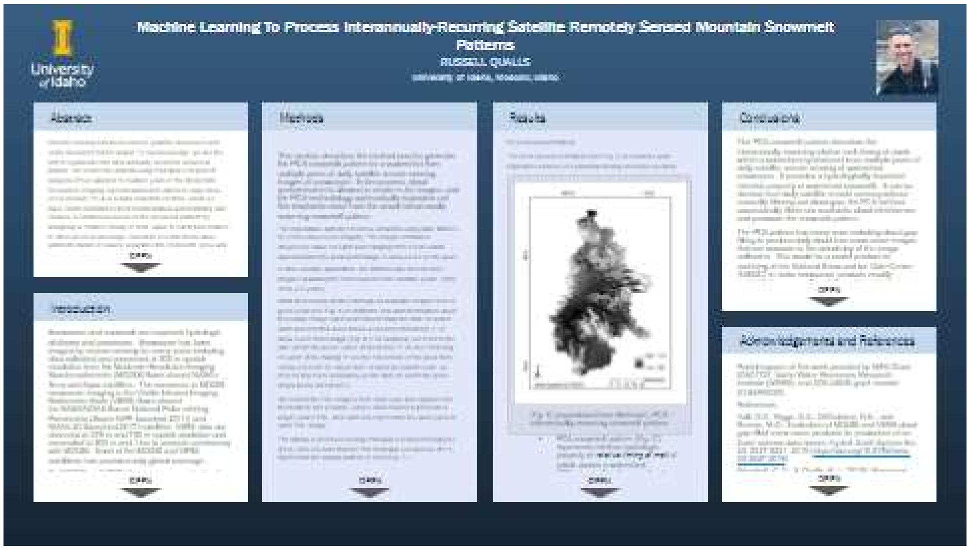
Machine Learning To Process Interannually-Recurring Satellite Remotely Sensed Mountain Snowmelt Patterns



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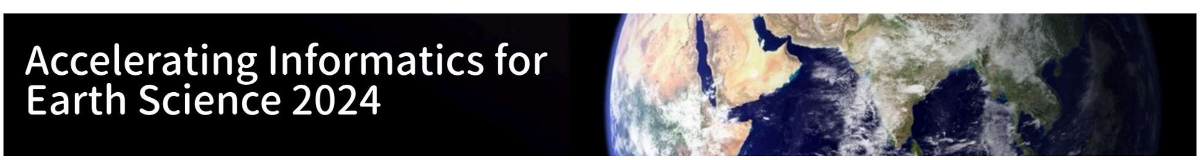


ABSTRACT

Remote sensing has been used to quantify snowcover and verify snowmelt model output. To our knowledge, we are the first to synthesize the inter-annually recurrent snowmelt pattern. We model the pattern using Principal Component Analysis (PCA) applied to multiple years of the MODerate Resolution Imaging Spectroradiameter (MODIS) daily snow cover product. PCA is a data reduction method, which we have found eliminates cloud contamination automatically and creates a continuous model of the snowmelt pattern by assigning a “relative timing of melt” value to each pixel relative to other pixels in an image. Selection of a threshold value within the range of values separates the model into snow and snow-free regions, and the interface represents the corresponding snowline. The model achieves accuracies of 85-98% in the spatial distribution of snow, closely reproducing the snowline, when fit to independent cloud free images over the Upper Snake River Basin in Wyoming, USA (shown below), from 2017 and 2018. Excellent results are also achieved with the PCA model as a cloud removal tool. We relate the spatial model results for the Upper Snake Basin with the time component of melt. when related with time the PCA model acts as the repeatable snow depletion curve (SDC) characteristic to the watershed, where a depletion curve describes change in snow covered area with time. The curve fits any snow melt season with a simple scaling procedure. This novel approach to modeling snow covered area produces spatial information about snowmelt which is repeatable and independent of snowpack and melt timing. The model input requires only remotely sensed imagery making it ideal for gauged and ungauged watersheds. The robust nature of this model opens new and exciting avenues of future research.

