SYNTHETIC YEAR-INDEPENDENT SPATIO-TEMPORAL PATTERNS OF SNOW DEPLETION

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ABSTRACT

Snow cover extent is a key variable which is critically important for climate and hydrologic studies. In recent years, the MODerate Resolution Imaging Spectroradiometer (MODIS) satellite sensor has been used in a number of studies and gained widespread acceptance for estimation of snow cover extent due to its high spatial and temporal resolution. Several researchers have observed that snow accumulation and ablation occur in reasonably regular patterns from one year to the next. Thus, information from satellite imagery across different years ought to be able to inform the spatial distribution of snow in one year based on information in another year. This is a vital piece of information which has not yet been fully recognized or exploited. We have developed a method to synthesize the regular, year-independent, spatio-temporal pattern of snow depletion from the beginning to the end of melt seasons, using a series of snow cover maps produced from MODIS data across multiple years (2001 to 2011) coupled with the melt-out dates of a collection of SNOwpack TELemetry (SNOTEL) stations. The synthesized spatial time series have the capability of extrapolating snow covered area in space (e.g., during cloud obscuration) and time (e.g., for forecasting snow cover ablation). The accuracy of this method has been evaluated over the headwaters of the Upper Snake River in Western Wyoming with very good results. This method has many applications including cloud removal, within-season snow cover ablation forecasting, climate change impacts on snow and runoff, and modeling climatology of snow. These applications can be extended for use in water management and water supply forecasting. (KEYWORDS: MODIS, SNOTEL, snow accumulation, snow ablation, snow cover extent)

INTRODUCTION

The fact that spatial and temporal patterns of snow distribution and ablation are similar from one year to the next has long been established in the literature (Sturm et al., 2010; Luce et al., 2004). For example, Luce et al. (2004) observed a high degree of similarity in the shape of dimensionless depletion curves for the Upper Sheep Creek basin of the Reynolds Creek Experimental Watershed located in Owyhee Mountains of southwest Idaho, USA for the period of nine years investigated. Similarly, a study conducted by König and Sturm (1998) in the Alaskan Arctic also revealed a remarkable similarity in the appearances of snow patterns observed over the study basin across a period of three years. According to the study, snow patterns occupied the same locations in three consecutive years and their edges tended to stay in the same place as the melt progressed. These repeated snow melt patterns observed by several researchers across different landscapes are not just as a result of mere coincidences but are largely controlled by some inherent factors peculiar to each landscape or environment (Adams, 1976).

Recurrent snow patterns have been used to directly model snow distribution, improve the output of physically based models, simulate spatially distributed snow water equivalent and evaluate distributed snowmelt models, among others (Blöschl et al., 2002; Sturm et al., 2010).

Undoubtedly, the importance of repeated snow patterns cannot be over emphasized as already highlighted above; however, the difficulty in establishing the temporal and spatial patterns of snow has been identified to be the major challenge to the effective use of these patterns (Sturm et al., 2010). If these challenges are met, information from the repetitive patterns of snow distribution and ablation can have a wider range of applications.

Despite many proposed methods to establish snow patterns and the extensive literature that presently exists on snow mapping, quantitative investigations of the spatial and temporal similarities between yearly snow patterns are still rare (Sturm et al., 2010). In this study, we present a method of establishing the spatial and temporal stability of snow patterns and the various applications of the established patterns.

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Study area

The study was carried out over a basin located in western Wyoming (Figure 1) that drains an area of 3465 mi^2 (8894 km^2). Elevations range from 5799 – 13760 feet amsl (1737 – 4194 m). The basin, designated by U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) 17040101, 02 and 03, known as the Snake Headwaters, Gross Ventre, and Greys-Hobock, respectively, serves as the headwaters of the Snake River and drains across the Snake River Plain of southern Idaho and represents an important water resource for agriculture, power generation, in-stream fish requirements, as well as municipal, commercial, and industrial uses.

