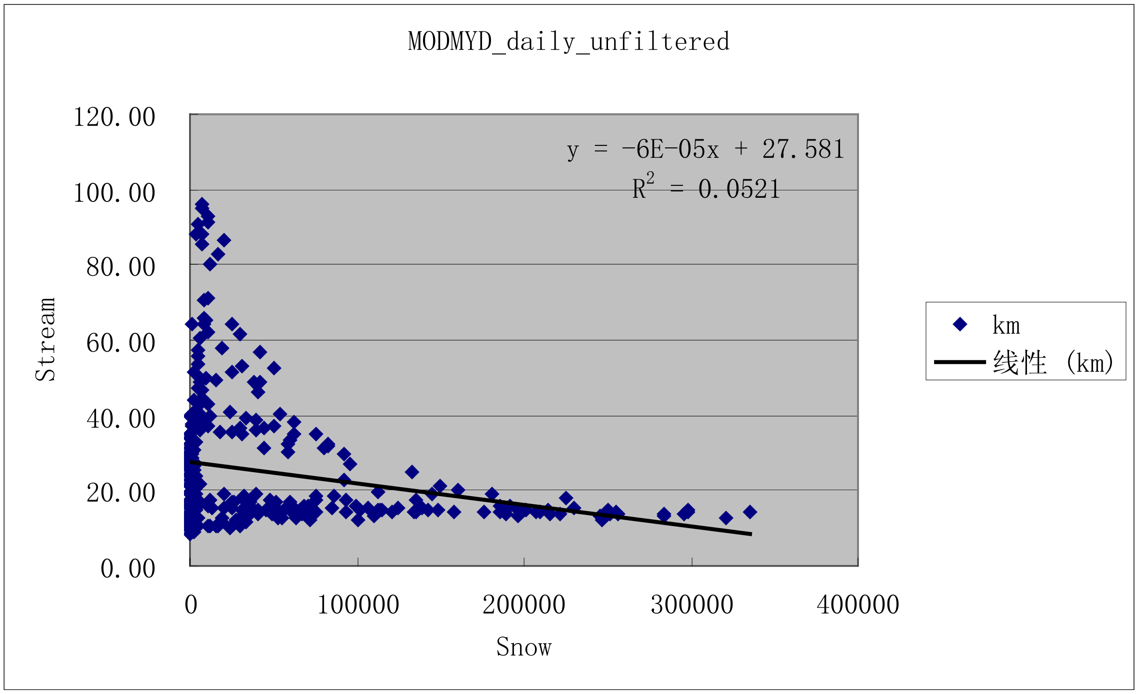

MODMYD_8day shift 1 period - Filtered
y = -1E-05x + 4.3414
R^2 = 0.0103
35
30
25
20
15
10
5
0
0
50000
100000
150000
200000
filter
线性（filter）