INTRODUCTION

Snowcover and snowmelt are important hydrologic attributes and processes. Snowcover has been imaged by remote sensing for many years including data collected and processed at 500 m spatial resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) flown aboard NASA's Terra and Aqua satellites. The successor to MODIS snowcover imaging is the Visible Infrared Imaging Radiometer Suite (VIIRS) flown aboard the NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP, launched 2011)) and NOAA-20 (launched 2017) satellites. VIIRS data are observed at 375 m and 750 m spatial resolution and resampled to 500 m and 1 km to promote consistency with MODIS. Each of the MODIS and VIIRS satellitese has provided daily global coverage.

On MODIS and VIIRS, the snowcover products rely on observations within the visible spectrum, so cloud cover frequently obscures the observations, especially in mountainous areas, and even more so during the spring snowmelt period. Fig. 1A. shows the degree of cloud cover (blue areas) even with 8 days of data composited to eliminate as much cloud cover as possible).

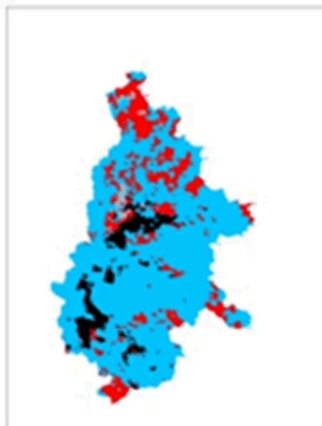


Fig. 1A Typical MODIS Snowcover 8-day composite image with cloud cover from May 23, 2011.

NASA has recently begun to produce a cloud-free MODIS snowcover product which looks backward to the last day a pixel was observed (i.e, without cloud cover) to identify its status of snow-covered or snow-free (Hall, et al., 2019), soncwsequently this cloud-free product looks retrospectively at the watershed, and there is still need for date-of-image cloud-free products.

Woodruff and Qualls (2019) distilled multiple years of remotely sensed imagery using Principal Component Analysis (PCA) to synthesize the inter-annually recurring spatial pattern of snowmelt. The PCA model provides the relative melt timing of pixels qacross a basin and represents an intrinsic hydrologic property of the watershed.

This poster describes how the PCA pattern is generated, and several of its uses. The example used is the Upper Snake Basin located in the northwest corner of the US state of Wyoming (Fig 1B.) The area of this basin is approximately 9000 km^2.