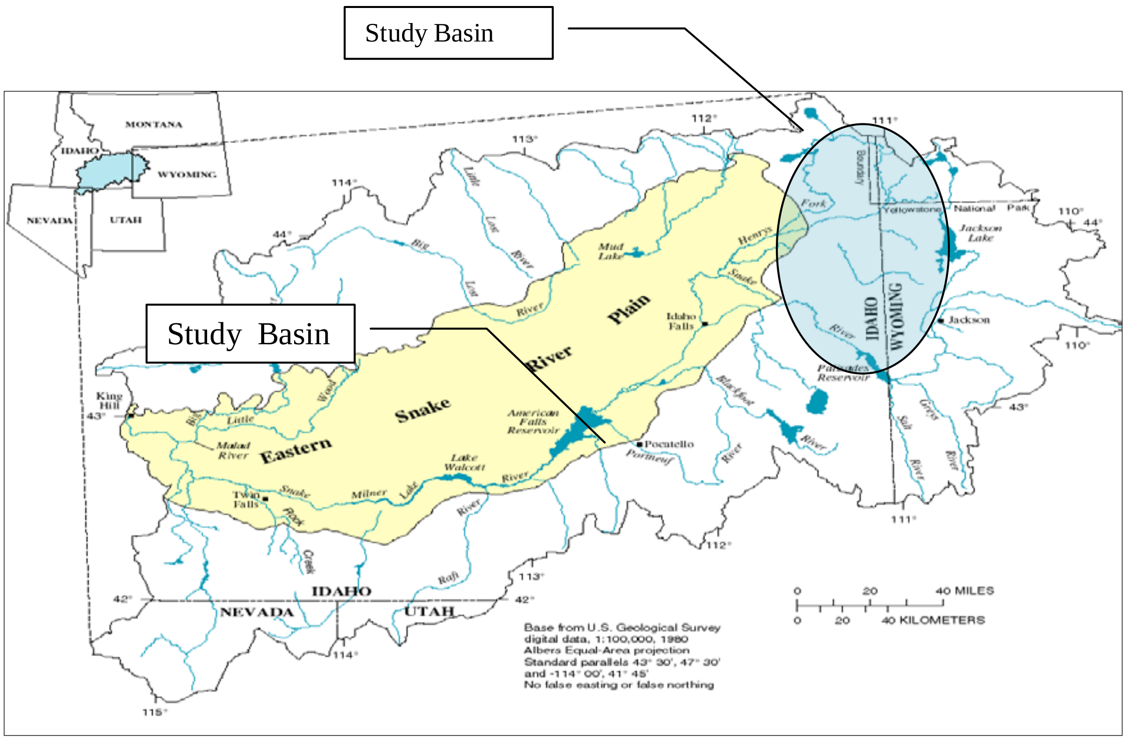

Figure 1. The Study Basin-Snake River above Palisades Reservoir.
Source: http://id.water.usgs.gov/nawqa/reports/ott98/figure/fig2.gif

METHODOLOGY

Below is the flowchart of the procedure followed in establishing the snow patterns and the application of the established pattern in cloud filtering. The chart involves two major steps:

STEP 1

Processing of Images (MODIS algorithm and ArcGIS)

Name the images (MODIS naming convention)

See Figure 3a ← Obtain Snow Cover Area Fractions ← (Pixels covered by snow) / (Total Pixels)

See Figure 3b ← Fit a Gaussian curve to the SCAF

See Figure 3c ← Normalize the dates of the Gaussian curves ← ND= (Day of year – Mean) / (Std. Deviation)

Assign the images with the corresponding ND ↔ The assigned ND enables us to compare images across the years, such that, images with the same NDs are comparable.

Store all the images in a Library

STEP 2:

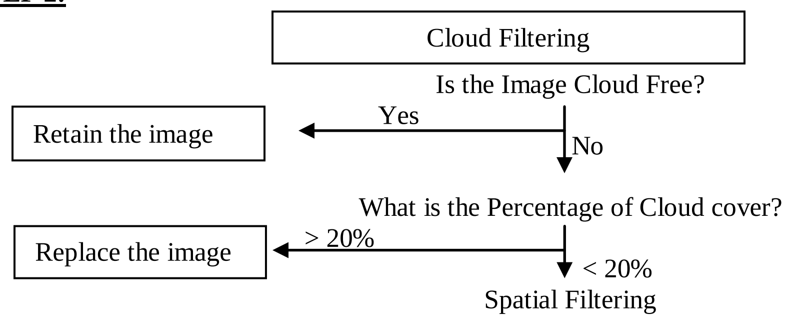

Figure 2. A flowchart of the procedure followed in establishing the snowmelt patterns in the study

