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# Multitemporal snow cover mapping in mountainous terrain for Landsat climate data record development

Christopher J. Crawford [a,*], Steven M. Manson [a], Marvin E. Bauer [b], Dorothy K. Hall [c]

[a] Department of Geography, University of Minnesota-Twin Cities, Minneapolis, MN 55455, United States
[b] Department of Forest Resources, University of Minnesota-Twin Cities, St. Paul, MN 55108, United States
[c] Cryospheric Sciences Laboratory, Code 615, NASA Goddard Space Flight Center, Greenbelt, MD 20771, United States

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ABSTRACT

A multitemporal method to map snow cover in mountainous terrain is proposed to guide Landsat climate data record (CDR) development. The Landsat image archive including MSS, TM, and ETM+ imagery was used to construct a prototype Landsat snow cover CDR for the interior northwestern United States. Landsat snow cover CDRs are designed to capture snow-covered area (SCA) variability at discrete bi-monthly intervals that correspond to ground-based snow telemetry (SNOTEL) snow-water-equivalent (SWE) measurements. The June 1 bi-monthly interval was selected for initial CDR development, and was based on peak snowmelt timing for this mountainous region. Fifty-four Landsat images from 1975 to 2011 were pre-processed that included image registration, top-of-the-atmosphere (TOA) reflectance conversion, cloud and shadow masking, and topographic normalization. Snow covered pixels were retrieved using the normalized difference snow index (NDSI) and unsupervised classification, and pixels having greater (less) than 50% snow cover were classified presence (absence). A normalized SCA equation was derived to independently estimate SCA given missing image coverage and cloud-shadow contamination. Relative frequency maps of missing pixels were assembled to assess whether systematic biases were embedded within this Landsat CDR. Our results suggest that it is possible to confidently estimate historical bi-monthly SCA from partially cloudy Landsat images. This multitemporal method is intended to guide Landsat CDR development for freshwater-scarce regions of the western US to monitor climate-driven changes in mountain snowpack extent.
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## 1. Introduction

Continental ice sheets, sea ice, permafrost, and hemispheric-scale seasonal snow cover play an important role in regulating the Earth's radiation balance, and poleward-equatorial latent heat transport during hemispheric cool-seasons (Barry, 2002). Equally important, mountain glaciers and seasonal snow cover (extent) in the form of mountain snowpack (depth) feed seasonal streamflow and replenish hydrological catchments (Barnett et al., 2005; Winther & Hall, 1999). Across the arid western US, mountain ranges serve as seasonal water towers that hold and release snowpack freshwater resources through successive snow accumulation and melt. Snow-fed streamflow contributes approximately 50–70% to the total western US annual water budget (Cayan, 1996). With an automated temporally discrete snow telemetry (SNOTEL) snow-water-equivalent (SWE) measurement network already in place for hydrological forecasting (Serreze et al., 1999), it is quite clear that spatially-explicit, satellite-derived climate data record (CDR) development can augment western US mountain snow-covered area (SCA) monitoring on past, present, and future timescales.

Evidence is mounting for alarming declines in western US mountain snowpack as well as decreasing Northern Hemisphere spring snow cover extent (Brown & Robinson, 2011; Derksen & Brown, 2012; Hamlet et al., 2005; Mote et al., 2005; Pierce et al., 2008). Declining snowpack trends have been linked to warming springtime temperatures that trigger earlier and faster snowmelt (Cayan et al., 2001; Westerling et al., 2006). Knowles et al. (2006) find in their assessment of precipitation–snow ratios that snowpack in lower elevation zones are melting faster with temperature-driven phase changes in water. Therefore, blending spatially derived snow cover CDRs, topographic models, SNOTEL SWE, and instrumental climate observations using time-series analysis techniques could advance efforts to examine historical trends in mountain snowpack extent, but has not been attempted because of lacking satellite CDR availability.

Over the past four decades, optical remote sensing has provided a critically important data source for observing the Earth's changing cryosphere. Multispectral imagery acquired by Advanced Very-High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat multispectral scanner system

* Corresponding author at: Department of Geography, University of Minnesota-Twin Cities, 414 Social Sciences, 267 19th Ave. S, Minneapolis, MN 55455, United States. Tel.: +1 612 625 8949.
*E-mail address:* crawf188@umn.edu (C.J. Crawford).

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(MSS), Landsat Thematic Mapper (TM), and Landsat Enhanced Thematic Mapper Plus (ETM+) platforms at different pixel resolutions enable snow cover retrieval over continental regions. Snow exhibits high–moderately high reflectances at visible wavelengths and low reflectances at near-infrared wavelengths (Warren, 1982; Wiscombe & Warren, 1980). These spectral characteristics allow for pixel level snow retrieval and classification at acceptable thematic and spatial accuracy (Dozier, 1984; Dozier & Painter, 2004; Hall & Martinec, 1985). Specific advantages to monitoring snow cover using satellite platforms include daily-weekly image acquisitions, broad-scale spatial coverage over remote mountain and high latitude regions (Dozier, 1989; Dozier & Painter, 2004; Hall & Martinec, 1985; Rosenthal & Dozier, 1996), and most importantly, the Landsat mission provides a fairly continuous historical image record at recurrent intervals. This paper uses the entire Landsat image archive to map mountain SCA since the 1970s.

A multitemporal method is proposed to guide Landsat snow cover CDR development for freshwater-scarce regions of the western US. Historically, the cost of digital imagery hindered multitemporal mapping and use of partially cloudy images. With a now freely available image archive at the USGS EROS Data Center (http://eros.usgs.gov/) from Landsat's MSS, TM, and ETM+ mission, the opportunity to construct CDRs on climatically relevant timescales is now possible without the high cost. On the other hand, raw data availability first requires that sound methods for Landsat CDR development be outlined through a concept description and data demonstration. This initial step ensures that Landsat snow cover CDR products are spatially and temporally accurate, radiometrically consistent, and interoperable with MODIS snow products from the outset (Hall et al., 2002b).