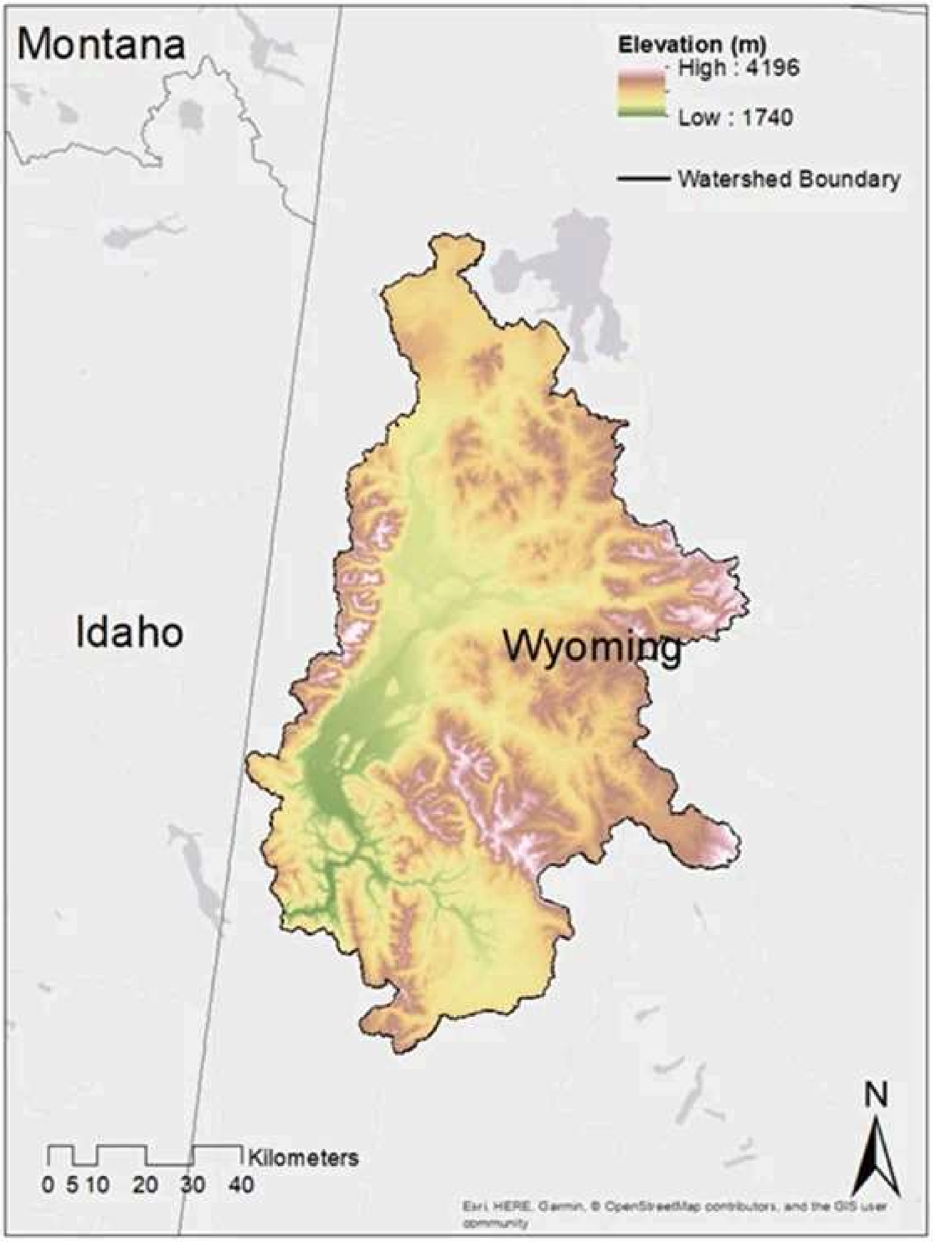


Fig. 1B. Upper Snake River basin, Wyoming, USA.

METHODS

This section describes the method used to generate the PCA snowmelt pattern for a watershed from multiple years of daily satellite remote sensing images of snowcover. In the process, cloud contamination is allowed to reside in the images, and the PCA methodology automatically separates out this stochastic noise from the actual interannually recurring snowmelt pattern.

The repeatable pattern of melt is extracted using daily MODIS or VIIRS snow cover imagery. The images contain a snowcover value for each pixel ranging from 0-100 which approximates the areal percentage of snowcover on the pixel.

In this example application, the pattern was derived from images spanning the melt seasons from multiple years, 2000-2016 (17 years).

Initial processing iterates through all available images from a given year (see Fig. A) to distill the relevant information down to a single image each year representing the date on which each pixel melted down below a specified threshold, c, of snow cover percentage (Fig. B).For simplicity, we refer to the date when the pixel's value drops below "c" as the "First Day of Land" (FDL) taking "c" as the conversion of the pixel from "snow-covered" to "snow-free" or land (in current work, we refer to this more accurately as the date on which the pixel drops below threshold c).

We collect the FDL images from each year and organize the information into a matrix, where each column represents a single year's FDL, and each row represents the same pixel in each FDL image.

The Matrix is processed using Principal Component Analysis (PCA) and it results that the first Principal Component (PC1) represents the spatial pattern of melt (Fig. C.)

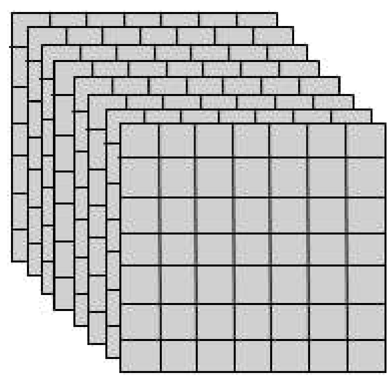
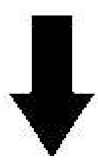


Fig A. Series of daily MODIS or VIIRS snowcover images during annual snowmelt period.



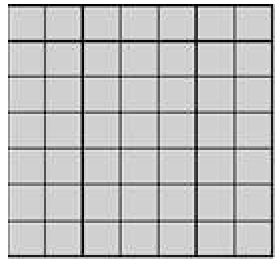
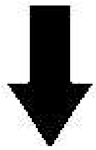


Fig. B. Annual synthesis image of "First Day of Land" (FDL) dates distilled from collection of daily images.