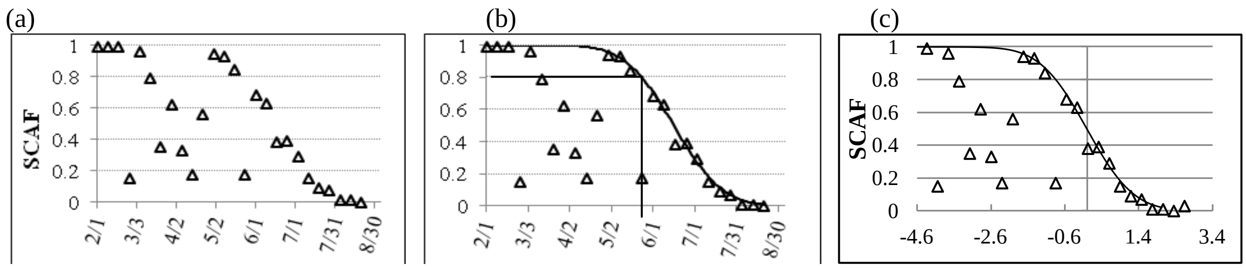

Figure 3. (a) Plot of snow cover area fractions (SCAF) from MODIS images in 2011 snowmelt season (b) Plot of SCAF from MODIS images in 2011 fitted with a Gaussian curve (c) Plot of SCAF from MODIS images in 2011 with normalized dates (ND). The observed scatter (points well below the CDC curve) was largely associated with periods of cloud cover. **Note**: The line in plot ‘b’ pointed to the image corresponding to the 80% centile

Three hundred and eight remotely sensed images (MODIS 8-day snow cover images) were used, covering the period from February into August for the years 2001-2011. Each MODIS image covered a large portion of the Northwestern United States. The images were processed in ArcGIS to extract the basin area, and then calculate the fraction of snow covered area within the basin.

Identifying and establishing the stability of spatial and temporal patterns of snow during the ablation process constitute a major challenge to the effective use of patterns. Hence, it was important to (i) Identify if there are patterns (ii) confirm the repetitiveness and the accuracy of the observed patterns, if they exist. Once these are done, the established patterns can be used for wider applications. Visual comparison between images across the years was used to identify repeated patterns. The repetitiveness and the accuracy of the patterns were confirmed using the normalized dates (ND) and the ArcGIS software.

RESULTS AND DISCUSSION

Identifying the Patterns

The time series of the MODIS images of the entire basin were visually compared and qualitatively examined in order to know if there are easily recognizable patterns that are repeated across the years. Figure 4 shows the time series of snowmelt images for the entire study basin during the snow ablation seasons of 2008, 2006, and 2002.

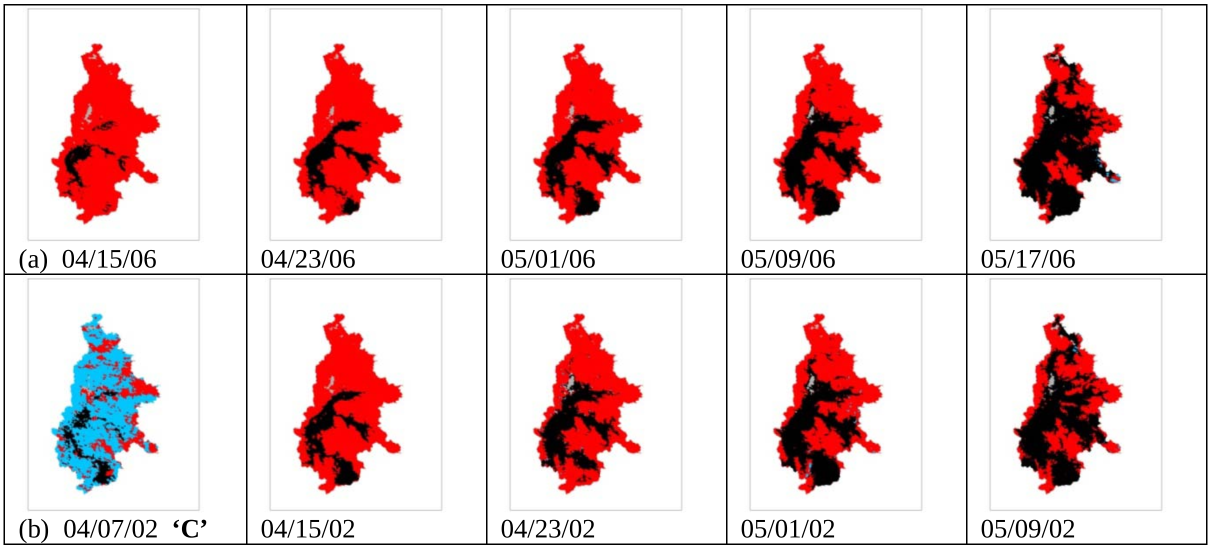

Figure 4. MODIS 8-day snow cover products showing the progression of snow melt for the entire basin from (a) April 15 to May 17, 2006 (b) April 7 to May 9, 2002. The time interval is 8 days. Red represents snow while black, grey, and blue represents land, inland water and cloud, respectively. ‘C’ indicates cloudy periods i.e when the percentage of cloud cover exceeds 15%