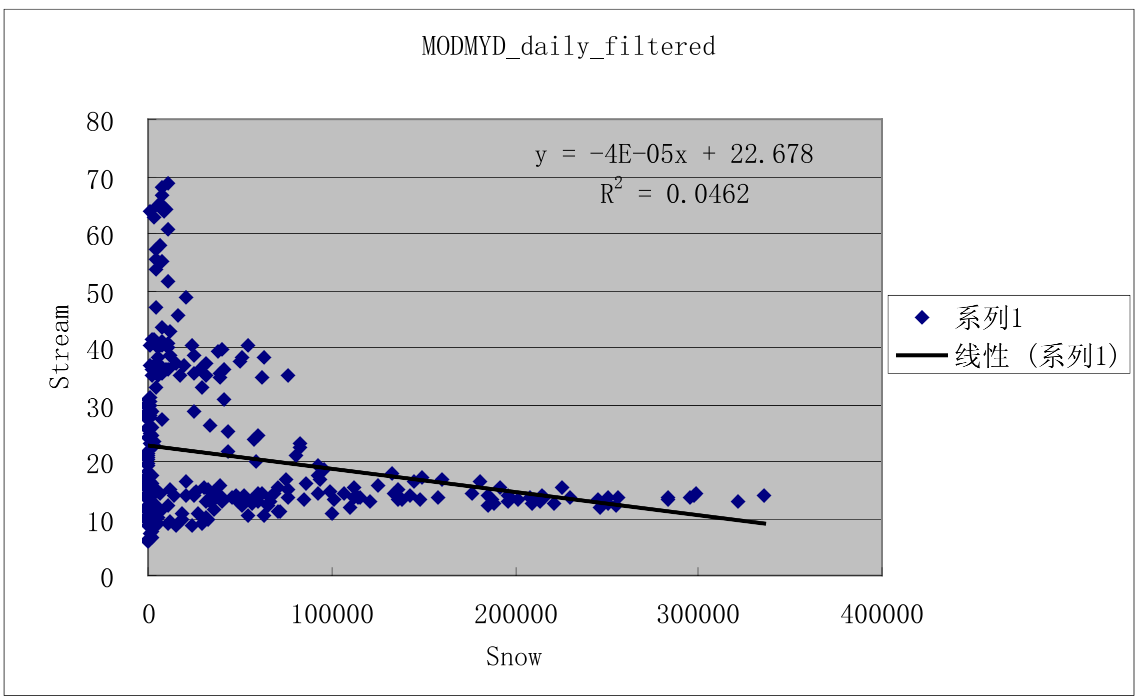

shift1_MODMYD_8day_unfiltered
y = -157.68x + 23841
R2 = 0.0049
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Stream
0
20
40
60
80
100
Snow
shift1
线性 (shift1)

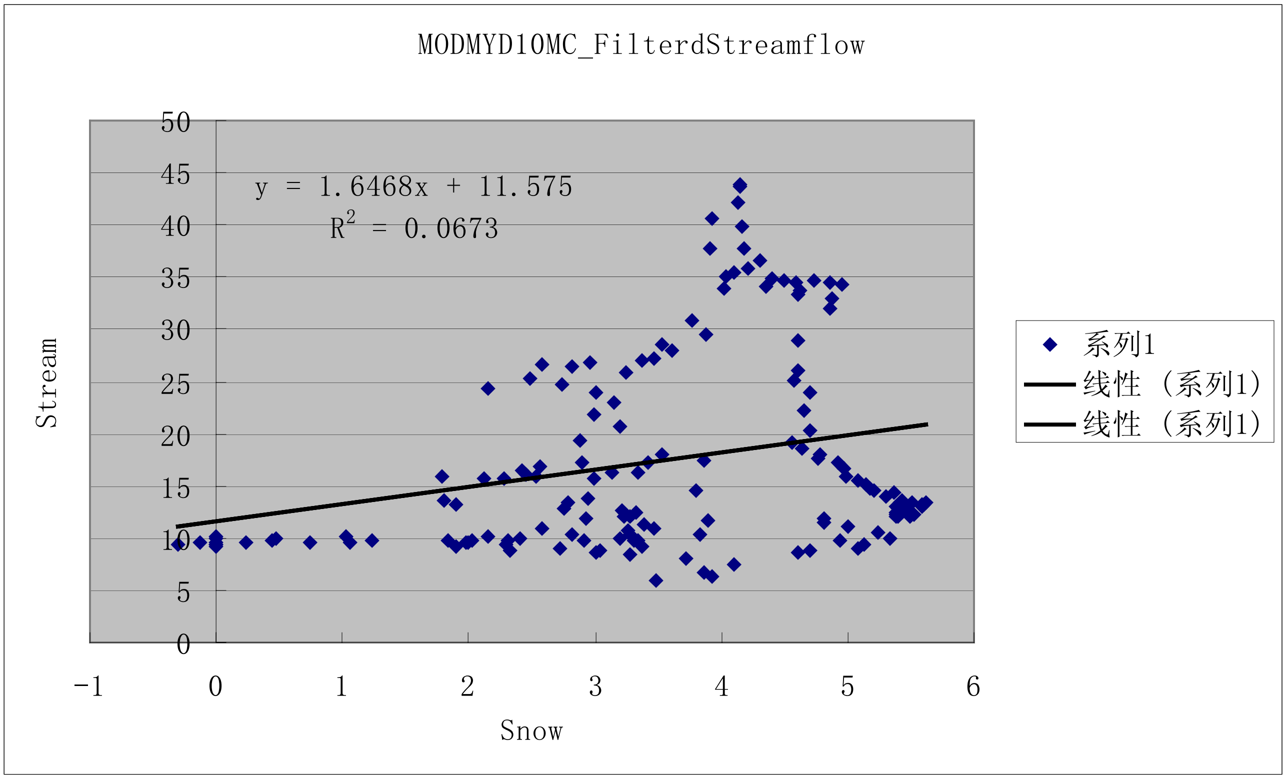

MODMYD_shift_1day_filtered
y = -8.6649x + 18109
R2 = 0.0197
250000
200000
150000
100000
50000
0
-50000
Stream
0.00
500.00
1000.00
1500.00
2000.00
2500.00
3000.00
Snow
shift1day
线性 (shift1day)