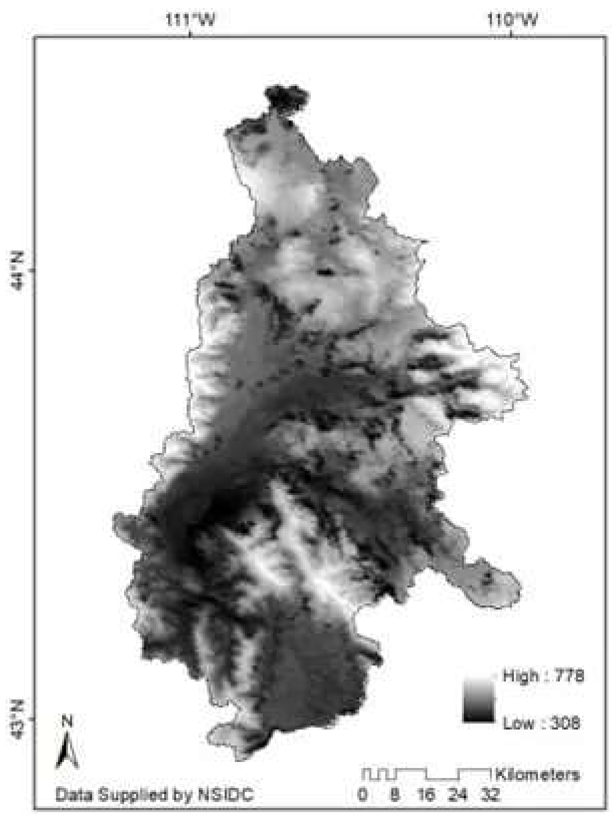


Fig. C. Interannually recurrent Snowmelt Pattern synthesized by PCA from collection of annual FDL images. Dark areas represent early melt; lighter colors represent areas which melt later in melt season; pixels with similar colors melt at approximately the same time as each other each year even though the date of that melt may vary widely from year to year.

RESULTS

PCA Snowmelt Pattern

The PCA snowmelt Pattern from Fig. C in methods (and reproduced below) is a principal finding from this research.

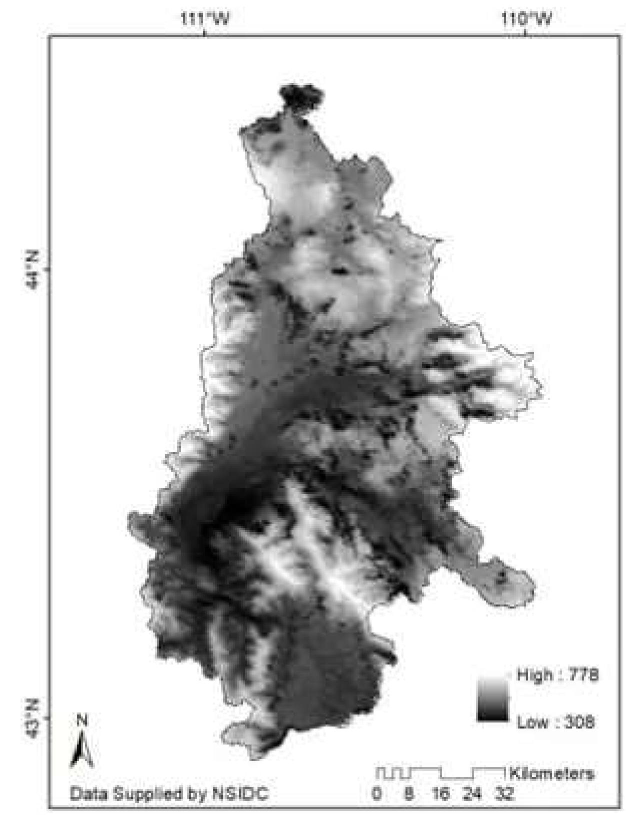


Fig. C (reproduced from Methods), PCA interannually-recurring snowmelt pattern.