<u>Establishing the Accuracy of the Patterns</u>

Based on the normalized dates assigned to the images and the degree of repetitiveness of the snow patterns both spatially and temporally, we selected images within the same range of snow covered area fractions and normalized dates across all the years from the library of images. To further confirm the spatial consistency of snow during the melt season, images representing similar centile across the years are subtracted from each other using arcGIS software. With this procedure, the portions of the basin that either agree or differ on snow cover state between two images were revealed (Figure 5). The figure shows an average accuracy of 93% in spatial consistency between all the MODIS images investigated.

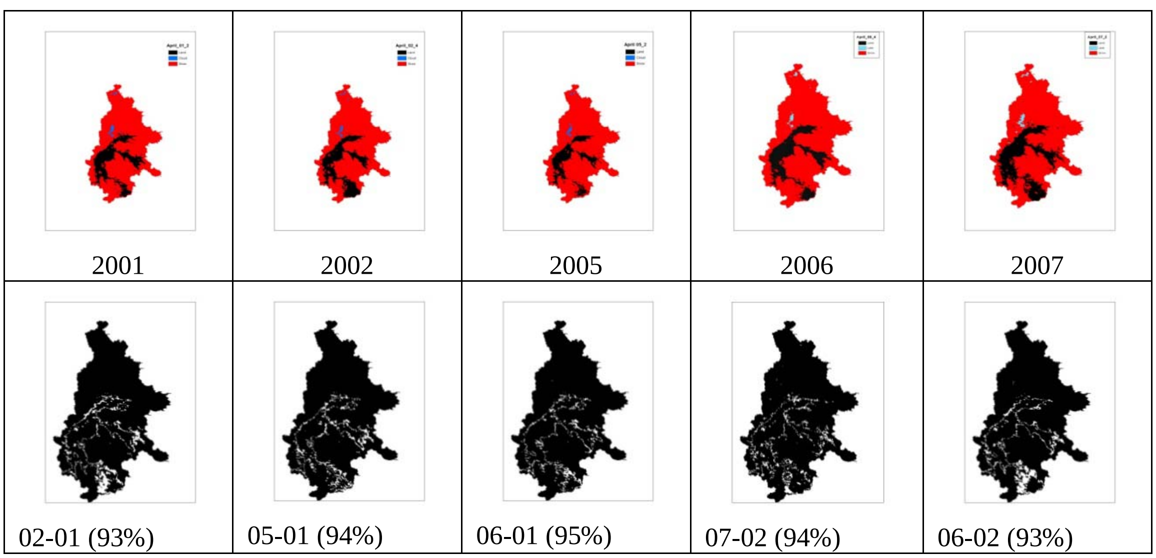

Figure 5. Degree of accuracy of snow images across five years (a) Top panel consists of images corresponding to the 90% centile. But the assigned normalized dates correspond to the SCAF of each of the images (b) Lower Panel consists of differences (represented by white color) and similarities between the images (represented by black color)

Application 1: Cloud Cover Removal

Cloud obscuration in snow maps severely limits the temporal continuity of the satellite coverage and as a result severely constrains their use (Hall et al., 2007). Figure 6 (a and b) shows the basin-wide snow cover images for 2011 before and after cloud removal, respectively.