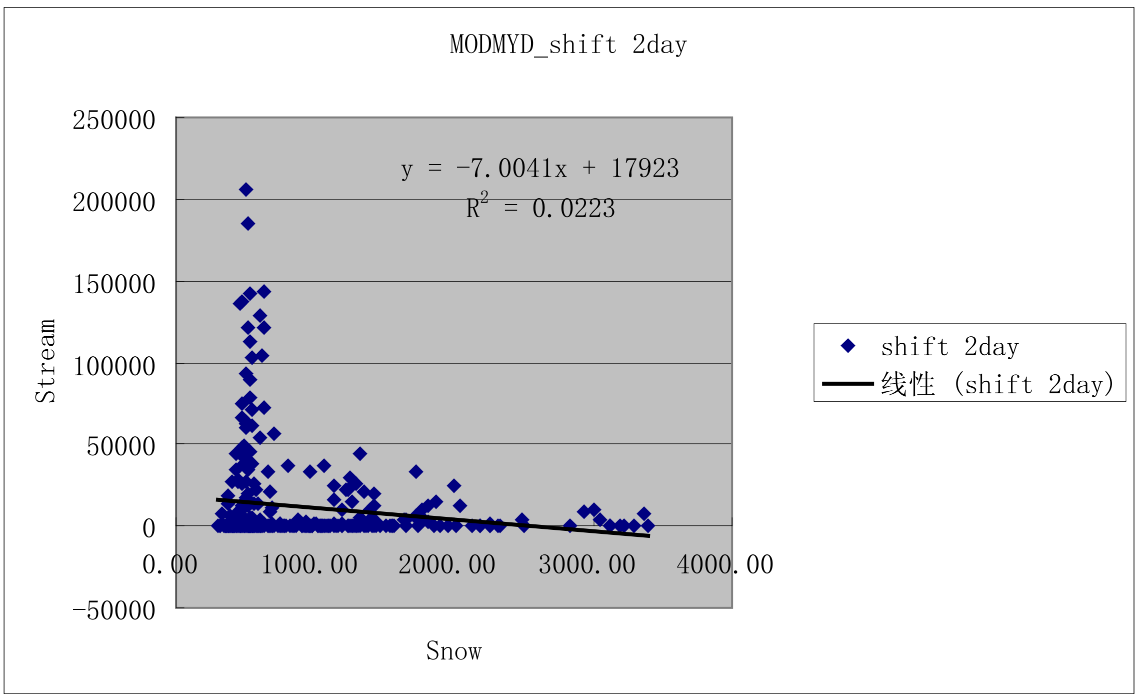

MODMYD_shift1day_unfiltered
y = -7.1461x + 18049
R^2 = 0.0232
Stream
250000
200000
150000
100000
50000
0
-50000
0.00
1000.00
2000.00
3000.00
4000.00
Snow
shift1day
线性 (shift1day)


MODMYD_faily_filtered_log
y = 0.0198x + 7.994
R^2 = 0.0078
Stream
14
12
10
8
6
4
2
0
-2
0.00
20.00
40.00
60.00
80.00
Snow
ln
线性 (ln)


MODMYD_daily_unfiltered
y = -6E-05x + 27.581
R2 = 0.0521
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stream
0
100000
200000
300000
400000
Snow
km
线性 (km)


MODMYD_daily_filtered
y = -4E-05x + 22.678
R2 = 0.0462
80
70
60
50
40
30
20
10
0
Stream
0
100000
200000
300000
400000
Snow
系列1
线性 (系列1)


MODMYD10MC_FilterdStreamflow
y = 1.6468x + 11.575
R2 = 0.0673
Stream
Snow
50
45
40
35
30
25
20
15
10
5
0
-1
0
1
2
3
4
5
6
系列1
线性（系列1）
线性（系列1）


MODMYD_shift 2day
y = -7.0041x + 17923
R2 = 0.0223
Stream
Snow
250000
200000
150000
100000
50000
0
-50000
0.00
1000.00
2000.00
3000.00
4000.00
shift 2day
线性（shift 2day）