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Automated mapping of persistent ice and snow cover across the western U.S. with Landsat

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ABSTRACT

We implemented an automated approach for mapping persistent ice and snow cover (PISC) across the conterminous western U.S. using all available Landsat TM and ETM+ scenes acquired during the late summer/early fall period between 2010 and 2014. Two separate validation approaches indicate this dataset provides a more accurate representation of glacial ice and perennial snow cover for the region than either the U.S. glacier database derived from US Geological Survey (USGS) Digital Raster Graphics (DRG) maps (based on aerial photography primarily from the 1960s–1980s) or the National Land Cover Database 2011 perennial ice and snow cover class. Our 2010–2014 Landsat-derived dataset indicates 28% less glacier and perennial snow cover than the USGS DRG dataset. There are larger differences between the datasets in some regions, such as the Rocky Mountains of Northwest Wyoming and Southwest Montana, where the Landsat dataset indicates 54% less PISC area. Analysis of Landsat scenes from 1987–1988 and 2008–2010 for three regions using a more conventional, semi-automated approach indicates substantial decreases in glaciers and perennial snow cover that correlate with differences between PISC mapped by the USGS DRG dataset and the automated Landsat-derived dataset. This suggests that most of the differences in PISC between the USGS DRG and the Landsat-derived dataset can be attributed to decreases in PISC, as opposed to differences between mapping techniques. While the dataset produced by the automated Landsat mapping approach is not designed to serve as a conventional glacier inventory that provides glacier outlines and attribute information, it allows for an updated estimate of PISC for the conterminous U.S. as well as for smaller regions. Additionally, the new dataset highlights areas where decreases in PISC have been most significant over the past 25–50 years.

1. Introduction

Glaciers act as sensitive indicators of climate change (Lemke et al., 2007; Oerlemans, 2005), responding to both changes in temperature and precipitation (McCabe and Fountain, 2013). Along with perennial and seasonal snow cover, they often serve as an important source of freshwater runoff for people living downstream (Barnett et al., 2005; Immerzeel et al., 2010), but can also pose a risk to these populations due to glacial lake outburst floods and other hazards (Kääb et al., 2005; Moore et al., 2009; Richardson and Reynolds, 2000). Perennial snow cover is also common in regions with glaciers and is often present in regions where glaciers are absent or have recently disappeared.

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Substantial evidence indicates that the majority of the world's glaciers are currently retreating (Dyurgerov and Meier, 2000; Kaser et al., 2006; Stocker et al., 2014), although rates of ice loss vary substantially across regions and over time. Extensive loss of glacier ice has been documented across the Western conterminous United States and the neighboring Canadian provinces of British Columbia and Alberta. Glacier area decreased by 7% between 1958 and 1998 in the North Cascades of Washington (Granshaw and Fountain, 2006), the region with the largest concentration of ice cover in the conterminous U.S. Several hundred kilometers to the south, glaciers have declined in area on Mount Adams by 49% between 1904 and 2006 (Sitts et al., 2010). Further south, in the Sierra Nevada of California, an average ice loss of 55% occurred between 1903 and 2004 (Basagic and Fountain, 2011). In the Rocky Mountains of Wyoming, ice cover decreased in the Wind River Range by approximately 47% between 1900 and 2006 (DeVisser and Fountain, 2015), and 39% between 1967 and 2006 (Maloof et al., 2014). In the nearby Teton Range, ice cover declined by

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25% between 1967 and 2006 (Edmunds et al., 2012). In Glacier National Park in northwest Montana, glaciers in the Blackfoot-Jackson Basin declined in area by 66% between 1850 and 1979 (Hall and Fagre, 2003) and by 29% between 1966 and 2005 (US Geological Survey 2013). Finally, in adjacent areas of Canada, glaciers decreased in area by 11% in British Columbia and 24% in Alberta between 1985 and 2005 (Bolch et al., 2010).

Although the loss of ice has been well documented for individual glaciers and small regions and many of these efforts have produced updated glacier inventories, the best available glacier database covering the entire conterminous western U.S. remains a dataset that is based on aerial photography flown primarily between the 1960s and 1980s. This dataset, hereafter referred to as the USGS DRG dataset, is derived from 1:100,000 US Geological Survey Digital Raster Graphics (DRG) map products and is available online at http://glaciers.us/Downloads (Fountain et al., 2007). The well-documented pattern of glacier retreat across the region means that this inventory, which is generally 25–50 years old, will not reflect the current state of glaciers and perennial snow cover across many areas in the region. An updated inventory of glaciers and perennial snow covering the entire region and attributable to a well constrained period within the last few years is thus needed. A comprehensive, precise inventory of glaciers covering the entire region based on recent high spatial resolution imagery at sub-meter resolution would require a substantial amount of resources to acquire and process the necessary imagery as well as digitize and label all glacier and perennial snow cover features. While updated DRGs and associated National Hydrography Dataset layers have been produced for many areas, the majority of the updates are based on imagery 5–15 years old that cover a >10 year range in dates and have not been compiled into a single regional inventory of glaciers and perennial snow cover. More importantly, given high rates of change for glaciers and perennial snow cover, any updated dataset is likely to become outdated within just a few years.