- PCA snowmelt pattern (Fig. C) represents intrinsic hydrologic property of *relative timing of melt* of pixels across a watershed.
- PCA snowmelt pattern applies to any year.
- PCA snowmelt pattern has broad applications. Examples include:
  - Image cloud-gap-filling
  - Production of nearly complete cloud-free time series of snowcover images.
  - Distributed snowmelt runoff modeling
  - Climate change snowmelt simulation/assessment
  - Serve as example technique for processing other snow-relevant data sets such as albedo.
  - Providing a component to model snow water equivalent (SWE)

Cloud-Gap Filling

Cloud obscuration has been a significant problem preventing widespread use of MODIS (and now VIIRS) snowcover images in modeling snowmelt. The PCA snowmelt pattern can be used to fill cloud-gaps in snowcover images with great accuracy, and produce nearly complete time series of cloud-free imagery.

Fig. D. shows a typical binary MODIS snowcover image (separated by threshold c-value, where values above c, shown in blue, are considered snowcovered, and values below c, shown in brown are considered snowfree land). An artificial cloud (diagonal cross-hatching) has been imposed over the image, darkening the snow and snow-free areas. Brighter blue and brown areas are cloudless. The two areas encircled by red ovals each contain small sections where the snowline (interface between blue and brown) is visible without cloud cover. These small interface segments can be located on the PCA snowmelt pattern (Fig. C), and used to infill the cloud-obscured snowline across the whole image (black line). As can be seen, the black modeled snowline from the PCA image nearly perfectly traces the actual snowline (blue/brown interface) from the MODIS image. The PCA model is a powerful tool to generate cloud-free images.