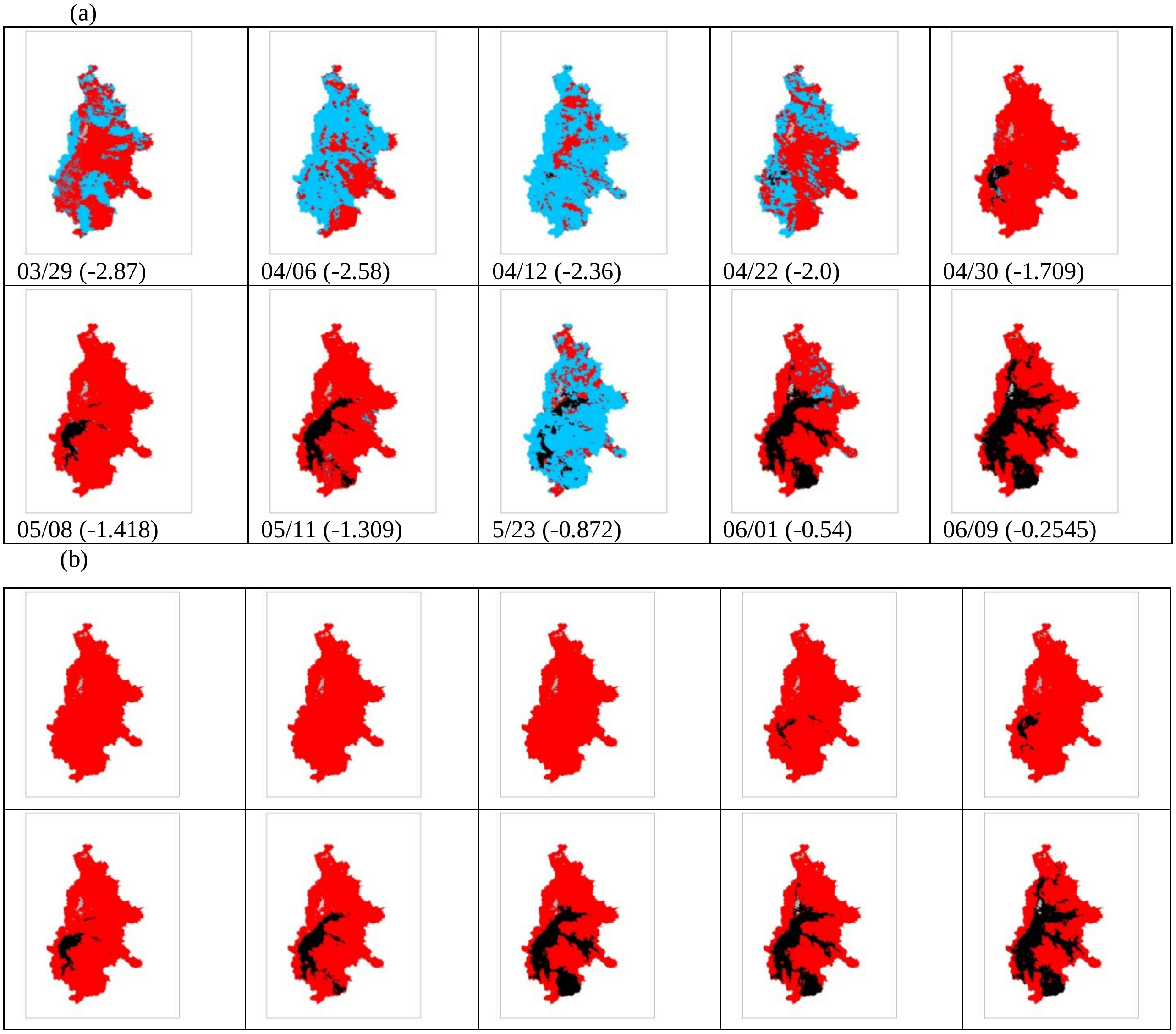

Figure 6. Time series of 8-day MODIS images for the study basin located in western Wyoming in 2011 (a) before cloud removal (the ND of melt and the corresponding calendar dates are written under each image) (b) after cloud removal. Colors red, blue and black represent snow, cloud and land, respectively.

The synthesized images stored in the library were used as a template to determine what state for cloud obscured areas, snow or no snow, ought to be expected, given the spatial pattern of snow cover on the visible portion of the image in comparison to the synthesized template. This procedure was able to filter the cloud cover from over 95% of all the images in 2011 (Figure 6b). However, this filtering approach could sometimes lead to overestimation or under estimation of the snow cover images (±0 to 3%) where there is need to replace images.

Application 2: Processing of Spatial Images for Pre-MODIS Years

Figure 7 shows the time series of spatial images generated for 1996 prior to the installation of MODIS. First, depletion curves for years prior to the launch of MODIS snow cover products were constructed using the relationship between the melt-out dates of snow at eleven Snow Telemetry (SNOTEL) stations located within the study area and SCAF derived from the available MODIS images as explained in Qualls and Arogundade (2012).