This paper introduces an operational multitemporal method to map SCA in mountainous terrain to support Landsat CDR development. A prototype Landsat snow cover CDR for peak snowmelt is demonstrated for an interior northwestern US sub-region, namely the central Idaho and southwestern Montana mountains. This continental sub-region was selected for its Pacific Ocean influenced climatology, intermountain hydrological basin significance, and high topographic relief within the broader northern Rocky Mountain region. This study region is also motivated by the need for more basic satellite research on continental snow cover patterns and processes in mountainous terrain. The paper is organized as follows. Section two outlines a multitemporal method for snow cover mapping in mountainous terrain using the Landsat image archive. This section describes how Landsat snow cover CDRs are derived using a normalized SCA equation, and assesses whether the prototype Landsat CDR contains systematic biases that arise from missing imagery and/or cloud-shadow contamination. The Landsat snow cover CDR is then evaluated to determine whether scale parameterization influences the probability distribution and time domain variance of SCA. Section three presents the results obtained from the multitemporal method and prototype SCA time-series. Section four discusses current Landsat snow cover CDR development including efforts to monitor climate-driven changes in mountain snowpack extent.

## 2. Multitemporal method for Landsat CDR development

### 2.1. Landsat archival imagery and study region description

Landsat World Reference System (WRS)-1 and WRS-2 path–row image acquisitions over the prototype study region depend on the sensor and year of acquisition (Table 1). For this June 1 snow cover CDR, Landsat MSS, TM, ETM+ SLC-on, and ETM+ SLC-off images were collected during the Julian dates 143 and 158 for 1973–2011. Scan line coverage (SLC) 'on' and 'off' images reflect time periods for 'pre' and 'post' sensor malfunctions on Landsat ETM+. Landsat ETM+ SLC-off images have stripes that contain missing pixels across the image. SLC-off pixels have no data and are considered missing coverage. All images were pre-processed, mosaicked, and classified for snow cover using the multitemporal method outlined below.

**Table 1**
Archival Landsat imagery used for June 1 snow cover CDR development.

| Landsat sensor | Julian bi-monthly interval | Time period | Path–rows | Images used (n) |
|---|---|---|---|---|
| MSS 1–3 | 143–158 | 1973–1983 | 42–29, 43–29 | 5 |
| MSS 4–5 | 143–158 | 1982–1995 | 39–29, 40–29 | 4 |
| TM 4–5 | 143–158 | 1984–2011 | 39–29, 40–29 | 33 |
| ETM + 7 SLC-on | 143–158 | 1999–2003 | 39–29, 40–29 | 4 |
| ETM + 7 SLC-off | 143–158 | 2003–2011 | 39–29, 40–29 | 8 |

The Landsat snow cover CDR demonstrated is a prototype time-series of June 1 SCA for the central Idaho and southwestern Montana mountains (Fig. 1). This June 1 CDR captures SCA variability during peak snowmelt for 1975–2011 (Figs. 2 and 3). Much of the SCA on or near June 1 for this region is confined to mid-high elevations — low elevation zones have already melted out. The central Idaho and southwestern Montana mountains are situated within a continental semi-arid climate zone (Mitchell, 1976) with both local and regional hydrological significance. These snow-fed rivers and tributaries form the headwaters of the Columbia and Missouri River basins and support potable water uses, hydropower generation, fishery migration, agricultural irrigation, and recreation.

### 2.2. Landsat snow cover CDR design

Seasonal mountain snowpack across the Idaho–Montana region begins to accumulate in mid-October and reaches maximum SWE around early-mid April (Cayan, 1996). During the winter season (December–March), SCA in mountainous terrain more or less remains near maximum coverage at high elevations with lower elevations exhibiting daily–weekly variability due to short-term meteorological conditions. Once spring arrives, snow cover (snowpack) begins to successively melt with increasing solar irradiance, decreasing albedo, and warming springtime temperatures. Thus, variability in mountain SCA during snow accumulation and snowmelt periods has been, is, and will continue to be retrieved by each Landsat overpass.

Landsat snow cover CDR development is limited by the 16–18 day repeat schedule, which roughly corresponds to a bi-monthly interval. This temporal structure enables the potential to fully use all available Landsat images through compositing, especially in areas where image overlap allows 8–9 day coverage. Landsat snow cover CDRs are based on SNOTEL SWE bi-monthly sampling intervals centered on days 1 and 15 of each calendar month (Serreze et al., 1999), where Landsat images on days 8–22 are assigned to the mid-month interval, and days 23–7 mark the end–beginning month interval (Fig. 2). These discrete bi-monthly intervals allow for SCA to be mapped at seasonal, interannual, and decadal timescales across a defined spatial domain. This spatial domain involves a latitude–longitude grid that covers an explicit geographic area. This Landsat CDR grid design provides a workable geographic scale to manage data volume and overlapping images, preserve spectral properties, and facilitate statistical integration with gridded ground-based instrumental climate records.

### 2.3. Image registration

Geo-referencing images to a target coordinate system requires either ground control points or ancillary spatial data such as a digital elevation model (DEM) to accurately assign pixels to an exact latitude–longitude position (Seidel et al., 1983). Most available Landsat images from the EROS Data Center have already been processed to a standard-level of geometric and terrain accuracy (http://landsat.usgs.gov/Landsat_Processing_Details.php). Geometric errors may

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