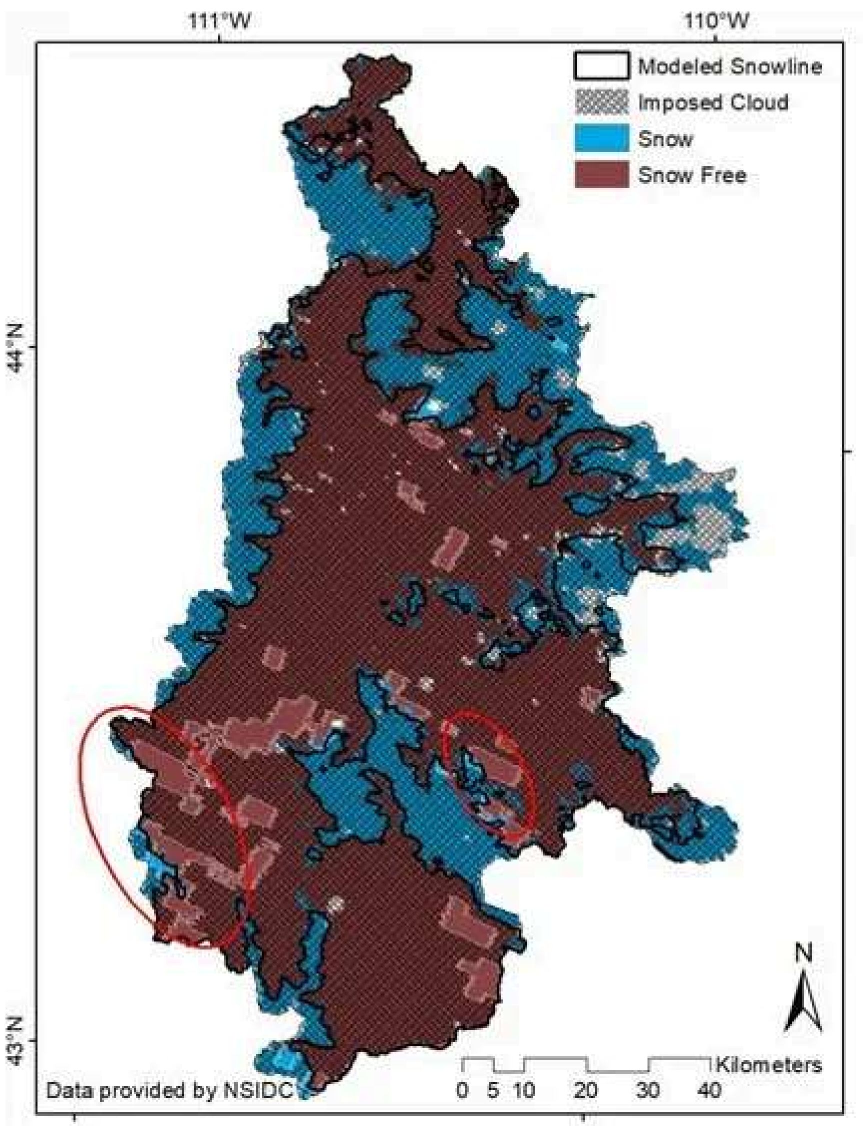


Fig. D. Cloud-gap filling example

Production of Snow Depletion Curves (SDC) for snowmelt modeling and intercomparison of meltout across years.

Identification of 25, 50 and 75 percent snowcover snowlines on the inter-annually recurrent snowmelt pattern