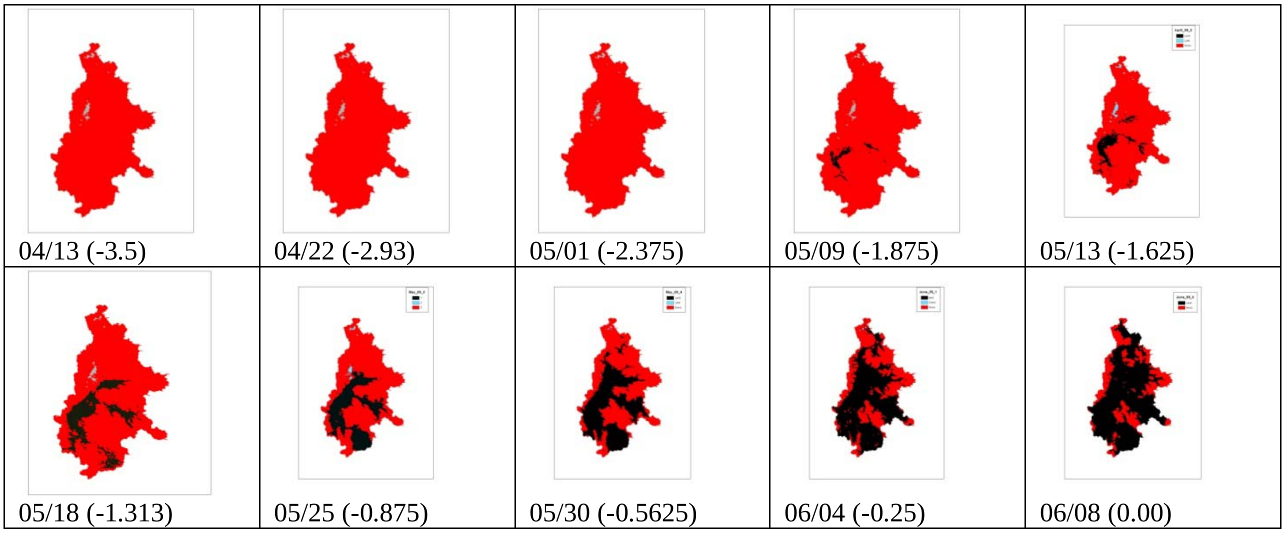

Figure 7. Time series of spatial images generated from the knowledge of spatial and temporal repetitiveness of snowmelt patterns: The normalized dates and the calendar dates for the year (1996) are written under each of the images.

Subsequently, the dates of the depletion curves were normalized (using the mean and the standard deviation of the Gaussian curve as explained in the chart provided in Figure 2) in order to make them comparable with the assigned ND of the images stored in the library (see Figure 2). Thus, the processed spatial images for 1996 (Figure 7) are generated from the library based on the normalized dates.

Study Limitations

Elevation plays a vital role in the consistency of snowmelt patterns in our study basin. It is therefore difficult to say how this model will work in other environments, especially environments where controls such as topography and vegetation are not dominant. Likewise, unusual snowmelt patterns are likely to occur whenever snow transport events occur from atypical directions and this may affect the accuracy of our model. However, our method should work in any environment where the control (e.g elevation) is interannually repeatable.

CONCLUSIONS

Similarities in snow patterns from year to year have a variety of uses but the difficulty in establishing the spatial and temporal stability of the patterns often limits their applications. Once the stability in the patterns are established, they can be used effectively in circumventing the problem of cloud obscuration as well as generating time series of MODIS images for periods pre-dating the launch of MODIS instrument.

Given the confirmation of year-to-year similarity in the observed snowmelt patterns in the study basin which are largely due to controlling factors such as topographical parameters (elevation, aspect and slope), vegetation and synoptic weather patterns that are relatively constant from year to year, we were able to achieve the following:

1. Establish the stability of snowmelt patterns in space and time
2. Confirm the accuracy of the year-to-year similarity in the snowmelt patterns
3. Illustrate how the problem of cloud obscuration and snow/cloud discrimination can be alleviated through the knowledge of snow patterns
4. Demonstrate how spatial images for years predating the launch of MODIS instrument can be generated through the knowledge of snow ablation patterns

While the results presented are for a basin that drains an area of 8,894km^2, the concepts are applicable to smaller or larger basins. The snow modeling community will find the methods and results of this study very useful.

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