Recently, several studies have demonstrated the feasibility of monitoring snow and ice conditions across individual glaciers or small basins using ground-based high spatial resolution time lapse photography (Farinotti et al., 2010; Bernard et al., 2013). In addition, airborne monitoring approaches have been increasingly utilized to provide regularly updated estimates of snow cover conditions including areal extent and snow depth for portions of mountain ranges (McGurk and Painter, 2013). Despite the effectiveness of these approaches and the rich information they can provide, implementing these approaches across a region as large as the Western U.S. has not been feasible due to high costs.

A potential alternative to techniques using regular ground-based or airborne monitoring approaches is to use an automated mapping approach to develop a map of persistent ice and snow covered area (PISC) from satellite imagery that can be updated automatically every few years as new imagery becomes available. Data from the Landsat series of sensors have been widely used for nearly thirty years for mapping glaciers and perennial snow cover (Aniya et al., 1996; Hall et al., 1987; Jacobs et al., 1997; Ventura et al., 1987), with recent efforts covering regions as large or larger than the western U.S. (Bolch et al., 2010; Guo et al., 2015; Rastner et al., 2012). Many recent mapping efforts have begun to incorporate semi-automated mapping approaches rather than traditional manual digitization techniques. Even semi-automated mapping approaches, however, typically still require a substantial effort to select the most appropriate scenes to minimize cloud-cover and seasonal snow cover. The effort required for scene selection becomes quite substantial if the region of interest covers more than a few Landsat scenes, as is the case in the western U.S.

In 2008, the US Geological Survey made all Landsat scenes available to the scientific community at no-cost, enabling new research that exploited the availability of numerous scenes acquired over time covering a single frame (referred to as a path/row). Since the opening of the archive, a number of recent studies covering a wide range of remote sensing applications have demonstrated the utility of processing stacks of Landsat scenes to monitor the evolution of land surface characteristics and ultimately extract information that could not be provided by individual scenes or even annual scene acquisitions. These studies have included impervious surface mapping (Zhang and Weng, 2016), surface water monitoring (Tulbure and Broich, 2013), forest mapping (Zhu and Liu, 2014), and seasonal snow cover monitoring (Macander et al., 2015). Along these lines, Selkowitz and Forster (2015) recently developed an automated PISC mapping approach that considers all available Landsat scenes for a given time period (typically 5 years) and does not require an analyst to select the most appropriate scenes. This type of fully automated approach has some disadvantages because it does not capitalize on an analyst's ability to select the best scenes or distinguish between ice and seasonal snow cover based on contextual clues. It has an important advantage, however, in that it can be implemented for a large region such as the western U.S. quickly and with far fewer resources than would be required for a conventional manual or semi-automated glacier inventory.

Here we present an updated 30 m resolution map of PISC across the conterminous western United States developed using a fully automated mapping approach that exploits all available Landsat TM and ETM+ scenes acquired between August 20 and September 30 during the 2010–2014 period. The approach can potentially be implemented in any region with sufficient Landsat scene availability. The new dataset allows for updated estimates of PISC area across the western U.S. and for individual sub-regions or mountain ranges, and, in conjunction with the existing glacier inventory derived from USGS topographic maps, can be used to construct rough estimates of changes in PISC area since the mid to late 20th century.

Before proceeding, it is important to note that while glaciers are moving bodies of ice and perennial snow cover patches are merely snowfields that persist for many years without disappearing, in practice, it is not always straightforward to differentiate between small glaciers and perennial snow cover patches. This is particularly true when mapping is conducted via remote sensing. In the United States, standard topographic maps produced by the USGS and used to construct the US Glacier inventory have not, in most cases, formally differentiated between glaciers and perennial snow cover patches, and in some cases may even include late lying seasonal snow cover patches (Fountain et al., 2007). While we recognize that an ideal dataset would effectively distinguish between glaciers, perennial snow cover, and late lying seasonal snow cover, we also recognize that this is often not possible when inventories are developed using remote sensing. Therefore, we refer to all areas mapped as perennial ice or snow features as persistent ice or snow cover (PISC) to avoid any confusion.

2. Study area and methods

2.1. Study area

The Landsat-derived PISC map covers the western half of the conterminous United States and includes all mountain ranges where PISC was mapped in the USGS DRG dataset (Fig. 1). The major mountain ranges of the western United States with perennial snow and ice features include the Cascades in Washington, Oregon, and northern California, the Olympic Mountains in Washington, the Sierra Nevada in California, and the Rocky Mountains in Colorado, Wyoming, Montana, and Idaho. Several small glaciers and perennial snow cover patches have also been identified in smaller mountain ranges located between the coastal