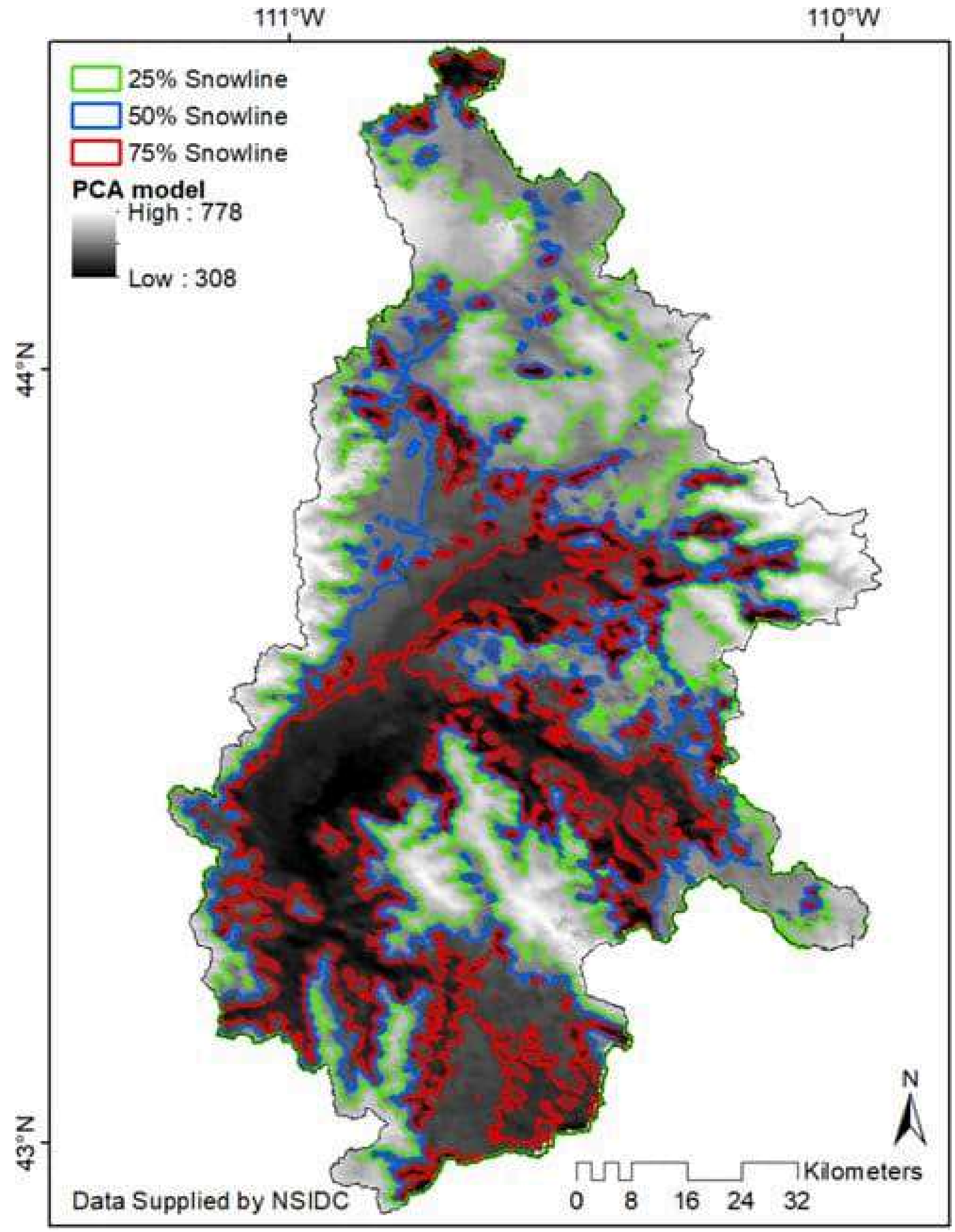


Fig. E. Superposition of snowlines from different dates (and images) during melt season where there remained 75, 50 and 25% snowcovered area. These values of snowcovered area can be plotted as a time series (adding in incremental values of % snowcover from other daily images throughout melt season) to represent SDCs (Fig.F) for spatially-lumped snowmelt models.

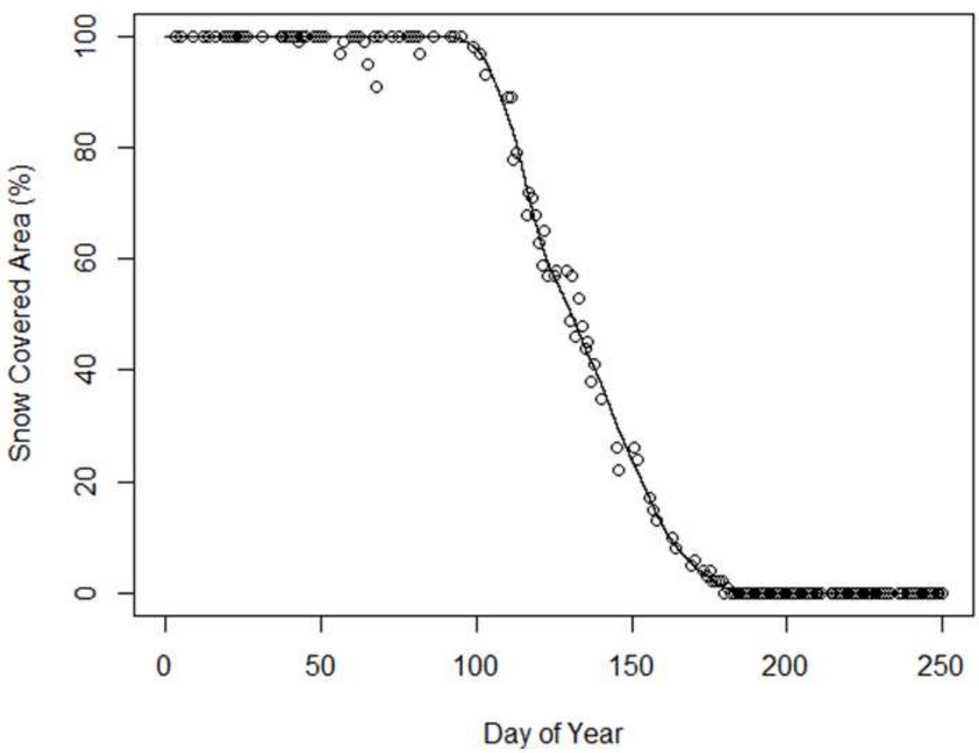


Fig. F. Snow depletion curve (SDC). Time series graph of melt-season snow covered area (2006)

CONCLUSIONS

The PCA snowmelt pattern describes the interannually-recurring relative melt timing of pixels within a watershed synthesized from multiple years of daily satellite remote sensing of watershed snowcover. It provides a hydrologically important intrinisic property of watershed snowmelt. It can be derived from daily satellite remote sensing without manually filtering out cloud gap; the PCA method automatically filters out stochastic cloud interference and produces the snowmelt pattern.

The PCA pattern has many uses including cloud-gap-filling to produce daily cloud-free snow-cover images that are accurate to the actual day of the image collection. This would be a useful product for archiving at the National Snow and Ice Date Center (NSIDC) to make snowcover products readily available for snowmelt modeling, either distributed or lumped.

The general PCA method may be useful for processing other snow products such as albedo. This machine learning technique has the potential to open many additional uses for NASA snow products by generating value-added products for end-users.

ACKNOWLEDGEMENTS AND REFERENCES

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References

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TRANSCRIPT